JOHN WESLEY MITCHELL

BIOGRAPHICAL NOTES

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BACKGROUND

JOHN WESLEY MITCHELL (Jack to his friends) was born in Christchurch, New Zealand, on 3 December 1913, the only child of John Wesley Mitchell and Lucy Ruth Snowball. On both sides of his family he was descended from pioneering emigrants. William Mitchell was born in Edinburgh about 1590. With his brother John, he emigrated to Bermuda in 1612, sailing from London in the "Samuel," owned and commanded by Samuel Stone. The two brothers and Samuel Stone are buried in the Old Devonshire Churchyard on Middle Road between Hamilton and St. Georges. William Mitchell married Elizabeth Gibbs before 1619, and their great-grandson, John Mitchell I, migrated to the eastern shore of Maryland in 1684 where he began acquiring land on the southern bank of the Choptank River near what is now Cornersville in Dorchester County. These acquisitions were continued by his son, John Mitchell II, who was born in 1709 and died in 1815 at the age of 106 years. The Mitchells Garden plantation was surveyed in 1750, and John Mitchell II and many of his descendants were buried in the cemetery there until 1863. His grandson, John Wesley Mitchell I, was born in Easton, Talbot County, Maryland, in 1791 and later returned to the plantation at Cornersville where John Wesley Mitchell II was born in 1823. John Wesley Mitchell III was born in Avalon, Talbot County, in 1851. He moved to Derby, Connecticut, after the end of the Civil War and married Mary Jane Bennett there in 1882. John Wesley Mitchell IV was born in 1884 in Derby. The family later moved to Stratford where he attended high school. He took civil engineering

courses at the Stevens Institute of Technology, Hoboken, New Jersey, and was engaged in surveying work in Chile, Western Australia and New Zealand before his marriage in Waimate, South Canterbury, New Zealand, in 1911.

Lucy Ruth Snowball was descended from Allport and Willett families of the Warwickshire and Buckinghamshire Counties of England. Daniel Allport married Sarah Broadhouse in All Saints Church, West Bromwich, on 8 February 1746. Their great-grandson, Thomas Allport Sr., was baptized in St. Mary's Church, Handsworth, on 16 October 1803. He married Jane Weetman in St. Peter's Church, Harbourne, Birmingham, on 10 August 1823 and was a silversmith in Winson Green. Their son Thomas Allport Jr. was born there on 18 September 1824 and became a thimble maker. The family of seven left Gravesend on 17 November 1841 in the barque "London" of 388 tons and after a voyage of nearly five months arrived in Nelson, New Zealand, on 10 April 1842. They existed by "subsistence farming" in the Stoke Valley, for which their previous experience could scarcely have prepared them. Thomas Allport Sr. died 8 October 1875 and his wife Jane on 1 December 1875. They are buried in the cemetery of St. Barnabas Church, Stoke, a little over a mile from the birthplace of Lord Rutherford.

Thomas Allport Jr. went to Australia in search of work in 1843 or 1844 and married Rachel Willett at Richmond River in northeast New South Wales on 22 March 1847. She was the daughter of George Willett who was baptized in Shenley, Buckinghamshire, 10 September 1804 and of Sarah Maria Tompkins who was born in Stony Stratford in October 1811. They married in 1827, and Rachel was born in Shenley

about 1831 and baptized 1 April 1836. Records of the family in the parishes of Shenley and Leckhampstead near Stony Stratford go back to 1608. George and Sarah Willett with their four children sailed from Deptford on the "St. Vincent" of 628 tons on 8 April and arrived in Sydney on 31 July 1844 after a voyage of nearly three-and-a-half months. They first settled in the Richmond River district of northern New South Wales and then moved to Warwick in the Darling Downs area of southern Queensland. George died on 9 March 1883 and Sarah on 11 January 1902 at the age of 90 years.

After their marriage in Australia, Thomas Jr. and Rachel Allport returned to Nelson and farmed in the Stoke Valley where their daughter Sarah was born 20 August 1855. They moved to Tuamarina in 1865 and thence to Picton. They had eleven children. Thomas Jr. died on 24 February 1900 and Rachel on 6 June 1921 at the age of 90 years. They are buried in Picton Cemetery. Sarah Allport married John Snowball in Picton on 10 March 1881. They farmed at Inglewood near Mt. Egmont in Taranaki where Lucy Ruth Snowball was born 16 August 1887. There were three other children. John Snowball was born in Washington, County of Durham, 22 May 1849. He was the great-great grandson of John Snowball who was born in 1720, died 20 June 1780, and is buried in Hartburn Churchyard. John Snowball was a nephew of Edward Snowball who was born at the White House, Capheaton, Northumberland, 25 January 1830, served his apprenticeship from age 16 at the works of Robert Stephenson and Co., and married Isabel, Robert Stephenson's daughter, before becoming chief draughtsman of the Hyde Park Locomotive Works in Glasgow from 1864 to 1901. He died

on 1 June 1911 at the seaside resort of Girvan. He had been a member of the Institution of Engineers and Shipbuilders for 41 years.

EARLY LIFE IN NEW ZEALAND

Mitchell grew up in Canterbury in close contact with nature around the tussock-covered hillsides of the sheep runs of the foothill ranges of the Southern Alps and the volcanic Banks Peninsula. His father was interested in the flora and geology of New Zealand and had acquired most of the available natural history books. These were usually well illustrated, and Mitchell studied them from an early age. He was encouraged by his father and mother to recognize the native birds and their songs and to learn about their habits. He collected, pressed and mounted specimens and learned the names of the native ferns, plants, shrubs and trees, grouping them in their ecological associations. He also collected specimens and thin chips from the andesitic and basaltic lava flows and radiating trachyte dykes around the crater rim of the Lyttleton volcano, being particularly fascinated by cavities lined with beautiful transparent crystallites which he later learned to be of chabazite, heulandite and other zeolites.

After its formation in 1925, he spent weekends with his father and groups of the Canterbury Mountaineering Club tramping and climbing on Banks Peninsula and the peaks of the foothills. As he grew older and, together with the members of the club more experienced, the range of their expeditions extended to the upper Waimakariri river valley between the foothills and the Southern Alps and through

Arthur's Pass and the other high mountain passes to Westland. They climbed many peaks in these areas and encountered snowfields and glacier ice for the first time.

He visited South Westland several times and after 1929 traveled by train from Christchurch to Ross on the West Coast and thence by bicycle the ninety miles through the dense rain forest to Waiho and the Franz Josef Glacier. On the West Coast, he found what were for him entirely new associations in the flora of the rain forest and, for the first time, metamorphic rocks. Mitchell spent three weeks in 1930 in the old lake bed of the upper Rakaia Valley in Canterbury with C. Caldenius of the Geochronological Institute of Stockholm, smoothing vertical strips on the cliffs and cutting out sections of the varved glacial silt deposits for comparison with those of Sweden. He worked during the summer vacations of 1931-1933 first as a porter and then as a guide at the Franz Josef Glacier Hotel and accompanied many overseas visitors on their expeditions. He always collected and pressed specimens from the successive zones of vegetation from the rain forest at sea level to the highest alpine levels. Within this period, he accompanied Lord Bledisloe, then the Governor General, and Lady Bledisloe on botanical expeditions during which they collected the ferns of the rain forest. His first paper on *The Vegetation of the Arthur Pass National Park* was published in 1935.(77) On all his climbing expeditions he carried a geological hammer, collected specimens from the different regional zones of metamorphic rocks of the Southern Alps, and made thin sections from them when he returned to Christchurch.

He had hoped to study geology at the university, but Professor R. Speight, who had made major contributions to knowledge of the Lyttleton and Akaroa volcanoes of Banks Peninsula, had retired and become Curator of the Canterbury Museum, to be succeeded by a palaeontologist and stratigrapher. Mitchell had no interest in these areas. He began to accompany "Bobby" Speight on his field expeditions in 1930 and was given a thorough and systematic training in crystallography, optical mineralogy, and the petrology of igneous and metamorphic rocks by him. He made many hundreds of thin sections of exceptional quality, including sections of nephrite in which the individual actinolite needles were fully resolved, and learned to use the polarizing microscope as a scientific instrument. He owed much of his lifelong interest in crystalline solids and the processes of physical and chemical change in the solid state to this informal work which satisfied his research instincts. He was, however, warned by Professor H. G. Denham, the head of the Chemistry Department at the university, that he would fail his final B.Sc. examinations if he spent so much time on outside interests. Without being aware of it, he was laying sound foundations for the future. He learned systematic inorganic and physical chemistry from the excellent lectures of H. G. Denham and organic chemistry from those of J. Packer. In mathematics, he was particularly interested in all aspects of geometry and symmetry, in vector methods and vector analysis, and in linear algebra and matrix methods. The lectures of C. C. Farr, F.R.S., and the laboratory work in the Department of Physics failed to challenge him although he was really interested in the subject.

In 1934, he was awarded the Charles Cook Memorial Prize of Canterbury University College for his work on metamorphic petrology and spent his last eight months in New Zealand in 1934-35 on the West Coast of the South Island, systematically studying the zones of regional metamorphism in the Southern Alps and the nephrite masses of the Pounamou formation on the Griffin Range and in the Arahura Valley of northern Westland. He left this open-air life with great reluctance but always retained his interest in natural history.

FORMAL EDUCATION IN NEW ZEALAND

Mitchell completed his primary education at Sydenham School in Christchurch in November 1925, winning the Dux Medal of the school. He went to the Christchurch Boys' High School in March 1926 with a Junior National Scholarship, was awarded a Senior National Scholarship in 1928 and the Walton Mathematics Prize in 1930. He entered Canterbury University College with a University National Scholarhip in 1931 and was awarded the B.Sc. degree in 1934 and the Senior Scholarship of the University of New Zealand in chemistry, having taken courses in mathematics, chemistry and physics. After a further year of study and research, he was awarded the M.Sc. degree in 1935 with First Class Honours in Chemistry and an Overseas Science Research Scholarship of the Royal Commission for the Exhibition of 1851. For the M.Sc. degree, he took the advanced papers in organic chemistry and presented a thesis in physical chemistry which led to an accurate evaluation of the standard potential of zinc and knowledge of the transport properties of zinc bromide solutions.[144]

During the course of this work, he grew his first single crystal which was spontaneously nucleated in a spherical flask filled with a zinc bromide solution with the composition $ZnBr_2.6H_2O$.

UNIVERSITY OF OXFORD

Mitchell left New Zealand in August 1935 and sailed from Sydney through the Suez Canal to Tilbury. He visited Professor Osborn in the Department of Geology of the University of Sydney and Professor E. J. Hartung who had studied the photolysis of silver halides with a microbalance in the nineteen twenties, in the Department of Chemistry of the University of Melbourne. At Oxford he worked with C. N. Hinshelwood, F.R.S. (later Sir Cyril Hinshelwood, P.R.S.), in the Balliol-Trinity Laboratories and became a member of Trinity College, living in college for two years. He first studied the termolecular reaction of nitric oxide with hydrogen and deuterium,[126] interpreting the observations in terms of binary collision complexes, and then the influence of hydrogen and deuterium on the thermal decomposition of diethyl ether in the low-pressure region.[127] There was a profound difference between the deduction of reaction mechanisms in homogeneous gas reactions from observations of pressure changes and the direct observation in thin sections with the petrographic microscope of the solid state reactions of contact and regional metamorphism and the consequences of diffusion processes in ultrabasic zoned bodies. He found the investigation of the photocatalysed thermal decomposition of acetaldehyde, the quantum efficiency for which increased from unity at 100° to several hundreds between 300 and 400° C, to be far more challenging.[128] The quantum efficiency was reduced to unity

by the addition of low pressures of nitric oxide which reacted with and inactivated the methyl free radicals responsible for the catalysing chain reaction. Mitchell then spent a year tutoring students and, with H. W. Thompson, F.R.S., in establishing a laboratory course in atomic and molecular spectroscopy in the Old Chemistry Department. He made a series of discharge tubes for atomic spectra with Pyrex-tungsten glass-metal seals. This experience proved to be important for his later work on high-intensity argon-filled discharge tubes. H. W. Thompson was interested in the thiophosgene molecule. Mitchell photographed the ultraviolet absorption spectrum and made a high-intensity sealed-off helium discharge tube with a water-cooled helical discharge channel and a surrounding cylindrical reflector. With this tube, which had a high efficiency, he photographed the Raman spectrum of thiophosgene stimulated by the red line of helium and was able to analyse the Raman and ultraviolet spectra.

His experiences left him with a deep and lasting affection for Oxford. C. N. Hinshelwood had eased the rather difficult transition from New Zealand with warm encouragement and understanding. E. J. Bowen, F.R.S., roused his interest in photochemical problems, and he learned more systematic inorganic chemistry from N. V. Sidgwick, F.R.S. The Raman work was done with the large-aperture spectrograph of D. J. Jackson, F.R.S., in the Clarendon Laboratory. He had close contacts with the physicists who had come to Oxford from German-speaking countries and attended many of their lectures, particularly those on thermodynamics, wave mechanics and quantum statistics.

He played squash, enjoyed following the footpaths through the meadows, punting on the Cherwell with the bright blue kingfishers on the willow trees, and cycling to the villages of the surrounding countryside. His vacations in 1936 and 1937 were spent in France and Germany, in learning the languages in which he became fluent, and in climbing in Switzerland from huts of the Swiss Alpine Club. He learned Italian in 1938.

He became a member of the Faraday Society at the discussion meeting on "Reaction Kinetics" held at the University of Manchester in September 1937 and thereafter attended many of the discussion meetings. At this time he was uncertain about his future. He knew that he was not interested in continuing research in chemical kinetics in either the gas or liquid phases, but he had not found an alternative area and was having a problem in finding a position. The Faraday Discussion on "Chemical Reactions Involving Solids" at the University of Bristol in April 1938 was of particular significance for him. It provided a link to his work on the chemical reactions of metamorphic petrology, and he realized from the paper presented by R. Hilsch and R. W. Pohl that he could be enthusiastic over the study of chemical and photochemical reactions in single crystals of alkali halides by spectroscopic observations and measurements of electrical conductivity.

At this time he decided that he wanted to be involved in teaching and research in physics rather than in chemistry, but he had taken no formal advanced courses in physics, and there were few opportunities for employment. The problem was resolved during the summer of

1938 when he met E. A. Greswell, a member of the Governing Body of Repton School, at the Trinity College Gaudy and was asked if he would be interested in teaching VIth form and first-year physics classes at Repton.

REPTON SCHOOL

At Repton from September 1938 until June 1940, he concentrated his energies on systematically studying the whole range of university physics with all the relevant mathematics, on teaching the candidates for university scholarship examinations, and on formulating tough problems for them. He accompanied groups of students on several climbing expeditions and spent vacations climbing in Wales, in the Black Coullin of Skye from Loch Scavaig, in Switzerland and in northern Italy. He played squash regularly with the students.

ARMAMENT RESEARCH DEPARTMENT

Mitchell joined the Armament Research Department of the Ministry of Supply as a Scientific Officer in June 1940. He was given the task of selecting, loading, and proofing propellants in test batches of small arms ammunition at Woolwich Arsenal and was in East London during the Battle of Britain. The greased brass cartridge cases of 0.5" Browning ammunition, fired in action off Malta, were then found to extrude backwards and shatter the breech blocks of the guns. He was assigned the task of working intensively with the staff of the cartridge case factory at Woolwich to resolve the problem. This was his first experience of plastic deformation and fracture. He made axial sections of the cases, polished and etched the surfaces to observe the grain structure with the microscope, and

measured hardness contours with a Vickers Diamond Pyramid machine. The cases proved to be of relatively soft coarse-grained brass with a work-hardened outer surface and sharp hardness gradients. The dies and the annealing schedules were redesigned, cases of uniform hardness produced, and the problem eliminated. He was promoted to the rank of Senior Scientific Officer and sent to Grantham to work on ammunition for the 20 mm Hispano-Suiza gun. This included the study of the interaction of armour-piercing shells with targets. It very soon became clear that direct observations by ultra-high-speed photography were needed. The available flash tubes and spark sources gave blurred images, did not provide a flash of sufficient intensity, and triggered with a variable delay after the input pulse. Mitchell had read the books on electrical discharges in gases by Townshend, Loeb and Meek while at Oxford together with papers on photoelectric cells with alkali-metal activated cathodes. It seemed that a discharge tube was needed with a stable axial dark current which would allow a guided axial spark discharge to be initiated with an extremely short delay upon application of a triggering pulse at the cathode. His experience at Oxford allowed him to make discharge tubes with potassium-activated copper electrodes which were filled with a mixture of argon and hydrogen at near-atmospheric pressure. The hydrogen was added to form potassium hydride on the cathode surface and to quench the long-lived metastable state of argon. The photosensitive cathodes maintained a very small stable axial current. With a 2 μF capacitor at 7.5 kv, the axial spark discharge gave, quite reproducibly, a narrow peak in the light output at 0.75 μsec after

application of the triggering pulse with a peak rate of working of 12 megawatts and an effective photographic duration of less than 1.5 μsec. These discharge tubes called "Arditrons" allowed sharply defined photographs of 2- and 6-pounder shells to be taken in flight and after passage through sheets of armour-plate, together with photographs of mosquitoes in flight at 15X magnification. The tubes were used extensively for the study of a wide range of problems of operational interest, and the invention was patented by the Ministry of Supply in Great Britain and the United States. (78, 80, 81 and 83)

Mitchell was then transferred to the headquarters branch of the Armament Research Establishment at Fort Halstead near Sevenoaks, Kent. The discharge tube allowed accurately timed, high definition, schlieren photographs to be made of the shock waves associated with shells in flight and with the detonation of small high-explosive charges. Interactions between these shock waves and between shock waves and surfaces were recorded and analysed in collaboration with C. K. Thornhill of the Theoretical Physics Division of N. F. Mott, F.R.S. (later Sir Nevill Mott). This work brought him into contact with Mott and his team of theorists. He attended seminars given by Mott on topics in metal physics and other areas of solid state physics including the Gurney-Mott theory of photographic sensitivity. He was really enthusiastic over the research programs on plastic deformation and fracture of metals, on surface physics and on the silver halide photographic system which were being proposed and discussed and was invited to join the group which Mott was building up for the H. H. Wills Physical Laboratory of the University of Bristol. He accepted the offer of a lectureship in experimental physics from A. M. Tyndall, F.R.S., and began working in Bristol in September 1945.

UNIVERSITY OF BRISTOL 1945-1959

Thin films of metals

The research program at Bristol was initiated with the investigation of properties of surfaces of metals which would be relevant to the study of the initial stages of low-temperature oxidation. N. F. Mott had proposed a theory according to which oxygen molecules, adsorbed on the surface of a thin oxide film, are dissociated and charged negatively by electrons tunneling from the metal. Cations or vacant cation lattice sites then drift across the film in the field thus established so that cations can combine with the oxygen ions at the surface to build an oxide film up to a limiting thickness determined essentially by the tunneling distance.[131,132] Observations of the adsorption of oxygen on clean surfaces, of the dissociation and charging of the oxygen molecules, and of the initial growth of oxide films were needed for the evaluation of this theory.

It was clear that surfaces parallel to crystallographic planes sectioned from single crystals of metals could not be used for the work because initially clean surfaces could not be produced. This meant that the experimental system had to be provided by thin films of metals deposited from the vapour under high-vacuum conditions on either outgassed polycrystalline tungsten or glass substrates. In the first experimental work, the deposition and migration of copper atoms on the facetted surface of the tungsten tip of a field emission electron microscope was studied by F. Ashworth.[10, 11] He observed the formation of adsorbed monolayers and aggregates of copper atoms and their reaction with oxygen. Impacts of oxygen molecules on the

tip produced bright spots in the dark images of planar facets. These rotated and dissociated into two spots. Since this phenomenon was observed with oxygen, nitrogen and hydrogen, but not with argon, it was concluded that the dissociation of molecules into atoms was being observed. The field emission microscope allowed the time available before the contamination of the surface by the adsorption of active residual gas molecules to be determined by direct observation and by the increase in the applied voltage needed to maintain a constant current.

The next problem was to obtain reproducible values for the work functions of randomly oriented micropolycrystalline surfaces of thin films of metals deposited on polycrystalline tungsten and glass substrates. The change in the work function accompanying the adsorption of oxygen on the surface was needed to allow the evaluation of the surface dipole moments of the adsorbed oxygen atoms or molecules. The unsaturated diode method was improved by R. Bourion.[20] He measured the contact difference of potential between a tungsten filament and a tungsten filament covered with a thin film of copper from the displacement of the characteristic curve of the space charge limited current. Measurements with a high level of reproducibility could not be made by this method, and the curve obtained after adsorbing oxygen on the copper surface was never parallel to the reference curve so that a precise value for the contact potential difference could not be determined.[21,22]

A major advance was then made in the measurement of the work functions of clean surfaces of thin films by the electron gun method. A symmetrical magnetically focussed electron gun was designed in

which electrons from a tungsten emitter were accelerated to a central anode at a potential of about 100 V and then retarded to a tungsten collector substrate. This electron gun allowed the hot emitter and the collector to be separated by 6 to 10 cm and produced a defined beam of 5 to 10 eV electrons without serious divergence. With this apparatus, E. W. J. Mitchell (later Sir William Mitchell, F.R.S.) obtained reproducible values of 4.61 ± 0.04, 4.33 ± 0.05, 4.25 ± 0.05, and 4.83 ± 0.06 eV for the work functions of copper, silver, aluminium and germanium, deposited as thin films on a polycrystalline tungsten substrate.[74,75,76] The characteristic curve for a copper surface with a given oxygen coverage was never parallel to that for a clean copper surface, and the contact potential difference between them was a function of the retarding potential. From these results and those obtained with the diode method, it was clear that it would be difficult to obtain reproducible results for gas-covered surfaces with free electron methods, and attention was therefore focused on the Kelvin method.

H. P. Myers had worked with the group on the secondary emission of copper and silver films for primary electron energies below 10 eV, using the high-vacuum and other techniques which had been developed.[135] He then moved to Marischal College, Aberdeen, and measured the contact difference of potential between thin films of copper and silver deposited on tungsten by a Kelvin method, finding a value of 0.24 ± 0.03 V in agreement with the results of the electron gun retarding potential method.[136]

At Bristol, J. C. Rivière used a much improved design of Kelvin apparatus with a vibrating capacitor having closely spaced plates to measure contact potential differences between thin films of copper,

silver, aluminium and gold, taken in pairs, and between silver or gold and nickel, tungsten, molybdenum and iron.[149,150] He obtained self-consistent results with a high level of accuracy and reproducibility. A major advance in high-vacuum technique was introduced with the use of evaporated films of molybdenum as extremely efficient gettering surfaces, following the work of E. B. Dorling[35] which will be discussed later. This sealed the surfaces and reduced the residual pressure of active gases below the limit of the Bayard-Alpert gauge and, from rate of contamination measurements, below 10^{-12} mm Hg. The contact differences of potential remained constant for several weeks, demonstrating the effective clean-up of residual active gases.

This work was continued by C. G. Matthews who measured contact differences of potential between pairs of the metals, copper, silver, gold and tungsten, and made corrections for stray capacitance.[73] One of the main objectives of this research program had been to study the contact potential difference between a metallic surface and a reference surface as a function of increasing gas pressure. With the molybdenum gettering system which had to be used to obtain reproducible results with clean surfaces, Rivière and Matthews found that it was not possible to maintain a stable constant pressure of oxygen in the range of measurement of the Pirani gauge from 10^{-5} to 10^{-2} mm Hg.

A value for the change in work function resulting from the adsorption of oxygen on copper was particularly desired. The problems with the Kelvin method and active gases led to the design of a self-gettering system for the photoelectric method with which P. A. Schroeder measured the work functions of copper and silver.[151]

The internal surface of a spherical bulb and the target were covered with the same evaporated thin film apart from the internal surface of a small-diameter tube surrounding the target lead which isolated the target from the surface of the bulb, and a bubble window. Residual active gases were progressively removed during evaporation of the metal, and a stable clean final surface resulted. For the measurements, the 2144 and 2265 Å lines of a cadmium spark were isolated with a quartz monochromator and focussed on the target with a quartz lens. Remarkably reproducible values were obtained for the work functions of the pure metals, 4.39 eV for silver for both wavelengths, 4.65 eV for 2144 Å and 4.60 eV for 2265 Å for copper. These were in excellent agreement with the values of E. W. J. Mitchell measured by the electron gun method. After these measurements were made, oxygen was allowed to saturate the surfaces and then pumped out. The retarding potential curves gave a contact potential difference between the clean copper and the oxygen-covered target of -0.44 V for 2144 Å and -0.38 V for 2265 Å for copper, and -0.60 V for 2144 Å and -0.54 V for 2265 Å for silver. This gave work functions of 5.09 and 4.98 eV for copper, and 4.99 and 4.93 eV for silver, covered with oxygen. The main objective of this program had now been achieved. The measurements of contact differences of potential provided valuable experience in the development of ultra-high vacuum techniques.

The results for thin films with a randomly oriented micropolycrystalline structure which were deposited at room temperature on polycrystalline tungsten or glass substrates depended only on the external surface, and no information on the structure, properties and reactivity of the films was needed. A parallel research program

had therefore been initiated in 1948. Of particular interest was the quantitative study of the adsorption of oxygen and the initial stages of oxidation. Based on the model with smooth plane parallel surfaces which was current, it was thought that oxidation might be followed by the change in resistance measured at a low temperature. Apparatus was therefore designed for adsorption and resistance measurements and used by J. A. Allen and J. W. Mitchell.[6, 7, 8] The thin films for adsorption and oxidation measurements were deposited from a central bead of copper or aluminium heated by a molybdenum or tantalum filament at the centre of a spherical bulb of 8 cm diameter. This provided a self-gettering system of essentially zero dead space with which a thin film of uniform thickness was deposited with the bulb at -183°, 18° or 100° C. Small strips for resistance measurements were defined by a glass mask and deposited on plane surfaces at the same temperatures with contacts for current and potential measurements. Copper films with thicknesses between 400 and 600 Å were dull green in color at -183° C. The surface areas, determined by the adsorption of oxygen, were found to be many times the geometrical area. This factor was proportional to the mass of the film, suggesting that the films had a uniform porous structure. As deposited under high-vacuum conditions at -183° C, they had a resistance much higher than that corresponding to the bulk resistivity and experienced a slow small decay. When the films were warmed to 20° C, the red reflection of metallic copper appeared, and the resistivity decayed rapidly according to a hyperbolic law. At the same time, the surface area determined by oxygen adsorption at -183° C decreased to about twice the geometrical area. The rates of these changes were

decreased by the adsorption of a small fraction of a monolayer of oxygen at -183° C, and the changes were completely inhibited by less than a monolayer. The surface area and resistivity of thin films deposited at -183° C and fully annealed at 20 or 100° C was always greater than that of films deposited at these temperatures. Measurements of the amount of oxygen adsorbed or reacted with copper films showed that no more than monolayer adsorption was involved below 240° K. This was not consistent with the theory proposed by Mott for oxidation at low temperatures,[131,132] and it seemed that thermal activation was required for the dissociation of oxygen molecules on a copper surface before oxidation could proceed. At higher temperatures, the reaction rate determined from measurements of gas adsorption and reaction was found to vary with the thickness of oxide film according to a square or cubic law in accordance with the theory of N. F. Mott and N. Cabrera.[134]

Films of aluminium with a nominal thickness of 700 Å, assuming bulk density, were deposited in the spherical bulbs at 20° C. Oxygen was admitted at -183° C and measurements of the amount adsorbed and reacted made at successively higher temperatures. The measurements were quite reproducible. The self-gettering method for producing a clean surface was of particular value for work with aluminium. The measurements showed that 3.6×10^{15} cm^{-2} oxygen molecules were very rapidly adsorbed on the clean aluminium surface at -183° C corresponding to an oxide layer with a thickness of 13.3 Å and that rapid growth ceased after a few minutes. After 120 minutes, this thickness increased to 15.5 Å at 20° C and to 18.8 Å at 250° C and thereafter further increased slowly to a limiting value. The observations at

-183° C with thin aluminium films were in good agreement with the theoretical predictions.

A thin film of copper, deposited on a glass substrate at -183° C, has a resistivity about 500 times that of bulk copper. The resistance decays according to a hyperbolic law with a relatively small decrement. Far more rapid decay occurs at higher temperatures, and at 20° C the bulk resistivity is approached. At any point on the hyperbolic curve, decay was arrested, and the resistance rapidly increased by the admission of oxygen or a chemisorbed active gas such as carbon monoxide or nitric oxide. The resistance then passed through a maximum and slowly decreased.

Since surface diffusion was evidently involved in the decrease in the number of accessible adsorption sites and accompanying decrease of resistance of thin films of copper, the same properties were studied for thin films of silver by D. G. Holloway[62] and for thin films of tungsten, molybdenum and tantalum by E. B. Dorling.[35] From the estimates of J. K. Mackenzie,[72] the activation energy for surface diffusion is about one-twentieth of the sublimation energy, giving values of 0.145, 0.175, and 0.31 eV for silver, copper and molybdenum. If the surface migration hypothesis were correct, changes depending on surface diffusion should occur more rapidly with silver and less rapidly with molybdenum than with copper films. The apparatus had the same design as that used by Allen and Mitchell.[7] Thin films of silver deposited in the spherical bulbs at -183° C were dull bluish purple in colour. They developed the characteristic metallic reflection of silver on annealing at higher temperatures.

This change at 20° C was prevented by the admission of oxygen or nitric oxide at -183° C. It then occurred at 78° C. The number of adsorption sites on films deposited at -183° C was proportional to the mass of the film. It decreased to a constant limiting value on annealing at higher temperatures. The resistance of a thin film of silver deposited at -183° C decayed from 50 to 48 ohms according to a hyperbolic law during one hour. After one hour at 20° C, the resistance, measured at -183° C, had fallen to 8 ohms. The decay curves were remarkably reproducible. The films were stabilized by annealing at 100° C, and the resistance then changed reversibly when they were cooled to lower temperatures and reheated. As with copper films, the resistance was increased by the adsorption of oxygen and nitric oxide.

E. B. Dorling[35] measured the number of adsorption sites on thin films of tungsten, molybdenum and tantalum deposited at -183° C and at 20° C from the number of oxygen molecules rapidly adsorbed at -183° C. The number was much greater for films deposited at -183° C than at 20° C. It was proportional to the mass of the film and decreased at a much slower rate on annealing than for thin films of silver or copper. Because of their large and relatively stable surface area, thin films of molybdenum provided an almost ideal gettering system which was used extensively in subsequent work.

In all of this work, the surface areas of the thin films were calculated from the number of oxygen molecules rapidly adsorbed at -183° C. The change in the number of accessible adsorption sites was an important parameter in the establishment of a reliable and useful model for the structure of the film which was an overall objec-

tive of the work. Because of the possibility of chemical reaction with oxygen, it seemed that the surface areas should be confirmed with measurements of physical absorption. The Brunauer, Emmett and Teller adsorption isotherm with ethane at -183° C was used by C. C. Evans[39, 40] for the measurement of the surface areas of copper films deposited at -183° C, at 18° C, and at -183° C followed by annealing at 18° C, in the spherical system of Allen and Mitchell.[7] The areas were found to be appreciably greater than those determined by rapid oxygen adsorption, suggesting that oxygen adsorption might be favoured at a fraction of active sites such as those which might be associated with isolated atoms on planar facets. The surface areas of unannealed films deposited at -183° C were proportional to the mass of the films as had been established by measurements of chemisorption of oxygen. Films deposited at 100° C were found to have a surface area approximately twice the geometrical area. C. C. Evans then repeated the work of Allen on the adsorption of oxygen at -183° C on unannealed thin films of copper deposited at -183° C. He confirmed the linear variation of the number of adsorbed molecules with the mass of the film and found a mean slope of 1.5×10^{20} molecules gm^{-1}. The linear relation with a much smaller slope applied to films deposited at -183° C and annealed at 18° C for two hours but not to films deposited at 18° C. Evans then repeated the work on the effect of oxygen on the resistance of thin copper films using apparatus of much improved and simpler design.[39, 40] Longer films of constant width and uniform thickness were deposited from an axial bead on the cylindrical wall of a tube provided with current and

potential leads. The system gave reproducible results with a higher sensitivity for the measurement of small resistance changes than that previously used.

The planning and design of the experimental work on thin films of metals was based on a model which evolved from the observations of Allen and Holloway and was refined following the work of Dorling and C. C. Evans. The observation that the number of accessible adsorption sites was proportional to the mass of a film established that films deposited at -183° C had a uniform porous granular structure. It was proposed that they consisted of very small crystallites with small area contacts to adjacent crystallites. This accounted for the large surface area factors. The high resistance was attributed to contact resistance between the crystallites. The decay with time of the resistance was accounted for by the surface diffusion of atoms to the contacts with increase in the contact area. The rate of decay was reduced to zero by the admission of oxygen at a low pressure which would prevent the surface migration of metal atoms. At higher pressures of oxygen the resistance increased very rapidly to a maximum value due to a decrease in the contact area from stresses developed by the adsorption of oxygen molecules around the perimeters of the contact areas. This porosity was retained with a reduction in the number of accessible sites when the films were annealed at 20° or 100° C. Films deposited at 20° or 100° C on the glass substrate of the spherical bulbs of the self-gettering system had a surface area factor of about 2. Their very clean final surfaces provided optimum conditions for the study of the initial stages of the adsorption and reaction of metals with oxygen, carbon monoxide and nitric oxide.

The proposed model for a thin film deposited at -183° C was evaluated by Holloway[62] for a system of small-radius spheres having a resistance determined by very small circular contact areas. He found that the observed properties could be reproduced with reasonable values for the parameters. The essential features of the model were consistent with a study of crystallite size by the broadening of X-ray diffraction lines by H. D. Keith.[68] He deposited copper films with a thickness up to 2000 Å on a cylindrical copper substrate at -183° C in a high vacuum. This was used as the diffracting surface for an evacuated all-glass Seemann-Bohlin type focusing camera. A narrow beam of CuKα radiation from a curved quartz crystal monochromator passed through an entrance slit and thin bubble window to the copper film. The diffracted beams from the (200) and (311) planes emerged through a second bubble window and were photographically recorded. The diffuse uniform diffraction lines showed that the films deposited and maintained at -183° C consisted of aggregates of randomly oriented microcrystallites. There was no evidence for any preferred orientation. A nominal particle size of 40 ± 5 Å was estimated from the broadening of the diffraction lines measured with a microdensitometer. When the films were annealed in vacuum to room temperature, the lines sharpened, and the estimated particle size increased to at least 400 Å. The estimated particle size increased to only 60 Å when the films were exposed to oxygen before annealing to room temperature. These observations were consistent with the proposed model. After the completion of this work, the research program on the properties and structure of thin films of metals was terminated. These studies on the properties of thin

films of metals were made possible by the outstandingly skillful glass-blowing and good-natured, patient perseverance of J. H. Burrow, B.Sc., and D. A. Jones, to whom the graduate students and research associates were deeply indebted.

Silver halide photographic sensitivity and dislocations

Early in 1948, Mitchell was encouraged by N. F. Mott to undertake serious work on the photosensitivity of the silver halide system. His interest in the photochemical properties of alkali and silver halide crystals had been aroused by the Faraday Society Discussion of 1938, and since going to Bristol in 1945 he had read all the publications of the Göttingen school. The experimental approach of R. W. Pohl and his coworkers based on successive essentially simple experiments with single crystals and physical measurements of relevant properties appealed to him. He visited Göttingen in April of 1948 and returned with a set of reprints of the papers of O. Stasiw and J. Teltow[155] on experimental work with crystals of silver halides containing sensitizing impurities.

Mitchell had been uneasy with the mechanisms of the Gurney-Mott theory[49] since he had first become acquainted with them at a seminar given by Mott in 1944. The theory provided a mechanism for the concentration of silver atoms at a silver or silver sulphide speck on the surface of a silver halide microcrystal accompanied by the escape of halogen molecules from the surface. Mitchell could not understand how silver atoms could separate without recombination at a surface from which halogen molecules were escaping. He felt that the positive holes, released with the electrons, had to be trapped

and inactivated by products of chemical sensitization. He could also not understand how electrons diffusing by a random walk process could be selectively trapped by one particular uncharged silver or silver sulphide speck when there had to be many such equivalent specks on the surface of a sensitized microcrystal. It seemed to him that one photochemically produced cluster of silver atoms would have to be positively charged to provide a site-directing Coulomb field for conduction electrons in the concentration process and to repel positive holes. He found no mention of these concerns in the review article on the Gurney-Mott theory published by Berg in 1948 (18) which also discussed the formation and properties of the internal latent image. According to the theory, the sensitizing silver sulphide had a photochemically inert role, its function being simply to concentrate silver atoms liberated by the action of light. After reading the paper by Berg, Mitchell realized that the formation of the internal latent image presented another problem. The model for a silver halide crystal of the Gurney-Mott theory had a perfect lattice, and the only structural defects were the interstitial silver ions and vacant silver ion lattice sites of Frenkel disorder. The question was: how could space be made available for the separation of clusters of silver atoms within a perfect crystal with only Frenkel disorder? This seemed to require the involvement of mobile vacant halide ion lattice sites.

With this background, he approached the detailed study of the papers of Stasiw and Teltow. He saw that the problems could be resolved if vacant halide ion lattice sites were involved in internal sensitization by dissolved molecules of silver sulphide. In the mod-

el which he proposed for the interpretation of their experimental results, the excess charge of the S^{2-} ion was compensated by an adjacent vacant halide ion lattice site. The transfer of an electron to this vacancy created an F-center adjacent to an S^{-} ion. With this F-center model, the holes were trapped by the F-centers, releasing mobile vacant halide ion lattice sites with a unit positive charge. These combined with photoelectrons to form uncharged planar aggregates of F-centers which adsorbed a vacant halide ion lattice site above a small critical size to become positively charged aggregates and provide a focussing field for subsequently liberated photoelectrons. Beyond a further critical size, the planar aggregates collapsed to form internal clusters of silver atoms.(82, 85, 19) This model incorporated the essential physical features which characterized all of Mitchell's subsequent work on latent image formation. The latent image was formed by a photoaggregation process from silver atoms, chemically equivalent to sensitizing molecules. These molecules provided effective traps for positive holes and released positive ionic charge carriers in the process. Aggregates above a critical size carried a positive charge, repelled positive holes, and provided a site-directing Coulomb field for photoelectrons. This model was discussed with C. E. K. Mees, F.R.S., when he visited Bristol in 1948. He invited Mitchell to spend the summer of 1949 at the Eastman Kodak Research Laboratories in Rochester, New York.

Mitchell now initiated a program of experimental research on silver halide photographic sensitivity with financial support from Kodak, Ltd. The first silver halide crystals produced were heavily fogged. The fog was decreased but not eliminated by treatment with

the halogen, and it was suspected that it was due to the incorporation of a fine dispersion of particles of silica or of silicates. The crystals were used for the study of surface electrolysis which produced beautiful fern-like growths of silver[86] and with H. D. Keith for the study of the processes of chemical development, initiated by the fog specks.[69] Many model experiments on the electrode theory of development were also designed and carried out. The crystals which had been annealed in the halogen to reduce the fog formed no developable surface latent image on exposure and did not provide a useful model for a silver halide emulsion microcrystal.

In the early experimental work, the dried silver halide precipitate was melted in a stream of the hydrogen halide to eliminate silver oxide. The liquid was then filtered through a succession of fine borosilicate glass capillaries to remove the particles believed to be responsible for the fog. This reduced the surface density of fog specks without completely eliminating them. At this time, the emphasis was on preventing the formation of a surface scum of silver oxide on the molten halide. In later work, the use of the hydrogen halide was avoided by melting the silver halide precipitate in nitrogen and filtering the liquid through a succession of very fine capillaries. The precipitate contained silver oxide produced by hydrolysis during final washing. It melted to a liquid with suspended particles and dissolved silver oxide which wetted the walls of the capillaries. The suspended particles were removed by the filtration. A slow stream of the halogen was then passed through the liquid to eliminate the dissolved silver oxide and reduce the concentration of iodide in silver chloride and silver bromide to a very low value.

This procedure completely eliminated the fog. Oxidation with atmospheric oxygen and filtration was repeated several times followed by passage of bromine through the melt. The resulting silver halide had an extremely low photosensitivity and a concentration of paramagnetic ions below the detection limit of the E.S.R. method. It appeared that fine capillaries lined with adsorbed silver oxide provided an efficient chromatographic system for the removal of heavy metal ions. The importance of this was not appreciated at the time.

Thin sheet crystals usually with near {001} surfaces were grown by crystallizing molten discs of silver halide between glass plates by passage across a steep temperature gradient.[56, 30] The sheets were stress birefringent before separation from the plates, and their crystal structure was seen when they were examined between crossed polarizers. They had a few large single crystal areas and were cut into sections about 6 mm square and mounted on 3" x 1" slides with a thin film of Canada Balsam. These thin sheet crystals provided a new system for research on photographic sensitivity and were used by workers in many countries. With these crystals, optimally sensitized with silver oxide and lightly annealed, J. M. Hedges and J. W. Mitchell found in November 1952 that a developable surface latent image was formed on exposure which solarized rapidly. A sub-surface internal latent image was formed which did not solarize and initiated development after treatment of the surface with a dilute solution of a silver halide solvent. The internal development centres appeared to be distributed around the boundaries of a sub-structure of the crystals. Exposure for a longer period resulted in the almost continuous decoration of the dislocations in these sub-grain boundaries with particles of photolytic silver. No particles separated within

the sub-grains. This allowed the first observations of dislocations within crystals to be made.[55,105,123] Decoration after deformation showed arrays of dislocations within the sub-grains, leaving no doubt that the elementary processes of plastic deformation were being observed for the first time. The observations made with crystals which had received a latent-image-forming exposure resolved the problem of the nature and formation of the internal latent image. It was formed by the separation of clusters of silver atoms along the dislocation lines of the sub-grain structure of the crystals. This was confirmed by the deposition of silver atoms on the surface of a silver bromide crystal from an atomic beam under high-vacuum conditions. They diffused from the surface and separated along the dislocation lines to give a developable image. Gold atoms did not diffuse in this way.[42]

The crystals provided a transparent model for the study of the elementary dislocation processes involved in the plastic deformation of single crystals of metals with the face-centred-cubic structure.[94] They also provided a model which reliably reproduced the properties of the silver halide microcrystals of photographic emulsions.[41,42] Both research programmes led to branching chains of new discovery. Small-angle tilt sub-boundaries were observed with regularly spaced arrays of parallel edge dislocations. Small-angle twist sub-boundaries with regular hexagonal networks of screw dislocations were recognized for the first time, and their vector geometry was analysed by F. C. Frank, F.R.S. (later Sir Charles Frank)[47] P. V. McD. Clark[30] showed that silver chloride and silver bromide were hardened by the formation of mixed crystals, with a maximum hardness for the equimolar concentration,

and by the incorporation of small molar concentrations of silver iodide. This increased both the yield stress and the flow stress of the crystals. D. A. Jones[65] observed arrays of prismatic and of helical prismatic dislocations along the twelve <110> directions radiating from imbedded glass spheres. They were introduced to relax the shear stress fields resulting from the differential contraction between the silver halide and the glass spheres on cooling from the temperature of the melting point. The formation of prismatic dislocation loops had been discussed by F. Seitz,[154] and they were now observed for the first time. Prismatic punching at growing particles of silver in silver chloride crystals was observed by A. S. Parasnis[143] and around particles of gold in silver halides by J. T. Bartlett.[14] These systems provided a model for the generation of prismatic dislocations during precipitation hardening of alloys such as were later observed by transmission electron microscopy.

J. T. Bartlett found that in thin sheet crystals of silver halides, optimally sensitized with silver oxide, both the monatomic surface terraces and the dislocation half-loops associated with the initiation of plastic deformation at the crystal surface could be decorated by the separation of particles of photolytic silver.[15] The loops expanded rapidly along the surface introducing successions of dislocation lines parallel to the trace of the glide planes in the surface. This allowed the determination of the glide planes and the study and evaluation of the Burgers vectors of dislocations involved in interactions on intersecting glide planes.[16, 17] Dislocation arrays on twin boundaries and their interaction with dislocations

gliding toward them were observed at the same time.[13] This work with the silver halide thin sheet crystal model system contributed to the understanding of the dislocation structure of sub-grain boundaries, of surface dislocation-generation processes, of the interactions of glissile dislocations, and of the properties of prismatic dislocations.[97,105,123]

Over the same period, work was proceeding in which the thin sheet crystals were used as a model system for the study of photosensitivity. Hedges and Mitchell found that a silver bromide crystal was sensitized by the deposition of 10^{14} Ag atoms cm^{-2} from an atomic beam and fogged by 10^{15} atoms cm^{-2}.[56] The fogging film was completely transferred to sub-surface sites by exposure to light. T. Evans (later F.R.S.) sensitized the thin sheet silver bromide crystals by all the methods of photographic technology and showed that they provided an excellent model for the study of the formation and properties of the surface latent image.[42] This experimental work was presented in a Friday Evening Discourse given at the Royal Institution on February 13, 1953.[88] P. V. McD. Clark[33] continued this work with crystals of silver chloride and with mixed crystals of chlorobromide and bromoiodide. It was established for the first time that a mixture of sodium aurous dithiosulphate and potassium or ammonium chloroiridite provided a powerful sensitizer for the formation of the surface latent image.[42, 33] D. A. Jones[64] studied the formation of etch pits at the points of emergence of dislocations by sodium thiosulphate solutions, and Mitchell[95] showed that these areas provided preferential sites for sulphide sensitization. He found that crystals of silver bromide with less than 0.01 mol% of

silver sulphide were heavily fogged and had a very low level of surface sensitivity. They were efficiently sensitized by a fraction of a monolayer of silver sulphide adsorbed at the surface.[96] This was inconsistent with the F-centre model which had already been abandoned. He also established that sensitizing silver sulphide was chemically involved in the formation of the surface latent image. Photoproducts, formed during exposure, were removed by treatment with an oxidizing solution which did not attack unexposed silver sulphide.[98] This was contrary to the assumption of photochemical inertness of Sheppard and of Gurney and Mott.

One challenging problem remained in 1957. This was to establish the mechanism by which silver nuclei grew to microscopically visible particles of photolytic silver within silver halide crystals when there were no vacant anion lattice sites. The problem was resolved by A. S. Parasnis[143] with silver chloride crystals sensitized with cuprous chloride. He showed that very small prismatic loops were generated at and displaced away from the particle interface along the twelve radiating <110> directions. The internal stress field created by the separation of silver atoms at the interface was relaxed by the same mechanism as the thermal stress field around an imbedded glass sphere in the previous work of Jones. The successful outcome of the researches on dislocations and the role of dislocations in chemical and photochemical reactivity depended on the use of the optical microscope near its resolution limit. Mitchell had recognized the potentialities of the optical microscope for the study of chemical reactions in crystalline solids and learned the technique of mounting thin sections in cooked Canada Balsam for examination

with high-resolution objectives during the course of his petrographic researches in New Zealand.

The carefully designed and relevant simple experiments with the thin sheet silver halide crystals provided information on the elementary processes involved in the formation of the latent image and particles of photolytic silver. Thin sheet crystals of the highest achievable purity and perfection were insensitive.[93] They had a very small electron range when exposed to wavelengths longer than 400 nm.[23,24] E. Braun found that the electron lifetime was increased from 10^{-10} to 10^{-7} sec by sensitization with silver oxide.[23] Sensitization with silver, silver oxide, silver sulphide or silver-gold sulphide was necessary before there was significant photoconductivity or photosensitivity. Bromine was not liberated from the surfaces of silver bromide crystals until after an internal latent image had been formed and the surface products of sensitization modified by photoreactions. The full significance of these experimental observations was not realized at the time.

During the ten years between 1948 and 1958, Mitchell discussed latent image formation by the intrinsic primary electronic process in which electron-hole pairs were created by fast particles or by the absorption of photons of sufficient energy by the silver halide crystal as in the Gurney-Mott theory. He introduced the concept that the holes were trapped by adsorbed or incorporated sensitizing molecules. Recombination with electrons at the trapping site was prevented by the rapid dissociation of the positively charged centres by dissociation with passage of a silver ion into an interstitial position. He also introduced the concept of the photochemically produced positively charged latent image centre provided by a cluster of three or more silver atoms which adsorbed a silver ion to

become a positively charged Ag_4^+ or Ag_n^+ cluster. This provided a deep trap for photoelectrons and repelled positive holes. A high quantum efficiency was ensured by the restoration of the positive charge by the rapid adsorption of a silver ion from an adjacent site.

These proposals for which there was much circumstantial but little direct evidence were consistent with the experimental observations which had accumulated, and with the scientific and patent literature. They profoundly changed the theory of the concentration process in latent image formation. The latent image was not formed by the primary photolysis of the silver halide crystal with separation of clusters of silver atoms and escape of halogen molecules from the surface, as in the Gurney-Mott theory. It was formed by the effective photoaggregation of silver atoms, chemically equivalent to products of chemical sensitization. This photoaggregation theory evolved between 1954[87, 36, 42] and 1957. In 1956, Professor H. Frieser, the Director of the Agfa Research Laboratories in Leverkusen, and Professor J. Eggert, the Director of the Photographisches Institut of the E.T.H. in Zürich, asked Mitchell to write a monograph for publication as a special issue of Photographisches Korrespondenz. This was to present a self-consistent discussion of the whole range of photographic phenomena from the nucleation and growth of silver halide microcrystals through chemical and spectral sensitization and the formation and properties of the latent image to development. It was published in 1957.[90] The theory was refined during the preparation of this monograph and the role of Ag_2 molecules in latent image formation discussed. Two further papers were published in 1957, the Renwick Memorial Lecture to the Royal Photographic Society,[91]

and a review article in Reports on Progress in Physics.[92] These defined the essential features of the new photoaggregation theory. The theory was reviewed again in 1958[95] and the photoionization of sensitizing molecules by the decay of dye excitons further emphasized. It was extensively and critically discussed at an international conference held at the University of Liège in September 1959. According to H. Sauvenier, the editor of the proceedings, Mitchell was there subjected to "un feu rouillant des questions." His replies were summarized and brought together in an extended written contribution.[98]

Other research work

Mitchell was always interested in the design of simple experiments to establish theoretical hypotheses and avoid controversy. Following Sheppard, both Gurney and Mott, and Berg assumed that sensitizing silver sulphide remained unchanged on a silver bromide crystal even though, according to the direct photolysis theory, halogen was liberated at the surface. This did not seem to be reasonable. J. H. Burrow and Mitchell[37] evaporated a very thin blue-violet film of silver onto the surface of a spherical bulb under high-vacuum conditions from a central bead of silver on a heated tungsten filament. The film was instantly converted to a brown film of silver sulphide on admission of a low pressure of hydrogen sulphide. Excess hydrogen sulphide was then removed. Bromine, admitted at an extremely low pressure, very rapidly converted the brown film of silver sulphide back to a blue-violet film of silver, and the reaction product, sulphur dibromide, condensed as a rim in a side-arm at the liquid air

level. Without the silver sulphide, a thin film of silver reacted instantly with bromine. T. Evans[42] then showed that silver bromide crystals sensitized with silver sulphide were fogged by exposure to bromine under the same conditions and thus established the relevance of the observations to the photographic system. Bromine molecules, if liberated at the surface during exposure, evidently reacted preferentially with sensitizing silver sulphide molecules.

The plastic deformation of single crystals of alkali chlorides and the decoration of dislocations in these crystals was studied by D. J. Barber and K. B. Harvey.[12] They found that aurous ions diffused into the crystals when they were heated at 600-650° C in a sealed-off tube containing auric chloride or metallic gold with a low pressure of chlorine. On carefully controlled cooling below 450° C with sodium chloride crystals, very fine particles of gold precipitated along dislocation lines making them visible. Harvey[54] also showed that crystals of sodium chloride containing 1 mol% of barium chloride could be used for the study of plastic deformation. The fine dispersion of particles of the two-phase system was dissolved by heating the crystals to 650° C. Nucleation and growth of barium chloride particles occurred preferentially along dislocation lines on cooling below 450° C, giving clear decoration. The dislocation arrays of the polygonized sub-structures of bent crystals were decorated with particles of gold or barium chloride by these methods, but systems of glissile dislocations introduced at room temperature were inevitably modified by annealing and climb processes at 650° C. The alkali halide crystals were therefore used for the study of these processes and of the generation of systems of prismatic dislocation loops around growing particles of gold.[97]

Mitchell's concern with experimental design in research with thermodynamic systems was illustrated by work undertaken by P. B. Price, Jr.,[145,146] a Fulbright Fellow who worked with the group in 1958-59. Masses of thin whiskers of cadmium had been grown by evaporating cadmium vapor from a heated source in a horizontal tube and allowing it to diffuse through an argon atmosphere to a cooler zone. This could give no information on the supersaturation and actual physical conditions of filamentary crystal growth. Mitchell was interested in these conditions. A cylindrical cell with plane ends was designed, constructed in Pyrex glass by J. H. Burrow, and mounted with a vertical axis. Layers of high-purity cadmium were deposited on the upper and lower surfaces of the cell which was filled with high-purity argon. A convection-free vertical temperature gradient was then created by heating the upper surface to 320° C, the melting point of cadmium, and the bottom surface to a lower temperature with a linear temperature gradient down the wall. The supersaturation which could be calculated increased as cadmium vapour diffused downward in the temperature gradient. When a steady state had been established, a very fine axial quartz fiber was introduced. Price was able to observe and photograph at magnifications of x 12.5 and x 35 the cadmium crystals which nucleated and grew along the quartz fiber at calculated supersaturations under the simplest possible conditions and to study the growth processes.

Teaching and other activities

Mitchell divided his time between research and teaching. He taught all the standard courses for first- and second-year students,

always with emphasis on the understanding and application of fundamental principles. He spent many hours in designing and setting up lecture demonstration experiments following the tradition of R. W. Pohl at Göttingen and in organizing experimental work for practical courses. He was firmly convinced that direct personal observation of the basic phenomena of experimental physics was an essential element in the sound training of any physicist and believed in the operational definition of physical concepts as far as this was appropriate. For third-year students, he gave courses on geometrical and physical optics, on heat, classical and statistical thermodynamics and on solid state physics.

During his fourteen years at Bristol, he gave many lectures and courses on topics in solid state physics at universities and at government and industrial research laboratories in Great Britain, Europe, the United States of America, Australia and New Zealand. Between 5 August and 9 September 1947 he gave a course of twelve lectures on the physical properties of metals, semi-conductors and ionic solids at Canterbury University College, Christchurch, New Zealand. From 20 October to 7 November 1947 he gave a course of nine lectures on the physics of the solid state at the University of Sydney.(79) From 8-15 September 1948 he gave six lectures on experimental work on ionic solids in parallel with theoretical lectures by N. F. Mott, F.R.S., at a summer school on the physics of ionic solids at the University of Bristol. This was followed 20-30 May 1952 by a summer school on semi-conductors and transistors at the University of Bristol at which he gave ten lectures on experimental advances in parallel with theoretical lectures by N. F. Mott, F.R.S., and D. Polder. He then sum-

marized the experimental and theoretical advances presented at this summer school in a course of ten lectures given 22-26 September 1952 at the University of Sydney. At the University of Strasbourg, he gave a course of fourteen lectures (in French) 19 June-20 July 1951 on the structure, ionic and electronic properties of ionic solids, on reactions in solids, and on the theory of latent image formation.

From 13 March to 26 April 1955, Mitchell visited the United States on a tour organized by the Office of Scientific Research of the Air Research and Development Command. He gave a lecture on dislocations in crystals of silver halides at a symposium of the Division of Solid State Physics at the March meeting of the American Physical Society in Baltimore, Maryland. He then gave lectures on the lattice and structural imperfections of crystals of silver halides and their involvement in the processes of chemical sensitization and the formation and development of the photographic latent image at ten universities and six industrial research laboratories. He visited the National Bureau of Standards in Washington, D.C., and the Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio. The purpose of the visit was to present the results of a successful program of basic research in solid state chemical physics which had led to unanticipated advances in two fields, silver halide imaging science and plastic deformation of crystalline materials. Mitchell gave a review lecture on dislocations in crystals of silver halides at the International Conference on Dislocations and Mechanical Properties of Crystals held at Lake Placid, New York, 6-8 September,[94] and a lecture on the sensitization of crystals of silver halides with sulphur compounds at the International Conference on Scientific Photo-

graphy held in Köln, Germany, 24-27 September 1956.[96] These were followed by many lectures on dislocation phenomena in silver halide crystals and the emerging photoaggregation theory of latent image formation until 1959 when his academic research interests shifted to the study of plastic deformation in single crystals of metals. During this period, he organized the 1950 Bristol Conference on *Fundamental Mechanisms of Photographic Sensitivity* and the 1954 Bristol Conference on *Defects in Crystalline Solids* and edited the volumes of proceedings.[84,89]

Mitchell had many wide-ranging discussions during his visits to industrial laboratories on the planning and design of creative experimental work in solid state physics, on possible new research systems, on the resolution of difficulties encountered, and on the interpretation of the observations. He was always interested in avenues of new discovery with potential for the development of commercial products. From his own experience, he had learned that the study of the problems of industrial applied science could be stimulating and lead to new advances in fundamental science. This was clearly exemplified by the work on the internal image in the silver halide grains of photographic emulsions which led to the first observations of dislocations within crystals and of many of their properties.

For exercise and relaxation while at Bristol, he played squash regularly, walked on Exmoor and Dartmoor, cycled in areas between the Cotswolds, the Wye Valley and Lands End and around Europe. He climbed on the Cornish cliffs, in Wales and the Lake District, in Switzerland and in Northern Italy. Most years from November to May

he suffered from chronic bronchitis which was accentuated by the smog resulting from the drift towards Bristol of emissions from the carbon black plant at Avonmouth over the sulphuric acid factory on the Avon. This cleared up when he was in the United States for six weeks in March and April of 1955 but returned as soon as he went back to Bristol. He remained in Bristol until the problems with dislocations and photographic sensitivity in which he was most interested had been studied and then moved to the University of Virginia in July 1959.

UNIVERSITY OF VIRGINIA 1959 - 1969

Plastic deformation of single crystals of α-phase copper-aluminium alloys with the $[321]\{1\bar{1}\bar{1}\}\{\bar{1}45\}$ orientation

Mitchell and his graduate students at Bristol showed that crystals of silver chloride and silver bromide provided a transparent model for a face-centred-cubic metal with which the dislocation structure of the sub-boundaries of a single crystal and the generation and propagation of dislocations under the action of shear stresses could be studied. Because of the lower critical stresses, the scale of the phenomena observed with the optical microscope at a magnification of x 1,500 corresponded approximately to that for a copper alloy studied with the electron microscope at x 20,000. This allowed large areas with low densities of events to be scanned, a circumstance which was favorable for the study of the elementary processes involved in the initiation of plastic deformation at the yield stress. It was established that these processes in dislocation-free single crystals of silver chloride or silver bromide always resulted from the nucleation

of dislocation half-loops at the free surface and their initial rapid expansion along the surface and then across the glide plane into the crystal. The dislocations of the arrays were parallel to the trace of the glide plane in the surface. The primary dislocations had long ranges and did not generate further small secondary dislocation loops during propagation. Not one Frank-Read source was observed during many years of observations.

Mitchell now wanted to compare observations of the elementary processes of plastic deformation in single crystals of face-centred-cubic metals with those made with single crystals of silver halides. The objective was to grow large accurately oriented square-sectioned single crystals of the highest possible purity and the highest achievable perfection. Early experimental work at Charlottesville showed that single crystals of pure copper were unsuitable. They were plastically deformed by very small stresses with the introduction of high densities of dislocations. Etching of polished {111} surfaces produced random distributions of closely spaced dislocation etch pits. For observations which could be discussed on other than a statistical basis, it seemed that the stacking fault energy had to be decreased so that the dislocations would dissociate into partials and remain on glide planes during propagation. This would allow physically meaningful microscopic observations to be made of elementary dislocation processes. Oriented single crystals of copper alloys of constant composition were evidently needed. This required a copper alloy with a very small separation between the liquidus and the solidus in the phase diagram. Study of the phase diagrams for binary copper alloys[53] showed that the copper-aluminium system was unique in having this

property up to a composition with about 7.5-at% aluminium. This system was therefore selected for the initial work. Alloys with a wide separation between the liquidus and the solidus, such as copper-germanium, would have given single crystals with an axial concentration gradient of germanium. The internal stresses resulting from the gradient in the lattice parameter would have been relaxed by the introduction of a lineage structure of parallel arrays of edge dislocations which would not have been eliminated by annealing. Both the yield stress and the flow stress would also have varied from one end of the crystal to the other.

The methods used for growing the crystals were described by Mitchell et al.[125] and by Nixon and Mitchell.[141] Split graphite moulds with a 4.5 mm edge square section and highly polished smoked surfaces were made. The single crystals were grown under high-vacuum conditions with high-frequency heating and were initially spontaneously nucleated. The alloy charge was melted and allowed to flow through a fine graphite capillary into the growth chamber to remove insoluble particles, which separated at the liquid surface. Crystallization followed the slow uniform upward displacement of the high-frequency heating coil. Accurately oriented seed crystals were now produced from a spontaneously nucleated crystal by spark-cutting and spark-planing to give a $(1\bar{1}\bar{1})$ and a $(\bar{1}4\bar{5})$ surface intersecting along the [321] direction. These seed crystals were used for growing $[321]\{1\bar{1}\bar{1}\}\{\bar{1}4\bar{5}\}$ axis crystals which were annealed in a high vacuum or in high-purity argon at a temperature within 100° C of the melting point. With this orientation, the $\{\bar{1}\bar{1}1\}\langle 10\bar{1}\rangle$ glide system is activated

at the yield point. Slip lines and narrow slip bands appear on the $\{1\bar{4}\bar{5}\}$ planes with no slip traces on the $\{1\bar{1}\bar{1}\}$ surfaces which contain the slip vector. Localized etching created etch pits at emergent dislocations on these surfaces. The intention was to study the initial slip processes by optical and interference microscopy, by observations of dislocation etch pits on flat {111} surfaces, and by high-resolution replica and transmission electron microscopy. All these methods required crystals or crystal sections with optically flat surfaces produced without the introduction of dislocations. Many powerful new techniques were developed during the course of this work. A chemical cloth-polishing and electropolishing method allowed optically flat surfaces to be produced.[5,125] Etch pit studies on the $(1\bar{1}\bar{1})$ surfaces showed that the first Cu-7.5-at.%-Al crystals[29] had a sub-grain structure with the order of 10^5 dislocations cm^{-2} associated with sub-grain boundaries. This residual dislocation density was reduced, but never below 10^4-10^3 cm^{-2}, by separating the seed chamber from the growth chamber by two narrow square-sectioned channels, the first along the edge with the split section, and the second along an adjacent edge at right angles.[125] This increased the size of the sub-grains which were free from internal dislocations.

The $[321]\{1\bar{1}\bar{1}\}\{\bar{1}4\bar{5}\}$ orientation crystals which had a homogeneous composition, uniform square cross-section and optically flat surfaces were mounted in square sectioned sockets with a low melting point alloy which expanded on freezing. They were strained in a tensile machine with two universal heads. This eliminated the development of a bending moment across active glide planes passing through the centre of the crystal. The earliest stages of slip line and narrow slip band

formation were studied with progressive improvement in the quality of the crystals and in the experimental techniques. For the same crystal, load-elongation curves were recorded, slip lines and slip bands studied with the interference microscope[125,129,130] and by uranium oxide pre-shadowed replica electron microscopy,[1,2,4] and dislocation etch pit distributions observed on $\{1\bar{1}\bar{1}\}$ surfaces.[60,61] From surface topography and etch pit distributions, J. C. Chevrier[29] and W. E. Nixon[137] found that crystals with less than 3-at.%-Al deformed by nearly homogeneous shear processes. Well defined slip lines were not observed, and random distributions of dislocation etch pits appeared on $\{1\bar{1}\bar{1}\}$ surfaces. Above 3-at.%-Al, localized heterogeneous shear processes were observed beyond the yield point. Dislocation generation and displacement occurred on clearly defined glide planes, and slip lines and narrow slip bands were introduced. The most detailed studies of surface topography were made by J. P. Monaghan,[125,129,130] J. S. Ahearn[1,2,4] and W. E. Nixon,[137] and of dislocation etch pit distributions by B. J. Hockey.[60,61] Slip terraces appeared at the intersection of the glide plane with opposite $\{\bar{1}45\}$ surfaces but not with $\{1\bar{1}\bar{1}\}$ surfaces which contained the <101> slip vector. The widths of the narrow slip bands were measured together with the interference fringe displacements across them. This allowed the integrated shear displacement to be calculated and from this the number of dislocations generated or emerging at the surface. With this system, the widths and integrated shear displacements were found to be the same on opposite $\{\bar{1}45\}$ surfaces.[130] The individual bands were characterized by their surface contours on these surfaces determined with the interference microscope.[125] Those of most physical interest had

a constant shear angle and showed a linear rate of change in integrated shear displacement across the width of the band. Such bands were formed with higher probability near the centre of the gauge length and seemed to result from a reproducible process in which the opposite $\{\bar{1}45\}$ surfaces were equally involved.

Very narrow slip lines with a reproducible small integrated slip height first appeared on opposite $\{\bar{1}45\}$ surfaces at the yield point. These widened into narrow bands, and deformation then ceased. No dislocation motion occurred after the removal of the applied stress. When a crystal was electropolished again, remounted, and stressed to the yield point, slip lines formed near the edges of previous bands, and new narrow slip bands were introduced.[130] There was no displacement of dislocations within the bands because the corresponding volume of the crystal had been effectively hardened. The successive introduction of new independent bands elsewhere along the gauge length accounted for the observed elongation at the constant machine strain rate and the constant resolved shear stress of the yield point.

The terraces of the slip bands were studied by replica electron microscopy.[1,2,4,137] They extended at constant width for many millimetres across the $\{\bar{1}45\}$ surfaces. Their widths were measured and the number of dislocations introduced during their formation calculated. They tended to be clustered into groups separated by about 3 μm, often with intermediate clusters of slip terraces of narrower width. Information on the elementary slip processes was derived from measurements of the individual slip terraces. The integrated shear displacement across individual slip lines formed by narrow clusters of

slip terraces was approximately constant. The total number of dislocations generated or emerging at the two opposite $\{\bar{1}45\}$ surfaces was derived from the integrated shear displacements over a given corresponding length measured with the interference microscope and was the same at both surfaces.

The distribution within the crystals of the dislocations of the $\{\bar{1}\bar{1}1\}\langle 101\rangle$ primary glide system corresponding to the surface terraces was established by etching the external $\{1\bar{1}\bar{1}\}$ surfaces and parallel internal surfaces produced by spark-cutting, spark-planing, chemical and electrolytic polishing.[5,60,61] This produced optically flat accurately oriented surfaces. The etch pit distributions showed that dislocations were not generated by the operation of sources on the outer $\{1\bar{1}\bar{1}\}$ surfaces which contain the $\langle 101\rangle$ slip vector. Long sequences of dark etch pits were observed corresponding to pile-ups of many primary dislocations moving away from one $\{\bar{1}45\}$ surface on a closely spaced cluster of glide planes. Equivalent sequences of light etch pits corresponded to pile-ups of primary dislocations from the opposite surface on an adjacent cluster of glide planes. The characteristic dark and light etch pits established that the dislocations were in near-edge orientations.[60,61,125] A uniform mean surface density of dislocations was retained on the primary glide planes within the crystal. This was determined by counting etch pits. The number of dislocations corresponding to a unit width of slip band was known from the integrated shear displacement measured with the interference microscope. Calculations showed that more than 75% of the dislocations were retained within the crystal while less than 25% reached the opposite surface. No detailed correlations between slip

terraces on opposite surfaces were ever established by replica electron microscopy.

The operation of internal sources on primary glide planes in the intense stress fields around the heads of pile-ups was never observed. Neither was there any evidence for the propagation of shear displacements by the sequential activation of internal Frank-Read sources.[133,142] The large numbers of primary pile-ups involving many hundreds of dislocations could have arisen only by generation at the surface with the creation of the observed relatively wide surface terraces.

The operation of internal sources within the glide bands on the $\{\bar{1}1\bar{1}\}$, $\{111\}$ and $\{1\bar{1}\bar{1}\}$ secondary glide planes was always observed in etch pit distributions on sections with these and $\{\bar{1}\bar{1}1\}$ surfaces.[60,61] The sources evidently operated in the resultant stress fields created by the superposition on the applied stress of the intense internal stress fields between avalanches of primary dislocations passing in opposite directions on adjacent clusters of primary glide planes. The interactions between the secondary and primary dislocations produced sessile segments which were responsible for the observed internal hardening of the slip bands. Similar hardening processes with secondary dislocations near the edge of the slip bands terminated long-range propagation of primary dislocations and widening of the bands.

These observations of dislocation etch pits were supplemented by direct observations of the dislocations by transmission electron microscopy. The methods which were developed for producing precisely oriented highly polished $\{111\}$ surfaces allowed large-area thin foils with surfaces parallel to the primary $\{\bar{1}\bar{1}1\}$ planes to be produced.[57,60,125] These foils contained long arrays of parallel near-edge primary dislo-

cations with Burgers vectors of opposite sign moving in opposite directions on a few clusters of parallel planes. Extensive formation of parallel dipoles occurred. Approximately circular mats of sessile segments were formed by interactions between secondary and primary dislocations.[60,125] The observations were consistent with the conclusions drawn from the etch pit work and accounted for intense hardening at the yield stress within the slip bands.

The objective of the research on the plastic deformation of single crystals of Cu-X-at.%-Al alloys with the [321]{1$\bar{1}\bar{1}$}{$\bar{1}$4$\bar{5}$} orientation was to study the elementary dislocation processes responsible for the initial formation and widening of slip bands under optimized physical conditions with artifacts eliminated as far as possible by experimental design. The conclusions reached from the experimental observations at the end of this phase of the work were summarized in the following working hypothesis.

Plastic deformation was initiated by the creation at {$\bar{1}$4$\bar{5}$} surfaces of surface terraces and corresponding long-range avalanches of dislocations on narrow clusters of glide planes of the {$\bar{1}\bar{1}$1}<101> primary glide system. Dislocations were not generated at the {1$\bar{1}\bar{1}$} surfaces which contain the <101> slip vector. A return avalanche was generated on an adjacent narrow cluster of glide planes within the acute angle when a leading dislocation reached the opposite surface. This resulted in the generation of the same number of dislocations with Burgers vectors of opposite sign at the two surfaces with approximately uniform averaged densities of dislocations across the two clusters of glide planes. Quantitative measurements of integrated step heights with the interference microscope and of dislocation etch

pit distributions across the glide planes showed that more than 75% of the dislocations generated at one surface were retained within the crystal while less than 25% emerged at the opposite surface. It was proposed that this provided the unit process of plastic deformation in these single crystals and that the bands were widened by a succession of these processes. The bands were of the same width and integrated step height on opposite $\{\bar{1}4\bar{5}\}$ surfaces. It was established that the volume occupied by them was hardened as a result of the activation of internal sources on secondary glide planes between adjacent clusters of primary glide planes. This generated dislocation loops which interacted with the primary dislocations to give sessile segments. These interactions beyond the edges of the bands finally prevented further widening by blocking long-range propagation of primary dislocations. The model was consistent with the observations which had been made on slip lines and narrow bands of uniform shear formed at the yield stress near the centre of the gauge length. From these observations, it was clear that there was a reproducible elementary process and succession of elementary processes involving the long-range propagation of surface-generated dislocations in the plastic deformation of these crystals at the yield stress. Their operation was clearly recognized in particular narrow slip bands of uniform shear. It was, however, frequently obscured by a lack of detailed reproducibility in the formation of other bands, particularly away from the centre of the gauge length. This arose from the random activation of secondary sources which prevented long-range propagation of primary dislocations, giving non-correlated gaps in the slip bands on opposite surfaces. The only general conclusion covering all the slip bands which could be drawn

was that surface sources giving surface terraces and long-range avalanches of dislocations operated successively at the rate required to maintain the machine rate of elongation at the constant yield stress. After this work with [321]{1$\bar{1}\bar{1}$}{$\bar{1}$4$\bar{5}$} orientation single crystals of Cu-Al alloys, it was decided to grow crystals with other orientations to see if improved reproducibility might be achieved.

NATIONAL CHEMICAL LABORATORY 1963 - 1964

After 1959 there was increasing concern in Great Britain about the "brain drain" of British scientists to the United States, and Mitchell was approached on many occasions on the question of his returning. Sir Harry Melville, F.R.S., the Secretary of the Department of Scientific and Industrial Research, visited the University of Virginia in October 1962 to discuss the possibility of an appointment in the Scientific Civil Service. Following this visit, Mitchell spent a week at the National Chemical Laboratory in April 1963, discussed the present state and plans for the future of the Laboratory with Sir Harry Melville and the Director, J. S. Anderson, F.R.S., met the staff of the research groups, and learned of their research projects and interests. He accepted the offer of the Directorship of the Laboratory which was finally confirmed and announced in July and took up the position on 1 October 1963. He then learned for the first time, during a discussion with Sir Harry Melville, of the Report of the Brundrett Committee[25] and of the plans of the Government for the transfer of forty-two members of the staff of the Division of Inorganic and Mineral Chemistry to the Warren Spring Laboratory. This was the outstanding and powerful research unit under the leadership of

R. A. Wells and D. A. Everest which had attracted him to the National Chemical Laboratory the previous April. He requested that R. A. Wells be appointed as the Deputy Director of the Laboratory and wrote a report on its past, present and potential future. He resigned on May 7, 1964, when the recommendations of the Brundrett Committee were implemented and he learned of the intended abolition of the position of Director of the National Chemical Laboratory upon its incorporation as a division in the National Physical Laboratory. He returned to the University of Virginia in August 1964 and resumed his teaching and research activities. The unfortunate circumstances of his resignation were recorded in a letter to the Times written by J. S. Anderson, F.R.S.[9] Mitchell's analysis of the organization of basic research for the British chemical industry was presented in his Jubilee Memorial Lectures of the Society of Chemical Industry[101] given in Manchester, Edinburgh and Dublin in February 1965 which were widely studied in Japan and discussed in a Nature editorial of 10 July 1965.[48] In these lectures he discussed the role of basic research in increasing the value and volume of exports from industries dependent upon advances in the physical sciences for innovation, diversification and expansion. He emphasized (1) that manufacturing will always pass from advanced countries to developing countries with lower wage levels and (2) that an advanced country which has to export industrial products to survive must spare no effort and no expense to continuously further advance the level of its own science and technology. The important contributions of scientists in universities, industrial laboratories, national laboratories and sponsored research

institutes were discussed together with factors such as the critical size and the maintenance of the vitality of a research laboratory. The subsequent world-wide increase in competition from Japanese exports provided evidence for the relevance of Mitchell's penetrating analysis of the problems encountered in maintaining basic research activity when short-term product development and short-term profits are emphasized with neglect of long-term market share.

UNIVERSITY OF VIRGINIA 1969 - 1979

Plastic deformation of single crystals of α-phase copper-aluminium alloys with $[331]\{\bar{1}10\}\{\bar{1}\bar{1}6\}$ and $[\bar{1}2\bar{5}]\{1\bar{2}\bar{1}\}\{\bar{2}\bar{1}0\}$ orientations

The first ten years of research on the plastic deformation of single crystals of copper-aluminium alloys with the $[321]\{1\bar{1}\bar{1}\}\{\bar{1}4\bar{5}\}$ orientation resulted in a new model for the formation of slip lines and narrow slip bands. This single slip orientation had been selected because of the large Schmid factor of 0.4666 for the $(\bar{1}\bar{1}1)[101]$ primary glide system and the possibility of producing dislocation etch pits on the outer $\{1\bar{1}\bar{1}\}$ surfaces without the need for sectioning and polishing. It had disadvantages. In his etch pit studies on sections with $\{1\bar{1}\bar{1}\}$, $\{\bar{1}\bar{1}1\}$, $\{\bar{1}1\bar{1}\}$ and $\{111\}$ surfaces, Hockey observed extensive activation of glide systems on the $\{\bar{1}1\bar{1}\}$, $\{111\}$ and $\{1\bar{1}\bar{1}\}$ secondary glide planes which impeded the propagation of the primary dislocations and produced the hardened central volumes of the slip bands.[61] His observations by transmission electron microscopy with thin foils having surfaces parallel to $\{\bar{1}\bar{1}1\}$ planes[57] showed that the secondary dislocations were usually confined to thin discs between arrays of primary dislocations.[60] They were generat-

ed by sources activated by stresses resulting from the superposition on the applied stress of internal stresses due to avalanches of primary dislocations propagating in opposite directions on adjacent clusters of glide planes.

Single crystals with other orientations were next grown to see whether the reproducibility of the processes of slip band formation could be improved and the range of the primary dislocations increased by reducing the frequency of blocking interactions. J. S. Ahearn[2] found that only one of the two equivalent $\{\bar{1}\bar{1}1\}$ and $\{111\}$ glide planes was locally activated in the formation of a slip band in crystals with the $[110]\{\bar{1}10\}\{001\}$ orientation. On the active glide planes only one of the two equivalent $\langle 101\rangle$ and $\langle 011\rangle$ or $\langle \bar{1}01\rangle$ and $\langle 0\bar{1}1\rangle$ glide vectors was involved. There were no applied shear stresses on the $(\bar{1}1\bar{1})$ and $(1\bar{1}\bar{1})$ planes. The crystal axis was then rotated through 13.26° in the $[\bar{1}10]$ zone to give the $[331]\{\bar{1}10\}\{\bar{1}\bar{1}6\}$ orientation which proved to have many desirable features.[137, 58, 3, 147] The slip traces for a slip line or narrow slip band were continuous around all four surfaces. The traces of the $(\bar{1}\bar{1}1)$ primary glide plane in the $\{\bar{1}\bar{1}6\}$ surfaces were along $\langle\bar{1}10\rangle$ directions at right angles to the edges, and the contours of the interference fringes and shadowed slip terraces in replicas on the $\{\bar{1}10\}$ surfaces allowed the $(\bar{1}\bar{1}1)[101]$ and $(\bar{1}\bar{1}1)[011]$ equivalent coplanar glide systems to be distinguished. Detailed studies of the characteristic features of narrow slip bands formed during tensile deformation were made with single crystals with this orientation. There was a dramatic improvement in the reproducibility of the observations.

An orientation suitable for the simultaneous recording at low temperatures of elongation-time and stress-time curves for dislocation processes involving edge dislocations was also needed.[138, 58] This was provided by single crystals with the $[\bar{1}2\bar{5}]\{1\bar{2}\bar{1}\}\{\bar{2}\bar{1}0\}$ orientation for which the $(\bar{1}\bar{1}1)[101]$ primary glide system has a Schmid factor of 0.4899.[2] With this orientation the trace of the primary glide plane in the $\{\bar{2}\bar{1}0\}$ surfaces is at right angles to the edges, and the [101] glide vector lies in the $\{1\bar{2}\bar{1}\}$ surfaces so that there are no slip terraces. Deformation could be confined to the center of the crystal by reducing the cross-section with two parallel narrow flat-based grooves along the trace of the primary glide plane in the $\{1\bar{2}\bar{1}\}$ surfaces.[152,153] These were produced by spark-planing followed by electropolishing without spoiling the polished $\{\bar{2}\bar{1}0\}$ surfaces. This also proved to be the ideal orientation for the study of deformation by bending with a $[1\bar{2}\bar{1}]$ bending axis.[139]

The [331] axis crystals were strained to just beyond the yield point between well lubricated universal heads. The slip bands were studied by interference microscopy and by replica electron microscopy. The crystals were sectioned and dislocation etch pits produced on $\{1\bar{1}\bar{1}\}$ surfaces. It was found that slip bands formed near the centre of the gauge length had more reproducible characteristics than those formed nearer the sockets of the grips. This showed that internal bending moments, developed during plastic elongation, influenced the glide processes.

A number of significant new observations were made with crystals having this orientation. H. McD. Hobgood,[58] W. E. Nixon[137] and S. K. Ray[147] found that slip lines and narrow slip bands

were formed by the activation of only one of the two equivalent $(\bar{1}\bar{1}1)[101]$ and $(\bar{1}\bar{1}1)[011]$ coplanar glide systems. The resulting long-range internal stresses were then frequently compensated by the activation of the other glide system to the same extent with the formation of an adjacent slip line or slip band at a variable close separation. Two bands of uniform shear formed near the centre of the gauge length in this way gave striking interference patterns on the $\{\bar{1}10\}$ surfaces with no resultant fringe displacement.[58] There was also no resultant displacement of the fringes over an extended length normal to the trace of the $\{\bar{1}\bar{1}1\}$ glide planes, showing that the two equivalent glide systems were statistically activated to the same extent during the plastic elongation of the crystal.[54,58] The sensitive response of these crystals with two equivalent coplanar primary glide systems allowed the role of internal stresses in the process of plastic deformation to be clearly established. S. K. Ray[147] found that narrow slip lines were continuous around the four surfaces of the crystals with the same width and a constant integrated shear displacement on the $\{\bar{1}\bar{1}6\}$ surfaces. Since more than 75% of the dislocations corresponding to a slip line at one $\{\bar{1}\bar{1}6\}$ surface were retained on glide planes within the crystal, this showed that an equal number of dislocations had to be generated on the opposite side of the crystal to give the observed equal integrated shear displacement. This was consistent with the new model for the deformation process.

W. E. Nixon and Mitchell then plated [331] axis crystals with nickel apart from a central band about 5 mm wide around the trace of the primary glide planes. *With these crystals, they observed that*

very faint slip lines were introduced at the yield point which were continuous around all four surfaces. There was no discontinuity across the interference fringes on the $\{\bar{1}10\}$ surfaces, and those on opposite $\{\bar{1}\bar{1}6\}$ surfaces were of the same integrated step height. These fine slip lines were formed by long-range avalanches of surface-generated dislocations on two very closely spaced narrow clusters of glide planes. The $(\bar{1}\bar{1}1)\langle 101\rangle$ primary glide system was activated on one cluster and the $(\bar{1}\bar{1}1)\langle 011\rangle$ equivalent system to the same extent on the other. This work established, as far as seemed possible at the time, the nature of the elementary physical process involved in the formation of very narrow slip lines with minimum development of long-range internal stresses. The observations were fully consistent with the proposed model for the elementary process of slip line formation in a single crystal of high perfection under ideal physical conditions. Care had been taken to eliminate all the recognized artifacts.

The elastic constants of the α-phase copper-aluminium alloys were needed for calculations of the internal stress distributions associated with arrays of dislocations. Working within the group and using the methods which had been developed for the growth of accurately oriented crystals, L. S. Cain and J. T. Thomas measured the first and third order elastic constants for a series of alloys with ultrasonic resonance methods.[27,28] This allowed an important contribution to the understanding of the mechanisms of the plastic deformation processes to be made by D. A. Taliaferro and L F. Henry[156,157] who used computer simulation to study the internal stress distribution due to the approach of a 60° or edge dislocation to a surface

on an oblique glide plane. They found that an internal shear stress maximum which superimposed additively on the applied stress appeared on parallel glide planes at the surface and increased in magnitude as the dislocation approached the surface. For the $\{\bar{1}\bar{1}1\}$ primary glide planes of [331] axis crystals, the resolved internal shear stress was greater along the activated slip vector than along the equivalent alternative slip vector. This resulted in the generation of a returning dislocation avalanche with the same slip vector and accounted for the involvement of only one of the equivalent slip vectors in the formation of a narrow slip band of uniform shear. J. S. Ahearn[2] then calculated the resolved shear stresses on primary and secondary glide planes due to arrays of 60° dislocations on primary glide planes for the $[331]\{\bar{1}10\}\{\bar{1}\bar{1}6\}$ orientation using the stress field equations of anisotropic elasticity. This provided the basis for the detailed understanding of the activation of internal primary and of secondary sources and the blocking interactions between secondary and primary dislocations on adjacent clusters of glide planes which had been observed by transmission electron microscopy.[60,125]

Taken as a whole, the observations were consistent with the model according to which correlated dislocation generation processes at opposite surfaces of a crystal were responsible for the initial formation and widening of slip bands. It appeared that surface sources operated at the yield stress and that higher resultant stresses were required for the operation of internal sources. This was confirmed by T. N. Lovern[70] who lightly rubbed the four highly polished surfaces of single crystals with the $[331]\{\bar{1}10\}\{\bar{1}\bar{1}6\}$ orientation

on natural silk or on percale sheeting tightly stretched over a piece of plate glass. This introduced a uniform distribution of small interacting dislocation loops in a very thin sub-surface volume which inactivated surface sources at the yield stress. The crystals now yielded at a higher stress with activation of internal sources, and the characteristic slip bands were not formed. The formation of slip bands was prevented by rubbing only one of the $(\bar{1}\bar{1}6)$ surfaces or, as W. E. Nixon and Mitchell showed, by plating one of these surfaces with nickel. This provided further striking support for the proposed model.

Doubt was still expressed by other workers in the field as to the surface generation of dislocations and the long-range displacement of surface-generated dislocations. It seemed that relay-race mechanisms with sequential operation of internal Frank-Read sources were preferred.[133,142] To increase understanding of these properties, W. E. Nixon and M. H. Massey[139] studied the initial stages of plastic deformation in bending using single crystals having the $[\bar{1}2\bar{5}]\{1\bar{2}\bar{1}\}\{\bar{2}\bar{1}0\}$ orientation. They found that edge dislocations were generated at the surface where the shear stress had its maximum value and propagated in the decreasing stress field toward the neutral plane. The narrow cluster of glide planes between the surface and the neutral plane was filled with an approximately uniform linear density of dislocations. These dislocations could not cross the neutral plane because of the reversed shear stress. There was no activation of primary or secondary sources along the glide planes. The range of the dislocations was at least 3.2 mm. This work provid-

ed unequivocal and convincing evidence for the long-range propagation of edge dislocations in a copper-10.5 at.% aluminium alloy. Processes depending on Frank-Read mechanisms with sequential activation of internal sources were clearly excluded as an essential feature of the propagation process. No observations consistent with the operation of Frank-Read dislocation sources were ever made by Mitchell and his coworkers following the initial processes of plastic deformation of single crystals of copper alloys at the critical resolved shear stress of the yield point.

Measurement of dislocation propagation velocities in α-phase copper-aluminium alloys at 4.2 K

By 1967, a reasonable understanding had been reached of the mechanisms by which dislocations are generated and propagated in high-quality single crystals of copper-7.5-10.5 at.% aluminium alloys. With this necessary background, apparatus was designed which would allow the study of the rate of plastic relaxation processes at 77 and 4.2 K. It was established that narrow slip bands with the same characteristics were introduced at the yield point at temperatures of 4.2, 77 and 293 K. This was demonstrated by the quantitative study of surface topography and of etch pit distributions on polished sections.

At low temperatures the formation of these slip bands is accompanied by abrupt load drops. It was concluded that these had to result from a rapid succession of the unit processes of the model, and the number of dislocations moving during one of these processes had been determined. With this knowledge, it was possible to under-

take the measurement of the velocity of the dislocations because motion on one unit process ceased from work hardening due to propagation-blocking interactions before that on an adjacent unit was initiated. A reasonable estimate of the number of instantaneously moving dislocations during the formation of a slip band was therefore available.

The first measurements at 4.2 K were made by R. B. Schwarz and J. W. Mitchell with a grooved $[\bar{1}2\bar{5}]\{1\bar{2}\bar{1}\}\{\bar{2}\bar{1}0\}$ crystal, a central capacitor transducer for the measurement of the rate of elongation and a ceramic piezoelectric transducer mounted in the lower universal head for the stress measurement. The outputs were displayed simultaneously with a double-beam oscillograph giving elongation-time and stress-time curves. Load drops were observed at the yield point at 4.2 K. These resulted from the abrupt elongation associated with the formation of a narrow slip band and reduction in the stored elastic strain energy. The elongations produced compressive stress pulses which (1) travelled outward through the upper universal head, up the pull-tube to a second universal head and rigid block and back to the site of relaxation, and (2) travelled outward to the lower universal head back through the site of relaxation to the second universal head and back. The measured transit time was 400 μsec, and this determined the time for the relaxation process as dislocation motion abruptly ceased with the return of the stress pulses. The mechanical impedances of the upper universal head and the pull-tube were matched to the impedance of the crystal to prevent reflection of the stress pulses within the crystal and secondary dislocation processes.

(152,153)

After an initial interval of 30 μsec, elongation proceeded at a constant rate during the propagation of the stress pulses. This was determined by the dynamical characteristics of the mechanical system and the particle velocity of the moving upper half of the system which also determined the constant shear stress during relaxation. The measured constant rate of elongation gave the product of the number and velocity of the moving dislocations. This divided by the number of moving dislocations corresponding to the unit process of the model gave a mean velocity of 2.1×10^4 cm sec^{-1} at a resolved shear stress of 29.22 MPa. These were the first observations and measurements made in which the macroscopic mechanical inertial aspects of a fast-relaxation process were correlated with the microscopic dislocation mechanisms responsible for it.

Binary and ternary α-phase alloys of the Cu-Al-Ni-Pd system

The detailed study of dislocation relaxation processes in Cu-X-at.%-Al oriented single crystals established that primary dislocation avalanches were generated at highly polished surfaces of square-sectioned crystals without activation of internal sources. The surfaces at which the normal component of the shear displacement had a maximum value were favoured. The yield stress and the range of the dislocations increased with solute concentration. For concentrations of more than 3 at.% aluminium, a fraction of the dislocations generated at one surface were able to cross the primary glide planes to the opposite surface in crystals of the highest achievable perfection which had large sub-grains. Correlated return avalanches were then generated at that surface by the enhanced resultant stresses on adjacent clusters of glide planes. The repro-

ducibility of these processes increased with the resolved shear stress on the primary glide planes but was limited by the activation of internal sources on secondary glide planes. Sessile segments arising from dislocation interactions then blocked the long-range propagation of the primary dislocations. For higher velocity long-range dislocation motion at low temperatures, it was clearly desirable to increase the resolved shear stress on the glide planes by increasing the yield stress and to further harden the internal sources. The rate of the local relaxation process is determined by the stored elastic strain energy density as there is effectively no cross-head displacement during the short time interval.

Crystals with large sub-grains and low residual dislocation densities could be grown with Cu-7.5-at.%-Al alloys, but the sub-grain size decreased as the aluminium concentration was increased. The Cu-10.5-at.%-Al alloys gave the maximum yield stress for single crystals suitable for detailed study by the methods which had been developed. The properties of low solute concentration ternary alloys of the Cu-Al-Ni-Pd system were therefore studied. J. S. Ahearn[2] found that the secondary processes responsible for irreproducibility in the formation of narrow slip bands were much less in evidence with Cu-7.5- to 10.5-at.%-Al crystals containing 1-at.%-Ni. This was confirmed by W. E. Nixon[138] who also studied Cu-X-at.%-Al-X-at%-Ni crystals with X = 1 to 4. Optical flats of high perfection could be produced on the four surfaces of single crystals containing nickel by chemical polishing on a plane cotton surface followed by electropolishing.[5,138] Observations with the interference microscope showed that reproducible narrow slip bands of uniform shear were

formed with higher probability in the Cu-Al-Ni ternary alloy crystals than in Cu-Al alloy crystals at the same yield stress. It became clear that the introduction of aluminium and nickel gave more effective internal source-hardening than aluminium alone and a significant increase in the yield stress. Similar observations were then made with single crystals of Cu-X-at.%-Al-X-at.%-Pd alloys with X = 0.5 to 6 by H. McD. Hobgood[59] who also measured the lattice parameters of the binary and equiatomic concentration ternary alloys and found a very small change for the Cu-Al-Ni alloys from pure copper.

The narrow slip bands formed upon the initiation of plastic deformation at the yield point were studied for the ternary alloys by Nixon and by Hobgood. They made observations of surface topography by interference microscopy and by replica electron microscopy and found that the slip bands formed at 293 and 4.2 K had the same characteristic features as had been established for the Cu-Al alloy crystals. The important conclusion was that the same model could be used for the discussion of slip band formation at 293 and 4.2 K. Single crystals of these ternary alloys with the $[\bar{1}2\bar{5}]\{1\bar{2}\bar{1}\}\{\bar{2}\bar{1}0\}$ orientation were then strained in tension at 4.2 K using the apparatus of Schwarz and Mitchell.[152,153] Narrow slip bands were formed at the yield point with associated abrupt elongations and load drops. The analysis of the observations for the Cu-3-at.%-Al-3-at.%-Pd alloy gave a mean dislocation velocity of 2.8×10^{4} cm sec^{-1} at a yield stress of 73.35 MPa.

The pairs of (Al,Ni) and (Al,Pd) solutes in these ternary alloys

both form binary alloys with the CsCl structure and a high maximum melting point for the equiatomic composition.[53] This suggested that there should be strong mutual attraction between solute pairs in the copper matrix. In these circumstances, both the yield stress and the flow stress should be increased because of effective source-hardening from segregation and of interactions between glissile dislocations and solute pairs. It seemed that it should be possible to reach even higher dislocation velocities if the yield stress for a ternary alloy could be increased with increasing solute concentration without a corresponding increase in the flow stress. The Ni-Pd binary alloy system forms a continuous range of solid solutions with a minimum congruent melting point at the equiatomic concentration.[53] This implied possible repulsive interaction between Ni and Pd atoms in a copper matrix. The lattice parameter of copper is decreased by the addition of nickel and increased by that of palladium so that there should be compensation. The shear modulus of copper is increased by the addition of nickel and decreased by that of palladium so that there should again be compensation. It appeared from the theories of solute hardening[46] that there should in these circumstances be source-hardening by the segregation of nickel and palladium atoms at dislocations increasing the yield stress without an accompanying increase in the flow stress.

These considerations led S. K. Ray and Mitchell[147,148] to grow single crystals of the Cu-X-at.%-Ni-X-at.%-Pd alloys having X = 1 to 6 and the [331]{$\bar{1}$10}{$\bar{1}\bar{1}$6} orientation. They recorded load-elongation curves at 293 K which showed a smooth transition from the yield stress

to a lower flow stress. Crystals were then strained at 4.2 K and dislocation velocities evaluated from the characteristic abrupt elongations as in the earlier work of Schwarz, Nixon and Hobgood. For the Cu-X-at.%-Ni-X-at.%-Pd alloy single crystals with X = 5 and 6, the critical resolved shear stress at the yield point was 43.64 and 50.01 MPa and the lower limit for the dislocation velocity 7.63×10^4 and 1.17×10^5 cm sec^{-1}, respectively. These values are 3.6 and 5.6 times the dislocation velocity of 2.1×10^4 cm sec^{-1} found by Schwarz and Mitchell at 4.2 K and at a critical resolved shear stress of 29.22 MPa for the Cu-10.5-at.%-Al alloy. That there is indeed a very small probability for the occupation of adjacent lattice sites by pairs of nickel and palladium atoms was demonstrated by EXAFS studies of thin foils of these ternary alloys using synchrotron radiation.[159]

Accurately oriented single crystals with a uniform square cross-section and four smooth highly polished surfaces were used throughout this work. No dislocations were introduced after electropolishing and before the initiation of tensile deformation at the yield point. Reproducible values were obtained for the yield stress as a function of composition for single crystals of the α-phase Cu-Al,[141] Cu-Al-Ni,[138] Cu-Al-Pd,[59] Cu-Pd[148] and Cu-Ni-Pd[148] alloys at 293 K and 4.2 and for the flow stress of the Cu-Pd and Cu-Ni-Pd systems at 293 K.[148] These observations contributed to the understanding of the mechanisms of solute hardening.

The characteristic features of slip lines and narrow slip bands introduced at the yield point were studied for Cu-Al and Cu-Al-1-at.%-Ni single crystals by interference microscopy, replica electron

microscopy, dislocation etch pit configurations, and transmission electron microscopy with thin foils. The chemical cloth-polishing and dislocation etch pit methods could not be used with Cu-Pd, Cu-Al-Pd and Cu-Ni-Pd alloys. The four surfaces of square-sectioned single crystals of these harder alloys were polished on plane cotton surfaces with γ-alumina wetted with a solution of polyethylene oxide followed by electropolishing. This allowed the study of slip lines, narrow slip bands, and slip terraces by interference microscopy and replica electron microscopy. The results of these observations showed that essentially the same mechanisms were involved in the formation of slip lines and narrow slip bands in all the alloys of this system at both 293 and 4.2 K for all the orientations studied, provided that crystals of high perfection with the same dimensions and smooth highly polished surfaces were used. This conclusion applied particularly to the statistically reproducible narrow slip bands of uniform shear. The observed constant rate of elongation at a constant shear stress during the formation of narrow slip bands at 4.2 K showed that successive elementary processes were activated to maintain a constant average number of moving dislocations. This allowed calculations of dislocation velocities at 4.2 K to be made with the same model from measurements on single crystals of all the alloys.

The major objectives of the dislocation studies with oriented single crystals of α-phase copper alloys were thus achieved. These were (1) increased understanding of the mechanisms of solute hardening, (2) elucidation of the mechanisms of initial plastic deformation at the yield point and establishment of the elementary processes

involved, and (3) measurement of dislocation velocities at 4.2 K.

The researches of Mitchell and his graduate students on the initial stages of the plastic deformation of oriented single crystals of α-phase copper alloys extended over twenty years. They resulted in substantial advances in knowledge of the processes involved in the formation of slip lines and narrow slip bands in these crystals. The most reproducible observations were made with crystals of the Cu-7.5-at.%-Al and Cu-7.5-at.%-Al-1-at.%-Ni alloys. The three $[321]\{1\bar{1}\bar{1}\}\{\bar{1}45\}$, $[\bar{1}25]\{12\bar{1}\}\{\bar{2}\bar{1}0\}$ and $[331]\{\bar{1}10\}\{\bar{1}\bar{1}6\}$ orientations were used. For slip on the $\{\bar{1}\bar{1}1\}\langle 101\rangle$ primary glide system, slip terraces appeared on the $\{\bar{1}45\}$ and $\{\bar{2}\bar{1}0\}$ surfaces for the first two orientations but not on the other surfaces which contained the slip vector. The $\{1\bar{1}\bar{1}\}$ surfaces could be directly etched to produce dislocation etch pits. Slip lines appeared on all four surfaces of [331] axis crystals which had two equivalent coplanar primary glide systems. Many slip bands with a uniform constant shear angle were formed near the centre of the gauge length with crystals of this orientation.

Beyond the yield point, the crystals elongated at the machine strain rate at constant load by the successive introduction of discrete narrow slip bands. The local volume was hardened by the deformation process, and new bands were introduced elsewhere at the same resolved shear stress to maintain the strain rate. The integrated shear displacement, measured with the interference microscope, was the same on the opposite $\{\bar{1}45\}$, $\{\bar{2}\bar{1}0\}$ and $\{\bar{1}\bar{1}6\}$ surfaces for the three orientations and was constant around all four surfaces for a single slip band with either a $\langle 101\rangle$ or $\langle 011\rangle$ glide vector for

[331] axis crystals. These observations together with replica electron microscopy of the surface terraces and dislocation etch-pitting of $\{1\bar{1}\bar{1}\}$ surfaces showed that more than 75% of the dislocations corresponding to the integrated shear displacement at one $\{\bar{1}45\}$ surface were retained within the crystal. The observed constant integrated shear displacement could not be explained unless dislocations were generated in equal numbers at the opposite surfaces and propagated across the glide planes with retention of the same fraction within the crystal. This conclusion led to the elementary process of the new model for the formation of a narrow slip band in which correlated avalanches of dislocations were generated at opposite $\{\bar{1}45\}$, $\{\bar{2}10\}$ or $\{\bar{1}16\}$ surfaces on adjacent narrow clusters of glide planes. The slip bands were widened by successions of these elementary processes and hardened by the activation of secondary sources by internal stresses developed in the volume between the avalanches. The model depends on the long-range propagation of at least a few dislocations from one $\{\bar{1}45\}$, $\{\bar{2}10\}$ or $\{\bar{1}16\}$ surface to the opposite surface and upon the correlated involvement of the two surfaces. It was supported by the observation of long-range propagation in single crystals deformed by bending. In this case, dislocations generated at one surface are propagated into regions of decreasing shear stress under the influence of their mutual repulsion. There is no interference from interaction with dislocations propagating in the opposite direction. It was further supported by experiments in which one of the surfaces was hardened by light rubbing on silk or cotton cloth or by nickel plating. This destroyed the symmetry of the system, and

narrow slip bands were not formed at the yield stress. These experiments also established that dislocation sources operate at surfaces at which slip terraces are formed and not at surfaces containing the slip vector. The observations showed that the slip bands were produced by surface primary dislocation-generation processes together with activation of internal sources, giving propagation-blocking interactions. The statistical sequence of these processes was balanced to allow elongation at the constant machine strain rate at constant load. The microscopic reproducibility of the processes was improved by hardening the internal sources and reducing the applied shear stress on the secondary glide systems. This increased the proportion of uniform bands with a constant shear angle.

Other research work

In addition to the main program on dislocation phenomena during the plastic deformation of single crystals of alloys, Mitchell was interested in exploratory work in other areas. He was particularly interested in comparing the ultimate strength of dislocation-free thin filaments of cadmium with the theoretical limit. J. C. Crump and Mitchell[31, 34] grew single crystal filaments with surfaces parallel to {0001} and $\{01\bar{1}0\}$ planes, $[\bar{2}110]$ axes and uniform rectangular cross sections by slow distillation in an atmosphere of argon. The filaments were strained with a pneumatic tensile device in the electron microscope and the maximum elastic strain determined directly from measurements of electron diffraction patterns. The crystals failed at measured elastic strains between 3.8% and 4.5% along the $[\bar{2}110]$ direction. The corresponding normal stress was measured di-

rectly with the tensile device. The resolved shear stress at failure on the activated glide systems varied between G/11 and G/15 where G is the relevant shear modulus. This was within the range of estimated theoretical maximum strengths of crystals for deformation by a homogeneous shear process.[72] These were the first absolute measurements made of the maximum strength of a dislocation-free thin filament with atomically smooth surfaces. At this time, J. C. Crump[32, 33] also studied the development of hexagonal networks of dislocations by the condensation of vacancy loops in basal planes during the exposure of thin ribbons of cadmium to the beam in the electron microscope.

C. M. Drum[36, 37, 38] grew thin whiskers of aluminium nitride, observed axial dislocations with the electron microscope, and discussed their role in the growth of the crystals. Mitchell was also interested in the nucleation and growth of filamentary crystals in supersaturated aqueous solutions. He had observed that highly supersaturated solutions of potassium dihydrogen phosphate could be made and stored in Teflon or silicone-treated glass containers and that the formation of very fine filamentary nuclei could be observed with a phase contrast or with a polarizing microscope between crossed polarizers. Using a thin cell with silicone-treated surfaces, M. A. Lundquist[71] studied the nucleation of very fine needles and their rapid outward expansion in supersaturated solutions of potassium dihydrogen phosphate. The thickening of filaments by rapid propagation of waves of crystallization along extremely fine filamentary leaders was also observed. Successive kinematic growth waves were seen on the surfaces of narrow elongated tabular crystals.

P. E. Zanzucchi[160] wrote computer programs for plotting and indexing the spots of Laue diffraction patterns for any single crystal orientation on the scale of the camera for superposition on the photographically recorded patterns. This allowed higher precision to be achieved in the determination of crystal orientations. From the measurements of the lattice parameters of natural crystalline quartz made using the powder method by H. D. Keith[66, 67] at Bristol, it was recognized that precision was limited by the extent to which systematic errors could be minimized. The measurement of high-precision lattice parameters was now resumed with the large single crystals of germanium and silicon of high perfection which were available. Systematic errors were eliminated by careful experimental design and the use of the divergent beam or pseudo-Kossel back-reflection method. A computer program was written by P. E. Zanzucchi for plotting the divergent beam X-ray patterns with the experimental parameters. This allowed the application of the divergent beam method to this particular problem to be thoroughly analysed and the diffraction lines which would give the highest achievable precision identified. The analysis showed that a Bragg angle greater than 89° could be realized with $CoK\alpha_1$ radiation for the {620} reflections of germanium and with $GeK\alpha_1$ radiation for the {157} reflections of silicon. A microfocus Rigaku-Denki X-ray generator was used with thin cobalt or germanium targets, and the back-reflection diffraction patterns were recorded at accurately defined temperatures for the (620) and (157) reflections from germanium and silicon crystals having (111) surfaces. Calculations based on microdensitometer records of

the diffraction loops gave a = 5.65794 Å ± 0.00005 Å and a = 5.65802 Å ± 0.00005 Å for two germanium crystals at 25° C. For silicon, a = 5.4314 Å ± 0.0001 Å at 25° C. Very high precision was thus achieved in these measurements of the lattice parameter of large single crystals of germanium and silicon of the highest achievable quality.

With W. E. Nixon, Mitchell used his experience in producing monodisperse distributions of extremely small silver particles to make dispersions of lead particles with mean particle dimensions between 3 nm and 5 μm and a narrow size-frequency distribution. The superconductivity of the particles was characterized by measurements of magnetization as a function of temperature and magnetic field by T. L. Fariss, T. J. Bucelot, and B. S. Deaver, Jr.[44] The larger particles had the transition temperature of bulk lead 7.2 K. For particles with a characteristic dimension of less than 20 nm, this was lower by 0.1 K. A new system was thus provided for the study of the properties of particulate superconductors.

Mitchell had always been concerned with interactions between structural and lattice defects in crystals and with the equilibration processes. At Bristol, he had found that dislocation-free crystals of silver chloride and silver bromide could be readily produced whereas crystals of alkali halides always had many small dislocation loops. He attributed this to thermally reversible Frenkel disordering of the silver halides which can occur in a dislocation-free crystal compared with creation and annihilation of Schottky defects by climb processes with changing temperature at small dislocation loops in alkali halides. In a paper published in 1962,[99] he discussed

the equilibration processes in crystals which accompany temperature changes and precipitation processes and emphasized the important role of the screw dislocation in these processes in crystals, such as those of germanium and silicon, with vacancy disorder. He used the methods of statistical thermodynamics to prove that vacancies could be created and annihilated within a crystal at low supersaturations by climb processes involving screw and helical dislocations and derived quantitative relations between the supersaturation and the radius and pitch of the helix.

With W. E. Nixon, Mitchell developed an improved non-silver halide photorecording system based on organotellurium compounds.[140] By a new synthetic method, these compounds were made in high yield by reacting tellurium tetrachloride with substituted acetophenones in chloroform solution under reduced pressure at the lowest possible temperature. This gave pure crystalline trichlorotelluro-substituted-acetophenones which were then reacted with the substituted acetophenone under reduced pressure in ethylene dichloride solutions to give the photosensitive organotellurium system. A fine dispersion of cellulose triacetate was added to produce the coating solution. Coatings prepared from 4-methoxy- and 2.5-dimethoxy-acetophenone gave excellent results. They were sensitized by the addition of tetramethylpyrazine, which reacted with chlorine during exposure, and with duroquinone and durohydroquinone. Stable, dense, high-contrast, high-resolution images were produced directly after exposure to a xenon flash by dry thermal development on a hot plate at temperatures between 125 and 150° C. No fixation was needed.

This was an interesting covering power system with the same mass per unit area of tellurium in the dark and light areas of the final image. Exposure produced a very finely dispersed latent image, the particles of which were enlarged by thermal development to give a dense black image. There were no nuclei in the unexposed areas, and thermal decomposition gave a greatly reduced number per unit area of larger particles of tellurium with much smaller optical absorption.

Teaching 1959-1979

From 1959 to 1963, Mitchell taught first- and second-year courses on general and engineering physics and first-year graduate courses on classical and statistical thermodynamics and on geometrical and physical optics. He used demonstration experiments to illustrate fundamental principles wherever possible. He gave advanced graduate courses on classical, mathematical and X-ray crystallography and on solid state physics, and thoroughly enjoyed this teaching experience. There were no first- and second-year courses for intending physics majors, who attended engineering physics lectures, and he became concerned over the small number of majors, less than 10 during each of these four years.

On his return from England in 1964, he introduced a new three-semester course for physics majors with classical mechanics and special relativity in the first, electricity and magnetism with a relativistic approach to electromagnetism in the second, and atomic, nuclear and high-energy physics in the third semester. He used vector methods and SI units throughout this course. Between the spring semester of 1965 and that of 1969, he taught four cycles of the course,

and the number of intending physics majors increased from 18 to 66 during this period. For the third-year students, he taught a course on the energetics of physical systems covering classical and statistical thermodynamics, and introducing the full range of independent variables and thermodynamic functions. He included subjects such as solutions, phase diagrams of alloys, phase transformations, and properties of matter in states of fine dispersion. For third-year undergraduate and first-year graduate students in physics and astronomy, he taught a course on geometrical, physical, and quantum optics. He gave these courses, together with engineering physics and graduate courses in crystal and solid state physics as required, until his retirement.

Other activities 1959 - 1979

Within this period, Mitchell gave many lectures at conferences and symposia, universities, and government and industrial research laboratories in the United States and in other countries. There was great interest during the first ten years in the work which had been done at Bristol on dislocations in crystals of silver halides and the model systems which they provided for crystals of face-centred-cubic metals and silver halide emulsion microcrystals. As the research programme developed at Charlottesville, a gradual transition to lectures on the growth and plastic deformation of single crystals of α-phase binary and ternary alloys of the Cu-Al-Ni-Pd system occurred. The range of his interests is indicated by the following lectures and activities.

In September 1960, he gave the introductory lecture on the com-

parative properties of silicon and germanium, the binary III-V, II-VI compounds and silver and alkali halides from the point of view of systematic inorganic chemistry and the periodic table at a symposium on the chemistry of the solid state held at a meeting of the American Chemical Society in New York. In March 1961 he gave a review lecture on the direct observation of imperfections in crystals by optical and electron microscopy at the 90th annual meeting of the Metallurgical Society of AIME in St. Louis, Missouri. At an international conference on the chemical physics of non-metallic crystals at Northwestern University in Evanston, Illinois, in August 1961 he gave a lecture on the mechanisms of equilibration of lattice defects in real solids. In September 1962 he gave lectures on the role of dislocations in photographic sensitivity and the role of chemical sensitization in photographic sensitivity at a symposium on photographic sensitivity in Tokyo, Japan. This was followed by a seminar on dislocation arrays and the growth of microcrystals in relation to photographic sensitivity at the Ashigara Research Laboratories of the Fuji Photo Film Co. Ltd. In August 1966 he gave a review lecture on his work with J. C. Chevrier, B. J. Hockey, and J. P. Monaghan, Jr., on the nature and formation of bands of deformation in single crystals of α-phase copper-aluminium alloys at an international conference on deformation of crystalline solids in Ottawa, Canada. In September 1967 he gave a lecture on his work with J. S. Ahearn, Jr., B. J. Hockey, J. P. Monaghan, Jr., and R. K. Wild on dynamic dislocation phenomena in single crystals of α-phase copper-aluminium alloys at an international conference on the strength of metals and

alloys in Tokyo, Japan. Later in September he gave a lecture on the use of model systems for the study of chemical sensitization at an international congress on photographic science in Tokyo, Japan. In August 1968 he was chairman of the organizing committee and an editor of the proceedings of the sixth international symposium on the reactivity of solids, held at the Knolls Research Laboratory, General Electric Company, Schenectady, New York.[102]

During a sabbatical semester in 1972, he was a visiting lecturer at the Department of Physics of the University of Natal at Pietermaritzburg in South Africa and in August and September gave fifteen lectures on general subjects, the strength of metals, plastic deformation of single crystals of copper alloys and physical properties of silver halide crystals and photographic sensitivity. On his return journey to Charlottesville, he gave lectures on these subjects as appropriate at universities and research laboratories in Perth, Melbourne and Sydney in Australia, Delhi, Zürich, Göttingen, Paris, Oxford and Cambridge.

In May 1977 at a symposium organized by the Academy of Sciences of the U.S.S.R. in honour of the 80th birthday of Professor K. V. Chibisov, he gave a lecture on mechanisms of chemical sensitization and latent image formation. In September 1977 he gave a lecture on his work with W. E. Nixon on thermally developable light-sensitive systems based on organo-tellurium compounds at an international symposium on photo- and electro-imaging in Tokyo, Japan.

During this period he gave two critical review papers on his theoretical work on photographic sensitivity in March 1962 at a symposium on photographic processes organized by the Division of

Physical Chemistry of the American Chemical Society in Washington, D.C., and in October 1966 at a colloquium on the photographic interaction between radiation and matter organized by the Society of Photographic Scientists and Engineers in Washington, D.C. In June 1971 he gave a lecture on the properties of small clusters of atoms of silver and gold at a working symposium on the sizes, properties and reactions of latent images organized by the Society of Photographic Scientists and Engineers in Manchester, New Hampshire. He was aware of developments in the field of photographic science, but his energies were concentrated on the study of slip processes at the yield point in single crystals of α-phase copper alloys.

During the nineteen seventies, Mitchell found himself with a steadily decreasing amount of time available for reading, writing and research. This was a consequence of a substantial increase in the number of undergraduate students and in departmental and university committee assignments and other responsibilities. He retired in 1979 to engage in full-time study and research but continued to interact informally with the students.

ACTIVE RETIREMENT 1979-1993

Theory of photographic sensitivity

After twenty years of researches on the plastic deformation of oriented single crystals of copper alloys, Mitchell was elected a Senior Research Fellow of the University of Virginia and returned to silver halide imaging science. He was convinced that the experimental work at Bristol had provided a sound basis for the photoaggregation theory which he had formulated between 1953 and 1958. The essential features of the theory had, however, been rejected during the inter-

vening years by scientists of the Eastman Kodak Research Laboratories at Rochester, New York.[52] The design and interpretation of most of their published work with relatively insensitive model silver halide emulsion systems was based on the direct photolysis theory of Gurney and Mott as modified by Hamilton.[50]

As proposed in the nineteen fifties, the photoaggregation theory was an essentially qualitative theory. The experimental work had established that crystals of silver chloride and of silver bromide of the highest achievable purity and perfection showed negligible photoconductivity and were insensitive for normal photographic exposures to wavelengths longer than 400 nm with photon energies of 3 eV and less.[93, 24,105] Thermochemical calculations with the first law of thermodynamics established that a minimum photon energy of 4 eV (300 nm) was needed for the formation of a separated adsorbed silver atom and bromine atom at the surface of a silver bromide crystal.[114] It was difficult to understand how this could be disregarded by Hamilton and other supporters of Gurney-Mott direct photolysis theories of latent image formation and particularly by Tani. According to his modified electron transfer theory of spectral sensitization,[158] silver and halogen atoms could be liberated in high-purity silver bromide crystals by photons with energies between 2.5 and 1.5 eV. This was contrary to experimental observations and thermodynamic considerations which demanded a photochemical process for the formation of the latent image by the absorption of photons with energies in this range. Sensitizing non-halide molecules with silver or gold atoms and binding energies smaller than those of the silver halides had to be introduced to participate in the primary

electronic process. These could be photodissociated by lower energy photons than those needed for the silver halides and have occupied electronic energy levels in the energy gap from which electrons could be transferred to the conduction band following the absorption of photons with energies in the normal photographic range. This reasoning had led to the photoaggregation theory according to which the latent image is formed by silver and gold atoms chemically equivalent to sensitizing molecules. In a modern high-speed negative emulsion, these are Ag_2, Ag_2O, Ag_2S and (Ag,Au)S molecules adsorbed at the surfaces of the silver halide microcrystals. In this theory, the silver halide acts as a carrier for the sensitizing molecules which are involved in the primary electronic processes of latent image formation. It provides a transport medium for the electrons and interstitial cations released by photodissociation and a carrier for the latent image formed by their combination. It then provides the silver atoms of the final image by reduction in the developer, the initiation of which is catalysed by the latent image. Halogen molecules are not liberated at the surface during normal latent image-forming exposures of high-speed negative emulsions. This is consistent with the photoaggregation theory but not with the direct photolysis theories of Gurney-Mott, Hamilton and Tani. With these background ideas, Mitchell undertook the refinement of the photoaggregation theory.[118,124]

An essential feature of the theory which distinguished it from all the Gurney-Mott direct photolysis theories had been the photochemical formation of a positively charged Ag_4^+ latent image growth

nucleus and concentration centre from a sensitizing Ag_2 molecule by the addition of one Ag atom and adsorption of an Ag^+ ion. This concept had always been rejected by the proponents of the Gurney-Mott theories.[51] In the first paper of the series, Mitchell calculated the binding energy of an Ag^+ ion to a cluster of silver or of silver and gold atoms and showed that Ag_4^+ was indeed the minimum size of a positively charged cluster which would be stable in the silver halide grains of a dry emulsion.[103] He further showed that this cluster would have to increase in size to Ag_5^+ by the addition of an Ag atom before it would provide a stable development centre in an aqueous medium because of the large hydration energy of the Ag^+ ion.[104,106]

He was next concerned with quantitative aspects of the role of this positively charged centre in the concentration of silver atoms liberated by the action of light. In Gurney-Mott theories, photoelectrons are displaced by a three-dimensional random walk diffusion process, and there is an extremely small probability for the successive separation of silver atoms at the same site when there is a large number of equivalent sites. In the photoaggregation theory, they experience directed displacement toward the positively charged concentration centre. Mitchell calculated the mean drift range of a photoelectron during its lifetime in the radial Coulomb field of a centre with a unit positive charge.[106] This gave an optimum dimension for a thin hexagonal tabular grain with a central concentration speck in good agreement with experiment.[45]

The statistics of electron trapping processes in microcrystals of silver halides determine the distribution of photoelectrons be-

tween the conduction band and shallow and deep electron trapping states. Using the methods of statistical thermodynamics, Mitchell calculated the ratio of the probability that a photoelectron would be found in a trapping state to the probability of its being in the conduction band as a function of the volume of the microcrystal and the number and depth of the electron trapping states.[109,111] He showed that the probability that a conduction electron would be trapped at a shallow trapping state as in the Hamilton theory[50] was extremely small because of the very large density of states in the conduction band. A minimum trap depth was required before a single electron trap could be effective, and this was provided by the positively charged Ag_n^+ latent image centre.

The dependence of the range on the concentration of interstitial silver ions n_i was calculated and found to be proportional to $n_i^{-2/3}$. This explained the observed increase in sensitivity with decrease in concentration of interstitial silver ions. The statistical analysis also explained the observed progressive desensitization of spectrally sensitized silver halide emulsion grains with increasing number of adsorbed dye molecules.[113,114] If these molecules provide shallow trapping states, the probability that the electron will be in a trapping state and not in the conduction band increases with the number of adsorbed dye molecules.

Mitchell now introduced the language of donor and acceptor centres for the discussion of the processes of chemical and spectral sensitization and photochemical change in silver halide crystals.[113,116,118] Donor centres were provided by adsorbed or incorporated Ag_2, Ag_2O, Ag_2S and (Ag,Au)S sensitizing molecules and acceptor centres by

positively charged Ag_4^+, $AuAg_3^+$ and $Au_2Ag_2^+$ latent image centres. There were many donor and few acceptor centres during the initial exposure of a sensitized microcrystal. According to the photoaggregation theory, the sensitizing donor centres are involved in the primary electronic processes which follow the absorption of photons with wavelengths longer than 400 nm by either the silver halide or adsorbed dye molecules. Electrons are ejected from them with the formation of Ag_2^+, Ag_2O^+, Ag_2S^+ or $(Ag,Au)S^+$ centres by the decay of either intrinsic or dye excitons. This results from a three-electronic charge-carrier Auger process[119,121,124] involving the electron of the donor centre, that of the exciton and the hole of the exciton. The energy released by the combination of the donor electron and the exciton hole is carried away as kinetic energy by the exciton electron. Back-electron transfer is prevented by the rapid dissociation of the positively charged donor centre by passage of a silver or gold ion into an interstitial position. The electron is then attracted to and trapped by a positively charged latent image acceptor center. The positive charge is restored and the trap reset by the effective adsorption of an interstitial silver ion. An interstitial silver ion then drifts from the donor to the acceptor centre to eliminate space charge fluctuations. The result is the transfer of a silver atom from a donor to an acceptor centre. This photoaggregation process continues until the donor centres are exhausted, but this would represent gross overexposure of a modern high-speed negative emulsion in which a developable latent image is formed by the absorption of between 4 and 25 photons by a spectrally sensitized silver halide microcrystal.

Towards the end of this series of publications Mitchell discussed the important role of donor and acceptor centres provided by polyvalent cations in lower and higher valency states in catalysing the photoaggregation process.[117,124] Photocatalysis occurs when suitable polyvalent cationic donor and acceptor centres such as Fe^{2+} and Ir^{3+} ions are present in equimolar concentrations of the order of 10^{-7} to 10^{-8}, referred to the silver halide, with molar concentrations of sensitizing donor centres of the order of 10^{-5} to 10^{-6} and a few latent image acceptor centres. Electrons and holes are created by the decay of intrinsic or of dye excitons at cationic donor and acceptor centres and trapped at latent image acceptor and at sensitizing donor centres with accompanying ionic processes. This results in the catalysed transfer of silver or gold atoms from sensitizing donor to latent image acceptor centres.

Hedges and Mitchell made the first observations of dislocations with thin sheet crystals of silver bromide sensitized with silver oxide at Bristol in 1952.[55] Internal latent image and visible particles of photolytic silver formed along the dislocation lines during exposure. Evans and Mitchell then observed dislocations in microcrystals of silver bromide and rapid local dissolution at the points of emergence of the dislocations.[43] Mitchell discussed the role of dislocations in photographic sensitivity in 1962 and 1980.[100,107] In 1983, he published calculations of the densities and configurations of dislocations which should be introduced to relax internal strains associated with halide ion concentration gradients in silver halide microcrystals.[108] This work aroused little interest until direct observations of the dislocation configurations were made at

liquid helium temperatures with a 1 MV transmission electron microscope in commercial high-speed tabular emulsion grains with a silver bromoiodide core and a silver bromide shell by scientists of the Fuji Photo Film Co.[63] The points of emergence of dislocations through the surface of a crystal provide sites of enhanced reactivity during chemical sensitization. The surface latent image tends to be formed and chemical development initiated at these sites with higher probability than elsewhere on the surface. Mitchell gave a full account of the introduction of stable distributions of dislocations and of their role in determining the sensitivity of silver halide microcrystals at the Symposium held in October 1990 at the University of Tokyo on the occasion of the 80th birthday of Professor Shin Kikuchi.[122,123]

Between 1978 and 1991, Mitchell showed in the thirty papers which he published that the models of the photoaggregation theory allowed a self-consistent discussion to be given of the whole range of photographic phenomena. These included chemical sensitization,[118] spectral sensitization, desensitization and supersensitization,[113,114,115] latent image formation,[103,116,124] and the initiation of development.[104,106] He emphasized in a number of publications that aspects of the Gurney-Mott direct photolysis theories as modified by Hamilton and by Tani are inconsistent with experimental observations and with fundamental thermodynamic principles,[118,121] but they remained unconvinced. They claimed that their observations on latent image formation in relatively insensitive silver halide emulsions provided support for their Gurney-Mott direct photolysis models and continued to reject essential features of the photoaggregation theory. Mitchell respond-

ed with detailed analysis of the rejection.[51,120]

The Gurney-Mott models have little relevance to the design of high-speed negative emulsions, but very few papers on the properties of these emulsions have ever been published by scientists from the research laboratories of the photographic industry. Mitchell believed that his publications on dislocations and photographic sensitivity and on the models of the photoaggregation theory[123,124] provided a sound basis for the design of fully competitive high-speed negative and direct positive emulsions.

Other activities 1979 - 1993

During this period, Mitchell gave many lectures on the physical, photochemical and chemical properties of silver halide crystals, on chemical sensitization, and on the nature and formation of the photographic latent image. The advances which were made in basic understanding of commercial photographic systems were of great interest to many laboratories of the photographic industry and to the few universities involved in photographic research.

In July 1980, he reviewed the photoaggregation theory as it was at that time in a lecture at the Tokyo symposium on advances in photography organized by the Society of Photographic Science and Technology of Japan.[107] In September 1980, he gave lectures at the research laboratories of Kodak-Pathé, Vincennes, Paris; Agfa-Gevaert AG, Leverkusen, Germany; Ciba-Geigy, Marly, Fribourg, Switzerland; the Photographisches Institut, E.T.H., Zürich, Switzerland; and attended a symposium on model investigations of the photographic process organized by the Bulgarian Academy of Science in Drouzhba, Varna,

Bulgaria.

In March and April 1981, he was a visiting professor at the University of Kyoto under the Research Fellowship Programme of the Japan Society for the Promotion of Science. He gave twelve lectures on the physical properties and lattice and structural imperfections of crystals of silver halides and on the nature, formation and development of the photographic latent image. During this period he also gave lectures at the University of Tokyo and at professional meetings of the societies of photographic science in Kyoto and in Tokyo. In May and September 1981, he gave lectures at the research laboratories of Agfa-Gevaert AG in Leverkusen on latent image formation and properties and on spectral sensitization, desensitization and supersensitization. The quantitative theory of the concentration process in latent image formation was worked out in May and June 1981 and presented in a lecture at the University of Frankfurt on May 21 and at an international symposium on the fundamentals of latent image formation at Lake Placid, New York, on July 30.(106)

There was still interest in the work on dynamic dislocation phenomena in single crystals of copper alloys at 293 and 4.2 K, and he gave lectures on this subject in April and May at the Department of Metal Physics of the University of Kyoto and the Institut für Metallphysik of the University of Göttingen. In September, he reviewed the Charlottesville work on the plastic deformation of single crystals of copper alloys in a lecture at an international symposium on dislocation dynamics in solid solutions held in St. Andreasburg, Harz, Germany.

He gave a lecture on the concentration process in the formation of development centres in silver halide microcrystals in September 1982 at the international congress of photographic science held in Cambridge, England.[103,110] He was a guest professor in the Institut für Metallphysik of the Technische Universität, Carolo-Wilhelmina, Braunschweig, Germany, in April 1983 and gave lectures on the plastic deformation of single crystals of copper alloys. In May 1983, he gave a lecture on the statistics of electron-trapping processes in microcrystals of silver halides at the University of Frankfurt.[111] In this lecture, the methods of statistical mechanics were used for the first time for the discussion of the distribution of a few photoelectrons between trapping states and the conduction band. The same subject was presented at a lecture later in the month at the 36th annual meeting of the Society of Photographic Scientists and Engineers in San Francisco at which Mitchell was awarded the Lieven Gevaert Medal of the Society. He gave two seminars on factors involved in the design of silver halide photographic emulsions for optimum performance at the research laboratories of Agfa-Gevaert AG, Leverkusen, in June 1984 and also a lecture on spectral sensitization, desensitization and supersensitization at the Institut für wissenschaftliche Photographie of the Technische Universität, Garching, Munich, Germany. At the international east-west symposium on the factors influencing photographic sensitivity in October 1984, held at Maui, Hawaii, he gave a lecture on the optimization of the negative imaging silver halide photographic system.[112] In November 1984, he gave a lecture on quantitative aspects of the concentration

theory of latent image formation to the Society of Photographic Science and Technology of Japan in Kyoto in which he introduced the language of donor and acceptor centres for the first time.[113]

In April 1985, he gave lectures on the formation and properties of the photographic latent image at the research laboratories of the VEB Film Fabrik, Wolfen, and on chemical and spectral sensitization of silver halide photographic emulsions at the Akademie der Wissenschaften der DDR, Berlin-Adlershof, East Germany. He gave lectures on the elementary processes of the concentration theory of latent image formation[116] and on the supersensitization of spectrally sensitized silver halide imaging systems[115] in September 1986 at the research laboratories of Agfa-Gevaert AG, Leverkusen, Germany.

In 1988, interest in the use of silver halide crystals as model systems for the study of dislocation processes was revived, and he gave lectures on prismatic dislocation-punching at the Department of Nuclear and Chemical Engineering of the University of Maryland in March and on observations of dislocations in crystals of silver halides at the Department of Materials Science and Engineering, Massachusetts Institute of Technology, in April.

He presented a historical review of the direct photolysis and photoaggregation theories of latent image formation in May 1989 at the 42nd annual meeting in Boston, Massachusetts, of the Society for Imaging Science and Technology[118] and a lecture on Auger processes for the creation of free electrons and holes in sensitized crystals of silver halides in May 1990 at the 43rd annual meeting of the Society in Rochester, New York.[121] In October 1990, he gave a

lecture on dislocations and photographic sensitivity at a symposium held on the occasion of the 80th birthday of Professor Shin Kikuchi at the Sanjo Kaikan of the University of Tokyo.[122,123] This was followed by lectures on recent advances in the theory of photographic sensitivity at the research laboratories of the Konica Corporation, Hino City; Mitsubishi Paper Mills, Ltd., Kyoto; Fuji Photo Film Co. Ltd., Minami-Ashigara; and at Chiba University, Chiba City, Japan.

In May 1991 at the 44th annual meeting of the Society for Imaging Science and Technology in St. Paul, Minnesota, he compared and contrasted the electronic and ionic processes of the direct photolysis theories in sensitized crystals of silver halides with those of the photoaggregation theory.[124] He discussed again as in 1989[118] the areas in which problems encountered by the direct photolysis theories were resolved by the photoaggregation theory. Between 1983 and 1991, Mitchell gave a series of seminars on the properties of silver halide photographic systems at the Photo Products Research Laboratory of E. I. du Pont de Nemours and Co., in Brevard, North Carolina.

GENERAL INTERESTS

Approach to teaching and research

Mitchell had broad interests in many areas of experimental science. Above all, he was an experimental physicist who derived pleasure from teaching the fundamental concepts of physics and designing new lecture demonstration experiments to illustrate these concepts. In his approach, he was influenced by his close association over many years with Professor R. W. Pohl of the University of

Göttingen and by discussions with Professor P. W. Bridgman (Foreign member of Royal Society) of Harvard University. He believed that it was important for undergraduate students to acquire a thorough understanding of the ideas and methods of physics, and he spent many hours in preparing lectures and working out problems to enhance this understanding.

In final-year undergraduate and graduate teaching, his main interests were (1) in the energetics of physical systems - classical thermodynamics with the complete range of independent physical variables and thermodynamic functions, quantum statistics and statistical thermodynamics, (2) in geometrical, physical and quantum optics, (3) in classical, mathematical and X-ray crystallography, and (4) in the properties of crystalline solids. His courses in solid state physics emphasized the theory of symmetry, and the role of structural and systematic inorganic chemistry and the periodic table, in facilitating the understanding of variations in physical properties between different compounds and the design of new experimental systems. He valued the feed-back from personal discussions with undergraduate and graduate students and was always available to them.

In research work with his graduate students, he was concerned with establishing models for the discussion of the elementary processes of physical, photochemical, and chemical change in inorganic crystals. His particular interests were in direct microscopic observations wherever possible of the processes involved in the initiation of change and in the role of lattice and structural defects in these processes.

Single crystals of the highest achievable purity and perfection were grown for all the research work. The crystals of silver chloride and silver bromide proved to be insensitive. After sensitization with silver oxide, particles of silver separated along dislocation lines during exposure, making them visible with the optical microscope. Dislocation arrays and the elementary processes of dislocation generation, displacement, and interaction were observed. This work was continued with oriented square-sectioned single crystals of α-phase copper alloys with four highly polished plane surfaces. The object was to establish the nature of the elementary dislocation processes involved in initial plastic relaxation at the yield point. With all this experimental work, the emphasis was on critical experimental design focused on the elimination of secondary processes, artifacts, and previously unrecognized variables. The idealized simple physical system was realized as closely as possible and the classical experimental method then followed with logical successions of experiments and sequences of new discoveries. Many new experimental techniques were developed and applied to the study of dislocation processes in the same single crystal. This approach applied to silver halide systems had led to many advances in knowledge of the elementary processes of photochemical change.

At an early stage in his more theoretical work on the sensitivity of silver halide imaging systems, Mitchell was impressed by the complexity of the succession of physical and chemical processes involved from the growth of silver halide microcrystals, through chemical, spectral sensitization, and supersensitization to stabilization, la-

tent image formation and development. He realized that many of the publications from the research laboratories of the photographic industry were essentially irrelevant to competitive commercial products and that the patent literature of photographic technology had to be carefully analysed. He came to the conclusions (1) that the whole sequence of processes had to be considered in the formulation of any models for the discussion of physical, photochemical, and chemical change and (2) that the most useful criterion for the validity of the models was provided by the self-consistency of the mechanisms to which they led for the discussion of the successive processes. Apart from the formation of the latent image in dried emulsion coatings, these are chemical processes occurring in aqueous media. For the understanding of the whole system, knowledge of inorganic, organic, and physical chemistry was required together with crystal physics. Mitchell's background in these areas was evident in his publications on silver halide imaging science.

Interactions with industrial research laboratories

Mitchell shared with N. F. Mott, F.R.S., the feeling that it was important for some physicists of university faculties to maintain close contact with scientists engaged in basic research in industrial laboratories. He also felt that a fraction of the graduate students should be exposed to research problems which would acquaint them with the type of relevant basic research which should be pursued in these laboratories. With this in mind, he emphasized the selection and design of new experimental systems, new alloys, and the development of new techniques for experimental work. His

graduate students had no problems with the transition from graduate research to work in industrial or government laboratories.

Between 1945 and 1991, Mitchell gave many lectures and seminars to scientists in industrial laboratories and discussed their research work with them. These included Kodak Ltd. at Harrow, Middlesex; Ilford Ltd. at Brentwood, Essex; the 3M Pinnacles Research Laboratory at Harlow, Essex; the Philips Research Laboratory in Eindhoven, Netherlands; the Agfa-Gevaert Research Laboratory in Leverkusen, Germany; the Eastman Kodak Research Laboratories in Rochester, New York; the Polaroid Corporation in Cambridge, Massachusetts; Du Pont Imaging Products in Parlin, New Jersey, Wilmington, Delaware, and Brevard, North Carolina; 3M Central Research Laboratories in St. Paul, Minnesota; Bell Telephone Laboratories in Murray Hill, New Jersey; the Knolls Research Laboratory of the General Electric Company in Schenectady, New York; Fuji Photo Film Company Ltd. at Minami-Ashigara; and Konica Corp. at Hino City, Japan. He developed close and enduring personal friendships with many of the scientists working in these laboratories.

The organization of research in industry

Mitchell's interactions with industrial research laboratories extended over more than 45 years. He had many discussions on the role of basic research in industry with H. Frieser, Director of the Research Laboratories of Agfa AG at Leverkusen and later of the Institute for Photographic Science of the University of Munich; J. Eggert, former Director of Research for Agfa AG at Wolfen and later Director of the Photographisches Institut of the E.T.H. in Zürich; E. J. W.

Verwey of the Philips Research Laboratories in Eindhoven; C. E. K. Mees, F.R.S., Director of Research of the Eastman Kodak Research Laboratories in Rochester, New York; C. G. Suits, Director of the Knolls Research Laboratory of the General Electric Company in Schenectady, New York; and W. Shockley of the Bell Telephone Laboratories in Murray Hill, New Jersey, with whom he climbed on the cliffs of the Shawangunks in the Catskills of New York State. These interactions and his visits to the laboratories gave him deep insight into the problems encountered in the organization and maintenance of adequate levels of basic research. From 1945 until 1965, remarkable advances were made in knowledge of the physics and chemistry of crystalline solids. A high rate of new discovery was maintained by creative groups of outstanding scientists and engineers in industry. This led to inventions which were protected by patents, to new technologies, new products and new manufacturing operations. It continued a period of rapid expansion in industries based on the physical sciences which began with the establishment of industrial research laboratories in the early years of the century. The directors of research were distinguished scientists or engineers and the activities of the research scientists were managed by research scientists in an environment favorable for creative research and development. In the organization of the laboratory, the scientists were usually hired and grouped according to disciplines, and the needs of the company for new patents and new products were covered. With the retail demand for the new products, relatively little initial competition, and rapid growth of the industries, financial and marketing problems were not dominant factors.

This first phase of industrial research was analysed by Mitchell in the Jubilee Memorial Lectures of the Society of Chemical Industry in 1965.[101] After general approval of the area of work and the projects, the research was essentially self-managed by the scientists and engineers who devoted long hours of perseverent effort to it and created branching chains of new discovery and invention. These satisfied both the short-term and the long-term needs of the companies. Detailed management of the fundamental research which was undertaken by these scientists was not possible and was not needed. New discoveries cannot be defined in advance and can therefore not be made on demand within an assigned time.

Complex prevailing circumstances did not allow this rate of new discovery to be sustained. The companies expanded rapidly, and manufacturing capacity for new products was provided creating a demand for developments and services determined by these products. The research laboratories expanded, but the creative ability and enthusiasm of an increasing fraction of the scientists and engineers declined. Mitchell watched the developments with increasing concern. Around 1965, research management began to pass from scientists to managers with manufacturing, marketing or business administration experience. The groups in the research laboratories were reorganized to reflect product areas, manufacturing operations and marketing considerations. Detailed project management of the activities of the scientists and engineers was introduced with analysis and prior evaluation of projects and targeted completion times. This tended to result in concentration on the organization and management of short-term product

development and of incremental improvements in current products and processes. Development project management could be applied to central and divisional "research" laboratories and overall priorities established. The unpredictable long-term basic research and development which leads to new inventions, new patents, and fully competitive new products cannot be organized in this way and was progressively neglected.

This reorganization of research and development for industries dependent upon the physical sciences was driven by a number of factors. Not least among these was increasing competition from overseas manufacturing corporations with lower production costs. Overheads increased as the business, manufacturing and marketing administrations increased in scale, and there was ever-present pressure from the financial markets for short-term profitability. This resulted in the imposition of a short-term-profits approach on business and research management.

Since this approach seldom leads to competitive new technology and new enterprises, as has been well established by a declining number of new patents, smaller entrepreneurial companies, more effective in these respects, were acquired to provide for business expansion and to maintain market share. This increased the scale and diversification of the corporation and further accentuated the problems of correlated overall management of corporate research and development. The organizational environment of the large corporation was often inimical to basic research, and it tended to quench the enthusiasms of the entrepreneurs. Attempts were often made to license recent patents and new technology from more competitive and innovative firms. These were frequently unsuccessful if the corporations had nothing to offer in exchange.

Mitchell was always convinced that corporations are heavily handicapped if they rely on licensing patents and on acquisitions for business expansion and do not allow or encourage long-term basic research and aggressive in-house development of entirely new competitive products. For the survival of a corporation, long-term market share is more important than short-term profits, and this can be ensured only by the organization of in-house, long-term research and development and a scale of operations which makes this feasible and profitable. Mitchell recognized that there was an incompatibility between the confident, enthusiastic, uninterrupted and perseverent hard work needed for efficient creative activity and the management procedures and committee assignments of a large corporation intended to control and maximize this activity.

PERSONAL

Three countries

Mitchell never lost his attachment to New Zealand. He was very sensitive to natural beauty and preferred sandy beaches, rocky coastlines, open country, deep valleys and high mountains to crowded cities. He returned to New Zealand eleven times between 1945 and 1990, four of them with his wife after his retirement in 1979. He particularly enjoyed South Westland with the views of the Southern Alps from the sea coast and their reflections in the bush-fringed lakes. He loved the quiet of the dripping rain forest, with its fern-draped trees and fern-covered floor, broken only by the songs of the bell birds. He lived for twenty-one years in New Zealand and then for twenty-four years in England. During this period, he explored the

countryside of southern England, the Chilterns and the Cotswolds, and watched the sea birds around the coasts of Land's End and the Lizard and thence eastward to the chalk cliffs of Beachy Head. When he moved to Charlottesville, Virginia, in 1959, the rolling country of Albemarle County with pedigree cattle grazing in the fields and the Blue Ridge from the Shenandoah National Park to the Great Smoky Mountains replaced the country around Oxford and Bristol which he had enjoyed so much. The scale of everything was greatly enlarged from the small scales of New Zealand and England, and for the first time an automobile replaced a bicycle or public transport. Mitchell grew up in the last dominion of the British Empire, matured in the heartland, and then moved to the Old Dominion. This left him with deep attachments to all three but with a certain detachment and analytical perspective in his thoughts on relations between them.

Travel and vacation activity

From the age of ten, Mitchell carried a camera with him and made a continuous photographic record of his travels. These covered many areas of the globe. He made four journeys around the world and seven to Japan. While in Oxford and Bristol, he traveled extensively around Europe making walking, long bicycle and climbing trips in France, Belgium, Germany, Switzerland and Italy. He remembered with particular pleasure walking in 1953 with A. R. Reynolds of the English Department of the University of Bristol, along the route of R. L. Stevenson's *Travels with a Donkey in the Cevennes* from Le Monastier across the Massif Central through Le Pont de Montvert to Ales. Whenever he passed through Australia, he spent weekends bush-walking

with friends in the Blue Mountains of New South Wales and the Grampians of Victoria and taking photographs of the country with the wild flowers, kangaroos, koalas and other animals. He also visited the Kruger National Park and the game parks of Natal in South Africa. He enjoyed the tall trees around the Pacific, the redwoods and sequoias of California, the sugi or cryptomeria of Japan, the kauri of New Zealand and the jarrah and gums of Western Australia. Wherever he went, he was interested in the rocks, birds, animals, ferns, plants, shrubs and trees, and he accumulated many thousands of photographs. One of his favourite sequences of slides was *From the Golden Gate to the Golden Horn* through Kyoto, Nikko, Bangkok, Agra, Jaipur, Esphahan, Istanbul, Athens, Rome, Paris, Oxford, London, New York and back to San Francisco.

Languages

After experimental science, his main intellectual interests were in foreign languages, foreign affairs, and history. He was fluent in French, German and Italian, and his ability to converse and lecture easily in these languages was greatly appreciated from 1945 to 1959 when many European scientists had little knowledge of spoken English. During this period, he translated and revised translations of papers and participated in discussions at many international meetings on photographic science. He had an adequate knowledge of spoken Russian and Japanese and read papers on silver halide imaging science published in both these languages. He had a good knowledge of Japanese kanji. He regretted that occasions for conversation in foreign languages with academic colleagues in Europe and Japan decreased

steadily after 1959 as English became the universal language.

One of Mitchell's main relaxations came from reading French, German, Italian and Russian literature ranging from classics, plays and poetry through modern novels to paperback mysteries, detective stories, magazines and newspapers. He was interested in the structures of the spoken languages and had analysed the basic sentence patterns and worked out his own essential vocabularies.

Friends and entertainment

Mitchell had close personal friends in many countries with whom he kept regularly in touch by visits, cards, letters or telephone calls. These included New Zealand, Australia, South Africa, England, France, Belgium, Germany, Switzerland, Italy, Russia, the United States, Japan, China and India. He maintained contact with all of his graduate students who responded, and most of them became real friends. He enjoyed dinner parties with visiting scientists, friends and graduate students and had pleasure when they stayed with their families as house guests. He was happy to cook the meals and to show them Bristol, Charlottesville and the surrounding countrysides.

Marriage

By the time he married in 1968, he had four godsons, two in England, one in France and one in Italy, and two goddaughters, one in England and one in Germany. His marriage to Jo Overstreet Long ended in divorce, but he continued to have a warm relationship with his stepdaughter, Jody Karen Long. In 1976, he married Virginia Jacobs Hill who was born in South Orange, New Jersey. She was the widow of Chester James Hill, Jr., who had been a Professor of Psych-

ology at Lawrence University in Appleton, Wisconsin. After his death, she completed her degree courses at Lawrence and graduated with a major in French language and literature. She understood the problems of one whose main interests were in research and teaching and in the understanding of the elementary processes of complex systems, and she gave him the love and support which he needed. This began a particularly productive period of his career which extended into active retirement and during which he worked out many quantitative aspects of the photoaggregation theory of latent image formation. She typed all his papers, accompanied him on almost all his journeys, and together they welcomed their friends.

Relaxation at home

Their home in Charlottesville was comfortable with a good library and a well-equipped kitchen. There was an open fire in the living room for winter evenings. In the house, their main relaxation came from reading, from opera, orchestral music and nature programs on television and from colour slides taken during their extensive travels around the world. Mitchell grew African violets, Christmas and Easter cactus and other house plants under fluorescent lights in the basement and had feeders for the cardinals, crested tits and chickadees outside the kitchen window.

There was a big yard with nine large oak trees and much leaf-raking in the autumn. The woodpeckers attacked the dead branches. Beds of crocus, snowdrops, daffodils, tulips and other bulbs flowered in the springtime with the azaleas and dogwoods, and there were day lilies during the summer. A large bed of tomatoes produced a good crop through the hot summer months. The garden provided plenty of outdoor exercise and relaxation.

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EDUCATION AND DEGREES

Christchurch Boys High School, Christchurch, New Zealand, 1925-1930.

Canterbury University College, now University of Canterbury, Christchurch, New Zealand, 1931-1935. B.Sc. Degree, 1934. M.Sc. Degree, 1935.

University of Oxford, 1935-1938. D.Phil. Degree, 1938. D.Sc. Degree, 1960.

CAREER

Sixth form Physics Master, Repton School, Repton, Derby, 1938-1940.

Scientific Officer, 1940-1942, Senior Scientific Officer, 1942-1945, Armament Research and Development Establishment, Ministry of Supply.

Lecturer in Experimental Physics, University of Bristol, 1945-1948.

Reader in Experimental Physics, University of Bristol, 1948-1959.

Professor of Physics, University of Virginia, Charlottesville, Virginia, 1959-1965.

Director of the National Chemical Laboratory, Teddington, 1963-1964.

William Barton Rogers Professor of Physics, University of Virginia, 1965-1979.

Emeritus Professor and Senior Research Fellow, University of Virginia, 1979-

HONOURS AND AWARDS

1934 Senior Scholar, New Zealand University.

Charles Cook Memorial Prize, Canterbury University College.

1935 Overseas Science Research Scholarship of the Royal Commission for the Exhibition of 1851.

1950 Williamson Photographic Research Award of the Royal Photographic Society.

1955 11th Charles Vernon Boys Prize of the Physical Society.

1956 Fellow of the Royal Society.

11th Renwick Memorial Medal of the Royal Photographic Society.

1957 Fellow of the Royal Photographic Society.

1958 Silver Medal of the Austrian Photographic Society.

Corresponding Member, Deutsche Gesellschaft für Photographie.

1959 Corresponding Member, Royal Society of Liège, Belgium.

Fellow of the American Physical Society.

1963 Fellow of the Royal Institute of Chemistry.

1967 Honorary Member, Society of Photographic Scientists and Engineers, now the Society for Imaging Science and Technology.

1979 Honorary Member, Society of Photographic Science and Technology of Japan.

1981 Kulturpreis, Deutsche Gesellschaft für Photographie.

1983 Lieven-Gevaert Medal, Society of Photographic Scientists and Engineers.

1993 Commonwealth of Virginia, Life Achievement Award in Science.

GRADUATE STUDENTS AND RESEARCH ASSOCIATES

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(7) D. G. Holloway. Some experiments on the adsorption of gases on clean metallic surfaces. Ph.D. thesis, University of Bristol, March 1952.

(8) H. P. Myers (research associate). The secondary emission from copper and silver films obtained with primary electron energies below 10 eV. *Proc. R. Soc. Lond.* A215: 329, 1952.

H. P. Myers. A simple varying capacitor method for the measurement of contact potential difference in high vacuum. *Proc. Phys. Soc.* 66B: 493-499, 1953.

(9) E. B. Dorling. Some investigations into the structure of evaporated metal films. Ph.D. thesis, University of Bristol, July 1953.

(10) J. M. Hedges. Some experiments on photographic sensitivity. Ph.D. thesis, University of Bristol, September 1954.

(11) J. C. Rivière. Contact potential measurements on evaporated metal films by the Kelvin method. Ph.D. thesis, University of Bristol, September 1954.

J. C. Rivière. Contact potential difference measurements by the Kelvin method. *Proc. Phys. Soc.* 70B: 676-686, 1957.

(12) P. A. Schroeder. The effect of the adsorption of gases on the work functions of metallic surfaces. Ph.D. thesis, University of Bristol, April 1954.

(13) T. Evans. Crystal imperfections and chemical reactivity. Ph.D. thesis, University of Bristol, September 1955.

(14) P. V. McD. Clark (research associate). Development of methods for the production of thin sheet crystals of silver halides and study of their properties. 1956.

(15) C. C. Evans. Some further properties of evaporated copper films. Ph.D. thesis, University of Bristol, September 1956.

(16) C. G. Matthews. Contact potential measurements on evaporated metal films. Ph.D. thesis, University of Bristol, September 1957.

(17) P. B. Price (research associate). Twinning in cadmium dendrites, *Phil. Mag.* 4: 1229-1241, 1959.

P. B. Price. On the growth of cadmium crystals from the vapour. *Phil. Mag.* 5: 473-484, 1960.

(18) E. Braun. Photoconductivity in crystals of silver bromide. Ph.D. thesis, University of Bristol, March 1959.

(19) J. T. Bartlett. Dislocations in silver halide crystals. Ph.D. thesis, University of Bristol, July 1959.

(20) D. J. Barber. Dislocations and plastic deformation in alkali halide crystals. Ph.D. thesis, University of Bristol, August 1959.

(21) K. B. Harvey. Dislocations, foreign ions and vacancies in sodium chloride single crystals. Ph.D. thesis, University of Bristol, September 1959.

(22) D. A. Jones. Dislocations in the silver halides. Ph.D. thesis, University of Bristol, October 1959.

(23) A. S. Parasnis. A study of silver chloride. I. Defect structure. II. Photochemical properties. Ph.D. thesis, University of Bristol, October 1959.

(24) H. A. Davis. A study of the plastic deformation of single crystals of sodium chloride. M.S. thesis, University of Virginia, August 1960.

(25) H. T. Hudson. The deformation of single crystals of copper and alloys of copper. M.S. thesis, University of Virginia, August 1960.

(26) C. M. Drum. Mechanical properties of filamentary crystals of refractory oxides. M.S. thesis, University of Virginia, June 1961.

(27) M. A. Lundquist. Observations on the growth of KH_2PO_4 crystals from aqueous solution. M.S. thesis, University of Virginia, June 1962.

(28) J. C. Crump. Electron microscope observations on single crystals of zinc and cadmium. M.S. thesis, University of Virginia, May 1962.

(29) H. A. Davis. The initiation of plastic deformation in single crystals of sodium chloride. Ph.D. thesis, University of Virginia, June 1962.

(30) H. T. Hudson. The growth and deformation of single crystals of sodium chloride. Ph.D. thesis, University of Virginia, June 1962.

(31) J. C. Chevrier. Mechanical properties of copper-aluminium alloys. M.S. thesis, University of Virginia, June 1962.

(32) T. E. Hutchinson. Studies of the deformation of thin copper strips with the electron microscope. Ph.D. thesis, University of Virginia, July 1962.

(33) E. E. Laufer. Growth and surface equilibration of copper crystals. Ph.D. thesis, February 1963.

(34) C. M. Drum. Growth and perfection of aluminium nitride crystals. Ph.D. thesis, University of Virginia, May 1963.

C. M. Drum. Twist and axial imperfections in filamentary crystals of aluminium nitride, II. *J. appl. Phys.* 36, 824-829, 1965.

(35) J. C. Crump. Observations of dislocation phenomena in thin ribbons of cadmium. Ph.D. thesis, University of Virginia, May 1964.

(36) J. C. Chevrier. The early stages of plastic deformation of copper-aluminium alloys in the α-phase. Ph.D. thesis, University of Virginia, June 1964.

(37) W. A. Jesser. Zinc in cadmium films. M.S. thesis, University of Virginia, June 1964.

(38) A. C.Macdonald. Dislocation phenomena in single crystals of copper near the yield point. M.S. thesis, University of Virginia, June 1964.

(39) M. A. Lundquist. Supersaturated solutions: theory and experiment. Ph.D. thesis, University of Virginia, August 1965.

(40) J. P. Monaghan, Jr. The plastic deformation of single crystals of α-phase copper-aluminium alloys. M.S. thesis, University of Virginia, 1966.

(41) B. J. Hockey. The nature and formation of bands of deformation in single crystals of α-phase copper-aluminium alloys. Ph.D. thesis, University of Virginia, June 1968.

(42) J. S. Ahearn. The surface topography of plastically deformed single crystals of α-phase copper-aluminium alloys. M.S. thesis, University of Virginia, August 1968.

(43) J. P. Monaghan. Bands of deformation in single crystals of α-phase copper-aluminium alloys deformed in tension. Ph.D. thesis, University of Virginia, August 1968.

(44) L. F. Henry. Studies of plastic deformation in the zinc-cadmium and copper-aluminium alloy systems. Ph.D. thesis, University of Virginia, August 1969.

(45) H. McD. Hobgood. Plastic deformation of single crystals of α-phase copper aluminium alloys with [331] and [521] axial orientations. M.S. thesis, University of Virginia, June 1971.

(46) W. E. Nixon. Composition dependence of the mechanical properties of α-phase copper-aluminium alloys. M.S. thesis, University of Virginia, June 1971.

(47) D. A. Taliaferro. Surface stress distributions due to arrays of pure edge and 60° dislocations on oblique glide planes. M.S. thesis, University of Virginia, June 1971.

(48) J. S. Ahearn. The plastic deformation of α-phase copper-aluminum alloys as a function of temperature and orientation Ph.D. thesis, University of Virginia, June 1972.

(49) R. B. Schwarz. Measurement of dislocation velocities in α-phase Cu-Al alloys at low temperatures. Ph.D. thesis, University of Virginia, August 1972.

(50) H. McD. Hobgood. Study of plastic deformation in binary and ternary copper alloys at low temperatures. Ph.D. thesis, University of Virginia, May 1974.

(51) W. E. Nixon. The plastic deformation of single crystals of α-phase Cu-Al and Cu-Ni-Al alloys. Ph.D. thesis, University of Virginia, May 1974.

(52) P. Zanzucchi. Precision lattice measurements of single crystals of germanium and silicon. Ph.D. thesis, University of Virginia, August 1976.

(53) T. N. Lovern. The role of surface and internal sources in the plastic deformation of α-phase copper-aluminium alloys. Ph.D. thesis, University of Virginia, May 1979.

(54) S. K. Ray. Dynamic dislocation phenomena in single crystals of α-phase binary and ternary copper alloys. Ph.D. thesis, University of Virginia, May 1979.

CONTRIBUTED PAPERS PRESENTED AT MEETINGS OF THE AMERICAN PHYSICAL SOCIETY.

A. St. Louis, Missouri, March 25-28, 1963.

1. J. C. Crump and J. W. Mitchell, Bull. Amer. Phys. Soc. 8: 204 (1963). Electron microscope studies of fracture in thin ribbons of Cd.

2. C. M. Drum and J. W. Mitchell, Bull. Amer. Phys. Soc. 8: 204 (1963). Axial dislocations in thin ribbons of aluminum nitride.

3. E. E. Laufer and J. W. Mitchell, Bull. Amer. Phys. Soc. 8: 227 (1963). New observations on the thermal faceting of the surfaces of Cu crystals.

4. E. Grünbaum and J. W. Mitchell, Bull. Amer. Phys. Soc. 8: 227 (1963). Observations on the epitaxial overgrowth of nickel bromide on chromic bromide.

B. Washington, D. C., April 26-29, 1965.

5. J. C. Chevrier and J. W. Mitchell, Bull. Amer. Phys. Soc. 10: 453 (1965). Formation and propagation of Lüders bands on α-phase Cu-Al alloy single crystals.

6. J. C. Crump and J. W. Mitchell, Bull. Amer. Phys. Soc. 10: 453 (1965). Electron microscope observations of climb phenomena in thin ribbons of cadmium.

C. Charlottesville, Virginia, Nov. 1-3, 1965.

7. J. C. Crump and J. W. Mitchell, Bull. Amer. Phys. Soc. 11: 527 (1966). Observation of moiré patterns in superimposed thin crystals of cadmium.

D. Nashville, Tennessee, Dec. 1-3, 1966.

8. J. C. Crump and J. W. Mitchell, Bull. Amer. Phys. Soc. 11: 837 (1966). Observations on melting in the electron microscope.

9. L. F. Henry and J. W. Mitchell, Bull. Amer. Phys. Soc. 11: 837 (1966). Precipitation phenomena in cadmium zinc alloys.

10. J. P. Monaghan, Jr., and J. W. Mitchell, Bull. Amer. Phys. Soc. 11: 838 (1966). Interference microscope study of bands of deformation.

11. B. J. Hockey and J. W. Mitchell, Bull. Amer. Phys. Soc. 11: 839 (1966). Observations of dislocation multipoles in α-phase copper-aluminum alloys.

E. Boston, Massachusetts, Feb. 26-28, 1968.

12. J. P. Monaghan, Jr., and J. W. Mitchell, Bull. Amer. Phys. Soc. 13: 247 (1968). Bands of deformation in copper-aluminum at room temperature.

13. R. K. Wild and J. W. Mitchell, Bull. Amer. Phys. Soc. 13: 247 (1968). Deformation of single crystals of α-phase copper-aluminum alloys at 77° K.

14. J. S. Ahearn and J. W. Mitchell, Bull. Amer. Phys. Soc. 13: 247 (1968). Fine structure of bands of deformation in single crystals of α-phase copper-aluminum alloys.

15. L. F. Henry and J. W. Mitchell, Bull. Amer. Phys. Soc. 13: 247 (1968). Initial stages of plastic deformation in cadmium and cadmium-zinc alloys.

F. Gainesville, Florida, Nov. 6-8, 1969.

16. J. S. Ahearn and J. W. Mitchell, Bull. Amer. Phys. Soc. 14: 169 (1969). Plastic deformation of α-phase Cu-Al single crystals in polyslip orientations.

17. L. F. Henry and J. W. Mitchell, Bull. Amer. Phys. Soc. 14: 169 (1969). Dislocation velocities in single crystals of α-phase Cu-Al alloys at 4.2° K.

G. Washington, D. C., April 27-30, 1970.

18. J. S. Ahearn and J. W. Mitchell, Bull. Amer. Phys. Soc. 15: 575 (1970). Plastic deformation of α-phase Cu-Al-Ni single crystals.

19. J. S. Ahearn, L. F. Henry, and J. W. Mitchell, Bull. Amer. Phys. Soc. 15: 575 (1970). Determination of frictional stress and dislocation velocity in α-phase Cu-Al single crystals using the relaxation method.

H. Cleveland, Ohio, March 29-April 1, 1971.

20. J. S. Ahearn and J. W. Mitchell, Bull. Amer. Phys. Soc. 16: 406 (1971). Plastic deformation of single crystals of Cu-Al alloys at 4.2° K.

21. R. Schwarz and J. W. Mitchell, Bull. Amer. Phys. Soc. 16: 407 (1971). Strain-time analysis of relaxation processes in single crystals of α-phase Cu-Al alloys.

22. D. A. Taliaferro and J. W. Mitchell, Bull. Amer. Phys. Soc. 16: 447 (1971). Surface stresses due to arrays of dislocations on oblique glide planes.

I. Atlantic City, New Jersey, March 27-30, 1972.

23. W. E. Nixon and J. W. Mitchell, Bull. Amer. Phys. Soc. 17: 285 (1972). Local strain angle in heterogeneous plastic deformation of Cu-Al alloys.

24. R. B. Schwarz and J. W. Mitchell, Bull. Amer. Phys. Soc. 17: 285 (1972). Dislocation velocity measurements at 4.2° K.

J. San Diego, California, March 19-22, 1973.

25. W. E. Nixon and J. W. Mitchell, Bull. Amer. Phys. Soc. 18: 445 (1973). Plastic deformation of ternary copper alloys at low temperatures.

K. Philadelphia, Pennsylvania, March 25-28, 1974.

26. W. E. Nixon and J. W. Mitchell, Bull. Amer. Phys. Soc. 19: 366 (1974). Stress pulse initiation of plastic deformation at 4.2° K in Cu-10.5-at%-Al alloys.

27. H. McD. Hobgood and J. W. Mitchell, Bull. Amer. Phys. Soc. 19: 367 (1974). Mechanical properties of α-phase Cu-Al-Pd alloys.

L. San Diego, California, March 24, 1977.

28. J. W. Mitchell, S. K. Ray, and W. E. Nixon, Bull. Amer. Phys. Soc. 22: 348 (1977). Dislocation ranges in single crystals of α-phase Cu-Al alloys.

29. T. N. Lovern, W. E. Nixon, and J. W. Mitchell, Bull, Amer. Phys. Soc. 22: 443 (1977). Activation of internal dislocation sources in single crystals of α-phase Cu-Al alloys.

30. W. E. Nixon, S. K. Ray and J. W. Mitchell, Bull. Amer. Phys. Soc. 22: 443 (1977). Dislocation generation and interaction processes in single crystals of α-phase Cu-Al alloys.

M. Washington, D. C., March 27-30, 1978.

31. W. E. Nixon, M. H. Massey, and J. W. Mitchell, Bull. Amer. Phys. Soc. 23: 252 (1978). Dislocation generation and displace-

ment in single crystals of Cu-10.5-at%-Al alloy deformed in bending.

32. S. K. Ray, W. E. Nixon, and J. W. Mitchell, Bull. Amer. Phys. Soc. 23: 252 (1978). Yield stresses and dislocation velocities in single crystals of Cu-Ni-Pd alloys at 300 and 4.2° K.

INVITED PAPERS PRESENTED AT MEETINGS OF THE AMERICAN PHYSICAL SOCIETY

1. Baltimore, Maryland, March 17-19, 1955.
   J. W. Mitchell, Bull. Amer. Phys. Soc. 30: 26 (1955).
   Research on the silver halides - dislocations and other properties.

2. Gatlinburg, Tennessee, April 7-9, 1960.
   J. W. Mitchell, Bull. Amer. Phys. Soc. 5: 440 (1960).
   The plastic deformation of crystals of silver halides.

3. Washington, D. C., April 24-27, 1961.
   J. W. Mitchell, Bull. Amer. Phys. Soc. 6: 279 (1961).
   Interactions between dislocations in crystals of silver halides.

4. Cleveland, Ohio, Nov. 23-24, 1962.
   J. W. Mitchell, Bull. Amer. Phys. Soc. 7: 547 (1962).
   Dislocation phenomena in cadmium crystals.

5. Chattanooga, Tennessee, Nov. 5-7, 1964.
   J. W. Mitchell, Bull. Amer. Phys. Soc. 10: 248 (1965).
   Dislocation phenomena in thin crystals of cadmium.

6. Charlottesville, Virginia, Nov. 1-2, 1965.
   J. W. Mitchell, Bull. Amer. Phys. Soc. 11: 530 (1966).
   Nature and formation of Lüders bands in copper alloys.

7. Denver, Colorado, March 31-April 3, 1975.
   J. W. Mitchell, Bull. Amer. Phys. Soc. 20: 443 (1975).
   The measurement of dislocation velocities at low temperatures.

8. Miami Beach, Florida, November 21-23, 1977.
   J. W. Mitchell, Bull. Amer. Phys. Soc. 22: 1245 (1977).
   Dislocation generation and multiplication processes during plastic deformation of ionic crystals and metals.

ANNUAL MEETINGS OF THE SOCIETY OF PHOTOGRAPHIC SCIENTISTS AND ENGINEERS WHICH BECAME THE SOCIETY FOR IMAGING SCIENCE AND TECHNOLOGY IN 1985

1. Chicago, Illinois, 15-19 May, 1967. Awarded the Honorary Membership of the Society.
2. Los Angeles, California, 12-16 May, 1969. Lecture on surface and space-charge distributions at the surface of a silver bromide crystal in vacuum and in an aqueous medium.
3. Rochester, New York, 9-14 May, 1982. Lecture on image formation processes in core-shell emulsions.
4. San Francisco, California, 31 May-3 June, 1983. Awarded the Lieven-Gevaert Medal of the Society. Lecture on the statistics of electron trapping processes in microcrystals of silver halides.
5. Boston, Massachusetts, 20-24 May, 1984. Lecture on spectral sensitization and desensitization.
6. Atlantic City, New Jersey, 12-16 May, 1985. Lecture on the supersensitization of spectral sensitizing systems.
7. Minneapolis, Minnesota, 18-22 May, 1986.
8. Rochester, New York, 17-21 May, 1987.
9. Arlington, Virginia, 22-26 May, 1988.
10. Boston, Massachusetts, 14-19 May, 1989. (1) Lecture on chemical sensitization and latent image formation - a historical perspective. (2) Lecture at the Edgerton Symposium on discharge tubes as light sources for high-speed photography.
11. Rochester, New York, 20-25 May, 1990. Lecture on Auger processes for the creation of free electrons and holes in sensitized crystals of silver halides.
12. St. Paul, Minnesota, 12-17 May, 1991. Lecture on electronic and ionic processes in sensitized silver halide systems.
13. Cambridge, Massachusetts, 10-14 May, 1993. Lecture on the silver halide photographic emulsion grain.

DIRECT LINEAGE OF JOHN WESLEY MITCHELL

1. William Mitchell, I.

   Born: Edinburgh, about 1590.

   Emigrated to Bermuda, 1612.

   Married: Elizabeth Gibbs, before 1619.

   Died: Bermuda, buried in Old Devonshire Churchyard.

2. William Mitchell, II

   Born: Bermuda, 1623.

   Married:

   Died: Bermuda, buried in Old Devonshire Churchyard.

3. William Mitchell, III.

   Born: Bermuda, 1640.

   Married:

   Died: Bermuda, buried in Old Devonshire Churchyard.

4. John Mitchell, I.
   Son of William Mitchell, III.

   Born: Bermuda.

   Emigrated to Dorchester County, Maryland, 1684.

   Married:

   Died: Cornersville, Dorchester County, Maryland, 1754.

5. John Mitchell, II.

   Born: Cornersville, 1709.

   Married: (1) Clare . . . . .

   (2) Sarah, widow of Thomas Engel, before 1762.

   Died: Cornersville, May 28, 1815; aged 106 years.

   Buried in Mitchell's Garden Cemetery near Cornersville.

6. Reuben Mitchell.
Son of John Mitchell II and Clare Mitchell.

Born: Cornersville, 1749.

Married: Ruth Lee Williams, April 10, 1776.

Died: Easton, Talbot County, Maryland, 1832.

7. John Wesley Mitchell, I.

Born: Easton, March 10, 1791.

Married: Mary Hubbard, January 3, 1811.

Died: Cornersville, April 27, 1859. Buried in Mitchell's Garden Cemetery.

8. John Wesley Mitchell, II.

Born: Cornersville, 1823.

Married: Susan Elizabeth . . . . .

Died:

9. John Wesley Mitchell, III.

Born: Avalon, Talbot County, Maryland, August 1851.

Married: Mary Jane Bennett, Derby, Connecticut, 1882.

Died: Stratford, Connecticut.

10. John Wesley Mitchell, IV.

Born: Derby, Connecticut, June 8, 1884.

Married: Lucy Ruth Snowball, Waimate, South Canterbury, New Zealand, June 10, 1911.

Died: Christchurch, New Zealand, April 4, 1954.

11. John Wesley Mitchell, V.

Born: Christchurch, New Zealand, December 3, 1913.

Married: Virginia Jacobs Hill, widow of Chester James Hill, Las Cruces, New Mexico, August 2, 1976.

Died:

LINEAGE OF LUCY RUTH SNOWBALL

1. Daniel Alport.

   Born:

   Married: Sarah Broadhouse, All Saints Church, West Bromwich, February 8, 1746. (Baptized in same church on December 5, 1725).

   Died:

2. Thomas Alport.

   Baptized: All Saints Church, West Bromwich, May 21, 1749.

   Marrried: Sarah Gilbert, All Saints Church, West Bromwich, August 7, 1774. (Baptized July 7, 1755, and buried January 14, 1798, in the same church).

   Buried: St. Mary's Church, Handsworth, January 7, 1819.

3. John Allport.

   Baptized: All Saints Church, West Bromwich, October 15, 1775.

   Married: Elizabeth Evans, Aston, October 6, 1799.

   Buried: St. Mary's Church, Handsworth, March 13, 1804.

4. Thomas Allport, Sr.

   Baptized: St. Mary's Church, Handsworth, October 16, 1803.

   Married: Jane Weetman, St. Peter's Church, Harbourne, Birmingham, August 10, 1823.

   Died: Stoke, Nelson, Marlborough, New Zealand, October 8, 1875 and buried in the cemetery of St. Barnabas Church, Stoke, with his wife who died December 1, 1875.

5. Thomas Allport, Jr.

   Born: Winson Green, Birmingham, September 18, 1824. Baptized in St. Phillips Church, Birmingham (which became Birmingham Cathetral in 1905), November 8, 1824.

   Married: Rachel Willett, Richmond River, Northeast New South Wales, March 22, 1847.

   Died: Picton, New Zealand, February 24, 1900. Buried in the Picton Cemetery with his wife who died June 6, 1921.

6. Sarah Allport.

Born Stoke, Nelson, New Zealand, August 20, 1855.

Married: John Snowball, Picton, New Zealand, March 10, 1881.

Died: Inglewood, Taranaki, New Zealand, June 3, 1895. Buried in Inglewood Cemetery.

7. Lucy Ruth Snowball.

Born: Inglewood, Taranaki, August 16, 1887.

Married: John Wesley Mitchell, Waimate, South Canterbury, New Zealand, June 10, 1911.

Died: Christchurch, New Zealand, April 5, 1970.

LINEAGE OF RACHEL WILLETT

1. Newman Williat, yeoman farmer.

   Born:

   Married: Dorrithie Walker.

   Died: Will dated November 24, 1608.

2. Hugh Williat.

   Born:

   Married: Agnes Adams, Swanbourne, November 15, 1609.

   Died: Will dated October 28, 1656.

3. Hugh Williatt.

   Baptized: Leckhampstead, June 6, 1624.

   Married: Alice Tattum, at Leckhampstead, 1642.

   Buried: Great Norwood, September 29, 1679.

4. Hugh Williatt, 2nd. Tenant of Manor of Whaddon.

   Baptized: Great Norwood, March 1652.

   Married: Bridget . . . .(who was buried at Whaddon September 16, 1729)

   Died: Whaddon, 1713 (will proved June 11, 1713).

5. Richard Willett.

   Baptized: Whaddon, May 22, 1698.

   Married: Elizabeth Barby, Whaddon, January 13, 1725.

   Buried:

6. Richard Willett.

   Baptized: Whaddon, January 9, 1736.

   Married: Mary Daniel, Newton Longville, June 29, 1760 (Baptized in Newton Longville June 23, 1734, and buried in Whaddon, November 26, 1782).

   Buried: Whaddon, November 7, 1801.

7. John Williatt.

   Baptized: Newton Longville, November 11, 1764.

   Married: Sarah Turvey, October 11, 1790. (Buried in Shenley February 22, 1830).

   Buried: Shenley, February 5, 1837.

8. George Willett.

   Baptized: Shenley, September 10, 1804.

   Married: Sarah Maria Tompkins, 1827. (Born Calverton, Stony Stratford, Buckinghamshire, October 1811. Died Warwick, Queensland, Australia, January 11, 1902.)

   Died: Warwick, Queensland, Australia, March 9, 1883.

9. Rachel Willett.

   Born: About 1831.

   Baptized: Shenley, April 1, 1836.

   Married: Thomas Allport, Richmond River, New South Wales, Australia March 22, 1846.

   Died: Picton, New Zealand, June 6, 1921.

LINEAGE OF JOHN SNOWBALL

1. John Snowball, Prior Hall.

   Born: 1720.

   Married: Anne Maughan (Born 1730. Died March 28, 1802)

   Died: June 20, 1780. Buried Hartburn Church Yard.

2. Cuthbert Snowball, Copperton White House.

   Born: 1753.

   Married: Mary Codling.

   Died: May 13, 1805. Buried Hartburn Church Yard.

3. John Snowball.

   Born: 1782.

   Married: Mary Hedley (Born 1792).

   Died:

4a. Cuthbert Snowball, Graviston farmer.

   Born: 1821.

   Married: Eleanor Charlton (Born 1827. Died, Washington, North umberland, Chester-le-Street, June 26, 1875).

   Died: Washington, County of Durham, August 21, 1862.

4b. Edward Snowball, brother of Cuthbert Snowball.

   Born: White House, Capheaton, Northumberland, January 25, 1830.

   Married: Isabel Stephenson, daughter of Robert Stephenson.

   Died: Girvan, Scotland, June 1, 1911.

5. John Snowball.

   Born: Washington, County of Durham, England, May 22, 1849.

   Married: (1) *Sarah Allport, Picton, New Zealand, March 10, 1881.*

   (2) Jessie Maude Flanders (Born 1870, Clifton Hill, Victoria, Australia. Died October 25, 1952).

   Died: Black Rock, Sandringham, Melbourne, May 1, 1933. Buried in Cheltenham Cemetery, Melbourne, Australia.

PARTIAL LIST OF LECTURES, CONFERENCES AND OTHER ACTIVITIES, 1945-1959

1947 9-10 April. Discussion of the Faraday Society on electrode processes held at the University of Manchester.

5 August-9 September. Course of twelve lectures on the physical properties of metals, semiconductors and ionic solids, given at Canterbury College, Christchurch, New Zealand.

3 September. Lecture on high-speed photography to the Christchurch Branch of the Royal Society of New Zealand.

11-12 September. Three lectures on ionic solids, semiconductors and metals at the Department of Physics, University of Otago, Dunedin, New Zealand.

26 September. Lecture on cohesion in solids to the Christchurch Branch of the New Zealand Institute of Chemistry.

20 October to 7 November. Course of nine lectures on the physics of the solid state at the University of Sydney. Published by C.S.I.R.O., the Commonwealth Scientific and Industrial Research Organization.

23 and 30 October. Two lectures on high-speed photography at the National Standards Laboratory, University Grounds, Sydney.

10-17 November. Four lectures on high-speed photography at the University of Melbourne.

12 November. Lecture on the plasticity of metals at the Division of Tribophysics of C.S.I.R.O., University of Melbourne.

18 November. Lecture on the photographic process to the Victoria Division of the Australian Branch of the Institute of Physics at the University of Melbourne.

1948 8-14 April. Visit to the Institute of Physics, University of Göttingen, Germany.

15-17 April. Lecture on the sensitivity of silver halide grains at a colloquium on photographic sensitivity held at the University of Liège, Belgium.

3 June. Introduction to a discussion on the production of very high vacua at a symposium on vacuum technique, Research Department, Metropolitan-Vickers Electrical Co. Ltd., Trafford Park, Manchester.

19 July. C. E. K. Mees of the Eastman Kodak Research Laboratories, Rochester, visited the H. H. Wills Physical Laboratory and attended a seminar on the sensitization of crystals of silver bromide with silver sulphide.

8-15 September. Six lectures on experimental work with ionic solids in parallel with theoretical lectures by N. F. Mott given at a summer school on the physics of solids with particular reference to ionic solids, held at the H. H. Wills Physical Laboratory, University of Bristol.

1-6 October. Colloquium on reactions in the solid state, held at the Sorbonne, University of Paris.

9 and 25 November. Lecture on gas-filled discharge tubes as light sources for high-speed photography, given to the Illuminating Engineering Society in London and in Glasgow.

1949 27-28 March. Visit to the Department of Physics, University of Groningen, Netherlands.

30 March. Lecture on principles underlying the design of semiconducting systems at the Philips Research Laboratory, Eindhoven, Netherlands.

6-8 April. Lecture on the properties of silver halides containing traces of silver sulphide, at international conference on photographic science Eidgenössische Technischen Hochschule, Zürich.

12-14 April. Discussion of the Faraday Society on crystal growth, held at the H. H. Wills Physical Laboratory, University of Bristol.

5-19 July and 17 August-7 September. Visit to Eastman Kodak Research Laboratories, Rochester, New York.

19-23 July. Visit to the Knolls Research Laboratory, Rochester, New York.

25-26 July. Visit to the Massachusetts Institute of Technology for discussions on flash discharge tubes with H. Edgerton.

27 July. Visit to P. W. Bridgeman at the Department of Physics, Harvard University, Cambridge, Massachusetts.

29 July. Visit to W. Shockley, W. Brattain and J. R. Haynes at the Bell Telephone Laboratories, Murray Hill, New Jersey.

1 August. Visit to National Bureau of Standards, Washington, D. C

3 August. Visit to Naval Research Laboratory, Washington, D. C.

15 December. Lecture on the fundamental physics of luminescence to the British Institute of Radiology, London.

1950 28-31 March. Lecture on lattice defects and latent image formation in silver halides at conference on fundamental mechanisms of photographic sensitivity held at the H. H. Wills Physical Laboratory, University of Bristol. Conference organized and volume of proceedings edited by J. W. Mitchell.

12-14 April. Introductory paper on techniques and paper (with J. A. Allen) on the adsorption of gases on copper films presented at a Discussion of the Faraday Society on Heterogeneous Catalysis held at the University of Liverpool.

11-14 July. Presentation of paper (with E. W. J. Mitchell) on work function of germanium at a conference on semiconducting materials, held at the University of Reading.

1951 25 January. Lecture on the physics of semiconductors in the Department of Physics, University of Birmingham.

10-17 March. Series of lectures on the F-center theory of photographic sensitivity at the Department of Physics, University of Liège, Belgium.

19 June-20 July. Course of fourteen lectures (in French) on the structure and ionic and electronic properties of ionic solids, on reactions in solids, and on the theory of latent image formation, given while a visiting professor at the University of Strasbourg, France.

24-29 September. Two lectures on surface conduction phenomena in crystals of silver halides and the nature of the sensitivity centers and the formation of the latent image in microcrystals, given at a colloquium on the sensitivity of crystals and of photographic emulsions, held at the University of Paris.

1952 20-30 May. Ten lectures on experimental advances, given in parallel with theoretical lectures by N. F. Mott and D. Polder at a summer school on semiconductors and transistors held in the H. H. Wills Physical Laboratory, University of Bristol.

23 June-2 July. Five lectures on recent experimental advances in knowledge of the silver halide photographic system, given at the Eastman Kodak Research Laboratories, Rochester, New York.

3 July. Visit to the Knolls Research Laboratory, General Electric Company, Schenedtady, for discussions with L. Apker, M. Hebb and F. E. Williams.

22-26 September. Course of ten lectures on the physics of semiconductors and transistors at the University of Sydney, organized by the Division of Physics of the National Standards Laboratory, University Grounds, Sydney.

23 September. Lecture on recent experimental research on the nature and formation of the latent image and on photographic development to the New South Wales Division of the Australian Branch of the Institute of Physics.

29 September-3 October. Four lectures on experimental work at Bristol on the properties of thin films of metals, given to the Division of Tribophysics of C.S.I.R.O at the University of Melbourne.

2 October. Lecture on the photographic process to the Victoria Division of the Australian Branch of the Institute of Physics.

1953 13 February. Friday evening discourse on some experiments on photographic sensitivity at the Royal Institution, London.

23 June. Lecture on semiconductivity, adsorption and catalysis at the Gordon Research Conference on Catalysis, New London, New Hampshire.

24 July. Lecture on solid state physics and catalysis by metals, oxide semiconductors and insulating oxides at the Riverside Laboratory of the Universal Oil Products Company, Chicago, Illinois.

4 August. Lecture on model experiments on chemical sensitization and latent image formation with silver halide crystals having dislocation sub-structures at the Eastman Kodak Research Laboratories, Rochester, New York.

19-25 September. Lecture on a contribution to the theory of photographic sensitivity at the international conference on the science and applications of photography held in London on the occasion of the centenary of the Royal Photographic Society.

1954 1 February. Lecture on the photographic process at the Imperial College of Science and Technology, London.

13-17 July. Conference on defects in crystalline solids at the H. H. Wills Physical Laboratory, University of Bristol, organized by J. W. Mitchell. Paper (with T. Evans) presented on crystal imperfections and chemical reactivity.

26 July. Lecture on dislocations in crystals of silver halides at the Institute of Physics, University of Göttingen, on the occasion of the 70th birthday of R. W. Pohl.

1955 14 March-25 April. Lecture tour of universities, government and industrial laboratories in the United States of America, organized by the Office of Scientific Research of the Air Research and Development Command.

18 March. Lecture on dislocations in crystals of silver halides at a Division of Solid State Physics symposium at the spring meeting of the American Physical Society, Baltimore, Maryland.

17 May. Lecture on recent research on the mechanisms of photographic sensitivity at the British Gelatin and Glue Research Association, London.

20 June-7 July. Seminars on experimental work on thin sheet crystals of silver halides and practical demonstrations of the production and application of thin sheet crystals at the Eastman Kodak Research Laboratories, Rochester, New York.

19-29 September. Visits to Divisions of Tribophysics and of Chemical Physics of C.S.I.R.O., Melbourne, Australia.

22 September. Lecture on recent developments in the theory of the photographic process to the Victoria Division of the Australian Branch of the Institute of Physics, Melbourne, Australia.

18 October. Lecture on crystals of silver halides delivered on the occasion of the award of the 11th Charles Vernon Boys Prize, at the Physical Society, London.

1956 29 March. Colloquium on the theory of latent image formation in sensitized crystals of silver halides at the Photographisches Institut, Eidgenössischen Technischen Hochschule, Zürich, Switzerland.

5-6 April. Visit to the Research Laboratories of Agfa, Leverkusen, Germany.

13 April. Lecture on the nature of photographic sensitivity to the Deutsche Gesellschaft für Photographie, Sektion wissenschaftliche Photographie, Köln, Germany, on the occasion of the 65th birthday of Professor J. Eggert.

1 May. Colloquium on dislocation networks in crystals at the Cavendish Laboratory, University of Cambridge.

10 May. Lecture on recent advances in the theory of photographic sensitivity in the Department of Physics of the University of Exeter.

4-14 August. Visit to Eastman Kodak Research Laboratories, Rochester, New York.

20 August-5 September. Visit to the Knolls Research Laboratory, General Electric Company, Schenectady, New York.

6-8 September. Lecture on dislocations in crystals of silver halides at the International Conference on Dislocations and Mechanical Properties of Crystals held at Lake Placid, New York.

13-22 September. Visit to Physikalisches Institut, University of Göttingen.

15 September. Colloquium on dislocation networks in crystals at the Physikalisches Institut, University of Göttingen.

24-27 September. Lecture on the sensitization of crystals of silver halides with sulphur compounds at the International Conference on Scientific Photography in Köln, Germany.

1 November. Lecture on dislocations in action to the Metallurgical Society of the University of Birmingham.

4 December. Lecture on the nature of photographic sensitivity on the occasion of the award of the 11th Renwick Memorial of the Royal Photographic Society, London.

1957 8-12 January. Lectures on the decoration of dislocations in silver and alkali halides and on the chemical sensitization of silver halide crystals at the University of Ghent, Belgium

17-18 May. Lecture on surface mobility on evaporated thin films at a discussion meeting on the Growth and Texture of Evaporated Films held at the Cavendish Laboratory, University of Cambridge.

1-6 July. Introductory lecture on photographic sensitivity at the International Colloquium on Particle Photography, University of Strasbourg, France.

1958 17-19 March. Conference on the Mechanical Properties of Whiskers and Thin Films held at the Cavendish Laboratory, University of Cambridge, and the Tube Investments Research Laboratories, Hinxton Hall, Cambridge.

24-29 March. Three lectures on observations of dislocations in inorganic crystals, dislocations in crystals of silver halides, and on dislocations in crystals of alkali halides at a Vacation School on Dislocations in Metals and Inorganic Crystals held at the H. H. Wills Physical Laboratory, University of Bristol.

18-22 August. Lecture on photoconductivity in crystals of silver bromide (with E. A. Braun) at the International Conference on Semiconductors, University of Rochester, Rochester, New York.

27-29 August. Lecture on the production of crystals of ionic solids of low dislocation density at the International Conference on Crystal Growth, Cooperstown, New York.

6-11 November. Lecture on dislocations in ionic crystals at the 44th National Congress of Physics, Italian Society of Physics, held at the Institute of Physics, University of Palermo, Sicily.

18-20 December. Lecture on the creation of dislocations during precipitation (with A. S. Parasnis) at a Conference on Interfacial Phenomena organized by the Physical Society and held at the Cavendish Laboratory, University of Cambridge.

1959 26 February. Colloquium on dislocations in crystals of silver halides, Clarendon Laboratory, University of Oxford.

13-16 July. Four lectures on the direct observation of dislocations in crystals by etching and decoration at a summer school held at the Cavendish Laboratory, University of Cambridge.

31 August-1 September. Visit to Research Chemistry Branch, Atomic Energy of Canada, Ltd., Chalk River, Ontario, CAnada.

2-4 September. Paper on precipitation reactions in crystals of silver and alkali halides presented at a Discussion of the Faraday Society on Crystal Imperfections and Reactivity of Solids, Queen's University, Kingston, Ontario, Canada.

9-11 September. Introductory talk and papers on the measurement of surface areas of thin films of copper (with J. A. Allen and C. C. Evans) and on the influence of the adsorption of oxygen on the resistivity of thin films of copper (with C. C. Evans) presented at International Conference on the Structure and Properties of Thin Films held at Bolton Landing, Lake George, New York.

14-19 September. Participation in discussions at International Colloquium on Scientific Photography held at the University of Liège, Belgium.

21-22 September. Lecture on observations of the role of dislocations in stress-relaxation processes in crystals of silver halides at the Philips Research Laboratories, Eindhoven, Netherlands.

PARTIAL LIST OF LECTURES, CONFERENCES AND OTHER ACTIVITIES 1959-1979

1960 2 April. Lecture on recent research on the deformation of crystals to the Chesapeake Section of the American Association of Physics Teachers, Charlottesville, Virginia

13 May. Colloquium on dislocation generation and propagation processes during stress relaxation in silver halide crystals at the Department of Physics, University of Illinois, Urbana, Illinois.

2 June. Colloquium on the plastic deformation of crystals of silver halides at the U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland.

11-16 September. Introductory lecture on the comparative physical properties of silicon and germanium, III-V, II-VI compounds and silver and alkali halides, at a Symposium on the Chemistry of the Solid State, American Chemical Society, New York.

2 December. Lecture on the catalytic chemistry of photographic sensitivity to the Catalysis Club of Philadelphia, at the Club House in Chester, Pennsylvania.

1961 1 March. Review lecture on the direct observation of imperfections in crystals by optical and electron microscopy at the 90th annual meeting of the Metallurgical Society of AIME, St. Louis, Missouri.

21-24 March. International Conference on Photoconductivity, Cornell University, Ithaca, New York.

25-30 June. Dislocation processes in crystals of silver halides, Gordon Research Conference on Physical Metallurgy, Meridan, New Hampshire.

27-31 August. Lecture on mechanisms of equilibration of lattice defects in real solids at the International Conference on Chemical Physics of Nonmetallic Crystals, Northwestern University, Evanston, Illinois.

13 September. Seminar on dislocations in ionic crystals at the Argonne National Laboratory, Argonne, Illinois.

13 September. Colloquium on dislocations in crystals of silver halides at the Northwestern Institute of Technology, Evanston, Illinois.

1962 21 March. Lecture on dislocations in crystals of silver and alkali halides, Department of Physics, University of Delaware, Newark, Delaware.

22-25 March. Introductory lecture on some aspects of the theory of photographic sensitivity at a Symposium on the Photographic Process, Division of Physical Chemistry. American Chemical Society, Washington, D. C.

28-30 May. Symposium on Physics and Chemistry of Ceramics organized by Office of Naval Research at the Pennsylvania State University, University Park, Pennsylvania.

23-24 July. Visit to National Standards Laboratory, University Grounds, Sydney, Australia.

25-31 July. Visits to Divisions of Tribophysics and of Chemical Physics of the Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia.

6-12 September. Lecture on hexagonal networks of linear imperfections in single crystals of cadmium (with J. C. Crump III) at International Conference on Crystal Lattice Defects, Kyoto, Japan.

14 September. Lectures on the role of dislocations in photographic sensitivity and on the role of chemical sensitization in photographic sensitivity at a Symposium on Photographic Sensitivity, Tokyo, Japan.

15 September. Seminar on noble metal sensitization at the Ashigara Research Laboratories, Fuji Photo Film Co. Ltd., Ashigara, Kanagawa, Japan.

17 September. Seminar on dislocation arrays and the growth of microcrystals of silver halides in relation to photographic sensitivity at the Ashigara Research Laboratories, Fuji Photo Film Co. Ltd., Ashigara, Kanagawa, Japan.

18 September. Visit to Institute for Solid State Physics, University of Tokyo, Azabu, Tokyo, Japan.

5 December. Lecture on etching and decoration of dislocations in the study of sub-structures at a Conference on the Role of Sub-structures in the Mechanical Behaviour of Metals organized by Air Force Systems Command, Orlando Air Force Base, Orlando, Florida.

1963 17-18 January. Conference on Transport Processes in Crystalline Insulators, Princeton University, Princeton, New Jersey.

5 February. Lecture on the roles of crystal imperfections and chemical sensitization in the formation of the latent image, Rochester Section of the Optical Society of America, Rochester, New York.

18 March. Colloquium on dislocation processes in thin films of cadmium, Department of Metallurgy, University of Pennsylvania, Philadelphia, Pennsylvania.

13 May. Paper on interfacial dislocations in nickel bromide grown epitaxially on thin chromic bromide crystals (with E. Grünbaum) presented at a Conference on Single Crystal Films, Blue Bell, Pennsylvania.

1963-64 1 October, 1963-31 August, 1964. Director of the National Chemical Laboratory, Teddington, Middlesex, England.

1965 14 January. Lecture on experimental work with large thin sheet crystals of silver halides to the Rochester Chapter of the Society of Photographic Scientists and Engineers, Rochester, New York.

12 February. Jubilee Memorial Lecture of the Society of Chemical Industry on the organization of basic research for the British chemical industry, delivered in Manchester, followed by lectures in Edinburgh and Dublin.

8 April. Lecture on crystal structures and lattice and structural imperfections in crystalline solids, Department of Physics, Washington and Lee University, Lexington, Virginia.

7-8 June. Conference on Environment Sensitive Mechanical Behavior at Research Institute for Advanced Studies, Martin-Marietta Corporation, Baltimore, Maryland.

1966 7 April. Lecture on the strength of crystals, Department of Physics, Emory and Henry University, Abingdon, Virginia.

30 June. Colloquium on the ultimate strength of thin ribbons of cadmium, Department of Physics, Georgetown University, Washington, D. C.

11-13 July. International Symposium on Reaction Mechanisms in Inorganic Solids, Department of Chemistry, University of Aberdeen.

22-26 August. Lecture on the nature and formation of bands of deformation in single crystals of α-phase copper-aluminium alloys (with J. C. Chevrier, B. J. Hockey, and J. P. Monaghan, Jr.) at International Conference on Deformation of Crystalline Solids, National Research Council of Canada, Ottawa, Canada.

26-29 October. Review of the foundations of photographic theory at Colloquium on the Photographic Interaction between Radiation and Matter, Society of Photographic Scientists and Engineers, Washington, D. C.

1967 9 May. Colloquium on precipitation processes and accompanying generation of systems of prismatic dislocations in inorganic systems, Department of Physics, University of Illinois, Urbaba, Illinois.

15-19 May. Awarded the honorary membership of the Society of Photographic Scientists and Engineers at the 20th annual meeting of the Society in Chicago, Illinois.

20 May. Lecture on lattice and structural imperfections in crystals of silver halides, Department of Physics, University of Kansas, Lawrence, Kansas.

20 May. Lecture on lattice and structural imperfections in crystals of silver halides, Department of Physics, University of Kansas, Lawrence, Kansas.

17-21 July. Lecture on plastic deformation of single crystals of face-centred-cubic copper alloys at Gordon Research Conference on Physical Metallurgy, Meridan, New Hampshire.

4-8 September. Lecture on dynamic dislocation phenomena in single crystals of α-phase copper-aluminium alloys (With J. S. Ahearn, Jr., B. J. Hockey, J. P. Monaghan, Jr., and R. K. Wild), International Conference on the Strength of Metals and Alloys, Tokyo, Japan.

9 September. Lecture on dislocation configurations in silver halide photographic emulsion grains, Ashigara Research Laboratories, Fuji Photo Film Co. Ltd., Ashigara, Kanagawa, Japan.

13 September. Lecture on the plastic deformation of oriented single crystals of copper-aluminium alloys, Department of Physics, University of Tokyo, Tokyo, Japan.

14 September. Visit to National Research Institute of Metals, Nakameguro, Tokyo, Japan.

16 September. Lecture on interaction of electrons and holes with lattice and structural defects in crystals of silver halides at a Symposium on Electronic Processes in Silver Halide Crystals, Institute for Solid State Physics, University of Tokyo, Azabu, Tokyo, Japan.

18-20 September. Lecture on the use of model systems for the study of chemical sensitization at International Congress on Photographic Science, Tokyo, Japan.

26 September. Lecture on dislocation processes during the early stages of the plastic deformation of single crystals of α-phase copper-aluminium alloys. Department of Physics, University of Nagoya, Nagoya, Japan.

27 September. Lecture on dynamic dislocation phenomena in single crystals of copper-aluminium alloys, Department of Metal Physics, University of Kyoto, Kyoto, Japan.

29 September. Lecture on dislocation phenomena in single crystals of silver halides and α-phase copper-aluminium alloys at the Kyoto Technical University, Kyoto, Japan.

9 October. Lecture on dynamic dislocation phenomena in single crystals of copper-aluminium alloys, College of Engineering, Rutgers University, New Brunswick, New Jersey

1968 12 January. Colloquium on the plastic deformation of single crystals of copper-aluminium alloys, Department of Physical Metallurgy, Ohio State University, Columbus, Ohio.

25-30 August. Chairman of the Sixth International Symposium on the Reactivity of Solids held at the Knolls Research Laboratory, General Electric Company, Schenectady, New York

October 5. Lecture on the strength of metals to the Sixth Annual State Science Teachers Conference, Fredericksburg, Virginia.

1969 21-25 April. Conference on Fundamental Aspects of Dislocation Theory, National Bureau of Standards, Gaithersburg, Maryland.

12-16 May. Lecture on surface and space charge distributions at the surface of a silver bromide crystal in vacuum and in an aqueous medium at the 22nd annual meeting of the Society of Photographic Scientists and Engineers in Los Angeles California.

1970 2 February. Lecture on the role of mixed crystals of silver halides in the sensitivity of high-speed photographic emulsions at the 3M Central Research Laboratories, St. Paul, Minnesota.

30 March. Lecture on the concentration theory of photographic sensitivity at the Eastman Kodak Research Laboratories Rochester, New York.

8-11 June. Visit to the Research Laboratories of the Boeing Corporation, Seattle, Washington.

30 August-4 September. Paper on the formation of bands of deformation in single crystals of copper-aluminum alloys with polyslip orientations (with J. S. Ahearn, Jr., and H. McD. Hobgood) presented at an International Conference on the Strength of Metals and Alloys, Asilomar, Pacific Grove, California.

5-9 October. Visit to Division of Metal Physics, National Research Council Laboratories, Ottawa, Canada.

1971 1-4 June. Lecture on the properties of small clusters of atoms of silver and gold at a working Symposium on the Sizes, Properties and Reactions of Latent Images, organized by the Society of Photographic Scientists and Engineers, Manchester, New Hampshire.

2 November. Colloquium on dislocations in single crystals of silver halides and copper-aluminium alloys, Department of Physics, Brandeis University, Waltham, Massachusetts.

1972 10 August-28 September. Visiting lecturer, Department of Physics, University of Natal, Pietermaritzburg, South Africa.

General lectures

23 August. Atmospheric electricity. (Lecture 1)
24 August. Physical processes in thunderstorms. (Lecture 2)
30 August. The importance of technological advances based on solid state physics. (Lecture 3)
31 August. The significance of the discovery of new research systems and new materials for the physical sciences. (Lecture 4)
13 September. Public lecture on the strength of metals and alloys. (Lecture 5)

The physical properties of silver halide crystals and photographic sensitivity

8 September. Optical absorption, electronic and ionic conductivity. (Lecture 6)

12 September. Lattice imperfections and photochemical processes. (Lecture 7)

13 September. Model systems for research in photographic sensitivity. (Lecture 8).

14 September. The theory of the nature and formation of the photographic latent image. (Lecture 9)

26 September. The cohesive energy of small clusters of atoms of silver, gold and palladium and its importance for photographic sensitivity. (Lecture 10)

Studies of the plastic deformation of oriented single crystals of copper alloys

16 August. The production of accurately oriented single crystals of metals and alloys of high surface and internal perfection. (Lecture 11)

23 August. The design of tensile systems, of high sensitivity stress and strain transducers, and the mounting of single crystals for studies of plastic deformation. (Lecture 12)

30 August. Stress-strain curves for the tensile deformation of single crystals of copper-aluminium alloys at 293 and 4.2° K and their interpretation. (Lecture 13)

7 September. The detailed study of the role of dislocations in relaxation processes during the tensile deformation of single crystals of copper-aluminium alloys at 293 and 4.2° K. (Lecture 14).

13 September. The mechanisms involved in the formation of glide bands in single crystals of copper-aluminium alloys. (Lecture 15)

26 September. The high-velocity motion of dislocations during the discontinuous plastic deformation of single crystals of copper-aluminium alloys at 4.2° K. (Lecture 16)

28-29 September. Lectures 3 and 4 at the Department of Physics, University of Port Elizabeth, Port Elizabeth, South Africa.

7 September. Lecture 5 at the University of Natal, Durban, South Africa.

19 September. Lecture on dislocations in crystals of silver halides at the National Physical Research Laboratory, Pretoria, South Africa.

20 September. Lecture 16 at the National Physical Research Laboratory.

21 September. Lectures 3 and 4 at the Department of Physics, University of Witwatersrand, Johannesburg, South Africa.

22 September. Lecture on the dynamics of plastic deformation processes in single crystals of copper-aluminium alloys at 4.2° K at the Department of Physics, University of Pretoria, Pretoria, South Africa.

29 September. Lecture 10 at the Department of Chemistry, University of Western Australia, Perth, Australia.

2-12 October. Lectures 11-16 at the Division of Tribophysics, Commonwealth Scientific and Industrial Research Organization, University of Melbourne Grounds, Melbourne, Australia.

13 October. Lecture on design of new alloy systems with high strength and stress corrosion resistance at the National Standards Laboratory, Sydney, Australia.

27 October. Lecture on recent advances in experimental research on the plastic deformation of α-phase copper-aluminium alloys at the National Physical Laboratory of India, Delhi, India.

2-3 November. Lectures 13 and 14 at the Department of Physics, Indian Institute of Technology, Kanpur, Uttar Pradesh, India.

13-17 November. Four lectures on chemical and spectral sensitization and latent image formation with silver halide photographic emulsion grains at the Photographisches Institut, Eidgenössiche Technischen Hochschule, Zürich, Switzerland.

20 November-1 December. Lectures 11-16 as Gauss Visiting Professor at the Institut für Metallphysik, University of Göttingen, Germany.

4 December. Lecture on the plastic deformation of single crystals of α-phase copper-aluminium alloys at the Department of Solid State Physics, University of Paris,

6-8 December. Two lectures on dislocation processes during the tensile deformation of single crystals of copper-aluminium alloys at 293 and 4.2° K, at the Department of Metallurgy, University of Oxford.

11-15 December. Two lectures on the growth of single crystals and the initial stages of tensile deformation of single crystals of α-phase copper-aluminium alloys at 293 and 4.2° K at the Cavendish Laboratory, University of Cambridge.

1973 12-16 November. Six lectures on silver halide photographic research and metal physics to the Departments of Chemistry, Physics and Materials Science and Engineering, Washington State University, Pullman, Washington, with the titles: Photographic research: (1) The development of silver halide model systems for research on photographic sensitivity. (2) Experimental work with silver halide model systems on chemical and dye sensitization and the formation and properties of the photographic latent image. (3) Theoretical work on the nature and formation of the photographic latent image. Metal physics: (1) The production of accurately oriented single crystals of copper alloys of high purity and perfection. (2) The mechanisms of plastic deformation in single

crystals of copper-alloys. (3) Dynamic studies of dislocation phenomena in single crystals of copper alloys at 4.2° K.

1974 11 May. Colloquium on the measurement of dislocation velocities during the plastic deformation of single crystals of copper-aluminum alloys at 4.2° K at the Department of Physics, University of Illinois, Urbana, Illinois.

1975 26 February. Colloquium on experimental methods for the study of dislocation processes during the initial stages of the plastic deformation of single crystals of copper-aluminum alloys, National Bureau of Standards, Gaithersburg, Maryland.

10 April. Colloquium on the measurement of dislocation velocities during the plastic deformation of single crystals of copper-aluminum alloys at 4.2° K at the Department of Metallurgy and Material Science, University of Pennsylvania, Philadelphia.

1976 9 March. Lecture on the discovery of dislocations in crystals of silver halides at the Department of Physics, New Mexico State University, Las Cruces, New Mexico.

1977 16-20 May. Lecture on mechanisms of chemical sensitization and latent image formation at a Symposium on the Nature of the Photographic Latent Image in Silver Halide Systems in honour of the 80th birthday of Professor K. V. Chibisov, organized by the Academy of Sciences of the U.S.S.R., Moscow.

26-30 September. Lecture on thermally developable light-sensitive systems based on organo-tellurium compounds (with W. E. Nixon) at International Symposium on Photo- and Electro-imaging, organized by Society of Photographic Scientists and Engineers and Society of Photo-Optical Instrumentation Engineers, Tokyo, Japan.

1-4 October. Lectures at the Departments of Photographic Science and Metal Physics of the University of Kyoto, Kyoto, Japan.

1978 19 April. Lecture on the processes of latent image formation and development in silver halide photographic emulsions at the Department of Physics, Virginia Military Institute, Lexington, Virginia.

21-25 August. International Congress on Photographic Science, Rochester Institute of Technology, Rochester, New York.

27 October. Seminar on the processes of plastic deformation in single crystals of silver halides and face-centered-cubic copper alloys at the Martin Marietta Research Laboratories, Baltimore, Maryland.

PARTIAL LIST OF LECTURES, CONFERENCES AND OTHER ACTIVITIES 1979-1991

1980 21-25 July. Lecture on the concentration theory of latent image formation at the Tokyo Symposium on Advances in Photography, Society of Photographic Science and Technology of Japan, Tokyo, Japan.

16 September. Lecture on concentration specks and development centers, Research Laboratories, Kodak-Pathé, Vincennes, Paris, France.

18-19 September. Two lectures on the concentration theory of photographic sensitivity and the nature of the stable latent image in silver halide emulsion grains at the Research Laboratories, Agfa-Gevaert AG, Leverkusen, Germany.

24 September. Lecture on the concentration theory of latent image formation, Research Laboratories, Ciba-Geigy, Marly, Fribourg, Switzerland.

25-26 September. Lecture on recent progress in the theory of the formation of the photographic latent image, Photographisches Institut, Eidgenössische Technischen Hochschule, Zürich, Switzerland.

29 September -3 October. Review lecture on model systems for research in photographic sensitivity, International Symposium on Model Investigations of the Photographic Process, Bulgarian Academy of Science, Drouzhba, Varna, Bulgaria.

1981 28 January. Lecture on the concentration theory of latent image formation at the Polaroid Corporation, Cambridge, Massachusetts.

26 March-4 May. Visiting professor at the University of Kyoto under the Research Fellowship Programme of the Japan Society for the Promotion of Science. Twelve lectures given on physical properties and lattice and structural imperfections of crystals of silver halides and the nature, formation and development of the photographic latent image.

14 April. Lecture on dynamic dislocation phenomena in single crystals of copper alloys deformed at 4.2° K at the Department of Metal Physics, University of Kyoto.

17 April. Lecture on the concentration theory of photographic sensitivity to the Western Branch of the Society of Photographic Science and Technology of Japan, Kyoto, Japan.

22 April. Lecture on the historical evolution of the quantitative concentration theory of latent image formation to the Tokyo Chapter of the Society of Photographic Scientists and Engineers, Tokyo, Japan.

23 April. Visit to Imaging Science and Engineering Laboratory, Tokyo Institute of Technology, Yokohama, Japan.

30 April. Lecture on the discovery of dislocations and early researches with thin sheet crystals of silver halides, University of Tokyo, Tokyo, Japan.

1 May. Lecture on the formation of development centers in photographic emulsion grains at the University of Tokyo, Tokyo, Japan.

7 May. Awarded Kulturpreis of the Deutsche Gesellschaft für Photographie, Köln, Germany.

11 May. Lecture on the concentration theory of latent image formation in photographic emulsion grains at the Research Laboratories of Agfa-Gevaert AG, Leverkusen, Germany.

12 May. Lecture on the formation and properties of the stable latent image at the Research Laboratories of Agfa-Gevaert AG, Leverkusen, Germany.

14-15 May. Lecture on the plastic deformation of single crystals of copper-aluminium alloys at 293 and 4.2° K, at the Institut für Metallphysik, University of Göttingen, Germany.

18-19 May. Lecture on spectral sensitization, desensitization and supersensitization at the Max Planck Institut für Biologische Chemie, Nikolausberg, Göttingen, Germany.

21 May. Lecture on the quantitative theory of the concentration process, University of Frankfurt, Frankfurt-am-Main, Germany.

26-31 July. Lecture on the formation of the latent image in photographic emulsion grains, International Symposium on Fundamentals of Latent Image Formation, Society of Photographic Scientists and Engineers, Lake Placid, New York.

18 September. Lecture on the spectral sensitization, desensitization and supersensitization in silver halide systems at the Research Laboratory, Agfa-Gevaert AG, Leverkusen, Germany.

20-25 September. Lecture on dynamic dislocation phenomena in single crystals of copper-aluminium alloys at an International Symposium on Dislocation Dynamics in Solid Solutions sponsored by the Deutsche Gesellschaft für Metallurgie, St. Andreasburg, Harz, Germany.

1982 9-14 May. Lecture on image formation processes in core-shell emulsions at the 35th annual meeting of the Society of Photographic Scientists and Engineers, Rochester, New York.

6-10 September. Lecture on the concentration process in the formation of development centers in silver halide microcrystals, International Congress of Photographic Science, Cambridge, England.

1983 1 March. Lecture on the mechanisms of plastic deformation of copper alloy single crystals, Maryland Institute of Metals, Johns Hopkins University, Baltimore, Maryland.

14 April. Lecture on the concentration process in the formation of development centers in silver halide emulsion grains at the Research Laboratory, Agfa-Gevaert AG, Leverkusen, Germany.

15 April. Lecture on image formation processes in concentric shell emulsions at the Research Laboratories, Agfa-Gevaert AG, Leverkusen, Germany.

16-28 April. Guest professor, Institüt fur Metallphysik, Technische Universität, Carolo-Wilhelmina, Braunschweig, Germany. Lectures on the plastic deformation of single crystals of copper-aluminium alloys.

29 April. Lecture on the initial stages of the plastic deformation of single crystals of binary and ternary alloys of the Cu-Al-Ni-Pd system at the Institut für Metallphysik of the University of Göttingen, Göttingen, Germany.

3 May. Lecture on the statistics of electron trapping processes in microcrystals of silver halides, Tagung der wissenschaftliche Photographie, University of Frankfurt, Frankfurt am Main, Germany.

31 May-3 June. Awarded the Lieven Gevaert Medal of the Society. Lecture on the statistics of electron trapping processes in microcrystals of silver halides at the 36th annual meeting of the Society of Photographic Scientists and Engineers, San Francisco, California.

1984 22 March. Lecture on the statistics of electron trapping processes in crystals of silver halides, 3M Technical Forum, Minnesota Mining and Manufacturing Company, St. Paul, Minnesota.

22 March. The concentration process in the formation of development centers on silver halide microcrystals, Twin Cities Chapter of the Society of Photographic Scientists and Engineers, Minneapolis-St. Paul, Minnesota.

20-24 May. Lecture on spectral sensitization and desensitization at the 37th annual meeting of the Society of Photographic Scientists and Engineers, Boston, Massachusetts.

14-15 June. Two seminars on chemical sensitization and the formation and properties of the photographic latent image at the Research Laboratories of Agfa-Gevaert NV, Mortsel, Belgium.

18-19 June. Two seminars on factors involved in the design of silver halide photographic emulsions for optimum performance at the Research Laboratories of Agfa-Gevaert AG, Leverkusen, Germany.

21-22 June. Lecture on dislocation processes in the formation of narrow bands of deformation in single crystals of α-phase copper aluminium alloys, Institut für Metallphysik, Technische Universität, Carolo-Wilhelmina, Braunschweig, Germany.

25 June. Lecture on spectral sensitization, desensitization and supersensitization at the Institut für wissenschaftliche Photographie der Technischen Universität, Garching, Munich, Germany.

26 June. Lecture on quantitative aspects of the concentration theory of latent image formation, Deutsche Gesellschaft für Photographie, Sektion Wissenschaft und Technik, Munich, Germany.

28 October-4 November. Lecture on the optimization of the negative imaging silver halide photographic system at the International East-West Symposium on the Factors Influencing Photographic Sensitivity, Kaanapali, Maui, Hawaii.

8 November. Lecture on the optimization of the silver halide photographic system at the Ashigara Research Laboratories, Fuji Photo Film Co. Ltd., Minami-Ashigara, Kanagawa, Japan.

14 November. Lecture on quantitative aspects of the concentration theory of latent image formation, Society of Photographic Science and Technology of Japan, Kyoto, Japan.

1985 23 April. Lecture on the formation and properties of the photographic latent image at the Research Laboratories of the VEB Film Fabrik, Wolfen, East Germany.

24 April. Lecture on chemical and spectral sensitization of silver halide photographic emulsions at the Akademie der Wissenschaften der DDR, Berlin-Adlershof.

12-16 May. Lecture on the supersensitization of spectral sensitizing systems at the 38th annual meeting of the Society of Photographic Scientists and Engineers, Atlantic City, New Jersey.

1986 11-17 September. Lecture on the supersensitization of 1,1'-diethyl-2,2'-cyanine iodide at the International Congress on Photographic Science, Köln, Germany.

18 September. Lecture on the elementary processes of the concentration theory of latent image formation at the Research Laboratories of Agfa-Gevaert AG, Leverkusen, Germany.

19 September. Lecture on the supersensitization of spectrally sensitized silver halide imaging systems at the Research Laboratories of Agfa-Gevaert AG, Leverkusen, Germany.

25 September. Seminar on elementary processes in the concentration theory of latent image formation, Research Laboratory, Imaging Science Department, E. I. du Pont de Nemours and Co., Wilmington, Delaware.

1988 25 March. Lecture on prismatic dislocation punching in crystals of silver halides at the Department of Nuclear and Chemical Engineering, University of Maryland, College Park, Maryland.

28 April. Lecture on observations of dislocations in crystals of silver halides at the Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

23 August. Paper on solute pairing in solution-hardened binary and ternary face-centered-cubic alloys (with J. Wong, W. E. Nixon, and S. S. Laderman) presented at Fifth International EXAFS Conference, Seattle, Washington.

1989 12 January. Lecture on chemical sensitization and latent image formation from the viewpoint of the emulsion chemist at the Brevard Research Laboratory, Photoproducts Division, E. I. du Pont de Nemours and Co., Brevard, North Carolina.

14-19 May. (1) Lecture on chemical sensitization and latent image formation - a historical perspective - and (2) Lecture at the Edgerton Symposium on discharge tubes as light sources for high-speed photography at the 42nd annual meeting of the Society for Imaging Science and Technology, Boston, Massachusetts.

1990 11 January. Lecture on Auger electronic processes in chemically sensitized and in spectrally sensitized and supersensitized silver halide emulsion microcrystals at the Brevard Research Laboratory, E. I. du Pont de Nemours and Co., Brevard, North Carolina.

28 March. Lecture on the theory of the creation, diffusive and drift displacement, and trapping of electrons and holes in crystals of silver halides at the Brevard Research Laboratory, E. I. du Pont de Nemours and Co., Brevard, North Carolina.

2 May. Lecture on the role of electronic donor and acceptor centers in photochemical processes in crystals of silver halides at the Brevard Research Laboratory, E. I. du Pont de Nemours and Co., Brevard, North Carolina.

3 May. Lecture on electronic processes in crystals of silver bromide - the positively charged concentration speck, at the Brevard Research Laboratory, E. I. du Pont de Nemours and Co., Brevard, North Caroline.

20-25 May. Lecture on Auger processes for the creation of free electrons and holes in sensitized crystals of silver halides at the 43rd annual meeting of the Society for Imaging Science and Technology, Rochester, New York.

7 June. Lecture on the sensitization of silver halide photographic emulsions with silver sulfide and silver-gold sulfide at the Brevard Research Laboratory, E. I. du Pont de Nemours and Co., Brevard, North Carolina.

13 September. Lecture on double-, triple-, and multi-structured silver halide microcrystals for silver halide emulsions at the Brevard Research Laboratory, E. I. du Pont de Nemours and Co., Brevard, North Carolina.

22 October. Lecture on dislocations and photographic sensitivity at a Symposium on Proposals for the Future of Silver Halide Photography, held on the occasion of the 80th birthday of Professor Shin Kikuchi in the Sanjo Kaikan of Tokyo University, Tokyo, Japan.

25 October. Lecture on the photoaggregation theory of photographic sensitivity at the Research Laboratories of Konica Corporation, Hino City, Japan.

26 October. Lecture on electronic and ionic processes in the formation of the photographic latent image at the Department of Imaging Science, Chiba University, Chiba City, Japan.

31 October. Lecture on Auger processes and the photoaggregation theory of photographic sensitivity at the photoproducts research laboratories of Mitsubishi Paper Mills, Ltd., Kyoto, Japan.

5 November. Lecture on the role of iodide ion concentration gradients in the controlled introduction of dislocation arrays in silver bromide emulsion microcrystals at the Ashigara Research Laboratories, Fuji Photo Film Co. Ltd., Minami-Ashigara, Japan.

6 December. Lecture on spectral sensitization for the infrared with silver halide photographic emulsions at the Brevard Research Laboratory, E. I. du Pont de Nemours & Co., Brevard, North Carolina.

1991 6 March. Lecture on dislocations in microcrystals of silver halides at the Brevard Research Laboratory, E. I. du Pont de Nemours and Co., Brevard, North Carolina.

12-17 May. Lecture on electronic and ionic processes in sensitized silver halide systems at the 44th annual meeting of the Society for Imaging Science and Technology, St. Paul, Minnesota.

6 June. Lecture on electronic and ionic processes in sensitized silver halide systems at the Brevard Research Laboratory, E. I. du Pont de Nemours and Co., Brevard, North Carolina.

1993 10 May. Lecture on the silver halide photographic emulsion grain at the 46th annual meeting of the Society for Imaging Science, Cambridge, Massachusetts.