Abstract. Helmut Alexander was one of the four initiators of the “International Symposium on Dislocations in Tetrahedrally Coordinated Semiconductors” (Hünfeld 1978). This conference was the beginning of a conference series which got its new name EDS (Extended Defects in Semiconductors) first in 1980. He who gave his name to the “Helmut Alexander Award” of the EDS conference died on the third of December, 2009. The international advisory committee of EDS honoured his scientific work in 2002 recognizing him by instituting an award for the best poster presentation for a young scientist at the running conference session. The authors try to review his life with some of his scientific highlights.

Helmut Alexander was born on July 30, 1928 at Mannheim as son of a parish priest. Formative influences on his childhood and youth were his home and the Second World War. His parents strongly supported his special interest in literature and music. In 1944 he was called up by the German Navy (Marine), but soon fell ill with severe tuberculosis. This disease forced him for many years to exercise restraint. He went to grammar school (Gymnasium) in Neustadt/Weinstrasse, from which he graduated with the “Abitur” in 1947. He began to study physics at the University of Mainz in 1949 and obtained his diploma in 1957 at the University of Darmstadt. After a short time at Siemens he began to work for a doctoral thesis at the “Max-Planck-Institut für Metallforschung” in Stuttgart.

1. The beginnings of his scientific career in Göttingen

1.1. Plasticity of germanium compared to that of copper; doctoral thesis

In the first days of 1959, Peter Haasen, just appointed the director of the “Institut für Metallphysik” (IfM) at the university, arrived at Göttingen. He came from the “Max-Planck-Institut für Metallforschung” at Stuttgart and with him came Helmut Alexander, a graduate student busy with a doctoral thesis on Plastic Deformation of Germanium (1961 Plastische Verformung von Germanium Z. Metallkde. 52 344).

The topic of this thesis did not appear to be very exciting. Many materials scientists in leading research centers of the USA, Great Britain, France, Russia and now also at Stuttgart were investigating the problem of plasticity and its interpretation. However, their work concentrated on metals and alloys, not on semiconductors.

Why then germanium? Helmut Alexander’s answer to this question is given in his thesis (1960): “... to characterize the deformation mechanism of the diamond lattice by its correspondence and differences with the cubic face-centered lattice by a method, which brought to a large extent a
quantitative understanding for the latter lattice type ... ". The method which he refers to is the dynamical tensile test.

For a graduate student at the IfM like Helmut Alexander, the experimental work on germanium started with a piece of raw material, which had to be purified by zone-pulling, then grown with prescribed orientation as a single-crystalline slab, followed by cutting into specimens, mechanical and chemical polishing of their surfaces etc. However, the great challenge on the way towards a tensile test with germanium was to conceive and produce the grips connecting the specimen with the deformation machine. For this problem, until then unsolved, Helmut Alexander found a very elegant solution, which was basic for the success of his work. However, the tensile test remained a delicate procedure. It was later replaced by the compression test, as soon as the equivalence of both tests was shown in the first diploma thesis supervised by Helmut Alexander.

The two main results, which he obtained in his thesis, were starting points for his further research activity in Göttingen and later Cologne.

When a constant elongation velocity is imposed on a copper specimen, the transition from elastic to plastic deformation occurs at a critical (shear) stress $\tau_c$ (see Fig. 1), which is weakly temperature-dependent. For germanium, Alexander observed a quite different beginning of plastic deformation: the shear stress runs through a maximum $\tau_{uy}$ (upper yield point) and then drops to a minimum $\tau_l$ (lower yield point), the whole stage being exponentially dependent on temperature. As a consequence, germanium is brittle at room temperature, while copper is ductile even at 4 K.

To explore the dislocation mechanisms responsible for that yield range of germanium became a key activity of the semiconductor group which was established at the IfM in the following years.

![Figure 1. Schematic diagram showing dynamic stress-strain curves (τ versus ε), as measured with specimens uniaxially deformed with constant strain rate, for cubic face-centered (fcc) metals like Cu and elemental semiconductors like Ge and Si.](image-url)
Concerning the following deformation stages (see Fig.1), Alexander found astonishing similarities between copper and germanium. For both materials, the start of plastic deformation continues with a stage I of easy glide, followed by a stage II with constant and $T$-independent hardening rate $\Theta_{II} = (d\tau/da)_{II}$, and finally leads to a stage III with decreasing hardening rate. In particular, stage II was – and is still – mysterious. As Alexander’s work showed, $\Theta_{II}/G$ ($G$: shear modulus) has the same value for copper and germanium.

1.2. Dislocation formation and deformation stages in germanium; Venia Legendi

Which dislocation arrangement can produce the same and $T$-independent $\Theta_{II}/G$ in two such different materials? At that time, electron microscopy had become available as a tool to make dislocations visible. However, to apply it, thin foils had to be prepared from the material, in which dislocations were exposed to large image forces towards the foil surface. In copper dislocations are highly mobile at room temperature, they react to the image forces and run out of the foil, if not pinned. As one of the experts in the field said, one observes the laggards of an army. On the other hand, in germanium dislocations are immobile at room temperature. Therefore, in specimens cooled fast after deformation under stress applied to room temperature, the electron microscope should give an image of the army.

![Figure 2. Start to Helmut Alexander's university career (1960). The photo shows him one day after he handed in his thesis to Peter Haasen and on the day of his engagement with Ingeborg Feld, later to become his wife. (The authors want to thank Ingeborg Alexander for kindly giving us this private photo).](image)

Certainly, Helmut Alexander immediately realized the great chance to solve one of the basic problems of metal plasticity, i.e. an interpretation of stage II, by an electron microscopic study of
dislocations in germanium. In 1961 the IfM got an electron microscope, and Helmut Alexander decided to work on “Electron microscopy of frozen-in dislocations” for a postdoctoral thesis (Habilitation). A prerequisite for the realization of such a plan was Peter Haasen’s offer to him to continue as a “wissenschaftlicher Assistent”. It also meant a jump in his private income from zero-payment to a fair salary opening new possibilities also in his private life (see figure 2).

In 1966, he obtained the Habilitation and was awarded by the Faculty of Physics the **Venia Legendi**. From now on he had the right and the duty to teach students.

In 1968, he published the results of his electron microscopic investigations on plastically deformed germanium as two articles (1968 Elektronenmikroskopie eingefrorener Versetzungen **phys. stat. sol.** 26 725; **phys. stat. sol.** 27 391). He showed that the dislocations in fact are frozen-in and neither the preparation of TEM foils nor electron irradiation in the microscope under normal imaging conditions nor image forces acting on the dislocations near to the foil surfaces influence the as-deformed dislocation arrangement.

While Helmut Alexander studied frozen-in dislocation arrangements in Ge, scientists in Stuttgart had applied neutron irradiation to pin dislocations in deformed Cu and to observe their arrangements during work hardening by electron microscopy. From a very thorough investigation, Alexander inferred a distinct similarity of dislocation arrangements in Ge to those observed in Cu for ranges I and II (see Fig. 1). This finding not only confirmed the relevance of the observations, made by Essmann (1963 phys. stat. sol. 3 932; 1965 phys. stat. sol. 12, 707; 723) in Stuttgart for Cu, but also served to arrive at a fundamental insight into work hardening. In their review of 1968, Alexander and Haasen write: “… It is the slip geometry, interaction between slip systems, dislocations reactions, etc., that determine dislocation structure and work hardening during uniaxial deformation, not dislocation mobility, point defect formation, dislocation core structure, etc.. The former are properties of the Bravais lattice only, being the same for fcc and diamond-type crystals; the latter depend on the binding character, crystal unit cell, etc. …”

Furthermore Alexander succeeded in finding the answer to another basic question: are the stages I and II of the deformation curve (see Fig. 1) determined by typical dislocation structures? Varying the deformation temperature from 520°C to 800°C, Alexander generated dislocation patterns that were much more three-dimensional ones with dislocations less fixed to the primary planes than at 520°C. However, the work hardening curve shows the three stages for both temperatures. In their review Alexander and Haasen concluded: “This indicates that there is no typical dislocation structure responsible for the three stages of the stress-strain-curve.”

#### 1.3. A microscopic model on the beginnings of the plasticity in semiconductors; a student group’s work and the Alexander-Haasen theory

Every year at the beginning of the winter period, the IfM offered to students a practical training consisting of ten experiments within two weeks. For students, who wanted to perform a diploma thesis at the IfM, or elected the subject “Metallphysik” for one of the four oral examinations at the end of the thesis, successful participation in that training was obligatory. As an unusual feature, nearly all scientists at the IfM with their equipment were engaged in that training. The capacity was twenty students, but soon there were many more applicants, and a written examination was introduced to obtain a ranking. The students, who had to work intensively during vacation to prepare for the exam and experiments in rapid succession, got as a benefit in return a picture of the research activities of the IfM, and thus the capability to judge the relevance and difficulties of a diploma thesis at the IfM. This combination of student’s practical training with the institute’s cutting-edge research possibly explains, why the IfM, which had in 1959 shifted from the faculty of chemistry to that of physics, was able to successfully compete for students among the renowned institutions of Göttingen physics.

The IfM also had a small local advantage. Its position inside the historical city walls, opposite to a cinema, a student’s theater and restaurant, led the students working at the IfM to move with some part
of their private life to the IfM and to combine e.g. during evening a long-term experiment with the visit of a movie or restaurant.

One of the two first diploma subjects that Peter Haasen allocated in Göttingen was on the plasticity of InSb and thus developed the nucleus of the semiconductor group. As soon as appointed “wissenschaftlicher Assistent”, Helmut Alexander became the leader of this group. While for his post-doctoral thesis he worked on the stages I to III, which were similar in copper and germanium, he directed the research activity of the group towards an understanding of the beginnings of plasticity in germanium. The students began to construct machines for dynamical and static compression, for germanium single crystal growth with low initial dislocation density and low impurity content, methods for oriented polishing of specimens, for the analysis of dislocations by etch-pits, for counting large etch-pit densities using optical and electron microscopy, and for local slip measurements among others. The objective of this work was to model the beginning of plasticity by dislocation properties. One great aim of Helmut Alexander and Peter Haasen was to develop a microscopic theory, based on dislocation (1) multiplication, (2) motion, (3) interaction, and (4) on a statistical model relating microscopic dislocation processes and macroscopic plasticity.

One might follow the progress of the group’s work by looking at its first publications (written in German, the titles given here have been translated):

“Plastic deformation of Ge single crystals” by H. Alexander (1961 Z. Metallkde. 52 344, his doctoral thesis);
“Plastic deformation of Ge and InSb in dynamic compression” by S. Schäfer, H. Alexander, and P. Haasen (1964 phys.stat. sol. 5 247);
“Deformation inhomogeneity of Ge within the yield region” by W. Schröter, H. Alexander, and P. Haasen (1964 phys.stat. sol. 7 983);
“Dislocation density and local slip in Ge single crystals” by K. Berner and H. Alexander (1967 phys. stat. sol. 15 963);
“Measurement of the dislocation velocity in Ge” by S. Schäfer (1967 phys. stat. sol. 19 297).

An independent appreciation of this research from outside came 1967, when Alexander and Haasen were invited to write a review for the prestigious book series “Solid State Physics”, edited by Seitz, Turnbull and Ehrenreich. In their article on “Dislocations and Plastic Flow in the Diamond Structure” (1968 Sol. State Phys. 22 27-158) the authors gave as the essence of all that work a set of mathematical equations, whose solutions showed an astonishing agreement with measured curves of the initial stage for dynamic as well as for static deformation conditions. The Alexander-Haasen theory was born, until today the basic description of semiconductor plasticity. A key to the success of it was a dislocation multiplication law, discovered by Helmut Alexander and his student Klaus Berner.

With this review and the publication of his habilitation thesis also in 1968, Helmut Alexander became an internationally renowned authority in the field of semiconductor plasticity. He continued working on this field when leaving Göttingen for Cologne.

1.4. Electronic states at dislocations in silicon and germanium; first results and move to the “Universität zu Köln”

There is a further research activity that Alexander started in Göttingen and continued with in Cologne, the results of which brought him and his group a high repute in the international community. William B. Shockley from Bell Laboratories, Nobel Prize winner for the discovery of the transistor, had made in 1953 a very interesting conjecture about the electrical activity of dislocations in silicon and germanium (Phys. Rev. 91 228). He argued, that an edge-type dislocation in those materials should have a one-dimensional arrangement of dangling bonds in the dislocation core at the edge of the inserted half-plane (see Fig. 3).
In the electrically neutral state, they should be occupied by one electron and then be half-filled. With the overlap of neighboring dangling bonds a one dimensional metal should be associated with the dislocation core.

Shockley's conjecture was an issue hotly disputed in the semiconductor group, specifically regarding experiments that could prove or disprove it. Under the guidance of Peter Haasen, one of the authors (Schroeter W 1967 *phys. stat. sol.* 21 211) performed a doctoral thesis on the Hall effect of dislocations in p-type germanium. He showed that dislocations with edge-component are associated with electronic states whose occupation follows Shockley's conjecture.

But how to prove the properties of a one-dimensional metal? This was the point of intensive discussions in particular between Helmut Alexander and Reiner Labusch, a young theoretician educated in the school of Friedrich Hund and now working at the IfM. He had made some calculations and found that electron paramagnetic resonance (EPR) could be a promising method.

However, application of EPR to germanium was difficult because a strong spin-lattice coupling and multiple hyperfine interactions broaden all EPR lines in Ge. One could try silicon, but experiments with plastically deformed silicon were rare, one earlier application of EPR to deformed silicon at Bell Laboratories failed. Nevertheless, Helmut Alexander decided that the experiment should be repeated. Pieces of silicon, obtained from industry, were plastically deformed and measured at a neighboring institute, having the facility to measure EPR down to 20K (liquid hydrogen). Wilhelm Sander, the EPR-expert there indeed detected an EPR-line in plastically deformed silicon, but no fine structure, especially relevant for its interpretation, could be resolved. H. Alexander, R. Labusch, and W. Sander published this first evidence in 1965 (*Solid State Commun.* 3 357). At the time it was clear that for the differentiation between a one dimensional metal and a row of localized states, the EPR-experiment and the deformation procedure needed further refinements. To arrive at them became one of the major challenges for Alexander's work in Cologne.

1968 was not only the year, in which Helmut Alexander published two of his most important articles, but also brought him the offer of a full professorship in Cologne.

2. Helmut Alexander in Cologne (1968 – 1997)

When Helmut Alexander came to Cologne to build up the “Abteilung für Metallphysik im II. Physikalischen Institut der Universität zu Köln”, he had to take over the heritage of an already existing “Metallphysik”- group which at that time was part of the Institute of Theoretical Physics. The main subject of prior research in this group was the investigation of magnetic properties and transport

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**Figure 3.** A 60° shuffle dislocation; bold lines indicate the extra half-plane inserted from the bottom.
phenomena of metallic alloys. This field of research was very different from his former activities. Nevertheless, he accepted this challenge and decided to lead both this “Magnetiker”-group and the “Germanisten”-group for all the time until he retired in 1993. He focused his interest in this line of research on magnetism of metallic compounds with a ferromagnetic component, with special respect to the liquid phase. One main result was: The liquid phase of Au-Co is not ferromagnetic, as it was suggested in the literature (Busch G, Guentherodt H J 1968 Phys. Letters 27A 110). Magnetic measurements could be conducted with greater precision than conventional, purely thermal analysis, and allowed corrections to phase diagrams, as well as the study of properties of alloys at high temperature, such as precipitation kinetics.

2.1. Electron microscopy and dislocation velocity
In 1968, in Helmut Alexander’s new lab in Cologne existed a modern TEM (Siemens Elmiskop IA) facility and a small TEM group consisting of four doctoral students. Soon he continued to investigate the early stages of deformation. The search for dislocation sources by TEM and Lang topography was successful. More and more the activities changed from Ge to Si, being a material better suited to EPR measurements.

When Ray and Cockayne (Ray I L F and Cockayne D J H 1970 Phil. Mag. 22 853; 1971 Proc. Roy. Soc. A325 543) published the results of their newly developed TEM weak beam technique applied to silicon a fundamental change of dislocation models and theory occurred. Nearly all the dislocations appeared to be dissociated into partial dislocations with a stacking fault ribbon between them. This result was revolutionary as it decided the discussions whether the dislocations were glide or shuffle set ones - until then with a clear tendency to prefer the shuffle set model.

The weak beam technique was applied to III-V compounds to measure the splitting width of dislocations and to calculate the stacking fault energies. Alexander suggested a correlation of the “reduced stacking fault energies $\gamma'$” with the ionicities $f_i$ of the compounds where $\gamma'$ is the stacking fault energy referred to the specific area per atom in the {111}-plane. In a plot of $\gamma'$ vs $f_i$ the values for six III-V compounds fall on a single line. (Fig. 4) (Gottschalk H, Patzer G and Alexander H 1978 phys. stat.sol. (a) 45 207; Fig. 5, p. 216: Copyright Wiley-VCH Verlag GmbH & Co. KGaA, reproduced with permission). A stacking fault represents a plane of hcp-type stacking inserted into the cubic sphalerite lattice. Thus, decreasing stacking fault energies in the cubic lattice point to an increasing preference of the hexagonal structure. Indeed, compound semiconductors with ionicities larger than the cross-over point found in Fig. 4 near $f_i = 0.47$, such as most of the III-nitride compounds and alloys, preferentially crystallize in the wurtzite structure, showing the relevance of the findings summarized in Fig. 4.

![Figure 4. Reduced stacking fault energy $\gamma'$ vs the iconicity $f_i$ of III-V compounds.](image-url)
One of the milestones of the early Cologne years was the development of a deformation mode to generate long straight dislocation segments of well defined types (Wessel K and Alexander H 1977 *Phil. Mag.* 35 1523). A Si specimen with the standard stress axis [213] was predeformed at high temperature (750°C) to introduce dislocations, then cooled to 420°C to be deformed for a second time under high stress and finally cooled to room temperature under the full stress applied. As a result the dislocations became aligned straight along the <110>-directions so that three types of dislocations appeared: two kinds of 60°-dislocations, one with a 30° partial moving in front and a 90° partial trailing (30/90) and another one with the 90° partial moving in front followed by the 30° partial (90/30), and screw dislocations (30/30) (Fig. 5). Additionally, a very surprising result was obtained: the measured dissociation widths of the three dislocation types differed significantly from their equilibrium widths measured in annealed specimens.

The evidence for the glide set dislocation model led to the assumption that dislocations move in their split state. Consequently, the mobility of a dislocation should be composed of the mobilities of both partials. From measurements of the splitting widths of the three dislocation types ratios of the mobilities were derived and it was found that a unique velocity e.g. for 60° dislocations does not exist. Instead, different mobilities are expected for 30/90 and 90/30 dislocations. A particularity is the behavior of screw dislocations (30/30) with a strongly reduced mobility of the trailing 30° partial. The reason is not fully understood but there are indications for EPR active centers sited on the partial.

An important step forward for this research was achieved when a new TEM microscope was installed (Philips EM 400T) in 1980. At 120 keV much brighter images could be obtained so that the use of the weak beam technique became much easier.

Dislocations in Si at 420°C move very slowly. Though there is indeed some plastic deformation the material behaves on a macroscopic scale like a brittle one and, consequently, a lot of specimens were broken. The fraction of good high stress specimens grew significantly after the heated pistons in the testing machine formerly made of stainless steel were replaced by quartz glass ones with an ingenious device allowing to perfectly align the two opposing surfaces of the pistons (Küsters K H and Alexander H 1983 *Physica B+C* 116 594).

**Figure 5.** Dislocations in Si after high stress deformation. PQ = 30/30; PK = 90/30; PU = 30/90 (see text).
High-stress deformed specimens with a population of only three types of straight dislocation have been very interesting for a lot of investigations using very different measuring methods. The idea was to ascribe special properties to the different dislocation types. For a while Alexander’s lab was worldwide the only one to produce uniaxial high-stress deformed specimens of Si. Helmut Alexander, always open to cooperation, willingly gave specimens to other research groups all over the world.

One of the continuing threads in Helmut Alexander’s scientific life had always been the mobility of dislocations. Therefore, beside the microscopic investigations precise macroscopic measurements of dislocation velocities in high stress/low temperature deformed Si were performed by etch pitting (Alexander H, Kisielowski-Kemmerich C, Swalski A T 1987 *phys. stat. sol. (a)* **104** 183). The fact that dislocations at the surfaces bend when the specimen is deformed for a second time was considered. These measurements showed the difference of the velocities of the two 60° dislocations (30/90 and 90/30).

The influence of light on dislocation mobility, the photoplastic effect, was also investigated using the etch pit method (Küsters and Alexander 1983; see above). The surprising result that only the 30/90 and not the 90/30 dislocation is affected by illumination, was further evidence for the special role of the trailing 30° partial.

Figure 6. Anomalously wide dissociated dislocations in high stress/low temperature deformed Si. Uniaxial stress was applied along <2 1 11> a) $g = (022)$; the partial dislocations in the “main” glide plane are visible. b) $g = (-1 -1 1)$; the stacking faults in the “main” glide plane appear with a dark contrast.

If the stress axis is parallel to <2 1 11>, the forces acting on the partials are directed so as to separate the partials more and more. Thus large stacking faults are generated, mainly at screw dislocations. Such anomalously wide split dislocations are in an extreme non-equilibrium state. The stacking fault tries to pull back the partials. Relaxation experiments by heating in the microscope gave some interesting results (Alexander H, Eppenstein H, Gottschalk H and Wendler S 1979 *J. Mic.* **118** 13; Fig. 6). Surprisingly, not all screw dislocations were extremely widened (left part of fig. 6a).

Helmut Alexander was not only interested in conventional TEM available in his Cologne institute but also in HREM applications. Therefore, he left Cologne in 1985 for a four months stay as a guest scientist at the Department of Physics of the Arizona State University, Tempe, Az., USA. The subject of his research was HREM lattice imaging of split dislocations in Si (Alexander H, Spence J C H, Shindo D, Gottschalk H and Long N 1986 *Phil. Mag. A* **53** 627). John Spence continued this line of
research after Helmut Alexander returned to Cologne, and it culminated with an important joint paper (Kolar H R, Spence J C H and Alexander H 1996 Phys. Rev. Lett. 77 4031) in which the activation energy for dislocation motion could be distinguished into the kink formation and migration energies. The results were obtained on widely split dislocations by HREM in situ relaxation experiments at 600°C and at 130°C.

The result $W_m = 1.24$ eV is in accordance with earlier relaxation experiments performed in Cologne using the conventional TEM with a heating stage at 100°C to 140°C. From the measured displacement changes of the partials the kink migration energy $W_m$ was estimated to be $1.0 - 1.2$ eV (Gottschalk H, Alexander H and Dietz V 1987 Inst. Phys. Conf. Ser. No 87 Sect. 5 339).

Some years later Helmut Alexander saw a chance to measure dislocation velocities in Si on a microscopic scale using a new technique. Dislocations in high temperature deformed and annealed specimens contain mainly edge dislocations which are fairly straight. The dislocations are not split continuously on their whole length. Many constrictions occur which could be correlated to jogs (Tillmann J 1976 Diploma Thesis Univ. Köln; Farber B Ya and Gottschalk H 1991 Springer Proceedings in Physics 54 Polycrystalline Semiconductors II 242; Fig. 7). At low temperatures, for Si about 400°C, jogs act as strong obstacles against the dislocation motion (Fig. 8). The distances the dislocations had moved between the jogs in a subsequent high stress deformation at this low temperature were measured. The jogs marked the starting positions of the dislocation segments (Fig.8). (Gottschalk H, Hiller N, Sauerland S, Specht P, Alexander H 1993 phys. stat. sol. (a) 138 547; p. 548, Figs. 1 and 2: Copyright Wiley-VCH Verlag GmbH & Co. KGaA, reproduced with permission).

![Figure 7. 60°-dislocation dipole in Si (TEM Weak Beam), top: Plane view on the glide plane: constrictions c; bottom: same area; dislocation viewed parallel to the glide plane: jog pairs j. The dislocation segments between the jog pairs are split.](image-url)
Figure 8. Free segments of near edge dislocations have moved while jogs (the constrictions) are still lying along a smooth line representing the former course of the dislocation (dashed line). Deformation parameters: \( T = 370^\circ\) C, \( \tau = 50\) MPa, \( t = 300\) s (top); \( T = 420^\circ\) C, \( \tau = 200\) MPa, \( t = 600\) s (bottom).

In 1985 the scientific equipment in Cologne was completed by a new scanning electron microscope, equipped with an EDX device (energy dispersive X-ray spectroscopy). This microscope added significant possibilities to characterize materials by imaging of electron induced physical effects. Besides SEM, equipment for the measurement of electron beam induced current, light beam induced current, scanning deep level transient spectroscopy and cathodoluminescence was built up.

That time marked an important step in Helmut Alexander’s life. Previously he had been a man of pure science, who strictly rejected collaboration with industrial institutes. But when he was asked to collaborate with a group of researchers of eight universities and some solar Si and solar cell producers to help to enhance the efficiency of multicrystalline Si solar cells he was enthusiastic. The ecological aspects of this “DIXSI” project convinced him so much that these activities moved to the center of his scientific interests for the last ten years of his scientific career. The experimental equipment available in his lab was well suited to examine these less pure Si wafers with respect to dislocations, grain boundaries and precipitates. Beside the raw material, fully processed solar cells were made available in this project to measure and to image by SEM methods the electrical properties of defects limiting the cell efficiency.

Helmut Alexander was so much engaged in this project that he developed a model of dislocation generation during the solidification of a cast Si block, which, unfortunately, remained unpublished.

A large part in Helmut Alexander’s career is characterized by teaching. He took this task very seriously and it is not exaggerating to call him an exemplary teacher. After having retired, his passion for teaching made him write a textbook on electron microscopy “Physikalische Grundlagen der Elektronenmikroskopie” (Physical Fundamentals of Electron Microscopy), which was published in 1997 (Teubner, Stuttgart). With this book one of his dreams came true.

2.2. Electron Paramagnetic Resonance and other electrical and optical investigations

After arriving in Cologne, Helmut Alexander decided to continue the study of dislocation structures in Si by EPR that had led to the very promising first results described in section 1.4. Wilhelm Sander had accepted around the time of Alexander’s change to Cologne a chair in the Physics Department of the
“Rheinisch-Westfälische Technische Hochschule Aachen”, where he established a modern EPR facility. With Aachen located 70 km from Cologne it was possible to establish a close cooperation. Udo Schmidt, who had started with a Diploma thesis in magnetism, but decided to change topics to investigate the EPR signals of dislocations in silicon, shuttled regularly between Cologne and Aachen to perform EPR measurements in the laboratory of W. Sander with samples prepared in Cologne. In 1970, one of the present authors (ERW) joined this line of research as a graduate student.

The analysis of the EPR signal introduced in silicon by plastic deformation made rapid progress with the sensitive instrumentation available in the Aachen lab, using well-controlled samples uniquely prepared with the dedicated instrumentation in Cologne. A key factor was the availability of low-temperature EPR measurements, generally using liquid hydrogen, an old Göttingen tradition, and for measurements below 20K a quite cumbersome liquid helium evaporation cryostat. A delicate fine structure of the EPR signal of plastically deformed Si was revealed and distinguished into lines near $g = 2.00$ denoted as Si-K1 (K for Köln, i.e. Cologne in German) and a complex set of lines appearing pairwise on both sides of the central spectrum denoted Si-K2. Udo Schmidt and ERW succeeded in determining the $g$-tensors and fine structure tensors of these spectra by analyzing the complex angular dependence upon rotation of the sample in the magnetic field at cryogenic temperature. The $g$-tensors revealed two lines with $S = \frac{1}{2}$ for each glide system, related to the glide systems of the plastic deformation geometry used to introduce the dislocations.

The fine structure tensor of Si-K2 proved to be aligned along the Burgers vector of the primary glide system (Schmidt U, Weber E, Alexander H, and Sander W 1974 Solid State Commun. 14 735) and could be interpreted either as $S = 1$ spectra in a multitude of crystal fields, or as sets of spectra with larger spin, ranging from $S = 1$ to $S = 3$ (Bartelsen L 1977 phys. stat. sol. (b) 81 471). The $g$-tensor of Si-K2, and of the Si-Y-line, were found to be orthorhombic with $C_{2v}$ symmetry, where the axis with the $g$-value closest to the free electron value lay along a $<110>$ direction perpendicular to the (total) Burgers vector of the respective slip system. The hyperfine structure of Si-K1 identified this defect as a typical dangling bond defect with an orbital inclined $22^\circ$ from a $<111>$ bond axis (Weber E and Alexander H J. de Physique 1979 40-C6, 101). These findings were strong evidence that the paramagnetic centers are located in screw dislocations, were the dislocation line even of the partials runs along the total Burgers vector of the dislocation.

To interpret these findings it is necessary to consider a realistic picture of the geometry of dislocations split into partials. Alexander prepared a now-famous sketch of the possible dangling bond geometries in a dissociated $60^\circ$ glide-set dislocation, containing a $30^\circ$ and a $90^\circ$ partial, see Fig. 9.
Figure 9: Dangling bonds in a dissociated 60° glide set dislocation. A stacking fault ribbon is bound by the two partials: on the left side the 30° partial, on the right side the 90° partial. (Partials are shown unreconstructed).

A more detailed analysis of the complex g-tensor geometries pointed to a vacancy in the core of a 30° partial of a screw dislocation as the most likely site of the unpaired electrons of Si-K1, and possibly the spins creating the Y-line (Kisielowski-Kemmerich C 1990 phys. stat. sol. 161 11). Si-K2 in this model could be caused by rows of such defects along the screw dislocation line direction, but this assignment still awaits further confirmation, especially by theory. Recent calculations (Lehto and Öberg 1997 *Phys. Rev.* B56 R 12706 and Csanyi G, Ismail-Beigi S and Arias T A 1998 *Phys. Rev. Lett.* 80 3984) are at variance with the Kisielowski-Kemmerich model.

Upon increasing the measurement temperature above 50K new lines appeared that were identified as three distinguishable spectra labeled Si-K3, K4 and K5 (Alexander H, Kenn M, Nordhofen B, and Weber E 1975 *Inst. Phys. Conf. Ser.* 23 433). The most intriguing finding was that the g-tensors of those spectra showed no relation to the deformation slip systems. A comparison of spectra obtained from samples deformed along <213>, *i.e.* with a primary glide system, and <110> where glide in four glide systems is preferred, clearly reveals this distinction (see Fig. 10): whereas the spectra taken at high temperatures (Si-K3, K4 and K5) are identical for both deformation conditions, those taken at low temperature (Si-K1) are quite different (Weber E and Alexander H *J. de Physique* 1979 40-C6, 101).

This finding allowed a very important conclusion: whereas the EPR spectra Si-K1 and Si-K2 are clearly related to the dislocation types present in the sample, Si-K3 to Si-K5 obviously were formed by defects introduced by deformation but left over far away from the dislocation core, interpreted as deformation-induced point defect clusters that are left as a debris from the dislocation motion.
Figure 10. Comparison of EPR spectra of plastically deformed silicon obtained at 31K and 145K for magnetic field along [1 1 -1], using samples prepared with different uniaxial deformation geometries.

All EPR spectra come from dangling-bond type defects, no evidence for one-dimensional conduction along the dislocation line as hypothesized by Shockley was ever found by the Alexander group. A very important finding was obtained by R. Erdmann: Light can transform spectrum Si-K1 into the Si-K2 spectrum of the same glide system (Erdmann R and Alexander H 1979 Phys. stat. sol. (a) 55 251).

Having achieved the differentiation between clearly dislocation-related defects and defects in point-defect clusters produced as debris of dislocation motion a very important issue was the question of the concentration of dislocation-related paramagnetic defects:

The quantitative analysis of the EPR spin density yielded a very low density of well-defined paramagnetic sites, corresponding to one atomic site in a hundred or more along the dislocation line. This allowed to suggest another major conclusion: that dislocation cores in silicon should be predominantly reconstructed, avoiding those rows of dangling bonds depicted in Figs. 3 and 9. Ossip’yan and his coworkers in Chernogolovka as well as Suezawa et al. in Sendai, Japan, pointed out that in addition to the Si-K1 to K5 spectra plastic deformation of silicon introduces a broad line called the ‘Y-line’ (Suezawa M, Sumino K, and Iwaizumi M 1981 Inst. Phys. Conf. Ser. 59 407) that remains upon thermal annealing of the samples in the 600-800°C range when Si-K1 to K5 disappear. However, even when taking into account the spin density of this line the above conclusion holds. Later, theoretical calculations by Bob Jones and his group confirmed this suggestion: perfect dislocations in silicon should show little electrical activity. Lightowlers and Higgs later pointed out that electrical activity (or at least photoluminescence) of dislocations in silicon is dominated by residual metal contamination that is almost unavoidably introduced during high-temperature treatment (Lightowlers E C, V. Higgs V, 1993 phys. stat. sol. (a) 138 665-672) and the latest speculation is that the Si-K1,K2 EPR lines, too, are related to point defect clusters at or near dislocations (Blumenau A T, R. Jones R, Öberg S, et al. 2001 Phys. Rev. Lett. 87 187404).

A wide body of literature exists on detailed analysis of the deep energy levels introduced by plastic deformation, to which the Alexander group contributed as well, summarized together with important results on the dislocation structure in a series of excellent reviews by Alexander, see below.
In conclusion, Helmut Alexander made a significant impact in our understanding of dislocations and plasticity in covalent semiconductors. Many modern technological developments profited from the understanding derived by the Alexander group in Göttingen and Cologne, such as the possibility to produce inexpensive solar cells out of silicon with high metal content, and the development of high-efficiency light emitting diodes and lasers in the lattice-mismatched thin film structures of III-nitrides with high dislocation densities. Therefore it is fitting that the International Advisory Board of the EDS conference series decided to dedicate a best-poster award given in his name at each conference to a young scientist in this field.

![Helmut Alexander 1993.](image)

More than 120 scientists including the authors of this article were acquainted thoroughly with Helmut Alexander as their academic teacher since the years of their graduate studies. We all appreciated his willingness to discuss actual scientific problems in depth at almost any time and we are grateful for the fruitful cooperation over many years. He will be alive in science by the inheritance of his scientific life – by his numerous publications and by these important reviews:

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