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Remembering Ulrich Gösele

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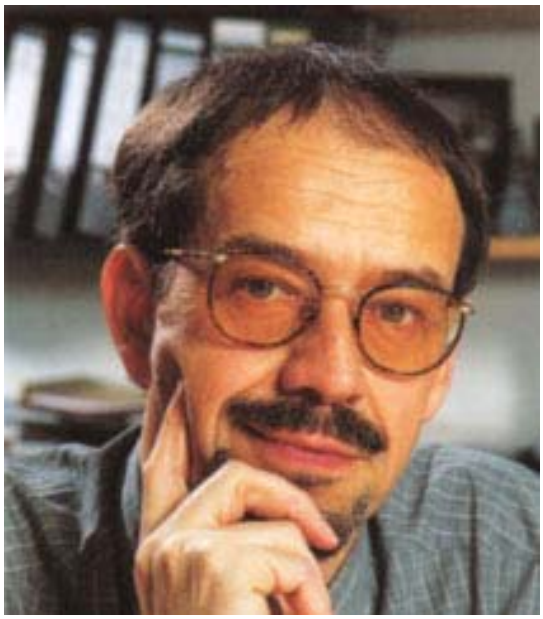


Prof. Dr. Ulrich M. Gösele died unexpectedly and far too early in Nov. 2009. He would certainly have participated in several sessions of this meeting; his untimely death deprived us of that pleasure. Prof. Ulrich Gösele was an outstanding scientist with a distinguished record in many fields, including porous semiconductor science and technology. In this contribution for "Pits and Pores" a personal account of his life is given, based not only on scientific collaboration but also on a longstanding friendship. He will be remembered not only for his outstanding contributions to science but also as a reliable and witty friend and a highly motivating mentor.

Introduction

Two years ago, during the 214th meeting of the ECS in Honolulu, Prof. Dr. Ulrich M. Gösele and I opened the "pits and pores" session" by paying tribute to our late and lamented friend Volker Lehmann, who died a tragic death in May 2006. Two years later I'm charged with commemorating my good friend Ulrich Gösele, who died almost a year ago on November 8th, 2009, in Halle, Germany. He was basically in good health and his totally unexpected death came as a shock to his three children, his extensive staff at the Max-Planck-Institute for Microstructure Physics, and his many friends and colleagues all

over the world. Just a few months earlier, in May 2009, he had celebrated his 60th birthday with an impressive international gathering of scientists and friends.

Ulrich Gösele was one of my closest friends; I have known him more than forty years. We have shared far more than just some scientific endeavors. In this paper I will give a personal overview of his life and scientific work, highlighting a few aspects of his personality, his way of doing research, his triumphs and disappointments. For a more detailed appraisal of his scientific contributions see also [1].

The Stuttgart Years

Ulrich Gösele was born on January 25th, 1949, in Stuttgart, Germany. He studied physics at the University of Stuttgart with an interlude at the Technical University Berlin and obtained his diploma in 1973. He did his doctoral work at the University of Stuttgart in conjunction with the Max-Planck-Institute (MPI) for Metals Research, where he stayed as a scientific staff member until 1984. He started as a theoretician, working on topics like diffusion-controlled reaction kinetics, radiation damage in metals, and transfer of electronic excitation energy in liquids and solids. Already in his earliest work he liked to be in the avant-garde – he used "the" one-and-only computer of the university for newfangled things like Monte Carlo simulations. This involved hauling heavy boxes of punch cards to the computer building, where a huge machine with a computing power that would have been put to shame by a present-day wrist watch would churn away at kilohertz clock rates.

I met Ulrich Gösele in 1969 and had the privilege of being his very good friend ever since. I profited right away then from his generous manner. He was always ahead of more dim-witted students like me but was not aloof and helped us with the more difficult subjects like quantum mechanics. We became really close when both of us commenced research for our diploma thesis, and subsequent PhD work, at the Max-Planck-Institute (MPI) for Metals Research in Stuttgart under the guidance of Prof. Seeger and (in my case) Prof. Wilkens. Our interaction in science then, and on various occasions later, was typically brief, but with far-reaching consequences.

1975 was a decisive year for Ulrich because I motivated or rather bullied him (as he called it) into working with B.O. Kolbesen and me on the topic of so-called swirl defects in silicon. We had just discovered that these agglomerates of native defects in large Si crystals were of interstitial type. This was contrary to the generally accepted dogma that intrinsic point defects in equilibrium at high temperatures must always be vacancies. We then proclaimed the new paradigm that self-interstitials and not vacancies would be the dominating intrinsic point defects in Si, giving substance to the heretical and ridiculed viewpoint, first suggested by our mentor Alfred Seeger together with K.P. Chik, that diffusion in Si involved self-interstitials.

We needed a theoretician to better understand our experimental findings, and my prodding did succeed in turning Ulrich Gösele towards the general field of defects and diffusion in semiconductors. Our first common paper [2] contained a first theory about the formation of these so-called swirl defects. While things turned out to be more complicated than envisioned then, interstitials in Si (and by now also in other semiconductors), as well as interstitial based diffusion, are now textbook topics, despite strong opposition from the orthodox in the beginning. We had (one is tempted to say: of course) many and sometimes quite frustrating battles with referees, and exchanged many letters (e-mail hadn't been invented yet), discussing the best ways to convince the referees and colleagues of what to us was obvious. Ulrich Gösele, sticking to this topic and his guns for

the rest of his life, eventually emerged successfully and became one of the leading authorities in the large field of defects and diffusion in semiconductors.

Figure 1 Ulrich Gösele receiving his PhD degree in 1975. Note the German-style “doctor-hat”.

Post-Doc Experience

Two one-year stays abroad interrupted his work at the MPI for Metals Research in Stuttgart. In Oct. 1976 he joined the Physical Metallurgy Division of the Atomic Energy Board in South Africa, where he acted as the temporary head of a research group that had close ties to Stuttgart. This became necessary because the previous director had lost his life in an airplane crash. Ulrich Gösele went there on short notice, taking his newly wed wife and his first child Andrea, a less than 2-year-old toddler, along. This incident, long past and now rather unimportant, nevertheless highlights one of Uli Gösele’s special character traits quite well: he felt a deep responsibility towards society and in particular towards fellow scientists. He was struggling to support his young wife, who was still finishing her own education, to be a good father to his daughter, and to work towards a career in science, and thus had no personal desire to go to South Africa with his family. However, he acknowledged that he was in a position where he could do a necessary and important job, and neither then nor later subscribed to the attitude “let somebody else do it”. He rather accepted some personal hardship as the price to pay for living up to his own work ethics.

In South Africa and back in Stuttgart he had to focus on metals research but was keen to resume semiconductor work again. He now wanted to find a place for a sabbatical where he could apply his substantial background on diffusion and diffusion mechanisms to suitable semiconductor challenges, and finally succeeded to join the IBM Watson Research Laboratories in Yorktown Heights, New York, USA, around May 1980. He could afford the expense of moving there with his family, because in 1977 he had been awarded the Otto-Hahn Medal of the Max-Planck Society (MPG) for outstanding scientific achievements, and that award came with funds specifically ear-marked for traveling abroad. He came to Yorktown Heights just when I left IBM there for Siemens in Germany, and we were in close contact via writing letters once more in preparation of his move. He took over my apartment and my car and worked in the same group that I just had left.

Figure 2 Ulrich Gösele, holding his daughter Andrea, with his wife Julia and his son Michael (in the perambulator) during my farewell party 1980 in Yorktown Heights.

Once more, he looked into research topics for which I had produced some new experimental results. This time the major concern was silicide formation. I had just produced what I fondly believe were the first high-resolution TEM pictures of hetero-interfaces like Si – PdSi, and a lot of explaining was needed. He also worked on some more general issues of defects in Si. In Yorktown Heights I had closely worked with Teh Tan (now a Professor at Duke University) and introduced Ulrich to him. The two of them not only became close friends for life, but also generated more than 125 papers concerning defects and diffusion in semiconductors, including seminal work on the oxygen precipitation in Si crystals.

Working with the scientists at Yorktown Heights broadened and strengthened not only Ulrich Gösele's background in semiconductor science and technology, but also his

appreciation of experimental work including transmission electron microscopy (TEM). While still a very good theoretician at heart, he had by now developed a deep understanding and appreciation of experimental work that made him a much sought-after partner for experimentalists. Since he had an exceptionally open mind and accepted only pure logic as the limit to invigorating and challenging speculations, he could interpret their findings within the accepted theoretical framework or alternatively within new and non-canonical models. Since he also was a good listener, it goes without saying that he attracted all kinds of scientists in need of a "sparring partner" for critical discussions of their ideas.

After he went back to Stuttgart he obtained his "Habilitation", a kind of extended second doctorate needed as a qualification for a university professorship in Germany. That was not without all the typical complications well known to interdisciplinary scientists – they find themselves caught in the middle. Ulrich found himself between a rock and a hard place for a while. The theoreticians didn't accept his thesis as proper theory, while the experimentalists could not find enough experiments in it.

Figure 3 Ulrich Gösele and Teh Tan at some MRS meeting in the late 80ties.

Siemens and Duke University

Around 1984, the confines of the MPI for Metals Research became too narrow for Ulrich since his main interest was now semiconductors. The Institute demanded that he should pursue "basic" research topics in metals (like the nature of radiation induced interstitials in fcc metals at low temperatures) and stop his (successful) work on what was perceived as "applied" research in semiconductors (like figuring out the kick-out mechanisms for Au diffusion Si). He couldn't accept this arbitrary distinction between "basic" and "applied" research that in Germany also served (and in the mind of some still serves) to discriminate between morally good and morally questionable science, and looked for a way out. Based on his acute sense for "practical" science (expressed also, for example, in early publications about rather technical and practical issues in building acoustics) and

his extensive and well-known background in semiconductor science and technology, Siemens Corporation in Munich, Germany, hired him as a research engineer for developing power devices, and he joined the R&D branch in München-Perlach.

Figure 4 The piece of art that started the U. Gösele – V. Lehmann cooperation, entitled: "Goethe und die Theoretische Elektrotechnik" (Goethe and the theory of electrical engineering) by Volker Lehmann, 1983. 80 cm x 80 cm; metal foil from the tops of wine bottles over wood relief. For details see [3].

As it happened, I had been working for Siemens in the same general department in München-Perlach for a few years by then, so we met again and had a splendid time together, interacting socially and scientifically. We even obtained a patent together and, most important for porous semiconductor research, Ulrich Gösele met Volker Lehmann, who had been working in my group since 1982, while pursuing his diploma in electrical engineering and after that a PhD in physics. Ulrich was intrigued by the remarkable piece of art he saw in my house (now in my office in Kiel) shown in Fig. 4, and that lead him straight to the artist: Volker Lehmann. Volker was my good friend by then, letting me have or buy some of his artwork [3].

He thus got to know my small group at Siemens that was pursuing the electrochemistry of Si "on the side", including first attempts at pore etching. He also was introduced to Si technology, and in particular to processing requirements specific to power-devices. The idea of bonding wafers as a new process to circumvent grave technological problems with very deep diffusions was born during this time. We had many discussions about that topic since I actually had succeeded in "bonding" Si pieces a few years earlier, with the goal of producing defined grain boundaries [4], and Ulrich was intrigued by the complex interface structures that were produced in this way.

Ulrich Gösele stayed in Munich for just one year. Then his previous relations with Duke University, North Carolina, USA, finally bore fruit: he was offered a full Professorship in Materials Science. Since he preferred independent research to a career in a company that ultimately would always tend to move him from research towards management, he accepted the offer and moved with his family to the USA.

Figure 5 Ulrich Gösele with his third child Bettina in Durham, North Carolina in 1988.

At Duke University he resumed work concerning defects and diffusion, including "nano" issues, but also started two new research areas that were partially based on his experience at Siemens. The first one was wafer bonding, for which he established a viable process outside of an expensive clean room, actually with the help of "post-docs" from Siemens, including V. Lehmann. The second area was electrochemistry of Si, including pore etching. He was acutely aware of the potential of this field that had already sprouted practical applications like the "ELYMAT" [5], but also a growing number of challenges to interdisciplinary scientists like the formation mechanisms of various pore structures. The decisive step was to induce V. Lehmann to join him for a year as a post-doc in 1989.

As far as porous semiconductors are concerned, his 1991 paper "Porous Silicon Formation – a Quantum Wire Effect" that he published together with V. Lehmann [6] is still his best-known paper; it has been cited more than 1,000 times. This paper, like several other ones with revolutionary ideas from him, was originally turned down by the referees ("zero out of 100 points, strongly oppose publication") but nonetheless, together with an independent famous paper to this topic by L. Canham [7], triggered thousands of papers in the general area of porous semiconductors.

V. Lehmann became a good friend of Ulrich Gösele and their cooperation lasted until the tragic death of Volker in 2006. The events around the publication of this paper are recounted in his own words in our last common paper eulogizing V. Lehmann [3]. This paper also recounts a long and for Ulrich Gösele not altogether savory story around a patent that went with it. Suffice it to say that Ulrich Gösele learned that while you can't win against large government organizations quantitatively, because this quickly turns into a contest of who has more money, you can beat them with quality - by doing superior research.

Director of a Max-Planck-Institute

In 1991, the Max-Planck-Society (MPG), the top basic research organization in Germany, offered Ulrich Gösele a position as one of the two directors for the newly founded Max-Planck-Institute for Microstructure Physics in Halle. Directors of Max-Planck-Institutes occupy the upper echelons in the German science establishment, and the offer was therefore a flattering recognition of his ability and achievements. However, it also posed a considerable dilemma.

After the reunification of Germany on October 3rd, 1990, the Institute of Solid State Physics and Electron Microscopy of Prof. Heinz Bethge in Halle, one of the few world-renowned research organizations in former socialist East Germany, was deemed to be an appropriate corner stone for one of the new Max-Planck Institutes planned for the new States of reunified Germany. The offer to succeed Heinz Bethge and to build up a Max-Planck-Institute honored not only Ulrich Göseles's scientific achievements, which were well known by now, but also recognized his ability to do outstanding work with experimentalists: the position was actually for the head of an experimental department. Ulrich Gösele, still well versed in theory, was finally accepted as an interdisciplinary scientist.

Ulrich Gösele now had to make a very difficult decision between two equally attractive (or unattractive, as the case may be) positions – that was the dilemma. He, and in particular his family that included by now three children, were deeply entrenched and at home in North Carolina, and his career potential at Duke University was as promising as it could be in the American scientific system. On the other hand, as the head of a MPG Institute, he would have complete freedom to do only the research he wanted to do, unencumbered by all the other duties demanded at universities. Moreover, he would be in complete control of a sizeable permanent staff, and – for American standards – extremely good permanent funding. The city of Halle, unfortunately, was situated in one of the most run-down and dreary areas of the former East Germany, and the quality of life in these surroundings was not high in 1991. His family abhorred the idea of settling down there and Ulrich Gösele was faced with a difficult choice. We discussed the pro's and con's a lot, and I know that the fact that he finally accepted the offer is at least partly due to his aforementioned ethics and his acute sense of responsibility for science and scientists. He strongly felt that the West had a moral obligation to help the East, and that one could not shrug off one's own duty in this matter if called upon and defer it to "somebody else".

His family moved to Halle with him but did not feel welcome and at home. Some nasty experiences of his children, who met with general hostility toward "foreigners", finally triggered a separation – his wife and his children moved back to the USA. While this was not a happy situation for all concerned, Ulrich Gösele never failed to support this family - not only from afar but by frequently visiting them in North Carolina, while at the same time keeping up relations with colleagues from Duke University.

Accepting the offer meant transforming a rather run-down place to a cutting-edge research institution. Even more challenging, it meant having to identify able but generally rather frustrated scientists and staff among the far too many employees left over from the socialist past, integrating as many of them as possible into the new institute, and instilling into them a new sense of pride and motivation. Many West Germans faced similar assignments in the years after reunification in all branches of society, and far too often many East Germans felt estranged and unappreciated as a result. Not so in Ulrich Gösele's department „Experimental Physics II" in Halle. His group soon prospered and grew; all indicators for success in doing first-rate science were met with flying colors as the years passed by.

The Scientist Ulrich Gösele

As a scientist Ulrich Gösele made lasting contributions in many areas. During his career he published more than 750 articles in refereed journals, and a similar number of conference papers. His papers have been cited collectively more than 20,000 times, leading to an *h*-factor of 67, which is impressively high in the field of solid state physics and semiconductor physics. The long list of his research interests includes topics like theory of point defects and diffusion processes in silicon and other semiconductors; defect formation during crystal growth or during device processing and implications on the electronic quality of the materials; quantum effects in porous silicon; science and technology of semiconductor wafer bonding; self-limited fabrication of nanostructures; quantum dots and quantum wires, atomic layer deposition (ALD); ferroelectric thin films, photonic crystals and silicon photonics. A few key topics are highlighted in what follows.

Diffusion and defects in semiconductors remained one of the pillars of Ulrich Gösele's work, and he not only introduced new diffusion mechanisms in Si, but also in III-V compounds. As mentioned before, the new diffusion models he pioneered, while hotly opposed during their conception and leading to many battles with referees, have now become textbook topics.

Ulrich Gösele was particularly well known and quite famous for his two seminal books on Semiconductor Wafer Bonding Science and Technology by Q.Y. Tong and U. Gösele, and by M. Alexe and U. Gösele [8, 9]. These two monographs together with the Proceedings of the ECS Wafer Bonding Symposia establish the standard reference today in this field.

In his later years he started work on nanowires, nanotubes and nanodots, mostly in the field of semiconductors - an endeavor that, needless to say, received almost instantaneous international recognition.

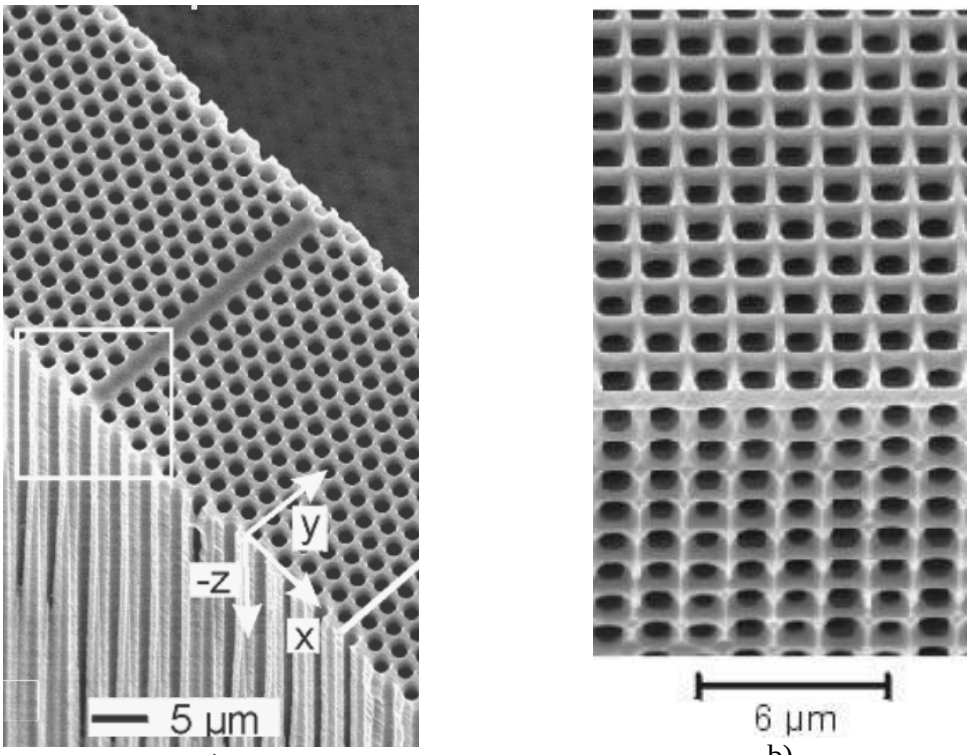
Within his large department he always maintained and encouraged strong groups that pursued interests that were not necessarily in his own personal focus, but that he deemed important. Foremost to mention is transmission electron microscopy (TEM), in which he made sure that Halle maintained the strong international position that it had enjoyed in the days of Heinz Bethge. Equally strong, and always nursed along and invigorated by Ulrich Gösele, were topics like functional oxides and interfaces.

The welfare of his East German fellow scientists and of the local environment was always important to him. He therefore encouraged or started suitable research endeavors and joint ventures that served local needs (such as the fledgling solar industry) in his general area. This did not always meet with the approval of some of his peers, who felt that anything that smacked of applied science or technology was beneath a Max-Planck Institute. Ulrich Gösele, however, did not shy away from applied science because, as pointed out above, he had learned early on in his career that supposedly applied research, such as

diffusion in silicon, quite often leads to very deep basic science questions that none of the orthodox could have come up (no to mention answer) by pure thought alone. In contrast, much of the “basic science” topics concerning, e.g., the precise nature of radiation-induced interstitials in metals that haunted his last years in Stuttgart, are almost completely forgotten by now. The quite successful research and development work on solar cell technology that he encouraged and pursued also bears witness to this.

As a fringe benefit of his widespread activities in many areas, his group grew to a size of about 100 people including doctoral students from all over the globe; most of them supported by third-party funding. That this was in no way detrimental to the quality of the research done under his direction is evidenced by the high percentage of publications in top journals, a record that compares rather favorably with that of more orthodox colleagues.

Considering research into porous semiconductors in Halle, he had made a conscious choice not to pursue microporous Si anymore but rather macroporous and mesoporous structures, frequently in collaboration with V. Lehmann at Siemens and my group in Kiel. While porous semiconductor research was only one of the many topics that were pursued under his guidance in Halle, it is well known to the community at large. In 2001, for example, Ralf B. Wehrspohn, his second in command in this area, and I started a large priority program funded by the German Research organization DFG concerning photonic crystals, and this was based to some extent on the macroporous work done in Halle and elsewhere. Many may remember the beautiful pictures of complex three-dimensional porous structures in Si with complex optical properties; Fig. 6 shows examples.



a) b)

Figure 6 a) Two dimensional photonic crystal first shown at the PSST meeting in [10], b) three-dimensional photonic crystal obtained by macropore etching [11].

From research into macro and mesoporous Si evolved substantial work in the related area of meso- and macropores in alumina. Quite impressive are also the results obtained from using porous materials, often with self-organized structures, as templates for a wide range of nano-structured functional materials, including highly original forays in the world of biomaterials.

Just as noteworthy as his scientific achievements are his interactions and his involvement with the many people he met while pursuing science. The spirit in Ulrich Gösele's group ran high, especially among the young people; their enthusiasm for doing science, their supreme motivation, their team spirit and the way they worked together and had fun together were commented upon repeatedly by his very pleased advisory board, to which I had the honor to belong. Ulrich Gösele was a supreme motivator and mentor - and a good listener, who could not only keep track of a rather large group, but also instilled a feeling of togetherness and purpose into all members. His door was always open and he always was the driving force for innovations in his large department.

Figure 7 Prof. Dr. Ulrich Gösele in May 2009, at the public celebration of his 60th birthday.

His work and personality were appreciated all over the world and recognized by many honors and awards. At the time of his death he was on the short list for more. He was also an active member of a number of learned societies. He sat, for example, on the Board of Directors of the Materials Research Society (MRS), USA. Besides his main occupation as the director of a large MPG institute he always kept an adjunct professorship with the University of Halle and Duke University; he also held a position as an Honorary Professor at the Chinese Academy of Sciences.

Ulrich Gösele was a much sought-after lecturer and keynote speaker because his presentations were never boring. He had a knack of making outrageous but logically irrefutable statements that could be quite infuriating on occasion, but were always to the point, and often led people to become aware of personal or societal biases in science or elsewhere. He always went to the root of problems and was therefore often approached for advice or asked to serve on committees charged with difficult tasks

Ulrich Gösele left an Institute that, according to an internal evaluation, was among the finest in the MPG. His family and staff sorely miss him, as do collaborators all over the world, and his many friends. All of us hope that his legacy will be kept in spirit and in body.

Prof. Dr. Ulrich Gösele has made lasting contributions to science and enriched the professional and private lives of many people. He died unexpectedly and far too early. He will be missed and remembered as an outstanding scientist and a caring friend.

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