

# autobiography

I grew up in the early post-war period in Stuttgart, Germany. This city is known for its automobile industry and for its large number of small and medium-sized industrial companies.

My father was an electrical engineer and he ran a factory for small electric motors. Over the decades, he set the main accents of the company with a whole series of his own inventions. In my parental home there was a lot of thinking, reading and discussing about science and technology. In addition to parental care, I owe to my father and my mother a critical, open, but cooperative way of thinking. This was later very beneficial to me, not least professionally. Still a young school boy, I used the technical possibilities of the company to build my first optical telescope together with my grandfather. This instrument was followed by a reflecting telescope, which could be used for more serious observations. And a few years later I was accepted as the youngest member of the Stuttgart observatory. That's how I came to physics via astronomy.

After attending high school, I joined Siemens company for a shortened

*by Knut Urban*

apprenticeship in the field of electrical engineering, which in the sixties, was the prerequisite for studying physics at the university. This was an important time for me, because learning the skills of practical electrical engineering, including design and working in production with ordinary workers not only helped me to acquire important professional knowledge, but also strengthened my social skills. Subsequently I enrolled at the Technical University of Stuttgart to study physics. Inspired by my work in the field of semiconductors at Bosch company already during my studies, I completed university with an experimental diploma thesis in the field of semiconductors. Here I learned a lot about low temperatures, about the optical properties of semiconductors and how these are influenced by crystal lattice defects. This was my entry into solid state physics and especially into the physics of defects in crystals.

A decisive factor for my entire further career was that Alfred Seeger, Professor of Solid State Physics at the University of

Stuttgart and Director of the Max Planck Institute for Metals Research, became interested in my results on the optical properties of plastically deformed germanium at low temperatures and offered me a doctoral thesis. Seeger was internationally recognized for his pioneering work in the field of crystal defects, and he was one of the most versatile solid state physicists of his time. Accordingly, the fields dealt with in his institute and the experimental and theoretical methods used were many and varied.

Seeger presented his doctoral students with challenging topics and trusted that they would manage to be successful. The cold water into which I had to jump according to his offer consisted of constructing an object stage for the new high-voltage electron microscope of the Max Planck Institute. The challenge was that the stage should allow samples to be cooled down to the temperature of liquid helium (-269 °C) without impairing the resolving power of the microscope, in order to study atomic lattice defects in metals. This had been attempted by other groups for about a decade without any success. The vibrations of the boiling

helium used for cooling and the instability of the low temperature spoiled the optical resolving power. Seeger offered to me to do the design and construction of the system at the Fritz Haber Institute in Berlin under Ernst Ruska, who later won the Nobel Prize as the inventor of the electron microscope. Ruska, who was an engineer through and through, was initially rather skeptical about the young physicist. But my work in the Siemens and Bosch workshops had prepared me for such a demanding job. And when I asked Ruska for an interview a few months later, and approached him with a large bundle of drawings under my arm, he was impressed. From then on, he followed my work with great interest, and he made all the facilities of his institute available to me. As it is not seldom the case, a newcomer who had new and independent ideas could make the breakthrough that had been denied to others.

The helium-cooled object facility in the high-voltage electron microscope then served us for many years as a unique platform for experiments carried out in-situ under direct high resolution observation. The microscope offered an attractive advantage: at high electron energy, atomic defects could be generated by electron-atom displacements, and at low energy, their secondary reactions could be observed at any desired temperature. I myself was rewarded by a number of new observations. The most important of these are certainly the discovery of the radiation-induced diffusion of atomic defects (brought about by electron-defect interaction) and the proof of the spinodal ordering in alloys, a sophisticated process based on special lattice symmetry properties, which had been theoretically treated and discussed for years, but had never been demonstrated experimentally.

In the second half of the eighties I left the Max Planck Institute becoming a Professor for Materials Science at the University of Erlangen. A few years later I moved to Research Center Jülich as Director of the Institute of Solid State Research. This position was combined with a Chair for Experimental Physics at RWTH Aachen University. In the meantime I had begun to take an interest in the new field of quasicrystals, for the discovery of which Dan Shechtman received the Nobel Prize

a few years later. I earned my entry ticket into the club of quasicrystal scientists with a paper in which I combined cryo- and high-temperature in-situ electron microscopy to show for the first time that the quasicrystalline phase in alloys developed by itself from the amorphous state at elevated temperatures, whereas previously it was believed that the only access to the quasicrystalline phase would be by quenching from the melt. Some years later, when I discovered by chance dislocations in one of our images, a kind of lattice defect closely related to plastic behavior in crystals, I became very engaged with quasicrystal plasticity and then worked in this field for many years. The discovery of dislocations was so exciting since it was against any expectation. Quasicrystals are based on six-dimensional lattice schemes and understanding the topology of such defects in these lattices turned out to be rather difficult. Similarly complicated was the formulation of a contrast theory for quantitative characterization of these defects in the electron microscope, which kept us busy for a long time. In addition, the observation of dislocations indicated that it might be possible to plastically deform quasicrystalline materials, which are in general very brittle, and we were able to prove this at high temperatures by performing in-situ experiments in the high-voltage electron microscope.

The eighties were exciting years for solid-state physics and materials science. Outstanding was the discovery of high-temperature superconductivity in oxide materials and the invention of scanning tunneling microscopy (STM). The multifaceted interest in new solid-state physics topics, which we learned from Alfred Seeger, and which he exemplified to us, has never left me throughout my professional life. And as someone who had just taken over a research institute at one of Germany's national research centers, which had reasonable financial resources for equipment and personnel, I threw myself into setting up two more working groups, one to set up STM and one to study oxide superconductors. STM had primarily been introduced as a surface physics technique. Following my interest in lattice defects, we built a novel STM, with which we were the first to study single dopant atoms in semiconductors, their electric fields, their diffusion and their behavior in the pn-junctions of

devices; highly interesting topics for advanced semiconductor technology. With the oxide superconductors, two things proved to be an advantage for us. We built the facility for the deposition of superconducting thin films and devices ourselves in order to realize our own ideas, and we used our state-of-the-art electron microscopes to directly check the quality of the results of film deposition and to continuously improve them. We achieved international records in Josephson-device and high-frequency performance, and our superconducting microwave resonators flew on an international communication satellite mission.

Electron microscopy at that time was more powerful than it had ever been before, and we were proud of our new instruments we were able to put into operation at the end of the eighties. Their resolution of about 2.4 Å at 200 kV and 1.7 Å at 300 kV was fantastic. On the other hand, they still hadn't reached atomic dimensions, which seemed to solid state physicists, including me, at that time to be something like the Holy Grail. It was therefore a great turn of events, that in September 1989 during the 'Drei-Ländertagung' (the traditional quadrennial meeting of the electron microscopy societies of Austria, Germany and Switzerland) at Salzburg, Austria, Maximilian Haider and Harald Rose told me about a project that would decisively change our future professional life, and of course that of electron microscopy in general. Harald Rose had just completed a theoretical study of a new aberration-corrected electron microscope objective lens which, according to a conservative estimate, had a chance of being technically realized with the current state of the art of electronics technology. A few months later we agreed to submit a joint application to the Volkswagen Foundation. The aim was to realize in Haider's laboratory at the European Molecular Biology Laboratory at Heidelberg the new semi-aplanatic corrector lens, known today as the 'Rose corrector', and to implement it into an appropriately modified commercial conventional transmission electron microscope (CTEM). Since in a CTEM one must also correct the off-axial aberrations, this is the more general case, which automatically includes the case of the correction of a scanning transmission electron microscope (STEM).

Due to a decision of the American funding agencies to no longer finance the development of aberration-corrected electron optics due to decades of failure in this field and the lack of interest from industry, the corresponding working groups had been dissolved worldwide.

The Volkswagen Foundation was in general also not prepared to finance pure instrument development. However we thought we had a fair chance to get funded because, as a team consisting of a theoretical and an experimental physicist specialized in electron optics and a materials scientist interested in a variety of fields, we were able to justify our project from the point of view of materials science application. As always after a real change of paradigm, it is today, now that the problem of aberration correction in electron optics is solved and atom-by-atom materials science studies are part of our everyday life, hardly possible to take oneself back in time, to a time when science was quite obviously not prepared for atomic-resolution electron microscopy. Materials science was about to enter the era of nanotechnology for which access to the atomic range of dimensions was highly desirable. But decades of promises, which then electron optics could not keep, the problem of correcting the aberrations of electron lenses was simply too difficult, had destroyed any confidence of materials scientists that electron optics would ever be able to help them. The biggest problem was therefore to convince my own colleagues, the materials scientists, that our concept was better and had a higher chance of eventually making the breakthrough than had been the case with all the earlier attempts.

In this situation I decided to offer and give numerous talks in materials-science oriented institutes in Germany and abroad, and I organized special sessions on conferences in order to advertise the need for atomic electron-optical resolution in materials science. The fact that we were well advised to intensively advertise for our plans became evident when it turned out much later that our proposal was accepted at the final reviewers' meeting with a knife-edge majority of a single vote. In 1997 the world's first aberration-corrected transmission electron microscope demonstrated a record resolution of

better than 1.4 Å (at 200 kV), almost doubling the resolution of the original, uncorrected instrument. This allowed us to demonstrate atomic resolution in crystals of germanium.

Every physicist learns in the first years at university that the atomic world obeys quantum physics, and this is in many ways so different from the classical physics we are used to in our everyday lives. So there was still a lot for us to learn if we wanted to understand the images we obtained in atomic dimensions. Contrary to what laypeople (intuitively) assume when they see the high-resolution images, the atoms cannot be seen directly. The electrons react to the atoms' electric fields, and special optical operations are required to obtain an image on this basis. What did we see at all, that was the question that was to occupy us intensively for the coming months. But the effort was richly rewarded; in the meantime the instrument had been moved to Jülich. Under special novel imaging conditions, which nobody had thought of before, we succeeded for the first time in seeing oxygen atoms in oxides.

The oxides are forming one of the most significant material classes. But electron microscopy had previously been blind to oxygen, as well as to other light atoms, due to their low scattering power. This now changed suddenly, the oxide chemists were enthusiastic, and we ourselves have been involved in the study of oxygen in materials for many years.

The first significant materials-science problems that were then solved by atomic aberration-corrected electron microscopy are the proof of the order of oxygen atoms in the copper-chain planes of YBaCuO, a phenomenon of fundamental importance for the theory of high-temperature superconductivity. Nobody had been able to directly see the oxygen in these materials before. Furthermore we could not only proof but also measure the understoichiometry of oxygen atoms in lattice defects in BaTiO (and other perovskites), which decided a long-lasting dispute in oxide chemistry. Here again, it turned out to be an advantage that we, as a materials science institute, had the competence in these fields, together with the competence in electron microscopic contrast theory, which allowed us to get the most out of the new instrument

developed together with our electron optical colleagues.

What fascinated me from the very beginning is that we found that by combining quantitative aberration-corrected electron microscopy and measurement with quantum-physical and optical image simulations in the computer, in tandem so to speak, we could measure atomic positions and atomic displacements with a precision of better than a picometer. This is actually an unimaginable dimension; it corresponds to one hundredth of the Bohr diameter of the smallest of all atoms, the hydrogen atom. Access to these tiny dimensions means access to where a lot of physics takes place. In addition, this combination of microscopy and computer simulation provides us with analytical information about the chemical nature and concentration of the atoms imaged.

In 2004 I was elected President of the German Physical Society, the oldest physics society in the world and with over 60,000 members also the largest. I have always felt it a special honor to serve this Society, which has had so many famous presidents in its history, personalities whom we can admire, but whose great contributions to the development of physics we can never match. The scientific community is international, and it is a great privilege to be able to meet like-minded people in all nations and to work together across borders. Many of my colleagues have become lifelong friends. This brief excerpt from my scientific life would not be complete without mentioning my years as a visiting professor at the Saclay Research Center near Paris, France, and at Tohoku University in Sendai, Japan, as well as my years of involvement and longer stays at universities in China, namely Tsinghua University in Beijing and Jiaotong University in Xi'an.

I was lucky to be able to work throughout my professional life on fantastic and rewarding projects and to have great and talented people as students, doctor students, staff and colleagues over the years. Working with them has been a great privilege, sometimes a challenge, but always a great pleasure. For this I will always be grateful from the bottom of my heart.