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It is with great pleasure that I convey my very best wishes to the Walter Schottky Institut (WSI) on the occasion of the 20th anniversary of its inauguration. Two decades have now passed by since this new central institute of Technische Universität München was officially opened on the 14th July 1988, following astonishingly short planning and building phases that lasted only two years. These achievements were the culmination of a remarkably concerted effort involving scientific, economic and political actions on which we now look back with admiration and, possibly, some silent envy. In particular, the very strong partnership between the university and Siemens AG and the unprecedented, transparent and non-bureaucratic support of the Bavarian government made the realisation of this ambitious plan possible and led to the formation of an interdisciplinary and worldwide leading research center for fundamental semiconductor electronics in the shortest possible time. The close cooperation of pertinent industry partners with university research and the rapid transfer of scientific knowledge into real world applications was a central goal of the institute from the very beginning and remains so to date.

I vividly recall from the time I was working as a state secretary in the science ministry, the dynamic scientific and political efforts that were behind the construction of the WSI and excitement and energy involved in bringing it into operation. The participants obviously had extremely high expectations for the scientific success of the institute, due to the very high level of the financial investments made. Today, twenty years later, we can justifiably say that the Walter Schottky Institut has more than fulfilled these high expectations and has developed into a truly world leading scientific center. Since its foundation, the institute has progressively earned its very strong international reputation and today is a beacon for science at the Technische Universität München whose light extends far beyond the borders of Bavaria.

These successes naturally place more demand on the office and laboratory space that is available to researchers. It is no surprise, therefore, that the building which was put into service in 1988 is no longer sufficient to fully accommodate the growing number of research groups, large pieces of research equipment and upcoming new thematic research areas. An additional building, currently in the planning and design phase, is urgently required and we now invest our energy and ambition to complete this extension on a timescale as short as possible, if not in the record time achieved during the construction of the Walter Schottky Institut. To accomplish this, we are supported by a special initiative of the Bavarian government called Bayern-2020 and a new research building initiative according to article 91 b of the Federal constitutional law. Following a proposal to extend the Walter Schottky Institut during 2007 that had to compete nationally with many other initiatives throughout Germany, the German government found the arguments to be most convincing and the financial support for a new building was granted without delay.

My thanks for twenty excellent years of the Walter Schottky Institut are extended to all the top quality scientists who have made this success possible. In particular, I mention the director of the institute, Professor Gerhard Abstreiter as the representative of their efforts. Furthermore, I also would like to thank the industrial partners and research partners outside the University for contributing to this success. My very best wishes for continued success in your work for the next 20 years!

Munich, May 2008

Dr. Thomas Goppel
Bavarian State Minister for Sciences, Research and Arts.
Twenty years of the Walter Schottky Institut at Technische Universität München, two decades of world class research and development in semiconductor nanotechnology. The Walter Schottky Institut is undoubtedly a success story without comparison that was founded through close collaboration between Technische Universität München, the Bavarian government and Siemens AG. This world class, multidisciplinary central research institute was inaugurated on the 14th July 1988, the culmination of almost two years of careful planning, development and construction.

I would like to take this opportunity to express my sincere gratitude to numerous people who were instrumental in the conception and planning of the institute; these include Fred Koch, Gerhard Abstreiter and Wilhelm Breng from the Physics Department of TU München, Klaus von Klitzing who had just been awarded the Nobel prize for Physics, the then TU president, and later science minister, Wolfgang Wild and Karl Heinz Beckurts who headed the central research laboratories at Siemens AG. In particular, the unfaltering commitment and efforts of Karl Heinz Beckurts will never be forgotten; he did not live to see the inauguration following his cowardly murder by the RAF terrorist group, an unimaginable loss for his family, an irreplaceable figure for science and German economy.

Already at a very early stage these pioneers recognised that semiconductor physics straddles the boundaries of different scientific disciplines and that it was only by bringing together researchers from physics and materials science that an internationally competitive research center could be created. The subsequent success story of the Walter Schottky Institut is testament to this vision; to date the WSI has become one of the world leading institutes for the fabrication and characterisation of ultrapure semiconductor multilayers and sophisticated nanostructures and has developed into an innovative research center that attracts some of the finest researchers from around the world. A large number of high level national and international collaborative research projects emerged over the years from this environment, not least the cluster of excellence Nanosystems Initiative Munich (NIM). These successes are firmly underscored by the facts that around 80% of all scientific members of staff are funded via external research contracts that have resulted in more than 1500 publications, not infrequently in the most prestigious journals such as Science and Nature. The high level of innovation to come was already evident during the planning and construction of the institute; the TUM and the state of Bavaria broke new ground by forming a close alliance with Siemens AG. This partnership was the first time that a university building was constructed in conjunction with industry, a model that has subsequently become a successful tradition in our university. At present BMW AG is undertaking a similar project, constructing the Institute for Advanced Study (IAS) on the Garching campus as a direct result of the excellence initiative.

During the past year, a proposal to extend the WSI via the construction of a new research building, the Center for Nanotechnology and Nanomaterials (CNN), was submitted to the national German government. A national science advisory board evaluated the proposal and both national and regional governments emphatically recommended to support the initiative since all criteria were, to quote, “convincingly satisfied in every way...”. In order for the German government to finance 50% of the cost of such a new building one of the major criteria was that it should be in the “national interest” of Germany and not just have regional importance within the state of Bavaria. National interest? - one can wholeheartedly say that CNN is of international importance and that the Walter Schottky Institute is a jewel in the crown of science next to the TUM itself! Today, I would like to set this crown upon the head of the entire Walter Schottky Institut, its founders and all the current researchers and members of staff. The WSI has “convincingly satisfied in every way...” each and every expectation that we have of our central institutes. As president of the TUM, I congratulate the institute on the occasion of its 20th anniversary and look forward with anticipation to at least another two decades of success as part of our university. The WSI will continue to set the gold standard for TUM’s corporate research institutes.

May 2008

Professor Wolfgang A. Herrmann
President
Technische Universität München
Chapter 2

History and Research Topics

Historical perspectives

The Walter Schottky Institut (WSI) is a central institute of Technische Universität München (TUM) that was founded in order to strengthen the interaction between basic physics and semiconductor electronics research. The idea to create such an interdisciplinary research facility first emerged in the early 1980’s. Semiconductor heterostructures had become a very popular field of research at that time, following the discoveries of many novel electronic and optical effects in low dimensional systems such as two-dimensional electron gases and quantum wells. The most prominent discoveries in contemporary semiconductor physics were the Quantum Hall Effect by Klaus von Klitzing in 1980 (Nobel prize 1985) and the Fractional Quantum Hall Effect by Daniel Tsui, Horst Störmer and Arthur Gossard in 1982 (Nobel prize for Tsui, Störmer and Laughlin (theory) in 1998). At the same time, various technologically relevant novel electronic and optical devices were proposed and developed. Specific examples include Quantum Well Lasers (Henry, Dingle, Holonyak, Tsang and others), Resonant Tunneling Diodes (Esaki, Tsu, Chang and others), or High Electron Mobility Transistors (Abstreiter, Ploog, Mimura and others). These devices provided new functionality and led to a wide variety of applications, for example in the field of communication technology (satellite receivers, optical communication, cellular phones). These achievements were based on the excellent materials control through epitaxial techniques, especially molecular beam epitaxy. These modern materials technologies allowed control of layered structures on an atomic scale and were widely employed in industrial laboratories in United States and Japan as basis for the realization of novel devices. In Munich, this kind of research and development was embedded in a collaborative research center funded by the German Research Foundation (SFB 128), where in one research area two-dimensional electron systems at semiconductor interfaces were studied. This work was concentrated at the chair of Fred Koch at the Physics Department of TUM, and the project leaders in the early eighties were Fred Koch, Klaus von Klitzing and Gerhard Abstreiter. Around the same time, closer interactions developed between the TUM physics groups and the research and development center of Siemens AG in the area of microstructured devices. In addition, a joint research program funded by Volkswagenstiftung was established between Gerhard Abstreiter and Klaus von Klitzing with Erich Gornik’s group at the University of Innsbruck. The successful projects were strongly dependent on high quality materials which were provided by only a very few sources: Günter Weimann from the research laboratory of Deutsche Bundespost in Darmstadt and Klaus Ploog from Max-Planck-Institut Stuttgart. At the time, these two laboratories were the only groups in Germany which could grow high quality GaAs based heterostructures. There was a strong need for an interdisciplinary research environment that combined high quality semiconductor hetero- and nanomaterials technology with basic physics as well as device development. In February 1985, Gerhard Abstreiter wrote a memorandum with the suggestion to create a new institute with a specific focus on semiconductor micromaterials research and device development. This proposal was discussed with Karl-Heinz Beckurts, who at that time was head of the Siemens research laboratories and had already expressed strong interest in strengthening collaborations between industry and the TUM. In September 1985 the proposal received additional impetus after it was announced that Klaus von Klitzing would receive the Nobel Prize in Physics for his discovery of the Quantum Hall Effect. Klaus von Klitzing had just left the Physics Department of TUM in early 1985 to take up a directorship at Max-Planck-Institut für Festkörperfororschung in Stuttgart. The Nobel Prize had an extremely positive impact on the initiative for the realization of a new research facility at TUM, and both Fred Koch and Wolfgang Brenig, at that time dean of the Physics Department of TUM, wrote supporting letters in October/November 1985, suggesting the creation of a research institute focusing on semiconductor physics and electronics. The name “Walter Schottky Institut” was suggested by Karl-Heinz Beckurts in a meeting at the Physics Department in Garching. Walter Schottky was a famous and well known physicist who worked for Siemens from 1927 until 1976 when he died just before his 90th birthday. His research combined basic physics with development of novel devices. The combination of materials technology, fundamental physics and device applications was planned to become the central mission and principle goal of the new institute. The idea to create such a research facility was strongly supported by Klaus von Klitzing and Wolfgang Wild, president of TUM and later Bavarian Minister for Sciences, Research and Arts. Already on December 17, 1985, there was a meeting at the Bayerische Staatsministerium für Unterricht und Kultur with Bavarian State Minister Hans Maier to discuss the boundary conditions for the foundation of a research institute for semiconductor electronics at TUM in collaboration with Siemens AG. Following an additional meeting of Klaus von Klitzing with Bavarian’s Minister President Franz Josef Strauß in February 1986, the final decision to create such an interdisciplinary research institute was made. It was the year of the hundreth birthday of Walter Schottky. From then on, it took only about two years until the new laboratories became operational in 1988. Re-

Minutes of the meeting to discuss the establishment of an institute for semiconductor and microelectronic research.

Inauguration ceremony on July 14th, 1988. Together with Federal Minister Dr. H. Riesenhuber and president of Siemens AG, Dr. K. Kaske.

A vision becomes reality – architects’ model and photograph of the Walter Schottky Institute during construction in 1987.
search in the new institute started in May, a few months before the official inauguration and opening ceremony on July 14th, 1988. This exceptionally short time for planning and construction of a modern institute building was made possible by the excellent cooperation between the Siemens AG, the Bavarian ministries and the TUM. Interests of university, industry and politics met here in a rare but fortunate circumstance. The realization of the WSI was based on an official TUM-Siemens collaboration effort called “Sonderforschungseinheit mikrostrukturierte Bauelemente”. As discussed already in the foreword, it was the first example where industry took the responsibility for the construction of a laboratory building at TUM. Many people were particularly helpful in setting up the new research institute. The strong commitment of Karl-Heinz Beckurts was essential for the whole project. In the early planning stage he became victim of a terrible bomb attack by terrorists belonging to the Rote Armee Fraktion (RAF), where he and his chauffeur were murdered. It is extremely sad and regrettably that he was no longer amongst us at the official opening of the WSI in summer 1988.

About the Walter Schottky Institut

The WSI building contains laboratories and offices with a total area of about 2400 m². The heart of the institute is a 250 m² clean room facility for state-of-the-art semiconductor technology. The costs for the building (16.4 million DM) were initially covered by Siemens. TUM bought the institute in 1992. The Bavarian State gave generous funding for the initial equipment (15 million DM) and created three new full professorships, with a total of 23 staff positions, one chair belonging to the Department of Electrical Engineering and Information Sciences and two to the Physics Department. Further support came from the Institute of Theoretical Physics of TUM, which in 1990 devoted one chair in order to provide theoretical support for the WSI. The following research groups were established:

- Semiconductor technology: Günter Weimann (from 1988 to 1995), Markus-Christian Amann (since 1997)
- Experimental semiconductor physics I: Gerhard Abstreiter (since 1987)
- Experimental semiconductor physics II: Erich Gornik (from 1988 to 1993), Martin Stutzmann (since 1993)
- Theoretical semiconductor physics: Peter Vogl (since 1990)

The main research interests have been:

- Fabrication and characterization of new semiconductor materials, material combinations, as well as functionalisation of semiconductor surfaces
- Development of novel methods for fabrication and characterization of nanostructures
- Basic physics with emphasis on electronic and optical properties of low dimensional systems
- Realisation of new semiconductor devices for applications in ultrafast electronics, optoelectronics, and as biological / chemical sensors
- Theory and simulation of modern semiconductor materials and devices
The early projects concentrated on Si, GaAs, and InP based systems, with emphasis on heteroepitaxy on an atomic scale. Device oriented projects have been the development of ultrafast and low-noise III-V hetero-field-effect-transistors, laser diodes in the wavelength range from 980 nm to 1.55 µm, vertical emitting laser diodes and Si/SiGe based devices. Fundamental research projects involved optical studies of quantum wires and dots, especially spatially resolved spectroscopy, transport and resonant tunneling in low dimensional systems, as well as the realization of novel devices based on quantum-effects. More recently, interests have shifted also towards newly emerging materials such as GaN and related alloys, diamond, or Antimonides and towards quantum control of charges, spins and photons for quantum information technology. In addition, the combination of semiconductors with biological systems has been investigated intensively since a couple of years ago. This new field of research opens the way towards novel biomedical applications, e.g. for diagnostics and sensing.

Soon after its foundation, the Walter Schottky Institut became an internationally well-known landmark for fabrication and characterization of high quality semiconductor hetero- and nanostructures. This was the basis for many national and international collaborations. The WSI played a key role in establishing various collaborative research centers funded by the German Research Foundation as well as national research programs supported by the Federal Ministry of Research. Other funding was obtained from Bayerische Forschungsstiftung, Volkswagenstiftung, European Union and industry. The total amount of annual external funding is on the average more than 3 million Euros. The numerous national and international collaborations resulted in many joint publications in refereed international journals. The total number of publications with contributions from the WSI is about 1600, which have been cited about 27000 times up to now (at present about 2500 citations per year) according to ISI Web of Science (June 2008). About 350 diploma (master) students have graduated from the WSI until now. In the same period, about 130 doctorate candidates have finished their theses. All of the graduates were able to find appropriate jobs in a very short time after finishing their thesis. About 70% of the PhDs are now working for high-tech industry. Twenty percent remained in academia, and one third of those are now professors at other universities or directors of research institutes. 10% went into other areas like patent business or consulting.

The number of researchers at the Walter Schottky Institut has grown continuously. Today it accommodates the research groups headed by Gerhard Abstreiter, Markus-Christian Amann, Martin Brandt, Anna Fontcuberta i Morral, Jonathan J. Finley, Alexander Holleitner, Martin Stutzmann, and Peter Vogl, with a total headcount of about 140, including junior research group leaders, scientific and technical staff, postdocs and visiting researchers, secretaries, and doctorate as well as diploma (master) students. Out of these, about 30 positions are funded by TUM, while basically all the doctorate positions are financed via research projects with external funding. Available laboratory and office space is by far not sufficient anymore and the WSI urgently needs an expansion. A new Center for Nanotechnology and Nano-materials is currently in the planning stage. It is expected that this shared facility will become operational in fall 2010. In addition to their extensive research activities, all groups are involved in teaching within their respective departments. Besides the usual teaching responsibilities in undergraduate and graduate courses, special emphasis is put on the education of diploma and doctoral students in the physics and technology of present and future nano-devices and of low dimensional semiconductor structures.
An Introduction to Semiconductors
On the 14th of November, 1876, the high school teacher Ferdinand Braun gave a presentation entitled “Experiments concerning deviations from Ohm’s Law in metallic conductors” in front of the illustrious Naturforschende Gesellschaft zu Leipzig. Neither Mr. Braun nor his critical audience were aware of the fact that they were just witnessing the birth of Semiconductor Physics. Indeed, what Ferdinand Braun had discovered by a long series of meticulous experiments, at first sight did not appear too exciting: if one equipped a solid crystal with two metallic contacts and applied an electrical voltage, two basic kinds of behavior could be observed. Either no measurable electrical current passed through the crystal. Then this crystal obviously was an electrical insulator and, therefore, was no longer of interest for further investigation of its electrical properties. Or, for the second type of crystals, a sizeable current could be measured. Then this crystal was a metallic conductor and obeyed Ohm’s Law. If one doubled the applied voltage, also the observed current was doubled. And if one inverted the electrical voltage applied to the two contacts, also the current was inverted. At least, that was the way it used to be until 1876...

The deviations from Ohm’s Law, which Ferdinand Braun reported to the Natural Society at Leipzig, were quite strange, indeed. Instead of using large electrical contacts, Mr. Braun had performed some of his experiments with very fine contact needles. In some crystals he then had observed an electrical current as in a usual conductor, but when he inverted the applied voltage, the current disappeared and the crystal apparently had converted to an insulator. Similarly unexpected was what happened when Braun changed the magnitude of the applied voltage. Then for these strange crystals the current increased much more strongly than allowed by Ohm’s Law.

What Ferdinand Braun had discovered was the first semiconductor device ever: a rectifying diode, which could transform alternating current into direct current, and many years later actually was used in the form of point contact diodes in radio receivers or radar units. Unfortunately, the reason for this strange behavior of his crystals remained entirely mysterious to Ferdinand Braun. The scientific explanation of this phenomenon only was given much later in 1939 by Walter Schottky, who at that time developed a theory for the electronic properties of semiconductor/metal-interfaces. Honoring this work, rectifying metal/semiconductor contacts now are known as Schottky diodes. As for Ferdinand Braun, he received the Nobel Prize for Physics in 1909 and today mainly is remembered for the invention of the cathode ray tube. As a matter of fact, due to the development of vacuum tubes, solid state electronics did not gain any practical importance until the first transistor was built by Bardeen, Brattain, and Shockley in 1947. Since then, however, solid state electronics based on semiconductor devices has revolutionized our world, which no longer can be imagined without this.

So what actually are semiconductors, what makes them so different from metallic conductors, and why are they so interesting for many applications? The scientific answer to these questions and the development of new semiconductor materials and devices is what semiconductor physics and technology is all about. It takes many years of intensive studies to master the basics of this important part of solid state physics. Here, we will try to convey the most important concepts concerning the unique properties of semiconductors with the help of a simple analogy.

In a regular periodic crystal lattice, electrons as the carriers of electrical current are not allowed to move around freely. Instead, they have to obey certain rules enforced by quantum mechanics. As a consequence, electrons have to occupy so-called “energy bands” which are separated from each other by small or large “band gaps”. This situation can be compared to a two-storey building consisting of a ground floor and a first floor. In the language of solid state physics, these two storeys are called “valence band” and “conduction band”, respectively. Both floors are covered by a well-ordered array of quadratic tiles, representing the periodic lattice of atoms in a semiconductor crystal. The movement of electrons in a crystal is then
An Introduction to Semiconductors

analogous to the movement of inhabitants in our building, whose most important purpose is to transport “charge” from one end of the building to the other. The inhabitants of our “semiconductor house” have to obey one additional important rule: at no time more than one inhabitant is allowed to occupy the space of a given tile! In the same way, electrons in a solid crystal have to obey the quantum-mechanical “exclusion principle” formulated by the famous physicist Wolfgang Pauli.

Now that the blueprints of our semiconductor building and the basic rules for its inhabitants have been defined, let us start to occupy this building with people. At first, all inhabitants can be accommodated on the ground floor, where they can move around more or less freely and transport their cargo across the building. This leads to a steady increase of the amount of cargo transported through the building, until the occupancy of the ground floor has increased so much that the inhabitants start to hinder one another on their way. Eventually, the stream of cargo will come to a complete stop, once all tiles in the ground floor are occupied by an inhabitant, so that nobody is able to move any more. Further inhabitants can only occupy the first floor, where they again have sufficient room to move about. As a consequence, the overall cargo stream through the building will again start to increase, reach a maximum, and eventually come to an end when also the first floor is fully occupied.

The fate of electrons in solids is quite similar to what happens to the inhabitants of our semiconductor building. In particular, it is easy to understand why both, electrical conductors and insulators exist in nature. Crystals in which energy bands are only partially filled will belong to the group of electrical conductors, since their electrons can move more or less freely through the crystal lattice. If, on the other hand, all energy bands are fully occupied or completely empty, no electrical current can pass through the crystal at all and we are dealing with an electrical insulator. Which situation will be encountered for a given solid crystal depends on how many electrons per atom are available to occupy the energy bands of the crystal. For example, almost all metals are very good electrical conductors due to a half-filled valence band and an empty conduction band. If, on the other hand, all energy bands are occupied by an inhabitant, so that nobody is able to move any more. Further inhabitants can only occupy the first floor, where they again have sufficient room to move about. As a consequence, the overall cargo stream through the building will again start to increase, reach a maximum, and eventually come to an end when also the first floor is fully occupied.

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Now, how do semiconductors fit into this picture? As already suggested by their name, semiconductors are solids which are able to pass an electrical current much better than insulators, but at the same time not as efficiently as an electrical conductor. Obviously, semiconductors are solids in which for one reason or the other a few of the many tiles on the ground floor remain empty or a few of the conduction band tiles are occupied, or both. This particular constellation can be achieved via three routes, all of which are of fundamental importance in semiconductor physics and, thus, will be treated in more detail in the following.

The starting point of our discussion will be the situation of an electrical insulator, where all tiles in the ground floor are occupied by exactly one inhabitant and all tiles in the first floor are empty. Thus, no charge transport can occur. To change this state of affairs, which is very unfavorable for device applications, semiconductor physicists have developed the concept of “doping”. Contrary to the very negative image in sports, doping in semiconductors can be used to exactly pre-determine the electrical conductivity of a given device by addition of a precisely calculated amount of impurity atoms. In the analogue of our semiconductor building, doping can be achieved by adding special tiles with the following properties. As a first example, so-called “acceptor tiles” can be added to the ground floor. These acceptor tiles have the unpleasant property of swallowing exactly one inhabitant of the fully occupied ground floor, thus creating a “hole” in the overall occupancy. This allows the other inhabitants of the ground floor to move again. The hole created by the acceptor-tiles also will move at the same time, however in the opposite direction as compared to the inhabitants. In the same way, acceptor atoms incorporated into a semiconductor crystal will create a hole in the occupancy of the valence band, which will act as a “missing electron” and, thus, as a positively charged particle in electrical transport. Therefore, doping of a semiconductor crystal with acceptor atoms is referred to as “p-type” doping (“p” as in positive). The second possibility to induce controlled electrical conduction in an insulator is the doping with donor impurities. In our semiconductor building, such “donor tiles” bring along one additional inhabitant, who has to occupy a free tile in the first floor, since all tiles of the ground floor are already occupied. Consequently, donor atoms added to a semiconductor crystal will provide additional electrons in the conduction band, which contribute to electronic charge transport in the expected way (“n-type” doping by additional negatively charged electrons).
In summary, it is indeed the possibility of doping with additional donor or acceptor atoms which distinguishes semiconductors from insulators or conductors as a third class of materials. Conductors will always pass electrical current with little resistance and independent of chemical details, no matter what. In the same way, insulators will always block electrical current. In contrast, semiconductors will either behave more like an insulator or more like a metal, depending on the level of doping. This provides semiconductors with the unique property to rectify, switch, or amplify electrical signals and, thus, to manipulate electrical current as it passes through the semiconductor crystal.

There is yet another way to produce additional holes in the valence band or electrons in the conduction band of a semiconductor without doping, namely by providing external energy in the form of heat or light. We all know from our own experience that it takes energy to walk up the stairs from the ground floor to the first floor. The same holds for the electrons in a semiconductor: electrons in the conduction band (first floor) have a higher energy than electrons in the valence band (ground floor). This difference in energy is determined by the band gap of the semiconductor, as already mentioned above. Since electrons are lazy, they prefer to stay on the ground floor. In order to move up to the first floor, they have to be stimulated by an external influence. One possibility is provided by the thermal movement of the atoms. At low temperatures, atoms are frozen at their lattice sites, but at higher temperatures they start to wiggle more and more and to push the electrons around. In the analogue of our semiconductor building, the thermal motion of the atoms can be visualized by a staircase leading from the ground floor to the first floor. The thermal motion of the atoms will push the electrons upwards step by step. The larger the band gap of the semiconductor, the longer the staircase and the smaller the number of electrons which actually make it all the way up to the first floor. However, in every well-planned building, there is also another possibility to reach the upper floors more easily: an elevator. In semiconductors, the job of the elevator is done by the elementary particles of light, the photons. If such a flash of light hits a semiconductor, it can directly elevate an electron from the valence band up to the conduction band. The stronger the light beam that falls onto the semiconductor, the more often the photon elevator will make the trip between the two floors, each time taking an electron with it. But also the other direction of electron transport is possible: electrons in the conduction band can return to the valence band, if there is a hole to accommodate the returning electron. This process is called “recombination”. To do this, the electrons can either take the staircase down, giving their energy back to the atoms, or they can take the photon elevator. Then, each time the elevator doors open in the valence band and an electron recombines with a hole, an elementary flash of light is emitted by the semiconductor. The energy of the emitted photon is the same as the band gap of the semiconductor. Semiconductors with a small band gap emit red photons, whereas semiconductors with a large band gap emit blue photons.

This interaction between electrons and photons in semiconductors provides the basis of optoelectronics, another very important application area. The fundamental optoelectronic devices are solar cells and light-emitting diodes (LEDs). In a solar cell, light enters the semiconductor from the outside and, via the photon elevator, lifts electrons from the valence into the conduction band. The excited electrons leave the semiconductor as an electrical current. In an LED, on the other hand, electrons are injected into the conduction band of the semiconductor through one contact and extracted from the valence band through a second contact, leaving holes behind. When the injected electrons recombine with these holes, they emit light, as discussed above.
An Introduction to Semiconductors

This short introduction into the basic properties and electronic processes of semiconductors should show why semiconductors are so important for electronics. They differ from metals and insulators through the fact that they can be doped, thus enabling complete control over their electrical conductivity necessary for tailor-made diodes and transistors. In addition we have seen how the existence of a band gap between the valence and the conduction band can be used for the absorption and emission of light. Unfortunately, we also have to pay a price for this flexibility. Since small amounts of foreign impurity atoms can considerably alter the electrical properties of semiconductors, the preparation and deposition of semiconductors requires ultra-pure environments and utmost care. And to emit or absorb light efficiently at different wavelengths, new semiconducting compounds with complex chemical compositions have to be synthesized, investigated, and optimized. This will be the topic of the next chapter.

But semiconductors are worth such an effort! Be it in computer sciences, the control of industrial processes, energy technology, information technology, consumer electronics, medical diagnostics, illumination technology or in airplanes, cars, appliances, phones, or watches: semiconductor devices are omnipresent and indispensable. Today, the direct annual market volume of semiconductor devices is about 300 Billion Euro, and the financial impact of semiconductors as a key enabling technology in many other markets is by far larger, still. Also in the future, semiconductors will be a part of our daily life, hopefully with a positive impact. A very visible example in the true sense of the words is the rapid progress in solid state lighting. Here, highly efficient LEDs are beginning to replace the old vacuum tube technology, much in the same way as 50 years ago solid state transistors have replaced vacuum tubes in analogue and digital signal processing. We all witness personally the current progress in computer processors, where Moore’s law is still alive and well. And last but not least semiconductors will help to provide the world population with clean and sustainable energy. The current prediction is that in the year 2010 alone, solar cells with an accumulated electrical power of 20 Gigawatt will be installed, the equivalent of about 20 nuclear power plants.

In the following chapters of this brochure you will find more information about the different areas which are of current interest in semiconductor physics and technology, and which are actively investigated at the Walter Schottky Institut. Enjoy!
Quartz Glass reaction vessel of a MOVPE growth system
Silicon has been one of the most important materials of the 20th century and continues to be a key component in many modern technologies. It was first introduced as a semiconductor material in 1954, when it became the basis for the first mass-produced semiconductor device, the bipolar transistor. Since then, silicon has been used in a wide range of applications, including microelectronics, optoelectronics, and quantum cryptography.

### Silicon

Silicon is a very versatile material that can be used in a variety of ways. It has a number of properties that make it ideal for use in devices and circuits, including a high thermal conductivity, a high electrical conductivity, and a high optical transparency. These properties make it ideal for use in devices that require high performance and efficiency, such as computers, smartphones, and other electronic devices.

Silicon is also a very versatile material in terms of its applications. It can be used in a variety of different ways, including as a semiconductor, an insulator, and a conductor. It can be used in a variety of different types of devices, including transistors, diodes, and capacitors. It can also be used in a variety of different types of circuits, including analog and digital circuits.

Silicon is also a very versatile material in terms of its processing. It can be processed in a variety of different ways, including as a single crystal, a polycrystal, or a thin film. It can be processed in a variety of different ways, including as a single crystal, a polycrystal, or a thin film. It can also be processed in a variety of different ways, including as a single crystal, a polycrystal, or a thin film.
ing the epitaxial growth techniques discussed below, the atoms have to move closer together than they would normally do in order for them to align with the atoms in the underlying Silicon crystal, forming strong chemical bonds. As a result, a considerable mechanical strain builds up between the growing layer of SiGe and the substrate that, providing that the layer does not become too thick or contain too much Germanium, is easily accommodated as an elastic strain in the growing layer. This is analogous to an elastic band or a spring, which can be compressed or extended without breaking to store mechanical strain energy. In the case of SiGe grown on a Silicon substrate, the SiGe layer is compressed so that separation between the atoms in the SiGe layer matches exactly the underlying Silicon substrate. The resulting perfect crystalline structure is important as it allows the electrons to flow through the SiGe layer unobstructedly. In the same way that an elastic band will snap if overstretched, the growing SiGe layer may lose its crystalline integrity if it is made too thick or the fraction of Silicon atoms replaced by Germanium becomes too high. Here too thick in reality means quite thin, since the thickness of the SiGe layer is typically below 100 nm, a length that is 1/10000 of a millimetre or 1/500 of the thickness of a human hair.

For applications, thin layers of SiGe are often inserted into Silicon crystals to act as the conducting active layer in a bipolar transistor. Such SiGe transistors exhibit maximum switching frequencies more than ten times higher than equivalent Silicon transistors and generate less heat per switching cycle. In the Walter Schottky Institut, multilayer SiGe structures are grown and studied using isotopically pure materials. Here, the main goal is the study of the magnetic properties of individual electrons and to store, transfer and process information based on their spin or intrinsic angular momentum. These concepts represent a completely new operation principle for information processing devices and form the basis of the field of Spintronics discussed in Chapter 10.

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Light and high frequencies – the III-V compound semiconductors

Until now we have focused our attention on Silicon and Germanium, two elements from the fourth group of the periodic table that have semiconducting properties. Because these materials are semiconducting in their natural, or elemental, state they are called elemental semiconductors. Fundamentally, in order for a material to be a semiconductor, all of the outermost electrons of each atom, so called valence electrons, must form bonds with neighbouring atoms in the crystal. For elemental semiconductors such as Silicon and Germanium each atom in the crystal is surrounded by four nearest neighbours with which chemical bonds can be formed and, moreover, each atom has four outermost electrons that participate in these bonds. Thus, all electrons of each atom are required to form bonds in the crystal and therefore are not available to conduct electricity through the solid. A similar situation can be realised when mixed alloys are formed between elements from group III of the periodic table and elements in group V. Here, a good example is the combination of Gallium and Arsenic in equal quantities to form a compound semiconductor known as Gallium Arsenide (GaAs). In a crystal of GaAs, the spatial arrangement of atoms is precisely the same as in Silicon, with the difference that each Ga atom is surrounded by four Arsenic atoms and vice versa. All the electrons, three from Gallium and five from Arsenic, distribute themselves between the atoms in the crystal such that there are on average four electrons per atom. This is the same situation that exists in Silicon and, as a result, alloys formed from atoms in group III and group V also tend to be semiconductors. Such compound semiconductors are often termed III-V materials.

In III-V materials, the electrons typically move much more rapidly than in Silicon, and transistors fabricated from special III-V semiconductor structures can be switched on and off at much higher frequencies than comparable Silicon devices. However, the major advantage of such compound semiconductors is that, unlike Silicon, electrical energy in the form of a current can be readily converted into light. All light emitting devices such as the infrared light emitting diode (LED) that sends information to your television from your remote control or the laser in CD and DVD players (see Chapter 8) are typically fabricated from compound III-V materials. In such devices, the conversion of electrical energy into light energy is much more efficient than for traditional light sources, such as incandescent light bulbs. Compound semiconductors are rapidly gaining importance as the incandescent light bulbs used for general lighting are gradually being replaced by LED’s, for example in the automobile industry or traffic signals.

Aluminium Gallium Arsenide - the archetypal compound semiconductor

An entirely new world of electronic and optoelectronic devices can be opened by combining different semiconductor materials in precisely fabricated mixed semiconductor multilayer crystal structures. Already by the end of the 1970’s it had been experimentally demonstrated...
that the resistance of semiconducting materials could be dramatically reduced by allowing the electrons to move in a region of the device that was spatially separated from regions of the device that were “doped” by controllably introducing impurities to generate additional charge carriers in the material. This can be achieved by growing a mixed crystal consisting of a layer of Aluminium-Gallium-Arsenide (AlGaAs) close to an extremely pure layer of GaAs. The AlGaAs layer is controllably doped by introducing a very low concentration, roughly 0.0001 %, of Silicon atoms in a thin layer. These Silicon impurities provide additional electrons that move into the adjacent ultrapure GaAs layer to carry the electric current through the semiconductor. Since the conducting electrons move in the pure GaAs layer, their motion is not disturbed by the presence of the impurity atoms, allowing them to readily pass through the material with a very low resistance. Semiconductor physicists characterise the ease by which electrons move using a quantity called the mobility, which is defined by the average velocity that the electrons move per unit electric field driving them in one direction. Using special methods for the fabrication of such AlGaAs/GaAs layers, researchers in the Walter Schottky Institut realised a mobility of 10 million cm$^2$/Vs at a temperature close to absolute zero (-273.15 °C). In order to place this value into context, the mobility of electrons in Silicon at room temperature is typically 1000 cm$^2$/Vs – the electrons in the GaAs at low temperatures move ten thousand times faster! This impressive result was enabled by the use of special mixed crystals and is due to the extremely high purity of the GaAs crystal. Such high electron mobility samples have been fabricated in the WSI for many other research groups in Germany and worldwide, to directly study the transport of charge carriers in semiconductors. The high speed of electrons in such high mobility AlGaAs/GaAs heterostructures are used to realise so-called field effect transistors, which are often used to realize amplifiers in mobile telephones operating at very high frequencies.

GaInAsP / InP – lasers for telecommunications and the internet

If you made a telephone call from Europe to the United States only a few years ago, there would typically be a noticeable delay since the signal was generally transmitted via an earth to satellite link. Due to the huge distances involved in such satellite communications (~70000 km – earth-satellite-earth), the signal is delayed by noticeable fractions of a second even though it propagates with velocities close to the speed of light. Nowadays, such information is encoded on infrared light pulses and transmitted terrestrially via a transatlantic fibre optical link. In order to send information over an optical fibre, it is not possible to use arbitrary colours of light since certain wavelengths of light are more strongly absorbed than others. It turns out that light in the infrared spectral region, with a wavelength around 1.55 µm, is most suitable for sending information over optical fibres. Light with a wavelength in this near infrared spectral window can be most easily generated using a thin film of a semiconductor formed by an alloy between the elements Gallium (Ga), Indium (In), Arsenic (As) and Phosphorous (P). The ratio in which these elements are mixed together to form the alloy has to be precisely controlled, with a precision better than ~1 %. This is necessary to provide exactly the correct light emission wavelength and, furthermore, to allow the thin GaInAsP film to be grown on a substrate of Indium Phosphide (InP). Compared to GaInAsP, InP is a semiconductor with a larger energy bandgap. As a result, the negatively (electrons) and positively (holes) charged particles that carry current in a semiconductor become trapped within the thin GaInAsP layer and have a very high probability to meet one another and recombine. Here, the term “recombine” means that an electron-hole pair annihilates to produce one photon of light (see Chapter 3). This direct conversion from an electrical current of electrons and holes into light can be extremely efficient, with efficiencies close to 100% in the best cases. Such materials were studied at the Walter Schottky Institut within the framework of a project funded by the European Union with the aims to realise tunable lasers for telecommunications applications. The properties of these lasers met the rigorous standards required for...
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telecommunication applications. Via a specially tailored device design, the emission wave-
length could be tuned with an additional electrical contact, even after the fabrication process.
Since signals sent at different wavelengths into an optical fibre do not influence each other, it
is possible to encode different information on different wavelength channels and, in this way,
dramatically enhance the information carrying capacity of a single glass fibre. As an example,
several hundred thousand telephone conversations can be simultaneously transmitted over
a single glass fibre with a thickness comparable to a human hair, using such wavelength divi-
sion multiplexing techniques.

Antimonides – a contribution to atmospheric analysis

A completely different optical application that demands finely tuned semiconductor light
emitters is absorption spectroscopy, a method used to detect minute traces of specific gases
in a sample. Here, one uses the fact that all gases absorb light strongly at characteristic fre-
quencies that correspond to the motion of the atoms forming the molecule, vibrating against
one another or rotating. Each different gas molecule has a distinct and characteristic series
of absorption resonances that uniquely identify it – in many ways this absorption spectrum
is like a fingerprint that identifies a particular molecule. By detecting the reduction of the in-
tensity of light after it has propagated through a sample of gas as a function of the frequency
of the light, it is possible to identify the types of gases present in a sample and their relative
concentrations. Such methods allow the detection of leaks in gas pipelines and provide a
direct method to control combustion processes by detecting the concentration of different
gases in the exhaust.

Usually, the strongest absorption lines lie even further into the infrared region of the spec-
trum than the 1.55 µm wavelengths used in optical telecommunications, in the range around
~2–3 µm. To generate light of such long wavelengths it is necessary to utilise semiconductors
with sufficiently small energy band gaps – again a challenge for materials physics. The solu-
tion is an element called “Antimony”. When one realises III-V materials by combining group-III
metallic elements such as Aluminium, Gallium or Indium with Antimony (Sb) and Arsenic (As)
as the group V elements, instead of Arsenic and Phosphorous (P), the resulting semi-
conductor can emit light with a wavelength around 2 µm. However, many questions that were
posed and solved a long time ago for other compound semiconductors are, so far, unsolved
for the Sb-based III-V compound materials. Examples of such questions include:

- What does the electronic structure of such semiconductors look like?
- How exactly does one have to control the content of Sb in such materials?
- How does one nanofabricate and process materials containing Antimony?
- How does one make a good electrical contact with III-Sb materials such that the current
flows with low electrical resistance from the contact into the Antimony compound?

Over the last few years researchers at Walter Schottky Institut have answered some of
these and many more questions and, by doing so, realised long wavelength emitters using
Sb-based III-V materials for applications in gas sensing. It was possible to fabricate edge
emitting laser structures using Antimony based III-V materials with an emission wavelength
that could be tuned from 2.2 µm to 3.3 µm – such devices are the longest wavelength emit-
ting bipolar laser diodes realised to date, worldwide, using III-V semiconductors. A further
milestone was reached in 2007 with the realisation of the world’s first surface emitting laser at
2.2 µm using Antimony based materials (see Chapter 8).

Nitrides – blue light from cold sources

Which format, Blu-Ray or HD-DVD? This is a systems question that was finally answered in
the last few months by the international optical data storage industry. The best material to
fabricate the most important component of such systems, the short wavelength blue laser,
has long been a topic of extensive research and debate. The generation of blue light using
semiconductors has been a major goal of the semiconductor and optoelectronics industry for
two major reasons. Firstly, optical storage media that operate using the shorter wavelength
blue light allow significantly larger data storage densities when compared with systems such
as CD-ROMs which use near infrared light. As an example, a Blu-Ray disk is capable of stor-
ing a total of 50 Gigabytes of information, roughly six times more than a double layer DVD
disc and almost forty times more data than a computer CD-ROM. Secondly, by mixing red,
green and blue light together one can generate white light using a semiconductor. This was
a major development for solid-state lighting. None of the semiconductor material systems dis-
cussed until now have a sufficiently large energy bandgap to allow them to generate high en-
ergy blue light. Zinc Oxide (ZnO) and Silicon Carbide (SiC) were both promising materials for
blue light emission that have been investigated over the past decades. Whilst these materials
generate blue light, they are notoriously difficult to work with and to process into light emitting
Chapter 4

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Epitaxy – fabrication of atomically perfect crystals

Epitaxy ... this term describes a fabrication method for the growth of crystals which exhibit a perfect three-dimensional arrangement of atoms in space, either in the form of thin crystalline layers with a thickness that is exact almost at the atomic level, or in the formation of nano-perfect three-dimensional arrangement of atoms in space, either in the form of thin crystalline layers with a thickness that is exact almost at the atomic level, or in the formation of nanostructures as discussed in the following chapter. The first methods that were developed used a molten mixture of different elements and crystals were grown by cooling the melt under controlled conditions. Nowadays, most of the semiconductor layers grown at the Walter Schottky Institut and worldwide are fabricated using one of two methods. The first of these methods involves sending a beam of the necessary materials (atoms or molecules) onto a crystalline substrate within an ultrahigh vacuum chamber with precisely controlled concentration, deposition rates and temperature. This method is known as Molecular Beam Epitaxy (MBE) since it utilizes molecular beams of the constituent elements. The second method which is commonly used involves deposition of material based on chemical reactions from source materials that are usually in the gas phase. This method is termed Metal Organic Vapour Phase Epitaxy (MOVPE), since the precursor gases are typically so-called metal-organic compounds.

MBE – crystal growth at the atomic level

Molecular Beam Epitaxy is a growth method that is based on simple physical principles but, technologically, can be extremely demanding, calling for a wide variety of sophisticated Ultra High Vacuum (UHV) components. In principle, an MBE growth system is a special form of an evaporation system. The various metal and semi-metal sources are heated in ceramic crucibles to a temperature ranging between several hundred degrees Celsius to more than 1000 °C, depending on the element, which in turn begin to evaporate. The pressure in the vacuum chamber of an MBE system is typically maintained at an extremely low level of below 10⁻⁸ mbar using suitable pumps. As a result, the evaporated atoms or molecules do not collide with one another. Instead, a well defined beam of atoms or molecules is emitted by the effusion cell, which gives the name of this particular growth method. Separate molecular beams from each of the component materials required to grow the epitaxial film are simulta-
neously incident on the growth substrate, and can be switched on and off using a series of shutters in front of each cell to control the growth of the semiconductor layer. For example, to grow a film of GaAs, the shutters of the Gallium and Arsenic effusion cells would be opened simultaneously to allow Gallium and Arsenic beams to reach the surface of the substrate at the same time.

During growth, metal atoms such as Aluminium or Gallium are readily incorporated into the growing surface of the wafer. Roughly speaking, every group-III metal atom that arrives on the substrate surface is incorporated into the crystal if a Ga-site exists for it to stick. In contrast, group-V atoms such as Arsenic do not stick readily to the surface, a very advantageous property as we will now see. Arsenic atoms arriving at the surface may be incorporated into the crystal, but they may also attach for a while and then detach again. As a result, Arsenic atoms will only be incorporated into the surface of the crystal if they find a place where a bond to a Gallium atom can be formed. Excess Arsenic will reevaporate and leave the surface. Since GaAs consists of alternating layers of Gallium and Arsenic atoms, the different incorporation probability of As compared with Ga ensures that the crystal grows layer by layer – a layer of Ga atoms is deposited due to their high sticking coefficient and is then covered by Arsenic before the cycle repeats itself. In this way, nature sorts the atoms arriving in the overlapping molecular beams and allows for the deposition of perfect crystals of alternating layers of Ga and As with incredible perfection.

In the discussion above we have considered only one type of metallic element from group III of the periodic table. However, to grow mixed crystals such as AlGaAs one would open shutters of the two group III elements (e.g. Al and Ga) and overlap their molecular beams on the substrate with a beam of As atoms. Since the group-III elements (Aluminium, Gallium or Indium) are all chemically similar to one another, they all are incorporated into the growing layer with similarly high probabilities. As a result, the Al and Ga atoms in the AlGaAs crystal distribute themselves statistically between the group III layers, with a concentration determined by the relative flux of different atoms incident on the surface. This means that, by carefully controlling the amount of Al and Ga, researchers can control the local Al content of the mixed AlGaAs crystal with very high precision. In this way it is possible to realise crystals with spatially varying composition – a so-called semiconductor heterostructure. This in turn enables us to precisely tailor the electronic and optical properties of the heterostructure to match the specific device structure needed. MBE is a method that allows the composition and thickness of mixed heterostructures to be controlled with atomic monolayer precision.

MOVPE – Crystals from gases

Molecular beam epitaxy, with beams of individual atoms that do not influence one another on their way from the source towards the substrate is, in many ways, the ideal method to realise perfect three dimensional arrangements of atoms in a semiconductor heterostructure crystal. However, it also has a number of disadvantages. From the materials point of view, there are
a number of elements with high vapour pressures that have a negative impact on the back-
ground pressure in the UHV chamber of the MBE system, making it rather difficult to control.
For example, phosphorous containing compounds could not be easily deposited in MBE
systems until the beginning of the 1990’s when new effusion cell technologies widened the
spectrum of materials that could be deposited using MBE. In addition, when the UHV system
must be opened due to the need for a repair, or for cleaning the system or refilling of the ef-
fusion cells, the system will typically be unsuitable for a number of weeks until the strict UHV
conditions are again reached inside the growth chamber. These long down times following
any kind of servicing of the MBE system is very undesirable for industrial production systems.
The need for high and constant throughput in industrial semiconductor growth systems ne-
cessesitates the use of another type of growth system – gas phase epitaxial growth.

During the 1970’s and 1980’s a growth method was developed in which the elements are not
provided in their pure elemental form but in the form of compounds that react on the growth
surface to deposit a semiconductor crystal. These precursors are typically either gaseous in
their natural form or are evaporated from liquids before being introduced into the growth ves-
sel. For the group III elements (Al, Ga, In), the precursor gases are typically organo-metallic
compounds such as Tri-Methyl-Gallium. The use of such precursor gases gives rise to the
name of this growth process “Metal Organic Vapour Phase Epitaxy” – or MOVPE. During the
synthesis of such a molecule based on methane (CH₄), typically a hydrogen atom is detached
before three of these de-hydrogenated backbone molecules (Methyl, CH₃) bond to a Gallium
atom to form Tri-Methyl-Gallium. The group-V elements are often supplied to the reaction as
hydrogen compounds. Examples include Arsine (AsH₃), which has one Arsenic atom bound to
three hydrogen atoms.

Typically, these precursor gases are mixed with hydrogen and flow through a glass reaction
vessel (see title image of this chapter) that contains a graphite block onto which the substrate
is attached. This graphite block is typically heated using lamps to a temperature between 500
and 800 °C before the reactive gases are introduced. As the gases flow over this hot zone of
the reactor containing the wafer, the gases are decomposed to form GaAs. For example, the
methyl groups break away from the Gallium atom and bind to the hydrogen from the Arsine
to produce methane. This reaction product is again gaseous and can be removed from the
reactor as a waste gas. The resulting Gallium and Arsenic atoms combine to form a new layer
of GaAs at the crystalline surface of the substrate.

During MOVPE growth, the flow of gases can be precisely controlled using so called mass
flow controllers that regulate the flow of the different reaction gases. This provides a high
degree of flexibility to grow crystals with a wide range of different compositions. However, the
use of compounds to grow the crystals instead of the pure elements as in MBE, requires a
fine mastery of the rates for different chemical reactions that occur at the substrate surface.
This can make the process rather complex, since the incorporation of a specific atom in the
crystal depends on a series of chemical reactions, each of which must be controlled precisely
by varying the relative concentrations, temperature and flow rates of different reagents. This
situation is aggravated by one further point. Most of the gases required for MOVPE growth
and some of the product gases are highly toxic. The safe use of such a growth system is only
possible when the exhaust gases can be safely cleaned and the whole environment from the
storage bottle to the waste gas storage system is controlled by a gas monitoring system. All
modern MOVPE systems employ such a gas monitoring safety system to prevent accidents.

Both of the epitaxial growth methods introduced here have their respective strengths and
weaknesses. Aluminium containing compounds are preferentially fabricated using MBE, and
this growth method is generally preferred when the material composition must be controlled
with atomic precision. In contrast, the deposition of Phosphorous and Nitrogen containing
materials is generally easier using MOVPE, and this method is preferred when high through-
put and high volume growth is required, for example in an industrial fabrication facility.

To summarise, a number of modern epitaxial growth methods are being developed and used
in the Walter Schottky Institut in order to grow a range of novel semiconductor structures and
multilayer systems. Such growth techniques are indispensable for the realisation of the special
samples studied by many research groups in the institute.
Schematics of the fabrication of quantum wires and quantum dots by the intersection of quantum wells using the cleaved edge overgrowth technique.
Semiconductor nanostructures constitute extremely promising building blocks for electronic, optoelectronic, and sensing devices. Nanostructures are defined as materials with characteristic sizes in the order of few nanometers ($10^{-9}$ m). Such small structures exhibit new physical and/or chemical properties which may lead to the development of novel devices with possible applications, e.g., in information technology, biomedical diagnostics, and energy as well as environmental technology. Another reason of their importance is that the reduction in size of the conventional microelectronics is coming to an end when the regime of a few nanometers will be reached. Nanostructures may lead to devices with different functionalities, for example, making use of quantum mechanical effects. One central research topic at the Walter Schottky Institut is the realization of semiconductor nanostructures, like quantum wires and quantum dots, by direct, bottom-up synthesis with epitaxial methods. Both chemical vapor phase epitaxy and molecular beam epitaxy are used. These crystal growth methods were described in Chapter 4. Here, we present selected examples how semiconductor quantum dots and quantum wires can be fabricated by self-assembly and self-organization.

As discussed in Chapter 4, during growth by molecular beam epitaxy ultra-pure sources of material are vaporized in separate ovens, so-called effusion cells. The atoms or molecules are released in a controlled way by the sources and are successively transported as a ‘beam’ to the substrate, where they are deposited. By mastering the release of the atoms and molecules, but also the conditions that lead to certain arrangements on the substrate, it is possible to fabricate complex alloys with precisely controlled compositions and geometries with sub-nanometer precision. The study of the growth mechanisms and the properties of the materials are important steps before novel devices and nanostructures for fundamental studies can be realized. Only with a deep understanding of the physical and chemical phenomena occurring during the synthesis, it is possible to create new forms of matter, controlled on the nanometer scale.

Quantum dots are semiconductor nanostructures that are spatially confined in three dimensions. Due to the small dimensions, discrete optical and electronic properties similar to atoms arise (see Chapter 6). The interest in quantum dots is strongly driven by applications like semiconductor laser devices, solar cells, as well as the control of quantum phenomena as the basis for future quantum information technology.

Molecular beam epitaxy allows the synthesis of different types of quantum dots. One of the most common methods is the so-called Stranski-Krastanow growth mode, in which the emitting material is grown on a lattice mismatched substrate (e.g., InAs on GaAs, or Ge on Si). The epitaxial layers are strained in this case due to the different lattice constants. This leads to a strain-driven transition from the layer-by-layer (two-dimensional) growth to three-dimensional island growth. This transition occurs at a critical layer thickness that depends on the chemical and physical properties of the materials combined, such as surface energies and lattice parameters. Different material systems, like InAs (InGaAs) on GaAs or on InP as well as Ge on Si are used at the WSI to fabricate quantum dots with this method, depending on the type
of application. In order to be able to study these quantum dots with spectroscopic methods or to demonstrate functionality of novel devices, it is necessary to overgrow the islands and thus embed them completely in a crystalline matrix. Diffusion and segregation processes will change the composition and shape of the quantum dots during overgrowth, which leads to altered optical and electrical properties. A main interest in quantum dots stems from the possibility to control electrons, spins, and photons, which is a basic requirement for applications in quantum information technology. For this purpose, it is necessary to be able to tune the properties of the dots, e.g. with an applied electric field. To this end, the quantum dots have to be embedded in a diode, or even more complex device structures, like micro-resonators.

The materials technology oriented research at WSI has been extensively devoted to the study of the self-assembly and formation mechanisms of such nanostructures. Only with the understanding of the growth mechanisms it is possible to find conditions under which the anticipated properties of the quantum dots are achieved, which depend sensitively on the exact shape and composition. A high control of these parameters, as well as of the density and position of the dots is essential.

The functionality of quantum dots is further increased when a couple or more of them are positioned in close proximity to each other, such that their electronic states can interact. The quantum mechanical coupling of different quantum dots is an important building block for quantum information technology. One method for obtaining pairs of quantum dots is the growth of a double layer of e.g. InAs on GaAs. First, a layer of quantum dots is deposited and capped with GaAs. If the capping layer is thin enough, a second layer of quantum dots will nucleate exactly onto the positions of the capped islands. This is due to the lattice distortion originating from the first layer, which still exists at the surface up to capping layer thicknesses of about 30 nm. Thus it is possible to realize coupled quantum dots with adjustable coupling strength by varying the separation of the dots from zero to about 30 nm. The resonant coupling of such quantum dot molecules can be tuned by embedding them into a diode structure. This has been demonstrated for the first time at WSI a couple of years ago.

Another concept for the precise spatial control of quantum dots is based on so-called double cleaved edge overgrowth, a method which was pioneered at the WSI. GaAs (100) surfaces are the most common planes for epitaxial growth. Atomically flat (110) surfaces can be fabricated perpendicular to the (100) plane by cleaving the GaAs wafer. In order to fabricate a single dot, one starts with an AlGaAs/GaAs/AlGaAs quantum well grown in a first step on the plane (100) wafer. A second quantum well is then grown onto the (110) plane after cleaving the sample inside the molecular beam epitaxy system (in-situ cleave). As a result, a quantum wire forms at the crossing of the two perpendicular quantum wells. Another, third quantum well, grown on a second (110) cleavage plane perpendicular to both previous planes, leads to the formation of a quantum dot at the intersection of the three quantum wells. All three spatial directions are controlled with the atomic precision of the molecular beam epitaxial process in this way. Single, as well as coupled, but also chains of quantum dots can be fabricated depending on the structure of the first epitaxial layer (multiple quantum wells). The main principle of the cleaved edge overgrowth technique is the growth on a surface that has been freshly cleaved in situ under the ultra-high vacuum conditions inside the epitaxy machine. Growth on such cleavage planes requires especially high purity conditions of the system, and only very few laboratories worldwide are able to fabricate high quality structures with this method. Nanostructures obtained by cleaved edge overgrowth are model systems for high quality low dimensional structures. For example, the quantum mechanical coupling of pairs of quantum dots was demonstrated for the first time with such samples at the WSI, already about 10 years ago.

Cleavage planes can also be used as templates for the ordered formation of self-assembled quantum dots. Here, one grows in a first step thin InGaAs layers embedded in GaAs. This results in a precise stripe pattern with alternating layers at the cleavage plane of such a sample. When growing lattice mismatched InAs on such a cleavage plane, one finds under certain growth conditions that this material accumulates only on the InGaAs stripes. Wires, quantum dot arrays, and on wider InAs stripes also double quantum dot arrays are formed, depending on the amount of InAs material deposited. The hope, that a more homogeneous size distribution of the quantum dots is achievable with this method, due to the spatial alignment of the nanostructures.

Free standing nanowires are a final example of engineered nanomaterials fabricated at WSI and presented here. Nanowires are one-dimensional crystalline structures, with diameters of the order of several nanometers and lengths in the range of μm. They are ideally suited for studying, for example, one-dimensional electric transport, due to their high length-to-width aspect ratio. Various materials systems and growth methods are used at WSI to fabricate such wire structures. These include GaAs, GaN, ZnO and Si based systems. In the case of GaAs it was possible to grow such nanowires with the high purity molecular beam epitaxial system. The wires could be also overgrown in radial direction with a hetero-shell structure. In addition, quantum dots could be embedded along the wire. These are very promising results for the fabrication of controlled wire-dot coupled systems. The project is still in its initial stage, but it is expected, that it will develop to a major future activity at the institute.

In this chapter, the importance of research on the synthesis of novel materials has been outlined. Indeed, thanks to the understanding of the growth mechanisms it has been and is possible to find new ways of producing new structures, which at the same time help the realization of new device concepts and to measure novel fundamental properties of lower dimensional systems.
Physics of Lower Dimensional Systems
Two-dimensional systems

Two-dimensional electronic systems can be realized at the interface between two different semiconductors or in thin layers embedded in materials with a larger band gap. A potential barrier exists at the interfaces e.g. for electrons in the conduction band. Charge carriers can only flow into the neighboring material if they have enough energy. One may say they are trapped in a trench. A detailed design of the layers enables one to realize semiconductor lasers, emitting at a specific wavelength (see Chapter 8). Quasi-free charge carriers in the conduction band are achieved by doping a semiconductor with atoms having one extra electron (see Chapters 3 and 4). In bulk semiconductors the free motion of electrons is hindered by scattering at the positively charged donor impurities. Hetero-epitaxy allows the spatial separation of charge carriers from the ionized donor impurities. To achieve this, one makes use of the confinement of charge carriers in one, two or even three spatial directions. Electrons then can move freely only in two or one direction or are completely localized. One talks of quantization of energy states in one-, two- or three-dimensional potential wells, as the confinement is based on quantum mechanical principles. The electronic and optical properties of charge carriers in such lower dimensional systems exhibit a wealth of fascinating physical properties, which have been studied extensively worldwide over the past 30 years. The most spectacular effects which have been discovered are the Quantum Hall Effect and the Fractional Quantum Hall Effect. These findings were honored with the Nobel Prize in Physics for Klaus von Klitzing (1985) as well as Bob Laughlin, Daniel Tsui, and Horst Störmer (1998). They initiated a world-wide boom of research in the area of “physics of lower dimensional systems”. The numerous contributions of the Walter Schottky Institut to this research are reflected in many publications, often in collaboration with national or international partners. Selected examples of physics phenomena in lower-dimensional systems are discussed in the following.

Many fascinating new effects appear, especially if a strong magnetic field is applied perpendicular to the two-dimensional electron system. Charge carriers are forced to move in circles due to the Lorentz force in a magnetic field. In quantum mechanics, this is described as quantization of the two-dimensional motion or energy of the electrons, somewhat similar to the orbital quantization in atoms. The electrons fill up these orbitals and at certain magnetic fields, the area of the sample is completely filled with such occupied states. In other words, a quantized level, a so-called Landau orbital, is then determined just by the universal constants \( h, e, \) and \( B \).

Quantum Hall Effect and Shubnikov-de Haas oscillations

The mean free path of the electrons can be as long as 1mm in optimized samples of highest purity. This corresponds to an increase of mobility by a factor of 1000 to 10000 compared to the bulk. An important high frequency device, which is based on the enhanced mobility, is the so-called High-Electron-Mobility-Transistor or HEMT, which is used as low-noise amplifier e.g. in satellite antennas or mobile phones. Many interesting basic physics phenomena and effects have been discovered in such high mobility two-dimensional electron systems, especially at low temperatures and in high magnetic fields (e.g. the Fractional Quantum Hall Effect). Only very few laboratories in the world are capable to fabricate such pure and high-quality hetero-structure samples. A special GaAs based molecular beam epitaxy system was installed at the Walter Schottky Institut in the mid-nineties in order to be able to grow GaAs/AlGaAs heterostructures of highest quality. This machine provides the materials basis for many research projects dealing with fundamental physics phenomena in lower dimensional electron systems within and outside the institute. Many fascinating new effects appear, especially if a strong magnetic field is applied perpendicular to the two-dimensional electron system. Charge carriers are forced to move in circles due to the Lorentz force in a magnetic field. In quantum mechanics, this is described as quantization of the two-dimensional motion or energy of the electrons, somewhat similar to the orbital quantization in atoms. The electrons fill up these orbitals and at certain magnetic fields, the area of the sample is completely filled with such occupied states. In other words, a quantized level, a so-called Landau orbital, is then determined just by the universal constants \( h, e, \) and \( B \).
One-dimensional systems – quantum wires

It was already mentioned that the edges of the samples play an important role in magneto-transport experiments due to the formation of edge channels. The motion of charge carriers is unidirectional in these edge channels. Motion in one dimension is fundamentally different from motion in two or three dimensions. This is already evident from simple classical examples. Flying birds have no problem to avoid other flying birds or obstacles by flying over or under, left or right (three dimensional motion). Soccer players can come close to the goal, and sometimes even score a goal, despite of the presence of the opposing team (two dimensional motion if the ball is kept low, three dimensional for high shots). Billiard is a typical game making use of two dimensional motion, obviously taking momentum and energy conservation into account. Motion in one dimension is completely different. Let’s consider a railway train which has a breakdown. As a result, the railway track is blocked for all other trains. The same holds for cars on a narrow road where a traffic jam builds up. An obstacle in a one-dimensional system stops motion collectively. Everybody “feels” the obstacle. Somehow this kind of behavior is also found for charge transport in different dimensions. The effect of an obstacle, e.g. a charged impurity, decays in space in two- and three-dimensional systems. In one-dimensional systems, however, all carriers get localized and current will be blocked at low temperatures. The behavior of the electrons needs to be described collectively. Only collective excitations are possible in one dimension. Another intriguing and fundamental effect in one-dimensional systems, e.g. quantum wires, is the appearance of quantized conductance or resistance in units of $\hbar/e^2$ without magnetic field. This means the current remains constant whilst the charge carrier concentration is changed. The deeper reason for this behavior lies in the fact that the velocity is increasing with increasing electron energy by the same amount as the electron density is decreased at this velocity. The product of both quantities determines the current and they cancel each other exactly in one-dimensional systems. This is a fundamental result which holds for all one-dimensional systems when the quantization of the carriers in two directions is strong enough that free motion is only possible in the third direction. It is also important that the quality of the quantum wire is high enough, so that the charge carriers move ballistically over the entire length of the wire, which means in our simple classical picture that the wire does not contain obstacles, which would scatter the electrons backwards. First experiments of this kind were performed with samples based on GaAs/AlGaAs heterostructures containing a high mobility two-dimensional electron gas. A quantum wire or quantum point contact is formed by special control electrodes fabricated by e-beam lithography on the sample surface. These so-called gate electrodes define a narrow channel, where the electrons can move only in one direction, giving rise to quantized conductance through the one-dimensional channel. E-beam lithography is required, as the separation of the gate electrodes has to be smaller than 100 nm in order to achieve a quantum wire. Another method to fabricate ballistic quantum wires at the WSI is based on cleaved edge overgrowth, a method discussed in Chapter 5. All length scales of the nanostructures are defined by the epitaxial process with this method and complicated three dimensional hetero- and nanostructure geometries including possibilities to study electron tunneling into two- and one-dimensional channels. The electronic structure of low-dimensional systems can be mapped with electron tunneling through ultrathin barriers. An emerging field for fabrication of quantum wires is also the direct self-assembly under special epitaxial conditions, as discussed in Chapter 5.

The Planck constant, and $e$, the elementary charge. Today, the unit of the electrical resistance is defined by the Quantum Hall Effect ($R_H = \frac{h}{e^2} = 24,812807\ldots \, \Omega$) and named after Klaus von Klitzing, who discovered this effect in 1980. The Quantum Hall Effect is fundamentally important in many areas of physics and has led also to various applications. Additional quantized Hall resistances are observed in between the so-called Integer Quantum Hall plateaus in samples with very high mobility. This so-called Fractional Quantum Hall Effect has its origin in the interaction between the electrons in a strong magnetic field. The effect was studied in great detail worldwide, both theoretically and experimentally over the past 20 years, often with high quality samples provided by the Walter Schottky Institute.

Physics of Lower Dimensional Systems

Experimental set-up for spectroscopy with high spatial resolution

Schematic view of a quantum wire transistor fabricated by cleaved edge overgrowth

Quantum point contact
Zero-dimensional systems – quantum dots

Carrier confinement in all three spatial directions on length scales less than 100 nm results in quantum dots. Electrons can only occupy discrete energy levels in such systems. A shell structure is forming, similar as in atoms, and quantum dots are therefore often called artificial atoms. Apart from the shell structure there is another important effect in small dots, the so-called Coulomb blockade. Coulomb blockade can be explained classically, as it is based on the electrostatic repulsion between the negatively charged electrons. Extra energy is needed to bring an electron onto a small dot if there are already one or more charges on it. A quantum dot can act as a Single Electron Transistor in combination with tunneling contacts and gate electrodes. In general, quantum dots are used to control a single charge, a single spin, and a single photon. Therefore they are model systems for Quantum Information Technology. Study and control of quantum dots is one of the main research areas at the WSI at present. Electrically controlled Quantum Dots are fabricated from high mobility two-dimensional electron systems by using control gates of special geometry, defined by e-beam lithography on top of the samples, either on Si or on GaAs. The gate electrodes define local potential minima which can be charged with individual electrons, one at a time. Test devices are produced and, in combination with point contacts, single charging can be detected. The nearby point contacts act as sensitive electrometers. Other kinds of quantum dots are fabricated by methods described in Chapter 5, like double cleaved edge overgrowth or self assembly of quantum dots in lattice mismatched systems, e.g. InAs on GaAs. Such quantum dots are of special interest for optical and coherent control of charges, spins, and photons, as they show excellent optical activity. Many pioneering results were achieved with optical spectroscopy of single and coupled quantum dots at the WSI. The first luminescence spectrum of a single quantum dot was measured already in the early 1990’s. Luminescence is the emission of light after excitation of the sample with photons, e.g. from a laser. Electrons are promoted from the occupied valence band states to the empty conduction band states by absorption of photons. The recombination of these carriers is measured via the emitted photons. Spectroscopy with high spatial resolution is required to be able to study single dots. Confocal microscopy and near field spectroscopy was developed at the WSI for this purpose. The recombination of electrons and holes is a characteristic signature of the energetic states in the semiconductor. In quantum dots these states are discrete, similar as in atoms, as described above. This leads to sharp spectral emission lines. An electron-hole pair forms a so-called exciton before recombination due to the Coulomb attraction of the differently charged carriers. This is analogous to a Hydrogen atom. The wavelength (color) of the emitted light is extremely sensitive to the occupation of the dot with electrons and / or holes. Two electron-hole pairs build a bi-exciton, in analogy to a hydrogen molecule. The emission of a bi-exciton is typically red-shifted due to the additional binding energy. Also one additional electron in the dot results in a specific shifted emission wavelength of the charged exciton. Charging can be controlled by embedding the quantum dot in a diode structure.

Control and manipulation of charge is the basis for future quantum devices. The pioneering work performed at the WSI in this field is manifold and includes for example the storage of a single charge, making use of stored charges for sensitive infrared detectors, the control and storage of single spins by applying circularly polarized light, the first observation of resonant coupling of two nearby quantum dots, the detection of single electron-hole pairs via photocurrent measurements (“smallest solar cell in the world”), the coherent control of such photocurrents and many more. These measurements were done on different kinds of quantum dots, fabricated at the WSI, often for the first time worldwide. These include thickness fluctuation dots in thin GaAs potential wells, often called natural dots, coupled quantum dots by double cleaved edge overgrowth, and self-assembled dots based on the InAs/GaAs and Ge/Si materials systems.

First measurements of excitons and biexcitons in a single dot - pioneering work at WSI

1 Photoluminescence of coupled quantum dots
2 Coherent control of coupled quantum dots
3 A single quantum dot photodiode

Chapter 6 Physics of Lower Dimensional Systems
Mother Nature has already mastered many nanophotonic effects. The Morpho butterfly has intensely blue iridescent wings due to two dimensional periodic light scatterers on their surface that preferentially scatter blue light. Researchers in the Walter Schottky Institut currently structure semiconductors with similar patterns to obtain an array of spectacular optical effects.
Optics in nanoscience is often called nanophotonics - a field of research with the primary goals of understanding the interaction of electromagnetic radiation (photons) with sub-wavelength sized materials and learning how to control and manipulate these light-matter couplings by tailoring the physical, chemical and quantum properties of the system. Semiconductor based nanophotonic systems typically have dimensions spanning the range from a few nanometres as in the case of a quantum dot “artificial atom”, nanowire or nanotube, to a few hundred nanometres corresponding to the wavelength range over which semiconducting materials interact strongly with light. It is only during the past twenty years or so, close to the age of the Walter Schottky Institut, that modern nanofabrication methods such as electron beam and nanoimprint lithography, direct laser writing and holographic interference lithography have provided researchers with the tools to controllably structure semiconducting materials on these sub-wavelength length scales and develop and make use of a diverse range of striking optical phenomena. When combined with novel fabrication methods for nanoscale light emitters, such as chemical synthesis and self assembly, a fascinating and broad range of photonic and electronic hybrid nanomaterials can be realized with widespread potential for applications across the fields of optics, information technology and engineering. However, many of the nanophotonic effects that are being studied and implemented are not new; Mother Nature has been optimising and using such phenomena for millions of years! Specific examples include the dramatic iridescent blue colour of the wings of a Morpho butterfly (Morpho rhetenor) that arise from sub-micrometer sized periodic light scatterers on the wing surface, the complex and highly optimised photochemical reactions involved in photosynthesis that harness, store and inter-convert optical energy in living organisms and the complex and highly optimised photochemical reactions involved in the optical resonator by two mirrors that have extremely high reflectivity, beyond 99%. Such 1D photonic crystal mirrors in a VCSEL are formed from many repeats of two semiconductor layers with different refractive indices that can be deposited using the modern epitaxial growth methods described in Chapter 4. Whilst a 1D photonic crystal can be readily made using semiconductor multilayer structures, for 2D photonic crystals the refractive index must be periodic in two spatial dimensions. Such systems can be realised by defining a periodic array of cylindrical air holes within a semiconductor using electron beam lithography and reactive ion etching to structure the material at the nanoscale. To produce photonic band gap effects in the visible and near infrared region of the optical spectrum, the holes need to have a radius below 100 nm and extremely smooth sidewalls with roughness of the order of only ten nanometres. Furthermore, the periodicity has to be in the range 150-250 nm to produce band gaps that overlap the wavelength range where typical semiconductor nanostructures are optically active. These fine tolerances are only attainable using extremely precise nanofabrication methods. Researchers in the WSI have been fabricating 2D photonic crystal structures for several years from both silicon on Insulator (SOI), GaInAs – GaAlAs and GaAsP semiconductor multi layer systems. Samples typically consist of a freestanding optically thin membrane of semiconductor (silicon or GaAs) that is perforated with a lattice of air holes to create the 2D photonic crystal. Light is then trapped within the thin membrane by total internal reflection at the upper and lower semiconductor-air interfaces and its propagation in the plane of the membrane is strongly modified by interaction with the photonic crystal structure.
Nanophotonics

Controlling the emission of light

To illustrate some of the novel and unusual effects that occur in 2D photonic crystal nanostructures and describe some of their potential applications, we discuss a specific semiconductor multilayer system consisting of a thin Al_{0.8}Ga_{0.2}As layer onto which an optically thin waveguide is grown from GaAs. A 2D photonic crystal is then patterned into the multilayer structure and the Al_{0.8}Ga_{0.2}As region serves as a sacrificial layer which is eventually removed in the last processing step to form a thin, freestanding, perforated membrane. In these experiments, the active GaAs core of the membrane waveguide typically contains self-assembled quantum dots (see Chapter 5) that act as internal light emitters when they are excited by a laser. By analysing the intensity, direction, and rate at which light is emitted from such embedded quantum dots, it is possible to probe the local photonic properties of the system and to tailor the design of the structure for a particular application. The average time required for an excited quantum dot to emit a photon, the so called spontaneous emission lifetime, is found to lengthen by a factor of ten in the photonic band gap, where light is able to propagate with much reduced loss. Detailed studies showed that more than ten times more light can be extracted from the semiconductor membrane patterned with the photonic crystal as compared to the same system without it. Such photonic band gap materials are, thus, extremely useful to enhance the light extraction efficiency from light emitting structures and as such have already been widely adopted and developed by the optoelectronics industry to produce high performance devices.

Trapping light in photonic crystals

By controllably tailoring the size of a single hole in such a 2D photonic crystal one disrupts the almost perfect translational symmetry of the photonic crystal and creates a tiny region where light can be trapped. Such a defect then constitutes a nanoscale optical resonator with a volume that can be reduced close to the ultimate limit of a cubic half wavelength. Optical measurements performed on a range of "L3-defect" resonators, so called since they consist of a line of three missing holes in a line, reveal six pronounced peaks corresponding to the resonant wavelengths of the cavity, where the electromagnetic energy is localised to length scales of only a few hundred nanometres. Such photonic crystal nanocavities allow established techniques from atom and ion quantum optics to be translated to solid state systems. Examples include the use of the so called Purcell effect to dramatically enhance the spontaneous emission rate into the cavity mode when compared to emission into other modes of the system. This effectively funnels light from the emitters into a specific direction and allows the realization of ultra-efficient nanometre scale lasers, so called thresholdless lasers, which begin to exhibit lasing for very low injected currents and exhibit much lower noise compared to typical semiconductor lasers in CD and DVD players.

Photons one at a time

Other technologies that have benefitted from the use of nanoscale optical cavities include curious light emitting devices that emit individual quanta of light, single photons, every time they are required to do so. Such single photon sources are the basic hardware required for the implementation of future quantum information technologies such as quantum cryptography that involves sending and receiving secret cryptographic keys encoded onto the properties of individual photons. Although secure quantum-key-distribution systems based on attenuated laser light pulses have been commercially available for a couple of years, they typically only permit quantum key distribution over short optical fibres (~10-100 km), since a large fraction of the laser pulses contain no photons at all. A true single-photon emitting device that provides precisely one photon per information carrying pulse would dramatically improve the performance of quantum key distribution systems, allowing cryptographic keys to be shared between communicating parties over long fibres with absolute security against eavesdropping. Key performance measures for such triggered single photon sources are their efficiency, defined as the fraction of single photons collected in the experiment or application per trigger, and the probability that they emit more than one photon per pulse. It turns out that single quantum dots are capable of emitting photons one at a time, and placing them inside 2D photonic crystals and defect nanocavities dramatically enhances their efficiency. To understand how a quantum dot can emit single photons let us consider the generation of light from a single InGaAs self-assembled quantum dot embedded within a GaAs photonic crystal. Since InGaAs has a lower-energy bandgap than the surrounding GaAs, the quantum dot forms an energy trap for electrons and holes - the negatively and positively charged particles that carry electric current and annihilate each other to generate light in a semiconductor. If the dot is sufficiently small it can only be populated by two electrons and two holes before the charges spill out into the surrounding GaAs material. If we now excite the system with a very short laser pulse, with duration of only one picosecond (1ps...
Delay signifying single photon generation. Electron microscope pictures of a quantum dot nanocavity single photon source (red curve) with a missing peak at zero time delay signifying single photon generation.

Nanophotonics

- one millionth of a millionth of a second), the dot is very rapidly filled with two electron-hole pairs. After the quantum dot has been filled it decays via emission of two photons with different colours; first one of the two electrons annihilates with one of the two holes to produce a photon at a particular wavelength ($\lambda_{1e-1h}$). This leaves only a single electron-hole pair in the dot that subsequently recombines, over timescales of a few nanoseconds, to generate a second photon at a different wavelength ($\lambda_{2e-2h}$). The two photons emitted by the quantum dot have unique wavelengths due to the Coulomb interaction between the charged electrons and holes in the dot. Since the time required to fill the dot with two electrons and holes is much shorter than the time required for the emitted photons to emerge, only one photon is emitted at either the wavelengths $\lambda_{1e-1h}$ or $\lambda_{2e-2h}$ per excitation pulse. In this way, each excitation cycle results in the dot emitting one, and only one, exciton photon and the quantum dot acts as a deterministic single photon source.

Researchers in the Walter Schottky Institute have been incorporating individual quantum dots into photonic crystal defect nanocavities to realize high efficiency single photon sources. Such sources have an efficiency that is more than ~10 times higher than for an equivalent single photon source, confirming that it is capable to deterministically produce single photons at a particular wavelength ($\lambda$). The two photons emitted by the quantum dot have unique wavelengths due to the Coulomb interaction between the charged electrons and holes in the dot. Since the time required to fill the dot with two electrons and holes is much shorter than the time required for the emitted photons to emerge, only one photon is emitted at either the wavelengths $\lambda_{1e-1h}$ or $\lambda_{2e-2h}$ per excitation pulse. In this way, each excitation cycle results in the dot emitting one, and only one, exciton photon and the quantum dot acts as a deterministic single photon source.

As the quality of an optical nanocavity is improved further it becomes capable of trapping photons over longer and longer timescales before they escape. At some point, single photons generated by a quantum dot in the cavity remain trapped long enough to be re-absorbed by the same emitter. Energy is then periodically exchanged between the emitter and the photon field of the cavity mode in a process known as a vacuum Rabi oscillation. Such vacuum Rabi oscillations couple the quantum photon field of the cavity with the 1e-1h optical transition in the quantum dot. The emitter and photon form a special, and particularly useful, quantum mechanical state that is neither photon nor electron-hole pair – it is a curious quantum mechanical mixture of the two situations. This is akin to the Gedanken experiment of Schrödinger’s cat, made famous by one of the discoverers of quantum mechanics, Erwin Schrödinger. In this experiment an unfortunate cat is trapped in a box and exists in a quantum mechanical state of limbo; it is both alive and dead at the same time, provided that its quantum state is not tested by measurement. The half electron-hole pair – half photon state in the experiments performed in the Walter Schottky Institute are a solid-state analogue of Schrödinger’s cat and has promise for emerging fields such as photon based quantum information processing and distribution of quantum mechanical states by exchanging entangled photons between different nodes in future networks of quantum computers. Recent work has led to the observation of such entangled states in electrically contacted photonic crystal nanocavities. This structure represents a system where the “cat” can be electrically put into its curious alive and dead state by tuning the voltage applied to a gate contact.

Quantum efficiencies in excess of ~20% at repetition frequencies higher than ~100MHz. These values are state of the art worldwide for solid state single photon sources and would dramatically extend the length of optical fibres over which single photon “quantum cryptographic keys” could be sent without them being lost.

Is the cat alive or dead?

Observation of solid state analogues of Schrödinger’s cat, namely strong light-matter coupling in an electrically tunable single dot nanocavity. The quantum mechanical entanglement between dot and cavity can be switched on and off using an electrical control voltage.

Nanophotonic sensors

Nanophotonic semiconductor structures can also be used for sensing applications; to detect minute changes of refractive index in miniscule quantities (~1 femtolitres) of gases or liquids via changes of their optical properties and, even, to optically detect the presence or absence of single metallic or semiconducting nanoparticles or biological molecules such as proteins, DNA or viruses. Label-free optical bio-sensing is a rapidly emerging research area with a very wide spectrum of potential applications ranging from medical and clinical diagnostics, to the measurement of glucose concentration in blood. There are various possibilities for optical bio-sensing, including the use of SPR sensors, surface-enhanced Raman spectroscopy (SERS) and surface-enhanced infrared absorption (SEIRA) sensors. In SPR sensors, a thin film of metal is deposited on a surface and a light beam is directed at an angle to the surface. The light reflects off the metal film and is partially absorbed by the metal, causing a shift in the wavelength of the light. This shift is proportional to the density of the molecules on the surface, allowing for sensitive detection of substances.

In SERS sensors, the metal film is excited by the laser pulse. The peak at zero time delay vanishes completely for the second photon source. The two photons emitted by the quantum dot have unique wavelengths due to the Coulomb interaction between the charged electrons and holes in the dot. Since the time required to fill the dot with two electrons and holes is much shorter than the time required for the emitted photons to emerge, only one photon is emitted at either the wavelengths $\lambda_{1e-1h}$ or $\lambda_{2e-2h}$ per excitation pulse. In this way, each excitation cycle results in the dot emitting one, and only one, exciton photon and the quantum dot acts as a deterministic single photon source.
Hybrid nanophotonic systems

In order to fully exploit the potential of the diverse range of organic and inorganic nanosystems that exist, an extremely important step will be the development of reliable electrical contacts to connect them to the outside world and electrically manipulate and readout their properties. The nanotechnology and nanomaterials group in the Walter Schottky Institute is investigating the possibility to build novel types of photo-electronic systems that consist of mixed inorganic and organic nanosystems such as molecules, nanocrystals, carbon nanotubes and photosynthetic “light harvesting” proteins. These types of “hybrid nanostuctures” can be constructed by combining sophisticated nanofabrication techniques such as chemical functionalisation and self-organisation with state of the art top-down nanolithography methods such as electron beam lithography and focussed ion beam writing. This approach allows the properties of the nanostructure to be probed by measuring the photocurrent response in an external electrical circuit. The photocurrent signals generated provide information on fundamental optical excitations, on charge and heat transfer processes within the hybrid nanostructures, on spin phenomena as well as on so-called “ballistic” electron transport that occurs without energy relaxation. An important focus of the investigation is the electronic integration of molecules and proteins into macroscopic circuits and their investigation using photocurrent transport spectroscopy. As a particular example, the nanotechnology and nanomaterials group at the WSI has been investigating photosynthetic reaction centres using carbon nanotubes that are covalently bonded to them. The photo system reaction center I is a chlorophyll protein complex located in thylakoid membranes of chloroplasts and cyanobacteria. This protein mediates a light-induced electron transfer through a series of redox reactions. The incorporation of such optoelectronically active proteins in a nano-electronic circuit is of very strong relevance for novel applications, since such light harvesting proteins have optical properties that are highly advantageous compared with man made nanostructures. First measurements are extremely promising, indicating that chemically modified proteins can be specifically contacted and, furthermore, are optoelectronically active.

One of the future dreams of such nanophotonics research is that, by combining nano-electronic and nano-photonic nanostructures, a new field of integrated photonics or quantum photonics will be opened up where light is used to represent, switch and distribute information and even to realise a photonic transistors that allow optical switching and logic operations to be performed using single photons. These dreams for the field of photonics are far behind electronics in terms of maturity. There are no large RAM-type photonic memories, photonic circuits are physically larger than their electronic integrated circuit counterparts and their functionality is rather limited even today. However, few or none of these issues are fundamentally impossible to overcome and the field is rapidly developing with the discovery and utilization of novel phenomena and the development of a wider range of potential applications that operate using the principles of quantum mechanics.
Semiconductor Laser Diodes
Semiconductor Laser Diodes

Semiconductor lasers

The research on basic semiconductor electronics and technology at the Walter Schottky Institut is mainly driven by the demand for new or better semiconductor devices needed for advanced optically based information technology systems. This particularly holds for novel semiconductor lasers that play a central role in future communications, sensing and consumer applications. Accordingly, our research activities are not restricted to the development and investigation of new semiconductor materials that can be considered as the raw materials for many new devices (Chapter 4), but also covers the device research and development. The latter not only implies the realisation of new device concepts, such as electronically tunable laser diodes, nanoscale or quantum cascade lasers, but also includes lots of device simulations and application-related device characterisation.

The main focus of our laser research is on near- and mid-infrared lasers for optical communications and trace gas sensing. Semiconductor lasers for optical communications usually operate around 1.3 and 1.55 µm wavelength and require very high switching rates, or modulation bandwidths, of the order 10 GHz corresponding to about 5000 digital TV channels or 1000 high-speed DSL lines. Lasers for sensing applications must emit exactly (±1 nm) at the targeted wavelength and need to be tunable continuously over a certain wavelength range (several %) to scan the gas absorption lines, such as CH₄ at 1.7 µm or CO₂ at 2.0 µm and 4.4 µm. Both types of lasers should emit light of a well defined optical polarisation and at a single frequency. A wide variety of different compound semiconductor materials such as AlGaAs/GaAs, AlGaInAs/InP or AlGaAsSb/GaSb are necessary to achieve the rather different target wavelengths that are needed. Sophisticated device concepts utilising sub-wavelength and nanoscale structures are employed to obtain polarisation stability and single-mode operation, as well as to customize other relevant device characteristics such as the spatial profile of the beam emerging from the laser and the frequency purity.

The three main laser research areas of the institute are broad-band communication lasers that can be switched off and on very rapidly, tuneable lasers for infrared gas-sensing applications, and completely new types of devices called quantum cascade lasers that emit light in the mid-infrared region of the spectrum. Below, we discuss these devices in more detail.

Broad-band lasers for optical communications

The huge bandwidth of fiber-based optical communications calls for the development of high-speed and widely tunable laser diodes in the ‘optical windows’ at 1.3 and 1.55 µm of the glass fibers. Thereby, a relative bandwidth of only 1 % at 1.55 µm corresponds to about 2000 GHz which in principle be covered by 200 equally spaced 10 GHz bandwidth lasers. To address these types of applications, the use of identical but electronically wavelength-tunable high-speed lasers would be more reasonable since these lasers can individually be adjusted to the channels of such a system. At the WSI, we explore and investigate the so-called Vertical-Cavity Surface-Emitting type of lasers (VCSELs) in the 1.3 and 1.55 µm wavelength ranges. They are capable of more than 10 GHz modulation speed and are tunable over a limited wavelength range. Due to the given wavelengths of the fiber-based communications, these VCSELs are made from InP-based compounds, covering the entire 1.3 to 2.3 µm wavelength range. Meanwhile, these InP-based VCSELs achieve 12 GHz modulation bandwidth and threshold currents below 1 mA. Because of their small size, some 20000 VCSELs can be made by our spin-off-company VERTILAS on 3 inch diameter InP-wafers in one processing step.

Lasers for infrared gas sensing

The detection and concentration measurement of gases is an important technique in environmental engineering, medicine, control of combustion processes and many other applications. Since most gases exhibit typical absorption lines in the near- and mid-infrared, the concentration can be detected contactlessly by using optical methods such as laser spectroscopy.
so that the emitted photons have a smaller energy. This results in long laser wavelengths that typically lie in the mid-infrared. Hence, applications of the QCLs are measurements and sensing in the mid- to far-infrared, and even Terahertz QCLs with wavelengths of the order 100 – 200 µm (1.5 – 3 THz) have been fabricated. An issue for all QCLs, particularly in the early years, has been to achieve laser operation at room-temperature and above to avoid the necessity of expensive cooling systems. For this purpose, it has been mandatory to reduce the threshold current density of the QCLs considerably.

At the WSI, research on low-threshold room-temperature QCLs in the 5-10 µm wavelength range has been carried out since about ten years. Doing a lot of ‘bandgap-engineering’ and introducing novel quantum well QCL structures, the so-called injectorless QCLs, researchers at the WSI were able to cut the room-temperature threshold current density down from 2 kA / cm² to about 0.4 kA / cm², surpassing any other QCL types fabricated to date. The bandstructure of the active region in these lasers is rather complex, consisting of nanoscale quantum well layers composed of four different semiconductor alloys. The successive improvement of the QCLs and the introduction of advanced device concepts and structures has led to this impressive reduction of the threshold current densities over the past years. With threshold values below 0.5 kA / cm², injectorless QCLs are hence very suitable for sensing and measurement applications at and even slightly above room temperature.
Modeling and Simulation of Semiconductor Devices
Theoretical modeling and numerical simulations are indispensable tools in the development of novel semiconductor devices to better understand, to accurately predict, and to control nanotechnology in the areas of nano-electronics and nano-sized lasers. The structural dimensions of modern devices have reached the size of a few nanometers, which is comparable to the dimension of a few atoms or small molecules. At those dimensions, the well-known laws of the macroscopic world no longer hold; instead, this world is governed by the laws of quantum mechanics. In this regime, objects such as electrons exhibit baffling properties, for example behaving simultaneously as waves and particles.

While we are nowadays able to control and deal with these quantum phenomena in principle, they do require completely new operational and fabrication paradigms compared to present day technologies that have not been implemented yet on an industrial scale. The theoretical research carried out at the WSI meets this challenge by designing and modeling novel quantum devices which pave the way towards next generation electronic and optoelectronic devices.

What can theory do?

Modern solid state theory is capable of accurately calculating the movements of atoms in solids as well as the mechanical, electronic, and optical properties of solids. There are robust and reliable tools available to predict virtually all properties of solids. However, these tools require one to solve millions and millions of equations. The methodical challenge is to develop computational methods that allow one to solve these equations efficiently and quickly, the methodical challenge is to identify the most relevant physical mechanisms and eliminate the less important ones. To this end very elaborate, truly predictive models have been developed at the WSI, which have been successfully applied to a few prototype systems as well as simple models that can guide colleagues around the world in qualitatively understanding and designing novel semiconductor devices.

The nextnano device simulator

A particularly useful modeling tool that has been developed by WSI researchers over the last few years is nextnano. This software package is now routinely used by hundreds of industrial and basic research groups all over the world. Nextnano is a versatile simulation tool for electronic and optoelectronic semiconductor nanodevices that calculates the quantum mechanical properties of arbitrarily shaped, multi-material structures - being limited only by the imagination of the user. Common applications include single electron transistors, light emitting diodes, quantum cascade lasers, efficient solar cells, organic semiconductors, spintronics, quantum computing devices, and new materials such as graphene or diluted nitrides.

Associated with several collaborative projects, the in-house simulation and theoretical modeling is currently particularly focusing on three subjects: spintronics, semiconductor-based quantum information processing, and quantum cascade lasers. All of these fields are active research areas not only at the WSI or nationally, but are being pursued worldwide.

Spintronic nanodevices

The field of spintronics is based on another peculiar quantum mechanical degree of freedom of electrons in the nanoworld that is called spin: while classical particles can rotate in any direction and with arbitrary speed, electrons can only rotate with a fixed speed and direction, either clockwise or counterclockwise. The well-known phenomenon of magnetism with its two poles - usually referred to as north and south - is a manifestation of this spin. The spintronics research may eventually lead to novel logics and storage devices that consume much less power than current devices do. We are designing novel spin devices that do not depend on externally applied magnetic fields but utilize intrinsic spin-related properties of electrons in nanostructures.
modeling and simulation of semiconductor devices

semiconductors, the so-called spin-orbit interaction. By injecting electrons from normal metal electrodes into suitably shaped nanostructures and using proper material combinations, our calculations indicate that one can achieve high degrees of spin polarization, which is a basic requirement for efficient spin devices.

Quantum information processing with solids

Quantum information theory attempts to develop and identify solid state systems that can act as massively parallel computers, so-called quantum computers. Currently, practically useful realizations of quantum computers are still out of reach, but there are many related ideas and concepts being pursued at the Walter Schottky Institut and, in fact, worldwide. A key element of quantum computers is the controlled interaction between microscopic objects, mostly electrons, which obey quantum mechanical laws. Unfortunately, microscopic objects are extremely sensitive to even the slightest perturbation by the environment and must therefore be carefully protected. A key advantage of simulations is that they free us from these tedious requirements and allow one to study idealized, perfectly unperturbed systems at first and turn off on perturbations at will one by one in order to study their effect in a precisely controlled fashion. One of the concepts for controlling entanglement, as the interaction between quantum mechanical objects is called, is based on electrons in adjacent quantum wires. Quantum wires can be fabricated with modern semiconductor technology; electrons can be confined to thin strip-shaped regions with a width of a few nanometer where they are free to move and can contribute to the electric current. In this manner, one can form effectively one-dimensional “wires”. The coupling between the electrons in adjacent quantum wires is controllable via electrodes and forms the basic element of a quantum computer, called a quantum bit.

Simulating quantum cascade lasers

Quantum cascade lasers promise the availability of tunable lasers, i.e. intense light sources, in the Terahertz frequency range (1 THz is 1 million Megahertz or 10¹² Hertz) which is ideally suited for sensing several gases and recognizing biological molecules quickly even at very low concentrations. The active part of a quantum cascade laser consists of several hundred layers of different semiconductors, as discussed in Chapter 4 and 8. In its simplest form, these layers are formed by alternating layers of Gallium Arsenide and Aluminum Arsenide. Electrons in Gallium Arsenide have a lower energy than electrons in Aluminum Arsenide. Consequently, electrons that get injected into Gallium Arsenide are repelled from Aluminum Arsenide and are confined into the Gallium Arsenide layers. Classically, such a structure would therefore be useless. One of the amazing properties of quantum mechanics, however, is the so-called tunneling effect, which allows the Gallium Arsenide electrons to tunnel through these so-called quantum barriers provided by the Aluminum Arsenide and thus “hop” from one Gallium Arsenide quantum well layer to the next one. This effect has led to the invention of the quantum cascade laser, where electrons traverse “cascades” of quantum wells and quantum barriers. A basic ingredient of a laser is the possibility for electrons to “fall down” from a higher to a lower energy state and to convert the excess energy into light. The quantum cascade structure is carefully designed in such a way that the tunneling electrons always arrive in a “high” state of the GaAs layers, fall down into the lower one by emitting light and tunnel to the next layer. During this propagation, they can also emit heat which accelerates their motion. Each step of this process must be carefully modeled, converted into a fabrication recipe, experimentally tested and measured, and then repeatedly optimized.

At the WSI, we have developed a quantitative model of quantum cascade structures that carefully takes into account all quantum mechanical processes relevant to this type of device. This model has allowed us to successfully predict and understand experimentally determined properties of quantum cascade lasers and to optimize their design.

It is common to all of these fields that progress depends crucially on the close and successful collaboration between innovative experimental work and state-of-the-art theoretical modeling.
Spintronics: Information Processing with Spins

Electrical detection of the spin orientation of Phosphorus donors.
Spintronics - Information Processing with Spins

Modern computers work by using electrons as the carriers of information and the preceding chapters have described how electrons can be positioned and transported in semiconductor devices in a controlled manner. The important property of electrons that is exploited for this application is their charge. However, electrons have a further fundamental physical property that was discovered in atomic physics already in the 1920s. In atoms, the electrons move around the much heavier nucleus, similar to the way that planets orbit around the sun. In addition, most planets rotate around their own axis, an effect that leads to day and night here on Earth. Something similar happens in the case of electrons, which also have a property resembling the rotation of planets around their own axis. This property is their spin.

Materials with coupled spins

Like the rotating Earth, which is a large magnet, each spin acts as a tiny magnet. These microscopic magnets can have huge effects in solids: If the spins align parallel to one another then a material known as a ferromagnet is formed. The magnetic properties of magnetite were known already in ancient times and the concept of a magnetic compass needle has been used since the middle ages. Today, the most relevant technical applications of magnets include motors and transformers. Moreover, modern information processing is unimaginable without magnetic materials: As an example, the storage of information on computer hard disks is realized with the help of small magnetic domains, in which either the north or the south pole points into a specific direction.

The physical processes involved in the movement of electrons through ferromagnetic materials and layer structures are studied intensively by solid-state physicists. Scattering processes between the spins of mobile electrons responsible for the current through the layer structure and the spins of localized electrons leading to the magnetic ordering give rise to effects such as the so-called giant magnetoresistance: The current through heterostructures containing two thin ferromagnetic layers depends on the relative orientation of the north and south poles in the two magnetic layers. Such effects can again be directly employed in information processing and are for example used in the read heads of hard discs. The significance of the research in this area is demonstrated by the Nobel Prize for Physics awarded to Peter Grünberg and Albert Fert in 2007 for the discovery and description of these magnetoresistive effects.

Using single spins

The parallel orientation of a large number of spins is a characteristic property of ferromagnets. However, some future applications of spins e.g. in quantum information processing require that single spins can be positioned and that their orientation can be precisely controlled and measured. These applications rely on the fact that a single spin can be oriented in any direction, similar to a compass needle. Therefore, more information can in principle be stored in a single spin compared to a classical bit, which can only contain the information "0" or "1". Similar to other quantum systems such as atoms, ions or superconducting devices, this property makes spins very attractive for the use in novel quantum information processing schemes based on so-called quantum bits or qubits. One of the particular quantum mechanical properties of qubits becomes evident again upon readout: While more information can be stored in a qubit, only the classical information of "0" and "1" can be obtained upon measurement. Nevertheless, qubits can be used very effectively e.g. for prime number factorization or data bank searching. Already commercially available are systems allowing secure communication via quantum mechanical encryption based on single qubits.

The physical properties of semiconductors and the highly developed semiconductor technology allow one to develop fundamentally new devices for quantum information processing working with single spins. Among the particular advantages of semiconductors for these "spintronics" are

- the possibility to realize artificial atoms in the form of quantum dots or donors, which are significantly larger than natural atoms and therefore easier to position and to address,
- the ability to vary the isotope composition of semiconductors at will, which allows to suppress the interaction of the electron spin with the spins of the nuclei,
- the capability to initialize and to read out the spin states via semiconductor-specific optical processes such as the creation and annihilation of electron-hole pairs and
- the potential to integrate devices based on single spins with conventional semiconductor electronics.

Artificial atoms

The diameter of an atom is about 0.1 nanometers or 0.000 000 01 centimeters. The use of the electron spin of natural atoms for spintronics applications would require methods to position atoms with such a high accuracy. Furthermore, techniques would be needed to control and read out spins with a similar spatial resolution. Both are extremely difficult to realize on such small length scales. Therefore, the fabrication of artificial atoms with significantly larger diameters is essential for the realization of solid-state devices based on single spins.

One possibility to obtain larger artificial atoms is the electronic doping of semiconductors, such as the doping of silicon by phosphorus. Phosphorus is an element of group V of the periodic table of elements, and possesses one additional electron when compared to silicon, which is an element in group IV. At room temperature, the additional electron of the phosphorus atom moves freely throughout the silicon crystal, as discussed in Chapter 3. In contrast,
At low temperatures this electron remains bound to the phosphorus atom and forms a state very similar to the single electron found in a hydrogen atom. This hydrogen-like state in the silicon crystal has a diameter of about 1 nanometer and is thereby significantly larger than natural atoms, making the electron spin of phosphorus donors a promising qubit candidate.

Even larger artificial atoms can be realized in the form of quantum dots. Similar to natural atoms, such quantum dots contain one or several electrons and, therefore, can also act as qubits. Self-organized quantum dots are formed when growing InAs on GaAs by molecular beam epitaxy. Due to the large mismatch of the crystal lattices of the two materials, Stranski-Krastanov growth leads to the formation of InGaAs quantum dots with a typical diameter of 10 nanometers (see Chapter 5).

Alternatively, quantum dots can also be fabricated from two-dimensional electron gases. To achieve this, thin metallic electrodes are deposited on the surface of special semiconductor heterostructures again grown by molecular beam epitaxy. These electrodes laterally structure the two-dimensional electron gas and define the size of the quantum dots. Also in this case, quantum dots containing single electrons can be formed. Furthermore, this approach allows the easy integration of electronic devices such as quantum point contacts to read the spin state. The typical lateral dimensions of such electrostatically-defined quantum dots is about 100 nanometers, even larger than the quantum dots obtained by self-organization.

Creation and life time of spin states

To be useful in quantum information processing, spins have to first be prepared in a well known orientation or spin state such as “up” or “down”. In self-organized InGaAs quantum dots, this has recently been demonstrated at the Walter Schottky Institut. Using specially prepared light, where the polarization is rotating, electron-hole pairs are created in the quantum dots and the spin state of both the electron and the hole is fully defined by the sense of rotation of the light. After a short period of time, the electron-hole pair annihilates, emitting a single photon or quantum of light. While this photon can be nicely used to measure the spin state of the charge carriers, the life time of the electron-hole pair is too short for it to be useful in quantum information processing. However, by placing the quantum dots inside a diode, the electron-hole pair can be broken up by applying a voltage, creating a single long-lived electron spin.

For how long does such an electron spin stay oriented in a magnetic field? As discussed, a spin can be oriented in any direction, similar to a compass needle. However, the compass needle will eventually move back into the state of lowest energy, pointing north. The same happens to spins. The time before the spins return into the state of lowest energy defines the timescale on which artificial atoms can be used as qubits. Researchers at the Walter Schottky Institut have shown that, in the case of self-organized InGaAs quantum dots, this so called relaxation can take significantly longer than 100 microseconds. This time is very long in comparison with most other qubit systems currently being investigated, where relaxation times as small as 1 nanosecond are often observed.

Isotopically pure semiconductors

The processes which bring the spins back into the state with lowest energy are caused by magnetic interactions. The atomic nuclei of all stable isotopes of group III and group V in the periodic table of elements carry a spin themselves. This leads to spin-spin interactions between the spin of the electron, used as a qubit, and the nuclear spins of the atoms forming the semiconductor host crystal. In contrast, the group-IV elements have isotopes which do not have a nuclear spin. Examples are carbon, silicon and germanium such as $^{12}$C, $^{30}$Si and $^{70}$Ge. Interactions between the spins of electrons and nuclei, therefore, do not take place in semiconductor crystals formed of these isotopes, so that even longer spin relaxation times can be realized in such materials. Using molecular beam epitaxy, researchers at the Walter Schottky Institut grow unique heterostructures consisting of nuclear spin-free isotopes and study the properties of artificial atoms such as donors and electrostatically-defined quantum dots in these structures, as well as methods to read the spin orientation.
Control of spin states via magnetic resonance

To make use of spins for quantum information processing, their orientation has to be fully controlled. This can be achieved via magnetic resonance. The method is well established, in particular for optical readout. However, when qubits in silicon or germanium shall be used, optical readout via the annihilation of electron-hole pairs such as described for self-organized quantum dots is not possible. Rather, alternative methods to determine the spin state via purely electrical measurements have to be developed for qubits in these materials. Researchers at the Walter Schottky Institut have pioneered a novel readout technique based on the transport of electrons from donors in silicon to states at the surface of silicon crystals. As discussed above in the context of the giant magnetoresistance, also this transport step depends on the relative orientation of the two spins involved, and can be detected via changes in the electrical current through the device. The characteristic Rabi oscillations of the current, caused by the rotation of the spins via magnetic resonance, are shown on the title page of this chapter.

Ferromagnetic semiconductors

The purely electrical measurement of the spin orientation would be made significantly easier, if mobile electrons with a preferential orientation of their spin could be realized in semiconductor devices. This can for example be achieved by cooling the samples studied in a magnetic field. An easier approach, which would also work at higher temperatures, could be the use of ferromagnetic contacts, preferentially made from semiconducting materials. To this end, so-called dilute magnetic semiconductors are grown and investigated at the Walter Schottky Institut. In this class of materials, magnetic ordering of the spins of mobile electrons is achieved via interaction with magnetic ions such as manganese, incorporated at a percent level into semiconductor host crystals. Examples of such dilute magnetic semiconductors include GaMnAs, GaMnP and GeMn. Issues such as the coupling between the mobile and the stationary spins, methods to control the magnetic properties e.g. via an electric field, stress or the incorporation of hydrogen as well as the homogeneity of the distribution of the magnetic ions throughout the crystals are currently studied intensively. As an example, molecular beam epitaxy of GeMn allows the controlled fabrication of manganese-rich nanoclusters, which act as local ferromagnets and lead to novel magnetoresistance effects.

Time will show whether we will use computers based on quantum information processing in the years to come. Independent of the particular application of spins, the systematic study of the spin degree of freedom in semiconductor materials and devices is essential to obtain a full understanding of the physics of this very important class of materials without which today’s life would be hardly imaginable.
Electro-optical-fluidic setup for switch/DNA measurements

Biosensors and Bioelectronics
The second decade after the foundation of the Walter Schottky Institut might be termed the Precambrian era, in analogy to geology – “life” appeared on solid-state samples in our laboratories. The combination of inorganic materials with organic molecules sparked great interest within the institute and a steadily increasing number of researchers are now devoting their studies to these hybrid systems. Today, almost a quarter of the scientists and students working in the Walter Schottky Institut are concerned with (bio)-physics, (bio)-chemistry, (bio)-technology or electrochemistry in various ways. The truly interdisciplinary character of this research poses new exciting problems and further enriches scientific life at the institute.

Semiconductor biosensors
A central focus of the bio-related research at the WSI is the development of biosensors. In the same way technological progress in the 20th century was driven by the development of microelectronics, the 21st century could be influenced by the impact of (nano-) biotechnology. Essential tools for future research on biological processes are novel methods to detect and analyze organic macromolecules such as nucleic acids, antibodies, enzymes, or other biologically relevant substances. A particular motivation for the development of biosensors for the life sciences is their application potential in medical practice. The vision of “personal analytical devices”, consisting of bio-chips and read-out instruments, which continuously monitor numerous bio-molecules and molecular processes in the human body and alert the user about dysfunctions in the organism before the outbreak of diseases, might soon become reality. Solid-state based systems, and in particular semiconductors, are ideal candidates for the development of complex analytical devices because of the highly sophisticated fabrication, miniaturization, and processing methods available today.

It all happens at the surface
In order to equip a semiconductor device with bio-functionality it is necessary to create a well-defined interface between the solid surface and the biological environment. However, the physics and chemistry of surfaces and interfaces can be complex, or as Wolfgang Pauli put it: “God created the crystal’s volume; its surface was made by the devil”. It turns out that taming the “interface devil” is a key to successful biosensor concepts; thus, many researchers at the WSI are concerned with the analysis and engineering of surface properties. Basic requirements are the compatibility of the sensor device with its biological environment, but also the device stability under hostile (physiological) operation conditions. However, the semiconductor/bio-interface must be much more than just a passive “buffer” between a liquid and a solid, it is the key parameter to render the surface functional! To this end, bio-molecules are immobilised on the device surface, where they act as capture probes or recognition elements for target molecules in the solution to be analyzed. The nature of these surface-tethered probe molecules can be very diverse, depending on the purpose of the sensor: single stranded DNA molecules may be immobilised to capture complementary target DNA sequences in the analyte (DNA chips), immobilised antibodies may be used to detect antigens or other antibo-
Biosensors and Bioelectronics

ies (immunosensors), or surfaces modified with enzymes may be employed to catalyze very specific biological reactions triggered by target molecules. The bio-functionalization of a wide range of material systems with specific electronic properties is intensively studied at the WSI. Among these are “conventional” semiconductors like Silicon, as well as more exotic wide bandgap semiconductors such as Gallium Nitride, Silicon Carbide, and Diamond.

From surfaces to bio-transducers

Once a functional bio-interface with specific receptors for target molecules has been established, a signal transducer must be implemented to convert the molecular binding event to an electrical signal which can be read-out and further analyzed by conventional means. A vast number of physical or (bio-) chemical effects can be employed as transduction mechanism, many of which are studied or newly developed in the WSI bio-labs. These include electric field effects, electrochemical charge-transfer reactions, enzymatic catalysis, molecular fluorescence (and energy transfer), or the monitoring of changes in the dynamic motion of molecules. Semiconductors are particularly powerful substrate materials, because their electrical (and optical) properties can be tuned and miniaturised electronic circuitry can be included. In addition, nano-structured device concepts as discussed in Chapter 5 can also be used. Here, specific examples include the use of two-dimensional conductive layers, one-dimensional “nanowires” or even zero-dimensional “quantum-dots”. These architectures open new applications and often feature strongly enhanced detection sensitivity. In addition, highly integrated “bio-chips” may be constructed by arraying numerous micro- or nano-meter sized sensors. Novel ion-selective field effect transistors (ISFET) and enzyme FETs (EnFET) have been developed at the WSI. Using SG-FETs (solution-gate FETs) based on surface conductive Diamond as well as on AlGaN/GaN high electron mobility transistors, researchers at the WSI have pioneered the fabrication of EnFETs using these chemically stable semiconductors for the detection of analytes such as penicillin or the neurotransmitter acetylcholine. Taking advantage of the excellent biocompatibility of both GaN and Diamond, the electronic coupling between cells and SG-FETs based on these semiconductors is being developed, which might enable exciting in-vitro as well as in-vivo applications.

A very important component in the prediction and understanding of sensor concepts is theoretical modelling. The nano device simulator (nextnano®) discussed in Chapter 8 is capable of calculating a wide range of specific properties, such as the electrical behaviour of complex heterostructures comprising solids, model bio-interfaces, and electrolytes. The understanding of the solid/liquid interface is crucial for a proper modelling of biosensors; especially relevant issues are charge transfer across the interface, ion adsorption, charge build-up and double layer formation, etc. Different experimental and theoretical approaches are being developed at the WSI to provide a detailed knowledge of this complex interface, which in the specific case of wide-band gap semiconductors has been so far largely unexplored. Besides the electronic detection schemes, optical phenomena are explored for sensing purposes, too, for example by employing photonic bandgap materials (see also Chapter 6). Engineered “defects” in periodic hole arrays in semiconductor membranes create sharp reso-
nances in their optical spectra. When bio-molecules adsorb to these defect locations, spectral shifts occur in the observed resonances that can be used to realise an optical biosensor.

Beyond sensing concepts, efforts at the WSI are directed towards creating “active” bio-interfaces, and new strategies for the efficient manipulation of biomolecules on surfaces are being developed. These investigations reveal fundamental interactions of biomolecules with force fields on surfaces. For instance, the light-induced movement of DNA (via dielectrophoresis) has been demonstrated on photo-addressable electrodes of amorphous Silicon. Other research is focused on switchable DNA layers (switchDNA method). Here, short ranged fields at electrically polarised interfaces are used to align (switch) short DNA molecules with high efficiency. At the same time, the orientation of these several ten nm long DNA strands is monitored by optical means (fluorescence energy transfer). These investigations provide fundamental insights about DNA as a charged macromolecule in strongly polarised environments. Driving molecules into motion at high frequencies endows the biointerface with unprecedented functionalities: It has been shown that proteins which bind to specific receptors at the DNAs’ top end slow the DNA switching process. The magnitude of this slow-down corresponds to the size of the attached protein – hence the method can be used to determine the size of target proteins with a chip-compatible format.

Future directions

In the future, the engineering of organic/inorganic heterostructures and biointerfaces will remain a central topic at the WSI. A further understanding of the interaction between solid substrates and bio-organic systems such as nucleic acids, proteins, or cells, is necessary to design the devices of tomorrow. Using nano-scale examination techniques, substantial effort will be directed towards the visualization, investigation and manipulation of single molecules, for instance by using electrochemical scanning tunneling microscopy to probe the charge transfer to or from single proteins. Semiconductor nanostructures will also be employed to emulate biological processes, e.g. to monitor the passage of individual biomolecules through artificial solid state nano-pores. Moreover, DNA scaffolds will be used as templates to create hybrid nanostructures of organic and inorganic nano-objects with novel functionalities.
Semiconductors and Energy: a perfect match!

One of the grand challenges of the future will be to provide the growing population of our earth with sustainable and environmentally compatible forms of energy. Most current energy scenarios in particular require a drastic reduction of the global carbon dioxide emission by at least a factor of two until 2050. Otherwise, it will not be possible to limit global warming to a tolerable level. Also in this area, which will be of utmost importance for us and even more so for our children, semiconductors already have an important impact, which will further increase in the next decades to come.

A readily visible sign of this development is the strong growth of photovoltaics in Germany, Europe, and throughout the world. As a direct measure of this development, let us have a look at the global annual production volume of semiconductor solar cells. This usually is given in Wpeak (Peak-Watt) and refers to the total electrical power harvested by all solar cells produced and installed during a given year under optimum solar irradiation conditions. In 1990, the annual global solar cell production was at a level of only 100 Megawatt, which corresponds to the power output of one single small thermal coal power plant. By the year 2000, the global solar cell production had increased to about 1 Gigawatt, which is the typical power produced by a nuclear reactor. Since then, photovoltaics has enjoyed an average growth rate of 30% per year, so that in 2007 solar cells with a combined power of almost 6 Gigawatt have been installed worldwide. As a consequence of this rapid growth, in 2006 for the first time more silicon has been used for the production of solar cells than in the microelectronics chip industry. It is quite likely that the rapid growth of semiconductor photovoltaics will also continue in the years to come. According to the usual “learning curve” linking the production costs of a new technology with the overall production volume, this increase in annual output of solar cells will also result in a further decrease of the price tag of solar cell modules. Since the cost of conventional energy sources is expected to increase considerably at the same time, photovoltaic energy generation is expected to become economically competitive with conventional energy sources between 2020 and 2030.

But already today, electrical energy produced by semiconductor solar cells has clear advantages in special applications. Solar cells produce electrical energy without any moving mechanical components and, therefore, require very little or even no maintenance. In addition, solar cells perform their work without consumption of fuels or other consumables, thus causing no additional costs during the remainder of their lifetime. Once installed, modern photovoltaic modules will produce energy for more than 30 years in a reliable and predictable way. Depending on their point of use, they will pay back the entire energy necessary for their production within a period of two to five years. And, at the end of their lifetime, they can be recycled or deposited of without negative effects on the environment. This renders solar cells particularly attractive for stand-alone applications without connection to an electrical grid and also for integration into other systems, ranging from pocket calculators to buildings.

As already mentioned in Chapter 3, the heart of a solar cell is made from a semiconductor layer, which captures the sunlight and transforms it directly into an electrical current. How well this transformation of the power from the sun into electrical power works is measured by the power efficiency of a solar cell. The current world record for solar cells made from silicon stands at 25%, which means that a quarter of the absorbed energy of the sun is available as electrical energy at the contact wires of the solar cell. This value is only slightly below the theoretically possible maximum efficiency of about 30%, which could be reached with silicon as the absorber material. To reach such high power efficiencies, however, the best available silicon crystals have to be used and, in addition, a lot of technological effort is necessary. This is impossible in a cost-effective mass production of silicon solar cells. Instead, most of today’s silicon solar cells are made from less expensive “polycrystalline” silicon, which consists of an irregular arrangement of smaller silicon crystals. Unfortunately, as for most other technological products also for silicon solar cells the general rule “less expensive = less effective” holds. Thus, polycrystalline silicon solar cells at present only achieve efficiencies between 15 and 20%. Still lower efficiencies of about 10% are achieved if the even more disordered “nanocrystalline” or “amorphous” silicon is used instead of polycrystalline silicon. On the other hand, these disordered variants of silicon can be used to produce so-called thin film solar cells, which only require about one hundredth of the amount of silicon necessary to make a polycrystalline silicon cell. Because of the increasing short- age of silicon raw material on the world market, these thin film solar cells, despite of their lower efficiency, may be an interesting alternative for particular applications. For example, thin film solar cells made from amorphous silicon have been used for many years to power pocket calculators or wrist watches, since these products consume so little power that high efficiencies are not really necessary. But the fact that most silicon solar cells produced today have power efficiencies which are significantly lower than the 30% predicted by theory also means that there is still a lot of room for improvement. This has motivated many researchers all over the world to look for possible ways to increase the efficiency of solar cells without increasing their cost. One particular problem of current interest concerns the development of simple processes to suppress the reflection of light by the surface of solar cells. A well-polished silicon wafer actually looks like a mirror, because it reflects more than 30% of the incoming light. The reflected light, however, can no longer penetrate the silicon absorber and is lost for the transformation into electrical energy. Without suitable countermeasures, the maximum efficiency of silicon solar cells would decrease to less than 20%, instead of the theoretically possible 30% without reflection losses. Therefore, all current solar cell designs employ more or less sophisticated strategies to minimize the reflection of sunlight. A particularly efficient way to avoid such reflection losses has recently been developed by scientists at the Walter Schottky Institute. This process is based on a simple chemical etching step, which is catalyzed by small metal nanoparticles deposited on the silicon. Within a few seconds, the metal-induced etching produces a specific nano-texture at the silicon surface, which decreases the reflection losses from more than 30% to less than 3%. Therefore, a silicon surface treated in such a way appears almost completely dark, which has inspired the scientists to call the resulting material “black silicon”. A further advantage of the newly developed process is that with slight modifications it can be applied to all forms of silicon (monocrystalline, polycrystalline, thin-film, and amorphous).
Semiconductors and Energy

Apart from silicon, many other semiconductor materials are being used for the production of solar cells, too. For example, the compound semiconductors GaAs or InP already introduced in Chapter 4 are the basic ingredients of high efficiency solar cells powering satellites and other space vehicles. More exotic compounds such as CdTe or CuInS\(_2\) ("CIS") are currently employed for the mass production of thin film solar modules. However, envisaging a large scale, global use of photovoltaics with a production volume of several 100 Gigawatt in the future, in addition to conversion efficiency more and more issues such as availability and cost of the raw materials or overall environmental compatibility will play an important role. Thus, Gallium or Indium both are relatively rare elements, which may not be available in sufficient quantities at a reasonable price. As a consequence of the solar cell boom, even silicon as the second most abundant chemical element on earth with an annual production of 60,000 tons in 2007 has become a rare commodity. This has lead to an undesirable, strong increase of the price for silicon raw material.

Therefore, organic solar cells are presently seen as a very attractive alternative in the field of photovoltaics. In organic semiconductors, inorganic elements such as silicon are replaced by carbon and hydrogen as the main chemical constituents of polymer chains or small organic molecules. These fundamental organic building blocks have been used since many years for the development of organic light-emitting diodes ("OLEDs") which, by now, start to appear in the consumer market. In contrast, organic solar cells are still in their infancy, with moderate conversion efficiencies of 5\% or less in the laboratory. Possible improvements in the future may actually come from a clever combination of organic and inorganic semiconductors in the form of "hybrid solar cells", making use of the respective advantages of both, the carbon and the silicon world. Still, extensive basic research and development work will be necessary to fully understand and exploit the potential of such a hybrid approach. As a small piece in this big puzzle, scientists at the Walter Schottky Institut in collaboration with industrial partners are currently studying how electrons can be transferred effectively between organic molecules and silicon nanoparticles under the influence of light, and how this basic charge transfer will impact on the design of efficient hybrid solar cells.

But semiconductor devices not only help to produce energy from the sun, they also are very important in saving precious energy in almost all aspects of modern life. Control units based on semiconductor electronics are indispensable in the optimization of energy-consuming processes and machines, thereby minimizing unwanted energy losses as much as possible. One of many examples are the ubiquitous semiconductor power supplies, which keep our mobile phones and laptop computers running. Without paying too much attention, we actually have become used to the fact that these power supplies perform reliably all over the world, are small and light weight, are given away with the main product almost for free, and still do their work with very little waste of energy. This is made possible by modern semiconductor devices which have replaced the old power supply technology based on heavy transformers. Further improvements are still to come with the more common use of "large band gap" semiconductors such as silicon carbide (SiC) or gallium nitride (GaN).

Probably the highest potential to save electrical energy today lies in electrical lighting. At present, the largest part of mankind makes use of antique and very inefficient light sources such as kerosene lamps or the good old Edison light bulb to squeeze a few more hours of light from the night. However, these conventional "light sources" transform most of the invested chemical or electrical energy into heat rather than into light. As a consequence, a large part of the 25\% of the global electrical energy produced at present which are used for lighting purposes literally go up the chimney. Again, semiconductor technology will have a great impact here in the near future. Enabled by the development of green and blue light-emitting diodes (LEDs) based on the wide band gap semiconductor material gallium nitride in the past decade, today high efficiency semiconductor light sources for all three basic colors (red, green, and blue) are readily available. By adding these three basic colors, all other colors (red, green, and blue) are readily available. By adding these three basic colors, all other colors including white can be produced, so that "solid state lighting" has become a technological reality. Also in this area, scientists from the Walter Schottky Institute have made important contributions: They have investigated and optimized the preparation of new light-emitting compound semiconductors, they have studied basic questions such as the doping or defects of wide band gap materials, or have developed novel laser-assisted processes which are now used in the mass production of high efficiency LEDs. Probably it still will take a couple of years until solid state lighting technology has been fully optimized and semiconductor light sources are common in every home. But it is quite certain that also here efficient and robust semiconductor technology sooner or later will replace the old vacuum tube technology of the last century. The second semiconductor revolution already has begun!
Already the 10th anniversary of the Walter Schottky Institut was celebrated with a scientific symposium. The experienced team of the Walter Schottky Institut, here after organizing the MSS6 conference in 1993, presented the latest clean room collection. The winter retreats of the groups take place in Zillertal or Wildschönau. The Sommerfest is the biggest party at the Walter Schottky Institut. Starting with talks by alumni, continuing with soccer and beach volleyball tournaments, it ends late at night around the grill.
Life at the Walter Schottky Institut

Public relations are taken seriously at the WSI, from lectures for young students to the open house, when the institute is shown to about 500 visitors once a year.
Life at the Walter Schottky Institut

The Christmas party with music and cabaret brings the hidden artistic talent of the institute to light. The high point of the evening is St. Nicholas, summarizing the year’s events.

The yearly hiking excursion goes to the mountains around Munich, the Chiemgau or Tyrol.

Having passed their exam, the new PhDs are pulled around the institute in cap and gown.
The WSI in Numbers
The WSI in Numbers

And so to facts and figures ... the statistical evolution of any organization such as the Walter Schottky Institut not only charts its development, growth and achievements, but also illustrates how human and academic factors have combined to promote the successes that we have enjoyed over the past twenty years. Rather than merely providing lists and tables detailing numbers of staff and students, research funding, publications, awards and prizes we have chosen instead to present a historical profile of the WSI in numbers.

Our institute, our staff and our students...

Immediately following its inauguration in May 1988, the WSI had a total working area of about 2400m² that was subdivided into laboratories, workshops, offices and administrative space. Three new full professorships were created by the Bavarian ministry of sciences, culture and arts; one seeded in the Faculty of Electrical Engineering and two that were incorporated into the Physics Department of the TUM. As is the case today, this strategy ensures that research topics in the WSI address both fundamental questions in semiconductor physics and allows novel ideas to be pursued to the point where new types of devices are realised and optimised. The number of researchers at the Walter Schottky Institut has grown continuously.

Today, the WSI accommodates the research groups headed by Gerhard Abstreiter, Markus-Christian Amann, Martin S. Brandt, Anna Fontcuberta i Morral, Jonathan J. Finley, Alexander Holleitner, Reinhard Scholz, Martin Stutzmann, and Peter Vogl, with a total headcount of about 140, including junior research group leaders, scientific and technical staff, postdocs and visiting researchers, secretaries, and doctors as well as diploma (master) students. Out of these, about 30 positions are funded by TUM, while basically all the doctoral student positions are financed via research projects with external funding.

From the earliest days of operation, the relatively small core of permanent members of staff was augmented by the “lifeblood” of all successful research institutes – students. About 350 diploma (master) students have graduated from the WSI until now. In the same period, 130 doctorate candidates have finished their theses. All of the students were able to find appropriate jobs in a very short time after finishing their work at the WSI. About 70% of the PhD graduates are now working for high-tech industry. Twenty percent remained in academia and one third of those are now professors at other universities or directors of research institutes. 10% went into other areas like intellectual property management or consulting.

The total number of Diploma and PhD theses completed in the WSI has risen steadily from less than twenty per year in the early 1990’s to over thirty in the last few years. Since 1997, most of the completed PhD theses have been published as a series of books that have served to make them more accessible to other scientists. This series currently numbers ninety three volumes and addresses a wide spectrum of topics from semiconductor nanoscience. Publication of PhD theses is one of the many activities supported by the WSI Alumni’s Association (Verein zur Förderung des Walter Schottky Instituts der Technischen Universität München e.V.) that was founded in 1997 to maintain contact with past, present and future alumni, guests and colleagues, and also to provide a forum for public relations and general activities.

Research funding

Over the last twenty years the Walter Schottky Institut has earned its reputation as being one of the top institutes worldwide for the production and characterisation of ultra high quality semiconductor heterostructures and for cutting edge research in semiconductor nanoscience. Something like 60-70% of the total annual budget of our institute (~4-5M€) comes from external research contracts financed by a wide variety of sources including the German Research Foundation (DFG), the German Ministry of Education and Research (BMBF), the State of Bavaria and the European Union. In addition, almost a quarter of our research income since 2004 has been drawn from a range of cutting edge projects conducted in close collaboration with industrial partners such as Degussa AG, Fujitsu Laboratories of Europe, Siemens and BMW, to name only a few. The total research income for the three years from 2004-2006 was 11.3 M€, not including seven projects funded as part of the Nanosystems Initiative Munich (NIM, www.nim.de) cluster of excellence, and several projects within the International Graduate School “Materials Science of Complex Interfaces” CompInt (www.comprint.ph.tum.de) and within the TUM International Graduate School of Science and Engineering (www.igse.de).

As mentioned above, several groups within the WSI are actively participating in the Nanosystems Initiative Munich (NIM), one of the first five Clusters of Excellence in Natural Sciences that were initially selected for funding by the German government Excellence Initiative on October 13th 2006. Within NIM, scientists from various research facilities in the Munich area in the fields of physics, biophysics, physical chemistry, biochemistry, pharmaceuticals, biology, electronics and medicine work closely together with the overall goal to design, produce and control a series of artificial and multifunctional nanosystems.
The WSI in Numbers

The Walter Schottky Institut has six principle investigators who actively participate in NIM, with a total of seven projects. Furthermore, a newly formed research group for Nanotechnology and Nanofabrication funded completely by NIM and headed by Alex Holleitner, who is a professor at the WSI since October 2007, are based within the institute. This new group is responsible for setting up a number of large pieces of shared nanofabrication equipment including Focused Ion-Beam (FIB) and electron beam (e-beam) nanofabrication systems, funded by NIM (~1.6 M€). In order to address an urgent need for improvements to the fundamental nanofabrication infrastructure of the WSI and to accommodate the ever growing number of independent junior research groups, funding for a ~14 M€ extension to the WSI was granted by the German government in late 2007. The new building, to be called the Center for Nanotechnology and Nanomaterials (CNN), is currently in the final stages of planning. Construction will commence in early 2009 on a site in immediate neighbourhood to the WSI in Garching and should be completed in 2010. CNN will provide a total working area of 2000 m² divided into laboratories, office space and seminar rooms and will provide a 600 m² state of the art nano-fabrication shared facility that will house special lithography (FIB, e-beam) and nano-analytical tools that are needed across a wide spectrum of nanoscience research. About half of the laboratory space in CNN will be devoted to special research laboratories of new research groups supported by NIM, the Technische Universität München and a wide range of other funding sources.

National and international collaborations

The expertise that has been built up in the WSI for the growth and fabrication of semiconducting materials and their associated nanostructures has naturally kindled a very large number of national and international collaborations over the past twenty years. These interactions have involved the growth of ultrapure semiconductor materials, including Si, Ge, Arsenides, Antimonides, Nitrides, Phosphides, Oxides, Ferromagnetic Semiconductors (see Chapter 4) and the fabrication of low-dimensional nanostructures (Chapters 5 – 7). The WSI has enjoyed many mutually beneficial exchanges of staff, students and knowhow with other research groups in both universities and industry, stemming from the four corners of the world. For example, over the past twenty years the WSI has collaborated with many groups throughout Germany and published almost one thousand papers together. Many hundreds of other papers have been written in collaboration with colleagues worldwide, spanning over forty different countries. The geographical distribution of WSI collaboration partners is illustrated by the maps of collaboration vectors that indicate the numbers of publications. By making such global links, scientists in the WSI have benefitted greatly from the free and open exchange of information that makes semiconductor nanoscience such a vibrant and rapidly moving field of research.

One of the objectives of any semiconductor research institute is to make the step from good scientific ideas and develop them into innovative products. Over the last years numerous patents were successfully applied for and three spin-off companies were founded by Walter Schottky Institut researchers.

Dr. Karl Eberl founded the company MBE Komponenten GmbH (www.mbe-components.com) in 1989 after completing his PhD thesis in the Walter Schottky Institut under the supervision of Gerhard Abstreiter. Dr. Eberl has a special place in our history as he was the very first PhD student to graduate from the WSI, researching the growth of SiGe-based semiconductor heterostructures. He then spotted an opening for the marketing of systems and components needed in the semiconductor industry for the fabrication of epitaxy components. First products were Silicon Sublimation Sources, Carbon Sublimation Sources and High Temperature Sources for Molecular Beam Epitaxy and the company is going from strength to strength almost twenty years after its foundation.

VERTILAS GmbH, with its headquarters nearby the WSI in Garching, was founded in December 2001 by associates of the Semiconductor Technology Group at the Walter Schottky Institut. The company develops, produces and distributes innovative laser diodes for optical communications technology, sensor engineering and measurement methods. With its newly developed laser diodes having a wavelength range of 1.3 µm to 2 µm, VERTILAS is one of the leading global providers in the field of long-wavelength VCSELs. In contrast to conventional laser diode technology, VERTILAS’ newly developed laser diodes emit normal to the wafer surface, hence the name Vertical-Cavity Surface-Emitting Lasers. These VCSEL diodes stand out for their high-speed data transfer capabilities (up to 10 Gbit/s), as well as for their small footprint.
structural shape, low current threshold and low power consumption. As discussed in Chap-
ter 8, long wavelength VCSELs constitute a core component of future laser-optical communi-
cation networks, through which fiber-to-the-home plans are being made possible for the first
time in a cost-effective manner. In addition to meeting increasing demand in optical commu-
nications, VERTILAS’ long wavelength products which have already propelled the company to a
leading position worldwide, offer numerous applications for use in gas sensor engineering and
optical measuring methods.

It is not only new experimental intellectual property that can be commercialised. After
completing his PhD in the group of Peter Vogl, Stefan Birner set about marketing nextnano³,
a software package for simulating the physical and electronic properties of realistic semi-
conductor heterostructure quantum devices (www.nextnano.de). As discussed in Chapter 9,
the software is extremely versatile and is capable of calculating the electronic properties of
arbitrary semiconductor nanostructures using the principles of quantum mechanics. Further-
more, the electrical current flowing through the structures can be calculated and the tool will
soon be able to simulate optical properties. The nextnano³ company recently received a grant
from the Federal Ministry of Education and Research EXIST-SEED program for University-
based start-ups to improve the business plan.

Publications

A fairly good measure of the scientific output of any fundamental research institute is pro-
vided by the numbers of publications in the scientific literature and also by the impact that
this published work has in the wider scientific community. Since opening in 1988 over 1600
publications have appeared with the affiliation Walter Schottky Institut, a remarkable figure
that translates to 3 publications every two weeks in the scientific literature over the past
twenty years. These 1600 publications have been cited more than 27 000 times and count
amongst them 77 papers in Physical Review Letters, 228 papers in Applied Physics Letters,
231 papers in Physical Review B and 17 papers in Science, Nature, Nature Materials and
Nature Physics. The scientific output of the Walter Schottky Institut has drawn increasing
attention over the two decades since the institute was founded, with almost 1400 citations of
work stemming from the WSI from January to June 2008 alone.

In addition to scientific publications, smart ideas and innovative technologies developed
within the WSI have been patented. The total numbers of patents written by members of the
Walter Schottky Institut translates to two per year since its foundation and many of the novel
concepts and innovative technologies have progressed from the research laboratory into
the commercial sector. Examples include the fundamental research on high electron mobil-
ity transistor (HEMT) that was performed in the 1980’s and 1990’s and is now exploited for
amplifiers in mobile and satellite communications and the laser lift-off of light-emitting diodes
used by Osram.

¹According to the Web of Science database – May 2008
Scientific prizes for staff and students

The high quality of the scientific work being performed in the Walter Schottky Institut is reflected by the large number of scientific prizes that have been awarded to our students and staff alike. Over the past twenty years more than twenty prizes for outstanding research have been awarded to our students at various international conferences in semiconductor physics. Indeed, at the upcoming International Conference on the Physics of Semiconductors (ICPS-29) that will be held in Rio de Janeiro, two of only eight Best Young Author Awards will be awarded to students from WSI. This figure can be put into context when we consider that this conference consists of more than thirteen hundred delegates worldwide, with a large fraction of younger scientists and students. Several students in our institute have also received awards for the best PhD thesis in the Faculty of Physics of TUM and other awards such as the Chorafas Prize, the Edison Prize from General Electric and the Corbett Prize of the ICDS have been conferred on our students. Collectively, these prizes are testament to the very high level of skill and dedication of our research students and we are very proud of each and every one of them.

In addition to numerous prizes for our students, more than 10 high ranking scientific prizes have been awarded to members of the institute including the most prestigious prize for young scientists working on fundamental research in condensed matter physics research in Germany, the Walter Schottky Prize from the Deutsche Physikalische Gesellschaft (DPG). Given the name of our institute, it seems fitting that this prize has been awarded to three members: Gerhard Abstreiter in 1986, Martin Stutzmann in 1988 and Jonathan Finley in 2007. Gerhard Abstreiter was also the recipient of a number of other high ranking scientific prizes including the Gottfried Wilhelm Leibniz Prize of the DFG in 1987, the Max Born Prize jointly awarded by the British Institute of Physics and the DPG in 1998 and the most highly ranked prize from the Bavarian Academy of Sciences, the Friedrich Wilhelm Joseph von Schelling Prize in 2006, to mention only a few. Prof. Amann was awarded the Karl Heinz Beckurts Prize in 2004 in combination with one of our PhD graduates, Dr. Markus Ortsiefer. This prize is awarded by the Karl Heinz Beckurts Foundation for outstanding advances in fundamental research and, moreover, the commercialisation of novel ideas with the highest levels of technical innovation.

Calls to professor positions

The high quality of the scientific members of staff in the Walter Schottky Institut is also reflected in offers to take up professor positions at other universities within Germany and, also, worldwide. To date, more than twenty of the researchers in the WSI have received offers to take up positions as professors and institute directors at other universities. Whilst some of the offers are inevitably accepted and represent the natural career progression of a young scientist, we are very happy that also many of the scientists chose to remain at the WSI and further their careers in the excellent scientific environment that exists in the Munich area.

Courses and teaching activities of WSI members

University life is defined by having regular and active contact between professors, researchers and undergraduate students at all stages of their studies. All scientific members of the WSI are actively and willingly involved in teaching undergraduate and graduate students and provide a broad base of lecture courses with topics ranging from basic physics through intermediate courses in solid-state physics and quantum mechanics to advanced special lectures on semiconductor physics, opto-electronics, solid-state theory, nano-photronics, physics of low-dimensional systems, bio-physics, quantum computing, renewable energy and quantum optics. Graduate students also have very close contact to undergraduates via problem classes and practical experiments, often embedded within research laboratories in the WSI. Members of the WSI combine traditional teaching methods with new technologies to provide a vibrant and enriching learning experience for the students. All lecture courses at the TUM are independently assessed by the students association, the so-called Fachschaft. Lectures presented by members of staff in the WSI have been consistently rated by the students to be amongst the best they hear and our lecture courses have regularly been commended through the award of the Golden Chalk; a prize that is awarded by the students themselves each semester for the best lectures. Only four of these prizes are awarded each semester across the entire spectrum of lectures presented in the Physics Department. We are very proud that over fourteen of these awards were won by WSI professors and staff in the last ten years. To place this figure into context, note that there are only eight awards per year across the whole of physics and 17.5% of all prizes have been awarded to WSI members over the past ten years, despite less than 10% of all lecture courses being offered by our institute. This proven excellence in teaching is something that all of us here at the WSI are very proud of.
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How to get to the WSI

Munich

Garching

Mittlerer Ring

direction from Nürnberg

direction from Stuttgart

direction from Salzburg

U B 11

Ludwig-Prandl-Straße

Lichtenbergstraße

Garching Forschungszentrum

Boltzmannstraße

Freisinger Landstraße

München Richtung Nürnberg

Richtung Stuttgart

Richtung Salzburg

U B 11

Garching

Am Coulombwall

Nord