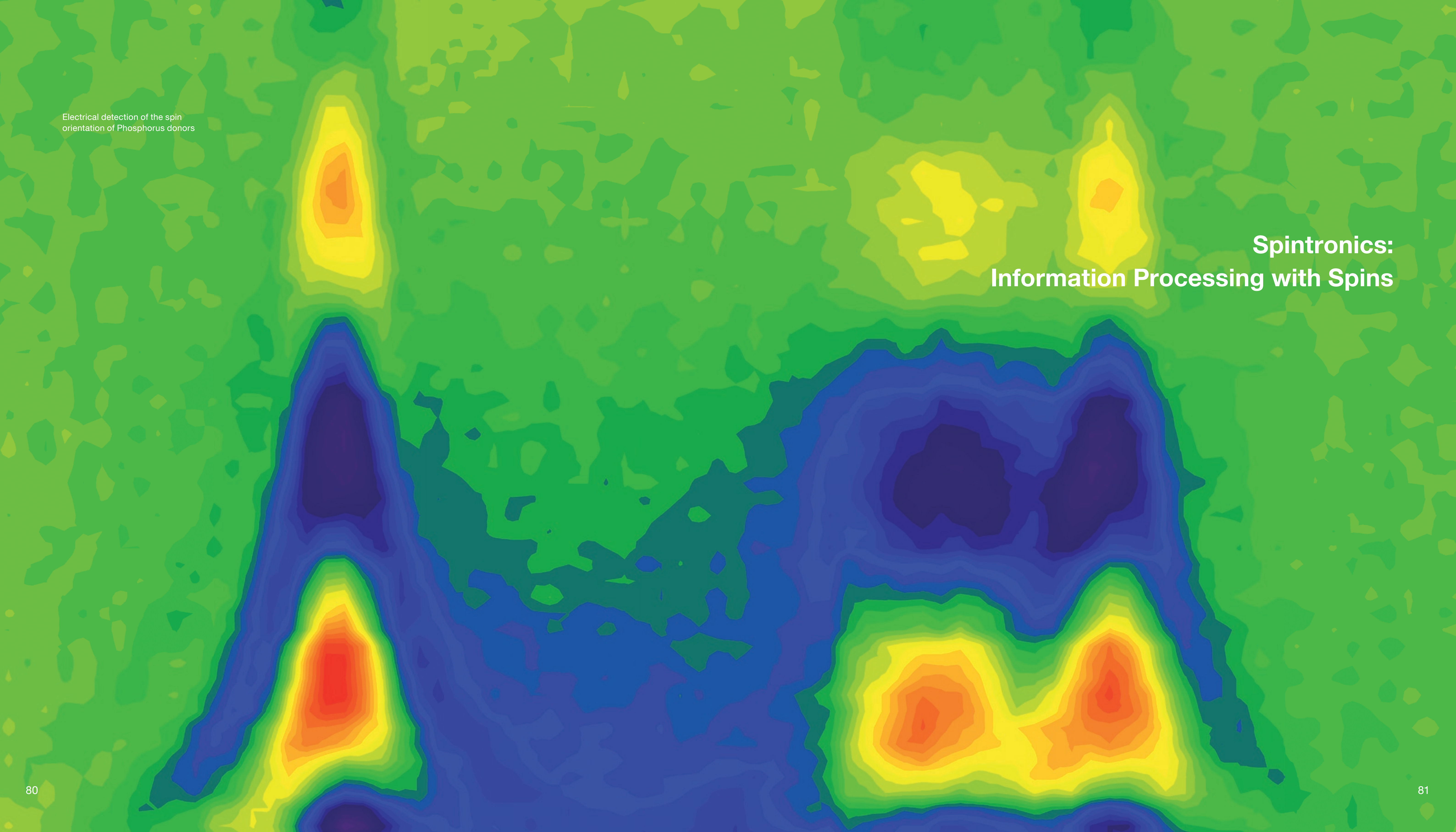


Electrical detection of the spin orientation of Phosphorus donors

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.

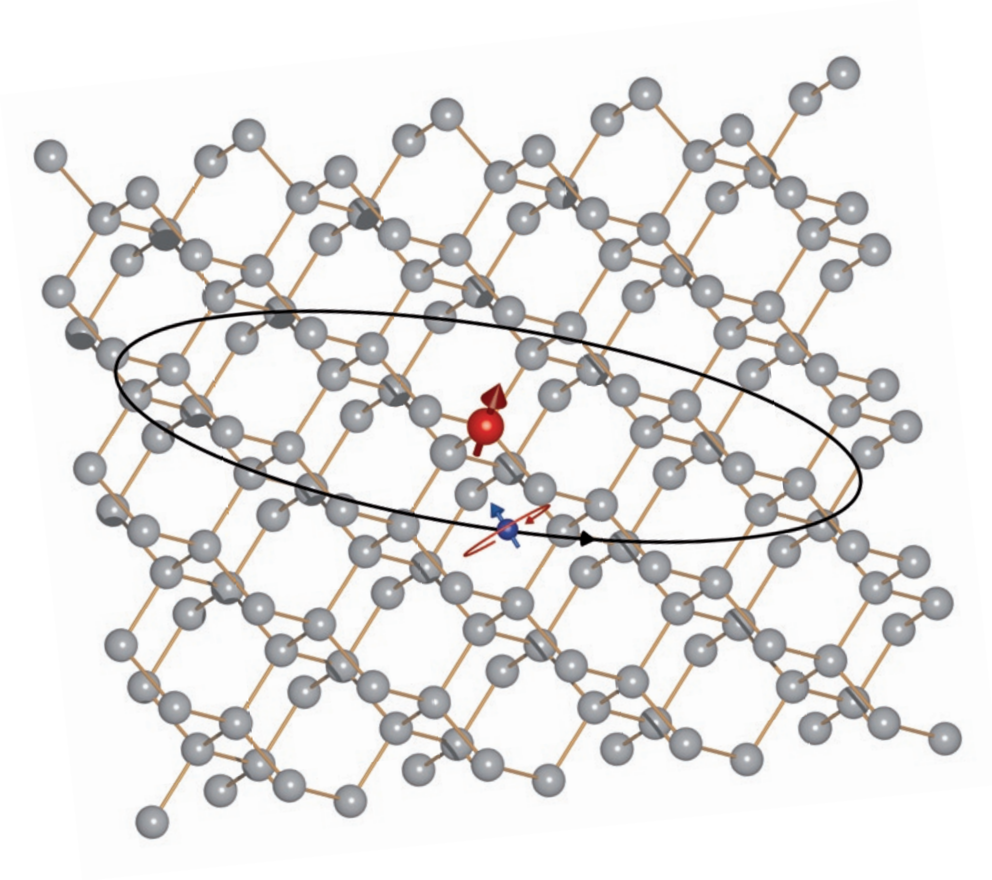
The physical properties of semiconductors and the highly developed semiconductor technology allow one to develop fundamentally new devices for quantum information processing working with single spins. Among the particular advantages of semiconductors for these “spintronics” are

- 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.

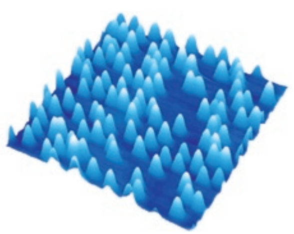
Artificial atoms

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.

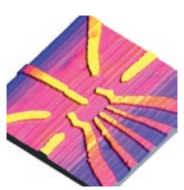
One possibility to obtain larger artificial atoms is the electronic doping of semiconductors, such as the doping of silicon by phosphorus. Phosphorus is an element of group V of the periodic table of elements, and possesses one additional electron when compared to silicon, which is an element in group IV. At room temperature, the additional electron of the phosphorus atom moves freely throughout the silicon crystal, as discussed in Chapter 3. In contrast,



Phosphorus donor in Silicon, shown in the Rutherford-Bohr model of the atom



Self-organized InGaAs quantum dots



Pair of electrostatically-defined quantum dots

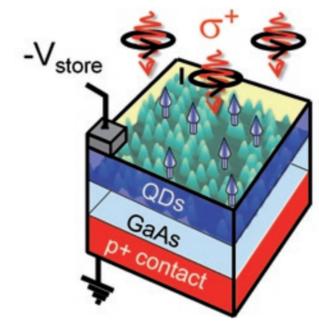
at low temperatures this electron remains bound to the phosphorus atom and forms a state very similar to the single electron found in a hydrogen atom. This hydrogen-like state in the silicon crystal has a diameter of about 1 nanometer and is thereby significantly larger than natural atoms, making the 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.

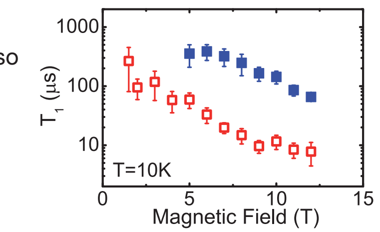
Creation and life time of spin states

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.



Storage of electron spins in self-organized InGaAs quantum dots

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.



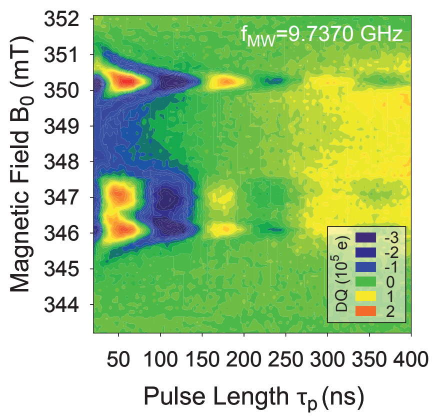
Comparison of the lifetime of the spin state of electrons (blue) and holes (red) in self-organized quantum dots

Isotopically pure semiconductors

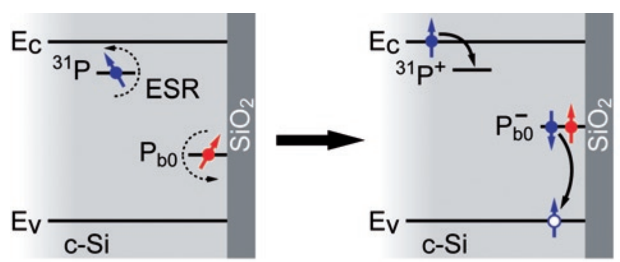
The processes which bring the spins back into the state with lowest energy are caused by magnetic interactions. The atomic nuclei of all stable isotopes of group III and group V in the periodic table of elements carry a spin themselves. This leads to spin-spin interactions between the spin of the electron, 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, ^{28}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

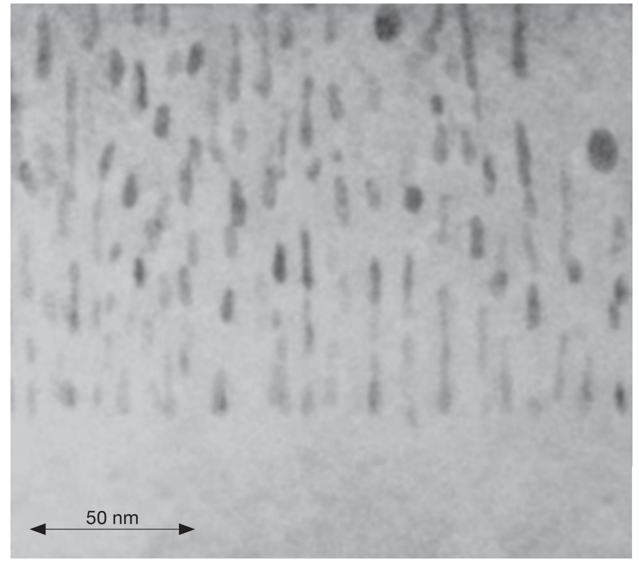
To make use of spins for quantum information processing, their orientation has to be fully controlled. This can be achieved via magnetic resonance. The method is well established, in particular for optical readout. However, when qubits in silicon or germanium shall be used, optical readout via the annihilation 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.



Electrical detection of the spin orientation of phosphorus donors



Spin-dependent transition of an electron from a phosphorus donor to a surface defect



Manganese-rich nanoclusters in Germanium

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.