博士論文 (要約)

Spin-orbit interaction of holes in Si-pMOS double quantum dots
（シリコンｐ MOS 二重量子ドットにおける正孔のスピン軌道相互作用）

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Abstract

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Spin-orbit interaction of holes in Si-pMOS double quantum dots
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Holes in silicon exhibit an enhanced spin-orbit interaction compared to electrons. This property can be used for electrical spin manipulation, but causes spin decoherence. At first we investigate the level detuning and magnetic field dependence of the Pauli spin blockade leakage current through a physically-defined p-type metal-oxide-semiconductor double quantum dot in silicon. The dependence of current peak positions on the level detuning shows spin funnel features which we attribute to mixing of the excited singlet with the spin-polarized triplet states, assisted by the strong spin-orbit interaction and interdot tunneling. The magnetic-field angle dependence of these features may present an alternative way to extract the Landé g-factor anisotropy. As a next step we investigate the spin-orbit interaction further by determining the direction of the so-called spin-orbit field. We therefore measure the magnetic- field dependence of the leakage current through the double dot in the Pauli spin blockade. The blockade is lifted by a finite magnetic field, with the lifting least effective when the external and spin-orbit fields are parallel. This way we can measure the direction or the spin-orbit field and determine that the in-plane electric field contributes significantly. The in-plane field has contributions from the side gates and the side wall geometry of the double quantum dot itself.

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Quantum computing - a very brief introduction

As classical computing is now approaching its limits, quantum computing is emerging as a promising concept that exploits the inherent superposition of quantum states for computation. The quantum computer uses a quantum mechanical 2-level system called a quantum bit or qubit. This is the quantum mechanical equivalent to the digital bit of a classical computer. Quantum computing allows for the more efficient solution of certain problems. Two famous examples are the Shor-algorithm [1], an algorithm for the factorization of large numbers that is important for cryptography, and the Grover algorithm [2], used for searching in large unsorted sets. However, the most important application will be in the field of physics itself: Namely, the simulation of less controllable quantum systems [3]. Recently, huge breakthroughs have been made by Google to demonstrate quantum supremacy in superconducting systems [4], which proves the viability of this concept.

In order to produce a physical implementation of quantum computing, we need a quantum 2-level system to assign the states of a classical bit $|0\rangle$ and $|1\rangle$, needed for computation, to physical (quantum) states. In order to gauge if a system is a good candidate for the implementation of a quantum computer, the so-called Di-Vincenzo criteria [5] are considered:

1. Scalability
   It must be possible to extend the system to many qubits, as with a few qubits alone a quantum computer can not be created.

2. Initialization
   The system can be initialized in a well defined quantum state.

3. Long coherence
   The system retains the defined state for a long time so that calculations can be finished in this time.

4. Manipulation
   An 'universal' set of gates allows for manipulation of the spin state, so that all possible states can be accessed.

5. Readout
   It is possible to efficiently read out the system in order to get the results of the preceding calculations.

If all these criteria are fulfilled, the system is a viable candidate for a quantum computer. In this thesis, we mainly discuss the last two criteria, namely manipulation and readout.

Quantum dots - a promising candidate for the implementation of the quantum computer

In 1998 Loss and DiVincenzo proposed to use electron spins in quantum dots (QDs) as qubits [6]. These so-called spin qubits are very promising candidates for the implementation of a quantum computer for several reasons [7–11]. First of all, electron spins provide a natural 2-level system with spin up $|\uparrow\rangle$ being assigned to the $|1\rangle$ state and spin down $|\downarrow\rangle$ to the $|0\rangle$ state. Furthermore quantum dots in semiconductors are inherently scalable and semiconductor systems have already been intensively studied [12–15]. Studies of lateral quantum dots started mainly in gallium arsenide (GaAs) [7, 9, 12, 14, 16–18]. Most of the techniques required to operate a quantum dot as a qubit have been established in GaAs since it was first thoroughly characterized in 1996 [12]. However, it turns out that due to the fact that both naturally occurring Ga isotopes have a nuclear spin, the time in which the state of the system is well defined, the so-called coherence time, is relatively short [7]. For this reason silicon (Si), devices are particularly interesting. They promise to be more suitable for the implementation of a quantum computer as only 5% of the isotopes of Si carry nuclear spins [19–23]. This enhances the coherence times by two orders of magnitude [22, 24]. The coherence can be even further improved by another two orders of magnitude if the silicon is isotopically purified [25–28]. In this case, the amount of nuclear spin carrying isotopes can be reduced to several 10s of ppm. Another advantage of silicon is the good compatibility with classical electronics, as most electronics are hosted in silicon [29]. This will allow for the fabrication of hybrid quantum computers, where tasks for which there is no advantage to using a quantum system will be performed by a classical computer and vice versa. Despite all of these advantages, however, valley degeneracy, which is present in silicon, complicates the fabrication and spin readout.

Holes in silicon

Holes in silicon have great potential as qubits. Due to their p-orbital nature (in contrast to the s-orbital nature of electrons), the holes are separated further from the nuclei and, thus, the hyperfine interaction is largely reduced and the coherence time potentially enhanced [30–33]. Another major advantage is the absence of valley degeneracy, which simplifies the fabrication [34]. Moreover, the spin-orbit (SO) interaction, an efficient coupling mechanism between spin and electric fields [35], is stronger compared to electrons. [36–40]. It can be exploited for spin manipulation via electric dipole spin resonance (EDSR) [36, 39, 41–47] so that an external source of spin-electric coupling (such as micromagnets [16, 48–50]) is not needed. Additionally, the strong SO interaction can lead to Landé g-factor anisotropy [44, 51], which enables further spin manipulation techniques such as g-tensor modulation resonance. This simplifies the device design and makes it more compatible with the standard complementary metal oxide semiconductor (CMOS) fabrication and thus benefits the upscaling and compatibility with classical electronics.

On the other hand, a large SO interaction beneficial for qubit controllability might also become a major decoherence source [52–54]. Similarly, it has adverse effect on the spin readout via the Pauli-spin-blockade (PSB) (a key technique for spin initialization and readout) [55–62]: the PSB gets lifted by relatively small magnetic fields of the order of tens of mT [55, 61, 63–65], whereas a field exceeding 100 mT is desirable to raise the Zeeman splitting reliably above typical thermal energies.

In the studies presented in this thesis, the holes in silicon are confined in a so-called physically defined p-type MOS (pMOS) Double Quantum Dot (DQD). The term ”physically defined” means that the quantum dots are not gate defined as in many previous works on lateral structures, but physically etched. The gates are also etched in the quantum well, and therefore metal deposition is not required for the inner quantum dot structures, but only for the last step where the leads are connected to the bonding pads. Therefore, the CMOS fabrication process can be used, which is advantageous because of its compatibility with the state-of-the-art fabrication techniques of silicon technology. In addition, MOS structures are the predominant system and holes the predominant charge carrier for classical electronics. This is important because for at least the decades to come, a quantum computer will be a very specialized system not capable of carrying out all operations efficiently, and therefore might only be useful in combination with a classical computer.

It is obvious that holes in Si are promising candidates for spin qubits. However, the details of the SO interaction are less understood in silicon hole devices compared to their electron counterparts. The objective of this thesis is to understand the details of spin-orbit interactions in order to utilize its benefits, while reducing the adverse effects on the coherence time and spin readout as much as possible.

Summary of our work

Recently, strong anisotropy in the hole Landé g-factor, a proportionality constant between the magnetic field and the Zeeman energy, has been shown for a nanowire type device [39], highlighting the importance of a thorough investigation of the spin-orbit interaction. While the g-factor and the SO interaction are related, their connection is not straight forward [66]. We will determine for the first time the direction of the so-called spin-orbit field, associated to the spin-orbit interaction, in a lateral hole double quantum dot.

To do so, we experimentally and theoretically investigate the spin-orbit field in a planar physically-defined, p-type metal-oxide-semiconductor double quantum dot in silicon. This means the double quantum dot is defined by etching rather than by using surface gates. The process is aligned with the CMOS fabrication process, thus combining the reproducibility of a well-researched industry-like fabrication process with the extra tunability of a lateral double quantum dot (compared to a standard CMOS transistor). We measure the magnetic-field dependence of the leakage current through the double dot in the PSB. We see that a finite magnetic field lifts the blockade. An especially important result is that this lifting changes with the energy detuning of the dot energy levels of the double quantum dot in the Pauli-spin-blocked regime. For every value of detuning we can see a finite value of the magnetic field which maximizes the lifting of the PSB [67]. This maximum has a funnel-like shape and we realize that this structure is analogous to the "spin funnels" first described by Petta *et al.* in 2005 [7]. These funnels represent the position where the singlet and one polarized triplet mix, two different spin states used for the operation of spin qubits. This represents the first observation in a direct current (DC) measurement. In all other experiments, initialization in specific spin state and thus a pulsed measurement is required. We circumvent these requirements by using a different set of states at the triplet resonance instead of the singlet resonance and the strong SO interaction of the host material. The efficiency of this process increases the closer the measurement is taken to the singlet-triplet resonance. It is important to note that this mixing is assumed to be mediated by the SO interaction.

Measuring our DQD structure for different angles for an in-plane magnetic field yields different openings of these "spin-funnels". As these spin-funnels openings are dependent on the g-factor, we can use the spin funnels to show that the g-factor changes depending on the direction of the external magnetic field. Utilizing an angle-dependent evolution of the spin-funnels we thus measure the anisotropy of the in-plane g-factor in a physical defined double quantum dot for the first time.

Through further investigations of the lifting with an angle-dependent magnetic field at the baseline, we find that the lifting least effective when the external and spin-orbit fields are parallel [64]. There is no enhancement of the lifting for a specific magnetic field, but the current is described by a Lorentzian in correspondence to the magnetic field. Our results are thus consistent with theory [55], which predicts Lorentzian dips that become wider with increasing alignment of the spin-orbit field. Applying this model to our system, we find that the spin-flip of a tunneling hole is due to a spin-orbit field pointing perpendicular to the double dot axis and almost fully out of the quantum-well plane.

We augment the measurements by a derivation of spin-orbit terms using group-symmetric representation theory. In this approach we consider the crystal, the interface and the quantum dot together. This is different than the majority of recent works where, *a priori*, a specific form of spin-orbit interactions was assumed. Our approach instead follows pioneering works that showed that abrupt potential changes at interfaces can result in terms contradicting the conventional knowledge, such as a “Dresselhaus” term in material with bulk inversion symmetry or a “Rashba” term in a macroscopically symmetric quantum well [68–70]. Correspondingly, we find terms that are generated by electric fields, but cannot be written simply as $\vec{E} \cdot (\vec{k} \times \vec{\sigma})$, a generic “Rashba” term. Instead, the theory predicts that without in-plane electric fields (a quantum well case), the SO field would be mostly within the plane, dominated by a sum of a Rashba- and a Dresselhaus-like term. Considering the predominant tunneling direction imposed by geometrical constraints and adding the in-plane fields to the theoretical model results in a field in the plane perpendicular to the direction of the tunneling current. We therefore interpret the observed SO field as originating in the electric fields with substantial in-plane components. This differs from previous results, where the spin-orbit interaction is exclusively caused by an out-of-plane electric field [71]. The next step was to investigate the origin of these in-plane fields, and we determined that they are generated by both the side gates and the side wall geometry by utilizing the capacitative model of the DQD.

In conclusion, we have measured the so-called “spin-funnels” in a direct current measurement for the first time, and thus demonstrated a novel way to measure the Landé g-factor anisotropy via a direct current measurement. The direct current measurement has the advantage of being much simpler than other ways to measure the g-factor and, allows us to probe excited states rather than the ground states in pulsed measurements of the spin-funnels. Neither has been shown before for this type of device. The emergence of the spin-funnels themselves and the strong g-factor anisotropy suggests strong SO interaction. While the g-factor anisotropy has been shown in a similar system, we are the first to determine the direction of the spin-orbit field. This is important step towards the development of a spin qubit in a p-type MOS (pMOS) system. This enables us to utilize the spin-orbit interaction as a spin manipulation mechanism while reducing the adverse effects of the leakage of the PSB, which then can still be utilized for spin readout. We have demonstrated that it is possible with simple direct current measurements. Our original theoretical derivation, which uniquely only relies on symmetries and geometry, gives our result additional significance. Using this technique in any hole system with strong spin orbit interaction will be helpful to optimize the performance as a spin qubit. With this knowledge about the system we can use it to implement EDSR for our device, as already demonstrated by other groups for other pMOS systems with strong spin-orbit interaction [32, 39].

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