論文の内容の要旨

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

氏　　名　　マルクス　マリアン　ニコラ　ヨアヒム

Holes in silicon are very promising for the implementation of spin-qubits in quantum dots. Silicon is the primary host material for classical electronics while holes are the predominant charge carriers. Therefore using holes should enhance the compatibility with classical electronics as the same fabrication process is utilized thus enabling chips hosting both classical and quantum circuits. This is important because at least in the next decades to come, a quantum computer will be a very specialized system not capable to carry out all operations efficiently and therefore might only be useful in combination with a classical computer. A maybe even more important advantage is that holes occupy the p-orbital thus reducing the hyperfine interaction vastly. This is expected to lead to improved coherence times. However in MOS structures, especially in p-type MOS the spin-orbit interaction is enhanced for holes. On the one hand this causes decoherence thus offsetting the advantage of removing hyperfine interaction. In particular the spin-orbit interaction may cause leakage in the Pauli spin blockade, a key technique for spin initialization and measurement. It blocks certain spin configuration from tunneling through the double quantum dot while others can tunnel. On the other hand however this spin-orbit interaction acts as a pseudo magnetic field thus enabling efficient electrical manipulation [1]. This makes holes in Si promising candidates for spin qubits. However, the details of the spin-orbit interaction are less understood in silicon hole devices compared to electron counterparts. To make further progress, it is crucial to understand these details to utilize the benefits while reducing the adverse effects as much as possible. This is the objective of this thesis.

Recently strong anisotropy in the hole Landé g-factor, a proportionality constant between the magnetic field and the energy, has been shown for a nanowire type device [2], highlighting the importance of an investigation of the spin-orbit interaction. While the g-factor and the spin-orbit interaction are related, their connection is not straight forward. 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 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 Pauli spin blockade. We see that a finite magnetic field lifts the blockade. It is an important result, 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 Pauli spin blockade [3]. This maximum has a funnel-like shape and we realize that this structure is analog to the "spin funnels" first described by Petta et al in 2005 [4]. 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 is the first time to be observed in a direct current 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 spin-orbit 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 spin-orbit interaction. Measuring this structure for different angles for an in-plane magnetic field yields to different openings of these "spin-funnels". Using the "spin funnels" we show that the g-factor changes depending on the direction of the external magnetic field. Utilizing angle-dependent evolution of those "spin-funnels" we 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 [5]. Here there is also no enhancement for the lifting for a specific magnetic field but the current is described by a Lorentzian in correspondence to the magnetic field. Our results are consistent with theory [6]. Lorentzian dips that are becoming wider the with increasing alignment of the spin-orbit field are predicted. Applying this model for 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 representations theory. Therefore 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 is to be assumed. Our approach instead goes along 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. 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. It 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 originated 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 [7].

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 to probe excited states rather than the ground states in the pulsed measurement of the "spin-funnels". Neither has been shown before for this type of device. The emergence of those spin-funnels itself and the strong g-factor anisotropy suggests strong spin-orbit 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 system. This enables us to utilize the spin-orbit interaction as a spin manipulation mechanism while reducing the inverse effects of the leakage of the Pauli spin blockade, which then can still be utilized for spin readout. We have demonstrated that it is possible with simple direct current measurements. The theoretical derivation only relying on symmetries and geometry, different from most recent works, gives our result additional validity. We are the first to show it for this type of system. Using this technique in any hole system with strong spin orbit interaction will be helpful to optimize the performance as a spin qubit. For our device in particular, with this knowledge about the system we can use it and implement electric dipole spin resonance (EDSR) as already demonstrated by other groups for other pMOS systems with strong spin-orbit interaction [1].

[1] R. Maurand, X. Jehl, D. Kotekar-Patil, A. Corna, H. Bohuslavskyi, R. Laviéville, L. Hutin, S. Barraud, M. Vinet, M. Sanquer, and S. De Franceschi, Nat. Commun. **7**, 13575 (2016).

[2] A. Crippa, R. Maurand, L. Bourdet, D. Kotekar-Patil, A. Amisse, X. Jehl, M. Sanquer, R. Laviéville, H. Bohuslavskyi, L. Hutin, S. Barraud, M. Vinet, Y.-M. Niquet, and S. De Franceschi, Phys. Rev. Lett. **120**, 137702 (2018).

[3] M. Marx, J. Yoneda, T. Otsuka, K. Takeda, Y. Yamaoka, T. Nakajima, S. Li, A. Noiri, T. Kodera, and S. Tarucha, Jpn. J. Appl. Phys. **58**, SBBI07 (2019).

[4] J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, Science **309**, 2180 (2005).

[5] M. Marx, J. Yoneda, Á. G. Rubio, P. Stano, T. Otsuka, K. Takeda, S. Li, Y. Yamaoka, T. Nakajima, A. Noiri, D. Loss, T. Kodera, and S. Tarucha, ArXiv 2003.07079 (2020).

[6] J. Danon and Y. V. Nazarov, Phys. Rev. B **80**, 041301 (2009).

[7] S. Takahashi, R. S. Deacon, K. Yoshida, A. Oiwa, K. Shibata, K. Hirakawa, Y. Tokura, and S. Tarucha, Phys. Rev. Lett. **104**, 246801 (2010).