Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp964-965

Spin Read-Out of Donors in Silicon

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1. Introduction

One of the main challenges in the realization of donor-based quantum computing is the read-out of single spins. While this has been demonstrated for electrostatically-defined [1] and self-organized quantum dots [2] as well as for the NV center in diamond [3], the successful determination of both the electron and the nuclear spin state of single donors is subject to intense work by several groups. Typically, the read-out of the electron spin state is attempted via a spin-to-charge conversion process involving two neighboring ^{31}P donor states or a single donor state and a neighboring electrostatically-defined quantum dot. However, any paramagnetic state can be used as a partner to read-out the donor spin state. To be able to manipulate the qubits, the donors have to be near to gate electrodes, which are insulated from the silicon substrate via an oxide. At the interface of the silicon and this oxide, defects such as unsaturated Si "dangling" bonds occur naturally in concentrations of typically between 10^{11} and 10^{13} cm^{-2}, depending on the exact oxide growth conditions. By passivation with hydrogen in a forming gas anneal or via compensation, the density of these defects can be reduced. However, they can also be used very conveniently as the partner required for spin-to-charge conversion [4].

2. Spin-to-charge conversion at the Si/SiO$_2$-interface

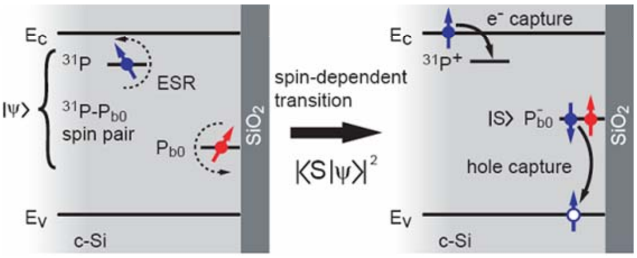

Fig. 1 Spin-to-charge conversion at the Si/SiO$_2$-interface.

Figure 1 shows a spin-dependent recombination process involving a ^{31}P donor electron and the dominant Si/SiO$_2$-interface defect named P$_{b0}$ [5]. As in the case of the charge transfer between neighboring P donors, the recombination step can only proceed if the ^{31}P-P$_{b0}$ pair is initially in a singlet spin configuration. In this case, a negatively charged P$_{b0}^-$ state is formed. If mobile charge carriers are present such as electrons and holes generated by illumination, an electron will be trapped by the positively charged ^{31}P and a hole by the negatively charged P$_{b0}$ center, leading to a reduction of the carrier densities and to a reduction of the conductivity. The symmetry of the spin pair and therefore also the electron spin state of the donor can thus be detected by changes in e.g. the photoconductivity.

To demonstrate the feasibility of this electrical read-out scheme of the electron spin state, let us look at an ensemble of ^{31}P-P$_{b0}$ pairs. Due to the spin-allowed recombination, most ^{31}P-P$_{b0}$ singlet pairs will have recombined in thermal equilibrium, most ^{31}P-P$_{b0}$ pairs remaining will be in a triplet configuration. Turning triplets into singlets via electron spin resonance of either the ^{31}P or the P$_{b0}$ (which is possible when the ^{31}P-P$_{b0}$ coupling is small), pair recombination is increased. Continuous resonance excitation will lead to a continuous oscillation of the ensemble being dominantly in the triplet or singlet configuration and, simultaneously, an oscillation of the ^{31}P-P$_{b0}$ recombination rate. As shown in Fig. 2, such Rabi oscillations in the conductivity can clearly be observed, demonstrating this spin read-out concept.

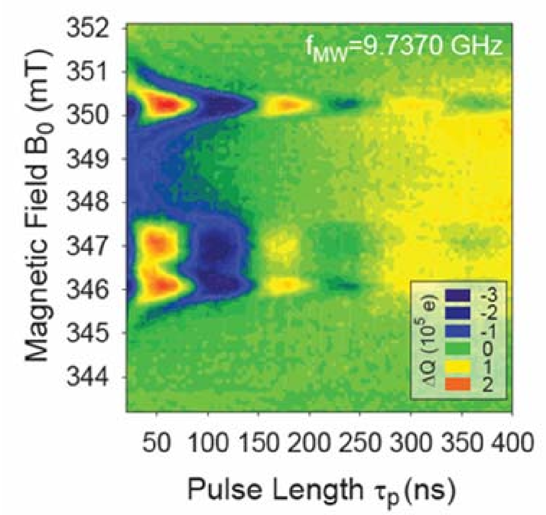

Fig. 2 Rabi oscillations of the ^{31}P-P$_{b0}$ recombination at the Si/SiO$_2$-interface observed by electrically detected magnetic resonance (EDMR).

3. Decoherence

A crucial parameter measuring the usability of particular physical realizations of qubits for quantum information processing is their decoherence time. The decoherence of spin states is usually measured with the help of echo experiments. However, the ^{31}P-P$_{b0}$ spin-to-charge conversion process is sensitive to the singlet-triplet symmetry of a spin pair, which is not changed by the formation of an echo in the transverse magnetization. A successful detection of such echoes via charge transport therefore requires so-called echo tomography [6], where after the second free evolution period a final $\pi/2$ pulse rotates the spin system back into singlet or triplet eigenstates of the pair. In samples consisting of thin doped Si layers with phosphorus concentrations of about 10^{17} cm^{-3} covered with a native oxide containing about 10^{13} cm^{-2} P_{b0} centers, we find that the recombination echos typically decay with a timeconstant of 1.7μs. A quantitative comparison of the echo decay time and the singlet recombination time of the ^{31}P-P_{b0} pair indicates that the decoherence is limited by the lifetime of the spin pair, rather than by spin-spin scattering e.g. within the ^{31}P spin ensemble.

4. Outlook

The results summarized above show that, at least for ensembles, the read-out of the electron spin state via ^{31}P-P_{b0} pairs is feasible. This observation opens up a wealth of opportunities: Using electrical gates on top of single phosphorus donors, it can be envisaged that by changing the gate voltages the coupling between the donor wave function and the read-out spin at the Si/SiO_2-interface can be varied, which would allow the selective addressing and reading of the single ^{31}P spins [7]. Electrical detection of spin resonance, but not yet actual spin read-out has already been achieved on samples containing as few as 50 P donors [8]. The observation of spin echos in the charge transport opens the possibility to apply pulse sequences such as DEER and ESEEM including free evolution times to study spin-spin interactions in these devices, allowing the determination of the coupling between the electron spins at ^{31}P and P_{b0} or between the donor electron spin and the nuclear spins of ^{29}Si, respectively, and ultimately the realization of entanglement between these spins. Furthermore, several different approaches for the electrical read-out of the nuclear spin state are being discussed. Irrespective of the possible use of this particular read-out scheme or even the use of donors for quantum information processing, these studies allow a more detailed understanding of the complex charge carrier and spin dynamics in semiconductor nanostructures.

Acknowledgements

Collaboration with H. Huebl, A. Stegner, F. Hoehne, J. Lu, B. Grolik and M. Stutzmann is gratefully acknowledged. The research into donor spin physics at the Schottky Institut is funded by Deutsche Forschungsgemeinschaft through SFB 631.

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