Measurement and control of spin quantum states utilizing semiconductor quantum dots

T. Otsuka[1,2,3], T. Nakajima[3], M. R. Delbecq[3], P. Stano[3,4], S. Amaha[3], J. Yoneda[3], K. Takeda[3], G. Allison[3], S. Li[3], A. Noiri[3], T. Ito[3], D. Loss[3,5], A. Ludwig[6], A. D. Wieck[6], and S. Tarucha[3]
[1]Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan
[2]Center for Science and Innovation in Spintronics, Tohoku University, Sendai 980-8577, Japan
[3]Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[4]Institute of Physics, Slovak Academy of Sciences, 845 11 Bratislava, Slovakia
[5]Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel
[6]Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany

Spin phenomena in semiconductor nanostructures are attractive targets in basic science and important in device applications. Semiconductor quantum dots (QDs) are nanostructures which confine electrons in small regions and work as artificial and controllable quantum states. They can handle single-electron spins. Single-electron spins in QDs are simple spin systems, show quantum mechanical properties, and nowadays are considered as a good candidate for quantum bits in quantum information processing. By utilizing the semiconductor QDs, we can measure and control the single-electron spin states.

To measure the single-electron spins in semiconductor nanostructures, local spin probes which can directly access the spin states are useful. We can realize such probes using semiconductor QDs. We can get the information of the spin states by analyzing the electron tunneling into spin-selective levels formed in the QDs which couple to the target structures. We can also measure the dynamics of the local electronic states by high-speed electric measurements utilizing high-frequency techniques called RF reflectometry. We measure the dynamics of the local single-electron spin and charge states in a semiconductor nanostructure which consists of a QD and an open electronic reservoir. This hybrid system is a simple model of an open quantum system. The change of the local spin and charge states inside of the target QD induced by the interaction between the QD and the reservoir is detected by the local probe. The relaxation times are different between the spin and the charge states. The observed difference is reproduced by a theoretical model treating the tunneling process [1].

Control of single-electron spin states is an essential operation of semiconductor quantum bits utilizing single-electron spins in QDs. The spins have relatively long quantum coherence times in solid-state devices. The control is realized by electron-spin resonances induced by the oscillatory shifts of the QD position by microwave's electric fields and the magnetic field gradient created by micro-magnets. We realize and improve the operation of the single-electron spins by optimizing the device structures and materials. We also fabricate the semiconductor multiple QD devices towards larger quantum bit systems. Scale-up of the quantum bit systems is important to realize larger-scale quantum algorithms. We demonstrate charge state control and single-spin operations in the scaled-up devices [2]. These results are important in the understanding of spin phenomena in semiconductor nanostructures and device applications like semiconductor quantum sensors and qubits.

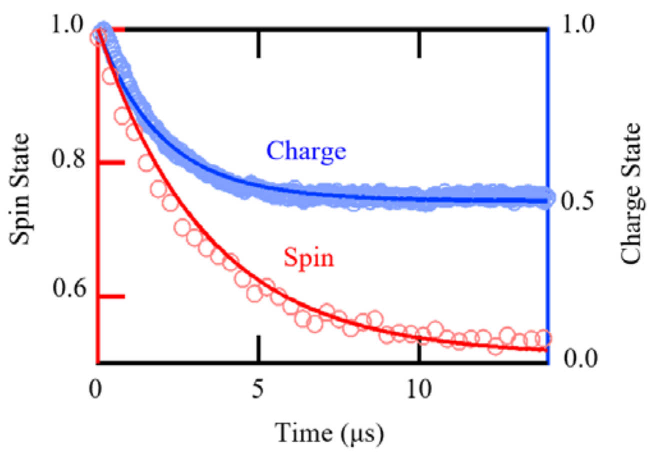

Fig. 1. Measured dynamics of the spin and charge states by a semiconductor quantum dot sensor.

Reference

1) T. Otsuka, T. Nakajima, M. R. Delbecq, P. Stano, S. Amaha, J. Yoneda, K. Takeda, G. Allison, S. Li, A. Noiri, T. Ito, D. Loss, A. Ludwig, A. D. Wieck, and S. Tarucha, Phys. Rev. B 99, 085402 (2019).
2) T. Ito, T. Otsuka, T. Nakajima, M. R. Delbecq, S. Amaha, J. Yoneda, K. Takeda, A. Noiri, G. Allison, A. Ludwig, A. D. Wieck, and S. Tarucha, Appl. Phys. Lett. 113, 093102 (2018).