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研究課題名（和文）Spin hot spots in semiconductor quantum dots

研究課題名（英文）Spin hot spots in semiconductor quantum dots

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研究成果の概要（和文）：本研究では半導体量子ドットデバイスにおけるスピン軌道相互作用を評価するための手法についての研究を行ってきた。この手法では、スピン緩和レートの外部磁場、および結晶方位に対する試料の向きについての異方性を活用する。私たちはこの手法について開発を行い、また強磁場を用いて、量子ドットの詳細を明らかにした。またこれらの結果について、Physical Review LettersやNature Communicationsなどの国際誌で発表した。

研究成果の学術的意義や社会的意義
本研究の学術的重要性は、半導体量子ドットにおけるスピン軌道相互作用について新しい評価手法を開発、実証したことである。これにより従来は不可能と思われてきた情報を推測することが可能となった。例えば、固体中に閉じ込められた単一電子の波動関数に関する情報である。この新しい手法を用いて、ライフタイムの長い量子ビットや、操作時間の短い量子ビット等、優れた特性を持つ半導体量子ビットの設計と作製を行うことができる。

研究成果の概要（英文）：The goal of this research was to propose ways for a characterization of the spin-orbit fields in semiconductor quantum dot devices. The idea was based on exploiting anisotropies of the spin relaxation rate with respect to the direction of the external magnetic field and the device orientation with respect to the crystal axes. We have developed such a method. It uses strong magnetic field and allows to uncover details of the quantum dot. The results of the research have been published in international journals including Physical Review Letters and Nature Communications.

研究分野：physics / condensed matter theory

キーワード：spin-orbit coupling　decoherence　quantum dot　spin qubit　nuclear spins

１．研究開始当初の背景

Semiconductor quantum dots are among the top candidates to implement quantum bits, hardware constituents of the foreseen quantum computer (see Fig. 1 for an illustration). Majority of these quantum dots are made in so called two-dimensional electron gas, in which the particle is strongly confined along one direction and more loosely confined in the remaining two. Together with the composition material, being nowadays most often gallium arsenide or silicon, this confinement geometry imprints certain intrinsic forces acting on the confined electron. Such internal forces which act on the electron spin are called spin-orbit interactions. They are the key element allowing to manipulate the spin of the confined electron by electrical fields. They enable the manipulation which is fast and tunable on small scales (sub-micrometer).

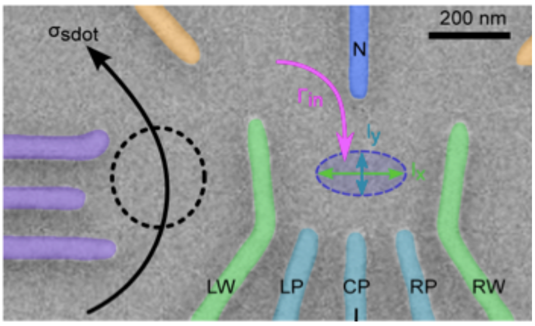

Fig.1: Illustration of a quantum dot device. Colored bars are metallic gates, quantum dot area is the ellipse on the right. Copyright Dominik Zumbühl’s Lab, University of Basel.

However, despite their crucial importance, the spin-orbit fields have so far remained largely unknown in quantum dot devices. It is because the standard methods to measure these interactions in the bulk (for example, based on the Shubnikov - de Hass oscillations) are not applicable in a confined system such as a quantum dot. The insufficient knowledge then makes difficult to improve existing qubits, as well as estimate the potential of new materials and device setups.

２．研究の目的

The primary goal of this research was to propose theoretically a way of a reliable characterization of the spin-orbit fields in a typical quantum dot device.

We have considered possibilities for characterization of the spin-orbit fields from the spin relaxation already several years ago [Phys. Rev. Lett. 96, 186602 (2006)]. The idea was based on so called spin-hot spots, which dominate the spin relaxation due to certain anti crossings in the spectra. They lead to pronounced anisotropies of the spin relaxation rate with respect to the direction of the external magnetic field and the device orientation with respect to the crystal axes. This program progressed in 2014 [Phys. Rev. Lett. 113, 256802 (2014)], where we could observe the predicted anisotropy in the spin-relaxation rate. However, we were not able to extract the spin-orbit fields, due to the fact that there was no method to estimate the actual quantum dot confinement.

This project originated in those ideas and was supposed to find a way to overcome the difficulties. The main goal was to bring the program aimed at spin-orbit fields characterization to a successful conclusion.

３．研究の方法

The research was primarily theoretical, based on microscopic modelling of semiconductor devices. On the one hand, it exploits extensive numerical simulations of the nanostructure and the device (see Fig. 2 for an illustration). On the other, it requires analytical understanding, which starts with effective mass description of the nanostructure, the application of the group theory analysis, the band structure theory, perturbation theory, and other standard tools of the theoretical condensed matter.

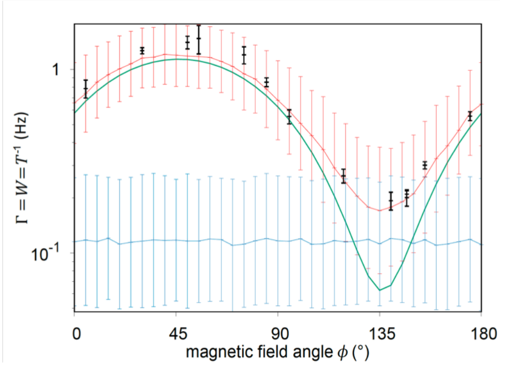

Fig.2: Illustration of results from numerical simulations. Spin relaxation rate (different colors denote different sources) as a function of the field direction. Figure by P. Stano.

An important part of the endeavor was a collaborative work with experimentalists, as we were interested not only in suggesting some theoretical method, but also proving that it works in real experiments. The research nature being a balanced combination of the theory and experiments is reflected also in a mixture of the outcomes, which include both theoretical and experimental publications and reports.

４．研究成果

In the project first year, we have made two advances. In [1], we have demonstrated how the effects of the spin-orbit fields can be disentangled from the effects of the hyperfine fields in a Pauli Spin Blockade experiment in so called double quantum dot. These two effects are the two major ways how the environmental noise influences the electron spin. They are usually entangled and not easy to separate, which makes it difficult is isolate the spin-orbit effects.

We progressed in the theory by the analysis of an optimal orientation of the quantum dot device with respect to the external magnetic field and the crystal orientation [2]. This allows for improved qubits with an optimal trade-off between a long qubit lifetime and a high manipulation speed. We found that the knowledge of the relative sign of the spin-orbit interaction strengths is needed to select the optimal dot geometry. We gave specific recipes for best performing qubits: the quantum dot grown along [001] crystallographic direction should have its main axis along [110] crystallographic direction for any material with tetrahedral symmetry (including GaAs and silicon).

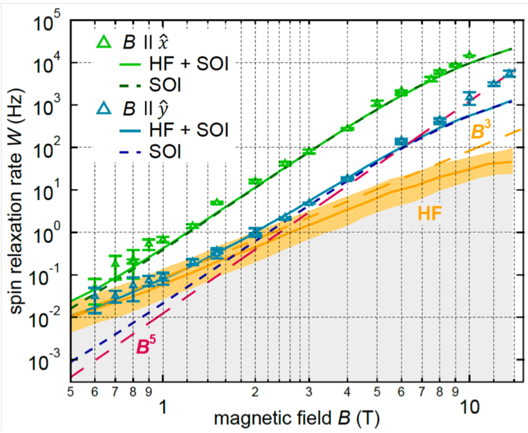

Fig.2: Illustration of results from an experiment. Spin relaxation rate as a function of the field magnitude. The blue point at B=0.7 T is the current world record of the spin lifetime of the electron in a nanostructure. Figure from Camenzind et al., Nat. Commun. 9, 3454 (2018). Copyright Nature Publishing.

In the second year, the essential advancement for the project success has been achieved: we have found how the structural information on the quantum dot confinement could be extracted, by adopting certain ideas which were pioneered in 60-ties and 70-ties in the experiments on two-dimensional electron gases. Namely, even though the thickness of the two-dimensional gas is very small, it is finite. A strong magnetic field applied within the two-dimensional place therefore affects the electron motion. This influence has been previously seen as a particle mass renormalization. We have discovered that in a quantum dot, the same effect will lead to a *spectral response*: Varying the magnetic field direction, the energies of the quantum dot states will oscillate, which is relatively straightforward to detect. It allows one to use the magnetic field as a spectroscopy tool, which uncovers the previously inaccessible details of the quantum dot structure. With this essential tool at hand, we could then finally fit the spin-orbit fields from the spin relaxation data, as originally envisioned already in 2006.

After working on the details in theory and experiments throughout the second year, we finalized the research by publishing the key results in the third year. The theoretical method was explained in [9], which establishes it for any two-dimensional quantum dot, being gallium arsenide, or silicon, but also for example in germanium, which gained popularity recently, and graphene. Shortly after we have expanded the method to include the effects on the spin in [7]. The spectroscopy method has been experimentally demonstrated in [11]. The full potential of the developed tools was demonstrated in [10], published in Nature Communications. In this work, we

- Demonstrate how the spin-orbit interaction strengths can be extracted for a quantum dot device, finding a spin-orbit length of 2.1 μm.
- Observe an electron spin relaxation assisted by nuclear spins. Such process has been predicted theoretically 16 years ago, but up to know never confirmed experimentally.
- We report the current world record of the electronic spin lifetime in a gated nanostructure, almost 1 minute long.

The new spectroscopy method that we developed was highlighted by the Physical Review Editors as "Editors' selection" [11] and resonated in media, for example in Physics News And Views [A], Phys.Org [B], AAAS EurekAlert! [C] or Russian Naked Science [D].

[A] https://physics.aps.org/articles/v12/56
[B] https://phys.org/news/2019-05-geometry-electron.html
[C] https://www.eurekalert.org/pub_releases/2019-05/uob-tgo052319.php
[D] https://naked-science.ru/article/physics/fiziki-vpervye-vychislili-formu

Overall, I am very pleased by the achievements reached in this project, and I consider them a significant advancement in the field of gated quantum dot spin qubits. I thank the JSPS for the kind support which helped us to achieve them.

５．主な発表論文等

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DOI:10.1103/PhysRevLett.117.20680

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６．研究組織

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