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Spin-Orbit Interaction in a Hole Nanowire and its Applications for Hybrid Quantum Systems

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Abstract

Spin-orbit interaction (SOI) often plays an important role in the semiconductor materials for spin manipulation because it can mediate interactions between the spin and electric field. With SOI it is feasible to couple individual spins with a photon in a microwave resonator which works as a "quantum bus" to exchange the quantum information between distant qubits. Ge/Si core-shell nanowire is an attractive platform for quantum control and information processing because it possesses a large SOI and possibly long coherence times due to the absence of the nuclear spin scattering. In this presentation, we list a few of our recent experiments that prove Ge/Si core-shell nanowire can be an important building block for quantum devices that make use of the SOI. First, the SOI in the nanowire is described and experimentally demonstrated through the study of the weak anti-localization. Then, the possible formation of a helical state in the nanowire geometry is described. Finally, the charge-photon interaction is demonstrated using quantum dots embedded in a microwave resonator, and the potential spin-photon coupling strength through SOI is estimated.

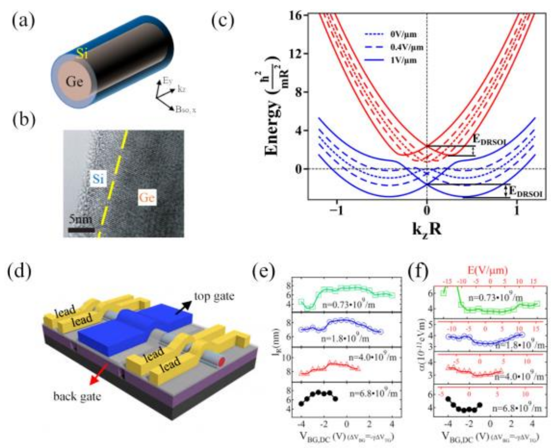

Fig. 1 (a) Schematic drawing and (b) TEM image of a Ge/Si nanowire. (c) Horizontal splitting of the low-energy hole spectrum in the $E-k$ diagram induced by external electrical field $\boldsymbol{E_y}$. (e) Rashba spin-orbit length l_R and (f) Rashba coefficient α changes with the applied electrical field.

1. Introduction

Quantum nanostructures where quantum states are coherently manipulated have been attracting much attention in terms of quantum computing and sensing. Spin-orbit interaction (SOI) is among the most essential properties which can be exploited for spin manipulation with pure electrical manners. With a similar mechanism, the coherent spin-light interaction is envisioned to be realized through SOI in a microwave cavity where the electromagnetic field from a single photon is enhanced. The SOI is as well essential to realize helical edge states in topological insulators. Nanowires-based artificial helical states coupled with the superconductors are currently being actively studied to search for Majorana zero modes which could be used for topological quantum computation. Extensive attention has been focused on the electron sector for decades, like in GaAs quantum well or InAs and InSb nanowires, the materials accumulating holes are rarely explored. The Ge/Si core-shell nanowire is a natural p-type one-dimensional (1D) heterostructure where the holes reside in the Ge core. It is attractive because of the theoretically predicted strong spin-orbit interaction for holes [1]. Regarding the spin-qubit application, the group-IV nature and the state-of-the-art isotopic purification of Si and Ge imply that Ge/Si is a promising platform for spin information devices with long coherence due to the absence of nuclear spin scattering.

2. Results

Electrical Modulation of Spin-Orbit Interaction

The Ge/Si core-shell nanowires used in this study were epitaxially synthesized by a two-step vapor-liquid-solid method and are dopant free [2], typically with a 2~3 nm Si shell surrounding a 10~20 nm wide Ge core (cartoon of Fig. 1(a)). The Si shell and Ge core lattice and interface are identified under the transmission electron microscope (TEM) as shown in Fig. 1(b). The evolution of the calculated hole spectrum as a function of electrical field $\boldsymbol{E_y}$ (with $\boldsymbol{E}$ in the y-direction) with the external magnetic field $\boldsymbol{B} = 0$ is shown in Fig. 1(c). Upon applying a transverse electrical field $\boldsymbol{E_y}$, the spin degeneracy is lifted with each band splitting into two branches. Similar to the conventional Rashba SOI, the spin splitting energy is linearly proportional to the electrical field strength. The splitting magnitude is about one or two orders stronger than the conventional SOI. The peculiar SOI is originated from the combination of quasi-degenerate low energy orbital levels of holes and the strong spin-orbit coupling at the atomic level (henceforth referred to as direct Rashba SOI, DRSOI).

The DRSOI strength is firstly evaluated from the feature of weak-antilocalization (WAL) through magnetoconductance (MC) measurements [3]. To observe the electrical tunability of SOI, a dual gated device is configurated (as shown by the cartoon in Fig. 1(d)) so that other physical characteristics can be mostly maintained at a constant. The main results are present in Fig. 1(e) and (f) that a 20~50% change of Rashba spin-orbit length l_R and the Rashba coefficient α as a function of electrical gating is observed. The spin splitting energy is tuned in a range $E_{DRSOI} = \hbar^2/2m^* l_R^2$ = 1.5~4 meV.

We also conducted the experimental measurements of the helical spin states in the near-ballistic one-dimensional (1D) transistors [4]. A typical measurement scheme involves the detection of quantized conductance in the 1D system. Strong Rashba type SOI can lift the spin degeneracy in momentum space with an asymmetrical electrical field $\boldsymbol{E}$ (here perpendicular to wire and substrate), resulting in an in-plane pseudo-magnetic field, *i.e.* Rashba spin–orbit field, $\boldsymbol{B_{SO}} \propto \boldsymbol{k} \times \boldsymbol{E}$, ideally oriented perpendicular to the wire axis and in-plane, where $\boldsymbol{k}$ is momentum. Applying a magnetic field ($\boldsymbol{B}$) perpendicular to $\boldsymbol{B_{SO}}$ will open a helical (Zeeman) gap of $E_Z = g\mu_B B$ with g and μ_B being the Landé g-factor and Bohr magneton, respectively. Inside the gap the conductance is e^2/h lower than outside. This gives the distinct transport signature of the helical state in the 1-D system. From the helical state measurement, we obtain the g factor of ~ 3.6 and the spin-orbit energy of 1.5~3meV.

Charge dipole-photon coupling

Ge/Si nanowire quantum dots coupled to a superconducting resonator is implemented with a device geometry shown in Fig. 2. A typical 50 Ω transmission line resonator is fabricated using a 100 nm MoRe superconducting thin film. Each nanowire is lying on a set of dense surface gates using an exfoliated h-BN flake as the gate dielectric layer. The charge state of double quantum dot (DQD) is controlled by the plunger gate voltage, V_L, V_R and V_B (Fig. 2 (b)). The eigenenergies of a charge qubit as a function of interdot detuning ε and tunneling strength t_c is termed as $\pm\frac{1}{2}\sqrt{\varepsilon^2 + (2t_c)^2}$. With the sweeping plunger gate voltages, we observed the magnitude and phase signal variation from the resonator transmission (Fig. 2(c) and (d)). A charge qubit coupled to a single-mode harmonic oscillator, which is well described by a Jaynes-Cummings (JC) model. The magnitude and phase response of resonator transmission is sensitive to the variation of quantum dot susceptibility, which is determined by the charge qubit-photon coupling strength and energy detuning. By changing the tunneling rate of DQD with a control gate, we observe a drastic phase change in Fig. 2(e), from which we obtain the coupling strength g_c is in the range $2\pi \times 35 \sim 55$ MHz. However, the strong charge-photon coupling regime is not observed because of the fast qubit dephasing. In a DQD geometry, the spin-photon coupling rate through SOI is estimated around 20 MHz [5].

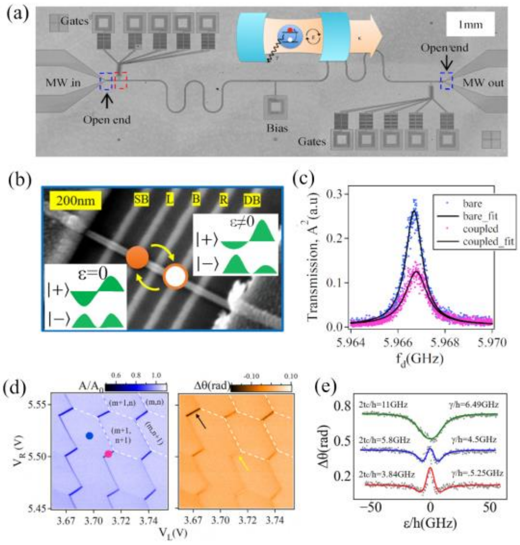

Fig. 2 (a) Optical image (b) closed up scanning electron micrograph of a NW quantum dot-cavity hybrid device. (c) Comparison of the resonantor transmission spectra with quantum dot state corresponding to blue and red postions in (d). (d) Magnitude and phase variation of the transmitted signal as a function of plunger gate voltage V_L and V_R. (e) Evolution of phase signal with a changing tunnel rate between dots with quantum dot state close to a charge degeneracy (yellow arrow in (d)).

3. Conclusions

We investigated a novel p-type group-IV Ge/Si core/shell heterostructure nanowire, by studying the peculiarly strong spin-orbit interaction and implementing a nanowire-based quantum dot coupled to a superconducting resonator. The results present the potential of the Ge/Si nanowire as a platform for spin qubits. The strength of spin-orbit interaction is evaluated as a few milli-eV and can be regulated with a modest electrical field. A charge qubit is established in the Ge/Si nanowire double quantum dot. Coupling the charge qubit to a resonator, the charge dipole coupling strength is extracted close to 100 MHz.

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