様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

令和　元 年　 ５ 月 ２７ 日現在

機関番号：８２４０１
研究種目：若手研究(B)
研究期間：2017～2018
課題番号：１７Ｋ１４０７６

研究課題名（和文）Electrically controlled spin qubit in Ge/Si nanowire with fast radio-frequency readout

研究課題名（英文）Electrically controlled spin qubit in Ge/Si nanowire with fast radio-frequency readout

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交付決定額（研究期間全体）：（直接経費）　　3,100,000円

研究成果の概要（和文）：Ｇｅ／Ｓｉナノワイヤへの最適化されたオーミックコンタクトを得た。 ナノワイヤ内で準弾道輸送を達成し、量子化コンダクタンスの特徴を測定した。 ｈｅｌｉｃａｌ ｓｐｉｎ ｓｔａｔｅはリエントラントコンダクタンスの特徴として検出されました。 ２．１ ｍｅＶの強いスピン軌道エネルギーと３．６のｇ因子を抽出した。 （Ｎａｎｏ Ｌｅｔｔ。２０１８）
我々はゲート規定量子ドットを作製した。源に接続されたマイクロ波伝送線路共振器は高速読み出しのために利用される。正孔 - 光子結合強度は数十ＭＨｚの大きさであると評価される。 （Ｎａｎｏ Ｌｅｔｔ。２０１９）

研究成果の学術的意義や社会的意義
Ｗｅ ｄｅｔｅｃｔ ｈｅｌｉｃａｌ ｇａｐ ａｎｄ ａ ｓｔｒｏｎｇ ｓｐｉｎ－ｏｒｂｉｔ ｉｎｔｅｒａｃｔｉｏｎ ｉｎ Ｇｅ／Ｓｉ NW, ｓｕｇｇｅｓｔｉｎｇ ｉｔ ａｓ ａ ｐｒｏｍｉｓｉｎｇ ｐｌａｔｆｏｒｍ ｆｏｒ ｓｔｕｄｙｉｎｇ Ｍａｊｏｒａｎａ ｐｈｙｓｉｃｓ．
Ｗｅ ｄｅｍｏｎｓｔｒａｔｅ ｔｈｅ ｈｏｌｅ－ｐｈｏｔｏｎ ｃｏｕｐｌｉｎｇ ｏｆ １０ｓＭＨｚ ｉｎ ｔｈｅ Ｇｅ／Ｓｉ ｑｕａｎｔｕｍ ｄｏｔｓ ｆｏｒ ｆｕｔｕｒｅ ｉｍｐｌｅｍｅｎｔａｔｉｏｎ ｏｆ ｃｏｈｅｒｅｎｔ ｈｏｌｅ－ｐｈｏｔｏｎ ｉｎｔｅｒａｃｔｉｏｎ ｉｎ Ｇｅ／Ｓｉ NWｓ．

研究成果の概要（英文）：We obtained the optimized ohmic contact to Ge/Si nanowire. With such devices, we achieved quasi-ballistic transport in the nanowire and measured quantized conductance features. The helical spin state was detected as a re-entrant conductance feature residing on conductance plateaus of 2e h, which is a strong experimental support of the existence of strong spin-orbit interaction. We extracted a strong spin-orbit energy of 2.1 meV and g-factor of 3.6 (Nano Lett. 2018).
We also fabricated the gate-defined quantum dots in nanowire with sub-100 nm pitch finger gates and exfoliated hBN dielectric. A microwave transmission line resonator connected to the source is utilized to for the fast readout. Moreover, the qubit energy can be separately tuned by the chemical potential difference and the tunnel coupling between the adjacent dots, thus switching on and off the coupling. The hole-photon coupling strength is evaluated to be in the magnitude of several tens of MHz. (Nano Lett. 2019)

研究分野：ナノ構造物理

キーワード：spin-orbit interaction　quantum dot　nanowire

１．研究開始当初の背景

Germanium/Silicon core/shell nanowires are a promising system for the study of 1-dimensional hole states. Owing to a large valance band offset of ~0.5 eV between Ge and Si, holes are naturally accumulated in the Ge core and strongly confined by the interface with the Si shell. The dopant-free growth leads to the high mobility with mean-free-path up to ~500 nm. Ge/Si core/shell NWs are a promising material system to investigate the unique transport i.e. helical hole states and to build qubit based on its quantum dots devices, due to the following desirable characteristics:

(1) both Ge and Si have a low density of nuclear spins (or can be grown with zero net nuclear spin), which through hyperfine coupling are the typical leading contributor to the limit of spin coherence times for III-V based qubit devices.

(2) A strong dipole-coupled Rashba type spin orbit interaction is predicted in Ge/Si NWs as a result of the quasi-degeneracy in its low energy valence bands.

Nevertheless, Ge/Si nanowire has not been well studied and the underlying physics has not been well understood. We have not noticed any direct experimental evidence of Rashba SOI in Ge/Si nanowire.

２．研究の目的

Our research goals were divided into three targets:

(1) Development of fabrication techniques to realize high-quality contact to Ge/Si nanowire and to build electrostatically defined quantum dots in Ge/Si nanowires using fine-resolution finger gates.

(2) Study of the spin physics in Ge/Si nanowires to reveal the details of its spin orbit interaction, and extract the g-factor for the nanowire.

(3) Detection of the charge states in the Ge/Si nanowire quantum dots using a microwave transmission line resonator.

３．研究の方法

(1) We develop a recipe to obtain the optimized metallic contact to Ge/Si nanowires by using wet and dry etching and electron-beam evaporation. The thin natural oxide on the surface of nanowire is removed by a short Hydrogen fluoride acid etching. Optimized ohmic contact is achieved which gives rise to a quasi-1-dimensional transport in the nanowire and enables the detection of helical state measurements. The Ge/Si nanowires used in this work is supplied by our collaborator Prof. Lieber at Harvard University, USA.

(2) We develop fabrication methods to transfer nanowires with sub-micrometer spatial resolution onto pre-patterned structures, e.g. gates, allowing the creation of complex devices. This method employs polymer stamps to pick up and transfer target materials and can be used both with nanowires, such as III-V nanowires, metallic nanowires, silicon nanowire, Ge/Si nanowire, etc., and the emerging two-dimensional layered materials, such as graphene, h-BN, etc. Using such technique, we are able

to fabricate electrostatically confined quantum dots devices with Ge/Si nanowire by transferring it onto the h-BN capped pre-defined finger gates.

(3) We measure the transport signature of helical hole states in a quantum point contact (QPC) device formed in a Ge/Si core/shell nanowire. The helical hole state is detected as a re-entrant conductance feature on conductance plateaus observed at integer multiples of $2e^2/h$. The attribution of this feature to a helical spin-gap can be supported by both magnetic field dependence and angular dependence, from which we also extract a strong spin-orbit energy and Landé g-factor for Ge/Si nanowire.

(4) We fabricate electrostatically confined double quantum dot (DQD) device in Ge/Si nanowire by transferring it onto the h-BN capped pre-defined finger gates. We couple it a microwave transmission line resonator by connecting its source lead to the resonator. The variation of the resonance transmission can be utilized as an invasive probe to recognize the qubit state.

４．研究成果

(1) Precision alignment system for single nanowires.

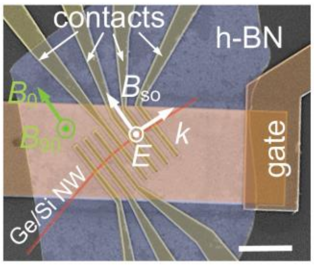

Figure 1. Micrograph of a QPC device. A Ge/Si NW (red) with Ti/Pd contacts (yellow) is located on a gold bottom gate (orange) with h-BN (blue) as the dielectric layer. Scale bar is 2 μm.

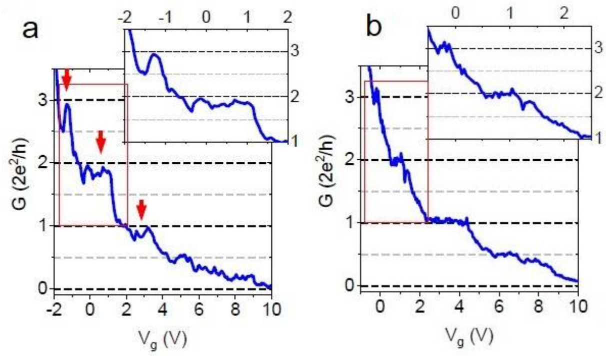

Figure 2. (a) Conductance trace with no B-field application measured at 7.5 K without DC bias. (b) Conductance traces with no B-field measured at 12K with 1mV DC bias.

We develop a micron-scale alignment system for the pick-up and positioning of single nanowires onto prefabricated gate structures or into complex circuits such as microwave resonators. The technique utilizes a home-made alignment system and the pickup and transfer of nanowires using fine indium whisker probes or polymer stamps. This alignment technique has been applied to all of the nanowire studies associated with this project being suitable for alignment of InSb, InAs, Ge/Si nanowires as well as carbon nanotubes. Examples of devices fabricated can be seen in the figures

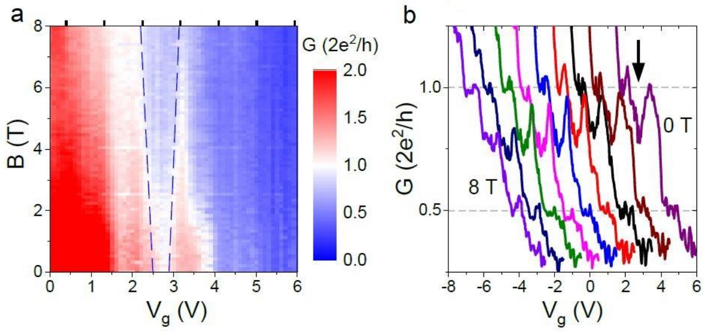

Figure 3. (a) Quantized conductance of the 1st mode as a function of $B \perp B_{so}$. The linear expansion of the re-entrant conductance is marked with blue dashed lines. (b) Lines cut in (a) from 0T to 8T. The black arrow indicates the re-entrant conductance feature.

in following sections.

(2) Realization of quasi-1-dimensional ballistic transport in Ge/Si nanowire

Figure 1 shows the image of a typical device. A Ge/Si NW is placed on a gold bottom gate covered with a thin h-BN flake used as a dielectric layer. The QPC is formed in the NW between any two Ti/Pd contacts. The subband occupation of the QPC can be set by controlling the chemical potential using bottom gate voltage V_g. The quasi-1-dimensional transport feature is then measured as the quantized conductance. In Fig. 2a, we plot the conductance trace measured between pinch-off and the 3rd mode in the device at 7.5 K. In order to give a better presentation of flat quantized conductance plateau, we also measure the conductance at high temperature of 12K and

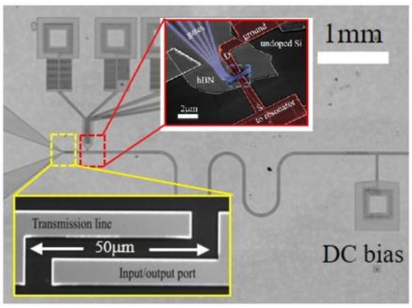

Figure 6. Micrograph of the left half panel of a typical MoRe transmission line resonator. Insets are the input/output coupler and nanowire DQD device.

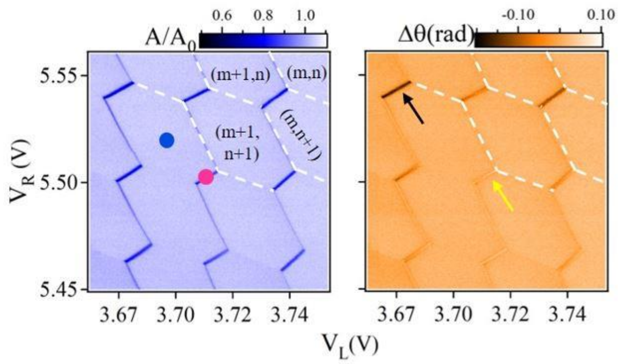

Figure 7. Magnitude and phase variation of the transmitted signal as a function of two finger gate voltages.

a finite DC bias of 1mV. The data is plotted in Fig. 2b. Under such circumstance, more pronounced flat plateaus are observed.

(3) Detection helical hole state in Ge/Si nanowire

In the QPC device, the presence of the substrate and gate impose an out-of-plane electric field E, resulting in an in-plane Rashba spin-orbit field $B_{so} \propto \boldsymbol{k} \times \boldsymbol{E}$ ideally oriented normal to the wire, where $\boldsymbol{k}$ is momentum. This SOI laterally shifts the two spin-degenerate subbands in momentum space and lifts the degeneracy. Applying a magnetic field B perpendicular to B_{so} can open a helical gap of $Ez = g\mu_B B$ with g and μ_B being the Landé g-factor and Bohr magneton, respectively. The helical gap is probed in measurements as a re-entrant conductance feature from integer to half-integer $2e^2/h$. We observe a pronounced conductance dip on the $2e^2/h$ plateau as the signature of helical gap. We firstly verify the linear expansion of helical gap with increasing magnetic field. We also confirm its θ-dependence of helical gap $\propto$ Ez sinθ, by rotating the magnetic field. A Landé g-factor of 3.6 and spin-orbit energy of 2.1 meV are extracted for the first conduction mode (Nano Letters 2018).

(4) Realization of double quantum dot in Ge/Si nanowire

DQD devices are fabricated using precise alignment of the single Ge/Si core/shell nanowires onto 100nm pitch gates. H-BN is used as a gate dielectric as it is a clean single crystal to improve device performance. An example device is shown in Fig. 4. The direct transport of DQD is characterized in a dilution refrigerator with dc current through the DQD down to pico-amperes. We observe clear honeycomb structure in the charge stability diagram indicating the formation of DQD as shown in figure 5 (Nano Letters 2019).

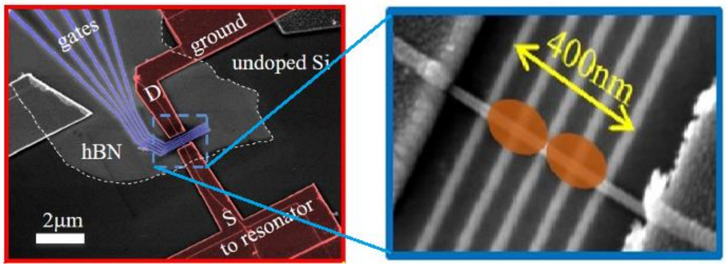

Figure 4. SEM images of the nanowire DQD device.

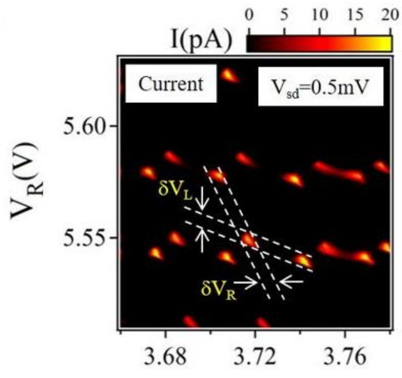

Figure 5. DC current plots as a function of two finger gate voltages representing the charge stability diagram with bias of 0.5mV.

(5) Detection of qubit state using a coupled microwave transmission line resonator

We couple the Ge/Si nanowire DQD to a transmission line resonator. A typical 50 Ω transmission line resonator fabricated using a 100 nm-thick MoRe superconducting thin film via e-beam lithography and etching as presented in figure 6. The resonance is centered at 5.967 GHz with a Q-factor of ~6000. We succeed to perform dissipative readout of charge states using the resonator. In Figure 7 we probe the resonator at the center frequency and simultaneously detect both the magnitude and phase of the resonator transmission. We observe a clear honeycomb structure. From fitting of the response with a theoretical model we evaluate charge dipole coupling rates as high as 85 MHz but charge decoherence rates of 10s of GHz indicating operation in the dispersive regime (Nano Letters 2019).

５．主な発表論文等

〔雑誌論文〕（計　2　件）

1. R. Wang, R. S. Deacon, J. Sun, J. Yao, C. M. Lieber, and K. Ishibashi, Gate tunable hole charge qubit formed in a Ge/Si nanowire double quantum dot coupled to microwave photons, Nano Letters 19(2), 1052-1060 (2019) 査読有
2. J. Sun, R. S. Deacon, R. Wang, J. Yao, C. M. Lieber and K. Ishibashi, Helical Hole State in Multiple Conduction Modes in Ge/Si Core/Shell Nanowire, Nano Letters 18 (10), 6144-6149 (2018) 査読有

〔学会発表〕（計　3　件）

1. “Helical State in Ge/Si Core/Shell Nanowire “, The 2nd CEMS International Symposium on Dynamics in Artificial Quantum Systems, Tokyo, January 15-17, 2018 Jian Sun
2. “Helical State in Ge/Si Core/Shell Nanowire “, The 65th JSAP Spring Meeting, Tokyo March 17-20, 2018 Jian Sun
3. “Helical State in Ge/Si Nanowire “, Kanagawa, February 15-16, 2018 Jian Sun

６．研究組織

（１）研究分担者

なし

（２）研究協力者

なし