Ge/Si core-shell nanowires for hybrid quantum systems

Rui Wang1, 3, Jian Sun2, 3, Russell S. Deacon3, 4 and Koji Ishibashi3, 4

1 Department of Physics, Tokyo University of Science, 1–3 Kagurazaka, Shinjuku, Tokyo 162–0825, Japan

2 Hunan Key Laboratory of Super Micro-structure and Ultrafast Process, School of Physics and Electronics, Central South University, Changsha 410083, China.

3 Advanced Device Laboratory, RIKEN, Wako, Saitama 351-0198, Japan.

4 Center for Emergent Matter Science (CEMS), RIKEN, Wako, Saitama 351-0198, Japan.

**Abstract.** Ge/Si core-shell nanowires are an attractive material to control and manipulate spins through the strong spin-orbit interaction for holes which are accumulated in the Ge core. They may find application as a spin-qubit coupled with microwave photons or for engineering of helical states that are an important component for realization of Majorana Fermions in combination with superconductivity. In this chapter, we describe magnetoresistance measurements in gated nanowire devices to study the spin-orbit interaction and the possible signatures of helical states in the nanowire. Toward the quantum mechanical spin-photon coupling, we also describe a charge qubit (double quantum dot) coupled with photons in a superconducting microwave resonator.

**Keywords.** Ge/Si nanowire, spin-orbit interaction, hole charge or spin qubit, light-matter interaction

1. Introduction

Quantum nanostructures where quantum states are coherently manipulated have been attracting much attention in terms of quantum computing and sensing. 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 [1]. The spin-orbit interaction (SOI) can play an important role in the manipulation of individual spins because it can mediate interactions between the spin and electric field [2]. With a similar mechanism, the SOI is useful to couple individual spins with a photon in a microwave resonator which works as a quantum bus through which the quantum information is exchanged between distant qubits [3]. The SOI is also essential to realize helical edge states in topological insulators [4]. The InAs and InSb nanowire 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 [5–8]. Ge/Si core-shell nanowires are an attractive alternative to these systems, also possessing a large SOI.

The Ge/Si core-shell nanowires used in this study form a p-type one-dimensional (1D) heterostructure with a nm Si shell surrounding a nm wide Ge core (Fig. 1(a)). The nanowires were epitaxially synthesized by a two-step vapor-liquid-solid method [9] and are dopant free. Under transmission electron microscope (TEM) the Si shell and Ge core lattice and interface are clearly identified as shown in Fig. 1(b). An eV valance band offset between Ge and Si makes holes naturally reside within the Ge core, confined as a one-dimensional hole gas (1DHG). The wires exhibit a high mobility with mean free paths up to nm having been reported [10].

In this chapter, we demonstrate that the Ge/Si core-shell nanowire can be an important building block for quantum devices that make use of the SOI as described above. First, the SOI in the nanowire is described and experimentally demonstrated through study of the weak anti-localization [11]. Then, the possible formation of a helical state in the nanowire geometry is described [12]. Finally the charge-photon interaction is demonstrated using quantum dots embedded in a microwave resonator [13].

2 Evaluation of the Strength of Spin-Orbit Interaction.

2.1 Spin-orbit interaction in a Ge/Si nanowire

A key property of the Ge/Si nanowire is the predicted strong Rashba type spin-orbit interaction (referred to henceforth in this work as direct Rashba SOI, DRSOI), originating from the combination of quasi-degenerate low energy orbital levels of holes and the strong spin-orbit coupling at the atomic level [14]. The spin splitting of the hole band can be easily introduced with a moderate external electrical field breaking the structural inversion symmetry. A direct dipolar coupling to an external transverse electrical field ensures the DRSOI scaling linearly with the core diameter , and that SOI is predicted to be one or two orders of magnitude larger than the conventional Rashba SOI (RSOI), which is inversely proportional to . This large and tunable SOI makes the Ge/Si nanowire especially suitable as a platform for spin qubits [15].

Fig. 1(c) shows the numerically calculated hole spectrum as a function of electrical field (with in the -direction) with the external magnetic field , according to the theoretical model described in Ref [14, 15]. Without considering the strain at the core-shell interface, the lowest two orbital levels at are quasi-degenerated and depart at large (short dash lines), where is the carrier wave number along the wire axis. Upon applying a transverse electrical field , the spin degeneracy is lifted with each band splitting into two branches. Like the conventional Rashba SOI, the spin splitting energy, , (the cross point with respect to the bottom of each orbital band) is linearly proportional to the electrical field strength, but is significantly larger in the case of the RSOI. For instance, with a moderate electric field strength of V/m (which can be easily achieved with electrical gating), the is about meV.

An applied magnetic field can lift the time reversal degeneracy. Fig. 2 presents the calculated eigenenergy and spin projection (in direction) of the lowest hole state as a function of a magnetic field applied in the plane with a fixed V/m. The case for is shown as a reference (Fig. 2(a)) where the spectrum is symmetric in the diagram. The spin projection along the direction shows an antisymmetric ground/excited state as a function , which is consistent with the principle of Rashba type SOI that the effective SOI field is expressed as with the Rashba constant and the spin orientation locked to the momentum.

An external magnetic field perpendicular to will induce a Zeeman splitting ( in direction of Fig2. (b)) and hence lift the Kramer degeneracy. The Zeeman energy gap is linearly proportional to the strength of . Under this circumstance, the helical state will be observed in the transport measurement as the appearance of a re-entrant dip in conductance when the Fermi level enters the Zeeman gap (See Sect.3 for further details). The position of the re-entrance is determined by the strength of . The spin projection of eigenstates is also affected by the external field (right panels in Fig. 2). Once the magnetic field deviates from the direction, as shown in Fig. 2(c) with an angle to , it leads to an asymmetric spectrum. The Zeeman splitting shows an angle dependent gap as . The Zeeman gap varnishes when (Fig. 2(d)). With the asymmetric spectrum the motion of carriers confines in a particular direction at the lowest ground state with a well-defined spin polarization. The linear dependence of on and the angular dependence of on determines the respective position and depth of the re-entrance in the conductance trace as a function of gate. These crucial criteria for the search of nanowire helical states are extensively discussed in Sect. 3.

2.2 Weak (anti-)localization

The SOI has been observed in various materials with different dimensionality. For instance, its strength has been extracted from the beat pattern of Shubnikov-de Haas oscillations [16, 17] and angle-resolved photoemission spectroscopy in two-dimensional systems, or from the avoid crossing of the orbital states in the magnetic field dependent spectroscopy in quantum dots [18, 19]. A typical method to extract the SOI strength in extended diffusive nanowires is to investigate the weak-antilocalization (WAL) or weak-localization (WL) through magnetoconductance (MC) measurements [20].

The WL and WAL in electrical transport are interpreted to originate from the quantum interference correction to the classical conductance in a diffusive system. Wavefunctions of a time-reversed pair of closed loop trajectories that are induced by random defect scattering interfere destructively (constructively) according to the presence (absence) of the SOI. An external magnetic field destroys the time-reversal symmetry, and a carrier acquires an additional phase dependence on the path due to the vector potential, which lifts the WAL or WL. Experimentally, with a sweeping magnetic field, an enhanced or suppressed conductance at a zero magnetic field is observed as a signature of WAL or WL, respectively.

Through analysis of the WL/WAL the strength of SOI has been extracted in various 1D nanostructures, i.e. InAs and InSb nanowires, and etched InGaAs quantum strips [21–23]. Among those studies, the WAL has always been investigated in devices with one global gate where the carrier density and electric field across the NWs are tuned simultaneously. Sweeping the gate voltage will alter several carrier characteristic lengths at the same time, such as mean free path, dephasing length and spin orbit length, hence making the analysis complicated. The Ge/Si nanowire considered in this report exhibits a much narrower diameter (typically nm) than the above-reported group III-V 1D structures, so the conductance is less sensitive to the external magnetic field. To extract a reliable value of the SOI and demonstrate the electrical field tunability of spin-orbit coupling, some practical issues have to be considered in the magneto-transport.

1. Due to the small cross-section of the Ge/Si nanowire, the specular scattering from the nanowire boundary significantly affects the transport behavior. We adopt a complete theoretical model to consider both the flux and spin precession cancellation, ensuring a reliable Rashba spin-orbit length.
2. Besides the strength, the tunability of the SOI by electrical modulation is of equal importance for controlled spin qubit manipulation and on/off switching of spin transistor or valves. A dual gated device architecture allows the exclusive investigation of the evolution of the spin-orbit length with electrical field while other physical characteristics can be maintained at a constant.
3. The universal conductance fluctuation (UCF) is always superimposed upon other features in the magnetoconductance, and is likely to merge with and obscure the feature of the WAL. By superimposing a small AC signal on the DC gate voltage, the UCF is largely removed from MC traces, enabling a good fitting to WAL theory models.

We quantitatively analyzed the WAL with a one-dimensional model in a “pure” regime, taking into account the nanowire boundary scatterings [22, 24, 25]:

, (1)

, (2)

*.*  (3)

Here, is the classical conductance without quantum correction. and are length and width of the wire with being the Plank constant, the carrier dephasing length, the spin relaxation length, and the Rashba spin-orbit length. The magnetic dephasing length is obtained according to the Beenakker and van Houten model in Eq. 2 considering flux cancellation, where is a magnetic length and constants and are geometrical coefficients for the case of specular (diffusive) boundary scattering [24]. Equation 3 describes the relation between the spin relaxation length and the Rashba spin-orbit length , where is a geometrical constant. This model was first proposed by Kettemann to elucidate the cancellation of WAL when wire width is close to or smaller than the spin-orbit length [25]. The characteristic lengths are also related to the corresponding times: , where is the diffusive coefficient, is mean free path and is Fermi velocity. Parameters *,* and are the phase decoherence, spin life and magnetic dephasing time, respectively.

Before discussing the measurement results it is worthwhile looking into the effect of geometrical confinement on the magneto-transport. Figure 3 (a) and (b) show the analytically derived magnetoconductance (MC) as a function of and (or ) using Eq. 1-3, without and with consideration of the cancellation of spin precession, respectively. Without the inclusion of geometrical confinement effects (, and assuming), should be shorter than to observe the WAL. For instance, when , the crossover of WAL and WL is observed in Fig. 3(a). In the case of the spin relaxation rate will decrease according to the Kettemann model, and the WAL is more difficult to detect. As shown in Fig. 3(b) when , a clear WAL is observed as a negative magneto-conductance. It is instructive for us to extract a reliable Rashba spin-orbit length from the experimental results in a Ge/Si nanowire with the typical width of nm. Similar suppression of WAL due to boundary scattering has been observed and discussed in InGaAs etched quantum wires and InSb nanowires [22, 23]. To study the validity of the Kettemann model in the nanowire with the set of characteristic length (*W, , , ,* ), we refer readers to Ref. [22] for more discussion.

2.3 Dual gated device

Ge/Si core/shell nanowires were dry transferred onto a target substrate using a home-made mechanical manipulator with micrometer precision [11, 26]. In Fig. 4(a) a schematic drawing of a dual gated device is shown. Simply speaking, the carrier density and the asymmetric electric field across the transport channel of the nanowire can be independently controlled by the top and back gates (denoted as TG and BG, respectively). Fig. 4(b) shows a false color scanning electron microscopic (SEM) image of a fabricated device with the surrounding circuitry. The magnetic field was applied perpendicular to the NW and substrate surface. The measurements are conducted at a temperature of K. To ensure transparent contacts the gate voltages for the contact gates (CG) were always kept negative. For detailed device information, we refer readers to Ref. [11].

To remove the Universal Conductance Fluctuations (UCF) a small AC voltage was superimposed on the gate allowing them to be averaged out. The time domain magnetoconductance (MC), , was measured by a standard lock-in technique. Each data point in the MC traces is an average over a two-seconds span with gate AC excitations as shown in Fig. 4(c). Fig. 4(d) shows the evolution of the MC for a m long device with increasing and a swept magnetic field up to 9 T. The DC gates are set to maintain , where is the conductance at zero magnetic field. With sufficient AC amplitude (usually of the whole DC scan range) the UCF can be significantly suppressed (blue line in Fig. 4(d)), ensuring a good fitting with the theoretical models previously discussed.

2.4 Electrical modulation of spin-orbit interaction

The electrical transport is first investigated at using a standard lock-in technique with a V source-drain AC excitation and a frequency of Hz. Only DC voltage is applied onto the gates toindependently modulate the carrier density ( and ). Upon electrical gating, the net carrier density is the summation of both gating effects, . The difference between the top and bottom gating breaks the structural inversion symmetry. The induced built-in electric field across the wire is derived as, ( is nanowire width, is the quantum capacitance of the nanowire). The electrical conductance of a m long wire as a function of and is presented in Fig. 5(a). The lever arm of TG and BG ( and ) is evaluated as, with and [11].

The magnetoconductance (MC) traces as a function of and are plotted in Fig. 5(b). The device could be completely pinched off with a sufficiently large positive gate voltage, showing a typical p-type transport. This is consistent with the observation that with increasing the pinch off voltage is shifted to a more negative . The hole mobility of the device is extracted with Drude’s model, , where is the mobility and is the elementary charge. The mobility is evaluated in a range of cm2V-1s-1 to cm2V-1s-1, which is consistent with other reports [10]. The mean free path is evaluated in a range of nm, whereis the effective mass of heavy holes in the Ge/Si NW, is the free electron mass, is the Fermi velocity and is the elastic scattering time. The mean free path indicates a quasi-1D diffusive transport regime in the NW. The mean free path and a built-in electrical field are used as parameters for the fitting. The measured MC traces in the full carrier density range are presented in Fig 5(c). All the MC traces show a clear WAL feature. By fitting with Eq. 1, we find that carrier dephasing length is around nm and spin relaxation length is around nm, implying a strong SOI in the Ge/Si nanowire. For each , is smaller than , as expected as WAL is always observed. Considering the geometry confinement in Eq. 3, we extract the Rashba spin-orbit length in the range nm, almost one order of magnitude shorter than those of InAs and InSb nanowires [21, 22].

The electric field control of the SOI strength was further implemented in the Ge/Si NW devices. By changing the TG and BG voltages with the relation (as indicated by the dots in Fig. 5(a)), the conductance was kept constant but the built-in electric field across the wire is varied. The built-in electric field () is proportional to an asymmetry of the carrier distribution, . In Fig. 6, we present the spin relaxation length , Rashba spin-orbit length and the Rashba coefficient as a function of gate voltage (and electric field of ), where . At four different carrier density conditions, a broad peak-like variation in is always observed when sweeping and . Fitting with the Kettemann model, the Rashba spin-orbit length is about times shorter than and a % change of is achieved through the gating. The maximum values of and always appear around the positions where the system is most balanced, i.e. where . Correspondingly, the Rashba SOI coefficient is smallest when inside the NW is minimized (Fig. 6(c)). These results hold the promise that the SOI in the Ge/Si nanowire can be efficiently tuned by electrical field. The Rashba constant is evaluated as , almost one order of magnitude larger than the conventional bulk Rashba constant nm2, a straightforward proof for the existence of the peculiar DRSOI in the Ge/Si NWs as theory predicts [14]. The spin splitting energy is tuned in a range meV, implying that the Ge/Si nanowire is a good platform for searching helical state and Majorana Fermions.

3 Detection of Helical Spin State in Ge/Si Core/Shell Nanowire

3.1 Principle

We have discussed the helical state in a general picture in Sect. 2. In this section we will focus on the experimental measurements of the helical spin states in the one-dimensional (1D) ballistic systems, e.g. the quantum wires or the quantum point contact (QPC) devices. A typical measurement scheme involves the detection of quantized conductance in the 1D system, which reflects the band dispersion. A gate voltage is applied to control the chemical potential and scan the Fermi energy crossing the energy modes. Summing over all modes, one obtains the conductance quantized at . The step size is twice the conductance quantum as the spin-up and spin-down modes are degenerate. Strong Rashba type SOI can lift the spin degeneracy in momentum space at zero magnetic field. However in this case the Kramer’s degeneracy is still preserved, which holds the conductance at an integral multiple of . Hence, the quantized conductance is measured exactly in the same way as the system without SOI.

The presence of the substrate and gate imposes an out of plane electric field , resulting in an in-plane pseudo-magnetic field, *i.e.* Rashba spin−orbit field, , ideally oriented perpendicular to the wire axis, where is momentum (Fig. 7). Applying a magnetic field () perpendicular to opens a helical gap of at the band touching points, with *g* and being the Landé *g*-factor and Bohr magneton, respectively. Inside the gap the conductance is lower than outside. This gives the distinct transport signature of the helical state in the 1-D system as a re-entrant conductance feature at the conductance plateau. An optimal situation is realized when the helical state and the SOI energy ( with and being effective mass and Rashba coefficient, respectively) are comparable. Under such circumstance, the widths of the plateau and re-entrant dip are both sizable and maximally visible [27]. Increasing the external magnetic field linearly enlarges this re-entrant conductance pattern associated with the helical gap.

According to the Hamiltonian of the Rashba SOI, , where is a unit vector along electric field , and is the vector of Pauli spin matrices, rotating the applied magnetic field towards by the angle of closes the helical gap sinusoidally since the helical gap is correlated to the component perpendicular to as . When is aligned with , the spin mixing vanishes, and a quenched helical gap is expected. Additionally, when rotating , two subbands are Zeeman split by an additional energy of . This angle dependency is a unique feature of the SOI and can be used to confirm its origin for the re-entrant conductance feature.

3.2 Experimental Considerations

In actual experiments the aforementioned re-entrant conductance feature that allows the identification of the helical state is fragile. It is preserved only in almost ballistic 1D wires. Importantly, the materials selected should have relatively large *g*-factor. Subsequently, the opened helical gap in the finite magnetic field of a few tesla should be in a detectable range of a few meV. Besides the selection of the material, several realistic and technical issues have to be considered during experiments.

3.2.1 Wire

In a 1D system, ballistic transport can only be realized and observed when the mean free path of the carriers is much longer than the channel length. The typical mean free path in the high quality III-V semiconductor nanowires and Ge/Si core/shell nanowires is a few hundreds of nanometers. Rainis and Loss demonstrated theoretically that in a disordered nanowire with a mean free path of nm, the re-entrant conductance feature can be completely smeared out when the channel length is much longer than the mean free path [27]. When channel length is close to that of the mean free path, the re-entrant feature is recognizable at an extremely low temperature. This points out that even with high quality nanowires, a nanodevice with its channel length much lower than few hundreds of nanometers and low measurement temperature of a few kelvins are necessary in order to see clear 1D transport and the re-entrant conductance.

3.2.2 Contacts

Ideally, the metal contacts to the semiconducting channel should be ohmic with sufficient transparency in order to measure the quantized conductance and the helical state induced re-entrant conductance feature. As a circuit in series, the output signal of a quantum wire or a QPC device are the summation of the channel resistance and contact resistance at the metal-semiconductor interfaces. The first conductance plateau of has a resistance of kΩ. Considering the poor contacts inducing a contact resistance of orders of magnitude larger than this value, the signal of the quantized conductance and the re-entrant conductance feature residing on it are heavily masked by the large background and become less distinguishable.

Now we consider a nanowire in a real device, which inevitably hosts unintentional charge disorders and has imperfect contacts. Electrons and holes therefore can be reflected at the metal contacts or at the potential barriers formed at charged disorders. Subsequently, even with the channel length of the same order or shorter than the mean free path, the reflections can lead to a periodic oscillating signal, the so-called Fabry-Pérot (FP) interference, which superposes on the conductance curve as a function of gate voltage. The re-entrant conductance feature associated with the helical gap is strongly masked by the superimposed FP oscillations, therefore easily causing the helical state to be indistinguishable in a realistic measurement [27].

3.2.3 Geometry

Due to the strong screening from the metallic contacts the gate voltage induces a non-uniform chemical potential distribution along the nanowire as shown in Fig. 8(a). The two segments of the wire near the contacts are therefore less electrostatically controlled with a so-called onset potential length . Due to the onset potential profile the effective channel length is shorter than the designed channel length , where . As described by Rainis *et al.*, in order to identify the re-entrant conductance of the helical state in the quantized conductance measurement an adiabatic potential profile in the channel must be fulfilled. The realistic onset potential length should be close to an optimal value , with being the Fermi velocity at zero field [27]. For either too small or too large masking effects stemming from the different mechanisms previously discussed are significant, making the re-entrant conductance feature difficult or impossible to observe (Fig. 8(b)).

3.3 Helical state studies in III-V Nanowires

3.3.1 GaAs nanowire

Quay *et al.* presented the first observation of the hole helical state in the cleaved-edge overgrowth 1D hole wire realized in a carbon-doped AlGaAs/GaAs/AlGaAs hole quantum well [28]. The re-entrant conductance feature as the signature of the helical state was observed on the measured conductance plateau of the second conduction mode (Fig. 9(a)). The helical gap in the first conduction mode possessed too small an energy scale to be measured in the experiment. They additionally demonstrated the Zeeman expansion of the helical gap with the application of a tesla magnetic field, which suggested an effective g-factor of in their system along the wire direction.

3.3.2 InAs nanowire

Heedt *et al.* reported the experimental observation of the re-entrant conductance feature in the lowest 1D subband associated with the electron helical state in an indium arsenide (InAs) nanowire [29]. The magnetic field dependence measurements clearly revealed the linear expansion of the helical gap with the application of the magnetic field normal to the SOI pseudo-field (Fig. 9(b)). Surprisingly, the re-entrant feature was still prominent even in the absence of magnetic field. They explained that the exchange interactions are enough to open the pseudo-helical gap by spin-flipping two-particle backscattering. Consequently, the transport signature of the helical state can be realized from all-electric origins without the application of magnetic field. Their measurements lead to the extraction of the spin-orbit energy of meV and *g*-factor of for the hosting material.

3.3.3 InSb nanowire

Kammhuber *et al.* detected the electron helical state in the lowest conduction mode of a 1D indium antimonide (InSb) nanowire [30]. The linear expansion of the re-entrant conductance width was observed with the increased magnetic field titled from the SOI field (Fig. 9(c)). Furthermore, they demonstrated the angular dependence of magnetic field for the first time, where the applied field was rotated with respect to the SOI field by small angles (Fig. 9(d)). Under such circumstance, the width of the helical gap was controlled following the sinusoidal law. They extracted a spin-orbit energy of meV and a *g*-factor of from the helical state measurements for the InSb nanowire.

3.4 Hole helical state detection in Ge/Si nanowires

Ge/Si nanowires have been predicted to have a considerable Landé *g*-factor of and strong dipole-Rashba spin−orbit interaction with an energy meV, making the system promising for the study of the helical state of a hole system [14, 31]. However, in Ge/Si nanowires with core diameter of nm, the hole subband separation is only several meV. Subsequently, detection of the helical state as a re-entrant conductance is more difficult than in the narrow gap III-V nanowires. In the following, the experimental measurement of the re-entrant conductance features associated with helical states are presented for the Ge/Si core/ shell hole nanowires [12].

3.4.1 Device

The device used to detect the helical state in the Ge/Si nanowire is shown in Fig. 10(a), which consists of a predefined metal gate on a SiO2/Si substrate, a hexagonal boron nitride (h-BN) flake of nm thickness as a dielectric layer, a nanowire of nm in diameter, and electrical contacts made from a titanium/palladium stack ( nm / nm). The h-BN flake and nanowires were dry-transferred using a mechanical manipulator with a viscoelastic membrane (Gelfilm, Gelpak) in sequence. Electrical contacts were defined using electron beam lithography and evaporation. To ensure the optimized contact condition, a short dip in buffered hydrofluoric acid strips the surface oxide of the nanowire before metal deposition.

3.4.2 Quasi-1D transport and re-entrant conductance

Differential conductance was measured in the vicinity of the first conduction mode as a function of gate voltage in the device with nm long Ge/Si junction at K (Figs. 10(b) and 10(c)). Quantized conductance plateaus at integer multiples of were observed, indicating a quasi-ballistic 1D transport dominating in the nanowire. The plateau of  reveals the nanowire possibly possessing a strong electron–electron interaction. More interestingly, on the plateaus the pronounced conductance re-entrant dips were observed without the application of magnetic field, as indicated by the red arrows in Fig. 10(b). A similar phenomenon has been reported previously by Heedt *et al.* in which the feature was referred to as a pseudo-helical gap introduced by the emergence of correlated two-particle backscattering and the Rashba SOI [26]. The conductance measurement at an elevated temperature of K and with a finite DC bias of mV suppresses the conductance fluctuations originating from e.g. Fabry-Pérot oscillations, as shown in Fig. 10(c). Moreover, under such circumstances, the zero-field pseudo-gap vanishes giving a clearer presentation of the flat quantized conductance plateaus. Quantized conductance plateaus and the re-entrant conductance can also be observed clearly as “diamonds” in the voltage bias spectroscopy (Fig. 10 (d)).

In our studies the quantized conductance and re-entrant conductance features were searched for in various devices with different geometries. The re-entrant conductance features were only found in a few cases, while quantized conductance features can be observed in a number of devices. For instance, severe fluctuations appeared in the conductance of a device with shorter junction lengths of nm, which heavily masked the quantized plateaus. In these devices, the onset potential length is possibly far from the optimal, or the contacts may have insufficient transparency. The re-entrant conductance feature was also found in a longer junction of nm. Further details maybe found in Ref. [12].

3.4.3 Magnetic field dependence

To verify the re-entrant conductance opened in the Ge/Si nanowire by magnetic field as well as its helical nature, the feature should exhibit the two aforementioned magnetic field dependences.

Firstly, the re-entrant conductance feature residing on the quantized conductance plateaus is found to expand linearly with increasing magnetic field applied perpendicularly to the SOI field (Fig. 11(a)), as expected for the helical state associated with SOI. Some weak conductance fluctuations contributed by Fabry-Pérot oscillations or other phenomenon are also found. Fortunately, these can be easily distinguished from the re-entrant conductance feature as they possess negligible magnetic response and present as vertical “strips” in Fig. 11(a). The expanded helical gap is also noticed in the voltage bias spectrum by comparing that measured without field in Figure 10(d) and measured at T in Figure 11(b).

Another important test before confirming the measured re-entrant conductance as a result of the transport via the helical state is the angular -field dependence. In this experiment, the device was rotated in the magnetic field using the nanowire as the axis. Figure 11(c) plots the angular dependence of the re-entrant conductance at a constant field strength of T and rotating from to . When external -field is rotated into the substrate plane, *i.e.* towards the SOI field, the helical gap is decreased. The helical gap energy is extracted and plotted as a function of in Figure 11(d). It can be fitted well to the sinusoidal law as expected. Combining the results of both and dependence, one can be convinced by the helical nature of the measured re-entrant conductance feature.

3.4.4 Extraction of Landé g-factor and SOI

From the linear field dependence of the helical state in a normal magnetic field, the Landé *g*-factor can be extracted. From the voltage bias spectra in Fig. 10 (d) and Fig. 11(b), it can be seen that increasing the magnetic field from T to T enhances the energy of the helical gap from meV to meV as a result of the enhanced . Subsequently, this gives a *g*-factor of . Additionally, the gate lever arm is calculated as meV/V from the voltage bias spectra. Hence, a similar *g*-factor of and a pseudo-helical gap meV can also be evaluated from the magnetic field dependence measurement in Fig. 11(a). The evaluated *g*-factor from the transport through the helical state is larger than previously reported *g*  extracted in the strongly confined quantum dots, but resembles the theoretical prediction for the Ge/Si nanowire in weak electric field of V/μm [31].

The strength of the SOI, , is roughly equal to the energy between the bottom of the subband to the center of the helical gap at zero magnetic field, as illustrated in Fig. 7(b). It is translated to be meV from the gate voltage span of V with the gate lever arm of meV/V (see Fig. 11(a)). The SOI length is calculated as nm, with being the effective mass of the heavy hole which is predominant in the low-energy regime in the Ge/Si nanowire. This result is consistent with meV evaluated from the weak antilocalization measurements introduced in Sect. 2. The Rashba coefficient is, therefore, calculated as .

4 Toward Spin-Photon Coupling

4.1 Double quantum dot embedded in a superconducting cavity

The strong and tunable spin-orbit coupling in Ge/Si nanowires has been demonstrated by the investigation of the weak-anticoalition and the helical state in the magneto transport described in the Sect. 2 and 3. In this section, we first focus on the experimental implementation of Ge/Si nanowire quantum dots coupled to a superconducting resonator, which is widely utilized as a sensitive dispersive read-out probe or coherent “quantum information bus” for the scalable quantum processor. With the extracted charge-photon coupling strength *gc* and the spin-orbit interaction energy, we will estimate the potential spin-photon coupling strength *gs* with the same setup. The strong coupling of an electron charge or spin with photons in an on-chip cavity has been accomplished recently [32, 33], but has yet to be extensively explored in the hole system. For this reason it is of fundamental interest to explore a hole-photon hybrid system based on Ge/Si nanowires.

A typical transmission line resonator is fabricated using a nm MoRe superconducting thin film as shown by the optical micrograph of Fig. 12 (upper panel). Close to each open end of the ½- microwave frequency resonator a Ge/Si nanowire device was placed bridging the center pin and ground plane in order to maximize the capacitively coupling strength. The magnified SEM images of a nanowire quantum device are shown in the bottom panel of Fig. 12. Each nanowire is lying on a set of dense surface gates using an exfoliated h-BN flake as the gate dielectric layer. The nanowires are dry transferred on top of the h-BN with a homemade micro-manipulator [26]. In the present study, we focused on one nanowire coupled to the resonator, so the nanowire at the other end was always pinched off. All the measurements were conducted in a dilution refrigerator with a base temperature of mK.

4.2 Model

A double quantum dot (DQD) is defined by applying voltages on the bottom gates. We ignore many body effects and assume a single hole confined in the DQD. Under certain gate conditions the DQD is isolated from the source-drain electrodes and only the inter-dot tunneling is allowed. The hole locates either on the left (L) or right (R) dot. The system can be treated as a charge qubit, which is described by the two-level system (TLS) model. Considering the spin degree of freedom, one has a Hamiltonian in a magnetic field, , where and are the Pauli operators in the position {*L, R*} and spin {↑, ↓} space [34]. and are the energy detuning and tunneling rate between left and right dots. and are the external applied (for Zeeman splitting) and the effective spin-orbit magnetic field, respectively. For simplicity all the parameters are in energy units.

The two orbital energy levels of a charge qubit as a function of and are calculated and shown in Fig. 13(a). The excited and ground orbital states are denoted as and , respectively, with their eigenenergy, . The presence of induces a hybridization of positional states and as an avoid gap in energy space.

An applied magnetic field will lift the spin degeneracy. Fig. 13(b) and (c) show the numerical calculation of four eigenenergy levels () in the regime of and , respectively. The eigenstates are represented in the {, , , } basis. The presence of spin-orbit interaction hybridizes the states of and when is close to the charge qubit energy and induces spin state mixing. For instance, clear anti-crossings of and are observed in Fig. 13(c) at when . The states of and are hybridized into two levels of and , the respective eigenstates at energy basis are denoted as and with the spin-orbit mixing angle . The hybridization opens the way to realize the spin-photon coupling, especially by utilizing the strong SOI in Ge/Si nanowire. As schematically illustrated by arrows in Fig. 13(b) and (c), a spin embedded in a resonator will couple to a photon by repeatedly absorbing/emitting the photon when photon energy (black arrows). The whole process maps to the -type transitions of ↔ ↔ at (indicated by green arrows). The electric-charge dipole coupling drives orbital transition of ↔ and spin-orbit interaction mixes ↔. For instance, with in (b) and mainly contribute to the respective states of and and vice versa in (c). The electrical dipole coupling primarily gives rise to the orbital transition of *E0* ↔ *E1* (or *E0* ↔ *E2*) in (b) (or (c)). In combination of the hybridization of and (in both (b) and (c)), the spin up/down transition is eventually realized in the manner of spin-photon coupling.

Our experiment focuses on a charge qubit coupled to a single mode harmonic oscillator, which is well described by a Jaynes-Cummings (JC) model with Hamiltonian

(4)

The first and second terms describe the bare resonator and qubit, respectively. The third term indicates the qubit-photon interaction, where is the effective coupling rate.  and are the photon creation and annihilation operators in the resonator. The mean photon number in the resonator is . are the charge qubit raising and lowering operators in the orbital basis { , } and the Pauli operator The qubit energy is , and resonator photon energy is where is the angular frequency. Fig. 13 (d-f) show the calculated quantum level spectrum of a closed Jaynes-Cummings system for (d) , (e) , and (f) where external drive and system decay are not considered The qubit-resonator energy detuning is defined as . The simulation parameters are close to the experiment for straightforward comparison (refer to Ref. [13] for more parameter details). A splitting feature is always observed whenever the qubit energy is swept across the photon level (Fig. 13(d)), indicating the charge-photon coupling. The gap is determined by parameter The qubit-photon hybridization is encoded by the superposition states as and , where the qubit is repeatedly absorbing/emitting the photon trapped in the resonator. The splitting reaches a maximum, equal to , if . Once the qubit is largely detuned from the photon level (Fig. 13(f)), the resonator mode obtains a dispersive shift by as much as depending on the qubit state. The dispersive shift of the resonance is utilized to probe the charge state of the DQD throughout the present work.

4.3 Charge stability in a double quantum dot

The charge number in the DQD is defined by the voltages of each finger gate (Fig. 14 (a)), denoted as *, , , ,* and *,* respectively. The response of resonator transmission is utilized to infer the charge state as the susceptibility of the DQD to microwave photons varies with gating. Fig. 14(b) shows the resonator transmission spectrum when the DQD is in the deep blockade (blue) and on the resonant tunneling condition between left and right dots (red). The lineshape shows a significant variation between these two conditions. The fundamental mode of the resonator is extracted when the DQD is in the Coulomb blockade regime, yielding the central frequency and a width . The lifetime of trapped photons in the cavity is . Using the response of the magnitude and phase of the resonator transmission, the charge stability diagram is presented in Fig. 14(c). A clear honeycomb-like pattern is observed, as outlined by the white dotted lines, showing a charge stability diagram of a DQD in the gate voltage sweeping range [35]. Combined with DC transport measurements [13], the charging energy of each dot is evaluated as and . The gates and source/drain capacitive lever-arms are , , and , respectively. The electrochemical potential of each dot considering the mutual capacitive coupling reads , where the cross capacitive coupling rate , the mutual capacitance between dots , and is the total capacitance of each dot. The energy detuning between left and right dot is determined as .

4.4 Tunable charge dipolar coupling

In the phase plot of Fig. 14(c), one may notice that both negative and positive phase shift are observed as highlighted by arrows in the graph. This is a signature of charge qubit-photon energy detuning . We now concentrate on one inter-dot charge transition line. The evolution of the phase signal for the same range of and is presented in Fig. 15(a) with altered in steps of mV. determines the tunneling rate between left and right dots. As increases (corresponded to a smaller tunneling rate ), the negative phase shift gradually changes to a positive shift. Line cuts of along the axis with different are compared in Fig. 15(b). The lineshapes of the phase shift spectrum show a clear variation as reduces. This is attributed to the tunnel rate undergoing an evolution from to as increases.

To quantitatively interpret the dynamical response of the resonance transmission, a complete quantum model is needed where the drive and leakage of resonator as well as qubit relaxation and decoherence are taken into account in addition to the JC model. By solving the Markovian master equation of Eq. 4, we can numerically calculate the steady state of the qubit and resonator transmission using the quantum toolbox in python, QuTip [36]. With input-output theory [34], the resonator transmission dependence on qubit state can also be analytically solved as:

, (5)

where is the input/output coupling rate of the resonator. Parameter is the qubit decoherence rate, which is the summation of the energy relaxation rate and the pure dephasing rate . is taken as the qubit being kept in the ground state with a weak drive. The phase variation in Fig. 15(b) is fitted by Eq. (5). The result shows that the inter-dot tunneling rate varies from to , in good agreement with the experimental observation. The coupling strength *gc* is in the range *2× 35 ~ 55* MHz, which is close to reports on similar devices in other semiconductor QD systems [32, 33, 37, 38]. However, the decoherence rate of the qubit varies in a range *2× 4.5 ~ 6.5* GHz, which is much larger than the coupling strength. As a result we do not observe the strong charge-photon coupling regime, which requires . To further verify the validity of fitting, we perform numerical calculations of the whole system with Eq. 4 using the fitted-out parameters as shown in Fig. 15(c). The simulation replicates most of the main features from the measurements.

Switching to spin-photon coupling may be a promising way to realize a strong coupling condition as spin is less prone to charge noise. It is of interest to estimate the potential spin-photon coupling via the SOI for the Ge/Si nanowire based on our current setup. When a DQD is in a deep blockade regime, the DQD is reduced to a single QD. The spin-photon coupling strength , with a typical single dot energy spacing , Zeeman splitting , single dot ground state size , and a moderate spin-orbit length . If inter-dot detuning ** is zero, the charge dipole becomes larger and we assume a charge qubit energy . The half inter-dot distance nm. The spin-photon coupling strength is then estimated as , and relates to the left and right dot wave function overlap [39]. Recent reports claim the coherence time of a hole spin qubit based on a p-type Ge quantum well reaches a few s [40], while that of electron spin in isotopic enriched Si quantum dot has been elevated to s [1, 41]. Further improvement of the coherence of hole spin qubit in Si or Ge materials is anticipated with isotopic purification. The reasonable large spin-photon coupling strength promises Ge/Si nanowire as an attractive platform for the coherent spin-photon interface.

Summary

The coherence times of spin qubits based on quantum dots has prolonged by four to five orders of magnitude over the past two decades, approaching the single spin operation fidelity threshold for an error-correction quantum computer. Two qubit logic gates have hence been implemented with high fidelity as evident by various benchmarking methods, bringing the universal quantum computation close to reality. Moreover, recent demonstration of single electron and spin coherently coupled to a superconducting resonator, makes the spin qubit-based quantum processor truly extensible. The impressive evolution is always accompanied with the progressive innovation of host semiconductor materials in combination with advanced control methods. The center of attention has been focused on electron based devices for decades, the hole materials are rarely explored but should not necessarily be ignored. We have attempted to investigate 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, to 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 modest electrical field as evident from the weak-antilocalization feature observed in magnetotransport measurements. In the presence of strong spin-orbit interaction, the electrical and magnetic field dependence of a helical state is witnessed, indicating that the system may be useful for study of engineered topological states for Majorana Fermions. Finally 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 MHz, and hence the potential spin-photon coupling strength through spin-orbit interaction is estimated around MHz.

Acknowledgments

The authors gratefully acknowledge Charles M. Lieber and Jun Yao for providing high quality Ge/Si nanowire as well as numerous fruitful discussions with Junsaku Nitta, Peter Stano and Daniel Loss.

References:

1. Yoneda J, Takeda K, Otsuka T, Nakajima T, Delbecq MR, Allison G, Honda T, Kodera T, Oda S, Hoshi Y, Usami N, Itoh KM, Tarucha S (2018) A quantum-dot spin qubit with coherence limited by charge noise and fidelity higher than 99.9%. Nat Nanotechnol 13:102–106. https://doi.org/10.1038/s41565-017-0014-x

2. Nadj-Perge S, Frolov SM, Bakkers EP a. M, Kouwenhoven LP (2010) Spin–orbit qubit in a semiconductor nanowire. Nature 468:1084–1087. https://doi.org/10.1038/nature09682

3. Majer J, Chow JM, Gambetta JM, Koch J, Johnson BR, Schreier JA, Frunzio L, Schuster DI, Houck AA, Wallraff A, Blais A, Devoret MH, Girvin SM, Schoelkopf RJ (2007) Coupling superconducting qubits via a cavity bus. Nature 449:443–447. https://doi.org/10.1038/nature06184

4. König M, Buhmann H, W. Molenkamp L, Hughes T, Liu C-X, Qi X-L, Zhang S-C (2008) The Quantum Spin Hall Effect: Theory and Experiment. J Phys Soc Jpn 77:031007. https://doi.org/10.1143/JPSJ.77.031007

5. Mourik V, Zuo K, Frolov SM, Plissard SR, Bakkers EP a. M, Kouwenhoven LP (2012) Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices. Science 336:1003–1007. https://doi.org/10.1126/science.1222360

6. Das A, Ronen Y, Most Y, Oreg Y, Heiblum M, Shtrikman H (2012) Zero-bias peaks and splitting in an Al–InAs nanowire topological superconductor as a signature of Majorana fermions. Nat Phys 8:887–895. https://doi.org/10.1038/nphys2479

7. Deng MT, Yu CL, Huang GY, Larsson M, Caroff P, Xu HQ (2012) Anomalous Zero-Bias Conductance Peak in a Nb–InSb Nanowire–Nb Hybrid Device. Nano Lett 12:6414–6419. https://doi.org/10.1021/nl303758w

8. Karzig T, Knapp C, Lutchyn RM, Bonderson P, Hastings MB, Nayak C, Alicea J, Flensberg K, Plugge S, Oreg Y, Marcus CM, Freedman MH (2017) Scalable designs for quasiparticle-poisoning-protected topological quantum computation with Majorana zero modes. Phys Rev B 95:235305. https://doi.org/10.1103/PhysRevB.95.235305

9. Lauhon LJ, Gudiksen MS, Wang D, Lieber CM (2002) Epitaxial core–shell and core–multishell nanowire heterostructures. Nature 420:57–61. https://doi.org/10.1038/nature01141

10. Lu W, Xiang J, Timko BP, Wu Y, Lieber CM (2005) One-dimensional hole gas in germanium/silicon nanowire heterostructures. Proc Natl Acad Sci 102:10046–10051. https://doi.org/10.1073/pnas.0504581102

11. Wang R, Deacon RS, Yao J, Lieber CM, Ishibashi K (2017) Electrical modulation of weak-antilocalization and spin–orbit interaction in dual gated Ge/Si core/shell nanowires. Semicond Sci Technol 32:094002. https://doi.org/10.1088/1361-6641/aa7ce6

12. Sun J, Deacon RS, Wang R, Yao J, Lieber CM, Ishibashi K (2018) Helical Hole State in Multiple Conduction Modes in Ge/Si Core/Shell Nanowire. Nano Lett 18:6144–6149. https://doi.org/10.1021/acs.nanolett.8b01799

13. Wang R, Deacon RS, Sun J, Yao J, Lieber CM, Ishibashi K (2019) Gate Tunable Hole Charge Qubit Formed in a Ge/Si Nanowire Double Quantum Dot Coupled to Microwave Photons. Nano Lett 19:1052–1060. https://doi.org/10.1021/acs.nanolett.8b04343

14. Kloeffel C, Trif M, Loss D (2011) Strong spin-orbit interaction and helical hole states in Ge/Si nanowires. Phys Rev B 84:195314. https://doi.org/10.1103/PhysRevB.84.195314

15. Kloeffel C, Trif M, Stano P, Loss D (2013) Circuit QED with hole-spin qubits in Ge/Si nanowire quantum dots. Phys Rev B 88:241405. https://doi.org/10.1103/PhysRevB.88.241405

16. Nitta J, Akazaki T, Takayanagi H, Enoki T (1997) Gate Control of Spin-Orbit Interaction in an Inverted In0.53Ga0.47As/In0.52Al0.48As Heterostructure Phys Rev Lett 78:1335–1338. https://doi.org/10.1103/PhysRevLett.78.1335

17. Heida JP, van Wees BJ, Kuipers JJ, Klapwijk TM, Borghs G (1998) Spin-orbit interaction in a two-dimensional electron gas in a InAs/AlSb quantum well with gate-controlled electron density. Phys Rev B 57:11911–11914. https://doi.org/10.1103/PhysRevB.57.11911

18. Fasth C, Fuhrer A, Samuelson L, Golovach VN, Loss D (2007) Direct Measurement of the Spin-Orbit Interaction in a Two-Electron InAs Nanowire Quantum Dot. Phys Rev Lett 98:266801. https://doi.org/10.1103/PhysRevLett.98.266801

19. Takahashi S, Deacon RS, Yoshida K, Oiwa A, Shibata K, Hirakawa K, Tokura Y, Tarucha S (2010) Large Anisotropy of the Spin-Orbit Interaction in a Single InAs Self-Assembled Quantum Dot. Phys Rev Lett 104:246801. https://doi.org/10.1103/PhysRevLett.104.246801

20. Bergmann G (1984) Weak localization in thin films: a time-of-flight experiment with conduction electrons. Phys Rep 107:1–58. https://doi.org/10.1016/0370-1573(84)90103-0

21. Scherübl Z, Fülöp G, Madsen MH, Nygård J, Csonka S (2016) Electrical tuning of Rashba spin-orbit interaction in multigated InAs nanowires. Phys Rev B 94:035444. https://doi.org/10.1103/PhysRevB.94.035444

22. van Weperen I, Tarasinski B, Eeltink D, Pribiag VS, Plissard SR, Bakkers EPAM, Kouwenhoven LP, Wimmer M (2015) Spin-orbit interaction in InSb nanowires. Phys Rev B 91:201413. https://doi.org/10.1103/PhysRevB.91.201413

23. Kunihashi Y, Kohda M, Nitta J (2009) Enhancement of Spin Lifetime in Gate-Fitted InGaAs Narrow Wires. Phys Rev Lett 102:226601. https://doi.org/10.1103/PhysRevLett.102.226601

24. Beenakker CWJ, van Houten H (1988) Boundary scattering and weak localization of electrons in a magnetic field. Phys Rev B 38:3232–3240. https://doi.org/10.1103/PhysRevB.38.3232

25. Kettemann S (2007) Dimensional Control of Antilocalization and Spin Relaxation in Quantum Wires. Phys Rev Lett 98:176808. https://doi.org/10.1103/PhysRevLett.98.176808

26. Wang R, Deacon RS, Car D, Bakkers EP a. M, Ishibashi K (2016) InSb nanowire double quantum dots coupled to a superconducting microwave cavity. Appl Phys Lett 108:203502. https://doi.org/10.1063/1.4950764

27. Rainis D, Loss D (2014) Conductance behavior in nanowires with spin-orbit interaction: A numerical study. Phys Rev B 90:235415. https://doi.org/10.1103/PhysRevB.90.235415

28. Quay CHL, Hughes TL, Sulpizio JA, Pfeiffer LN, Baldwin KW, West KW, Goldhaber-Gordon D, Picciotto R de (2010) Observation of a one-dimensional spin–orbit gap in a quantum wire. Nat Phys 6:336–339. https://doi.org/10.1038/nphys1626

29. Heedt S, Ziani NT, Crépin F, Prost W, Trellenkamp S, Schubert J, Grützmacher D, Trauzettel B, Schäpers T (2017) Signatures of interaction-induced helical gaps in nanowire quantum point contacts. Nat Phys 13:563–567. https://doi.org/10.1038/nphys4070

30. Kammhuber J, Cassidy MC, Pei F, Nowak MP, Vuik A, Gül Ö, Car D, Plissard SR, Bakkers EP a. M, Wimmer M, Kouwenhoven LP (2017) Conductance through a helical state in an Indium antimonide nanowire. Nat Commun 8:1–6. https://doi.org/10.1038/s41467-017-00315-y

31. Maier F, Kloeffel C, Loss D (2013) Tunable *g* factor and phonon-mediated hole spin relaxation in Ge/Si nanowire quantum dots. Phys Rev B 87:161305. https://doi.org/10.1103/PhysRevB.87.161305

32. Mi X, Cady JV, Zajac DM, Deelman PW, Petta JR (2017) Strong coupling of a single electron in silicon to a microwave photon. Science 355:156–158. https://doi.org/10.1126/science.aal2469

33. Mi X, Benito M, Putz S, Zajac DM, Taylor JM, Burkard G, Petta JR (2018) A coherent spin–photon interface in silicon. Nature 555:599–603. https://doi.org/10.1038/nature25769

34. Benito M, Mi X, Taylor JM, Petta JR, Burkard G (2017) Input-output theory for spin-photon coupling in Si double quantum dots. Phys Rev B 96:235434. https://doi.org/10.1103/PhysRevB.96.235434

35. Kouwenhoven LP, Austing DG, Tarucha S (2001) Few-electron quantum dots. Rep Prog Phys 64:701–736. https://doi.org/10.1088/0034-4885/64/6/201

36. Johansson JR, Nation PD, Nori F (2013) QuTiP 2: A Python framework for the dynamics of open quantum systems. Comput Phys Commun 184:1234–1240. https://doi.org/10.1016/j.cpc.2012.11.019

37. Frey T, Leek PJ, Beck M, Blais A, Ihn T, Ensslin K, Wallraff A (2012) Dipole Coupling of a Double Quantum Dot to a Microwave Resonator. Phys Rev Lett 108:046807. https://doi.org/10.1103/PhysRevLett.108.046807

38. Borjans F, Croot XG, Mi X, Gullans MJ, Petta JR (2020) Resonant microwave-mediated interactions between distant electron spins. Nature 577:195–198. https://doi.org/10.1038/s41586-019-1867-y

39. Hu X, Liu Y, Nori F (2012) Strong coupling of a spin qubit to a superconducting stripline cavity. Phys Rev B 86:035314. https://doi.org/10.1103/PhysRevB.86.035314

40. Hendrickx NW, Franke DP, Sammak A, Scappucci G, Veldhorst M (2020) Fast two-qubit logic with holes in germanium. Nature 577:487–491. https://doi.org/10.1038/s41586-019-1919-3

41. Veldhorst M, Hwang JCC, Yang CH, Leenstra AW, Ronde B de, Dehollain JP, Muhonen JT, Hudson FE, Itoh KM, Morello A, Dzurak AS (2014) An addressable quantum dot qubit with fault-tolerant control-fidelity. Nat Nanotechnol 9:981–985. https://doi.org/10.1038/nnano.2014.216