Quasiballistic quantum transport through Ge/Si core/shell nanowires

D Kotekar-Patil1,6, B-M Nguyen2,7, J Yoo2, S A Dayeh3,4,5 and S M Frolov1

1 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, United States of America
2 Center for Integrated Nanotechnologies, Los Alamos National Laboratory, Los Alamos, NM 87545, United States of America
3 Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, CA 92037, United States of America
4 Graduate Program of Materials Science and Engineering, University of California, San Diego, La Jolla, CA 92037, United States of America
5 Department of NanoEngineering, University of California, San Diego, La Jolla, CA 92037, United States of America

E-mail: dpatil@ntu.edu.sg

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Abstract
We study signatures of ballistic quantum transport of holes through Ge/Si core/shell nanowires at low temperatures. We observe Fabry–Pérot interference patterns as well as conductance plateaus at integer multiples of $2e^2/h$ at zero magnetic field. Magnetic field evolution of these plateaus reveals relatively large effective Landé $g$-factors. Ballistic effects are observed in nanowires with silicon shell thickness of 1–3 nm, but not in bare germanium wires. These findings inform the future development of spin and topological quantum devices which rely on ballistic sub-band-resolved transport.

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(Some figures may appear in colour only in the online journal)

1. Introduction

A surge of interest in devices based on nanowires (NWs) with strong spin-orbit interaction is due to their relevance for quantum computing [1–7] and for the realization of topological superconductivity and Majorana fermions [8, 9]. Silicon and germanium are both group IV elements. Both can provide nuclear free environment which is identified as the main source of decoherence in III–V materials. Additionally, spin-orbit interaction in germanium/silicon (Ge/Si) NWs was predicted and estimated experimentally to be strong [10–15]. The strong spin-orbit interaction in these material can allow for fast electrical control of spins. Moreover, spin relaxation times in Ge/Si core/shell NWs are predicted to be of the order of few tens of milliseconds under the right conditions and can be tuned with silicon shell thickness and longitudinal confinement [16]. This makes Ge/Si core/shell NWs an excellent candidate for spin qubits based on quantum dots. In addition, proximity-induced superconductivity has been demonstrated in these NWs [17, 18]. Landé $g$-factor is predicted to be relatively large and strongly dependent of electric and magnetic field orientation [10]. In recent experiments, relatively large Landé $g$-factors were reported [14, 19] in these NWs. Moreover, mobility upto 4200 cm$^2$ V$^{-1}$ s$^{-1}$ was recently reported [20]. Strong spin-orbit interaction, induced superconductivity along with large $g$-factors make Ge/Si core/shell NWs an excellent testbed for Majorana experiments, provided these effects are observed in the ballistic transport regime [15, 21–23].
In this paper, we report on transconductance resonances consistent with one-dimensional (1D) subbands occupied one-by-one as the top gate voltage is made more negative. At low temperatures (<1 K) transport is strongly dominated by Fabry–Pérot interference patterns. The magnetic field evolution of conductance resonances reveals large g-factors. These effects are observed for a range of silicon shell thicknesses without any obvious dependence on the thickness of the silicon shell, however devices without any shell did not show ballistic transport signatures and exhibited substantial charge instabilities. We estimate the subband spacing to be $\sim$20 meV, the low temperature mobility of up to 1000 cm$^2$ V$^{-1}$ s$^{-1}$ and the mean free path of 70 nm. The mean free path is larger than the core diameter consistent with the quasiballistic regime.

2. Fabrication

Ge/Si core/shell NWs are grown using the low pressure, cold-walled chemical vapor deposition. NWs are grown with various core diameters (15–55 nm) and shell thicknesses (0–4 nm) [24]. Figure 1(a) shows a high resolution transmission electron micrograph of a Ge/Si core/shell NW demonstrating a high degree of control over the silicon shell thickness [25–27]. To fabricate devices, the NWs are sonicated in isopropanol and then dropped onto Si$_3$N$_4$ substrates with alignment markers. In order to achieve the low ohmic contact resistance, a dip in hydrofluoric acid is performed to etch the native oxide on the silicon shell. Electron beam lithography and electron beam evaporation are used to define two 150 nm thick nickel contacts, 600–700 nm apart. This step is followed by a 30 s rapid thermal annealing at 300 °C. During annealing, Ni diffuses into the NW from both ends forming highly doped NiGe$_x$/NiSi$_{1-x}$ alloyed ohmic contacts [28–30]. Segments of the NW between the alloyed sections define the Ge/Si channel length ($L = 250–450$ nm). From the scanning electron microscope image contrast difference between the alloyed metallic regions and the unalloyed segment of the NW, Ge/Si device channel length is estimated [24]. The fabrication process is optimized to achieve a channel length of $L = 250–450$ nm and none of the devices are electrically shorted. As a last step, a top gate stack consisting of a 10 nm thick hafnium oxide gate dielectric is deposited using atomic layer deposition and then a 30 nm/100 nm thick Ti/Au top gate electrode is evaporated. The gate contact overlaps with the alloyed region, fully covering the unalloyed Ge/Si channel.

3. Signatures of conductance quantization

Electrical characterization is performed in a dilution refrigerator equipped with a 9 T magnet, using a standard lock-in technique at 27 Hz with an excitation voltage of 50 $\mu$V. Noise attenuation is done in 2 stages: at room temperature using $\pi$-filters, and at low temperatures using two-stage low-pass RC filters. Room temperature characterization of the same devices is reported by Nguyen et al [24]. The room temperature saturation resistance, which is the two-terminal resistance measured at highly negative top gate voltages ($V_g$), is in the range of 10 kΩ. The room temperature field effect mobility is 150–250 cm$^2$ V$^{-1}$ s$^{-1}$ for NWs with silicon shells independent of shell thickness, and 50 cm$^2$ V$^{-1}$ s$^{-1}$ for bare Ge NWs. Measurements in this work show that at low temperatures the saturation resistance is comparable to the room temperature resistance (1–20 kΩ). The low temperature field-effect mobility is in the range of 200–500 cm$^2$ V$^{-1}$ s$^{-1}$ with the highest mobility of 1000 cm$^2$ V$^{-1}$ s$^{-1}$, extracted from the pinch-off traces using gate-to-NW capacitance calculated by a self-consistent Poisson solver (see supplementary information, available online at stacks.iop.org/NANO/28/385204/mmedia).

As the gate voltage is swept from positive to negative, conductance increases in steps of $2e^2/h$ (figure 2(a)). We associate this with 1D spin-degenerate subband-resolved transport. Additionally, we observe a conductance plateau below the first $2e^2/h$ plateau. Such features are frequently reported in quantum point contacts [31–34] and are not the
focus of this work. We further investigate this device in the nonlinear regime where conductance through the NW is studied as a function of bias voltage \( V \) and gate voltage. Figure 2(b) shows the waterfall plot in which we observe accumulations of conductance traces near \( 2 e^2/h \) and \( 4 e^2/h \). However, plateaus at \( 0.5 \times 2 e^2/h \) that are expected in quantum point contacts at high bias, when the bias exceeds the subband spacing, could not be resolved due to strong current fluctuations at high bias. These large amplitude current fluctuations at frequencies 0.01–1 Hz observed at finite bias are not understood, though similar effects are observed in other 1D NWs [21].

Figure 2(c) shows the transconductance \( dG/dV \) of the data in the panel 2(b). High transconductance resonances move linearly as a function of \( V_g \) and \( V \). The difference in bias points where positive and negative slope transconductance resonances meet (forming diamond-shaped regions) indicate the energy separation between the 1D subbands. From figure 2(c), we observe that the first \( (E_{2,1}) \) and second \( (E_{3,2}) \) transconductance diamonds have approximately the same size of \( \approx 22 \) meV. This energy separation is consistent with transverse quantization in the NW for heavy holes with an effective mass of \( m_{th} = 0.28m_e \), where \( m_e \) is the free electron mass. Additionally, the slopes of the transconductance resonances are used to extract the gate lever arm parameter \( \alpha = dV/dV_g = 29.5 \) meV V\(^{-1}\).

4. Magnetotransport

Figure 3 shows the evolution of conductance steps as a function of magnetic field. We note that we only observe Zeeman splitting for the second and third conductance steps while the first step only exhibits a Zeeman shift rather than a splitting. In addition, there are other resonances in figure 3 which move linearly with magnetic field. We associate these resonances to quantum interference effects [35], similar \( g \)-factors can be extracted for these resonances. Zeeman splitting is given by \( \Delta E_z = g \mu_B B \), where \( \mu_B \) is the Bohr’s magneton. We use the lever arm parameter calculated from the transconductance diamond in figure 2(c) to convert the \( V_g \) axis into the energy scale. This gives a \( g \)-factor for each transition which we denote by \( g_1 = 2 \) for the first transition, \( g_2 = 10.7 \pm 2.3 \) for transition between the first and the second conductance steps and \( g_3 = 4.7 \pm 1.3 \) for transition between the second and the third conductance step.

Due to the large effective hole masses, the orbital effects of magnetic field are ignored when extracting \( g \)-factors, however they may contribute to the shifts of resonances in magnetic field, especially for the resonances with the smaller apparent \( g \)-factors. Large \( g \)-factors were also recently observed in Ge/Si NW quantum dots [14, 19].

5. Fabry–Pérot interference

All the devices measured in this work are fabricated using a nominally identical fabrication process. All the devices with silicon shell show similar two point resistances at room temperature and at low temperature. In a typical device, subband-resolved transport and conductance plateaux are scrambled due to backscattering and are replaced with Fabry–Pérot oscillations. Figures 4(a) and 4(b) show signatures of conductance quantization (shown in figures 2 and S1). We believe that the difference originates from microscopic details of the NW and the fabrication steps. The main difference between devices showing Fabry–Pérot and conductance plateaux is likely the arrangement of dominant scattering centers in the NW. Very low density of defects along with a finite-transparency contact in the NW is enough to result in backscattering of holes resulting in Fabry–Pérot oscillations. While sharp boundary between alloyed and unalloyed segments of the NW is observed in the SEM, individual Ni atoms may have diffused deeper into the NW creating additional scattering centers. Data shown in figure 4(a) are based on a NW device with diameter \( d = 35 \) nm, length \( L = 350 \) nm and shell thickness \( t_s = 1 \) nm at \( T = 400 \) mK. Mobility extracted from \( G(V_g) \) trace at \( T = 4 \) K is \( \approx 450 \) cm\(^2\) V\(^{-1}\) s\(^{-1}\). While this trace does not show conductance plateaus, it is a representative trace for many core/shell devices studied at temperatures below 1 K. With the application of negative gate...
Figure 3. Differential conductance as a function of magnetic field and $V_g$ at $V = 0$ V for field oriented at an angle of 45° to the NW. Black dashed lines mark the spin splitting of the first ($E_{11}$) and second conductance step ($E_{21}$ and $E_{22}$) and green dashed lines mark spin splitting of the third conductance step ($E_{31}$ and $E_{32}$).

Figure 4. (a) Differential conductance at $V = 0$ V and (b) transconductance map for a device with silicon shell thickness of 1 nm. $T = 400$ mK, $B = 0$ T (c) zoom-in of the checkerboard pattern marked by black box in panel (b).

To conclude, signatures compatible with conductance quantization are measured in Ge/Si NW devices. In the magneto-transport measurements we observe Zeeman splitting of these conductance steps. Magnetic field dependence reveals that the hole $g$-factor in our NWs is relatively large compared to previous reports. Moreover, the presence of a silicon shell on the NW results in quasi-ballistic transport which is absent in bare Ge NW (see supplementary information). The yield of devices showing conductance quantization can be improved in the future, for example by making devices based on higher mobility Ge/Si core/shell NWs [20].

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ORCID iDs

D Kotekar-Patil https://orcid.org/0000-0002-4069-1200

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