Conductance Quantization at Zero Magnetic Field in InSb Nanowires

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Supporting Information

ABSTRACT: Ballistic electron transport is a key requirement for existence of a topological phase transition in proximitized InSb nanowires. However, measurements of quantized conductance as direct evidence of ballistic transport have so far been obscured due to the increased chance of backscattering in one-dimensional nanowires. We show that by improving the nanowire—metal interface as well as the dielectric environment we can consistently achieve conductance quantization at zero magnetic field. Additionally we study the contribution of orbital effects to the sub-band dispersion for different orientation of the magnetic field, observing a near-degeneracy between the second and third sub-bands.

KEYWORDS: Quantum point contact, conductance quantization, nanowire, InSb, subband, orbital effects

Semiconducting nanowires made from InAs and InSb are prime candidates for the investigation of novel phenomena in electronic devices. The intrinsic strong spin–orbit interaction (SOI) and large g-factor combined with flexible fabrication has resulted in these materials being investigated for applications in quantum computing1–3 spintronics,4–6 and Cooper pair splitters.7,8 More recently, these nanowires have been investigated as solid-state hosts for Majorana zero modes (MZMs).9–12 By bringing a one-dimensional (1D) nanowire with strong SOI into close contact with a superconductor under an external magnetic field, a region with inverted band structure emerges, creating MZMs at its ends. Together with strong SOI and induced superconductivity, a key requirement for MZMs is quasi-ballistic electron transport along the length of the proximitized region in the nanowire, with a controlled odd number of occupied modes.13 In the absence of scattering, the motion of 1D confined electrons will be restricted to discrete energy bands resulting in quantized conductance plateaus.14,15 Measurements of quantized conductance in the nanowires therefore provide direct evidence for controlled mode occupation, as well as ballistic transport in these nanowires.

Although now routine in gate defined quantum point contacts (QPC) in two-dimensional electron gases (2DEGs),14–18 quantized conductance in one-dimensional semiconductor nanowires is more difficult to achieve. In a 1D nanowire, scattering events along the electrons path to and through the constriction between the source and drain contacts have an increased probability of reflection, obscuring the observation of quantized conductance.19 These scattering events may be due to impurities and imperfections in the crystal lattice or due to surface states that create inhomogeneities in the local electrostatic environment.20 A Schottky barrier between the nanowire and metallic contacts will result in additional backscattering events, further smearing out the quantized conductance plateaus. To date, quantized conductance in InSb nanowires has only been observed at high magnetic fields (>4 T), where electron backscattering is strongly suppressed.19 No quantization has been observed in InSb for magnetic fields below 1 T, where the topological transition is expected to take place.9

Here we demonstrate conductance quantization in InSb nanowires at zero magnetic field. We have developed a robust fabrication recipe for observing quantized conductance by optimizing both the metal—nanowire contact interface and dielectric environment through the use of hexagonal boron nitride (hBN) as a gate dielectric. We study the evolution of the quantized conductance plateaus with both source-drain bias as well as magnetic field, and extract values for the Lande g-factor of the first three sub-bands in the nanowire. Additionally we study the contribution of orbital effects to the sub-band dispersion for perpendicular magnetic fields.

Figure 1a shows a cross-sectional view of our devices. They consist of an intrinsic Si-substrate with local metallic gates made of Ti/Au (5/10 nm), on top of which a sheet of hexagonal boron nitride (hBN) is mechanically transferred as the...
dielectric. The chemical stability, atomic flatness, and high breakdown voltage \(^{21}\) together with the well established dry transfer mechanism \(^{22}\) makes hBN an ideal dielectric for our nanowire devices. InSb nanowires grown by metal–organic vapor phase epitaxy \(^{13,24}\) (1–3 \(\mu\)m long and 70–90 nm diameter) are transferred deterministically with a micro-manipulator \(^{25}\) onto the hBN dielectric. Electrical contacts to the nanowire (evaporated Cr/Au (10/100 nm), 150–400 nm spacing) are defined by electron beam lithography. Before contact deposition, the surface oxide of the nanowires is removed using sulfur passivation \(^{26}\) followed by a short in situ He-ion mill. Residual sulfur from the passivation step also induces surface doping, which aids contact transparency. Further details of the fabrication are included in the Supporting Information. A top view scanning electron microscope image of a finished device is shown in Figure 1b. The samples are mounted in a dilution refrigerator with a base temperature of 15 mK and measured using standard lock-in techniques at 73 Hz with an excitation \(V_{RMS} = 70 \mu V\). Voltage is applied to the outer contact and current measured through the grounded central contact, while the third, unused contact is left floating.

We first characterize each device by sweeping the voltage on the underlying gate \(V_{gate}\) at fixed bias voltage \(V_{bias} = 10 \text{mV}\) across the sample. Conductance is obtained directly from the measured current \(G = I/V_{bias}\) and an appropriate series resistance is subtracted in each case (see Supporting Information). Figure 1c plots the conductance of the nanowire as a function of gate voltage for four different devices fabricated on the same chip. Devices with both fine gates as well as wide back gates have been measured. We find that while fine gates allow more flexible gating, devices with wide back gates showed more pronounced conductance plateaus even after extensive tuning of the fine gates. Data from additional devices all fabricated on the same chip is included in the Supporting Information.

As seen in Figure 1c all devices show well-defined plateaus at \(G_0\) and \(3G_0\) but the plateaus at \(2G_0\) and \(4G_0\) appear smaller or even completely absent. Unlike QPCs formed in 2DEGs, nanowires possess rotational symmetry. This symmetry can give rise to additional orbital degeneracies in the energies for the second and third as well as the fourth and fifth sub-band (Figure 1d). \(^{27,28}\) In conductance measurements at finite bias, sub-bands that are close in energy or degenerate will be populated at similar values in gate voltage giving a double step of \(\frac{4e^2}{h}\) instead of \(\frac{2e^2}{h}\), which explains the suppressed plateaus at \(2\) and \(4G_0\) (Figure 1e). \(^{29}\)

To investigate this phenomenon in more detail, we measure the differential conductance \(G = dI/dV_{bias}\) as a function of gate voltage and bias voltage for one of these devices (corresponding to the green trace in Figure 1c). This data is shown in Figure 2a as a color plot, with line cuts along 0 and 10 mV bias voltage added in the bottom panel. At zero bias voltage an extended plateau is visible at \(1G_0\), together with an additional

![Figure 1](image1.png)

**Figure 1.** (a) Cross-sectional schematic and (b) false color SEM image of a typical device. An InSb nanowire (blue) contacted by Cr/Au (yellow) is deposited on Ti/Au metal gates (gray) covered with hexagonal boron nitride (green) as insulating dielectric. (c) Pinch-off traces of four different devices each showing quantized conductance plateaus at high bias voltage (\(V_{bias} = 10 \text{mV}\)). (d) Schematic diagram of the first five sub-bands in a nanowire. At zero magnetic field, each spin-degenerate sub-band below the Fermi level contributes a conductance of \(G_0 = 2e^2/h\). Due to the rotational symmetry of the nanowires \(E_2, E_3\) and \(E_4, E_5\) are almost degenerate. (e) Sketch of the expected conductance steps as a function of \(V_{gate}\) at high bias voltage showing suppression of the second and fourth plateaus due to orbital sub-band degeneracy.

![Figure 2](image2.png)

**Figure 2.** (a) Color-plot of the differential conductance \(G = dI/dV_{bias}\) as a function of \(V_{bias}\) and \(V_{gate}\) at \(B = 0 \text{T}\). A line cut along 0 mV (green) and 10 mV (orange) bias voltage is shown in the bottom panel. (b) Differential conductance \(G = dI/dV_{bias}\) as a function of \(V_{bias}\) and \(V_{gate}\) at \(B = 4 \text{T}\). An average line cut along 0 ± 0.2 mV bias voltage is shown in the bottom panel. Black dotted lines indicating plateaus of constant conductance are drawn as guide to the eye.
small plateau at 2G₀ which is not visible at the high conductance traces. The existence of this small 2G₀ plateau indicates that the device has a small, but finite energy splitting between the second and third sub-band. At finite bias voltage the conductance will only be quantized in integer values of G₀ if both μ₂ and μ₃ occupy the same sub-band. This creates diamond shaped regions of constant conductance indicated by black dotted lines in Figure 2a. At the tip of the diamond the two dotted lines cross when V₂₃ is equal to the sub-band energy spacing ΔE₂₃. From this we extract ΔE₂₃ and the lever-arm η of the bottom gate via ηV₂₃ = ΔE₂₃. A finite magnetic field breaks time reversal symmetry, lifting spin degeneracy and splitting the individual spin sub-bands E₁±/ by the Zeeman energy EₜZeeman = gμB. Here μB denotes the Bohr magneton and g the Landé g-factor. Experimentally this splitting manifests as the appearance of additional half integer steps N/2e²/h. At B = 4T (Figure 2b), we clearly observe Zeeman splitting of the first sub-band, where an additional plateau emerging at 0.5G₀ is coupled with a reduction in the 1G₀ plateau. However, the dispersion of the second plateau is strikingly different. Only a small plateau is visible at 1.5G₀ and the size of the 2G₀ plateau is increased, rather than reduced.

Conductance measurements at zero bias voltage with increasing magnetic field provide further insight into the sub-band dispersions. Figure 3 shows the (a) zero bias conductance and (b) transconductance dG/dV₃₄ as a function of magnetic field along B₂ and V₃₄ taken at V₂₃ = 0 mV. The level spacings plotted in (d,e) are marked by arrows of corresponding color. Red dashed lines indicating the sub-band spacing in (a,b) are drawn as guide to the eye. (c) Linecuts (of (a) in steps of 1T and offset by 200 mV for clarity. (d) Energy level spacings of E₁↑ − E₁↓ (yellow), E₂↓3 − E₁↑ (green), and E₂↓3 − E₁↓ (orange) extracted from the 0.5 and 1G₀ plateau in (a). A linear fit to E₁↑ − E₁↓ fixed at the origin gives the g-factor of the first sub-band g₁ = 39 ± 1. (e) Energy spacing of E₂,3↓ − E₃,3↑ extracted from the 2G₀ plateau with g₂,3 = 38 ± 1.

Figure 3. (a) Differential conductance G = dI/dV₂₃ and (b) transconductance dG/dV₃₄ as a function of magnetic field along B₂ and V₃₄ taken at V₂₃ = 0 mV. The level spacings plotted in (d,e) are marked by arrows of corresponding color. Red dashed lines indicating the sub-band spacing in (a,b) are drawn as guide to the eye. (c) Linecuts (of (a) in steps of 1T and offset by 200 mV for clarity. (d) Energy level spacings of E₁↑ − E₁↓ (yellow), E₂↓3 − E₁↑ (green), and E₂↓3 − E₁↓ (orange) extracted from the 0.5 and 1G₀ plateau in (a). A linear fit to E₁↑ − E₁↓ fixed at the origin gives the g-factor of the first sub-band g₁ = 39 ± 1. (e) Energy spacing of E₂,3↓ − E₃,3↑ extracted from the 2G₀ plateau with g₂,3 = 38 ± 1.
role of orbital effects in these nanowires is crucial for interpreting phase diagram measurements. We use the model presented in ref 37 together with the parameters of our device (wire radius: 35 nm; g-factor: 40) to simulate this change in the sub-band dispersion for a magnetic field perpendicular (Figure 4c) and parallel (Figure 4d) to the nanowire. A perpendicular magnetic field causes all four sub-bands $E_{2\uparrow\uparrow}$ and $E_{3\uparrow\downarrow}$ to shift higher in energy, decreasing their energy splitting for increasing magnetic field, until the levels cross. In contrast, a parallel magnetic field increases the energy splitting of $E_{2\uparrow\uparrow}$ and $E_{3\uparrow\downarrow}$ due to their different orbital angular momentum. While the simulations shown in Figure 4c do not perfectly match the experimental data presented in Figure 3a,b, as they show crossings of $E_{2\uparrow\uparrow}$ instead of an extended degeneracy, their qualitative behavior for differing orientations of magnetic field supports our interpretation of the data in terms of orbital effects.

We further confirm our interpretation of orbital effects by measuring the transconductance for differing orientations of magnetic field with respect to the nanowire axis, as shown in Figure 5. For magnetic fields orientated perpendicular to the nanowire, either along $B_x$ (Figure 5a,b), or $B_y$ (Figure 5c,d), a splitting is resolved at the beginning of the first plateau marking the onset of the 0.5 plateau at $B = 0.6$ T. However, both magnetic field directions show a transition directly from $1G_0$ to $2G_0$ across this magnetic field range, with no visible $1.5G_0$ plateau. However, for the magnetic field aligned along $B_y$ (mostly parallel to the nanowire) shown in Figure 5e,f, we do see a clear difference. Now two new plateaus emerge almost simultaneously around $B_x \approx 0.75$ T, with the second plateau at 1.5 and not at $2G_0$, in agreement with the results of the numerical simulations in Figure 4. The clear difference between parallel and perpendicular orientations is in agreement with our interpretation of the role of orbital effects in modifying the sub-band dispersions in these nanowires.

In conclusion we achieved substantial improvements in electrical transport measurements of InSb nanowires by using a high quality hBN dielectric and clearly demonstrated conductance quantization at zero magnetic field, as well the role of orbital effects in determining the behavior of energy sub-bands. Further investigation is required to resolve the differences between the numerical simulations of orbital effects and experimental data at low magnetic fields, which may result from an unusual modification of the sub-band states under electrostatic gating due to the strong SOI in these nanowires. In the future these technical improvements will allow the more detailed investigation of features in the first plateau, such as signatures of a helical gap, or the presence of a 0.7 anomaly. The large SOI in our InSb nanowire strongly influences the electron dispersion relation, and the tunability with magnetic field could add new insight into the underlying physics.

Figure 4. (a) Probability density of the first five sub-bands of a cylindrical nanowire. (b) Orientation of the nanowire with respect to the magnetic field axes. (c,d) Numerical simulations of the sub-band dispersion of a InSb nanowire in perpendicular (c) and parallel (d) magnetic field. The levels $E_{\uparrow\uparrow}$ are drawn in gray and $E_{\downarrow\downarrow}$ in blue.

Figure 5. Transconductance $dG/dV_{\text{gate}}$ and differential conductance $G$ for three different directions of the magnetic field all taken at $V_{\text{bias}} = 0$ mV. Green dashed lines indicating the sub-band spacing in (a,c,e) are drawn as guide to the eye, and red numbers label the height of the conductance plateaus. $B_x$ is increased from 0–2 T and $B_y$ from 0–1 T. (ab) Magnetic field aligned along $B_x$ and (c,d) $B_y$ both perpendicular to the nanowire. (e,f) Magnetic field aligned along $B_y$, parallel to the nanowire.
Detailed fabrication recipe, a discussion of the subtracted series resistance, and additional data of the main device as well as data of QPC devices fabricated with a SiO$_2$ dielectric (PDF).