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Observation of Conductance Quantization in InSb Nanowire Networks


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Supporting Information

ABSTRACT: Majorana zero modes (MZMs) are prime candidates for robust topological quantum bits, holding a great promise for quantum computing. Semiconducting nanowires with strong spin orbit coupling offer a promising platform to harness one-dimensional electron transport for Majorana physics. Demonstrating the topological nature of MZMs relies on braiding, accomplished by moving MZMs around each other in a certain sequence. Most of the proposed Majorana braiding circuits require nanowire networks with minimal disorder. Here, the electronic transport across a junction between two merged InSb nanowires is studied to investigate how disordered these nanowire networks are. Conductance quantization plateaus are observed in most of the contact pairs of the epitaxial InSb nanowire networks: the hallmark of ballistic transport behavior.

KEYWORDS: Semiconducting nanowires, networks, indium antimonide, conductance quantization, ballistic transport

Semiconducting nanowires (NWs) with strong spin–orbit coupling, for example, InSb or InAs, provide a promising platform to study Majorana-related physics. Majorana zero modes (MZMs) are predicted to appear in carefully engineered solid state systems, which can be utilized as building blocks for the topological quantum computer using their nonabelian properties. When a 1D semiconductor with low disorder and strong spin–orbit interaction (SOI) is brought into contact with a superconductor under an external magnetic field, MZMs appear at both ends of the proximitized semiconductor region. Signatures of MZMs have been experimentally observed in InSb and InAs semiconductor/superconductor hybrid NW systems. The ambitious goal of performing logical operations utilizing Majoranas and studying their non-Abelian properties, that is, braiding, requires NW networks. These networks are required to move MZMs around each other or to tune the coupling between each other in a certain sequence, according to most of the theoretical proposals. The semiconductor NW network system of our preference is InSb since it exhibits a higher electron mobility, stronger SOI, and larger Landé g-factor than InAs.

High structural quality InSb NW networks have been recently reported by Car et al. To date, several transport experiments have been performed on branched NW networks. However, one remaining unanswered question is the degree of disorder in this system. Disorder is a serious issue as it can mimic Majorana signatures or even can be completely detrimental to the topological protection of MZMs. In InSb NW devices, disorder has been diminished to the point where ballistic transport, whose hallmark is quantized conductance plateaus, is observed. A recent work has been published showing ballistic transport in the straight channels in InAs NW networks, mimicking single NWs. Yet, ballistic transport across the junction in NW networks, especially in InSb NWs, has not been reported yet.

Here, we study the electronic transport across the junction between two merged InSb NWs using the optimized nanofabrication recipe reported in refs and . In this work, the evolution of the quantized conductance plateaus in each contact pair is studied as a function of magnetic field, gate voltage, and source–drain bias voltage. Quantized conductance plateaus are observed consistently in most of the contact pairs of the epitaxially grown InSb NW networks in three different devices. The Landé-g factor of the first subband is extracted for each contact pair in the NW network. Additionally, the structural quality of the junction between the crossed NWs in a representative device has been inspected by cross-sectional transmission electron microscopy (XTEM) and correlated with the transport measurements. The InSb NW networks used in this work have been synthesized by gold (Au) catalyzed vapor–liquid–solid (VLS)
A typical InSb NW cross device. (a) A false-colored, 30°-tilted SEM image of an InSb NW cross (yellow) deposited on a p++-doped Si substrate (light gray) covered with 285 nm of SiO₂ (dark gray) and contacted with 10/210 nm of Cr/Au (purple). The NW network terminals are labeled A, B, C, and D. (b) Schematic illustration of the experimental setup. The Si substrate acts as a global back gate, and the SiO₂ is the gate dielectric. A gate voltage (V\text{gate}) is applied to the Si substrate. A source–drain voltage bias (V\text{bias}) is applied between two terminals of the NW network, and the current is monitored between these two terminals. The rest of the terminals are floated. All of the measurements are performed at a temperature of 300 mK and an out-of-plane magnetic field.

Differential conductance is measured using a standard lock-in technique by applying a small ac excitation voltage (V\text{ac}) at a fixed dc bias voltage and measuring the ac current (I\text{ac}) such that \( G = \frac{dI_{ac}}{dV_{ac}} \). The conductance plateaus are observed which is expected due to the magnetic field. No quantized conductance plateau is observed, which is expected due to the many possible scattering sources previously discussed. As the magnetic field is increased, backscattering of electrons is suppressed, and the first spin resolved conductance plateau \( \left( e^2/h \right) \) is revealed. It becomes more pronounced and flatter at higher magnetic fields. In some devices (Figure S7), higher plateaus \( \left( 2e^2/h, 3e^2/h \right) \) are observed. In this paper, the focus is on the first plateau which is present in all our devices. The line cuts in the bottom panels of the color plots in Figure 2 exhibit a clear evolution of the first conductance plateau.

Further details related to the NW networks growth and the structural quality of these networks have been reported in ref 26. After growth, the NW networks are in an epitaxial relationship to the InP substrate. The InSb NWs meet under an angle of 109.5° which corresponds to the crystallographic angle between two (111) B directions in a zinc blende crystal structure. Further details related to the NW network device after the fabrication process are explained in the Supporting Text in S1. Afterward, the sample is mounted in a 3He cryostat with a base temperature of 300 mK, single axis magnet of 9 T perpendicular to the substrate and measured using a standard lock-in technique at 73 Hz with an excitation field of \( B = 0 \). The channel length denoted by the contact spacing between the different contact pairs is measured from the top-view SEM image of the device shown in Figure 1a. The lengths of the two straight contact pairs labeled as A–C and B–D are 770 and 640 nm, respectively. The lengths of the kinked contact pairs A–B, A–D, B–C, and D–C are 700, 610, 700, and 700 nm, respectively. In principal, ballistic transport behavior is very challenging to realize in such a NW network with this geometry for the following reasons. The NW system already has a large surface-to-volume ratio which can cause electrons to scatter back to the source reservoir. In addition, the conductance plateau quality greatly depends on the channel length, that is, contact spacing. Our NW network devices have long contact spacing between the contact pairs (~700 nm), which is much larger than the electrons mean free path reported in single ballistic NW devices (~150 nm).23,32,34 Concerning the geometry of the NW network devices, the interface between merged NWs can induce additional scattering. Furthermore, electrons traversing the crossed networks are required to follow a bended trajectory to comply with the device geometry. This is in sharp contrast to the single nanowire case and will cause extra scattering even in a perfectly clean nanowire network system.

Figure 2b–d shows differential conductance \( \left( G = \frac{dI_{ac}}{dV_{bias}} = I_{ac}/V_{ac} \right) \) of three different contact pairs of the network (A–B, A–C, A–D) as a function of \( V_{gate} \) and \( B \) at \( V_{bias} = 0 \) mV (the data for B–C, B–D, C–D can be found in Figures S5 and S6). For increased clarity, line cuts at different \( B \) values, 0 T (green), 5 T (red), and 8 T (black), are shown in the bottom panels with a horizontal offset. At zero magnetic field, no quantized conductance plateaus are observed which is expected due to the many possible scattering sources previously discussed. As the magnetic field is increased, backscattering of electrons is suppressed, and the first spin resolved conductance plateau \( \left( e^2/h \right) \) is revealed. It becomes more pronounced and flatter at higher magnetic fields.
quantized plateau toward \( G = e^2/h \) with increasing \( B \) confirming that magnetic field helps ballistic transport by suppressing electrons’ backscattering. Most of the contact pairs in the NW network shows extended conductance plateaus around \( e^2/h \) (without any contact resistance being subtracted from the plots), except for one straight channel (A–C) that exhibits an unexpectedly reduced plateau value (around 0.3 \( \times \) \( e^2/h \)). Currently the reason for this unexpected low plateau of this particular channel is unclear. The fact that all the other contact pairs involving contact A or C (e.g., A–B, A–D, C–B, C–D) show regular plateau values (around \( e^2/h \)) indicates that the low plateau value of the A–C contact pair is not due to poor electrical contacts of A or C.

For further investigations, at \( B = 8.5 \) T, the differential conductance for different contact pairs in the NW network is measured as a function of \( V_{\text{bias}} \) and \( V_{\text{gate}} \) as illustrated in the color plots in Figure 3a–c. The color plots exhibit diamond shaped regions of constant conductance \( (G = e^2/h) \) highlighted by dotted black lines. Line cuts of these color plots, indicated by the green dotted line, along the vertical \( B \) direction (at \( V_{\text{bias}} = 0 \) mV along the dotted green line), the source and drain chemical potential \( (\mu_s, \mu_d) \) are aligned together in between \( E_{11} \) and \( E_{11} \) such that \( \Delta E_{\text{subband}} = E_{11} - E_{11} = \gamma B \Delta E_{\text{subband}} \). When the chemical potentials between \( E_{11} \) and \( E_{11} \) the bias voltage \( \Delta E_{\text{subband}} = E_{11} - E_{11} = eV_{\text{bias}} \) appears equivalent to the bias voltage \( \Delta E_{\text{subband}} = E_{11} - E_{11} = eV_{\text{bias}} \) enabled by the green dotted line, along \( (V_{\text{bias}} = 0 \) mV) are shown in the bottom panels. In the middle of the diamond, at zero bias voltage, a prolonged conductance plateau appears at \( e^2/h \). This can be explained by the energy spectrum shown in Figure 3d where the chemical potentials of the source and drain \( (\mu_s, \mu_d) \) are aligned together in between \( E_{11} \) and \( E_{11} \). At the tips of the diamond where the dotted lines cross each other, the bias voltage is equivalent to the first spin-split subband spacing \( (E_{11} - E_{11} = eV_{\text{bias}}) \) enabling the extraction of the subband spacing as illustrated schematically in the energy spectrum in Figure 3e. Accordingly, the Landé g-factor \( (g_1) \) of the first channel for each contact pair in the NW network can be extracted since the measured subband spacing is purely due to Zeeman splitting.
splitting (%Zeeman = gμBB). Using this approach, we estimate g1 of 43, 43, and 52 corresponding to the subband spacing, Δsubband, of 21, 21, and 25 meV for the different channels A−B, A−C, and A−D, respectively. The estimated g1 values for the different contact pairs are close to the expected InSb bulk value of 51. Data from additional devices are included demonstrating consistent results and ballistic transport in all three devices.

To gain more insight about the structural quality of the junction between crossed NWs in the measured NW networks, device II (its transport data is shown in S7 and S8) was sliced open using focused ion beam (FIB). A 50 nm thin lamella along one of the NWs (indicated by a red line in Figure 4a) was prepared and inspected in a transmission electron microscope (TEM). Both the cross-sectional TEM images (Figure 4c) and the energy-dispersive X-ray spectroscopy (EDX) map (Figure 4e) show a sharp and oxide-free interface between the crossed NWs. Moreover, the zinc blende crystal structure of the junction is confirmed by the FFT pattern of the lattice imaged along the [121] direction as shown in Figure 4d. The high quality of the junction based on this structural analysis supports the ballistic transport behavior observed in these devices.

We have demonstrated conductance quantization between most of the contact pairs in InSb NW networks at a nonzero magnetic field, and this observation is consistent over three different devices. Bias voltage spectroscopy on these quantized plateaus at a finite magnetic field measures spin-resolved subband spacing, enabling an estimation of Landé g-factor above 40 in these NW networks. The demonstration of ballistic transport through two orthogonal channels in an InSb NW network represents a major step toward braiding of Majorana zero modes. Further improvements are expected from appropriate nanowire surface passivation and the use of low-noise dielectrics.

ASSOCIATED CONTENT

Supporting Information

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REFERENCES

(3) Das Sarma, S.; Freedman, M.; Nayak, C. npj Quantum Inf. 2015, 1, 15001.