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Strong spin–orbit semiconductor nanowires coupled to a superconductor are predicted to host Majorana zero modes. Exchange (braiding) operations of Majorana modes form the logical gates of a topological quantum computer and require a network of nanowires. Here, we utilize an in-plane selective area growth technique for InSb–Al semiconductor–superconductor nanowire networks. Transport channels, free from extended defects, in InSb nanowire networks are realized on insulating, but heavily mismatched InP (111)B substrates by full relaxation of the lattice mismatch at the nanowire/substrate interface and nucleation of a complete network from a single nucleation site by optimizing the surface diffusion length of the adatoms. Essential quantum transport phenomena for topological quantum computing are demonstrated in these structures including phase-coherence lengths exceeding several micrometers with Aharonov–Bohm oscillations up to five harmonics and a hard superconducting gap accompanied by $2e$-periodic Coulomb oscillations with an Al-based Cooper pair island integrated in the nanowire network.

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ndium-antimonide (InSb) and Indium-arsenide (InAs) nano-
wires are promising candidates for realizing Majorana-based
topological quantum computers[1]. InSb, in particular, is inter-
esting for its high electron mobility, strong spin–orbit coupling and
large Landé g-factor[2–5]. Over the past years, extensive efforts have
been made to improve the quality of InSb nanowires, grown by the
vapor–liquid–solid (VLS) mechanism[6,7]. A major achievement is
the clean and epitaxial semiconductor–superconductor interface
relying on in situ metal evaporation and complex substrate pro-
cessing[8,9]. This has been critical for showing high quality Majorana
zero-modes, a milestone toward braiding experiments[10]. To braid
these Majorana states, scalable nanowire networks with a high
degree of interconnectivity are required[11]. Recently, out-of-plane
growth of InSb nanowire networks has been demonstrated by
merging multiple wires during VLS growth. Phase-coherent and
ballistic transport have been observed, demonstrating the high
quality of these network structures[8,12]. This technique, however,
requires predefined positioning of the nanowires with nanometer
accuracy in order to form networks, leading to a drastic decrease in
yield with increasing network complexity. Moreover, merging of
VLS nanowires inevitably forms a widening of the nanowire dia-
meter at and around the junction with a 75% chance of a defect
forming at the junction, which negatively affects the one-
dimensionality of the system[8].

A more scalable approach, would be to use an in-plane selec-
tive area growth (SAG) technique (i.e., parallel to the substrate
surface), that relies on a template or mask to selectively grow one
semiconductor material on top of another[13–19]. This technique
has several advantages over out-of-plane growth. First, the flex-
ibility of network designs is significantly enhanced, as the pre-
ferred design can be written and etched directly into a mask,
enabling complex structures. Second, the growth can be confined
within the mask, keeping the entire structure one-dimensional
with an easily controllable and constant cross-section size. Finally,
the technique excels in scalability, readily allowing for the growth
of complex structures suggested for Majorana braiding experi-
ments in a variety of theoretical proposals[11,20,21]. The large lattice
mismatch between InSb and any other III–V semiconductor
substrate material[22], however, poses an important challenge
making it difficult to grow defect-free InSb nanowires on large-
bandgap or insulating substrates. Furthermore, the disorder cre-
ated by the lattice mismatch can be detrimental to the topological
protection of Majorana states[23]. Most of the previous SAG studies
have focused on an InAs-based material system for nanowire
networks[14–17,19], which has a smaller lattice mismatch with InP
or GaAs substrates. InSb nanowires have been grown by SAG
using molecular beam epitaxy (MBE)[18,24]. Here, we demonstrate
an in-plane SAG technique for scalable and high-quality InSb
nanowire networks, which shows all the relevant quantum
transport properties (e.g., long coherence length and excellent-
induced superconducting properties) necessary for topological
qubits.

Results

Growth of in-plane selective area InSb networks. In this study,
we use InP as a substrate because it has a type I band alignment
with InSb and becomes semi-insulating at low temperatures. The
large bandgap of 1.34 eV compared to 0.17 eV of InSb ensures
good confinement[25]. The lattice mismatch between these mate-
rials is 10.4%, making large-scale defect-free growth of InSb a
challenge[26]. It is important to have defect-free single crystalline
material to obtain a high carrier mobility by reducing electron
scattering[27]. On a (100) substrate, many stacking faults are
expected to form inclined to the substrate (along the {111} planes)
to relax the lattice strain[13]. To avoid the formation of these

inclined defects, we use InP (111)B as the growth substrate. We
will show that strain from the lattice mismatch is relieved directly
at the substrate/nanowire interface. Moreover, atomically flat
twin planes can form parallel to the substrate, above which the
nanowires grow without extended defects, separating the
mismatch-induced disorder from the nanowire top part. On a
(111)B substrate, growth nuclei with an odd and even number of
horizontal twins will have a 180°-rotated crystallographic orien-
tation, with respect to each other. When these nuclei merge by
lateral growth, an inclined defect is formed at the interface; details
of the atomic structure of such a defect can be found in Sup-
plementary Fig. 1. These defects may act as scattering sites for
electrons and can be found in many reported SAG stu-
dies[13,17,19,27]. Therefore, it is important to enable growth of a
complete, in-plane network structure from a single nucleation
site, which is difficult to achieve for MBE-grown InSb[18,24]. For
this, a large surface diffusion length of the precursor material is
required, as well as a low nucleation probability. Here, we show
that metalorganic vapor-phase epitaxy (MOVPE)-grown InSb in-
plane selective area networks (InSANe) can indeed generate
complicated 1D networks from a single nucleation site.

First, the desired structures are etched into a 20-nm-thick
Si_xN_y mask (Supplementary Fig. 2), aligned to four different
crystal directions, the [−211], [−101], [−1–12], and [0–11], on
an InP (111)B substrate (Fig. 1a). These four orientations are all
three-fold symmetric, such that networks can be grown with
angles of 30, 60, and 90 degrees between two nanowires
(Supplementary Fig. 3). The growth starts by forming a nucleus
in one of the lines, which develops into an InSb island over time
(Fig. 1b, Supplementary Fig. 4). All nuclei are terminated with a
{111}B top facet and {110} side facets (Fig. 1b), regardless of the
line orientation, implying that surface growth kinetics and lateral
growth rates are identical for all <110> and <112> growth
directions. For longer growth times, the growth continues,
starting from this single nucleus, in the lateral direction following
the mask opening by growing {110} facets, as evidenced by atomic
force microscopy and transmission electron microscopy (TEM).
When the structure is fully grown in the in-plane direction, the
growth continues in the vertical <111>B direction. The height of
the InSb network can be precisely tuned by the growth time
(Supplementary Fig. 5). Under ideal conditions, a yield of up to
80% can be achieved for structures several microns in length
(Supplementary Fig. 6). When the InSb grows higher than the
mask, it also starts to expand in the lateral direction, especially at
acute corners of the structure (Supplementary Fig. 7), which is
not ideal for transport measurements as the one-dimensional
confinement is lost. An example of a network is shown in Fig. 1c
(and Supplementary Fig. 8), whose structure corresponds to the
proposed geometry of a four-topological-qubit device[20]. The
{110} planes of the original growth fronts are visible on the
convex corners of this structure (Fig. 1d). These facets do not
form on the concave corners due to the connection with another
branch of the network (Supplementary Fig. 7). Our platform
provides freedom of design and scalability for a plethora of device
structures (Supplementary Fig. 9).

In order to minimize the formation of inclined defects, the
number of nucleation sites in the mask openings per unit length
(n) is investigated as a function of the input V/III ratio of the tri-
methyl-indium (TMIn) and tri-methyl-antimony (TMSb) pre-
cursors. For this purpose, InSb is grown for a short time (1 min)
to observe the early stages of nucleation and understand the
nucleation probability as a function of V/III ratio. n is determined
for growth in the <112> and <110> oriented trenches for different
V/III ratios (Fig. 2). Datapoints are averages of ten 40 nm wide
and 50 μm long lines on each sample. The results show a clear
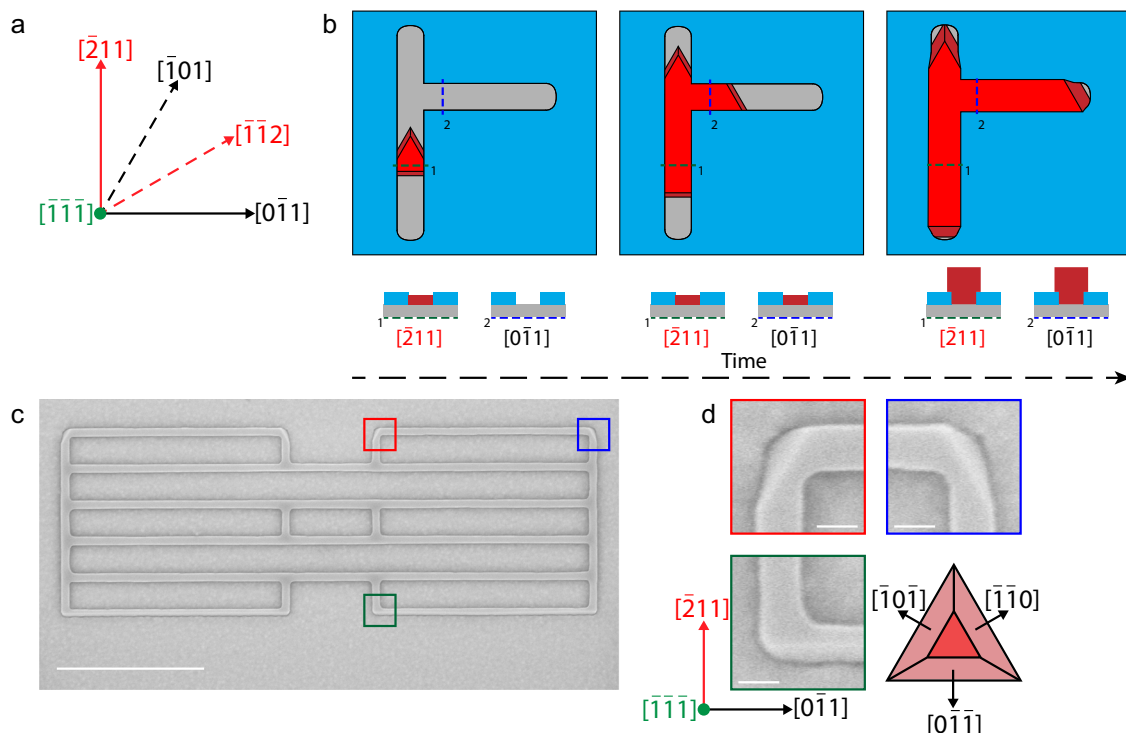decrease of n, and thus an increase of the diffusion length of the

Fig. 1 Controlled growth of in-plane selective area InSb networks. a The four growth directions on a (111)B substrate suitable for in-plane nanowire growth. **b** Time evolution for growth of an in-plane InSb (red) nanowire network on an InP (111)B substrate (gray) with a 20 nm thick Si_xN_y mask (light blue) for selectivity. The growth fronts remain the same during the growth of the network. Schematics of the cross-sections below show the relative height of the InSb compared to the height of the mask. The network grows much faster in the in-plane direction than the out-of-plane direction (Supplementary Fig. 5). **c** The in-plane InSb nanowires controllably grow in the <112> and the <110> families of crystal directions. Scale bar is 1 μm. **d** Zoom-in on the corners of the structure in **c**. Scale bar is 50 nm. The {110} facets that form the growth fronts are still visible at these edges.

adatoms on the InP surface, with increasing V/III ratio. At the highest TMSb pressures, the nucleation of InSb islands is completely inhibited. The inset in Fig. 2a is a logarithmic plot of the same data up to a V/III ratio of 20,000, showing a decrease of n with increasing V/III ratio. We note that there is no parasitic growth on the mask under any of these conditions. The red circle and black square (blue and green triangle) datapoints are all taken with the same TMIn (TMSb) partial pressure and varying TMSb (TMIn) partial pressure, respectively. Figure 2a shows that these datapoints all follow the same trend, indicating that not the total flow but the V/III ratio is important in the studied range. Figure 2b shows a scanning electron microscopy (SEM) image of nuclei grown using a low V/III ratio. The InSb islands are only tens of nanometers long and ~20 nm thick. Figure 2c shows an SEM image of a representative nucleus grown with a very high V/III ratio. Here, the InSb island is much longer (300 nm) and <20 nm high. The time series in Supplementary Fig. 5 shows that the InSb structures nucleate from a single site and over time, during growth under the same growth conditions, no new nucleation sites appear as all grown segments in a single structure are connected at all times. From these results, we conclude that Sb changes the surface energy on the InP substrate and enhances the surface diffusion of the In precursor material[28]. For the growth of large networks, a high V/III ratio is thus beneficial to have a minimum number of nucleation events. By integrating over the total volume of all nuclei in a 50 μm long line structure, we find that the lateral growth rate is determined by the TMIn flux (with higher flux giving faster growth rates) and the V/III ratio (with higher V/III ratio giving slower growth rates). The largest single crystalline networks we have fabricated with our method have a wire diameter of ~60 nm with lengths of up to 11 μm (Supplementary Fig. 9d).

Physical characterization. The structural quality of the in-plane wires has been investigated by TEM. Focused ion beam (FIB) sample preparation was used to cut out cross-sections parallel and perpendicular to the long axis of in-plane [−211] and [0–11] oriented nanowires. Figure 3a shows a cross-sectional view of a nanowire grown along the [−211] direction. The energy-dispersive X-ray spectroscopy (EDX) elemental mapping (Fig. 3b) shows the InP substrate (green) with the InSb nanowire (red) grown slightly higher than the Si_xN_y mask (blue, top indicated by a white dash on the right). An inverse fast Fourier transform (IFFT) of a zoom-in on the InSb/InP interface (Fig. 3c) shows misfit dislocations (Supplementary Note 1.1) and their confinement to the interface between the two materials. This real space image was constructed by filtering for the (110) periodicity in the fast Fourier transform (FFT) pattern of a high-resolution scanning TEM (STEM) image and subsequently creating an IFFT image. In this image, the ratio of the number of InP/InSb atomic columns is $96/87 = 1.1034$. The 10.34% decrease in vertical lattice planes is in good agreement with the reported value of a 10.4% lattice mismatch between InSb and InP[4], indicating that the heterostructure is fully relaxed (inelastically) at the interface in the lateral direction. Here, it should be mentioned that when imaging orthogonally to this crystal direction the InP/InSb interface cannot be imaged accurately due to the slight recess of the wire into the substrate. Most likely, along the long axis, misfit dislocation planes will also be present with the dislocation lines located at the interface, as we do not see vertically extending defects orthogonal to the long axis of the wires in TEM studies. An FFT of the InSb, the InSb/InP interface, and the InP regions of the high-resolution STEM image (Fig. 3d in green, blue, and purple box, respectively) show that the InSb and the InP are both single
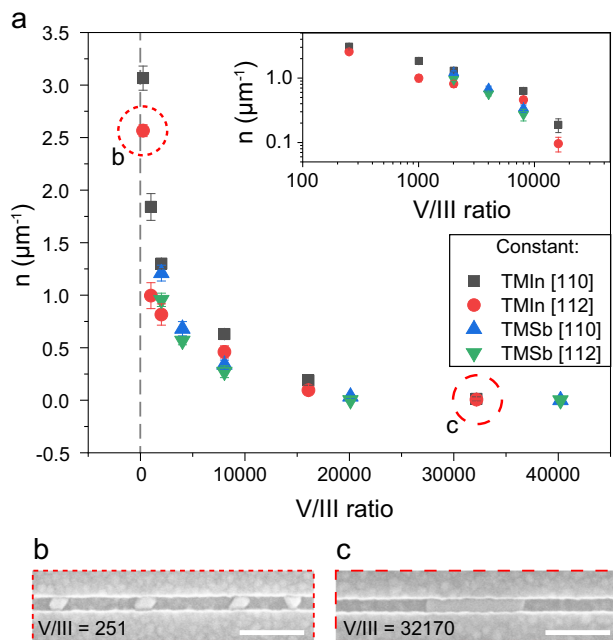
Fig. 2 Effect of V/III ratio on nucleation of InSb on InP. a The average number of nucleation points n per micrometer trench length as a function of the V/III ratio during the growth for different crystal directions of the mask openings ([110] and [112]). The datapoint averages are gathered by analyzing 500 μm length of mask opening (ten lines, each 50 μm long) and error bars represent the standard deviation. Varying the TMSb (TMIn) flow with constant TMIn (TMSb) flow leads to the same value for n as a function of V/III, showing that the total flow does not influence the nucleation of the InSb on the InP. At a ratio of 40,000, the nucleation of InSb is completely inhibited by Sb adatoms on the InP surface. Inset: logarithmic plot of the data up to a V/III ratio of 20,000. **b, c** Top-view SEM image showing the different morphologies of, and distance between, InSb islands for low **b** and high **c** V/III ratios. Scale bar in **b**, **c** is 200 nm.

crystalline, while the FFT pattern of the interface region displays a combination of two single crystalline patterns with a different lattice constant, indicating that the materials are fully relaxed. To visualize the presence of horizontal twin planes (Supplementary Note 1.4) in the InSb structures, we investigate a cross-section of a nanowire grown along the <110> direction (Fig. 3e). A zoom-in on the bottom part (Fig. 3f) reveals a set of two twin boundaries a few nanometers above the InP/InSb interface (Fig. 3g). Horizontal twin planes have in total been observed in 12 out of 17 TEM samples (six in perpendicular cuts of <110> grown wires and six in parallel cuts of <112> grown wires, the other five TEM samples did not show horizontal twin planes). The twin planes are always located within a few nanometers above the InSb/InP interface and a single crystalline InSb transport channel always forms above the horizontal twin. Once a twin plane is formed in a nucleus it will be extended into the rest of the network by lateral growth. We note that antiphase boundaries (Supplementary Note 1.2) and inclined twin planes (Supplementary Note 1.3) are absent in these structures. The complete relaxation of lattice strain at the nanowire/substrate interface (bottom part) followed by horizontal twin planes helps to separate the electron wavefunctions in the active region of the device from the interface disorder[29]. This effect allows us to fabricate in-plane InSb nanowires on InP that have quantum transport properties comparable to free-standing structures, as demonstrated by the high-quality quantum transport in the next section.

Quantum transport. We now turn to the quantum transport properties of our InSb InSANe system to demonstrate its feasibility for topological quantum information processing. The key ingredient in the measurement-based gate operation and topological qubit readout is the phase coherence, which can be revealed by the Aharonov–Bohm (AB) effect[11,20]. The magneto-conductance in Fig. 4a reveals the AB oscillations in a fabricated InSANe device shown in the inset of Fig. 4b. The oscillation amplitude is ~20% of e^2/h at 20 mK, about an order of magnitude larger than for previously reported InSb VLS nanowire network structures[8]. Therefore, higher harmonics (up to the third) in the FFT are observed (Fig. 4b). This means that the electron's interference due to phase coherence remains measurable after circulating through the loop 1.5 times, translating to ~9 microns in this device. We note that the precise value of the phase-coherence length is not crucial, and that a large AB amplitude, especially higher orders of AB oscillations, presents the qualitative advancement in this work compared to previous studies. A second device shows an even larger AB amplitude (~60% of e^2/h in Fig. 4c) and up to five harmonics in the FFT spectrum (Fig. 4d), with the SEM image of the device shown in the inset of Fig. 4d. The measured AB period matches the loop area in all measured devices, i.e., their periods equal h/ne (for the nth harmonic). This result corroborates that the lattice mismatch-induced disorder at the nanowire–substrate interface has negligible effect on the phase-coherent transport. Finally, we observe a sharp weak anti-localization (WAL) peak in the magneto-conductance of this device around zero-magnetic field (Fig. 4e), indicating the strong spin–orbit nature of the InSb nanowire. Fitting this WAL curve requires a new theoretical model applicable for nanowire networks, which will be developed in future studies.

The next important step is to introduce superconductivity in the InSb InSANe system. In order to form superconducting contacts for the creation of Majorana zero modes, the InSANe InSb samples, after growth, are transferred from an MOVPE to an MBE system. Here, the surface oxides are removed using atomic hydrogen cleaning under (ultra-high vacuum) UHV conditions followed by 7 nm aluminum deposition at a sample temperature of ~120 K, leading to a clean and smooth InSb–Al interface (Supplementary Fig. 10)[8].

Since in situ shadowing methods to selectively grow superconductors on these InSb in-plane structures are not yet developed, we exploit a reliable selective etching recipe to selectively etch Al on InSb. This novel fabrication recipe enables us to define the positions of tunnel barriers and the Al film by lithography, facilitating flexible device designs. Figure 5a shows such a device where part of the Al is selectively etched away, and a tunnel gate electrode is added to deplete the InSb wire locally. A super-gate is deposited on the superconducting region of the nanowire whose cross-section is shown in Fig. 5b. The differential conductance on this normal–nanowire–superconductor (N––NW–S) device reflects the quasi-particle density-of-states in the proximitized nanowire segment, i.e., the induced superconducting gap as shown in Fig. 5c with a line-cut in Fig. 5d. The sub-gap conductance reaches zero, indicating a hard gap, a necessary condition for topological protection. Magnetic field dependence of accidental quantum dot levels reveals an effective g-factor of 18.6 (Supplementary Fig. 11), smaller than the bare InSb g-factor of ~50 (Supplementary Fig. 12), but significantly larger than that of Al ($|g| = 2$), indicating the wavefunction hybridizes between InSb and Al[29,30]. The measured hard gap with a gap size close to Al bulk, together with the effective g-factor defined by the coupling between Al and InSb, suggest that the electron wavefunction is mainly distributed near the top of the wire (close to Al) where the wire is single crystalline with no noticeable disorder[31–33]. This again supports that disorder at the
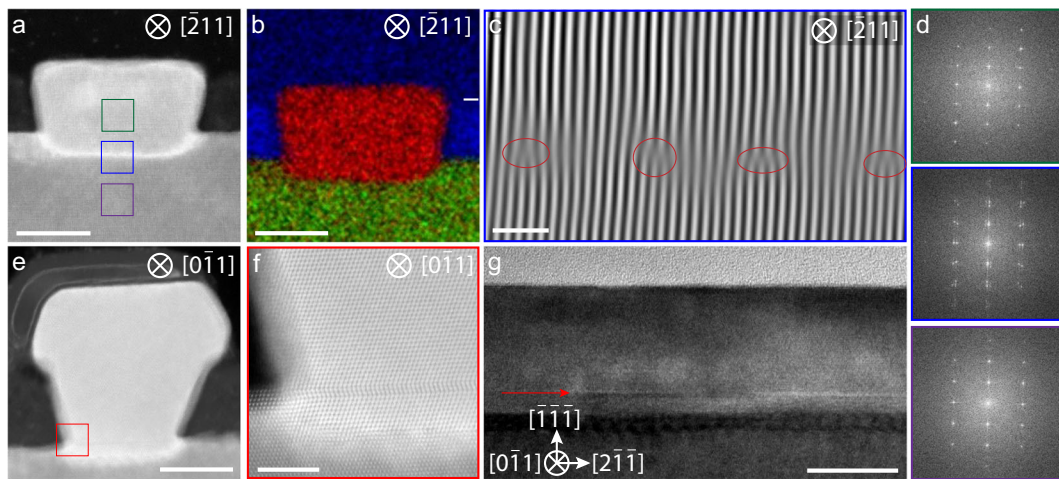
Fig. 3 Crystal quality analysis of InSb nanowires and the InSb/InP interface. a Cross-section transmission electron microscope (TEM) image of an in-plane selective area (InSANe) InSb nanowire grown and imaged along the [−211] direction. Scale bar is 20 nm. **b** EDX map of **a** with P (green), Sb (red), and Si (blue) depicted showing the InSb nanowire, the InP substrate, and the Si_xN_y mask. The top of the mask is indicated by a white dash on the right; note that SiOx has been deposited on top of the sample to protect it during focused ion beam sample preparation. Scale bar is 20 nm. **c** Zoom-in on the InSb/InP interface in **a** (blue square) focusing on the atomic columns using an inverse fast Fourier transform (FFT) procedure filtered for the (110) periodicity. Scale bar is 1 nm. The vertical lines represent the columns of atoms which, at the interface of InSb/InP, show misfit dislocations, encircled in red. Counting the ratio of InSb columns and InP columns gives a lattice mismatch of 10.34%. **d** Fast Fourier transform of the InSb nanowire (**a**, green), the InSb/InP interface (**a**, blue), and the InP substrate (**a**, purple), demonstrating that the InSb and InP regions are both single crystalline. The FFT of the InSb/InP interface region shows double spots indicating two different lattice parameters. **e** Cross-section TEM image of an InSANe InSb nanowire grown and imaged along the [0–11] direction. Scale bar is 20 nm. **f** Zoom-in of **e** where a pair of horizontal twin planes can be observed a few nanometers above the InP/InSb interface. Scale bar is 5 nm. **g** Cut along a <112> direction grown wire, looking in the perpendicular <110> zone axis. A few nanometers above the InP/InSb interface, a horizontal twin plane can be observed along the entire observed length of the wire, indicated here by a red arrow. Scale bar is 20 nm.
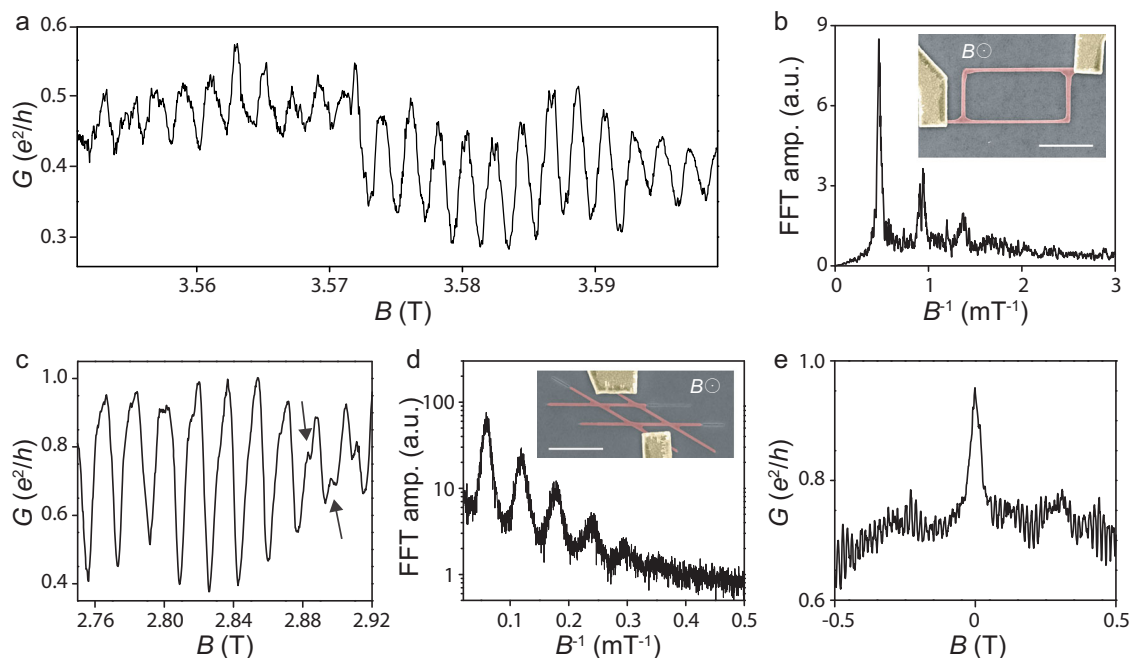

Fig. 4 Aharonov–Bohm and WAL effects in InSANe nanowire loops. a Magneto-conductance of device A shows Aharonov–Bohm (AB) oscillations with a period of ~2 mT. **b** Fast Fourier transform (FFT) spectrum of the AB oscillations from device A, indicating the frequency peaks up to the third-order harmonic. Inset, false-color scanning electron microscopy (SEM) image of the device. An InSb nanowire loop (red) is in contact with normal metal electrodes Cr/Au (yellow) with an out-of-plane magnetic field and a fridge temperature of 20 mK. The device has a global top gate that is not shown in the SEM image. Scale bar is 1 μm. The measured AB period matches the loop area of ~2 μm². **c** Magneto-conductance of device B shows a larger AB period and oscillation amplitude (~0.6 e^2/h), due to its smaller loop area compared to device A. The arrows indicate oscillations due to higher AB harmonics. **d** FFT spectrum of device B (SEM in inset with scale bar 1 μm) showing up to five harmonic peaks. **e** Magneto-conductance of device B (ensemble averaged) shows a sharp WAL peak at $B = 0$ T.
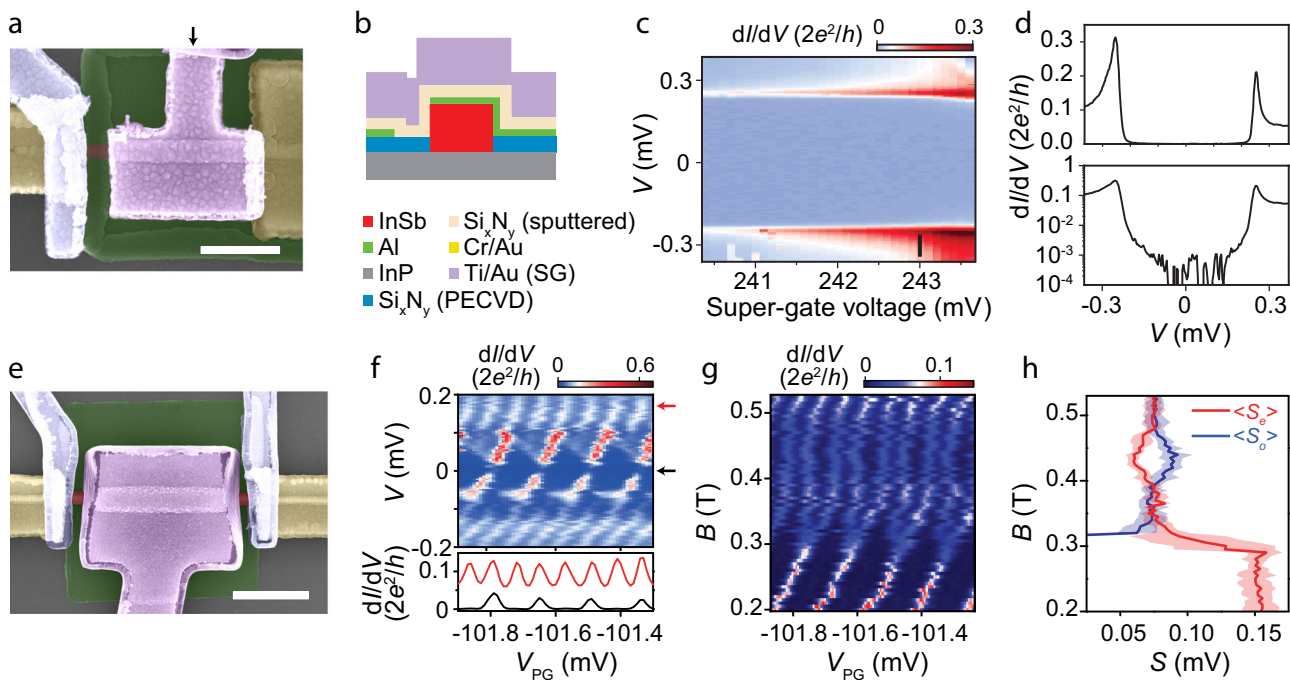
Fig. 5 Hard gap and 2e-periodic Coulomb blockade in InSANe InSb–Al hybrid nanowire devices. a False-color scanning electron microscopy (SEM) of a typical normal–nanowire–superconductor (N–NW–S) device for illustration purpose, with a schematic of the device cross-section **b** at the position indicated by the black arrow in **a**. The InSb nanowire (red) is covered by a 7 nm thick Al layer (green, covered by the etch mask). Part of the Al film on the nanowire is selectively etched before normal metal electrodes deposition (yellow, Cr/Au), and gate-tuneable tunnel barrier. The tunnel- and super-gates are Ti/Au (blue and purple, respectively), deposited on top and separated from the wire by a Si_xN_y dielectric layer as seen in the cross-section schematic on the right. Scale bar is 500 nm. Fridge temperature is 20 mK. **c** Differential conductance (dI/dV) as a function of bias voltage (V) and super-gate voltage in the tunneling regime, resolving a hard superconducting gap ($\Delta{\sim}250$ μeV) with the line-cuts (both linear and logarithmic scale) shown in **d** at gate voltage indicated by black bar in **c**. The sub-gap/above-gap conductance suppression reaches two orders of magnitude. **e**: False-color SEM of the superconducting island device. The Al island on the nanowire is ~1 μm long, with a top plunger gate (purple) to tune the electron density, and two tunnel-gates (blue) to control the tunnel coupling to the two leads. Scale bar is 500 nm. **f** Differential conductance of the island device as a function of bias and plunger-gate voltage resolving the Coulomb blockade diamonds. The horizontal line-cut at zero bias (black curve) shows 2e-periodic Coulomb oscillations where each peak corresponds to adding/removing two electrons (one Cooper pair), suggesting negligible quasi-particle poisoning. At higher bias voltage where quasi-particle can be excited, the Coulomb oscillations become 1e-periodic. **g** Magnetic field dependence of the Coulomb oscillations at zero bias voltage with the field direction along the wire. The 2e-peaks split into 1e-peaks at ~0.3 Tesla, indicating a sub-gap state crosses zero energy. **h** Even (S_e red) and odd (S_o blue) peak spacing extracted from **g**, with error bars indicated with shaded areas, showing possible Majorana or Andreev oscillations.

InP/InSb interface has a negligible effect (see Supplementary Fig. 13, a cross-section TEM of a typical device).

Finally, we explore the transport of a hybrid InSb/Al island device (Fig. 5e), with a finite charging energy. The charging energy of the hybrid island can mediate the coupling between the two Majorana states for qubit operations and readout[11,20,34]. If the charging energy is less than the superconducting gap, the system ground state energetically 'favors' even number of electrons, i.e., all electrons on the island form Cooper pairs in the superconducting condensate[35]. In transport, each Coulomb blockade diamond then corresponds to two electrons (one Cooper pair), as shown in Fig. 5f, as well as in Supplementary Fig. 14. The 2e-periodic Coulomb oscillation at zero bias (black curve) indicates negligible quasi-particle poisoning. A higher bias voltage can excite quasi-particles, resulting in the regular 1e-periodic Coulomb oscillations (red curve). Applying a magnetic field along the nanowire splits the 2e-peaks into 1e-peaks (Fig. 5g), with oscillating even/odd peak spacing (Fig. 5h). This 2e–1e transition might be interpreted as the appearance of two Majorana states, which allows the coherent 'teleportation' of a single electron[35]. The oscillating peak spacing could be attributed to overlapping Majorana wavefunctions[36]. We note that a trivial explanation for the 2e–1e transition based on Andreev bound states cannot be ruled out at this point[37–39].

Discussion

We have studied the growth dynamics of in-plane InSb nanowires on InP (111)B substrates. Despite the large mismatch between the wires and the substrate, single crystalline transport channels, free from extended defects, are formed due to immediate strain relaxation at the nanowire–substrate interface. Correspondingly, these in-plane InSb-based devices show high-quality quantum transport, with long phase-coherence length, a hard superconducting gap, 2e-Coulomb blockade peaks, and possible Majorana/Andreev signatures. The next step is to establish Majorana zero modes in these structures by performing key experiments like correlation and Majorana braiding[40].

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R.L.M.O.H.V., S.M.E.P., J.J., C.T., and E.P.A.M.B. carried out the substrate processing and the InSb synthesis. D.X., V.S., Q.W., M.W.A.d.M., B.H., K.V., J.D.S.B., L.P.K., and H.Z. fabricated the devices and performed the transport measurements. J.S.L., M.P., and C.J.P. have deposited the superconductor. S.K. and J.J. have performed the FIB cuts for the TEM lamella and M.A.V. is responsible for the TEM analysis. A.S., A.M., and L.M. performed the theoretical modeling of defect formations. R.L.M.O.H.V., D.X., M.A.V., H.Z., and E.P.A.M.B. have authored the paper, with contributions from all authors.

Competing interests

The authors declare no competing interests.

Additional information

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