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Parity-preserving and magnetic field-resilient superconductivity in InSb nanowires with Sn shells

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Improving materials used to make qubits is crucial to further progress in quantum information processing. Of particular interest are semiconductor-superconductor heterostructures that are expected to form the basis of topological quantum computing. We grow semiconductor indium antimonide nanowires that are coated with shells of tin of uniform thickness. No interdiffusion is observed at the interface between Sn and InSb. Tunnel junctions are prepared by in-situ shadowing. Despite the lack of lattice matching between Sn and InSb a 15 nm thick shell of tin is found to induce a hard superconducting gap, with superconductivity persisting in magnetic field up to 4T. A small island of Sn-InSb exhibits the two-electron charging effect. These findings suggest a less restrictive approach to fabricating superconducting and topological quantum circuits.

As we enter the era of intermediate-scale quantum circuits (1, 2), materials considerations come into renewed focus through their impact on quantum gate fidelity. The most successful solid state approaches rely either on superconductors (3), or on semiconductors (4), with the future topological platform requiring a hybrid of the two (5). The search continues for the ultimate material capable of delivering low intrinsic decoherence. In this context, the effort to realize qubits based on Majorana zero modes that are expected to be topologically immune to decoherence (6–9) has accelerated the discovery of high quality interfaces between superconducting metals and low-dimensional semiconductors (10–13).

Only a few superconductors have been explored for Majorana qubits, most notably aluminum, which is also the material of choice for transmon quantum processors (1). Among the advantages of aluminum are its self-limiting native oxide and a hard gap induced in proximate semiconductors (10, 12, 14, 15). Submicrometer islands of aluminum exhibit two-electron charging patterns: due to Cooper pairing it requires less total energy to add electrons in pairs rather than one-by-one (16–23). This effect is a prerequisite for long quasiparticle stability times, crucial to both topological

quantum computing and transmon qubits. Among the disadvantages of aluminum are a relatively small superconducting gap with a temperature equivalent of 1 K, and a low critical magnetic field. This confines quantum computing based on superconducting aluminum to ultralow temperatures and places stringent constraints on the design of future topological qubits, which will require a precise balance of several energy scales (24).

Here we present induced superconductivity in InSb nanowires (25, 26) with Sn shells. InSb is the highest electron mobility group III-V semiconductor with strong spin-orbit coupling (27) and large Landé g-factors in the conduction band (28). These are the primary ingredients of the Majorana recipe (29, 30), making InSb an optimal material for the investigation of induced topological superconductivity (31–35).

We find that InSb nanowires coupled to tin exhibit a hard induced superconducting gap with a magnitude of up to 700 μeV . Superconductivity persists to magnetic fields up to 4 Tesla for 15 nm thick Sn shells. Islands of tin do exhibit 2e-periodic charging patterns, where e is the elementary charge. These results are obtained even though Sn and InSb have no epitaxial relationship, which was previously viewed

as essential (12, 14).

Our first goal was to investigate electron tunneling into Sn through InSb in the normal metal-superconductor (N-S) configuration. For this we needed a nanowire with only one end covered by tin. We used the uncovered end to define a tunneling barrier and an N-contact. In order to prevent unintentional damage to InSb that results from etching away part of the Sn shell, we employed in-situ nanoscale shadowing (12, 23). An InSb flake, standing in front of the nanowire, shadowed the bottom of the wire during deposition of Sn in ultrahigh vacuum (36) (Fig. 1A). We expect that junctions defined by wet etching or liftoff would yield similar results (37, 38).

To prepare an N-S device, the tin-coated nanowire was positioned onto a doped Si/SiO_x substrate which was used as a back gate (BG) (Fig. 1B). A side gate (SG) was used to define and tune the tunneling barrier near the edge of the tin-free segment. The tunneling spectrum revealed a two-orders-of-magnitude suppression in conductance around zero bias (Fig. 1C). This so-called hard gap indicates the elimination of decoherence pathways caused by disorder and spurious sub-gap states. A superconducting tunneling peak is at ± 680 μeV , which is comparable to the gap of tin. In magnetic field, the hard gap was found to persist beyond 2 Tesla, with the gap “softening” at higher fields and fully closing around 4 Tesla (Fig. 1D). Magnetic field resilience is an indicator of a thin uniform shell and this resilience is another advantage of Sn as topological, spin and some superconducting qubits operate at high magnetic fields. More data on device presented in Fig. 1 (device A) is found in fig. S1.

Next, we study superconductor-superconductor (S-S) devices with both ends of the nanowire covered by tin, and only a narrow break in the shell to define an InSb weak link (Fig. 2A). For this fabrication we used a previously developed method of shadowing the Sn flux by criss-crossing nanowires (12). We first study tunneling between two tin islands (Fig. 2B). We observed a smooth nanowire pinch off void of accidental quantum dot states. Three finite-bias resonances were observed, marked 4Δ , $4\Delta/2$ and $4\Delta/3$ in Fig. 2B. This sequence is a manifestation of multiple Andreev reflection processes, which are characteristic of transparent S-S junctions. The positions of the resonances yield a value of $\Delta = 615 \mu\text{eV} \pm 10 \mu\text{eV}$, which is somewhat smaller than the gap observed in the N-S device (Fig. 1C). At $V_{\text{BG}} < -1$ V only the 4Δ resonance was observed. We interpret this as the superconducting tunneling regime. Because the S-S tunneling resonance is a peak in current, it appears as a peak-dip structure in differential conductance.

The resonance at zero bias in Fig. 2B is the Josephson supercurrent. This effect is best studied in the current-bias configuration (Fig. 2C). The switching current (I_{sw}) from superconducting to normal state is a peak in differential

resistance. I_{sw} decays smoothly with decreasing V_{BG} . The current-voltage characteristics are weakly hysteretic which is reflected in the asymmetry of I_{sw} in positive and negative current bias. In magnetic field, the Josephson effect is observed up to 1.5 T and remains appreciable with sharp switching up to 0.5 T (fig. S4). This notable field range is a positive development for schemes that require coupling and decoupling of topologically superconducting islands at finite magnetic field for Majorana fusion or braiding (39, 40). Measurements on continuous-shell nanowires without shadow junctions yielded supercurrents in the range 10–30 μA corresponding to the critical current density of 2×10^6 A/cm² (fig. S7). The extracted products $I_{\text{sw}}R_{\text{N}}$ (R_{N} is the normal state resistance) are in the range 125–225 μeV , which is of the same order of magnitude as the gap.

In Fig. 3 we present key findings on 2e charging of a tin island. The island was defined between two nanowire-shadow junctions in the N-S-N geometry (Fig. 3A). At zero magnetic field, we observed a single family of Coulomb peak resonances consistent with charging the entire island (Fig. 3B). At a finite magnetic field of 1 T, the frequency of Coulomb resonances doubled (Fig. 3, C and D). We attribute the data at zero field to 2e charging, and the data at finite field to 1e charging. The transition from 2e to 1e is caused by the superconducting gap or the lowest subgap state dropping in energy below the charging energy, which we estimate to be 0.3 meV (Figs. 3, E and F). At finite magnetic field, it costs less energy to add electrons to the island one-by-one, whereas near zero field, owing to hard gap superconductivity, it is advantageous to add electrons in pairs. More data on device presented in Fig. 3 (device C), as well as data from additional devices D, E, F are found in figs. S3 to S6.

The two-electron charging effect is central to topological quantum computing because the states of a topological qubit are distinguished by even/odd island charge parity. If only 1e charging periodicity were observed, it would mean that despite a well-defined superconducting gap, electrons can be added to an island one at a time and the ability to distinguish the states of a topological qubit is lost. 1e periodicity is also detrimental for transmon qubits where single electron tunneling is a decoherence mechanism.

Tin is an unusual material that has two different crystal phases with a phase transition at 13°C. The low-temperature α -Sn has a diamond cubic lattice, whereas the high temperature β -Sn is tetragonal. The electronic properties of the two phases are very different. α -Sn is a semimetal that can also be a topological insulator in monolayer form (41–43), whereas β -Sn is a metal with a superconducting transition temperature of 3.7 K.

For tin on InSb nanowires we assess the structural properties and elemental distribution using transmission electron microscopy (TEM). TEM images reveal a polycryst-

talline Sn shell of uniform thickness around the InSb nanowire (Fig. 4A): the shell features grains of sizes 25×25 nm to 50×60 nm (Fig. 4B) (see also fig. S8). The Sn-InSb interface is abrupt and some Sn grains show epitaxial relationship with InSb. The high-resolution annular bright field-scanning TEM image (Fig. 4C) shows a section of the interface where the {111} planes of zincblende InSb are aligned with lattice planes of a Sn grain with a lattice distance of $2.04 \text{ \AA}$. This matches the {220} interplanar distance of β -Sn. This grain is one of 13 analyzed along the same nanowire (see fig. S9 and tables S1 and S2). 11 of the grains are identified as β -Sn from the fast Fourier transform analysis of the interplanar distances (Fig. 4C, inset). Only two of those β -Sn grains show a preferential epitaxial relationship with InSb. In contrast, α -Sn is lattice matched to InSb and can grow epitaxially (44). The predominantly β -Sn shell observed at room temperature by TEM is in agreement with superconductivity observed at low temperatures, suggesting that no phase transformation of Sn occurred upon device cooldown.

In addition to the uniform shell thickness, the nanowire shadow junctions used in S-S and N-S-N devices are sharp with Sn islands defined abruptly on each side of the junction (Fig. 4C). Energy-dispersive x-ray spectroscopy (EDX) confirms that the Sn islands are isolated from each other and no interdiffusion between Sn and In is detected (Fig. 4, D and E). A uniform 3-nm-thick AlO_x passivation layer covers the entire nanowire; this layer maintains integrity and smoothness of the shell on the scale of at least 3 months. Oxidation at the Sn-InSb interfaces is not detected but cannot be fully excluded.

Our results illustrate that neither defect-free epitaxial wire-shell interfaces nor single vacuum cycle growth of nanowire and shell are crucial requirements for the demonstration of hard gap, field-resilient superconductivity and 2e charging. We conclude that the key components in attaining robust induced superconductivity are (i) removal of InSb native oxide using atomic hydrogen prior to Sn growth, followed by (ii) liquid nitrogen cooling of the nanowires during metal evaporation to produce a homogeneous ultrathin shell and (iii) immediate passivation of the wire-shell hybrid with a stable dielectric. Figure S10 illustrates that when the sample is allowed to warm up without AlO_x passivation immediately after the cryogenic Sn shell growth, tin coagulates into discontinuous grains.

Without the need for epitaxial matching many more superconductor-semiconductor combinations can be tried in search for decoherence-free qubit materials (23, 38, 45–47). An immediate follow-up of our work are experiments on Sn-InSb devices in the Majorana geometry in search for clear signatures of topological superconductivity, as well as characterization of coherence times of Sn-based transmon qubits.

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SUPPLEMENTARY MATERIALS

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Materials and Methods

Figs. S1 to S10

Tables S1 and S2

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Fig. 1. Proximity-induced superconductivity with a hard gap. (A) Scanning electron micrograph (SEM) showing a triangular InSb flake that stood in the path of a beam of Sn atoms, shadowing the InSb nanowire standing behind. Dark streaks on the InSb substrate are also due to shadowing of the Sn beam by nanowires and flakes. The inset shows the direction of Sn beam and indicates the shadowed and exposed segments of the nanowire. (B) SEM of an N-S device (device A) with a flake-shadowed Sn-InSb nanowire and Ti/Au contacts and a side gate. Magnetic field is in the plane of the sample as shown by the arrow. (C) Zero magnetic field tunneling conductance spectrum of device A in linear scale (top) and logarithmic scale (bottom), $V_{BG} = 7.5$ V, $V_{SG} = -0.4$ V. (D) Magnetic field evolution (top) of the zero-field spectrum shown in panel (C). Line cuts at two specific source-drain bias voltages are shown in the bottom. Measurements performed at the base temperature of a dilution refrigerator estimated to be 30 mK.

Fig. 2. Superconducting tunneling. (A) SEM of device B (S-S device). Inset zooms in the shadow junction where Sn shell is visible. (B) Differential conductance as a function of source-drain voltage bias V and back gate voltage, V_{BG} . The double arrows mark resonances 4Δ , $4\Delta/2$ and $4\Delta/3$. (C) Bottom: Differential resistance as a function of current bias I and V_{BG} . Top: Extracted switching current I_{SW} (black) and $I_{SW} R_N$ (red) as a function of back gate voltage. Measurements performed at the base temperature of a dilution refrigerator estimated to be 30 mK.

Fig. 3. Magnetic field dependence of the charging of tin islands. (A) SEM of device C showing the Sn island, two shadow junctions with bare InSb, side gates SG1 and SG2 and Ti/Au source-drain contacts, which cover the outside Sn segments and suppress superconductivity there. (B and C) $2e$ and $1e$ tunneling conductance resonances measured at $V = -80 \mu\text{V}$ at $B = 0$ T and $B = 1$ T, respectively. (D) Magnetic field evolution of conductance along the dashed cut in panel (B). (E and F) V vs gate spectroscopy at $B = 0$ T and $B = 1$ T, respectively. The duration of data acquisition for each panel is of the order of 1 hour, and the parity pattern is reproducible over days. Measurements performed at the base temperature of a dilution refrigerator estimated to be 30 mK.

Fig. 4. Imaging of the InSb-Sn interface. (A) Side-view transmission electron microscopy (TEM) image of an InSb-Sn nanowire along the $\langle 112 \rangle$ zone axis showing a homogeneously thin shell. Arrow indicates imaging axis with respect to the hexagonal nanowire cross-section. (B) Higher magnification TEM of the AlO_x (red) - Sn (green) - InSb (blue) stack. The Sn grain boundaries are highlighted by arrows. (C) High resolution scanning transmission electron microscopy (HR-STEM) image of the Sn-InSb interface. The insets show Fourier transforms to the left and to the right of the interface. (D) High-angle annular dark-field STEM image of a shadow junction. (E) Energy-dispersive x-ray spectroscopy (EDX) elemental mapping of the shadow junction in (D). The Al-rich layer (red) corresponds to AlO_x , oxygen not shown for clarity.