Supplementary Information for

Giant supercurrent states in a superconductor-InAs/GaSb-superconductor junction

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Materials and Methods

The InAs/GaSb bilayer sample was grown by molecular beam epitaxy on a GaSb substrate. The thickness of GaSb and InAs quantum well layers was 5.0 nm and 10.0 nm, respectively. The bilayer was sandwiched by two AlSb barrier layers with several buffer layers deposited below and an InAs cap layer above. A mesa of the bilayer was defined by photolithography and wet chemical etching processes. Ammonium hydroxide solution and citric acid/hydrogen peroxide solution were used to selectively etch AlSb/GaSb and InAs layers, respectively. Au/Ti (200/10 nm thick) electrodes were deposited by an e-beam evaporator to connect the InAs/GaSb bilayer at the four corners of the mesa. A second photolithography patterning and wet etching were performed to expose the InAs layer in the center of the mesa. The sample was then immediately transferred to a sputtering machine after the wet etching, and superconducting Ta (240 nm thick) electrodes are directly sputtered on top of it to form a Ta-bilayer-Ta junction. Au wires were glued by silver epoxy to Au/Ti electrodes and Ta electrodes for measurements. As a reference, a Hall bar sample was made from the same wafer. A gate was fabricated on the reference sample after covering the whole sample by a layer (∼100 nm) of atomic-layer-deposition-grown Al_2O_3. The carrier density, mobility and their dependence on the gate voltage were measured in this reference sample.

The dc I-V characteristics of the sample were measured with dc voltage or current sources and digital multimeters in a quasi-four terminal configuration as shown in Fig. 1(b), where I and V signals are sent/taken from the two Ta electrodes. For differential resistance measurements, a small ac current ($\sim$ 10 nA, 13 Hz) was summed with the dc current then feed to the junction, and the ac voltage response of the sample was measured by the standard lock-in technique.

Data in Fig. 1(c) were taken in a 3He cryostat with base $T = 0.3$ K. All other data shown here were taken in two dilution refrigerators with base $T = 90$ mK and 30 mK, respectively. The normal-state resistance of the junction varies slightly during different cool downs. For all measurements in magnetic field, the field direction was perpendicular to the sample surface.

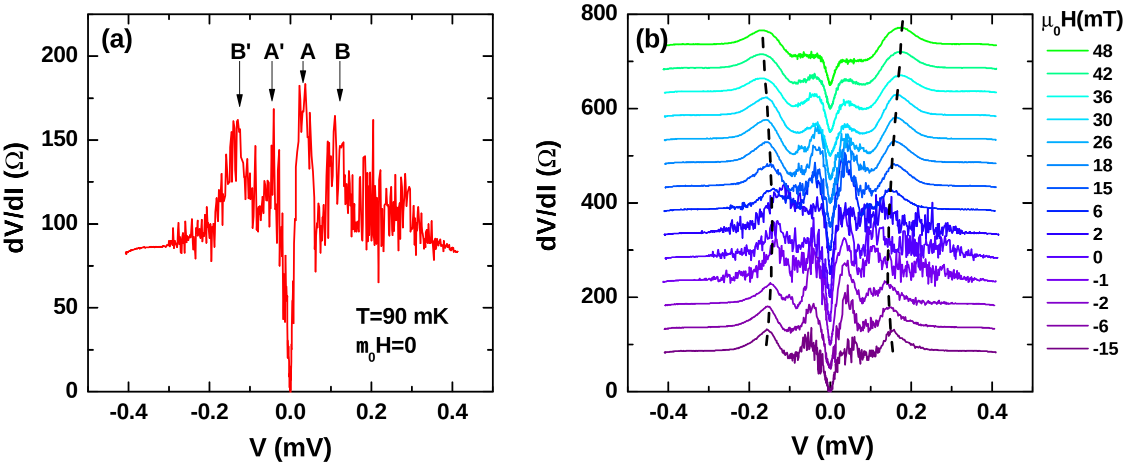

Fig. S1: **Differential resistance at $T = 90$ mK.** (a) dV/dI(V) in zero field. This is the same set of data as shown in Fig. 1(e). (b) Field dependence of dV/dI(V). The same set of data is also shown in Fig. 2(c) as dV/dI(I). A smaller field range is chosen to show details of the fluctuations in dV/dI near zero field. Two hand-drawn dashed lines highlight the B and B' peak positions. As shown, the voltage difference between two peaks, $\Delta_{B-B'}$, increases as field increases in small fields.

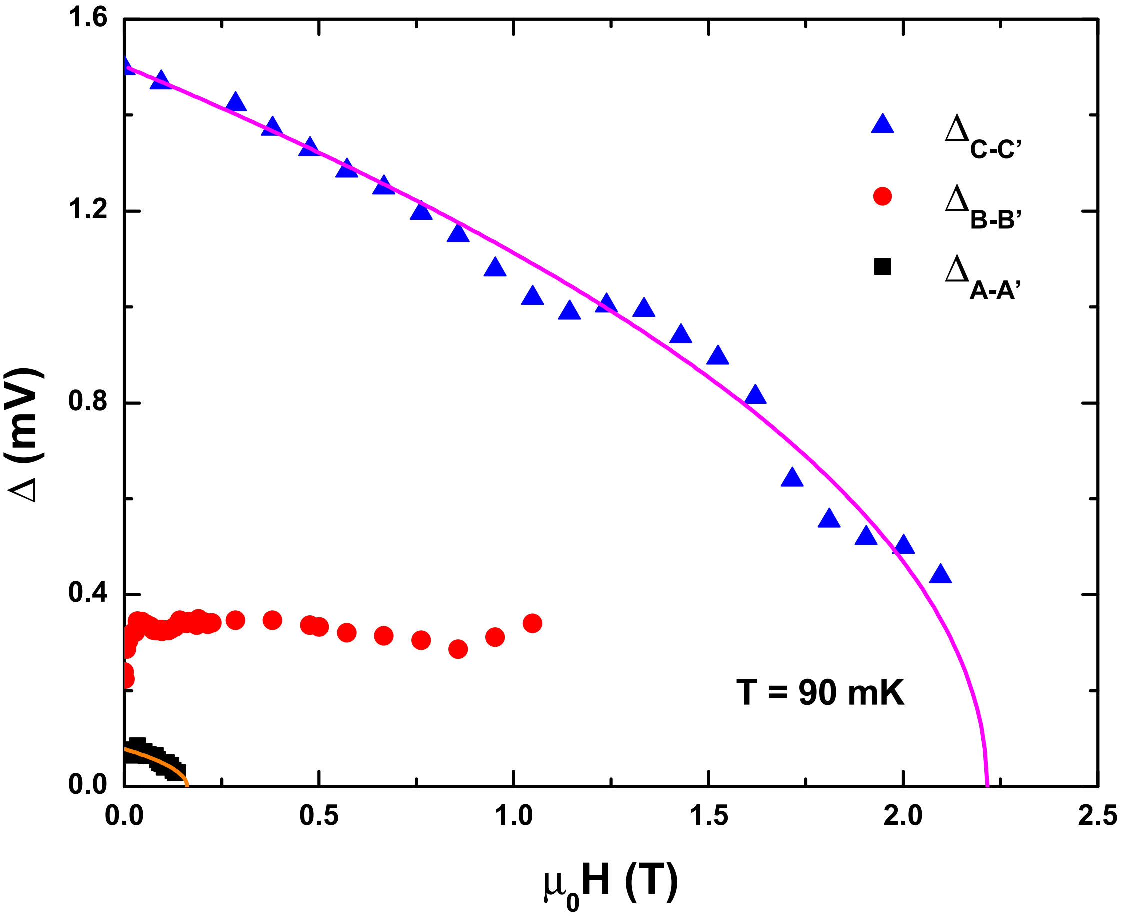

Fig. S2: **Evolution of peak separation in magnetic field** ($T = 90$ **mK).** $\Delta_{A-A'}$ is the voltage separation for pairs A and A'. It decreases monotonically as field increases (also shown in Fig. 2(d)). $\Delta_{A-A'}$, $\Delta_{B-B'}$, and $\Delta_{C-C'}$ are totally suppressed by fields of 0.14 T, 1.1 T, and 2.2 T, respectively. Solid lines are BCS fits for $\Delta_{A-A'}$ and $\Delta_{C-C'}$.

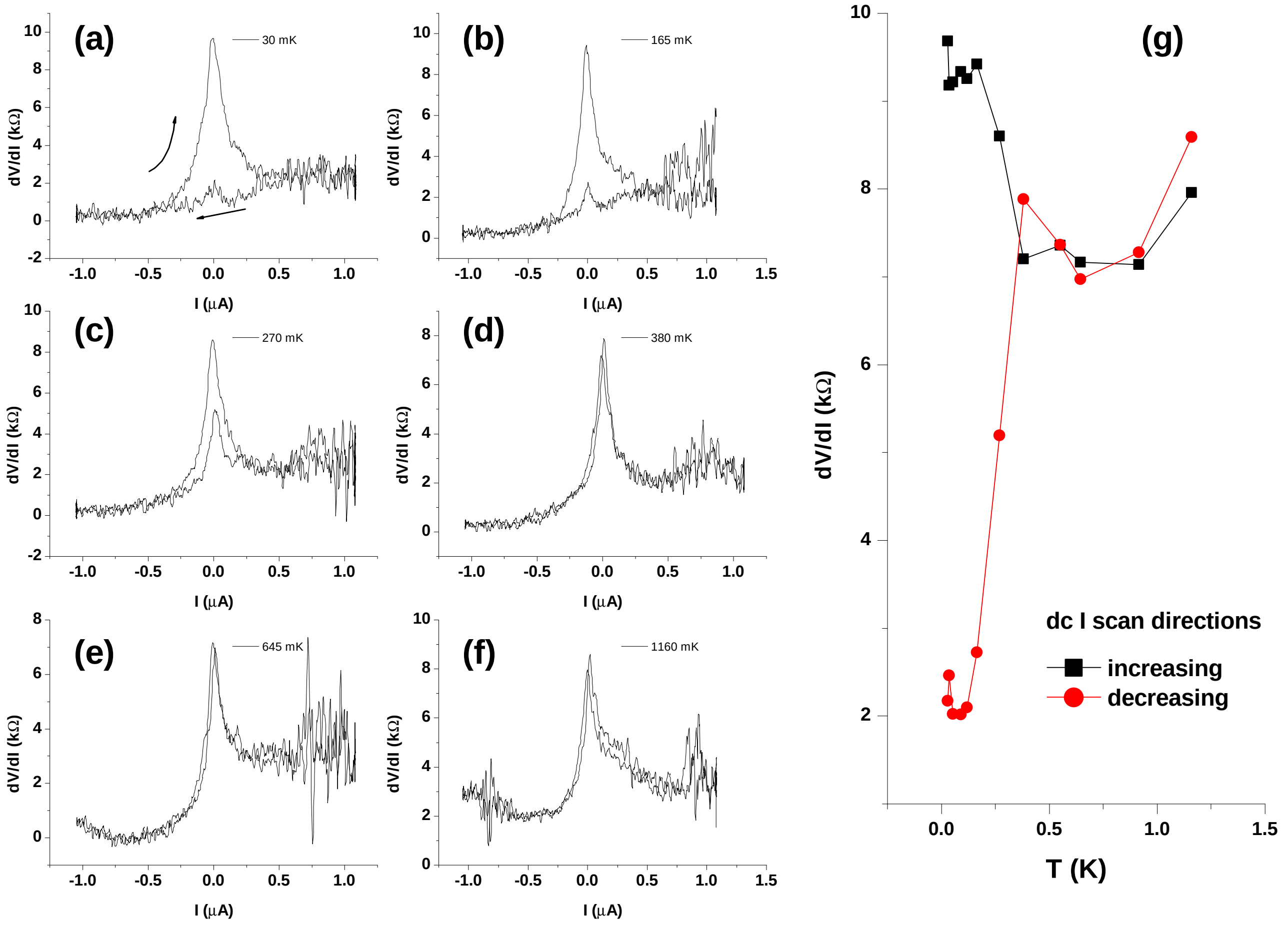

Fig. S3: **Temperature dependence of dV/dI(I) of the bilayer through a quantum point contact defined by Ta electrodes in zero magnetic field.** (a-f) At low temperatures, strong hysteresis exists near dc $I = 0$. Arrows represent current scan directions. As T increases, hysteresis decreases and vanishes at $T \approx 400$ mK. The peak values at $I = 0$ are shown for different temperatures in (g).

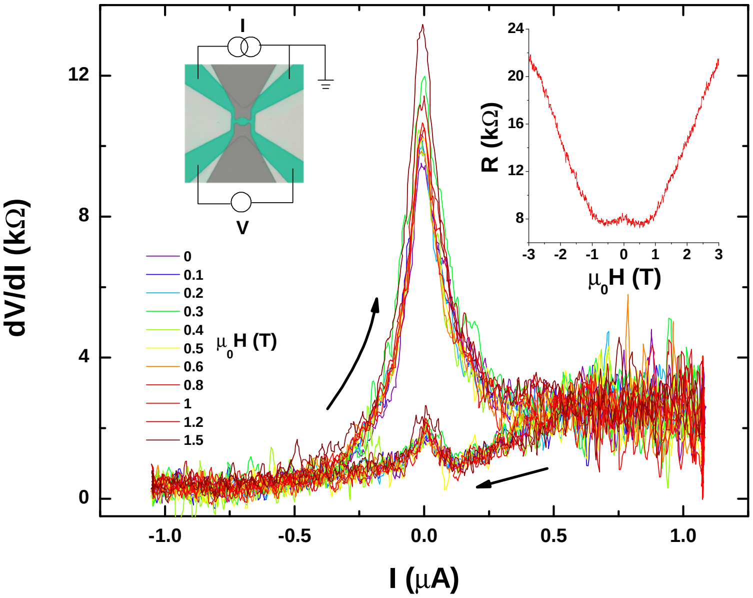

Fig. S4: **dV/dI(I) of the InAs/GaSb bilayer through a quantum point contact defined by Ta electrodes at T = 30 mK.** The measurement configuration is shown in the left inset. In all magnetic fields, dV/dI(I) shows hysteresis near zero I, when the dc bias I scan direction (arrows in main plot) changes. Furthermore, the traces show weak field dependence, except the larger peak near dc $I = 0$. The right inset shows the field dependence of the ac resistance R (or differential resistance at zero bias, $\mathrm{d}V/\mathrm{d}I|_{I=0}$) for the larger peak.

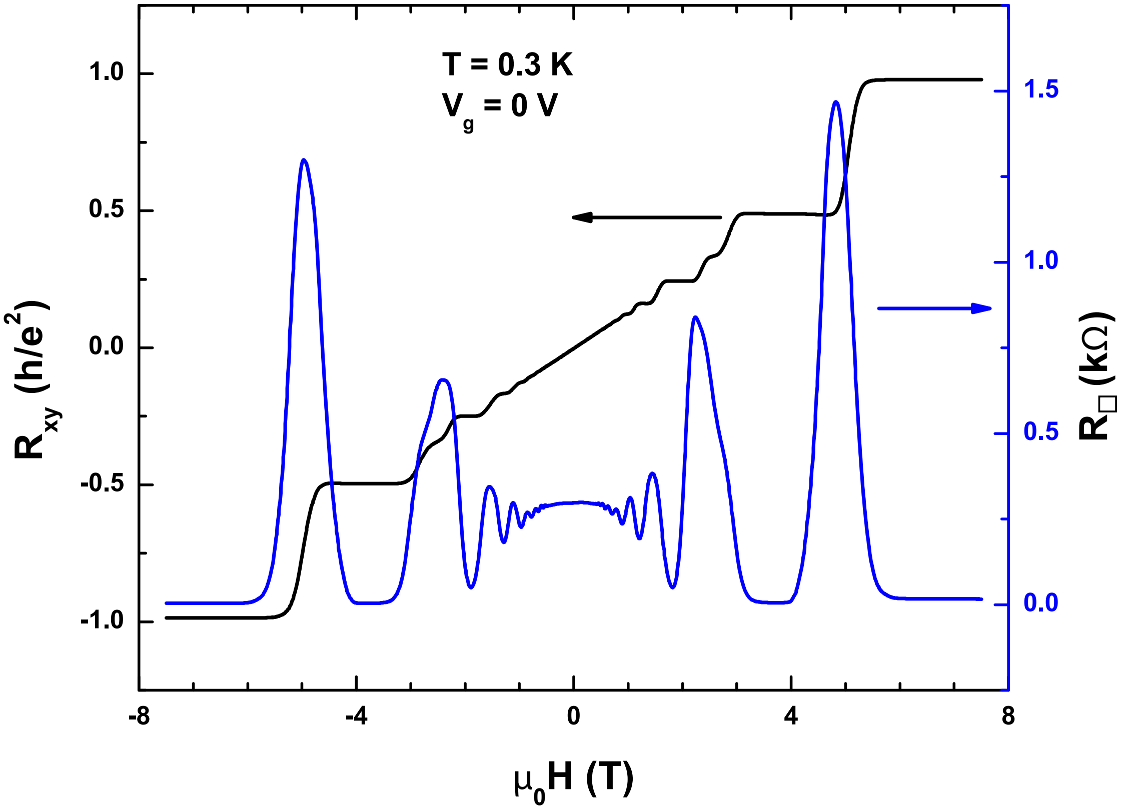

Fig. S5: **Quantum Hall measurement of the reference Hall bar sample at $T = 0.3$ K.** $R_\square$ is the longitudinal sheet resistivity. R_{xy} is the Hall resistance.