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Search for Majorana Fermions in Topological Superconductors

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Search for Majorana Fermions in Topological Superconductors

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Abstract

The goal of this project is to search for Majorana fermions (a new quantum particle) in a topological superconductor (a new quantum matter achieved in a topological insulator proximitized by an s-wave superconductor).

Majorana fermions (MFs) are electron-like particles that are their own anti-particles. MFs are shown to obey non-Abelian statistics and, thus, can be harnessed to make a fault-resistant topological quantum computer. With the arrival of topological insulators, novel schemes to create MFs have been proposed in hybrid systems by combining a topological insulator with a conventional superconductor.

In this LDRD project, we will follow the theoretical proposals to search for MFs in one-dimensional (1D) topological superconductors. 1D topological superconductor will be created inside of a quantum point contact (with the metal pinch-off gates made of conventional s-wave superconductors such as niobium) in a two-dimensional topological insulator (such as inverted type-II InAs/GaSb heterostructure).

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1. INTRODUCTION

Majorana fermions (MFs), predicted in 1937 by the Italian theorist Ettore Majorana, are electron-like particles that are their own anti-particles. MFs are shown to obey non-Abelian statistics and, thus, can be harnessed to make a fault-resistant topological quantum computer. Over the last decade, searching for MFs has mainly been focused on the exotic $5/2$ fractional quantum Hall effect (FQHE). With the arrival of topological insulators, new schemes to create MFs have been proposed in hybrid systems by combining a topological insulator with a conventional superconductor. Compared to FQHE, this new approach of creating MFs is promised to be more versatile and the requirement of material quality is less stringent. Since 2008, a global race has been on to realize yet-elusive MFs in low dimensional semiconductor systems.

In this section, I will give a brief introduction on Majorana fermions in p-wave superconductors.

In general, a charged fermion cannot be its own anti-particle, due to charge conjugation. For example, an electron has negative charge of -1 (in units of 1.6022×10^{-19} Coulomb). A positron, the antiparticle of electron, has positive charge of $+1$. So, electron and positron are different. However, this distinction is blurred in a *superconductor* [1]. Due to the formation of electron pairs (or Cooper pairs), electron number is no longer conserved. As a result, electron and hole (a type of quasiparticles in solid state physics, similar to positron) can be viewed as the same particle. This idea is illustrated in Fig. 1.

Under the band picture of superconductor, the electron (filled states at energy E above the Fermi level) and hole (empty states at $-E$ below the Fermi level) excitations can be represented by the creation and annihilation operators $\gamma(E)$ and $\gamma^\dagger(-E)$, respectively. Now, the physics picture in Fig. 1b can be written abstractively as $\gamma(E) = \gamma^\dagger(-E)$. If there exist states at the Fermi level of $E=0$, then, $\gamma(0) = \gamma^\dagger(0)$. In other words, Majorana fermions are born. Of course, the condition of an $E=0$ Fermi level is very rare in superconductors. In fact, most of the known superconductors are the so-called s-wave superconductor and their Fermi level always is $E>0$. Only in some exotic superconductors, for example, the so-called chiral p-wave superconductors, the $E=0$ Fermi level can occur at some nodes in the Fermi surface,

It has been generally believed that the ground state of the fractional quantum Hall effect at Landau level filling $\nu=5/2$ is a p-wave superconducting state. Recent experiments seem to support this claim [2]. However, the p-wave pairing in the $5/2$ quantum Hall effect is very fragile and it is only stable in the highest mobility samples at the temperatures close to absolute zero. In recent years, with the discovery of topological insulators, new schemes to generate chiral p-wave superconductors by combining the surface state (edge state) of a three-dimensional (two-dimensional) topological insulator and a conventional s-wave superconductor have emerged. It was shown that the p-wave pairing in these hybrid systems is robust and Majorana fermions are stable at relatively high temperatures.

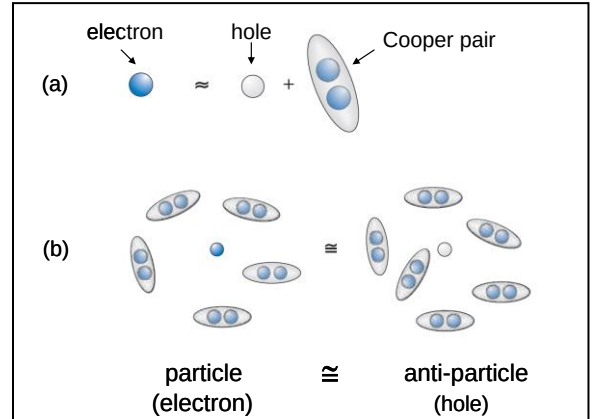


Fig.1-1 (adopted from Ref. [1]) (a) in a superconductor, a positive-charged hole can attract a Cooper pair and acquire negative charge. As a result, the whole entity behaves more or less like an electron. (b) Cooper pairs cluster around holes and thin out around electrons. As a result, no rigorous distinction between holes and electrons remains.

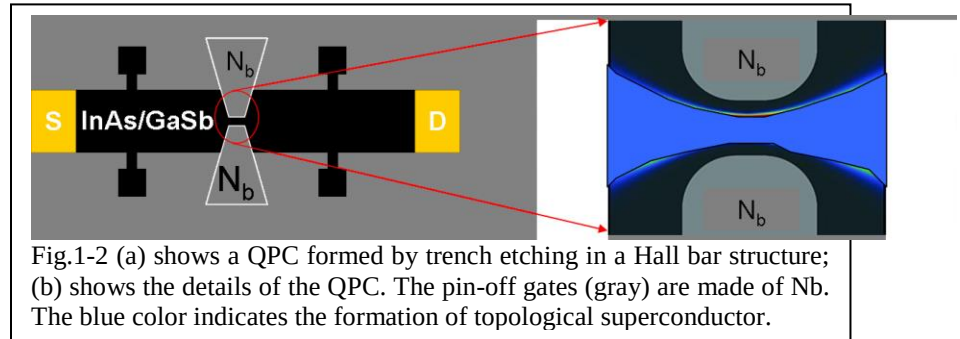
1.1. Creating topological superconductor

To this goal, we propose to create topological superconductor in a hybrid system consisting of a conventional s-wave superconductor and a two-dimensional (2D) topological insulator. This idea was motivated by the

theoretical prediction in Refs. [3,4]. In this model, a nanowire with strong spin-orbit coupling strength is placed near an s-wave superconductor. The proximity effect can induce an exotic superconductivity (called topological superconductivity) in the nanowire. Majorana fermions were shown to form at the ends of the nanowire. In a recent paper [5] published in Science by Kouwenhoven's group at Delft University, evidence of Majorana fermions was reported in an experimental setup precisely following the above theoretical proposal.

In our approach of creating topological superconductor, a quantum point contact (QPC) with the metal pinch-off gate made of niobium (Nb), a conventional s-wave superconductor, is fabricated in the inverted type II InAs/GaSb heterostructure, a 2D topological insulator. The proximity effect is expected to turn the region between the two pinch-off gates superconducting. Figure 2 displays a cartoon picture of a proposed device. First, a Hall bar is fabricated. Then, a trench etching QPC is defined, either by photo or E-beam lithography technique. After this, a dielectric layer, such as Si_3N_4 , will be deposited over the whole device area. Finally, a metal front gate, made of Al or Ti/Au, will be thermally deposited over the Hall bar area. In experiment, we will tune the gate bias so that the Fermi energy is in the mini-gap region of the inverted type-II InAs/GaSb heterostructure. Under this condition, it is believed that type-II InAs/GaSb becomes a two-dimensional topological insulator and spin polarized edge channels will form. Coupled with nearby superconducting Nb, 1D topological superconducting state is expected to be induced inside the QPC.

In order to confirm the formation of topological superconductor, we will carry out tunneling conductance measurements. In detail, we apply a small DC bias between the source and drain and measure the current as we vary the pinch-off and front gate voltages. In a conventional QPC, quantized conductance (G) steps will be observed at the values of $G = N \times e^2/h$ (N an integer), assuming full spin polarization. In case of a topological superconductor forming inside the QPC, only the steps with the quantized values of $G = 2 \times e^2/h, 6 \times e^2/h, 10 \times e^2/h \dots$ will be observed [6].



1.2. Searching for Majorana Fermions

To create Majorana fermions in the above device structures, one of the two QPC pinch-off gates needs to be replaced with a ferromagnetic insulator [3,4], such as EuO. Quantum transport measurements will be carried out to search for Majorana fermions. First, we will examine the differential tunneling conductance at different gate biases. It is expected that a zero-bias peak should show up in the differential conductance as the Fermi level is tuned into the mini-gap regime where the system becomes a two-dimensional topological insulator. Furthermore, temperature and magnetic field dependence of this zero-bias tunneling peak will be studied, which may give us the information on the stability of Majorana fermions.

We note that evidence of Majorana fermions has been reported recently by Kouwenhoven's group at Delft University in Netherland [5]. Compared to the work by this group, our proposed research has several advantages. First, MFs are to be created in QPC-defined nanowires in planner type-II InAs/GaSb heterostructures, versus in InSb nanowires by the Dutch group. As a result, the need of an external magnetic field will be eliminated. Second, our experimental setup allows us to take the advantage of high quality MBE growth of type II InAs/GaSb heterostructure. Finally, the top-down approach to create 1D topological superconductor proposed in this work, if successful, will naturally lead to scale-up integration.

2. SUPERCONDUCTING PROXIMITY EFFECT IN INVERTED INAS/GASB QUANTUM WELL STRUCTURES WITH TA ELECTRODE

Although the physics of a semiconductor (Sm) heterostructure in contact with a superconductor (S) has been studied extensively for several decades, the subject has seen renewed interest with the possibility of realizing Majorana fermions in strong spin-orbit coupled Sm–S hybrid structures [1-6]. The emergence of Majorana fermions in solid-state systems may have profound implications in quantum computation [7-9] and it has triggered an avalanche of research activities [1-6, 10-13]. Recently, two-dimensional topological insulators (or quantum spin Hall insulators) have attracted a great deal of attention due to its being a more promising material system in realizing Majorana fermions [14]. Among the probable quantum spin Hall insulators, type-II InAs/GaSb quantum wells (QWs) [14] is a rising candidate. It was shown that with an inverted band structure this material can support dissipationless time-reversal symmetry protected spin edge channels and display quantum spin Hall effect [15,16]. When in proximity to a superconductor, it can host Majorana zero-modes [1,17,18], providing an unrivaled platform for attempting intriguing theoretical proposes. Furthermore, InAs QWs are particularly suited for fabricating hybrid Sm–S devices, owing to the low electron effective mass and high mobility as well as the low Schottky barrier interface to superconductors [19]. Therefore, it is of fundamental interest to study the proximity-coupled InAs/GaSb hybrid structures.

In this section, we report on a systematic study of the proximity effect in top-gated InAs/GaSb QWs in contact with a superconducting Ta electrode. We find that the electronic transport across the InAs–Ta junction exhibits distinct zero-bias behavior, either a conductance (dI/dV) peak or dip, depending on the interfacial transparency. We show that although a zero-bias dI/dV peak is often seen across relatively resistive junctions [20], the conductance spectra of transparent interface recover the characteristic lineshape of Blonder-Tinkham-Klapwijk (BTK) theory [21], with a dI/dV dip occurring at zero bias and two coherent-peak-like features at bias voltages corresponding to the superconducting gap of Ta.

The InAs/GaSb QW bilayer studied in this work was grown by molecular beam epitaxy, following the recipe described in ref. [14]. The inset of Figure 2-1a illustrates the schematic of the QW structure, in which a 150 Å InAs QW and a 40 Å GaSb QW are sandwiched between AlSb barriers. Two-dimensional electrons and holes are expected to coexist in this system and confined in the InAs and GaSb QWs, respectively. Transport characterization of the material has been reported previously [22]. Integer quantum Hall effect is found fully developed in both the electron- and hole-dominated regimes, attesting the high quality of the material. To fabricate Sm–S hybrid devices, we first define a 20 μm x 24 μm InAs/GaSb mesa using conventional photolithography technique and wet chemical etching. Ammonium hydroxide is used to etch AlSb and GaSb selectively, while citric acid/hydrogen peroxide solution is used to remove InAs. Normal-metal Au/Ti (200/10 nm thick) electrodes are then patterned to connect with both the InAs and GaSb QWs at the four corners of the mesa, and superconducting Ta (70 nm thick) electrodes are sputter-deposited directly on top of the InAs layer (forming InAs–Ta junctions) after removing the InAs cap layer, the 500 Å AlSb top barrier and the GaSb QW. The transition temperature T_c of the Ta electrodes is ~ 1.4 K. Finally, a 100nm-thick SiO₂ dielectric layer is deposited using plasma-enhanced chemical vapor deposition and an Au/Ti top gate is fabricated on SiO₂ and covering the entire InAs/GaSb mesa. The inset of Figure 2-1c shows a scanning

electron microscope image of one of the three devices we have studied. The minimum distance between two Ta electrodes is $\sim 2 \mu\text{m}$.

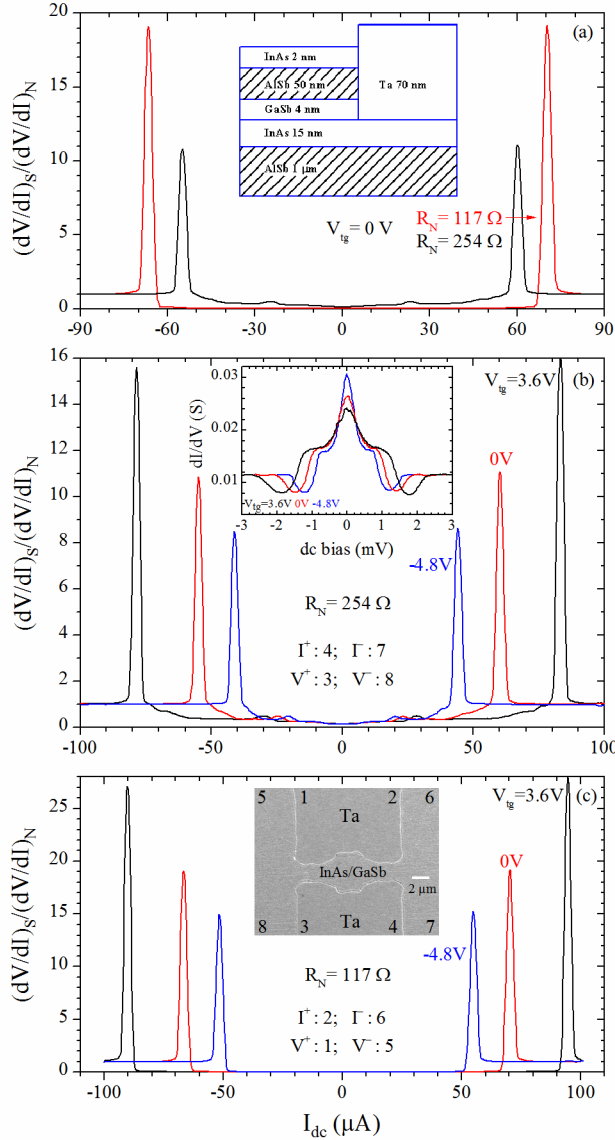


Figure 2-1. (a) Normalized dV/dI spectra of two InAs-Ta junctions as a function of I_{dc} . One junction (black curve) has a zero-bias resistance $\sim 38 \Omega$ with an interfacial area of $\sim 82 \mu\text{m}^2$, while the other junction (red curve) is highly transparent, exhibiting a zero-bias resistance $\sim 4.2 \Omega$ with an interfacial area of $\sim 140 \mu\text{m}^2$. Inset: Schematic cross section of an InAs-Ta junction (not to scale). (b, c) Normalized dV/dI spectra of the two junctions at different V_{tg} . Inset to (b): dI/dV spectra of the relatively resistive junction near zero-bias voltage. Inset to (c): Scanning electron microscope image of a device and schematics of the contact configuration. All data were taken at $T = 0.33 \text{ K}$.

From now on, we focus on the transport across Sm-S junctions with respect to external parameters such as carrier density (by tuning the top-gate voltage V_{tg}), temperature, and magnetic field. The differential resistance dV/dI (or conductance dI/dV) of the junction is measured either using a dc method (*i.e.*, I - V measurement) and then calculated numerically or using a standard dc + ac lock-in technique with a typical ac current of 50 nA. Consistent results are obtained between these two methods. Three-terminal configuration is used to measure Sm-S junctions.

For example, the top InAs–Ta junction in the inset of Figure 2-1c can be measured by sending a current from I^+ : 2 to I^- : 6 while recording the voltage between V^+ : 1 and V^- : 5. Since the separation between the two superconducting electrodes in our devices is always much greater than the correlation length of Ta (only a few tens of nm) [23], no supercurrent is observed across the Ta–InAs–Ta junction and no cross-talk effect is expected between the transport across the two InAs–Ta junctions.

Figure 2-1a shows the dV/dI spectra of two InAs–Ta junctions as a function of the dc current I_{dc} . Each spectrum is normalized to its high-bias value $R_N = (dV/dI)_N$ at $I_{dc} = 100 \mu A$, which consists of the normal-state resistance of the Ta electrode ($R_{N,Ta}$) and that of the junction. The sharp dV/dI peaks at high bias are likely due to the current-driven destruction of superconductivity in the Ta electrode [24,25] and its position indicates the corresponding critical current. We find that the dV/dI peaks become weakened and moving towards zero bias with increasing temperature, and eventually vanished around T_c (data not shown). The position of the peaks depends on the interfacial transparency and the applied V_{tg} . Larger critical current is observed for a more transparent InAs–Ta junction (red curve in Figure 2-1a) and for positive V_{tg} voltages corresponding to higher electron concentration in InAs/GaSb QWs. A great advantage of InAs/GaSb-based Sm–S hybrid devices is that the charge carriers are continuously tunable from purely electron to two-carrier hole dominated regime through the charge neutrality point^{16, 22, 26-28}, which is at $V_{tg} \approx -4.8$ V for our devices. Such a tunability was not achieved in earlier studies of InAs–Nb junctions [20], in which case modulation doping with Te was used to vary the electron concentration in different samples.

The charge transport across Sm–S junctions is often described by the interfacial conductance spectra, i.e., dI/dV versus dc bias V_{bias} . For the InAs–Ta junction with a zero-bias resistance $\sim 38 \Omega$ at $V_{tg} = 0$ V (inset to Figure 2-1b), the dI/dV spectra exhibit a pronounced peak at zero bias as well as two satellite dips below the normal-state conductance at high-bias voltages, consistent with that reported in previous works [20]. We note that anomalous zero-bias conductance peak is ubiquitous in transport measurement of superconducting hybrid structures but its origin is often of debate. For instance, Sheet *et al.* [29] argue that heating effects may cause a spurious conductance peak at zero bias, as the increase in bias voltage may lead the local current to exceed the critical current, giving rise to a V_{bias} -dependent decrease in dI/dV (due to the resistance increase at the transition). However, if this mechanism is dominant in our measurements, one would expect the dI/dV to exhibit a weak magnetic-field dependence at zero bias, when the heating effects vanish and the Ta electrode remains in the superconducting state. In this scenario, the effect of magnetic field is just to reduce the critical current, thus narrowing the width of the zero-bias conductance peak with increasing magnetic field. These expectations are in clear contrast with the magnetic-field dependent measurements shown in Figure 2-3(b) and 2-3(d) for a relatively resistive junction, where in the low magnetic field regime the differential conductance decreases substantially with increasing field. Moreover, via examining the V_{tg} -dependence of the zero-bias conductance (inset to Figure 2-1b), one can further argue that the transport across the junction is not in the thermal regime, where the dV/dI is expected to be dominated by the Maxwell resistance proportional to the bulk resistivity of the QWs [29]. For our devices, when the InAs/GaSb QWs are tuned close to its charge neutrality point ($V_{tg} = -4.8$ V), the system would become more resistive than the case of $V_{tg} = 0$ V or 3.6 V, leading to a

smaller value of zero-bias conductance (larger Maxwell resistance). This is again in contrast with our experimental data.

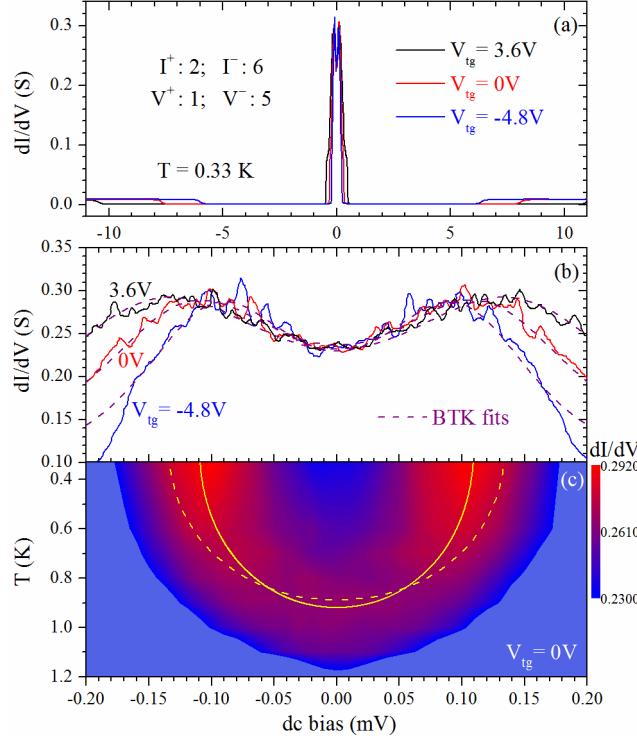


Figure 2-2. (a) dI/dV spectra of a transparent InAs-Ta junction in a relatively large dc bias voltage range and at different V_{tg} . (b) Zoom-in spectra of (a) near zero bias. Dash lines illustrate BTK fits to the data, as described in the main text. The data presented in (a) and (b) were taken at $T = 0.33$ K. (c) Contour plot of dI/dV with respect to dc bias voltage and temperature at $V_{tg} = 0$ V. Color contrast highlights the evolution of the two coherent-peak-like shoulders in dI/dV spectra, which follows a BCS-like gap dependence (solid line) with $\Delta_0 = 0.11$ meV $= 1.39 k_B T_c$ and $T_c = 0.92$ K. Quantitative fitting using BTK theory leads to $\Delta_{0.33K}/e = 0.13$ meV with $Z = 0.42$ and $\Gamma = 0.015$ meV. For comparison, dash line shows the conventional BCS temperature dependence with $\Delta_0 = 0.13$ meV $= 1.76 k_B T_c$ and $T_c = 0.86$ K.

A better interpretation of our observations for the relatively resistive junctions is the original proposal of ref. [20], inspired by the work of van Wees *et al.* [30]. Following their interpretation, the anomalous zero-bias conductance peak is attributed to a multiple reflection process between the InAs-Ta interface and the AlSb back wall of the InAs QW, while the unusual broadening of the peak is due to the presence of a spatially nonuniform local bias between the InAs layer and the Ta electrode. The microscopic process underlying the proximity effect at the InAs-Ta interface is the so-called Andreev reflection [31]: at temperatures well below the superconducting gap of Ta, an electron in the InAs QW cannot transmit through the InAs-Ta interface, but rather is reflected as a coherent hole with simultaneous generation of a Cooper pair in Ta. Due to the long mean free path of charge carriers in our devices and the thin thickness of QWs, the electrons and Andreev holes may undergo multiple normal reflections between the two walls of InAs QW, giving rise to “excess” conductance at zero bias. This process is phase-coherent, therefore sensitive to magnetic field and back-scattering. In this scenario, when the system is tuned towards charge neutrality, the scatters in InAs QW would become less screened

and one would expect a substantial increase in excess conductance, which is consistent with our measurements shown in the inset of Figure 2-1b.

Another prediction from the theory of van Wees *et al.*[30] is the vanishing excess conductance for an ideal Sm–S interface with the assumption of classical scattering in the Sm. Below we will demonstrate that this behavior is indeed evidenced in the dI/dV spectra of more *transparent* InAs–Ta junctions and BTK-like spectral lineshape is recovered with the extracted superconducting gap of Ta consistent with that from temperature dependent transport measurements. Here, the highly transparent Sm–S junctions are achieved by choosing Ta as the superconducting material and more importantly by minimizing the interval between the ammonium hydroxide etching and Ta sputter deposition, i.e., minimizing the exposure time of fresh InAs surface to air. In Figure 2-2a we plot the dI/dV spectra of a transparent InAs–Ta junction in a relatively large dc bias voltage range and at different V_{tg} . The sharp drop in conductance around $\pm(0.2-0.4)$ meV corresponds to the superconducting transition of the Ta electrode, whose normal-state resistance is estimated to be $R_{N,Ta} = 107 \Omega$. Figure 2-2b shows the zoom-in spectra of Figure 2-2a at low-bias voltages, where a zero-bias conductance *dip* is clearly evidenced and accompanied by two coherent-peak-like shoulders. The positions of the shoulders depend on V_{tg} ; it moves to higher bias voltage with increasing carrier density in InAs QW, which allows for larger critical current as shown in Figure 2-1c.

The observed dI/dV spectral lineshape of transparent InAs–Ta junctions can be analyzed quantitatively using the standard BTK theory [21], after subtracting a common $R_{N,Ta}$ from the spectra taken at different V_{tg} values. Explicitly, the interfacial conductance of the junction is given by

$$\frac{dI}{dV}(V) = \frac{Ne}{h} \int_{-\infty}^{\infty} \frac{df_0(E-eV)}{dV} [1 + A(E) - B(E)] dE, \quad (1)$$

where N is the number of modes in InAs QW, $f_0(E)$ is the Fermi Dirac function, and $A(E)$ and

$B(E)$ are probabilities of Andreev and ordinary reflection at the interface. The values of $A(E)$ and $B(E)$ at temperature T depend on the superconducting gap Δ_T of Ta as well as the interfacial barrier strength Z (dimensionless) with $Z = 0$ for perfect interface and $Z \rightarrow \infty$ in the tunneling regime. The dash lines in Figure 2-2b show best fits to the data using Eq. (1) and the corresponding fitting parameters are summarized in Table 1. A depairing parameter Γ is also introduced as the complex component of the quasiparticle energy E , $E \rightarrow E + i\Gamma$, to take account

of the inelastic scattering and achieve best fits [32]. We note that for three different V_{tg} , similar Z values are obtained and $\Gamma \ll \Delta_{0.33K}$ (attesting the validity of our fitting). The obtained Z values are comparable with the lowest reported value of 0.4 for Nb–InAs–Nb Josephson junctions [33]. In Figure 2-2c we plot the contour plot of dI/dV for the transparent InAs–Ta junction with respect to dc bias voltage and temperature at $V_{tg} = 0$ V. Here, the color contrast (red) highlights the temperature evolution of the two shoulders in dI/dV spectra, whose positions are correlated with the temperature dependence of the superconducting gap and following a Bardeen-Cooper-Schrieffer (BCS)-like behavior (solid line) with $\Delta_0 = 0.11$ meV and $T_c = 0.92$ K. The gap to critical temperature ratio of $\Delta_0/k_B T_c = 1.39$ is slightly smaller than the BCS value of 1.76. For comparison, we also plot the conventional BCS temperature dependence in Figure 2-2c with

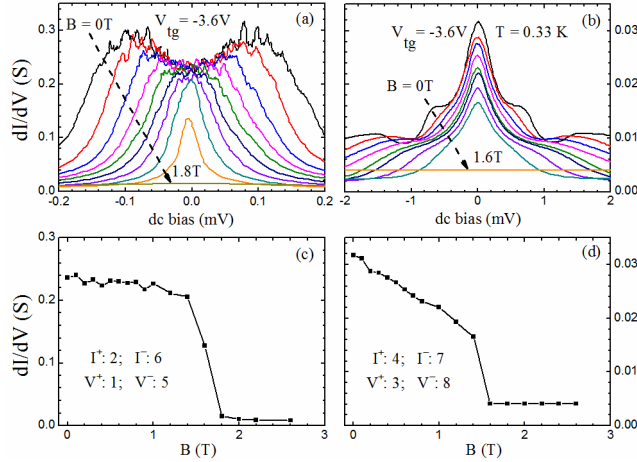
$\Delta_0 = 0.13 \text{ meV} = 1.76 k_B T_c$ and $T_c = 0.86 \text{ K}$ (dash line), where the Δ_0 value is extracted from best BTK fit [34].

Table 1. BTK fitting parameters of the three dash lines shown in Figure 2-2b.

$V_{tg} \text{ (V)}$	$R_{N,Ta} \text{ (}\Omega\text{)}$	$\Delta_{0.33K} \text{ (meV)}$	Z	$\Gamma \text{ (meV)}$
3.6	107	0.16	0.45	0.045
0	107	0.13	0.42	0.015
-4.8	107	0.11	0.43	0.002

Figure 2-3 presents the magnetic-field dependence of the dI/dV spectra across a transparent and a relatively resistive InAs–Ta junction. For the transparent junction, the effect of magnetic field is simply closing the superconducting gap, therefore the zero-bias conductance values remain nearly constant below the critical field (Figure 2-3c). The zero-bias conductance peak of the relatively resistive junction, on the other hand, decreases substantially with increasing magnetic field (Figure 2-3d).

Figure 2-3. Magnetic-field dependence of the dI/dV spectra across (a) a transparent InAs–Ta junction and (b) a



relatively resistive junction. (c) and (d) plot the magnetic-field dependence of the zero-bias conductance of the two junctions. All data were taken at $T = 0.33 \text{ K}$ and the magnetic field was applied perpendicular to the QWs.

In conclusion, we show that the electronic transport across InAs–Ta junction depends on its interfacial (Schottky) barrier strength and the Andreev reflection process. When the interface is imperfect, the measured conductance spectra exhibit a broad peak at zero bias and the peak amplitude is sensitive to magnetic field, the bias voltage across the junction, and temperature. When a highly transparent InAs–Ta interface is achieved, however, a zero-bias conductance dip appears as well as two coherent-peak-like features forming at bias voltages corresponding to the superconducting gap of Ta. Our work thus demonstrates the need of achieving highly transparent interfaces in InAs/GaSb-based hybrid structures for studying the intriguing Andreev bound states in this recently discovered two-dimensional topological system.

3. GIANT SUPERCURRENT STATES IN A SUPERCONDUCTOR-INAS/GASB-SUPERCONDUCTOR JUNCTION

Superconductivity in topological materials has attracted a great deal of interest in both electron physics and material sciences since the theoretical predictions that Majorana fermions can be realized in topological superconductors [1, 2, 3, 4]. Theoretical predictions show that topological superconductivity can be realized in a type II, band-inverted, InAs/GaSb quantum well if it is in proximity to a conventional superconductor. Here we report observations of the proximity effect induced giant supercurrent states in an InAs/GaSb bilayer system that is sandwiched between two superconducting tantalum electrodes to form a superconductor-InAs/GaSb-superconductor junction. Electron transport results show that the supercurrent states can be preserved in a surprisingly large temperature-magnetic field (T-H) parameter space. In addition, the evolution of differential resistance in T and H reveals an interesting superconducting gap structure.

Majorana Fermions, which are their own anti-particles, possess non-Abelian properties and can be utilized in topological quantum computations [2]. It is therefore not surprising that the search for Majorana fermions in solid state systems has attracted a great deal of attention in recent years. Among many theoretical proposals, hybrid systems of an s-wave superconductor in proximity to a 2D topological insulator (TI) with strong spin-orbit coupling [1,3, 5-8] are amongst the most promising. Out of the theoretically known 2D TI systems, HgTe/HgCdTe [9-11] and InAs/GaSb [12-14] systems are currently under extensive experimental study. In both cases, the conventional semiconductor will have a phase transition to a quantum spin Hall (QSH) insulator when the quantum well (QW) width exceeds a critical value d_c [9,12,15]. In the QSH regime, a 2D TI exhibits an insulating bulk and conductive protected helical edge states. When put in proximity to a conventional s-wave superconductor, it has been shown that superconductivity (which would then necessarily be of topological nature) can be induced in the edge channels. Recent transport experiments in HgTe/HgCdTe [16] and InAs/GaSb [17] samples have shown probable edge-mode superconductivity in these 2D topological insulators. In this section, we show the observation of giant supercurrent states in a high quality superconductor-InAs/GaSb-superconductor hybrid device.

Molecular beam epitaxy techniques were utilized to grow high quality InAs/GaSb bilayer structures. The growth structure of the InAs/GaSb quantum well bilayer is similar to that reported in the past [18], except that the InAs QW width is in the critical regime of $d_c \sim 10$ nm (with a GaSb QW width of 5 nm) [19]. An eight-band Kane model calculation shows that at this critical width d_c , the lowest electron energy band (E_1) in InAs will touch the highest hole energy band (H_1) in GaSb at $k=0$ in momentum space, forming a Dirac cone-like feature in the band structure [11]. Given that the critical width is approximate (even with a realistic eight band Kane model), we can say that the bulk system has a very small (or vanishing) gap near or in the topological regime. Superconducting tantalum (Ta) electrodes were directly deposited onto the InAs layer after photolithography patterning and wet chemical etching procedures to expose that layer. A Ta-bilayer-Ta junction was formed (Fig.3- 3-1(a) and (b)). The minimum separation of the two superconducting Ta electrodes is $L \approx 2 \mu\text{m}$.

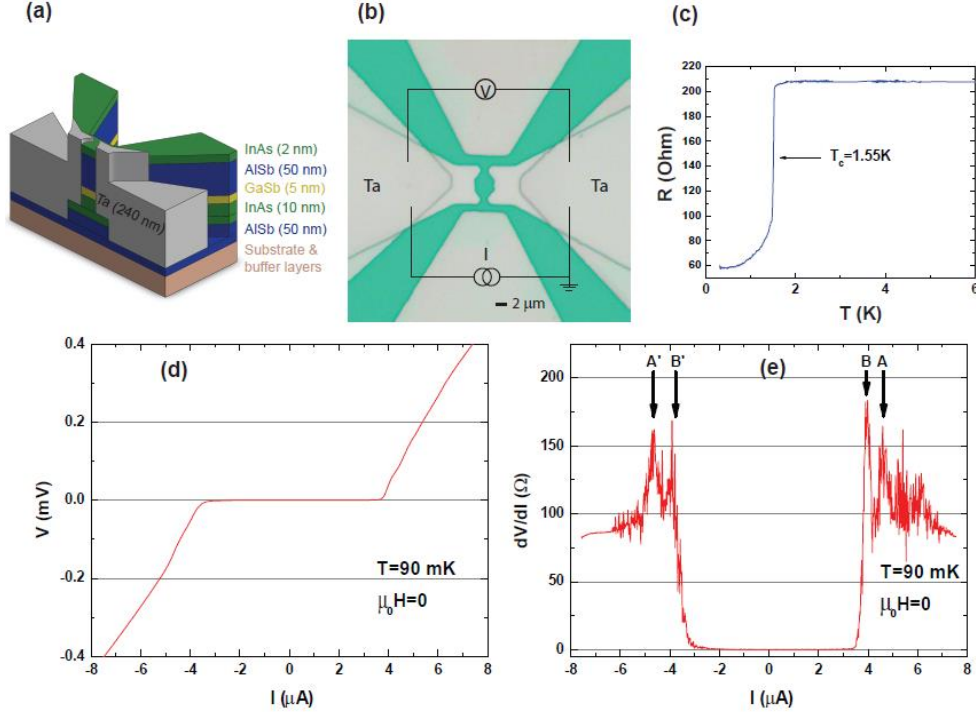


Figure 3-1: Sample structure and zero magnetic field transport. (a) Layer structure of the Ta-InAs/GaSb-Ta junction (not to scale; cutting along the horizontal center in (b)). (b) Optical image of the sample. The junction is at the center. Two terminal electrical transport measurement setup is overlaid on the image. I represents either a dc current source (for I - V measurements) or sum of an ac and a dc currents (for differential resistance measurements). V is either a multimeter or a combination of a multimeter and a lock-in amplifier. (c) $R(T)$ of the junction shows a superconducting transition $T_c \approx 1.5$ K. (d) A typical dc I - V and (e) a differential resistance vs. I traces are shown, respectively, at $T=90$ mK and $\mu_0 H=0$ T. A (or B) and A' (or B') mark the position of dV/dI peaks in positive and negative bias, respectively.

Fig.3- 3-1(c) shows the temperature (T) dependence of the junction resistance (R) in absence of a magnetic field (H). A sharp superconducting transition of the Ta leads can be seen at 1.5 K, with no noticeable change of resistance near 4.47 K (the superconducting transition temperature T_c of Ta bulk). The finite resistance at low temperature is due to a section of the bilayer between the two Ta electrodes. As temperature is further decreased, a dissipationless supercurrent is observed to pass through the junction as shown in Fig. 3-3-1(d) and (e). A typical dc current-voltage (I - V) trace at $T=90$ mK is shown in Fig. 3-3-1(d). For large I ($|I| > 20$ μ A, not shown), the I - V curve is simply a straight line indicating a normal state following the Ohm's law. As $|I|$ decreases below a critical value $I_c \approx 3.5$ μ A, voltage across the junction maintains a zero value and clearly demonstrates a complete superconducting path throughout the junction, which is consistent with the differential resistance (dV/dI) result shown in Fig. 3-3-1(e). In the intermediate I regime between $I_c < |I| \leq 8$ μ A, visible fluctuations are observed in the I - V trace. These fluctuations become more clearly seen in the dV/dI curve of Fig. 3-3-1(e) (see also Fig. 3-3-2(b)). We notice that these are time domain fluctuations. Details of the fluctuations in dV/dI are not reproduced in repeated measurements. This is different from the fluctuations observed in strained HgTe [11], where aperiodic fluctuations in dV/dI are reproducible in voltage bias for different dV/dI

measurements. In Fig. 3-3-1(e), two pairs of dV/dI peaks (marked as A, A' and B, B' in graph) can be seen above the fluctuating background. These peaks (or differential conductance dips) near zero bias normally signal the breakdown of Cooper pairs near the critical current I_c .

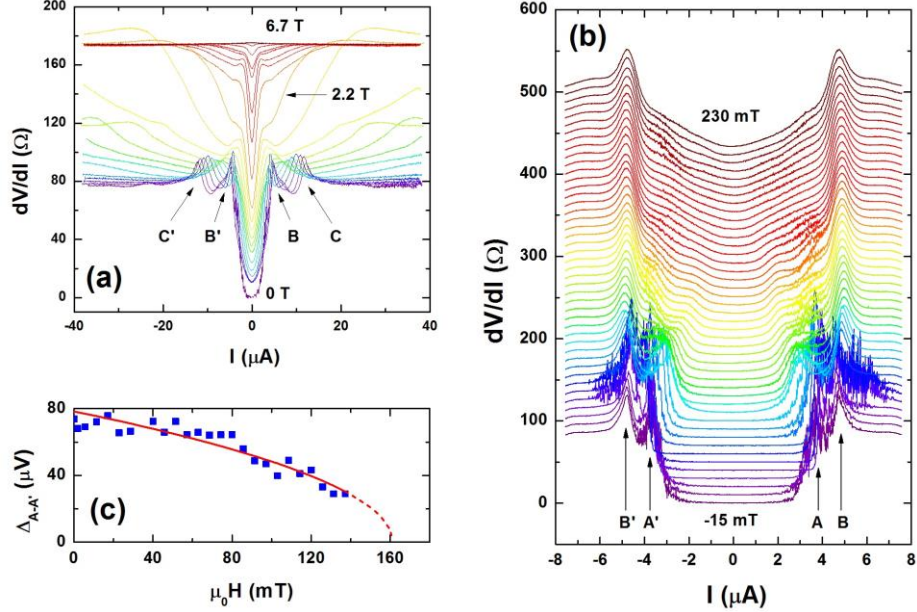


Figure 3-2: Magnetic field dependence of dV/dI vs. I at $T=90$ mK. (a) dV/dI vs. I in a large dc I range. From bottom to top, applied magnetic field increases from 0 T to 6.7 T. B (B') and C (C') mark peaks positions. (b) Detail plots of dV/dI in small magnetic fields. From bottom to top, field increases from -15 mT to 230 mT. Curves are shifted vertically for clarity. (c) Voltage difference between peaks A and A' ($\Delta_{A-A'}$) as a function of applied field. Both

solid and dashed lines show a phenomenological fit as $\Delta_{A-A'} = c \left(1 - \frac{H}{H_{c1}}\right)^{1/2}$ with $c=78.3 \mu V$ and $\mu_0 H_{c1}=161$ mT.

In Fig. 3-3-2(a), dV/dI is displayed over a large dc bias current range. An additional pair of pronounced dV/dI peaks (C and C') appear at higher bias current. We note that the current positions of all three peaks are reproducible and robust against the time-domain fluctuations but sensitive to external magnetic field. With increasing field, the existing peaks occur at smaller currents. By tracking the field dependence of peaks, we may acquire information about the superconducting gap structures. For example, the A and A' peaks disappear at ~ 140 mT (Fig. 3-3-2(b)). Surprisingly, at the same field, the fluctuations in dV/dI are also greatly suppressed, too. This thus indicates a direct link between the appearance of A (A') peaks and the dV/dI fluctuations. By plotting the same data in Fig. 3-3-2(b) as dV/dI vs. V , where V is the dc bias across the junction, one can define the voltage difference between a pair of peaks, for example, $\Delta_{A-A'}(H=0)=74 \mu V$ is for peaks A and A' . Fig. 3-3-2(c) shows the $\Delta_{A-A'}$ evolution in fields based on the data in Fig. 3-3-2(b). This dependence can be fitted well by a BCS-gap-like

phenomenological equation $\Delta_{A-A'}(H) = c \left(1 - \frac{H}{H_{c1}}\right)^{1/2}$ with $c=78.3 \mu V$ and $\mu_0 H_{c1}=161$ mT

(Solid and dashed lines in Fig. 3-3-2(c)). Considering the small energy gap associated with the A (A') peaks and that the A (A') peaks are destroyed by relatively weak magnetic field [10], here we propose to attribute the A (A') peaks to the onset of the induced superconductivity in the edge

channels. This assignment is also consistent with a recent observation. As shown in a band inverted InAs/GaSb S-N-S junction in Ref.[17], the induced edge channel superconductivity is very weak, *i.e.*, it shows up only in a small current ($\sim$ nA) and magnetic field ($\sim$ mT) region. For B and B' peaks, $\Delta_{B-B'}(H=0)=0.25$ mV and the peaks vanish at $\mu_0 H=1.1$ T. For C and C' peaks, $\Delta_{C-C'}(H=0)=1.5$ mV and they vanish at $\mu_0 H=2.2$ T. Assuming that Δ corresponds to a superconducting gap, the corresponding critical temperatures are $T_c=0.26$ K, 0.82 K, and 4.9 K for A , B and C peaks, respectively. We note that the C peak critical temperature is close to the T_c of superconducting Ta bulk. With a further increase of the magnetic field, the minimum of dV/dI at $I=0$ (zero bias conductance peak) increases and becomes a local maximum at zero bias at ~ 5.7 T. At even higher fields, only a weak peak at zero bias current remains, which resembles the dV/dI of bilayer itself.

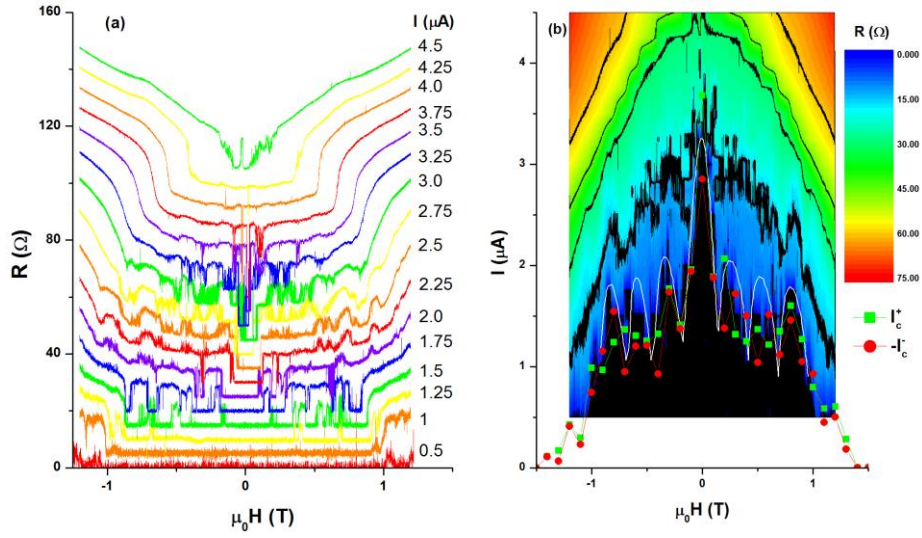


Figure 3-3: Magnetic field dependence of R at $T=30$ mK. (a) $R(H)$ traces at fixed dc I excitations. Curves are shifted vertically for clarity. (b) A contour plot of $R(H,I)$ based on data in (a). The lower central black colored area shows the supercurrent region. Critical current values ($I_c^\pm$) from dc I - V measurements at given H fields agree with the supercurrent region in the contour plot. I_c^+ (green symbols) and $-I_c^-$ (red symbols) are absolute values of the positive and negative critical currents, respectively. A hand-drawn white line outlines the lobes.

To further investigate the parameter space where supercurrent can exist, dc resistance (R) versus magnetic field traces, $R(H, T=30$ mK) at various DC bias currents (I) are shown in Fig. 3-3-3(a). For the lowest I , the superconducting region is surprisingly wide and spans $-1.1 < \mu_0 H(T) < 1.0$, *i.e.*, the critical field $\mu_0 H_c(T=30$ mK, $I=0.5$ μA) ≈ 1 T. This value is much larger than the critical field of Ta bulk ($\mu_0 H_c(T=0)=0.082$ T, Ref. [20]), but consistent with the field where B and B' peaks vanish (Fig. 3-3-2(a)). Therefore, we attribute B and B' peaks to the induced superconductivity through bulk transport in the bilayer. As the excitation I increases, the critical field $H_c(I)$ decreases as expected. However, some $R > 0$ (*i.e.*, non-superconducting) regions show

up inside the superconducting regime (Fig. 3-3-3(a)). This interlace of superconducting and non-superconducting regions indicates a Fraunhofer pattern as normally seen in conventional Josephson junctions [21]. Fig. 3-3-3(b) displays the same set of data in Fig. 3-3-3(a) as a contour plot. The black region in the lower central part outlines the superconducting region, which shows a Fraunhofer-like pattern with a central lobe and six side lobes (three on each side). Critical current values (I_c^+ and $-I_c^-$, green and red symbols in the plot, respectively) at fixed H field from another set of dc I - V measurements agree with the contour plot. Unlike the standard Fraunhofer pattern, where high order side lobes exist (though their height decays quickly), all higher order (>3) side lobes simply vanish in this sample. Moreover, assuming the S-N-S junction area of this sample is about $4 \mu\text{m}^2$ (using the area where two electrodes are the closest to each other), $\mu_0 H = 1$ T field corresponds to about $2000 \Phi_0$ in this junction, or approximately $300 \Phi_0$ per lobe, where $\Phi_0 = h/2e$ is the flux quantum. This number is much larger than that of a typical Fraunhofer pattern, which is 1 per lobe for topological trivial superconductivity or 2 per lobe for topological non-trivial superconductivity. It is also interesting to point it out that the zero field resistance value becomes a local maximum for $I > 4.4 \mu\text{A} > I_c \sim 3.5 \mu\text{A}$, which is probably due to a zero field transition to the normal state of the junction.

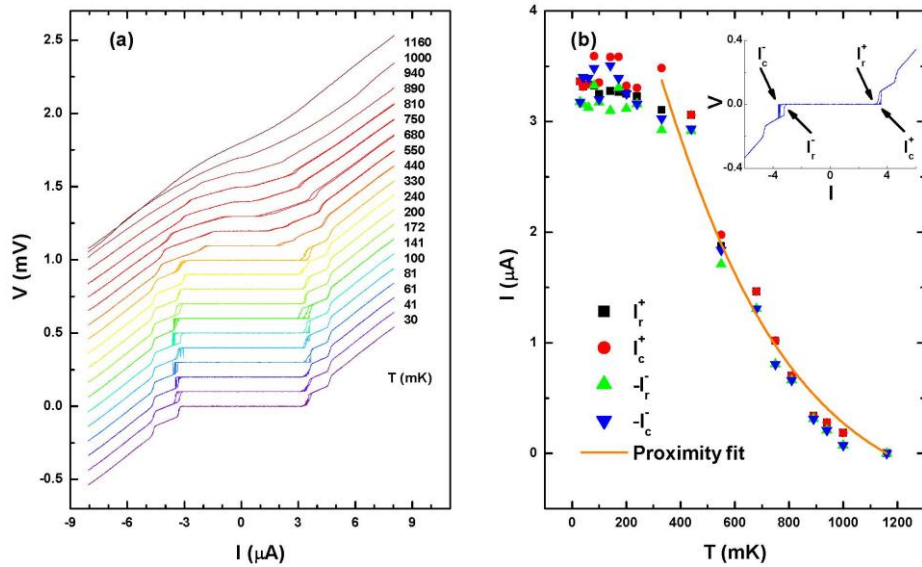


Figure 3-4: Temperature dependence of I - V in zero field. (a) Each I - V trace at a given temperature includes both up and down current scans. Curves are shifted vertically for clarity. (b) Inset: I - V trace at 141 mK is shown as an example to demonstrate the definition of $I_c^\pm$ and $I_r^\pm$, which are positive or negative critical current and retrapping current, respectively. Main plot: Temperature dependence of $I_c^\pm$ and $I_r^\pm$. Solid line shows a fit based on proximity effect for high temperature data ($T \gtrsim 400$ mK). The fitting equation is $I_c \propto \left(\frac{\Delta_N(T)}{\cosh[L/2\xi_N(T)]} \right)^2 \frac{1}{\xi_N(T)}$, which gives $T_c = 1.16$ K and $\xi_N(T_c) \approx 497$ nm.

The temperature dependence of I - V in zero magnetic field is shown in Fig. 3-4(a). For each temperature, a dc current is scanned in both increasing and decreasing directions to cover whole supercurrent region. The superconducting region shrinks as temperature increases and completely vanishes at $T \sim 1.16$ K, which we take as the T_c of the induced superconductivity in this junction. Hysteresis loops exist in some traces near the critical current I_c . One can trace the temperature dependence of the critical current I_c and the retrapping current I_r (outer and inner boundaries of the hysteresis loop, respectively) as shown in Fig. 3-3-4(b). In most traces, I_c and I_r are roughly the same, or the hysteresis loop is very small or unnoticeable. In addition, both I_c and I_r have a weak temperature dependence at $T < 400$ mK, then a quick decay at higher temperatures. Data at $T > 400$ mK can be fitted by the proximity-effect theory [22] as the solid line in the plot. Based on this theory, $I_c \propto \left(\frac{\Delta_N(T)}{\cosh[L/2\xi_N(T)]} \right)^2 \frac{1}{\xi_N(T)}$, where $\Delta_N(T)$ is the induced superconducting gap in the bilayer and $\xi_N(T)$ is the coherence length of the bilayer. The expression of $\xi_N(T)$ is known in the two limiting cases classified by the ratio of the mean free path in bilayer, l_N , and the superconducting coherence length in superconductor Ta, ξ_S . In the “clean limit”, *i.e.*, $\xi_S \ll l_N$, $\xi_N(T) = \hbar v_N / 2\pi k_B T$. In the “dirty limit”, *i.e.*, $\xi_S \gg l_N$, $\xi_N(T) = \sqrt{\hbar v_N l_N / 6\pi k_B T}$. v_N is the Fermi velocity in the bilayer, and k_B is the Boltzmann constant. Measurements in a reference sample (see Methods) show $l_N = 822$ nm in the bilayer at $T = 0.3$ K. Given $\xi_S = 78$ nm in Ta bulk [20], our junction is in the clean limit. The fit in Fig. 3-3-4(b) shows two independent fitting parameters $T_c = 1.16$ K and $\xi_N(T_c) \approx 497$ nm, which agrees well with the value of $\xi_N(T) = 480$ nm obtained by directly plugging $T = T_c = 1.16$ K into the clean limit expression.

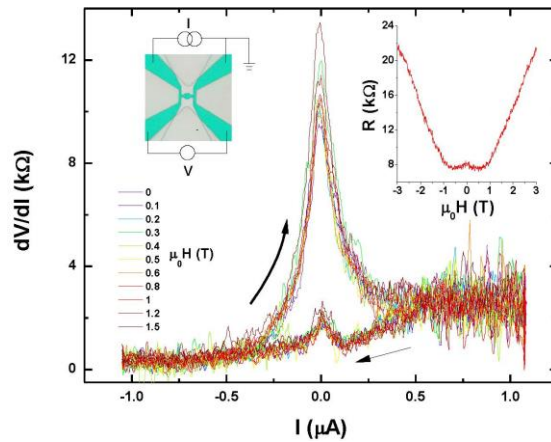


Figure 3-5: $dV/dI(I)$ of the InAs/GaSb bilayer through a Ta-electrodes-defined quantum point contact at $T = 30$ mK. Measurement configuration is shown in the left inset. In all magnetic fields, $dV/dI(I)$ shows hysteresis near zero I , when the dc bias I scan direction (arrows in main plot) changes. Furthermore, the traces show weak field dependence, except the larger peaks near dc $I = 0$. Right inset shows the field dependence of ac resistance R (or differential resistance at zero bias, $dV/dI|_{I=0}$) for the larger peak.

To complete our electronic transport measurements in our device, we show in Figs. 3-**Error!** **Reference source not found.** and 3-3-6 the differential resistance curves of the bilayer itself through a Ta-electrodes defined quantum point contact. At low temperatures, dV/dI shows hysteresis with changing of the dc excitation current directions. Interestingly, this hysteresis decreases as temperature increases and vanishes at about 400 mK, which is also the temperature where saturation of $I_c(T)$ vanishes (Fig. 3-3-4(b)). This coincidence could indicate a link between these two different observations.

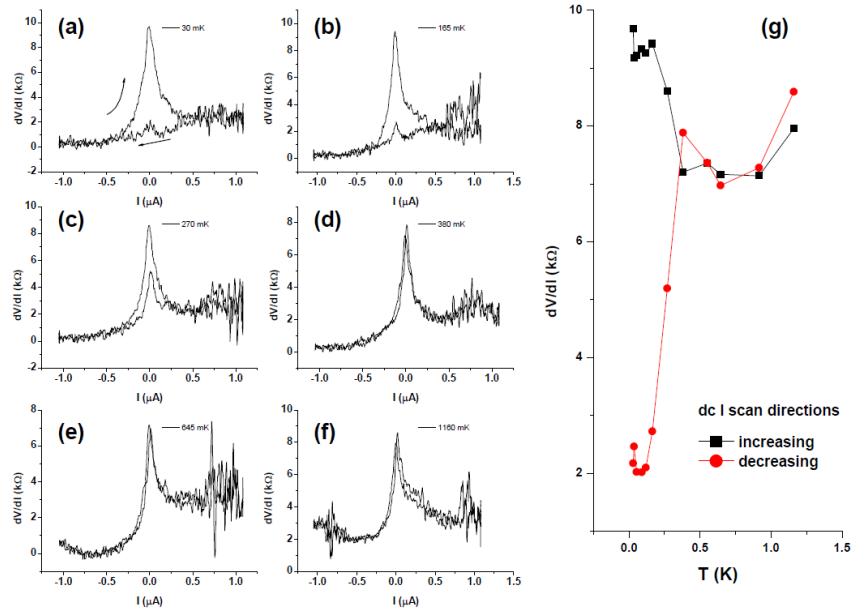


Figure 3-6: Temperature dependence of $dV/dI(I)$ of the bilayer through a Ta-electrodes defined quantum point contact in zero magnetic field. (a-f) At low temperatures, strong hysteresis exists near dc $I=0$. Arrows represent current scan directions. As T increases, hysteresis decreases and vanishes at $T \approx 400$ mK. The peaks values at $I=0$ are shown for different temperatures in (g).

Measurements in the junction show that the induced superconductivity may exist in both edge channels and the bulk. For edge mode superconductivity, the critical temperature and field are 0.23 K and 140 mT, respectively. The induced superconductivity in bilayer bulk has a $T_c = 1.16$ K, $\mu_0 H_c(T=30 \text{ mK}) \approx 1$ T and $I_c(T=30 \text{ mK}) = 3.5 \mu\text{A}$. Comparing to the superconductivity in bulk Ta, the induced superconductivity is very strong, despite the very large semiconductor region ($L \sim 2 \mu\text{m}$) in the junction. Since $L \gg \xi_S$, the Josephson current is expected to be exponentially weak, while it is not the case in this sample. This unusually large proximity effect has been reported in high transition temperature superconductors as the “giant proximity effect” [23]. To fully understand aforementioned results in this junction sample, a Hall bar sample with an electrostatic gate was fabricated from the same bilayer wafer as a reference sample. Quantum Hall measurements on this reference sample show that bilayer wafer sheet resistivity is 0.315 k Ω , the charge carrier density is $n = 1.8 \times 10^{11} \text{ cm}^{-2}$ and the mobility is

$\mu=1.17 \times 10^5 \text{ cm}^2/\text{Vs}$ at 0.3 K and zero gate voltage. Given the effective mass of InAs $m^*=0.023 m_e$ (m_e is the free electron mass), one can estimate the Fermi level in the bilayer specimen as $E_F=0.5 \text{ meV}$ or 5.6 K. As for the junction sample, its normal resistance $R_N \sim 60 \Omega \ll h/2e^2$, which means the bulk transport is the dominant factor in this critical QW width sample.

We propose the following possible origins for the greatly enhanced superconductivity induced inside the bilayer. First, we note that the semiconductor-superconductor coupling, or the transparency of the junction, can strongly affect the proximity induced pairing potential in the semiconductor (Δ_N) and $\Delta_N = \Delta_S \times \lambda/(\lambda+\Delta_S)$ [24]. Here, Δ_S is the pairing potential in Ta and λ represents the semiconductor-superconductor coupling. Given T_c s of the Ta electrodes and the induced superconductivity in the bilayer are 1.5 K and 1.16 K, respectively, the parameter λ can be determined from the aforementioned equation, and $\lambda=3.4 \Delta_S$. This means the junction is very transparent and it is in the strong tunneling region [24]. Therefore, a strong proximity effect is expected. Second, a strong spin-orbit (S-O) interaction can also enhance the T_c [24]. In this bilayer system, the S-O interaction is strong, $E_{SO}=0.38 \text{ eV}$ for InAs and 0.75 eV for GaSb [26], much larger than other energy scales, such as Δ_S , Zeeman energy, etc. Experimentally, the S-O enhanced superconductivity has been observed in many other systems, such as in Pb films [2]. In addition, the long mean free path inside the bilayer plays an important role. Due to the large separation of two superconducting electrodes, direct phase coherence of Cooper pairs from different electrodes is very unlikely. However, the bilayer with large μ , l_N , and ξ_N provides an ideal medium to enable the phase coherence between two Ta electrodes via the Andreev reflections at the S-N boundaries. Finally, according to the Kogan-Nakagawa mechanism [27], T_c could be greatly enhanced by magnetic field in clean samples with long mean free path. Indeed, a field induced increase of induced superconducting gap, or equivalently $\Delta_{B-B'}$, can be clearly observed in the small field region.

In summary, we have observed giant supercurrent states in a superconductor-InAs/GaSb bilayer-superconductor junction with critical QW width through transport measurements. The induced supercurrent states seem to exist both in the edge channels and the bulk of the bilayer. Moreover, the bulk supercurrent states are unexpectedly strong in the temperature-magnetic field parameter space, contrasting to the conventional expectation that only an exponentially weak supercurrent is expected in such a thick junction. New features, such as the concurrence of differential resistance peaks near the superconducting gap and the fluctuations, are interesting and may have important implications in the search for Majorana fermions in superconductor-InAs/GaSb bilayer-superconductor junction devices.

4. CONCLUSIONS

We discovered giant supercurrent states in a superconductor-InAs/GaSb bilayer-superconductor junction with critical QW width through transport measurements. The induced superconductivity seems to exist both in the edge channels and the bulk of the bilayer. Moreover, the bulk supercurrent states are unexpectedly strong in the temperature–magnetic field parameter space, contrasting to the conventional expectation that only an exponentially weak supercurrent is expected in such a thick junction. This robust proximity induced superconductivity provides an ideal platform for studying Majorana fermion physics. Also in this sample, new features, such as the concurrence of differential resistance peaks near the superconducting gap and the fluctuations, are interesting and expected to inspire further in-depth studies.

Moreover, we observed that the transport across the Ta-InAs/GaSb-Ta junction depends largely on the interfacial transparency, exhibiting distinct zero-bias behaviors. We have also achieved high quality MBE growth of InAs/GaSb bilayers. Our 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. conventional photolithography and wet chemical etching processes were utilized for device fabrication. 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. Superconducting Ta electrodes are directly sputtered on top of it to form a Ta-bilayer-Ta junction. The dc I-V of the sample was measured with dc voltage or current sources and digital multimeters in a two terminal configuration. For differential resistance measurements, a small ac current was summed with the dc current then feed to the junction, the ac voltage response of the sample was measured by the standard lock-in technique. All measurements were carried out in dilution refrigerators.

The new quantum matter studied in this LDRD project may be of interest to both DSA and EC PMU's in the areas of, for example, quantum information science and low error rate topological qubits. This research is also of interest to DATL and BMC research challenges. The research results in this project will have significant near-term impact on BES core program. They are synergistic with existing core program and provide interesting new science direction for quantum transport field in Solid state physics. Sandia's unique combination of capabilities and expertise has enabled these accomplishments.

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