Superconducting proximity effect in InAsSb surface quantum wells with in-situ Al contact

William Mayer¹, William F. Schiola¹, Joseph Yuan¹, Mehdi Hatefipour¹, Wendy L. Sarney², Stefan P. Svensson², Asher C. Leff², Tiago Campos³, Kaushini S. Wickramasinghe¹, Matthieu C. Dartailh¹, Igor Žutić³, and Javad Shabani⁴

¹Center for Quantum Phenomena, Department of Physics, New York University, NY 10003, USA
²US Army Combat Capabilities Command, Army Research Laboratory, Adelphi, MD 20783, USA and
³Department of Physics, University at Buffalo, State University of New York, Buffalo, New York 14260, USA

We demonstrate robust superconducting proximity effect in InAs₀.₅Sb₀.₅ quantum wells grown with epitaxial Al contact, which has important implications for mesoscopic and topological superconductivity. Unlike more commonly studied InAs and InSb semiconductors, bulk InAs₀.₅Sb₀.₅ supports stronger spin-orbit coupling (SOC) and large g-factor. However, these potentially desirable properties have not been previously measured in epitaxial heterostructures with superconductors, which could serve as a platform for fault-tolerant topological quantum computing. Through structural and transport characterization we observe high-quality interfaces and strong spin-orbit coupling. We fabricate Josephson junctions based on InAs₀.₅Sb₀.₅ quantum wells and observe strong proximity effect. These junctions exhibit product of normal resistance and critical current, \( I_R N = 270 \mu V \), and excess current, \( I_e R N = 200 \mu V \) at contact separations of 500 nm. Both of these quantities demonstrate a robust and long-range proximity effect with highly-transparent contacts.

A given material can be transformed through proximity effects whereby it acquires correlations from its neighbors, for example, becoming superconducting or magnetic. Such proximity effects not only complement the conventional methods of designing materials by doping or functionalization, but can also override their various limitations and enable novel states of matter [1]. A striking example of this approach is semiconductors with strong spin-orbit coupling (SOC) and large g-factor, in proximity to conventional superconductors. Such structures are predicted to support topological superconductivity with exotic quasi-particle excitations including Majorana bound states (MBS), which hold promise for fault-tolerant quantum computing [2–5]. Through braiding (exchange) of MBS it is possible to reveal their peculiar non-Abelian statistics and implement fault-tolerant quantum gates [6, 7].

Most efforts to realize MBS have been focused on one-dimensional (1D) systems [8–12], typically relying on proximitized InAs and InSb nanowires in applied magnetic field. However, their geometry has inherent difficulties to implement braiding and poses strong constraints on materials parameters to achieve topological superconductivity [13–15]. Instead, to overcome these limitations there is a growing interest in 2D platforms of proximitized semiconductors [11, 22], which would also support topological superconductivity. These advantages have recently been demonstrated in planar Josephson junctions [16, 23, 24] where the phase transition between trivial and topological superconductivity can be tuned using gate voltage and superconducting phase. This allows for more complicated networks that could support fusion, braiding, and large-scale Majorana manipulation.

To study proximity-induced superconductivity it is natural to consider a narrowband III-V semiconductor (Sm) with strong SOC and large g-factor in contact with a superconductor (S). It is well-known that Fermi level surface-pinning in In-based III-V semiconductors could allow for the fabrication of transparent S-Sm interfaces. Surprisingly, previous work has extensively studied InAs- and InSb-based junctions, but not InAs₀.₅Sb₀.₅, which can support even stronger SOC and large g-factor. Due to strong SOC, CuPt-ordered InAs₀.₅Sb₀.₅ was predicted to be a candidate for a novel type of a topological semimetal with inverted bands and triple degeneracy points in the bulk spectrum [25]. Here we report experimental demonstration of robust superconducting proximity effect in InAs₀.₅Sb₀.₅ samples. This is realized in a versatile 2D platform, based on the recent advances in epitaxial Al growth on InAs/InGaAs quantum wells (QWs) [26]. Our growth technique overcomes common difficulties encountered in novel S-Sm combinations, typically including distinct classes of materials with very different crystal structures, lattice constants, and melting points. Growth conditions must be carefully optimized and combined with the appropriate selection of metallic phases in order to suppress the strong tendency for island formation and film agglomeration during growth. Remarkably, using comprehensive materials characterization, we demonstrate that in our S-Sm systems we achieve the optimal outcome of a flat, abrupt, and impurity-free interface with high transparency. In contrast, it has proven difficult to show consistent high-quality S-Sm devices using in-situ ion milling of the native oxide [27].

The motivation to study InAs₀.₅Sb₀.₅ goes beyond...
proximity effects. In the past it was recognized as an important material for infrared applications \cite{28}, but there remains limited data available on quantum transport \cite{3}. More recently, the discovery of ultrafast lasers with spin-polarized carriers \cite{29} calls for semiconductors with very short spin-relaxation times which is also expected from InAs\_5Sb\_0.5 considering its strong SOC.

Our experiments on InAs\_5Sb\_0.5-based two-dimensional electron gas (2DEG) are complemented by numerical studies of its electronic structure, SOC and \textit{g}-factor. From the previous work, it is reported that InAs\_5Sb\_0.5 can exhibit significantly larger spin-splitting \cite{30}, compared to InAs or InSb in which transport properties have been extensively explored. The bulk \textit{g}-factor of InAs\_5Sb\_0.5 is expected to reach up to -120 and exhibit SOC almost an order of magnitude stronger than InAs \cite{30}. We find that the \textit{g}-factor is suppressed in narrow quantum wells, while the linear term in spin-orbit coupling decreases as quantum well width is increased.

We use standard 8-band $\vec{k} \cdot \vec{p}$ method \cite{31} to calculate the subband structure of the surface InAs\_5Sb\_0.5 QW. The quantum confinement along the growth direction was addressed by using the finite difference method \cite{32} with a discretization step of 0.5 nm which is sufficient to achieve convergence. For computational efficiency, we describe the metal-semiconductor interface as a hard-wall barrier acting as a confinement layer for the carriers. The material parameters were taken from Ref. \cite{33} while the bowing parameter for the InAs\_5Sb\_0.5 alloy was taken from Ref. \cite{34}.

Since the system has broken inversion symmetry, the energy dispersion, $\varepsilon_{\sigma}(k_z)$, is spin-split due to the Rashba SOC. In Figure 1, we show the computed Rashba SOC parameter, $\alpha$, for the first conduction subband, computed as the linear slope of energy difference $\Delta E = \varepsilon_{1,\sigma}(k_z) - \varepsilon_{1,\sigma'}(k_z)$, very close to the $\Gamma$-point \cite{35}. In order to understand the quantum confinement as well as the effect of the alloy composition, $x$, we consider three InAs\_1-xSbx layer sizes and vary the composition $x$ from pure InAs to pure InSb. The gap at the InAs\_1-xSbx/InAs\_0.37Al\_0.63Sb interface is a broken one, i.e., the valence band edge is higher in energy than the conduction band edge and by increasing InAs\_1-xSbx layer size the confined states energy cross each other. In this situation, no spin-splitting was computed since the conduction and valence subbands crossed. Furthermore, the trend that the smaller the InAs\_1-xSbx layer size, the larger the Rashba parameter is due to the fact that the electron has a higher probability to be found near the interfaces than in the middle of the layer. Indeed, as we reduce the InAs\_1-xSbx layer size the Rashba SOC parameter becomes larger. We found that the highest value is around $\alpha = 0.35$ eV/Å for the 10 nm InAs\_0.4Sb\_0.6 layer, $\alpha = 0.2$ eV/Å for the 20 nm InAs\_0.5Sb\_0.5 layer, and $\alpha = 0.12$ eV/Å for the 30 nm InAs\_0.6Sb\_0.4 layer.

The \textit{g}-factor was computed using second order L"{o}wdin partitioning \cite{36,37}. In the bulk limit it converges to the Roth formula for an effective \textit{g}-factor \cite{38},

$$
g^* = 2 \left(1 - \frac{m_e}{m^*} \frac{\Delta_{SS}}{3 E_g + 2 \Delta_{SS}} \right),
$$

where $\Delta_{SS}$ is the spin-orbit splitting of the valence bands, $E_g$ is the energy gap, while $m_e$ and $m^*$ are free electron mass and effective respectively. In Table \ref{tab:bulk_g}, we show the bulk \textit{g}-factor for the InAs\_0.37Al\_0.63Sb barrier, InAs, InSb and as well for three selected InAs\_1-xSbx compositions. As we increase the composition, $x$, the

\begin{table}[h]
\centering
\caption{Bulk \textit{g}-factor using Roth formula.}
\begin{tabular}{|c|c|}
\hline
Material & $g^*$ \\
\hline
In\_0.37Al\_0.63Sb & -4.65 \\
InAs & -14.61 \\
InAs\_0.6Sb\_0.4 & -70.86 \\
InAs\_0.5Sb\_0.5 & -99.08 \\
InAs\_0.4Sb\_0.6 & -116.82 \\
InSb & -49.23 \\
\hline
\end{tabular}
\label{tab:bulk_g}
\end{table}
band gap of the material decreases and since the main contribution to the \( g \)-factor comes from \( 1/E_g \) \cite{37}, we obtain the largest \( g \)-factor values for compositions varying from \( x = 0.4 \) to \( x = 0.6 \).

With quantum confinement, \( g \)-factor is typically lower than the corresponding bulk value. This trend can also be inferred from Eq. \( 1 \) since for a highly-confined system the effective band gap increases (as the energy difference from conduction to valence band also increases). We show calculated \( g \)-factor for a confined system, both along the growth direction, \( g_z \) in Figure 1, as well as for the perpendicular to the growth direction, \( g_{x,y} \) in Figure 1. Due to the quantum confinement and SOC, the \( g \)-factor is anisotropic, i.e., \( \Delta g = g_{x,y} - g_z \neq 0 \), \cite{39} with \( g_z \) being larger in magnitude than \( g_{x,y} \). Moreover, following the trends of Roth formula in Eq. \( 1 \), as we increase the InAs\(_{1-x}\)Sb\(_x\) layer size the \( g \)-factor also increases. We found that the largest \( g \)-factor is for a 30 nm InAs\(_{0.5}\)Sb\(_{0.5}\) QW. Above calculations show that there is a sweet spot in terms of QW width where \( g \)-factor and SOC are both strong. Motivated by this fact we focus the rest of our studies on 20 nm QWs.

Molecular beam epitaxy (MBE) growth of large-area InAs\(_{0.5}\)Sb\(_{0.5}\) surface QWs in epitaxial contact to Al-InAs films can form the basis for combining proximity effects with high \( g \)-factor, strong SOC systems. Growth of semiconductor InAs\(_{0.5}\)Sb\(_{0.5}\) is rather difficult since there is no insulating lattice-matched substrate immediately available. In this work, we pursue the process of compositional grading which allows growth of bulk unstrained, relaxed InAs\(_{0.5}\)Sb\(_{0.5}\) of any composition onto GaSb, as previously reported \cite{39, 40, 41}. Following earlier work, our samples have a 2.6 µm GaInSb compositional grade followed by a 0.25 µm In\(_{0.37}\)Al\(_{0.63}\)Sb virtual substrate (VS) and a 200 Å InAs\(_{0.5}\)Sb\(_{0.5}\) layer.

Figure 2: (a) Unstrained Al on InAs\(_{0.5}\)Sb\(_{0.5}\) with respective lattice constants 4.05 Å and 6.27 Å, projected onto the plane of growth. (b) Three-dimensional rendering of the Al-InAs\(_{0.5}\)Sb\(_{0.5}\) interface from the perspective of the transmission electron microscope image below. (c) Layer diagram of the InAs\(_{0.5}\)Sb\(_{0.5}\) surface quantum well with Al contact. (d) Cross-sectional transmission electron microscope image of the Al-InAs\(_{0.5}\)Sb\(_{0.5}\) interface along the \( \langle 110 \rangle \) zone axis with unstrained Al and InAs\(_{0.5}\)Sb\(_{0.5}\) lattices overlaid.

For the Al layer deposition, the substrate temperature was measured with a K-space BandiT system operating in pyrometry mode. Measurements of (004) triple-axis x-ray diffraction allowed us to verify the composition of the VS. We cannot examine the InAs\(_{0.5}\)Sb\(_{0.5}\) layer, since it is too thin relative to the VS and the compositional grade, but test structures with thicker InAs\(_{0.5}\)Sb\(_{0.5}\) layers were grown with this recipe and their composition was verified by X-ray crystallography.

For samples with Al, after the top InAs\(_{0.5}\)Sb\(_{0.5}\) layer was grown, all shutters were closed and the sources were cooled to idling temperatures. The residual gases were pumped overnight, allowing the background pressure in the chamber to reach the 10\(^{-11}\) Torr range. The next day, the sample was pointed towards the cryo-shroud for two hours and 40 minutes, allowing it to fall below 0°C. We deposited a 200 Å layer of Al onto the InAs\(_{0.5}\)Sb\(_{0.5}\) surface at a growth rate of 0.09 Å/s. In this work, we present data from nominally identical structures, one with and one without an in-situ Al layer. Figure 2 shows a cross sectional transmission electron microscope image of the interface between the InAs\(_{0.5}\)Sb\(_{0.5}\) and Al layers along the \( \langle 110 \rangle \) zone axis, while Figure 2b shows a 3D rendering of the interface from the same perspective. The substrate and InAs\(_{0.5}\)Sb\(_{0.5}\) are oriented along a \( \langle 001 \rangle \) growth direction. The Al film consists of large domains predominantly aligned along \( (110) \), tilted ~4 degrees from the interfacial plane. The high resolution images of this region and numerous others show that the d-spacing of the growth direction planes is 2.9 Å, corresponding to that for Al along \( (110) \). The orientation relationships of the crystal planes and the FFT pattern corresponds to Al examined at a zone axis with a \( (110) \) growth direction.

We studied the magnetoresistance of the InAs\(_{0.5}\)Sb\(_{0.5}\) surface 2DEG without Al in van der Paw geometry. Magnetotransport measurements were performed at \( T = 1.5 \) K using standard lock-in techniques using ac excitations \( I_{ac} = 50 \) nA–1 µA at low frequencies. We find mobilities of \( \mu = 25,000 \) cm\(^2\)/Vs at a carrier density \( n = 8 \times 10^{11} \) cm\(^{-2}\).

In the presence of strong SOC the Shubnikov-de Haas oscillations show two frequencies, signaling two Fermi surfaces, as can be seen in Figure 3a, which suggests...
occupation of two spin-subbands. Figure 3(b) shows the result of the Fourier transform in the range of 1 T to 5 T. There are three clear peaks, which indicate spin-split subbands with frequencies \( f_+ = 17.2 \) T, \( f_- = 14.2 \) T and a peak for the total frequency at \( f_{tot} = 33 \) T. The densities can be directly calculated from \( n_\pm = qf_\pm/\hbar \) where \( q \) is electron charge and \( \hbar \) is Planck's constant. We obtain \( n_+ = 4.2 \times 10^{11} \) cm\(^{-2} \), \( n_- = 3.4 \times 10^{11} \) cm\(^{-2} \) with \( n_{tot} = 7.6 \times 10^{11} \) cm\(^{-2} \) which agrees with the Hall data shown in Figure 3(c). This suggests spin-split subband separation is very large as expected for InAs\(_{0.5}\)Sb\(_{0.5}\). If this splitting was all due to the linear Rashba SOC term, we obtain its parameter \( \alpha = (\Delta n \hbar^2/m^*)/\sqrt{\pi/[2(n_{tot} - \Delta n)]} = 0.8 \) eV/Å, where \( \Delta n = n_+ - n_- \), assuming a band mass of \( m^* = 0.011 m_e \) at 50% composition. Our \( \vec{k} \cdot \vec{p} \) calculation for this QW width predicts \( \alpha = 0.2 \) eV/Å which is lower than the estimated \( \alpha = 0.8 \) eV/Å from extracted parameters suggesting there are contributions from Dresselhaus SOC terms in Sb compounds. We also like to note that Schrodinger Poisson calculation for our 20 nm QW show one electronic subband is occupied. We further characterize the superconducting proximity effect in a Josephson junction (JJ) on an InAs\(_{0.5}\)Sb\(_{0.5}\) 2DEG with epitaxial Al contacts, as depicted schematically in Figure 4(a). Josephson junctions are fabricated with electron beam lithography followed by selective etching to remove a thin strip of Al. The junction is 4 μm wide and has a 500 nm length separation between the superconducting electrodes. Measurements are performed in a dilution fridge with mixing chamber temperature of 7 mK and an estimated electron temperature of 20 mK. We consider 4-point geometry using standard dc current bias techniques. The I-V characteristics of the junction are shown in Figure 4(b). The voltage drop across the junction is zero (the supercurrent) up to a critical value of driving current denoted the critical current, \( I_c \sim 1.16 \) μA. The quality of the device can be characterized by a study of the \( I_c R_N \) and \( I_{ex} R_N \) products, where \( R_N \) is the normal resistance of the JJ. The excess current \( I_{ex} \) is the difference between the measured current through the junction and the expected current based on the junction’s \( R_N \). This occurs due to Andreev reflections and depends primarily on interface transparency. The critical current \( I_c \) is the amount of current that can be carried by Andreev bound states through the junction with zero resistance. \( I_c \) requires coherent charge transport across the semiconductor region and is therefore a measure of both interface transparency and 2DEG mobility. Using the BCS relation \( \Delta_M = 1.75k_BT_c \), we find that \( \Delta_M = 210 \) μV (see Supporting Information). From \( \Delta_M \) we can estimate the superconducting coherence length in our samples given by \( \xi_0 = \hbar v_F/(\pi \Delta_M) \), where \( v_F \) is the Fermi velocity, which yields \( \xi_0 = 800 \) nm for our sample. The mean free path \( l_c \sim 550 \) nm is obtained from transport measurements in a van der Pauw geometry. From these parameters we expect the device to approach the
dirty limit \( (\xi_0 \gg \ell_c) \). This implies we should also consider the dirty coherence length \( \xi_{0,d} = \sqrt{\frac{\mu_c}{\pi e^2}} \) which yields \( \xi_{0,d} \approx 660 \) nm.

The junction is neither clearly ballistic \( (\ell_c \gg L) \) nor diffusive \( (L \gg \ell_c) \). The Andreev process that carries the supercurrent across the Sm region is characterized by the induced gap \( \Delta_{\text{ind}} \) in the Sm below the S, rather than the bulk Al gap, \( \Delta_{\text{Al}} \). To characterize an S-Sm-S junction in the short limit, the product of the critical current and the normal state resistance, which is related to the gap via \( I_cR_N = \varphi \Delta_{\text{Al}}/e \), is often used, where \( \varphi \) is a constant of order unity. Experimentally, we find \( I_cR_N = 270 \) µV where \( I_c = 1.16 \) µA, \( R_N = 230 \) Ω, in the junction with \( d = 500 \) nm contact separation at \( T = 20 \) mK. The supercurrent continues to persist to longer separations due to the high mobility of the InAs\(_{0.5}\)Sb\(_{0.5}\) channel. At \( d = 1 \) µm separation we still observe a substantial supercurrent \( I_c = 570 \) nA with product of \( I_cR_N = 280 \) µV, raw data is presented in supplementary information. The product of \( I_cR_N \) can be compared to theoretical values for fully transparent junctions in the short ballistic and short diffusive limits, for which \( \varphi = \pi \) and 1.32(\( \pi/2 \)), respectively [45, 46]. For our sample, we find \( I_cR_N \) is 37% of the ballistic limit and 57% of the diffusive limit.

High interface transparency corresponds to a high probability of Andreev reflection at the interface. Since the Sm extends under the S regions, the interface between Sm and S should be highly transparent due to the large area of contact and in-situ epitaxial Al growth [47]. The Andreev process that carries supercurrent across the Sm region is characterized by the excess current \( (I_{ex}) \) through the junction \( I_{ex} = I - V/R_N \) [48]. Excess current does not require coherent charge transport across the junction as it follows simply from charge conservation at the S-Sm interfaces. \( I_{ex} \) can be calculated by extrapolating from the high current normal regime to zero voltage as shown in Figure 4b with a dotted line. The excess current in our sample is found to be \( I_{ex} = 1 \) µA.

When considering interface quality the more relevant quantity is the product \( I_{ex}R_N \). The product \( I_{ex}R_N \) can be compared to the superconducting gap with the relation \( I_{ex}R_N = \varphi' \Delta_{\text{Al}}/e \). In the case of a fully transparent S-Sm interface \( \varphi' = 1.467 \) for a diffusive junction [49] and \( \varphi' = 8/3 \) for a ballistic junction [48]. For our sample, \( I_{ex}R_N = 200 \) µV, which is 35% of ballistic limit and 65% of diffusive value for our 500 nm JJ. Such a large \( I_{ex}R_N \) product demonstrates the high interface transparency that can be achieved with epitaxial Al growth on InAs\(_{0.5}\)Sb\(_{0.5}\).

In conclusion, we have demonstrated robust superconducting proximity effect in two-dimensional epitaxial Al-InAs\(_{0.5}\)Sb\(_{0.5}\) systems. Using an optimized MBE growth we have achieved both high-electron mobilities in InAs\(_{0.5}\)Sb\(_{0.5}\) and successful growth of thin film Al. Outstanding transport properties were confirmed in the normal and superconducting state by Shubnikov-de Haas oscillations and current-voltage measurements, which establish strong spin-orbit coupling and large values of critical current in Josephson junctions. Remarkably, the latter property, made possible by high interface transparency, is consistent with a large proximity-induced superconducting gap in InAs\(_{0.5}\)Sb\(_{0.5}\) of \( \sim 270 \) µeV. The supercurrent between two Al contacts can be sustained in InAs\(_{0.5}\)Sb\(_{0.5}\) across at least 1000 nm.

While these results clearly indicate that InAs\(_{0.5}\)Sb\(_{0.5}\)-based junction provide a suitable platform to explore topological superconductivity, they also have broader implications. We expect that spin-orbit coupling in InAs\(_{0.5}\)Sb\(_{0.5}\) could be further controlled through electrostatic gating or magnetic structures [19, 50, 51] to modify quantum transport both in the normal and superconducting state. Moreover, having established high-quality metal/InAs\(_{0.5}\)Sb\(_{0.5}\) junctions, it is possible to explore applications based on geometrical effects, and the extraordinary room-temperature magnetoresistance which can exceed 1,000,000 in InSb [52].

Acknowledgement This work was partially supported by NSF DMR 1836687, the US Army research office, US ONR N000141712793, NSF ECCS-1810266, and the University at Buffalo Center for Computational Research.

Supplementary information

A. Temperature dependence of supercurrent

The product \( I_cR_N \) can be directly varied by changing the Al superconducting gap by increasing temperature. Figure 5 shows the temperature dependence of \( I_cR_N \) for our 500 nm sample. The critical temperature of in-situ Al thin films is slightly enhanced over the bulk value of 1.2 K to near 1.4 K [20, 53]. As lowest temperatures, we observe hysteretic behavior indicated by the two critical currents—labeled \( I_{c+} \) and \( I_{c-} \) in upper panel of Figure 5 and corresponding to the junction going from the superconducting to resistive state. This hysteresis disappears at higher temperatures. This is understood as electron heating of the junction in the resistive state suppressing \( I_{c-} \) for lower temperatures [54]. At higher temperature, in our case 600 mK, both sides decay identically. This behavior has been previously observed in InAs structures [54, 55].

B. Measurement of 1µm Josephson junction

We have also fabricated JJs with separation of Al electrode of 1µm with width of 4µm. The width is similar to the 500 nm JJ reported in the main manuscript. Figure 6 shows the small signal lock-in measurement of the JJ as a function of current bias. The DC bias current was varied from \(-3 \) mA to \( 3 \) mA (black) and from \( 3 \) mA to \(-3 \) mA (red), exhibiting hysteretic behavior at \( T = 20 \) mK. The critical current of 570 nA with normal resistance of 500 Ω is observed.
FIG. 5: (Color online) (a) I-V curves of a Josephson junction on InAs$_{0.5}$Sb$_{0.5}$ at various temperatures. (b) Temperature dependence of the $I_cR_N$ products.

FIG. 6: Characterization of the supercurrent of a Josephson junction with 1 µm contact separation.

[1] I. Žutić, A. Matos-Abiague, B. Scharf, H. Dery, and K. Belashchenko, Materials Today 22, 85 (2019), URL http://www.sciencedirect.com/science/article/pii/S1369702118301111
[2] R. M. Lutchyn, J. D. Sau, and S. Das Sarma, Phys. Rev. Lett. 105, 077001 (2010), URL https://link.aps.org/doi/10.1103/PhysRevLett.105.077001
[3] Y. Oreg, G. Refael, and F. von Oppen, Phys. Rev. Lett. 105, 177002 (2010), URL https://link.aps.org/doi/10.1103/PhysRevLett.105.177002
[4] J. Alicea, Reports on Progress in Physics 75, 076501 (2012), URL https://doi.org/10.1088%2F0034-4885%2F75%2F7%2F076501
[5] J. E. Sestoft, T. Kanne, A. N. Gejl, M. von Soosten, J. S. Yodh, D. Sherman, B. Tarasinski, M. Wimmer, E. Johnson, M. Deng, et al., Phys. Rev. Materials 2, 044202 (2018), URL https://link.aps.org/doi/10.1103/PhysRevMaterials.2.044202
[6] C. Nayak, S. H. Simon, A. Stern, M. Freedman, and S. Das Sarma, Rev. Mod. Phys. 80, 1083 (2008).
[7] D. Aasen, M. Hell, R. V. Mishmash, A. Higginbotham, J. Danon, M. Leijnse, T. S. Jespersen, J. A. Folk, C. M. Marcus, K. Flensberg, et al., Phys. Rev. X 6, 031016 (2016), URL https://link.aps.org/doi/10.1103/PhysRevX.6.031016
[8] V. Mourik, K. Zuo, S. M. Frolov, S. R. Plissard, E. P. A. M. Bakkers, and L. P. Kouwenhoven, Science 336, 1003 (2012).
[9] Ö. Gıl, H. Zhang, F. K. de Vries, J. van Veen, K. Zuo, V. Mourik, S. Conesa-Boj, M. Nowak, D. J. van Weerom, M. Quintero-Pérez, et al., Nano Letters 17, 2690 (2017), URL https://doi.org/10.1021/acs.nanolett.7b00540
[10] M. T. Deng, S. Vaitiekenas, E. B. Hansen, J. Danon, M. Leijnse, K. Flensberg, J. Nygård, P. Krosgstrup, and C. M. Marcus, Science 354, 1557 (2016), ISSN 0036-8075.
[11] H. J. Suominen, M. Kjaergaard, A. R. Hamilton, J. Shabani, C. J. Palmstrøm, C. M. Marcus, and F. Nichele, Phys. Rev. Lett. 119, 176805 (2017), URL https://link.aps.org/doi/10.1103/PhysRevLett.119.176805
[12] H. Zhang, C.-X. Liu, S. Gazibegovic, D. Xu, J. A. Logan, G. Wang, N. van Loo, J. D. S. Bommer, M. W. A. de Moor, D. Car, et al., Nature 556, 74 (2018), URL https://doi.org/10.1038/nature26142
[13] K. Sengupta, I. Žutić, H.-J. Kwon, V. M. Yakovenko, and S. Das Sarma, Phys. Rev. B 63, 144531 (2001), URL https://link.aps.org/doi/10.1103/PhysRevB.63.144531
(1982).

[54] H. Courtois, M. Meschke, J. T. Peltonen, and J. P. Pekola, Phys. Rev. Lett. 101, 067002 (2008).

[55] W. Mayer, J. Yuan, K. S. Wickramasinghe, T. Nguyen, M. C. Dartialh, and J. Shabani, Applied Physics Letters 114, 103104 (2019), https://doi.org/10.1063/1.5067363, URL https://doi.org/10.1063/1.5067363.