



This is the accepted manuscript made available via CHORUS. The article has been published as:

Supercurrent through a single transverse mode in nanowire Josephson junctions

B. Zhang, Z. Li, H. Wu, M. Pendharkar, C. Dempsey, J. S. Lee, S. D. Harrington, C. J. Palmstrøm, and S. M. Frolov

Phys. Rev. B **111**, L161401 — Published 1 April 2025

DOI: [10.1103/PhysRevB.111.L161401](https://doi.org/10.1103/PhysRevB.111.L161401)

Supercurrent through a single transverse mode in nanowire Josephson junctions

B. Zhang,^{1,2,*} Z. Li,^{1,*} H. Wu,¹ M. Pendharkar,^{3,†} C. Dempsey,³
J.S. Lee,^{4,‡} S.D. Harrington,⁵ C.J. Palmström,^{3,4,5} and S.M. Frolov^{1,§}

¹*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, 15260, USA*

²*Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA*

³*Electrical and Computer Engineering, University of California, Santa Barbara, CA, 93106, USA*

⁴*California NanoSystems Institute, University of California Santa Barbara, Santa Barbara, CA, 93106, USA*

⁵*Materials Department, University of California Santa Barbara, Santa Barbara, CA, 93106, USA*

Hybrid superconductor-semiconductor materials are fueling research in mesoscopic physics and quantum technology. Recently demonstrated smooth β -Sn superconductor shells, due to the increased induced gap, are expanding the available parameter space to new regimes. Fabricated on quasiballistic InSb nanowires, with careful control over the hybrid interface, Sn shells yield measurable switching currents even when nanowire resistance is of order $10k\Omega$. In this regime Cooper pairs travel through a purely 1D quantum wire for at least part of their trajectory. Here, we focus on the evolution of proximity-induced supercurrent in magnetic field parallel to the nanowire. Long decay up to fields of 1T is observed. At the same time, the decay for higher occupied subbands is notably faster in some devices but not in others. We analyze this using a tight-binding numerical model that includes the Zeeman, orbital and spin-orbit effects. When the first subband is spin polarized, we observe a dramatic suppression of supercurrent, which is also confirmed by the model and suggests an absence of significant triplet supercurrent generation.

Semiconductor nanowire-based Josephson junctions have been explored as elements for superconducting transmon qubits [1, 2] and Andreev qubits [3]. The same one-dimensional (1D) super-semi hybrid system also fulfills basic requirements for emerging topological superconductivity and Majorana bound states (MBS) at nanowire ends [4–6]. Attempts at exploring MBS in nanowire Josephson junctions were through the search for fractional a.c Josephson effect [7–9]. Topological qubits based on nanowire Josephson junctions containing MBS have been proposed theoretically [10, 11]. Subbands are created by quantum confinement of nanowires geometry, with the momentum components perpendicular to the nanowire axis as discrete and quantized values [12]. In the simplest and purest form, Majorana modes are envisioned in a single-subband nanowire.

Mesoscopic electrical transport properties of supercurrents through quantum point contacts (QPC) [13] were studied using atomic break junctions [14, 15], and in two-dimensional electron gases [16–18]. InAs nanowires with transparent superconductor leads also feature few-subband transport [19–23].

While studies of supercurrents in nanowires or point contacts have led to an array of interesting discoveries so far [7, 20, 21, 24–30], one outstanding challenge remaining is that supercurrent in the last occupied transverse mode (single subband) is strongly suppressed. It is either not observed or too weak to enable detailed studies

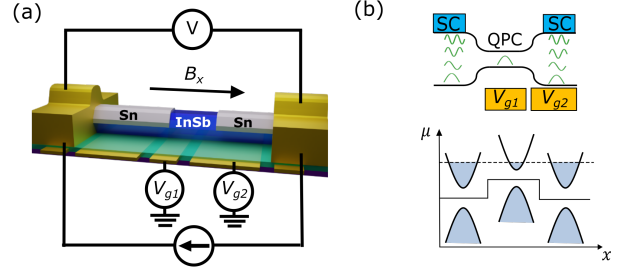


FIG. 1. (a) Schematic of a shadow nanowire Josephson Junction device. The wire is along $\hat{x}$ which is also the direction of external magnetic field B_x . (b) Cartoon of a single-mode junction controlled by electrostatic gates V_{g1} and V_{g2} . The leads are shown with higher subbands occupied. The lower panel corresponds to a chemical potential profile $\mu(x)$ used in tight-binding simulations.

[18, 19, 21, 23]. The reasons for this are not fully understood, however they are likely related to either finite interface transparency such as in devices involve ex-situ shell deposition, smaller induced gap such as in Al-InAs structures, residual scattering or other effects.

Our approach is to combine InSb nanowires with Sn shells and study proximity-induced supercurrent in the nanowires. Through advances in vapor-liquid-solid growth quasi-ballistic InSb nanowires were achieved [31, 32]. Quantized non-superconducting conductance has been established in InSb nanowires with normal metal electrodes [33, 34]. The recently introduced superconducting Sn shells facilitate transparent contacts, and critical current-normal state resistance products exceeding temperature and those previously available in Al-based nanowire junctions [35]. Junctions in the Sn shell are defined on InSb nanowires by nanowire shadowing, which reduces processing and increases the likelihood of ballistic

* These two authors contributed equally

† Current address: Department of Materials Science and Engineering, Stanford University, Stanford, CA, USA, 94305

‡ Current address: Department of Physics and Astronomy, University of Tennessee, Knoxville, TN, 37996, USA

§ frolovsm@pitt.edu

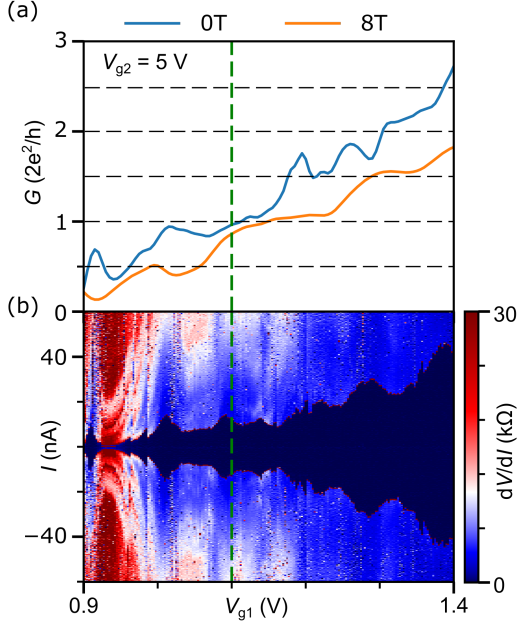


FIG. 2. (a) Differential conductance $G(dI/dV)$ taken at finite bias $V_{bias}=2$ mV at $B=0$ T and at zero bias for $B=8$ T. (b) Current bias measurement of differential resistance $R(dV/dI)$ showing the evolution of supercurrent at $B=0$ T. In this figure $V_{g2} = 5$ V. Green dashed line is used to indicate the approximate boundary between the first mode and higher modes based on conductance. Panels (a) and (b) are from separate measurements on Device A.

devices. Junction made with InSb nanowires and NbTiN leads are studied with same method, and the measurement results are compared with that in Sn-InSb devices as additional supplementary materials.

Subband-resolved transport is verified through the measurements of conductance at finite bias, and the evolution of it with gate voltage, source drain bias voltage and magnetic field. In the gate voltage and conductance range that corresponds to the first occupied transverse mode, we observe supercurrents as high as 20 nA. We investigate the gate voltage and magnetic field evolution of supercurrents in several nanowire devices both in the single-mode and in the multi-mode regimes. The mechanisms of decay of supercurrent with magnetic field are studied including the relative contributions of orbital interference phenomena, residual disorder, spin-orbit and Zeeman effects by comparing the data to a tight-binding model. The spin-polarization of the first subband at finite field suppressed supercurrent dramatically, leading us to conclude that no triplet supercurrent was generated.

Fig. 1(a) presents a schematic diagram of the nanowire Josephson junction device. An InSb nanowire (blue) is half-covered by a Sn shell (silver) and positioned above local gate electrodes (gold), with Ti/Au contacts (gold). In order to prepare the junction itself, standing InSb nanowires approximately 100 nm in diameter are coated

with a 15 nm layer of Sn [35]. In front of the nanowire, another nanowire shadows the flux of Sn to create two disconnected Sn segments. Nanowires with such shadow-defined junctions are transferred onto chips patterned with local electrostatic gate electrodes covered by HfOx dielectric. Contacts to wires are made using standard electron beam lithography and thin film deposition of Ti/Au layers.

The supercurrent flows along the $\hat{x}$ direction, and an external magnetic field, B_x , is applied parallel to the wire. A current bias, I_{bias} , is applied across the device (illustrated by a black arrow), and the voltage across the device is measured using DC and AC multimeters in a two-point measurement setup. Two local bottom gates, V_{g1} and V_{g2} , are located beneath the junction region. Measurements are performed in a dilution refrigerator with a base temperature of ~ 50 mK equipped with a three-dimensional vector magnet.

Figure 1(b) uses cartoons to demonstrate the control of transverse mode numbers in the nanowire by local bottom gates during experiments, as well as the definition of local chemical potential in simulations. In the illustration, gate voltage V_{g1} precisely adjusts the number of conduction channels, resulting in a single occupied transverse mode in the region labeled QPC (quantum point contact). Meanwhile, gate voltage V_{g2} tunes one of the adjacent region which can have a higher subband occupancy. To emulate the realistic conditions in numerical simulations, we use two chemical potential μ settings, one for leads and one for the QPC.

In Fig. 2(a) we plot two gate traces of conductance, one at zero magnetic field and one at large magnetic field ($B=8$ T). The zero-field trace contains non-monotonic resonances due to quantum interference caused by backscattering, as well as charge jumps. This is in line with previous reports of quantum point contact behavior in nanowires [33, 34]. Backscattering can be suppressed by large magnetic field, therefore the high magnetic field trace demonstrates a sequence of spin-resolved plateaus at $G_0/2 = 1 \times e^2/h$ values. Using the high magnetic field trace as reference, we approximately identify the gate voltage interval that corresponds to the single occupied mode at $B=0$ ($V_{g1} < 1.1$ V, green dashed line), around conductance value of $G_0 = 2e^2/h$. For the data shown, we estimate the highest conductance to be $6G_0$, corresponding to a maximum of 6 transverse modes. Comprehensive evidence of QPC behavior in device A is obtained from the magnetic field evolution of finite-voltage bias conductance maps for various gate voltage settings, which demonstrate diamond-shaped regions of relatively flat conductance in bias-gate space, and Zeeman splitting of these plateaus (see Supplementary Material at [36] and Fig.3).

In Fig. 2(b) we plot the current bias data that closely corresponds to the conductance traces from panel (a). The supercurrent appears as dark-blue regions around zero bias. On the left side of the green line, for more negative gate voltages, supercurrent is carried by the

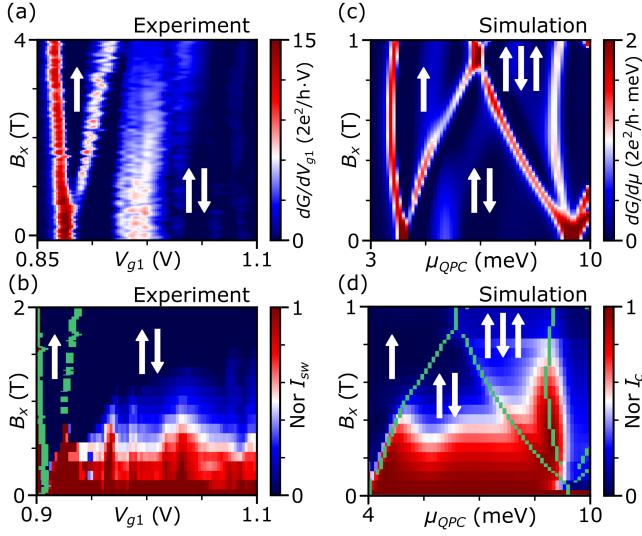


FIG. 3. Comparison between experiment (a, b) and simulation (c, d): (a, c) Transconductance dG/dV_{g1} vs B_x and V_{g1} (μ_2) is measured at $V_{bias} = 2\text{mV}$ (0mV for simulation). $V_{g2} = 5\text{ V}$. The electron spin at each mode is indicated with white arrows. (b, d) Normalized I_{sw}/I_c (Experiment/Simulation) is plotted as a function of B_x and V_{g1} (μ_2). The boundary between the lowest spin-full mode and spin-polarized mode, extracted from (a), is indicated with a green line. The chemical potential under the leads, $\mu_1, \mu_3 = 20\text{ meV}$, allows for a maximum of 6 available subbands through the leads. Other simulation parameters include spin-orbit strength $\alpha = 100\text{nm}\cdot\text{meV}$, Zeeman g-factor ($g = 50$), effective mass $m_{eff} = 0.015m_e$, temperature $T = 100\text{mK}$, site disorder $\delta U = 0\text{meV}$.

first transverse mode. The magnitude of the first mode switching current I_{sw} in these and other data is from 10 to 20 nA. Given the normal state resistance around $13\text{ k}\Omega$ ($1G_0$), the $I_{sw}R_N$ product falls within the range of $150\text{-}250\text{ }\mu\text{eV}$ (Fig. S14). This value somewhat suppressed compared to the more open regime, but is of the same order as the superconducting gap of Sn ($\Delta = 650\text{ }\mu\text{eV}$) and is consistent with values reported in previous studies [30, 35]. Thus signal levels allow for a deeper investigation of supercurrent in the few-subband regime.

The first question we investigate is the evolution of supercurrent as spin polarization develops in the QPC region, when the plateau $G_0/2 = 1 \times e^2/h$ develops at finite magnetic field. The emergence of the plateau is demonstrated in Fig. 3(a) in the transconductance map - the characteristic "V"-shaped region corresponds to the spin-polarized plateau. Spin polarization becomes resolved at fields between 0.5-1.0 T, while supercurrents are generally observed up to 2 T. This allows for the study of the effect of spin polarization on supercurrent.

Fig. 3(b) shows supercurrents extracted from gate voltage sweeps at fields between 0 and 2 T. A switching current I_{sw} is a current at which finite voltage develops across the junction, this may or may not closely follow the Josephson critical current which is a measure of Josephson coupling energy. In data processing, switch-

ing current is defined as I_{bias} for which differential resistance exceeds $2\text{ k}\Omega$. We extract the boundary of the spin-polarized region from panel (a) using peak finder scripts, and superimpose them with current evolution 2D map in panel(b) with green squares. Note that panel (a) is at $V_{bias} = 2\text{ mV}$ while panel b is at zero voltage, meaning the boundaries may be shifted. To quantify the decay rate of I_{sw} in magnetic fields and compare it for different gate voltages, we normalize the magnitude of the switching current as $Nor\ I_{sw}(B, V) = I_{sw}(B, V)/I_{sw}(B = 0, V)$ and plot it as a function of B_x and V_g .

Overall, the first mode supercurrent exhibits a decay up to $B_x = 1\text{ T}$, eventually disappearing as the system transits to the normal state. However, we found no supercurrent within the spin-up band, or at least the signal is rapidly suppressed in that region. At the same time, supercurrent found in the region of the phase diagram directly adjacent to the spin-polarized "V". This serves as an additional confirmation that it corresponds to the single subband regime with two spin channels.

We conduct a numerical investigation of the system's microscopic properties using a tight-binding model that mirrors the experimental geometry, as shown in Fig.1(b). This model was designed to study supercurrent interference in nanowires using KWANT [26, 37, 38]. It includes the effects of spin-orbit interaction, the orbital vector potential, Zeeman splitting, electron temperature, and on-site disorder. To reproduce the quantized conductance results observed in our experiment, no disorder is considered here ($\delta U = 0\text{ meV}$), same as what the initial version of the model did [26].

The new aspect here is the varied chemical potential along the nanowire, allowing for the possibility that the number of occupied subbands is not constant throughout the device. For the results in Fig. 3(c) we set chemical potentials in both the leads to $\mu_{lead} = 20\text{ meV}$, corresponding to a few occupied subbands (≈ 6), we then vary μ_{QPC} . The boundary between the lowest spin-full and spin-polarized modes is extracted from the conductance calculation and plotted alongside the normalized I_c in Fig.3(d) in a manner similar to how the experimental data are presented. The electron spin in each mode is labeled with white arrows. It should be noted that the values in the simulation do not exactly correspond to those in the experimental device but serve as indicators. For example, the boundary between G_0 and $1.5G_0$ converges at $B_x = 0.9T$ in the simulation, whereas they never intersect in the experiment, even up to $B_x = 8T$. In the $1.5G_0$ mode, we find that the supercurrent persists to a larger field compared to the first mode supercurrent, which is not observed experimentally but is likely due to microscopic details of the simulation.

In agreement with the experimental finding, the normalized I_c does not survive in the spin-polarized regime at $0.5G_0$. This indicates that the model correctly captures the system and does not predict triplet supercurrent under the most basic conditions. Experiments on superconductor-ferromagnet-superconductor

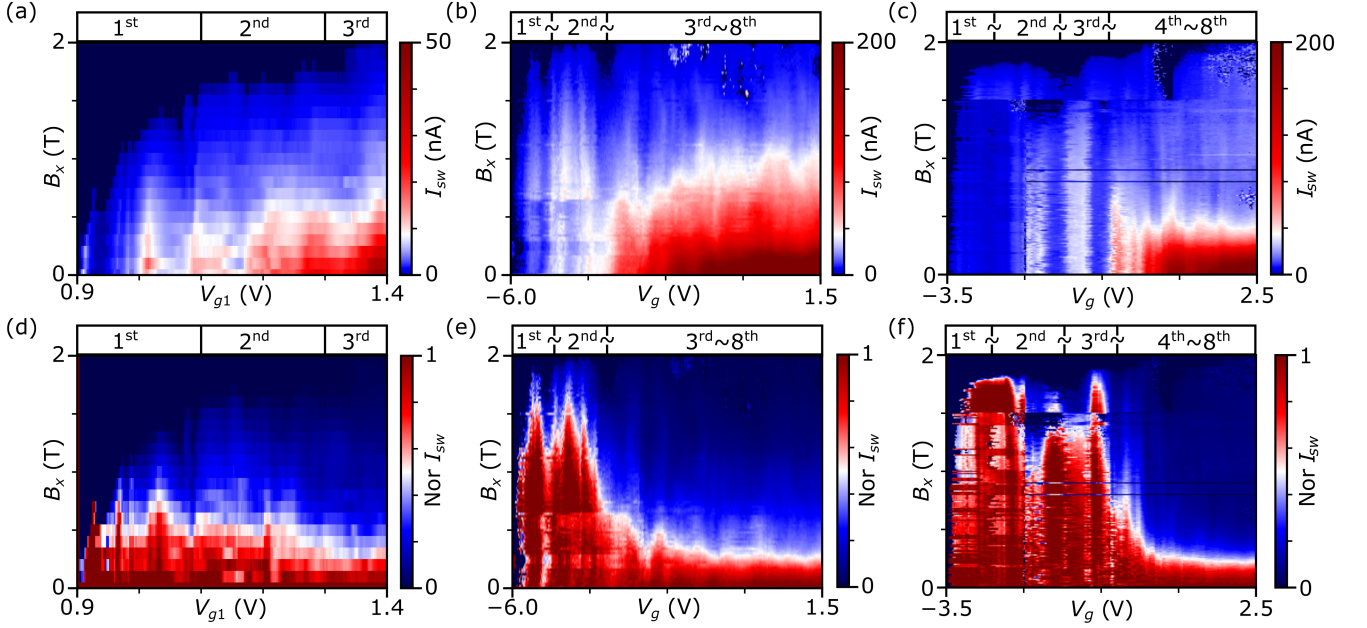


FIG. 4. (a)-(c) Magnitude of switching current I_{sw} extracted for gate scans and plotted as a function of gate voltages V_g and parallel external field B_x measured in Device A, B, and C. (d) Additional data for Fig. 3(b) (Device A) is presented, showcasing normalized I_{sw} at higher gate voltages (more modes). (e) and (f): Normalized I_{sw} as a function of B_x and V_g is measured in Device B and Device C. The boundary between different subbands are extracted at zero field and indicated by the yellow dashed line. The number of the highest transverse mode being occupied is labeled above each panel.

structures found that in junctions with pristine interfaces supercurrent vanishes in shorter junctions, while counterintuitively it survives to in longer junctions when interfaces are disordered [39]. A disordered interface is believed to facilitate spin flipping into triplet state and flipping back to singlet at the second interface. It is worth investigating if interface roughness, in combination with spin-orbit interaction and/or magnetic impurities could extend supercurrents into the spin-polarized regime in superconductor-semiconductor junctions, hinting at the generation of triplet supercurrents.

Earlier work on nanowires suggested that the single-mode supercurrents are unique, because without other occupied subbands there is no inter-subband interference. This interference was associated with rapid decay of supercurrents in magnetic field, and therefore a slower decay is expected for a single-subband junction [26].

In Fig. 4 we show switching current maps in gate-field space from three devices. Device A is the source of data in Figs. 2 and 3, where the few mode regime was carefully explored. Devices B and C are fabricated using the same Sn-InSb nanowires and in the same geometry (see Supplementary Material at [36] for device images and additional data). While conductance steps are observed, the QPC evidence is less comprehensive in devices B and C. On the other hand, B and C are studied into the more open regime. The number of occupied subbands is estimated from conductance and indicated above the figures.

In all three junctions, supercurrents grow at more positive gate voltages that correspond to higher subband

occupations [Figs. 4(a)(b)(c)]. In magnetic field, signal is observed up to, and occasionally beyond $B=2$ T. The magnetic field decay rate of switching current can be explored in maps normalized to zero-field values [Figs. 4(d)(e)(f)]. Devices B and C clearly exhibit a more rapid relative decay of switching current in the multi-mode regime, compared with the 1-2 mode regime. The rapid decay takes place at fields below approximately 0.5 T followed by a persistent lower signal. In the single-mode regime, no rapid decay is observed, yet the overall signal level is smaller and comparable to that seen at higher fields in the multi-mode regime (see Supplementary Material at [36] for detailed magnetic field dependence of current-voltage characteristics for all three devices.) Results in device A do not extend to more modes, but from the data available they are not in contradiction with findings from B and C.

We discuss the decay rates of supercurrent in magnetic field from the experimental and theory points of view. On the experiment side, one concern that should be mentioned is that smaller switching currents can deviate substantially from the actual Josephson critical currents. This concern is shared by all studies of switching currents on mesoscopic junctions. We note that, in contrast with many studies, here the switching into the normal state remains sharp in the regime of interest, at least near zero applied magnetic field. Another experimental concern is that the shapes of $I_{sw}(B)$ can be affected by presence of finite voltage resonances such as due to Multiple Andreev Reflections (MAR) frequently observed in these junctions

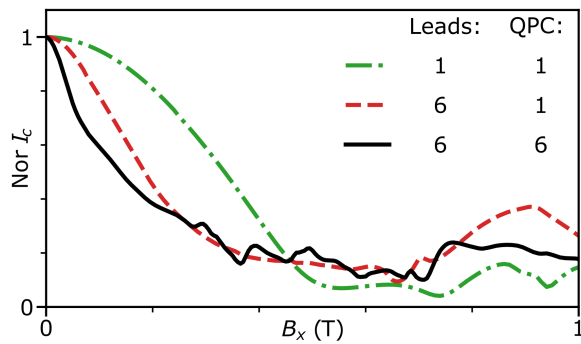


FIG. 5. Normalized critical current as a function of parallel field B_x for different combinations of terms in the Hamiltonian of the numerical model. The Zeeman effect ($g = 50$) and spin-orbit strength $\alpha = 100 \text{ nm} \cdot \text{meV}$ are present in all curves. The local chemical potential and corresponding number of conduction channels in the leads and QPC region are illustrated with a small diagram in each panel. $\mu = 5$ and 20 meV result in one and six spin-full transverse modes in the nanowires, respectively. The other simulation parameters are consistent with those used in Fig. 3 (b) and (d).

leading to peculiar non-monotonic field dependences (see Supplementary Material at [36] for examples.)

On the theoretical side, we started with a basic assumption of only a single mode occupied in the device. While this may be the case in the middle of the junction, the leads may have higher subband occupations. Interference between supercurrents carried by different subbands can take place in the leads and result in faster decay. The earlier model did not include this consideration, so we address it here.

Using KWANT, we numerically calculate the evolution of I_c in the parallel field B_x [Fig. 5]. The chemical potential in the leads and junction region is locally adjusted to 5 meV (one mode) or 20 meV (six modes). Spin-orbit interaction and Zeeman effect are present in all calculations. The effects of small disorder are explored in the

supplementary information. In agreement with earlier results [26], the model demonstrates the slowest decay when both the leads and the QPC region are set to one occupied subband. The decay is more rapid when the leads are set to 6 subbands, and opening the QPC to 6 subbands accelerates the decay further. The difference between QPC and 1 and at 6 is not dramatic when the leads are open.

Experimentally it is much more challenging to realize a device where the entire nanowire is in the single subband regime, compared with realizing a short QPC region. Supplementary information shows more maps for different settings of V_{g2} for device A. More negative settings of V_{g2} result, in principle, in a lower subband occupation in one of the leads. While the decay rates become more uniform at negative V_{g2} , the limited range of V_{g1} and the inability to tune the second lead region prevent us from concluding on the origins of this effect and whether the numerical simulations explain it. Since single-mode nanowires are desirable for Majorana zero mode experiments, future work should focus on realizing this regime and the insights obtained in the present work may be helpful.

Acknowledgments

We thank G. Badawy, S. Gazibegovic, E. Bakkers for providing InSb nanowires. We thank R. Mong for discussions. We acknowledge the use of shared facilities of the NSF Materials Research Science and Engineering Center (MRSEC) at the University of California Santa Barbara (DMR 1720256) and the Nanotech UCSB Nanofabrication Facility.

Work supported by the NSF PIRE:HYBRID OISE-1743717, NSF Quantum Foundry funded via the Q-AMASE-i program under award DMR-1906325, U.S. ONR and ARO and France ANR through Grant No. ANR-17-PIRE-0001 (HYBRID).

Curated library of data extending beyond what is presented in the paper, as well as simulation and data processing code are available at [40].

I. References

- [1] T. W. Larsen, K. D. Petersson, F. Kuemmeth, T. S. Jespersen, P. Krogstrup, J. Nygård, and C. M. Marcus, Semiconductor-nanowire-based superconducting qubit, *Physical review letters* **115**, 127001 (2015).
- [2] G. De Lange, B. Van Heck, A. Bruno, D. Van Woerkom, A. Geresdi, S. Plissard, E. Bakkers, A. Akhmerov, and L. DiCarlo, Realization of microwave quantum circuits using hybrid superconducting-semiconducting nanowire josephson elements, *Physical review letters* **115**, 127002 (2015).
- [3] M. Hays, V. Fatemi, D. Bouman, J. Cerrillo, S. Diamond, K. Serniak, T. Connolly, P. Krogstrup, J. Nygård, A. Levy Yeyati, *et al.*, Coherent manipulation of an andreev spin qubit, *Science* **373**, 430 (2021).
- [4] R. M. Lutchyn, J. D. Sau, and S. D. Sarma, Majorana fermions and a topological phase transition in semiconductor-superconductor heterostructures, *Physical review letters* **105**, 077001 (2010).
- [5] Y. Oreg, G. Refael, and F. Von Oppen, Helical liquids and majorana bound states in quantum wires, *Physical review letters* **105**, 177002 (2010).
- [6] S. Frolov, M. Manfra, and J. Sau, Topological superconductivity in hybrid devices, *Nature Physics* **16**, 718 (2020).
- [7] L. P. Rokhinson, X. Liu, and J. K. Furdyna, The fractional ac josephson effect in a semiconductor-superconductor nanowire as a signature of majorana particles, *Nature Physics* **8**, 795 (2012).

- [8] E. Bocquillon, R. S. Deacon, J. Wiedenmann, P. Leubner, T. M. Klapwijk, C. Brüne, K. Ishibashi, H. Buhmann, and L. W. Molenkamp, Gapless andreev bound states in the quantum spin hall insulator hgte, *Nature Nanotechnology* **12**, 137 (2017).
- [9] P. Zhang, S. Mudi, M. Pendharkar, J. Lee, C. Dempsey, A. McFadden, S. Harrington, J. Dong, H. Wu, A.-H. Chen, *et al.*, Missing odd-order shapiro steps do not uniquely indicate fractional josephson effect, *arXiv preprint arXiv:2211.08710* (2022).
- [10] B. Van Heck, A. Akhmerov, F. Hassler, M. Burrello, and C. Beenakker, Coulomb-assisted braiding of majorana fermions in a josephson junction array, *New Journal of Physics* **14**, 035019 (2012).
- [11] J. P. Stenger, M. Hatridge, S. M. Frolov, and D. Pekker, Braiding quantum circuit based on the 4π josephson effect, *Physical Review B* **99**, 035307 (2019).
- [12] R. M. Lutchyn, T. D. Stanescu, and S. Das Sarma, Search for majorana fermions in multiband semiconducting nanowires, *Physical review letters* **106**, 127001 (2011).
- [13] C. Beenakker and H. Van Houten, Josephson current through a superconducting quantum point contact shorter than the coherence length, *Physical review letters* **66**, 3056 (1991).
- [14] C. J. Muller, J. Van Ruitenbeek, and L. De Jongh, Conductance and supercurrent discontinuities in atomic-scale metallic constrictions of variable width, *Physical review letters* **69**, 140 (1992).
- [15] M. Goffman, R. Cron, A. L. Yeyati, P. Joyez, M. Devoret, D. Esteve, and C. Urbina, Supercurrent in atomic point contacts and andreev states, *Physical Review Letters* **85**, 170 (2000).
- [16] H. Takayanagi, T. Akazaki, and J. Nitta, Observation of maximum supercurrent quantization in a superconducting quantum point contact, *Physical review letters* **75**, 3533 (1995).
- [17] M. Kjærgaard, F. Nichele, H. Suominen, M. Nowak, M. Wimmer, A. Akhmerov, J. Folk, K. Flensberg, J. Shabani, w. C. Palmstrøm, *et al.*, Quantized conductance doubling and hard gap in a two-dimensional semiconductor–superconductor heterostructure, *Nature communications* **7**, 12841 (2016).
- [18] H. Irie, Y. Harada, H. Sugiyama, and T. Akazaki, Josephson coupling through one-dimensional ballistic channel in semiconductor-superconductor hybrid quantum point contacts, *Physical Review B* **89**, 165415 (2014).
- [19] T. Nishio, T. Kozakai, S. Amaha, M. Larsson, H. A. Nilsson, H. Xu, G. Zhang, K. Tateno, H. Takayanagi, and K. Ishibashi, Supercurrent through inas nanowires with highly transparent superconducting contacts, *Nanotechnology* **22**, 445701 (2011).
- [20] M. Goffman, C. Urbina, H. Pothier, J. Nygård, C. Marcus, and P. Krogstrup, Conduction channels of an inas-al nanowire josephson weak link, *New Journal of Physics* **19**, 092002 (2017).
- [21] J. Estrada Saldaña, R. Žitko, J. Cleuziou, E. Lee, V. Zannier, D. Ercolani, L. Sorba, R. Aguado, and S. De Franceschi, Charge localization and reentrant superconductivity in a quasi-ballistic inas nanowire coupled to superconductors, *Science advances* **5**, eaav1235 (2019).
- [22] D. J. Carrad, M. Bjergfelt, T. Kanne, M. Aagesen, F. Krizek, E. M. Fiordaliso, E. Johnson, J. Nygård, and T. S. Jespersen, Shadow epitaxy for in situ growth of generic semiconductor/superconductor hybrids, *Advanced Materials* **32**, 1908411 (2020).
- [23] S. Abay, D. Persson, H. Nilsson, F. Wu, H. Xu, M. Fogelström, V. Shumeiko, and P. Delsing, Charge transport in inas nanowire josephson junctions, *Physical Review B* **89**, 214508 (2014).
- [24] D. Szombati, S. Nadj-Perge, D. Car, S. Plissard, E. Bakkers, and L. Kouwenhoven, Josephson ϕ_0 -junction in nanowire quantum dots, *Nature Physics* **12**, 568 (2016).
- [25] E. M. Spanton, M. Deng, S. Vaitiekėnas, P. Krogstrup, J. Nygård, C. M. Marcus, and K. A. Moler, Current-phase relations of few-mode inas nanowire josephson junctions, *Nature Physics* **13**, 1177 (2017).
- [26] K. Zuo, V. Mourik, D. B. Szombati, B. Nijholt, D. J. Van Woerkom, A. Geresdi, J. Chen, V. P. Ostroukh, A. R. Akhmerov, S. R. Plissard, *et al.*, Supercurrent interference in few-mode nanowire josephson junctions, *Physical review letters* **119**, 187704 (2017).
- [27] A. Murani, A. Kasumov, S. Sengupta, Y. A. Kasumov, V. Volkov, I. Khodos, F. Brisset, R. Delagrangé, A. Chelianskii, R. Deblock, *et al.*, Ballistic edge states in bismuth nanowires revealed by squid interferometry, *Nature Communications* **8**, 15941 (2017).
- [28] K. Ueda, S. Matsuo, H. Kamata, S. Baba, Y. Sato, Y. Takeshige, K. Li, S. Jeppesen, L. Samuelson, H. Xu, *et al.*, Dominant nonlocal superconducting proximity effect due to electron-electron interaction in a ballistic double nanowire, *Science advances* **5**, eaaw2194 (2019).
- [29] N. Ligato, E. Strambini, F. Paolucci, and F. Giazotto, Preliminary demonstration of a persistent josephson phase-slip memory cell with topological protection, *Nature communications* **12**, 5200 (2021).
- [30] B. Zhang, Z. Li, V. Aguilar, P. Zhang, M. Pendharkar, C. P. Dempsey, J. Lee, S. D. Harrington, S. Tan, J. Meyer, *et al.*, Evidence of ϕ_0 -josephson junction from skewed diffraction patterns in sn-insb nanowires, *SciPost Physics* **18**, 013 (2025).
- [31] Ö. Gül, D. J. Van Woerkom, I. van Weperen, D. Car, S. R. Plissard, E. P. Bakkers, and L. P. Kouwenhoven, Towards high mobility insb nanowire devices, *Nanotechnology* **26**, 215202 (2015).
- [32] G. Badawy, S. Gazibegovic, F. Borsoi, S. Heedt, C.-A. Wang, S. Koelling, M. A. Verheijen, L. P. Kouwenhoven, and E. P. A. M. Bakkers, High mobility stemless insb nanowires, *Nano Lett.* **19**, 3575 (2019).
- [33] I. van Weperen, S. R. Plissard, E. P. Bakkers, S. M. Frolov, and L. P. Kouwenhoven, Quantized conductance in an insb nanowire, *Nano letters* **13**, 387 (2013).
- [34] J. Kammhuber, M. C. Cassidy, H. Zhang, O. Gül, F. Pei, M. W. De Moor, B. Nijholt, K. Watanabe, T. Taniguchi, D. Car, *et al.*, Conductance quantization at zero magnetic field in insb nanowires, *Nano letters* **16**, 3482 (2016).
- [35] M. Pendharkar, B. Zhang, H. Wu, A. Zarassi, P. Zhang, C. Dempsey, J. Lee, S. Harrington, G. Badawy, S. Gazibegovic, *et al.*, Parity-preserving and magnetic field-resilient superconductivity in insb nanowires with sn shells, *Science* **372**, 508 (2021).
- [36] See Supplemental Material at URL-will-be-inserted-by-publisher for the details of device fabrication method; the transport measurement setup; comprehensive data obtained from Device A-F; numerical model used to calcu-

- late Fig. 5. See also reference [26, 30, 31, 34, 41] therein.
- [37] C. W. Groth, M. Wimmer, A. R. Akhmerov, and X. Waintal, Kwant: a software package for quantum transport, *New Journal of Physics* **16**, 063065 (2014).
 - [38] B. Nijholt and A. R. Akhmerov, Orbital effect of magnetic field on the majorana phase diagram, *Physical Review B* **93**, 235434 (2016).
 - [39] S. M. Frolov, M. J. Stoutimore, T. A. Crane, D. J. Van Harlingen, V. A. Oboznov, V. V. Ryazanov, A. Rusi, C. Granata, and M. Russo, Imaging spontaneous currents in superconducting arrays of π -junctions, *Nature Physics* **4**, 32 (2008).
 - [40] Data and code for 'supercurrent through a single transverse mode in nanowire josephson junctions', <https://doi.org/10.5281/zenodo.7933597> (2023).
 - [41] D. Suyatin, C. Thelander, M. Björk, I. Maximov, and L. Samuelson, Sulfur passivation for ohmic contact formation to inas nanowires, *Nanotechnology* **18**, 105307 (2007).