Electrostatic control of the proximity effect in the bulk of semiconductor-superconductor hybrids

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The proximity effect in semiconductor-superconductor nanowires is expected to generate an induced gap in the semiconductor. The magnitude of this induced gap, together with the semiconductor properties like spin-orbit coupling and $g$-factor, depends on the coupling between the materials. It is predicted that this coupling can be adjusted through the use of electric fields.

We study this phenomenon in InSb/Al/Pt hybrids using nonlocal spectroscopy. We show that these hybrids can be tuned such that the semiconductor and superconductor are strongly coupled. In this case, the induced gap is similar to the superconducting gap in the Al/Pt shell and closes only at high magnetic fields. In contrast, the coupling can be suppressed which leads to a strong reduction of the induced gap and critical magnetic field. At the crossover between the strong-coupling and weak-coupling regimes, we observe the closing and reopening of the induced gap in the bulk of a nanowire. Contrary to expectations, it is not accompanied by the formation of zero-bias peaks in the local conductance spectra. As a result, this cannot be attributed conclusively to the anticipated topological phase transition and we discuss possible alternative explanations.
the local density of states. Yet, it remains unknown what information these observations provide about the proximity effect in the bulk of a hybrid. Advances in nanofabrication now enable the study of semiconductor-superconductor hybrids in a three-terminal geometry\cite{46,47}. In addition to the local density of states at the two ends of a nanowire, such devices allow the nonlocal conductance to be measured. Nonlocal transport is fundamentally carried by states in the nanowire that couple to both leads. Moreover, it requires their energy to reside in an energy window between the gap of the superconductor and the induced gap in the semiconductor\cite{48}, and thus can be used to directly determine the induced gap in the bulk of the hybrid\cite{49}. Measurements in this geometry have been used to observe the closing of the induced gap\cite{50}, map the local charge of ABSs\cite{51,52}, investigate the quasiparticle wavefunction composition\cite{53} and search for topological superconductivity in a variety of platforms\cite{54,55}.

In this article, we investigate the effect of gate-induced electric fields on the bulk of InSb nanowires, proximitized by Al/Pt films\cite{56}. To do this, we utilize nonlocal spectroscopy. We demonstrate that the devices can be tuned into a strongly-coupled regime with an induced gap close to that of the Al/Pt shell. Likewise, gate voltages can be used to significantly reduce the induced gap and eventually fully close it. By applying a parallel magnetic field, we show that wires in the strong-coupling regime can have critical magnetic fields close to that of the superconducting shell. On the other hand, a gate-reduced coupling drastically lowers the critical field.

The three-terminal devices presented in this work are fabricated using our shadow-wall lithography technique\cite{57,58}. In Fig. 1a we depict the device schematic of a nanowire hybrid used in these experiments. A set of pre-patterned bottom gates is separated from the InSb nanowire by a thin layer of HfO$_2$. Voltages on the two tunnel gates, $V_{TL}$ and $V_{TR}$, are used to induce tunnel barriers in the exposed semiconductor segments. The super gate voltage $V_{SG}$ is used to apply an electric field in the bulk of the hybrid. The nanowire is covered on three facets by an Al/Pt film, where the Pt serves to enhance the critical magnetic field of the Al film\cite{59}. This superconducting shell extends onto the substrate, forming the connection to ground. Two Cr/Au contacts are fabricated at the ends of the wire. The devices are measured by individually applying bias voltages, $V_L$ and $V_R$, to the left and right leads. The conductance matrix is obtained by measuring the differential conductances $G_{ij} \equiv dI/dV_{ij}$ with $i,j = L,R$ using standard lock-in techniques (see the Methods section for details of device fabrication and measurement).

In Fig. 1b, we illustrate the expected effect of electric fields on the bulk of the hybrid as calculated by\cite{60}. For negative gate voltages (Fig. 1b(i)), electrons accumulate near the semiconductor-superconductor interface which results in a strong coupling to the superconductor. As a consequence, the semiconductor properties of the hybrid are strongly renormalized. We refer to this as the strong-coupling regime in the rest of this work. On the other hand, electrons can accumulate far from the interface through the application of positive gate voltages (Fig. 1b(ii)). This results in a diminished coupling with unproximitized states in the hybrid, to which we refer as the weak-coupling regime. Finally, there is a crossover between these two regimes (Fig. 1b(iii)) where electrons still maintain superconducting correlations, while their semiconductor properties are only moderately renormalized. As a result, this crossover is expected to be optimal for the emergence of topological superconductivity\cite{61}. Furthermore, the application of an electric field also changes the electron density in the hybrid. Due to quantum confinement we expect the formation of discrete subbands, each with their own coupling strength. Thus, applied gate voltages should be able to tune the hybrid between the different subbands.

To characterize the different coupling regimes, we determine the induced gap in our devices using nonlocal spectroscopy. The transport mechanisms involved in such measurements are schematically depicted in Fig. 1c, together with an example of the resulting nonlocal conductance $g_{NL}$ in Fig. 1d. If the applied bias $V_L$ is below the induced gap $\Delta_i$, electrons from the lead can only enter the superconducting region through Andreev reflection (Fig. 1c(i)). This results in the formation of Cooper pairs, which drain away into the superconducting lead. As a consequence, no nonlocal conductance is observed below the induced gap (Fig. 1d). Similarly, electrons injected above the gap of the superconductor $\Delta_{SC}$ are likely to drain to the ground without reaching the other side\cite{62}. However, if the applied bias is larger than $\Delta_i$ but below $\Delta_{SC}$, injected electrons can reach the opposite lead of the device. This results in a finite nonlocal conductance as shown in Fig. 1d, from which $\Delta_i$ (dashed blue lines) and $\Delta_{SC}$ (dashed red lines) can be estimated. In the Methods section and Supplementary section I, we describe how these parameters are determined from the data. While this picture helps to understand three-terminal
measurements, we note that nonlocal processes can involve energy relaxation of the injected electrons as well as non-equilibrium effects not captured by the single-particle transport theory\(^2\). We further elaborate on this in Supplementary section II.D.

**Results and discussion**

First, we investigate the gate tunability of the induced gap. We measure the full conductance matrix of a device as a function of super gate voltage \(V_{SG}\) at zero magnetic field. In Fig. 2, we show such a measurement on a long nanowire hybrid (device B, 8 \(\mu m\) long). Panels a and d depict the nonlocal signals \(g_{RL}\) and \(g_{RR}\), which are displayed in purple and orange, respectively. Indeed, their deviation from zero above \(V_{SG} > 6\) V confirms that the hybrid has become gapless. We generically observe the tunability of the induced gap, and hence the coupling between the semiconductor and superconductor. However, the application of an electric field does not exclusively tune the coupling but also controls the density in the hybrid. Typically, we observe a sudden onset of the reduction of \(\Delta\) while the magnitude of the nonlocal signal increases concurrently. This behavior has theoretically been related to the occupation of an additional subband with a reduced coupling\(^8\). Still, it remains unknown how many subbands are active in our hybrids.

It is particularly interesting how the reduction of the induced gap is also reflected in the local signals \(g_{RL}\) and \(g_{RR}\), which are displayed in panels e and f in Fig. 2a, b. In the strong-coupling regime, the local signals exhibit two sharp coherence peaks and for the majority of the gate voltages, the sub-gap conductance does not actually go to zero. For increasing \(V_{SG}\), the peaks gradually become sharp coherence peaks and for the majority of the gate voltages, a clean superconducting gap. However, some states can be seen in these spectra which do not correlate between the two panels nor show up in the local signals—a confirmation that these states are confined to the local tunnel junctions. Exemplary linecuts in this regime of the full conductance matrix are shown in Fig. 2f. In \(g_{RL}\) and \(g_{RR}\), we see a typical local spectrum which in literature is referred to as a hard superconducting gap. While the sub-gap conductance does not actually go

[Fig. 2] Tunability of the induced superconducting gap through electrostatic gating. a–d Conductance matrix measured as a function of \(V_{SG}\), in the absence of a magnetic field on device B (8 \(\mu m\) long hybrid). At low \(V_{SG}\), a large induced gap is observed in \(g_{RR}\) and \(g_{RL}\) (panels c, d). For increasing \(V_{SG}\), the induced gap gradually decreases and eventually fully closes. At the same time, the superconducting gap in \(g_{RL}\) and \(g_{RR}\) (panels a, b) becomes soft. e Top: \(\Delta\) (blue) and \(\Delta_{SC}\) (red). Dark colors represent the mean of four values, obtained from the positive and negative biases of the two nonlocal signals. Similarly, the shaded areas correspond to the standard deviation. Bottom: calculated nonlocal slope at zero bias for \(g_{RL}\) (purple) and \(g_{RR}\) (orange). f Linecuts of the conductance matrix taken at \(V_{SG} = 1.26\) V in the strong-coupling regime, where a large induced gap is observed. g Linecuts of the conductance matrix taken at \(V_{SG} = 4.67\) V in the weak-coupling regime, where the induced gap is significantly reduced. h Linecuts of the conductance matrix taken at \(V_{SG} = 8.44\) V. The induced gap is closed as visible in \(g_{RR}\) and \(g_{RL}\), whereas the superconducting gap in \(g_{RL}\) and \(g_{RR}\) has turned soft.
to zero, we note that the junctions are relatively transparent. This results in a significant amount of Andreev reflection\(^2\), which contributes only to the local conductance. To confirm this, we have repeated similar measurements in the tunneling regime (see Supplementary information Fig. S9). Indeed, the hard gap is also visible in \(g_{RL}\) and \(g_{LR}\) (panels c, d), in \(g_{LL}\) and \(g_{RR}\) (panels a, b), a few sub-gap states localized in the vicinity of the tunnel junctions are observed. e Top panel: \(\Delta_\text{L}\) (blue) and \(\Delta_\text{SC}\) (red) in the strong-coupling regime. Bottom panel: Nonlocal slope extracted from \(g_{RL}\) (purple) and \(g_{LR}\) (orange).

Fig. 3 | Magnetic-field evolution of the induced superconducting gap. a–d Conductance matrix measured as a function of \(B_L\) for device C (1 \(\mu\)m hybrid) in the strong-coupling regime (\(V_{SG} = -0.75\) V), where the induced gap only closes at large magnetic fields as visible in \(g_{RL}\) and \(g_{LR}\) (panels c, d). In \(g_{LL}\) and \(g_{RR}\) (panels a, b), a few sub-gap states localized in the vicinity of the tunnel junctions are observed. e Top panel: \(\Delta_\text{L}\) (blue) and \(\Delta_\text{SC}\) (red) in the strong-coupling regime.

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properties are indeed strongly renormalized in this regime. Such a low $g$-factor and the absence of any states below $\Delta$ may suggest that the semiconductor is depleted. Yet, we observe that the induced critical field in the strong-coupling regime varies significantly from wire to wire and likely depends on the microscopic details (see Supplementary section II). Moreover, we note that the addition of Pt in the shell causes its $g$-factor to be reduced close to zero, so that the effective $g$-factor in the hybrid can be reduced below $g = 2$\(^{-1}\). In the weak-coupling regime (Fig. 3f-j) on the contrary, the induced gap closes quickly upon the application of the magnetic field. Thereafter, the spectrum remains gapless and filled with a plethora of states. This is also reflected in $g_{\parallel LL}$ and $g_{\parallel RR}$, where the same states are visible. From both the induced gap and the nonlocal slope in Fig. 3j, we observe an induced critical field $B^\parallel = 0.16$ T. We estimate a $g$-factor of $g = 54$, although this value can be overestimated as orbital effects of the magnetic field are more prominent in this regime. The rapid closing of the induced gap confirms that the hybrid inherits more of the semiconductor properties in the weak-coupling regime.

We next turn our attention to the crossover between these two regimes, which is expected to be optimal for the formation of a topological superconducting phase. In Fig. 4a-d, the conductance matrix of the same nanowire (device C, 1 \(\mu m\) hybrid) taken at $V_{SC} = -0.3$ V for device C (1 \(\mu m\) hybrid). A closing and reopening of the induced gap is observed in $g_{\parallel LL}$ and $g_{\parallel RR}$ (panels c, d), but it is not accompanied by the formation of zero-bias peaks in $g_{LL}$ and $g_{RR}$ (panels a, b). e $\Delta_i$ (blue) and $\Delta_{SC}$ (red) corresponding to the conductance matrix in (a-d). Bottom: Nonlocal slope extracted from $g_{LL}$ (purple) and $g_{RR}$ (orange). f-h Nonlocal conductance $g_{LL}$ presented for (f) $B_\parallel = 0$ T with a large induced gap. (g) $B_\parallel = 1.4$ T illustrating a closed induced gap. (h) $B_\parallel = 2.2$ T showing flat nonlocal conductance around zero-bias corresponding to a reopening of the induced gap.

Figure 4f-h provide linecuts from $g_{LL}$, emphasizing that the induced gap is finite at zero field, closed at intermediate field, and reopened at higher fields. However, neither of the local signals (Fig. 4a and b) exhibit zero-bias peaks. This suggests that the observed feature does not originate from a topological phase with Majorana zero modes at the ends, extended over the full length of the hybrid. Yet, it may be possible that the presence of tunnel gates generates a smooth potential profile near the ends of the wire. In this case, the local spectra only represent the presence of bound states formed on the smooth potential, while pushing the Majorana zero modes towards the center of the hybrid—effectively decoupling them from the leads. Similar effects are expected to be caused by the device disorder independent of the tunnel gate voltage. Accordingly, the gap reopening in the bulk should remain visible in the nonlocal spectra as this effectively measures the largest gap in the system, while no zero-bias peaks are observed in the local signals. This scenario is supported by the observation that the local signals $g_{LL}$ and $g_{RR}$ do not appear to depend on the length of the hybrid and are not always correlated, as we elaborate on Supplementary section II. On the contrary, it is also possible that the reopening of the gap has a topologically trivial origin. The hybrid segment of this device is only 1 \(\mu m\) long, so that it is likely to be within the short wire limit. In this case, the resulting spectrum is comprised of discrete energy levels with a small energy spacing. Both the Zeeman and orbital contributions of the magnetic field allow these states to come down and cross zero energy. However, in this limit there is no band structure forming in the nanowire, making the concept of topology ill-defined. Alternatively, the observed gap reopening can originate from two sets of trivial ABSs localized near the nanowire junctions. In this case, spatial overlap due to a long localization length
corresponding normalized nonlocal slope $S_{\text{norm}}$ as a function of $V_{\text{GC}}$ and $B_{\text{fi}}$. Dashed orange ellipses highlight the reopening of the induced gap, which occurs in a small but finite range of $V_{\text{GC}}$ values. Data taken on device C (1 μm long hybrid).

Finally, to enhance the picture we map out the induced gap of a nanowire as a function of parallel magnetic field and super gate voltage. In Fig. 5a, we present such an induced gap diagram for the same 1 μm long hybrid (device C). To complement this diagram, we show the corresponding normalized nonlocal slope $S_{\text{norm}}$ at zero bias in Fig. 5b. This quantity captures the collective behavior of the nonlocal slope from the two nonlocal signals, remaining close to zero whenever an induced gap is present in the hybrid. It is defined as $S_{\text{norm}} = |S_{\text{GC},LR}| / \sqrt{|S_{\text{GC},UL}|}$ where the normalization is done independently for every gate voltage. In the strong-coupling regime below $V_{\text{GC}} < -0.4 V$, we see that $\Delta_i$ decays slowly when the magnetic field is increased. It closes around $B_{\text{fi}} = 3.5$ T, which is also reflected in $S_{\text{norm}}$ as it deviates from zero. In contrast, above $V_{\text{GC}} > -0.1 V$ the semiconductor-superconductor coupling is strongly diminished which results in a significant reduction of $\Delta_i$ and $B_{\text{fi}}$. Near the crossover between $-0.4 V < V_{\text{GC}} < -0.1 V$ as indicated by the dashed orange ellipses, the closing of $\Delta_i$ is followed by its reopening at higher magnetic fields. This is also visible in the behavior of $S_{\text{norm}}$, which becomes finite when the gap closes and returns to zero at the reopening. Importantly, the reopening occurs in a finite but narrow range of gate voltages. While a strong reduction of $B_{\text{fi}}$ is generically observed in our hybrids, only one out of the eleven nanowires studied in detail showed a subsequent reopening of the induced gap. In Supplementary section II, we show phase diagrams and representative overviews of additional nanowires studied in this work.

In conclusion, we have demonstrated that electric fields can enable transport through the hybrid\(^{36}\). Likewise, such states can cross zero energy without invoking a topological phase transition. By mapping out the induced gap diagram of a 1 μm nanowire near the crossover, we do observe a closing and reopening of the induced gap in a finite range of magnetic fields and gate voltages. However, the corresponding local signals reveal an absence of zero-bias peaks. As a consequence, the gap reopening cannot be conclusively attributed to the existence of a topological phase. We speculate that the density in the hybrids is too high whenever the coupling is weakened\(^\text{42}\). In fact, it is currently unclear what are the optimal density and coupling for reaching a topological phase in InSb/Al based hybrids. Thus, a desirable future improvement would be to decouple the semiconductor and superconductor via an epitaxial barrier, such that density in the wire and the coupling could be tuned independently\(^{38}\).

**Methods**

**Device fabrication**

The nanowire hybrids presented in this work are fabricated on pre-patterned substrates, following the shadow-wall lithography technique described in refs.\(^{15,16}\). Intrinsic silicon wafers (2 Ω cm) with 285 nm thermal SiO\(_x\) serve as the base for the device substrates. Local bottom gates are patterned with standard electron-beam lithography (EBL) techniques, using PMMA 950k A2 spun at 4 krpm for one minute followed by 10 minutes of baking on a 185 °C hot plate. After development of the resist using a 3:1 solution of IPA and MIBK, 3 nm Ti and 17 nm Pd are deposited as the gate metal using e-beam evaporation at 0.5 Å/s and 1 Å/s, respectively. Subsequently, bond pads are patterned with EBL using PMMA 950k A6 spun at 4 krpm for one minute and hot-baked at 185 °C for 10 min. After development, 30 nm of W is sputtered using RF-sputtering at 150 W in an Ar pressure of 20 μbar. Next, the substrates are covered with 17 nm high-quality HfO\(_x\) gate dielectric grown at 110 °C using atomic layer deposition (ALD). Finally, shadow walls are patterned on top of the dielectric. FOX-25 (HSQ) is spun at 1.5 krpm for one minute, followed by 2 minutes of hot baking at 180 °C. The HSQ is then developed with MF-321 at 60 °C for 5 minutes and the substrates are subsequently dried using critical point dryer (CPD).

The InSb nanowires are grown using metalorganic vapor-phase epitaxy, as described in ref.\(^{39}\). The nanowires are placed on top of the gates using an optical nanomanipulator setup. Samples are placed in a custom e-beam evaporator, where the native nanowire oxide is removed and the superconductor is deposited. To obtain a pristine, oxide-free semiconductor surface, a gentle oxygen removal is accomplished via atomic hydrogen radical cleaning. For this purpose, a custom-made H radical generator is installed in the load lock of an aluminum electron-gun evaporator. It consists of a gas inlet for H\(_2\) molecules connected to a mass-flow controller and a tungsten filament at a temperature of about 1700 °C that dissociates a fraction of the molecules into hydrogen radicals. The optimal removal of the native oxide is achieved for a process duration of 60 mins and at a H\(_2\) pressure of 6.3 × 10\(^{-1}\) mbar. This recipe, which is used for all the devices shown in this paper, results in a constant EDX count of oxygen at the interface as shown in the previous works utilizing our shadow wall
When measuring the conductance matrix, the bias on the left contact of the device $V_L$ is swept first while the bias on the other side $V_R$ is set to zero. Before sweeping the bias, the thermal voltage is measured and the bias offsets are calibrated accordingly. The corresponding matrix elements $g_{LL}$ and $g_{LR}$ are recorded. Next, the right-contact bias $V_R$ is swept while setting the bias on the left contact $V_L$ to zero and the remaining two conductance matrix elements $g_{RL}$ and $g_{RR}$ are recorded. For the separate gate sweeps presented in this work, we aim to maintain a constant transmission in both the nanowire junctions. To do this, the two tunnel gate voltages $V_{TL}$ and $V_{TR}$ are automatically adjusted each time the super gate voltage is changed. This is done by looking at the out-of-gap local conductances $g_{LL}$ and $g_{RR}$. If one of the conductances is found to deviate more than 0.005 * $e^2/h$ from the specified value, the respective tunnel gate voltage is tuned to bring the out-of-gap local conductance back to the specified value.

**Data analysis**

We extract the induced gap $\Delta$ and the gap of the superconducting film $\Delta_{SC}$ from the nonlocal spectra $g_{RL}$ and $g_{RR}$ as a function of various device parameters like the super gate voltage $V_{SC}$ and the parallel magnetic field $B$. In such spectra, the nonlocal conductance is finite only in an energy window between $\Delta_{SC}$ and $\Delta$. For a given trace of the nonlocal conductance as a function of bias voltage, we determine an adaptive threshold based on the noise level at a large bias voltages. $\Delta_{SC}$ and $\Delta$ are estimated by checking when the nonlocal conductance exceeds the threshold value. This is done independently for both $g_{RL}$ and $g_{RR}$, as well as both positive and negative bias voltages. This results in four estimates of $\Delta_{SC}$ and $\Delta$ each, from which the mean and standard deviation are calculated and presented in the figures. Values of the nonlocal slope $S_{RL}$ and $S_{RR}$ are estimated as the numerical derivative of the data at zero bias voltage, after application of a Savitzky-Golay filter. A detailed description and examples can be found in the supplementary information.

**Data availability**

The raw data generated in this study, as well as the code used to analyze the data, have been deposited in the repository Zenodo and are available at https://doi.org/10.5281/zenodo.6913897.

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