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Semiconductor-ferromagnet-superconductor planar heterostructures for 1D topological superconductivity

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Hybrid structures of semiconducting (SM) nanowires, epitaxially grown superconductors (SC), and ferromagnetic-insulator (FI) layers have been explored experimentally and theoretically as alternative platforms for topological superconductivity at zero magnetic field. Here, we analyze a tripartite SM/FI/SC heterostructure but realized in a planar stacking geometry, where the thin FI layer acts as a spin-polarized barrier between the SM and the SC. We optimize the system’s geometrical parameters using microscopic simulations, finding the range of FI thicknesses for which the hybrid system can be tuned into the topological regime. Within this range, and thanks to the vertical confinement provided by the stacking geometry, trivial and topological phases alternate regularly as the external gate is varied, displaying a hard topological gap that can reach half of the SC one. This is a significant improvement compared to setups using hexagonal nanowires, which show erratic topological regions with typically smaller and softer gaps. Our proposal provides a magnetic field-free planar design for quasi-one-dimensional topological superconductivity with attractive properties for experimental control and scalability.

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INTRODUCTION

The interplay between superconductivity and magnetism in low-dimensional systems allows to engineer quantum phases absent in nature otherwise. Topological superconductors are paradigmatic examples, hosting Majorana-like quasiparticles at their boundaries or near defects. The exotic properties of these bound states, including their non-locality and non-Abelian exchange statistics, have attracted a growing interest in the field. In particular, they are ideal platforms for encoding and processing quantum information in a protected way.

Theory proposals suggested the onset of topological superconductivity in semiconductor (SM) nanowires with strong spin-orbit coupling when proximitized by a superconductor (SC). As an external magnetic field increases, the system undergoes a topological quantum phase transition, characterized by the closing and reopening of the superconducting gap. In the topological regime, sufficiently long wires feature zero-energy Majorana bound states at the ends. Robust zero-bias conductance peaks compatible in principle with Majorana states have been measured in nanowires over the last decade. Later works have shown zero-energy states also in two-dimensional (2D) SM/SC hybrids, an ideal platform for multi-wire designs with a measured high mobility. However, the strong external magnetic field needed for the topological transition is detrimental to superconductivity and sets strict constraints on the device geometry, since the applied field needs to be oriented parallel to each wire. This is an obstacle for experiments showing Majorana non-Abelian properties and, ultimately, for topological quantum devices. Devices based on magnetic flux through full-shell nanowires and the phase difference in superconducting junctions are alternatives considered recently. However, these designs offer drawbacks for device scaling, due to their magnetic field direction sensitivity or the difficulty of controlling the phase difference between many superconductors.

In this context, ferromagnetic insulators (FIs) offer a way to solve the above problems by inducing a local exchange field on the SM nanowire by proximity effect, eliminating the need for external magnetic fields. Recent experiments in hexagonal nanowires partially covered by overlapping SC and FI shells showed the appearance of zero-bias conductance peaks, spin-polarized subgap states, and supercurrent reversal. Concurrent theoretical works demonstrated the possibility of topological superconductivity in these tripartite systems by a combination of a direct induced exchange from the FI into the SM and an indirect one through the SC (present only in overlapping devices). A third mechanism whereby electrons tunnel from the SC to the SM through the spin-polarized FI barrier was identified for sufficiently thin FI layers in configurations where the SC and the SM are separated by the FI layer. We note that in devices where the three materials are in direct contact, a sharp distinction between the three mechanisms is artificial and the overall induced exchange field is due to a combination of all of them. In general, fine-tuning from back and side gates was necessary in order to push the SM electron wavefunction close to both the SC and FI layers, maximizing magnetic and superconducting correlations.

In this work we propose a planar SM/FI/SC heterostructure for the creation of a field-free quasi-one dimensional (1D) topological superconductor, Fig. 1(a). In this setup, a thin FI layer is grown between the SC and the SM. We note that, in principle, a planar SC/SM/FI heterostructure can also exhibit topological properties. However, we do not consider such an arrangement of materials because the growing conditions would lead to a highly disordered heterostructure. Due to the band alignment properties between materials, see Fig. 1(b), a charge accumulation layer appears at the...
promising platform for topological superconductivity, opening the possibility of defining complex topological wire structures.

RESULTS

Model

Following ref. 33, we describe the heterostructure in Fig. 1a with a Bogoliubov-de Gennes Hamiltonian that includes the conduction band electrons in the three materials. In the Nambu basis $\Psi_{k,i} = (\psi_{k,i}; \psi_{-k,i}; \psi_{k,-i}; \psi_{-k,-i})$, it is given by

$$H = \sum_{k,i} \left( \begin{array}{c} k^2/2m_e(z) + E_F(\vec{r}) - \phi(\vec{r}) + h_0(\vec{r}) \sigma_z \end{array} \right)_{z,i} + \frac{i}{2} \left[ \sigma_\mu(\vec{r}) \cdot \sigma_\nu(\vec{r}) - \sigma_\nu(\vec{r}) \cdot \sigma_\mu(\vec{r}) \right] \tau_z + \Delta(\vec{r}) \sigma_y \tau_z,$$

where $\sigma_i$ and $\tau_j$ are the Pauli matrices in spin and Nambu space. We consider a translation invariant system in the $x$-direction. Therefore, the position and momentum operators read as $\vec{r} = (y, z)$ and $\vec{k} = (k_x, -i\theta_y, -i\theta_z)$ in the above Hamiltonian, with $k_x$ being a good quantum number. The model parameters are the effective mass $m'$, the conduction-band bottom $E_0$, the exchange field $h_e$ (non-zero only in the FI), and the superconducting pairing potential $\Delta$ (non-zero only in the SC). Note that $\Delta(\vec{r})$ is real in the above equation. These parameters have a constant value inside each material. For our calculations, we use InAs for the SM, EuS as FI, and Al as SC. The material parameters are given in Supplementary Table I in the SI according to estimations and measurements that can be found in the literature. We also include quenched disorder in the outer surface of the SC, that is characteristic of this kind of heterostructures and beneficial for the superconducting proximity effect33,39. We have found that disorder in the FI (e.g., due to the corrugation of the EuS-Al interface40) does not significantly change the energy spectrum (not shown). Together with this, we include the electrostatic interactions $\phi(\vec{r})$ of the stacking of Fig. 1a by solving self-consistently the Schrödinger-Poisson equation in the Thomas–Fermi approximation39,41,42, as explained in Sec. Methods and in the SI.

Topological phase transition

The low-energy wavefunctions decay exponentially in the FI layer on a length scale approximately given by $\xi_{FI} = \sqrt{2E_{F,FI}m_e^*/\hbar^2}$, where $E_{F,FI}$ is the conduction band minimum in the FI with respect to the Fermi level. For our materials choice $\xi_{FI} \approx 2.3$ nm. As a consequence, the thickness of the FI layer determines the tunneling amplitude between the 2DEG and the SC: thicker FI layers decouple the 2DEG from the SC resulting in a reduction of the superconducting proximity effect, while thinner ones exhibit a reduced induced magnetization in the 2DEG. Hence, there is an optimal barrier thickness that allows for a sufficiently large induced exchange field and pairing potential in the 2DEG to drive the system into the topological regime.

The topological phase transition of the system occurs at a gap closing and reopening when the lowest energy subband crosses zero energy at the $k_x = 0$ high symmetry point. For this reason, in
illustrate that the topological criterion in 1D is fulfilled for effective parameters. We note that, for the optimal range of deviations found are due to the approximated character of the subbands do not show a topological crossing, see for instance varied, in contrast to the hexagonal wire case where some panels of Fig. 2. A thick barrier hinders tunneling through the FI, with the SC/FI layers. Hexagonal section, sometimes avoiding a good proximity effect case, where the appearance of the topological regions is more larger area in parameters space compared to the hexagonal wire found in these devices with the electrostatic confinement, whereas when \( \Delta_{\text{eff}} < h_{\text{eff}} \) it is localized mostly in the SM. We note that the regions with a large effective exchange field also exhibit a suppressed superconducting pairing, consistent with normal gapless states in the SM.

**Topological Phase Minigap**

The properties of a topological superconductor are highly dependent on the value and quality of the topological minigap, which we examine now. In Fig. 3, we consider a device with \( d_{\text{eff}} = 1.5 \text{ nm} \) as we sweep \( V_{\text{tg}} \). We show the energy subbands versus momentum \( k_x \) and the spin-resolved density of states (DOS) in three representative situations: before (left column), at (middle column), and after (right column) the topological transition. Before the transition, Fig. 3a, the heterostructure features a trivial gap and the above-gap states are mostly localized in the SC (black color curves). The DOS displays a hard gap around zero energy and the characteristic spin-split superconducting coherence peaks, see red and blue curves in Fig. 3d. From this plot we infer that the induced exchange field in the SC is around 100 \( \mu \text{eV} \) (~50% of the Al gap), consistent with the value found in experiments. A similar peak splitting is found in Fig. 3e, f, i.e., it is independent of the value of the gate potential.

At the topological transition, one subband crosses zero energy at \( k_x = 0 \), Fig. 3b. It results in a finite DOS inside the superconducting gap, see Fig. 3e. As we increase \( V_{\text{tg}} \), the superconducting gap reopens in the topological phase, Fig. 3c, accompanied by the onset of Majorana bound states at the ends of a finite-length quasi-1D wire defined by the SC stripe (not shown). The hard gap found in Fig. 3f, \( E_{\text{min}} \), has a typical value of tens to a hundred \( \mu \text{eV} \). We associate the large topological gaps found in these devices with the electrostatic confinement in the vertical direction. The thin SM layer, together with the top gate tuned to negative values, makes it possible to concentrate the weight of the wavefunction in the region where superconductivity, magnetism, and spin-orbit coupling coexist. This is signaled by the purple color of the lowest-energy subband in Fig. 3c.

Fig. 2  Topological phase diagrams for different FI thicknesses. Top row: energy spectrum at \( k_x = 0 \) as a function of the top-gate voltage \( V_{\text{tg}} \) for a FI thickness of (a) \( d_{\text{eff}} = 1 \text{ nm} \), (b) \( d_{\text{eff}} = 1.5 \text{ nm} \) and (c) \( d_{\text{eff}} = 4 \text{ nm} \). Colors represent the weight \( W_{\text{SC}} \) of each state in the superconducting Al layer. Shaded \( W_{\text{eff}} \) regions are those characterized by a trivial phase, i.e., \( Q = +1 \); while white regions correspond to a topological phase, i.e., \( Q = -1 \). Bottom row (d, e, f): effective exchange coupling \( h_{\text{eff}} \) (solid lines) and superconducting pairing amplitude \( \Delta_{\text{eff}} \) (dotted lines) for the lowest-energy state in (a), (b), (c), respectively, as given by Eqs. 2 and 3.

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Fig. 3  Topological phase transition and DOS. Dispersion relation for a device with EuS layer thickness \( d_{\text{fi}} = 1.5 \) nm, and for (a) \( V_{\text{tg}} = -925 \) mV (before the topological transition), (b) \( V_{\text{tg}} = -900 \) mV (at the topological transition), and (c) \( V_{\text{tg}} = -850 \) V (in the middle of the topological phase). In (d-f) we show the spin-resolved integrated DOS of the corresponding plot on the top. Only the (c, f) case is topological, with \( E_{\text{min}} \) being the topological minigap, i.e., the lowest-state energy at \( k_x = k_y \).

Fig. 4  Topological and trivial wavefunction profiles. a Transverse probability density at \( k_y = 0 \) for the lowest-energy state in a topological regime \( (V_{\text{tg}} = -850 \text{ mV}) \). For comparison, we also show in (b) the case in a topologically trivial regime \( (V_{\text{tg}} = 300 \text{ mV}) \). Parameters are the same as in Fig. 3, corresponding to \( d_{\text{fi}} = 1.5 \) nm.

The importance of the wavefunction localization is illustrated in Fig. 4, which shows the lowest-energy wavefunction probability density across the device. In the topological regime, Fig. 4a, the ground state wavefunction is concentrated below the SC, maximizing the proximity effects of the SC and FI layers on top. The vertical confinement (in the \( z \)-direction) is determined by the SM width, \( d_{\text{SM}} \), and the fact that there is an insulating substrate below. The lateral confinement (in the \( y \)-direction) is achieved by a negative top-gate voltage that depletes the SM everywhere except below the SC. We note that the SM wavefunction penetrates the FI layer all the way to the SC due to its moderate gap and thickness. In the trivial regime shown in Fig. 4b, the wavefunction spreads laterally through all the device cross-section (due to a \( V_{\text{tg}} \) value comparable to or larger than the band bending at the SM/FI interface), reducing the proximity effects.

**Optimal Thickness of the FI**

Finally, we vary the FI thickness to extract the optimal range for topological superconductivity, Fig. 5. The effective exchange coupling is shown in Fig. 5a and the effective superconducting pairing in Fig. 5b. The transverse modes considered (depicted with different colors) are the first four lowest-energy subbands that get populated starting from a depleted SM as we increase \( V_{\text{tg}} \). For each calculated point, we tune \( V_{\text{tg}} \) to the value where the subband is closer to the Fermi level \( (E = 0) \), where \( h_{\text{eff}} \) is maximum, see Fig. 2e, f. Therefore, each point corresponds to a different \( V_{\text{tg}} \) value. We observe that in general \( h_{\text{eff}} \) increases with \( d_{\text{fi}} \) because of the growing weight of the wavefunction inside the FI. In contrast, the effective superconducting pairing decreases with the FI thickness as the weight of the wavefunction in the SC diminishes.

The topological minigap is shown in Fig. 5c. It is calculated for the value of \( V_{\text{tg}} \) that maximizes \( E_{\text{min}} \) for each subband, i.e., well within the topological region. Depending on the transverse mode, its value ranges from tens to a hundred meV. Note that we have used the bulk SC gap for the Al layer, \( \Delta_0 = 230 \text{ meV} \). Nevertheless, SCs with larger gaps such as Pb, Nb, Ta, V, or Sn, which can also be grown epitaxially over InAs\(^{46-49}\), could help to increase the topological minigap. Interestingly, for the small SM thickness considered here (10 nm), \( E_{\text{min}} \) is essentially constant with \( d_{\text{fi}} \) for every transverse mode. This is again a consequence of the vertical confinement that tends to produce regular topological patterns. This regularity gets lost as the SM layer is made thicker, as shown in the SI. In this Appendix we also investigate the role of the SC thickness, finding similar results for thicknesses between 4 nm and 12 nm. For a SC with surface disorder, as the one considered here, the induced gap remains essentially
DISCUSSION

In this work we have proposed a planar heterostructure for topological superconductivity using a thin ferromagnetic insulator (FI) between a two-dimensional electron gas (2DEG) and a superconductor (SC). The thin FI acts as a spin-filter barrier for electrons tunneling through, inducing a sufficiently large exchange field that gives rise to a topological transition in the tripartite heterostructure. In this geometry, superconducting stripes define quasi-1D wires that can be gated from the top, avoiding bottom gates that might be ineffective due to the rather thick substrates needed to create high-quality semiconducting heterostructures.

For illustration, we have considered an experimentally tested material combination: InAs (SM), EuS (FI), and Al (SC). We have found topological regions for FI thicknesses between 1.5 and 3 nm. Outside this range, the FI is either too thick to allow tunneling between the SC and the SM, or too thin to have a significant influence on the SM electrons. The topological phase features a hard superconducting gap in a range between tens to a 100 μeV. This constitutes a significant improvement with respect to previous hexagonal nanowire geometries, where these gaps were only possible by fine-tuning side gates to push the wavefunction sufficiently close to the FI/SC layers. We associate this behavior to the vertical confinement of the wavefunction for thin SM layers. Most importantly, this vertical confinement also helps to create a rather regular phase diagram, with topological and trivial phases appearing at controlled values of the top-gate potential. The topological regions produced by the subsequent inverting subbands have moreover a similar Vtg-range and comparable topological minigaps. Experimentally, this is an advantageous property since it permits to search for the topological phase in a predictable manner rather than by randomly scanning parameters, as it is typically the case with hexagonal nanowires.

Concerning the experimental detection of Majorana states in this system, the planar platform offers the possibility to perform local tunneling spectroscopy to detect the presence of low-energy states bound to the wire’s end. Examples of such experiments in a planar geometry (in the absence of the FI) can be found in refs. 15, 16. Correlations between two or more local probes along the quasi-1D wire and non-local transport spectroscopy have just begun to be explored in planar devices50, 51. Another common tool to try to detect the presence of Majoranas is the anomalous behavior of the Josephson effect. Actually, phase-dependent zero-bias conductance peaks measured by tunneling spectroscopy at the end of Josephson junctions, as well as phase-dependent critical currents, have been studied recently in planar SM/SC heterostructures18, 28, 52 (again, in the absence of the FI but with applied magnetic field). Differently from hexagonal nanowires, the 2D structures described here require no magnetic field to reach the topological phase, allowing for different orientations of the effective wires and the design and control of complex wire networks of topological superconductors. This opens the door to more sophisticated and reliable Majorana detection experiments based on the spatial exchange or fusion of the Majorana bound states53-62.

Note added.— During the preparation of this manuscript, an independent work on a similar subject has been made available as a preprint63. Their results are consistent with the ones of this article. The authors study a similar stacking of materials, although there are some differences with our setup. The SC occupies the whole width of the planar heterostructure (instead of being a SC stripe like in our proposal) and they use periodic boundary conditions in the y-direction for its description. They moreover gate the system from the bottom and the exchange field is oriented in the z-direction. Despite of this, we agree on the main conclusion that the FI thickness should be of the order of the wavefunction penetration length in order to find topological superconductivity.

METHODS

Electrostatic interactions

We firstly describe the electrostatic interactions in the stacking of Fig. 1a by solving self-consistently the Schrödinger–Poisson equation in the Thomas–Fermi approximation39, 41, 42. We take into account the band
where relatively small perpendicular magnetic fields are perpendicular to the top gate that depletes the 2DEG everywhere except underneath the grounded SC stripe, which screens the electric field coming from the top gate. This allows controlling the lateral extension (in the y-direction) of the SM 1D channels. Moreover, the top gate allows for partial control of the local chemical potential in the effective wire. Our design is independent of the choice of the specific materials as long as they fulfill the requirements: the SM should feature a surface 2DEG, whereas the FI should have a moderate bandgap to allow electron tunneling, and a sufficiently large spin-splitting to induce the topological transition (but small enough not to suppress superconductivity in the SC).

Additional details on the electrostatic problem can be found in the SI. We obtain the self-consistent electrostatic potential $\psi(\mathbf{r})$ across the heterostructure along with the Rashba field $\mathbf{g}_R(\mathbf{r})$, non-zero only in the SM. The Rashba coupling is proportional to the electric field $\nabla \psi(\mathbf{r})$, which is mainly oriented in the $z$-direction, and it is accurately described using the procedure of ref. 65 and further discussed in the SI. The spin-orbit field $(-\mathbf{k} \times \mathbf{g}_R)$ is mainly oriented in the $y$-direction ($-\alpha_0 h_0 \sigma_0$, with small components in the $x$ and $z$ directions. We have verified that the electric field in the FI is negligible and, therefore, $\psi(\mathbf{r})$ is disregarded in that region in Eq. 1.

Ferromagnetic insulator layer

We describe the FI as a depleted wide-bandgap semiconductor with a spin-split conduction band lying above the Fermi level, as depicted schematically Fig. 1b. The topological phase can appear when the FI magnetization is not aligned with the spin-orbit field (which is oriented fundamentally in the $y$-direction in our device), and it is maximized when the magnetization and the spin-orbit field are perpendicular. In this work we assume that the FI exhibits a homogeneous in-plane magnetization along the $y$-direction and negligible stray fields, consistent with the measured easy-axis in thin EuS40. We note that our setup could tolerate in principle an arbitrary misalignment of the exchange field in the $z$-direction since this would still be perpendicular to the spin-orbit term. This is an advantage with respect to schemes relying on external magnetic fields, where relatively small perpendicular magnetic fields to the SC layer suppress superconductivity due to orbital effects.

Effective single-band parameters

After the calculation of the electrostatic interactions, we discretize the continuum Hamiltonian in Eq. 1 following a finite differences scheme with a grid of 0.1 nm. We diagonalize the resulting sparse Hamiltonian for different top-gate voltages $V_{tg}$ and longitudinal momenta $\xi_y$ using the routines implemented in ref. 66. From the low-energy eigenstates $\Psi_y(\mathbf{r})$ we obtain the topological invariant33,67-69 and estimate the effective parameters $h_{\text{eff}}$ and $\Delta_{\text{eff}}$ for the lowest-energy one as

$$h_{\text{eff}} \equiv \int \psi_y(\mathbf{r}) \sigma_0 \psi_y^{\dagger}(\mathbf{r}) d\mathbf{r} = h_0 W_0,$$

$$\Delta_{\text{eff}} \equiv \int \psi_y(\mathbf{r}) \sigma_0 \psi_y^{\dagger}(\mathbf{r}) d\mathbf{r} = \Delta_{0} W_{SC},$$

where $W_0$ is the weight of the lowest-energy state in the material $\beta = \{\text{SC}, \text{FI}\}$, $\sigma_0$ and $\tau_0$ are the identity matrices in spin and Nambu space, and $h_0$ and $\Delta_0$ are the parent exchange coupling in the FI and the parent superconducting pairing in the SC, respectively. The estimation in Eqs. 2 and 3 is valid for any subgap state $E_\gamma < \Delta_0$ when the heterostructure thicknesses $d_{\text{SC}} \ll \lambda_{SO}$ and $d_{\text{SC}} \ll \xi_{SO}$ being $\lambda_{SO}$ the spin-orbit length and $\xi_{SO}$ the superconducting coherence length. Additional details can be found in the SI. $h_{\text{eff}}$ and $\Delta_{\text{eff}}$ can be interpreted as the parameters entering in an effective single-band Oreg-Lutchyn Hamiltonian80 describing the lowest-energy subband. These quantities, together with the effective chemical potential $\mu_{\text{eff}}$, are useful to understand when the system undergoes a topological phase transition, as a large enough exchange field is needed to fulfill the 1D topological criterion, i.e., $|h_{\text{eff}}| \gtrsim \sqrt{\Delta_{\text{eff}} + \mu_{\text{eff}}}$.

DATA AVAILABILITY

Data are available from the corresponding author upon reasonable request.

CODE AVAILABILITY

Code is available from the corresponding author upon reasonable request.

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