Topological superconductivity in ferromagnetic hybrid nanowires

Samuel D. Escribano

Theoretical Condensed Matter Physics Department
Universidad Autónoma de Madrid

Introduction

Alfredo Levy Yeyati
UAM

Elsa Prada
ICMM-CSIC

Yuval Oreg
Weizmann Institute

Special acknowledgments.– S. Vaitiekenas and C. M. Marcus.

Further details on:

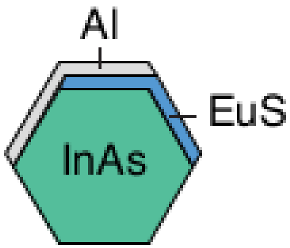
Samuel D. Escribano, Elsa Prada, Yuval Oreg and Alfredo Levy Yeyati, ***arXiv:2011.06566*** *(2020).*

Introduction

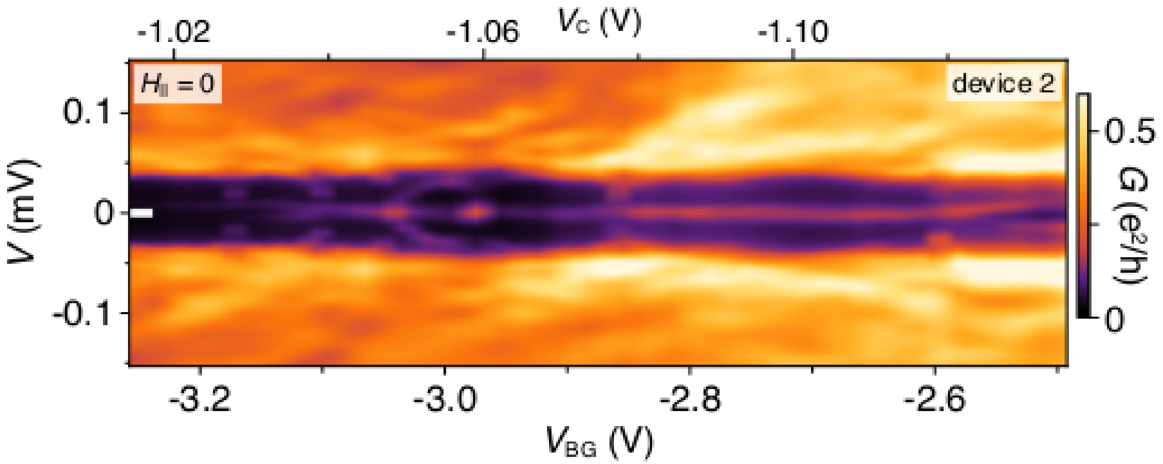
Experimental evidence

Charles Marcus' group:

- Y. Liu et al., App. Mat. **12**, 8780 (2020).
- Y. Liu et al., Nano Lett. **20**, 456 (2020).
- S. Vaitiekenas *et al.*, Nat. Phys. **17**, 43 (2021).



Overlapping device



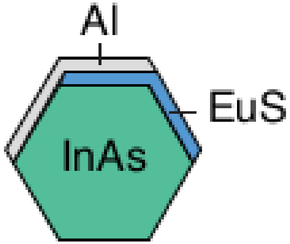
Introduction

Experimental evidence

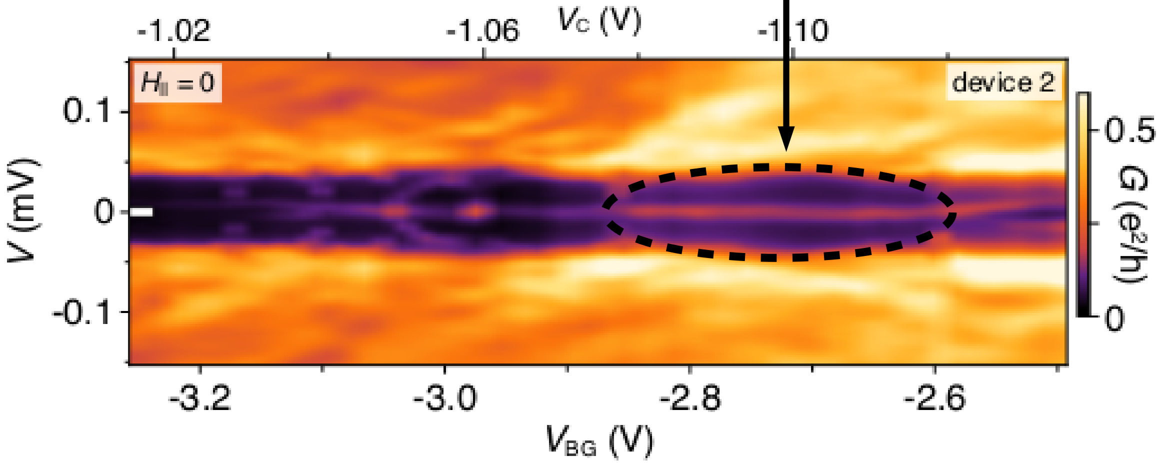
Charles Marcus' group:

- Y. Liu et al., App. Mat. **12**, 8780 (2020).
- Y. Liu et al., Nano Lett. **20**, 456 (2020).
- S. Vaitiekenas *et al.*, Nat. Phys. **17**, 43 (2021).

ZBP compatible with the existence of MBS



Overlapping device
(Shows ZBP)

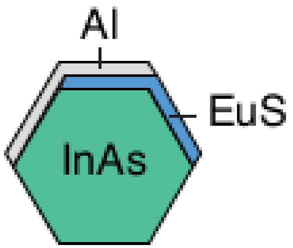


Introduction

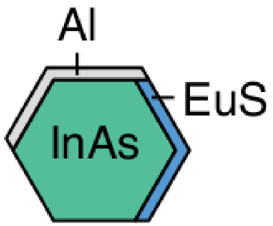
Experimental evidence

Charles Marcus' group:

- Y. Liu et al., App. Mat. **12**, 8780 (2020).
- Y. Liu et al., Nano Lett. **20**, 456 (2020).
- S. Vaitiekenas *et al.*, Nat. Phys. **17**, 43 (2021).



Overlapping device
(Shows ZBP)



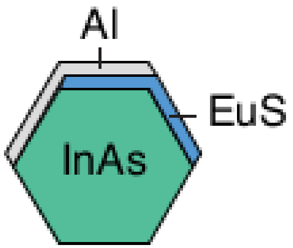
Non-overlapping device
(Doesn't show ZBP)

Introduction

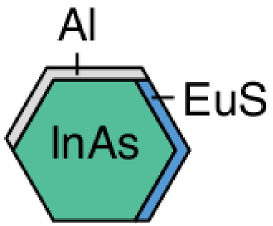
Experimental evidence

Charles Marcus' group:

- Y. Liu et al., App. Mat. **12**, 8780 (2020).
- Y. Liu et al., Nano Lett. **20**, 456 (2020).
- S. Vaitiekenas *et al.*, Nat. Phys. **17**, 43 (2021).



Overlapping device
(Shows ZBP)



Non-overlapping device
(Doesn't show ZBP)

Our work *(arXiv:2011.06566)*

We would like to:

- Give a comprehensive description of the heterostructure.
- Elucidate whether it can support MBS.
- Understand the differences between both setups.

Other concurrent theoretical works

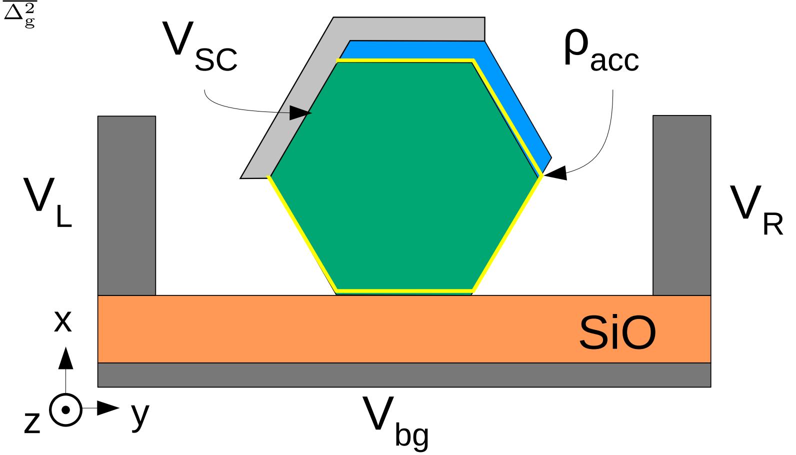
B. D. Woods *et al.*, arXiv:2011.01933
A. Maiani *et al.*, arXiv:2011.06547
C. X. Liu *et al.*, arXiv:2011.06567
J. Langbhen *et al.*, arXiv:2012.00055
A. Khindanov *et al.*, arXiv:2012.12934

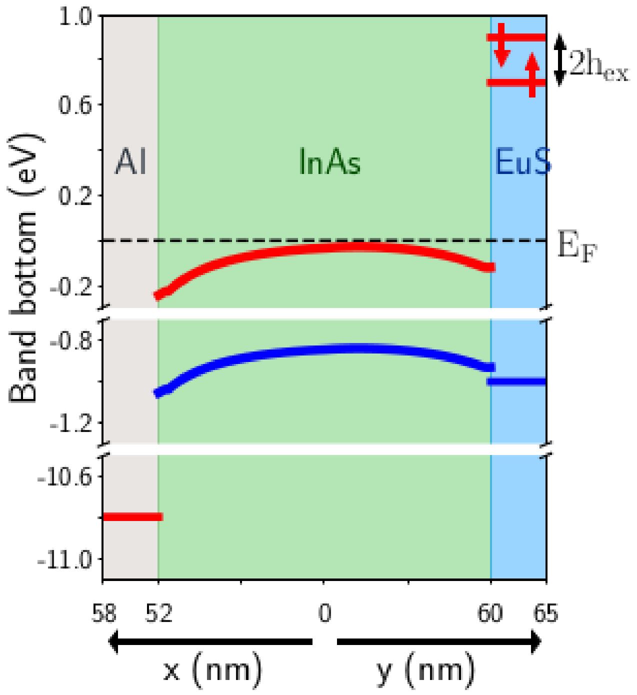
Full model

We include in the Hamiltonian all the materials involved in the heterostructure using realistic parameters. We also include self-consistent electrostatic interactions.

$$\mathrm{H}=\left(\frac{\hbar^2 k^2}{2m_{\mathrm{eff}}} - E_F(\vec{r}) + e\phi(\vec{r}) + h_{\mathrm{ex}}(\vec{r})\sigma_z\right)\tau_z + \vec{\alpha}\cdot\left(\vec{\sigma}\times\vec{k}\right)\tau_z + \Delta(\vec{r})\sigma_y\tau_y$$

$$\alpha(\vec{r}) = \vec{\alpha}_{\mathrm{int}} + \frac{eP_{\mathrm{fit}}^2}{3}\left[\frac{1}{\Delta_{\mathrm{g}}^2} - \frac{1}{(\Delta_{\mathrm{g}}+\Delta_{\mathrm{soff}})^2}\right]\vec{\nabla}\phi(\vec{r})$$



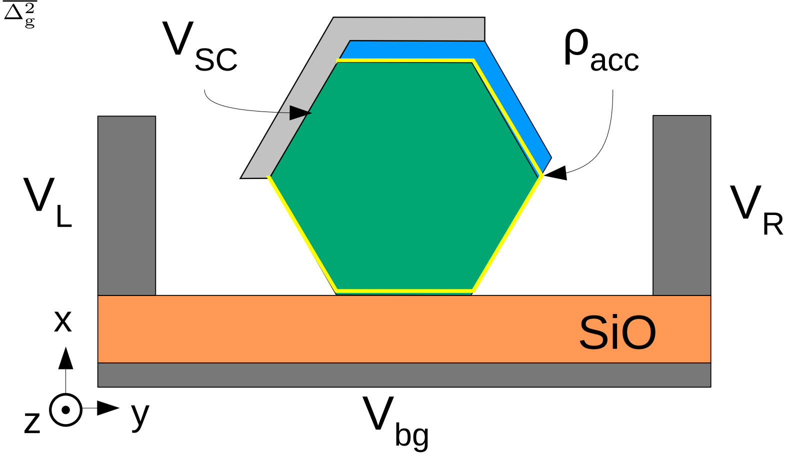


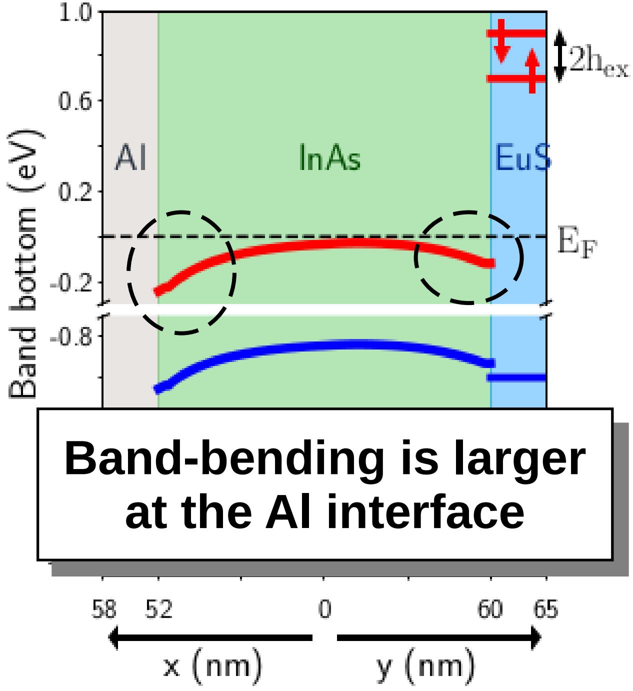
Full model

We include in the Hamiltonian all the materials involved in the heterostructure using realistic parameters. We also include self-consistent electrostatic interactions.

$$H=\left(\frac{\hbar^2 k^2}{2m_{\text{eff}}} - E_F(\vec{r}) + e\phi(\vec{r}) + h_{\text{ex}}(\vec{r})\sigma_z\right)\tau_z + \vec{\alpha}\cdot\left(\vec{\sigma}\times\vec{k}\right)\tau_z + \Delta(\vec{r})\sigma_y\tau_y$$

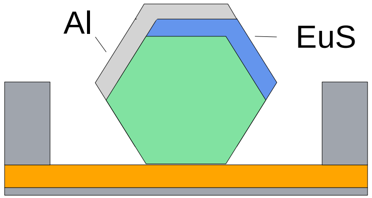
$$\alpha(\vec{r}) = \vec{\alpha}_{\text{int}} + \frac{eP_{\text{fit}}^2}{3}\left[\frac{1}{\Delta_g^2} - \frac{1}{(\Delta_g+\Delta_{\text{soff}})^2}\right]\vec{\nabla}\phi(\vec{r})$$

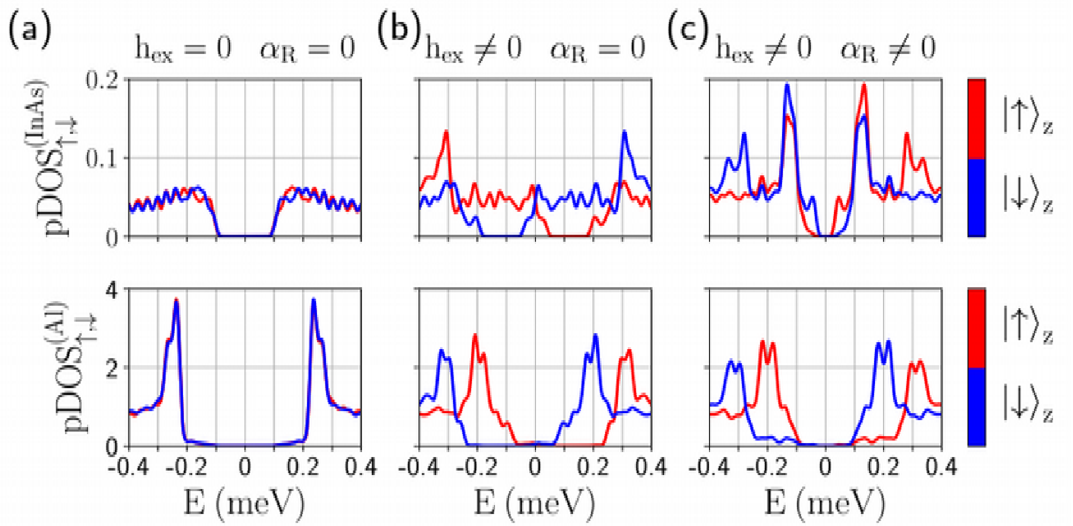




Full model

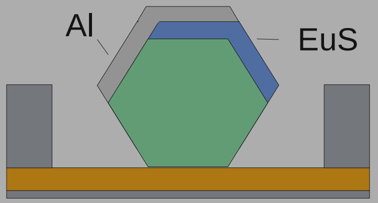
DOS for the **overlapping device** at specific gate voltages. We perform three different simulations.

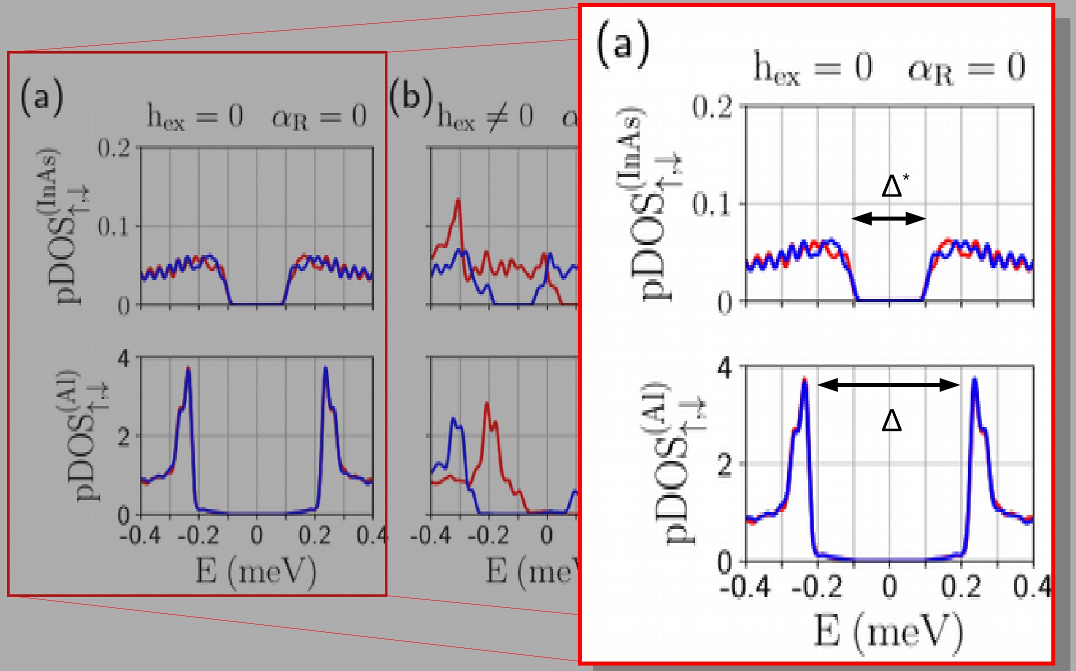




Full model

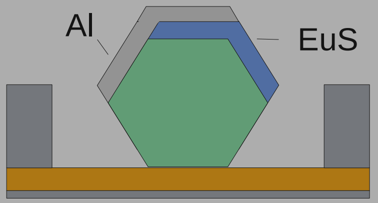
DOS for the **overlapping device** at specific gate voltages. We perform three different simulations.



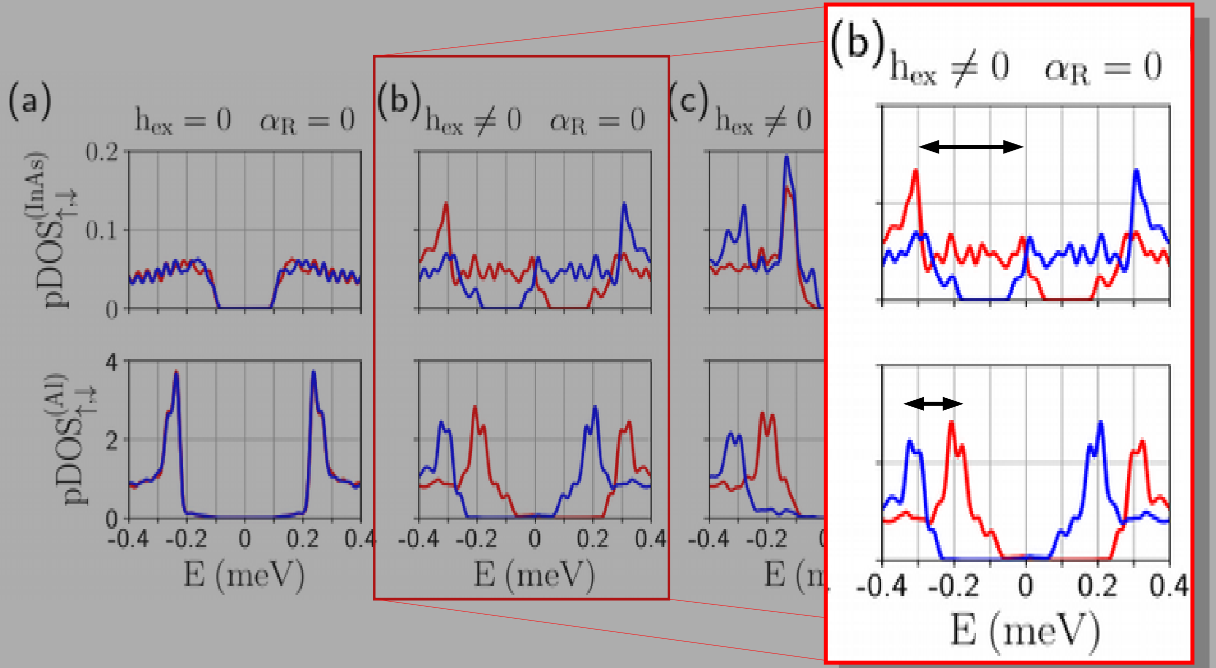


There is an induced gap Δ^* in the wire smaller than the parent gap Δ

Full model



DOS for the **overlapping device** at specific gate voltages. We perform three different simulations.

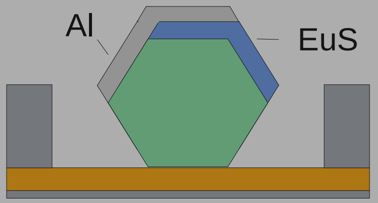


The induced exchange field in the **wire** is larger than Δ*

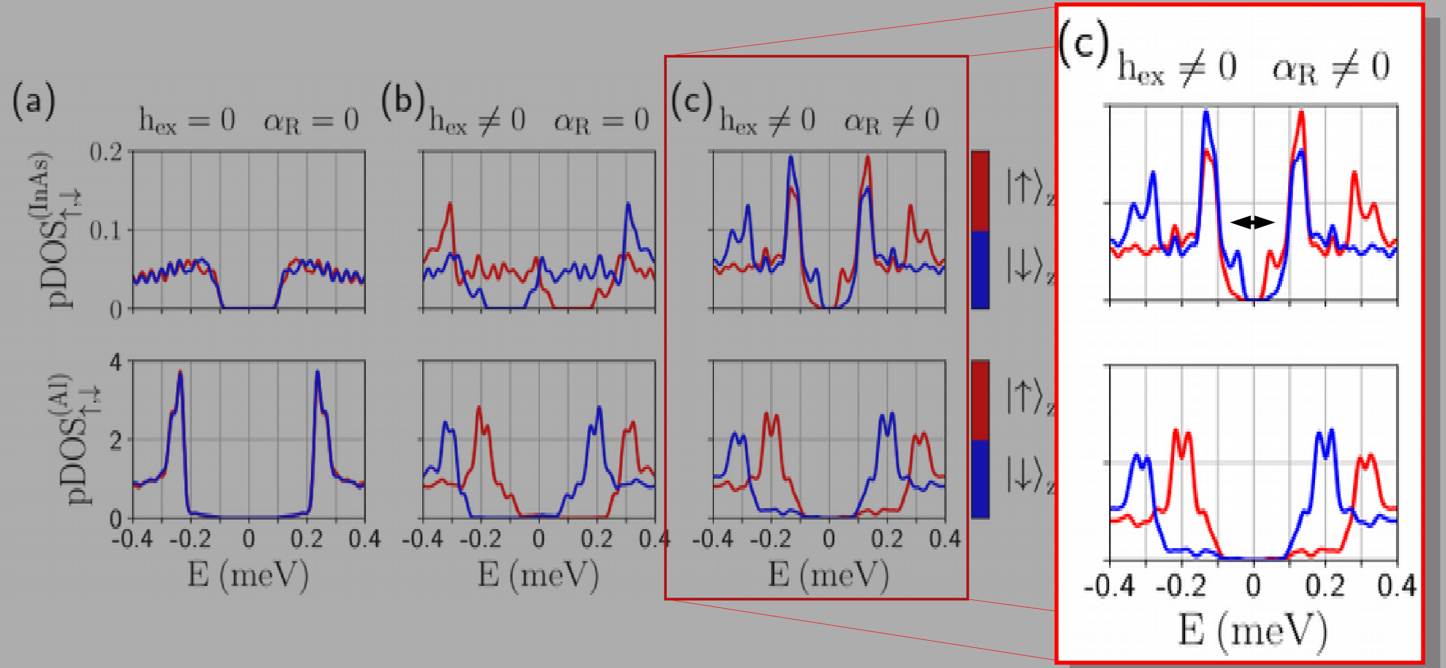
In the **SC** is just 0.06 meV, smaller than Δ

M. Rouko *et al.*, Phys. Rev. B **100**, 184501 (2019)

Full model



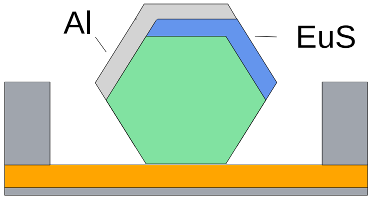
DOS for the **overlapping device** at specific gate voltages. We perform three different simulations.

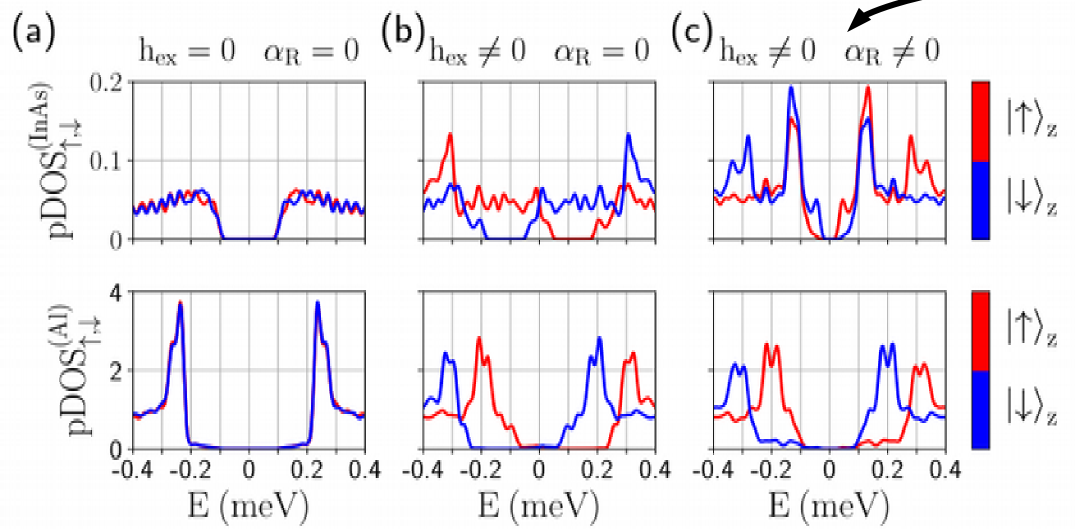


With SOC, a gap is reopen, signaling a topological phase transition

Full model

DOS for the **overlapping device** at specific gate voltages. We perform three different simulations.

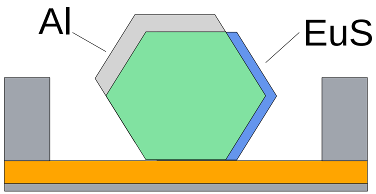




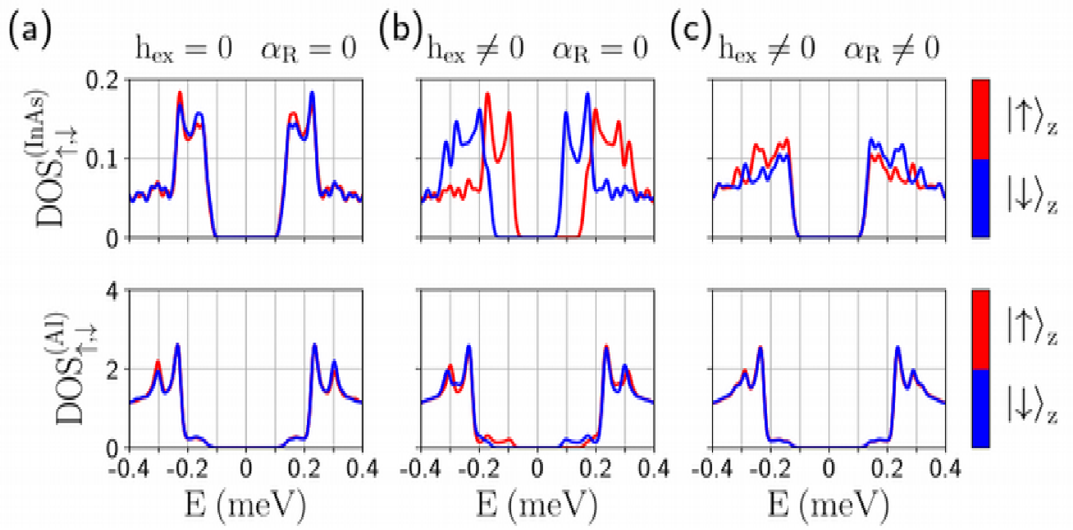
$\mathcal{Q} = -1$

Topologically **non-trivial**

Full model

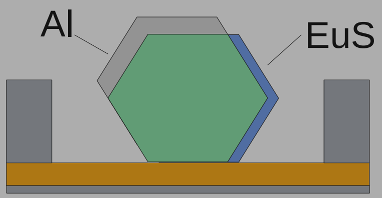


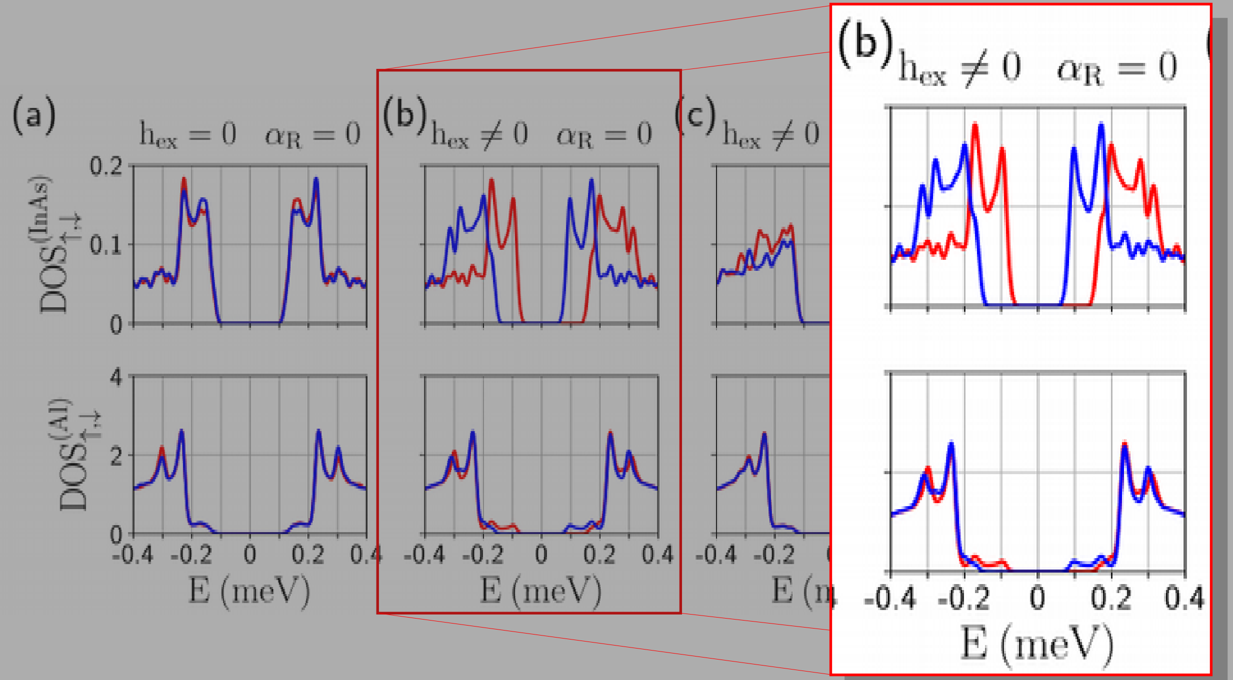
DOS for the **non-overlapping device** at specific gate voltages.
We perform three different simulations.



Full model

DOS for the **non-overlapping device** at specific gate voltages.
We perform three different simulations.

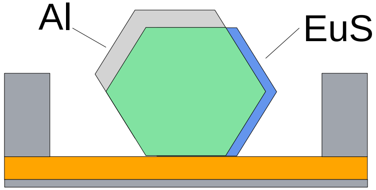


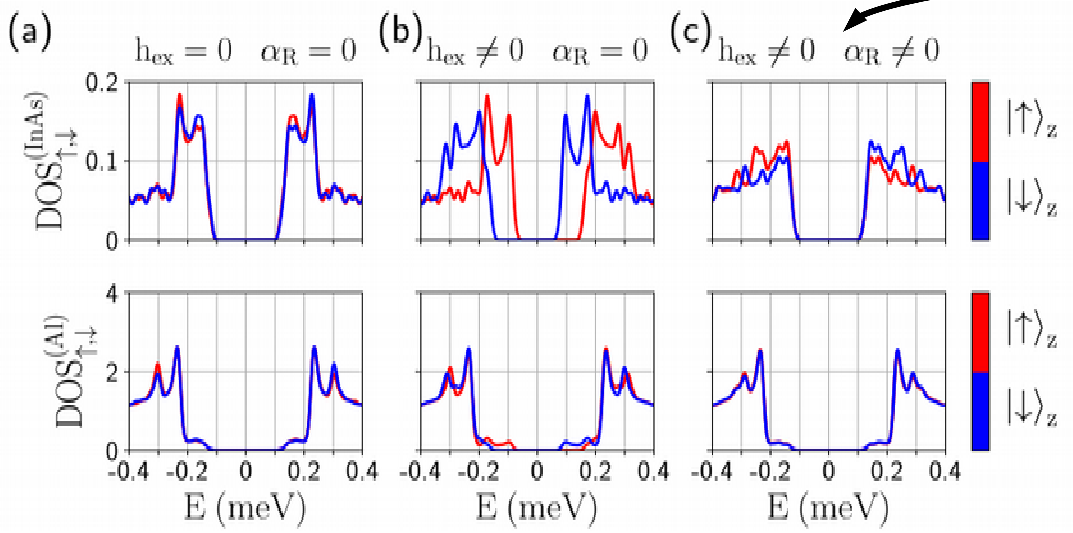


In the non-overlapping device, the induced exchange field is not large enough to close the gap

Full model

DOS for the **non-overlapping device** at specific gate voltages.
We perform three different simulations.





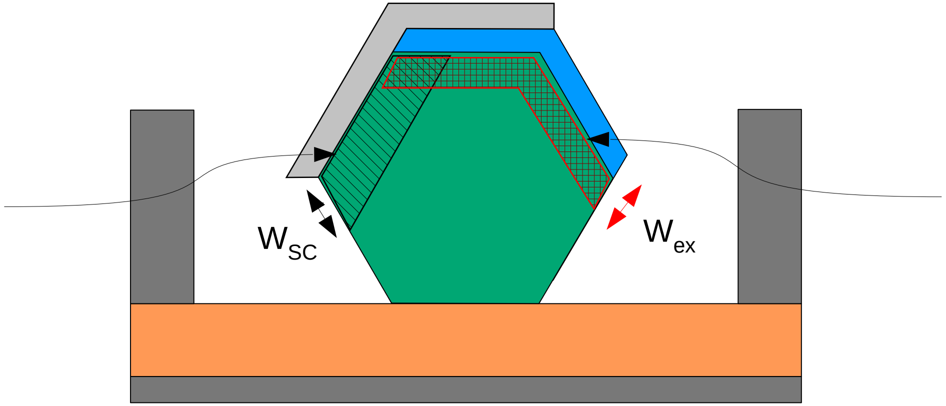
$\mathcal{Q} = +1$

Topologically **trivial**

Effective model

We “integrate out” the Al and the EuS, and we directly include the proximity effects into the InAs nanowire in an effective way. This reduces the computational cost and allows to find the phase diagram.

Superconducting proximity region characterized by Δ^* and h_{Al}

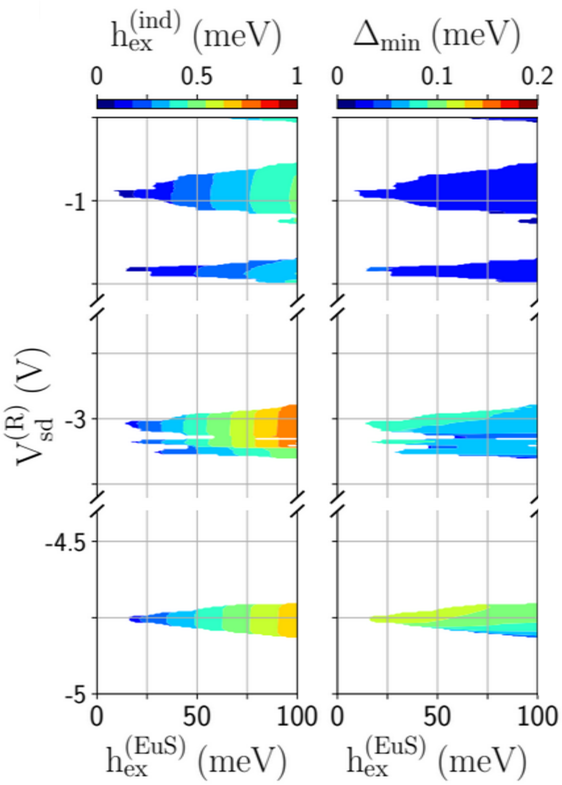


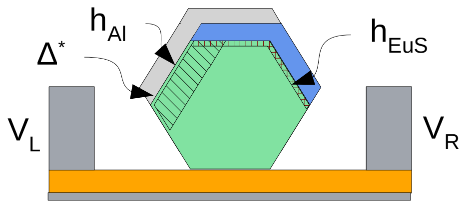
Ferromagnetic proximity region characterized by h_{EuS}

We choose W_{SC} and W_{ex} in such a way to reproduce (roughly) the same behaviour as in the full model.

Effective model

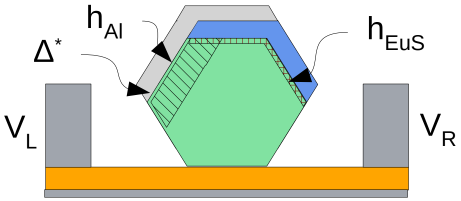
Phase diagrams for the **overlapping** device.

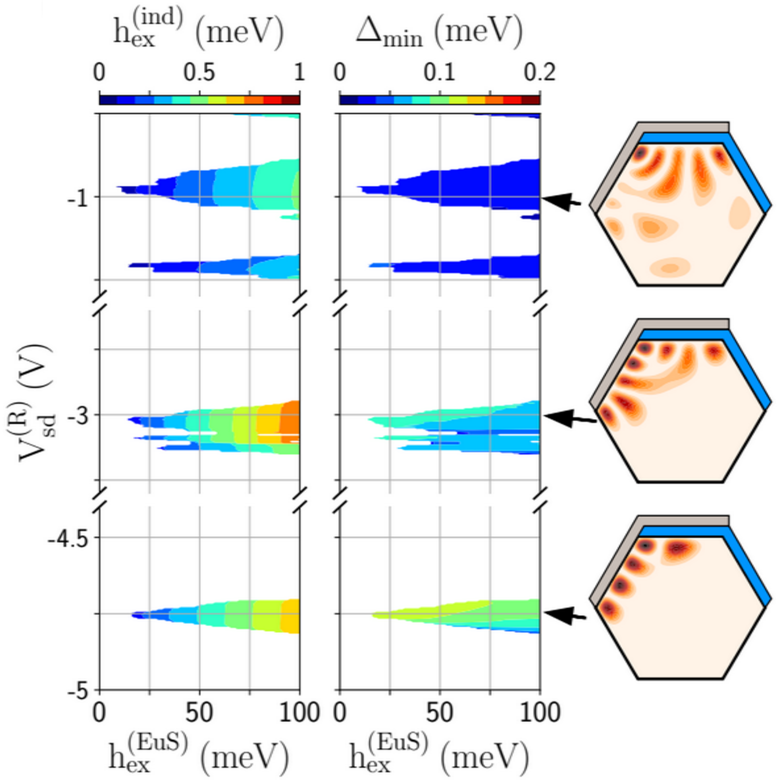




Effective model

Phase diagrams for the **overlapping** device.

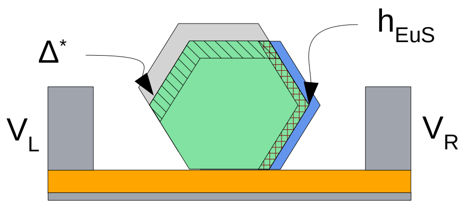


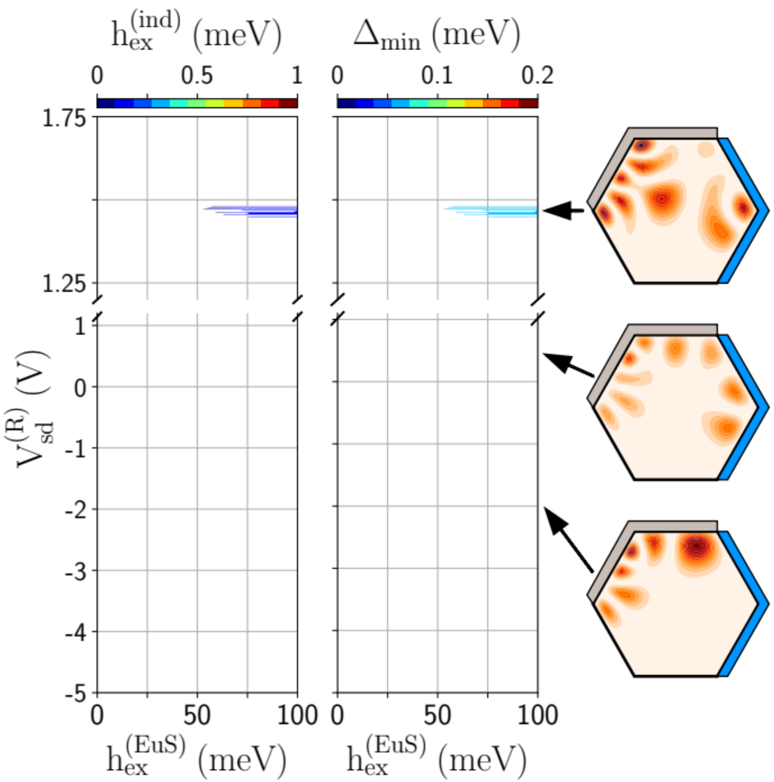


Increasing gate potential pushes wavefunction towards this region (the right part in this case)

Effective model

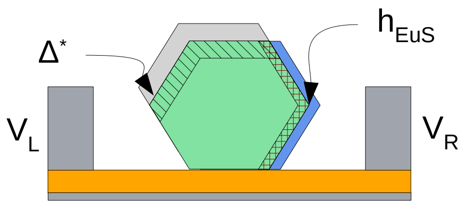
Phase diagram for the **non-overlapping** device.

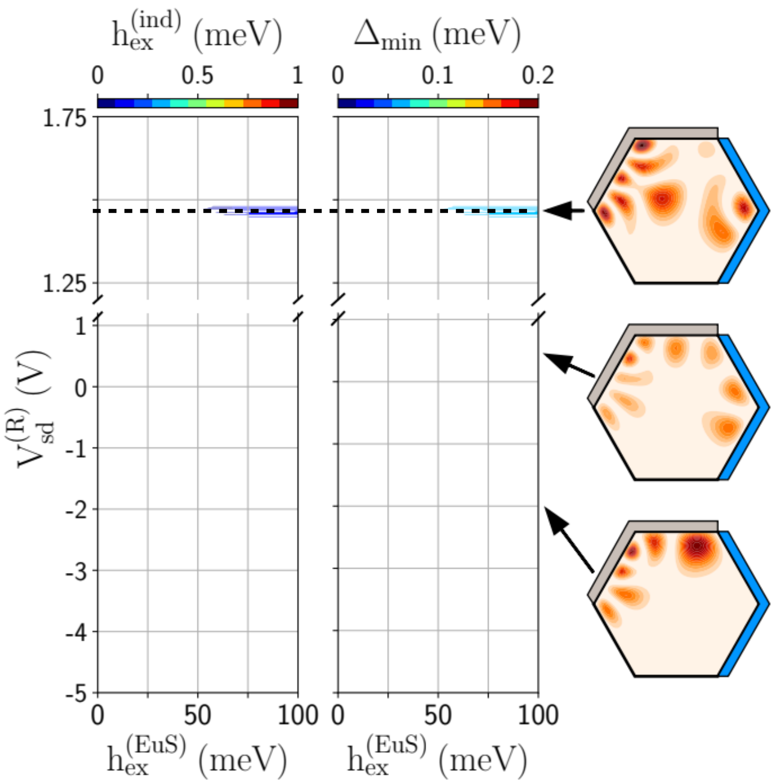


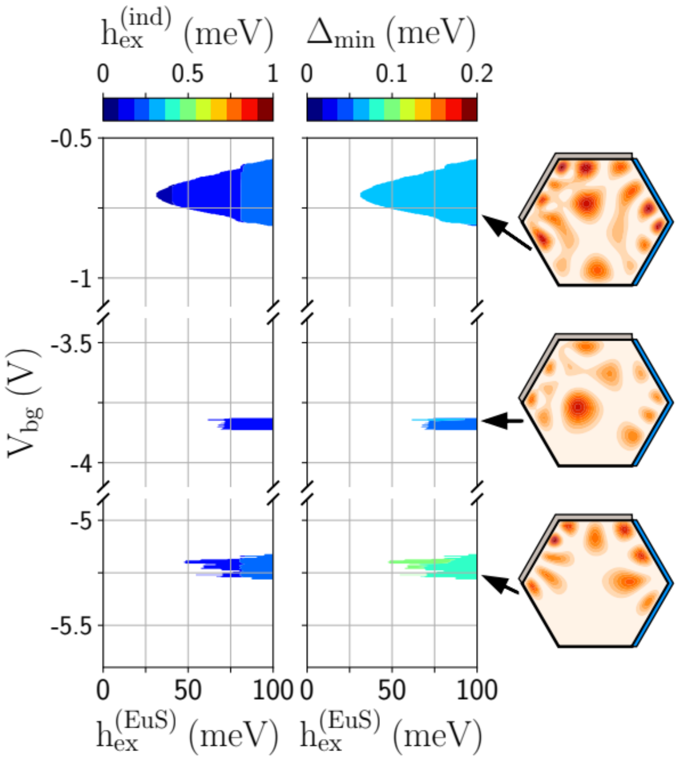


Effective model

Phase diagram for the **non-overlapping** device.

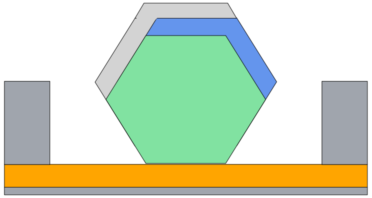




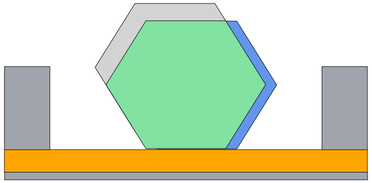


Conclusions

- InAs/Al/EuS heterostructures intrinsically incorporates the effect of a superconducting pairing, a Zeeman field, and SO interactions.
- In order to have MBS, the wavefunction needs to be localized close to the EuS-InAs and Al-InAs interfaces at the same time.
- The position of the wavefunction, and therefore the strength of the **proximity effects**, **can be controlled by the gates**.



Thank you for your attention!



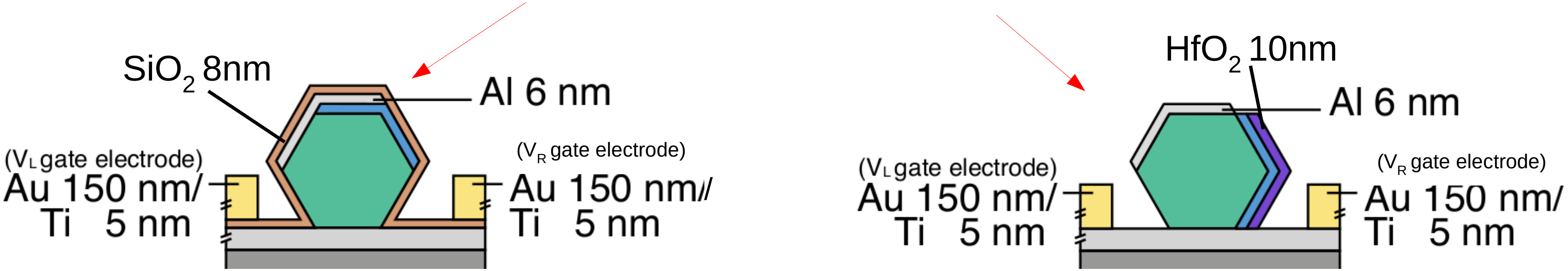
Supplementary Material

A: Effective Model

Model

The electrostatic potential is determined self-consistently (in the Thomas-Fermi approximation) using the Poisson equation. The electrostatic environment is taken into account through the dielectric permittivity.

$$\vec{\nabla}(\epsilon(\vec{r}) \cdot \vec{\nabla}\phi(\vec{r})) = \rho(\vec{r})$$

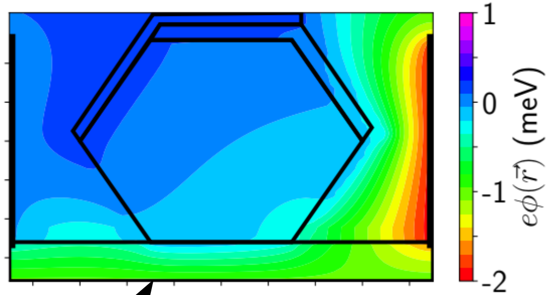


A recent experiment shows that there is an accumulation layer at the InAs-EuS interface similar to the one of the free facets. Thus, we include the same accumulation layer ρ_{acc} in the nanowire facets that are not in contact with Al. Additionally, we simulate the InAs-Al band bending imposing V_{SC} as boundary condition on the Al.

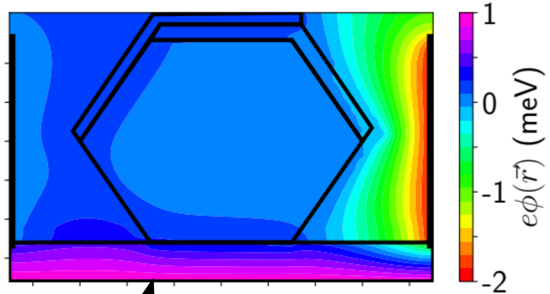
Model

Overlapping device

Non-overlapping device

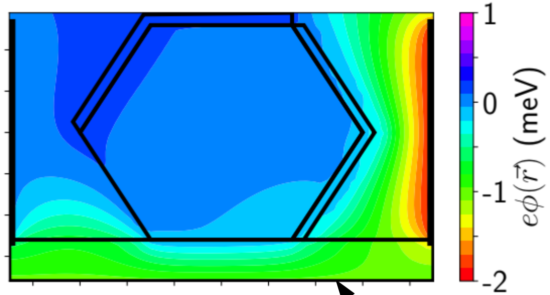


V_{bg}=-1V

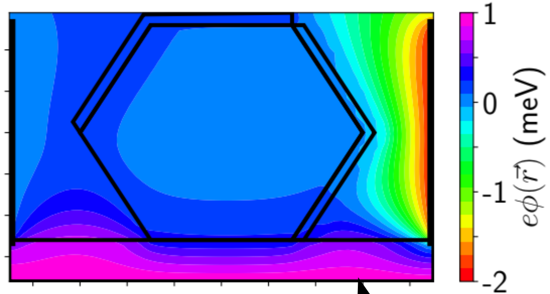


V_{bg}=1V

As the back-gate voltage is increased, the wavefunction is pushed towards the bottom of the wire.



V_{bg}=-1V

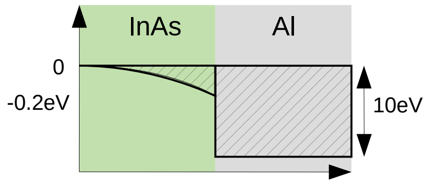


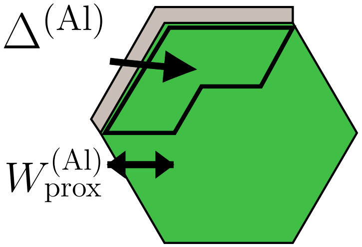
V_{bg}=1V

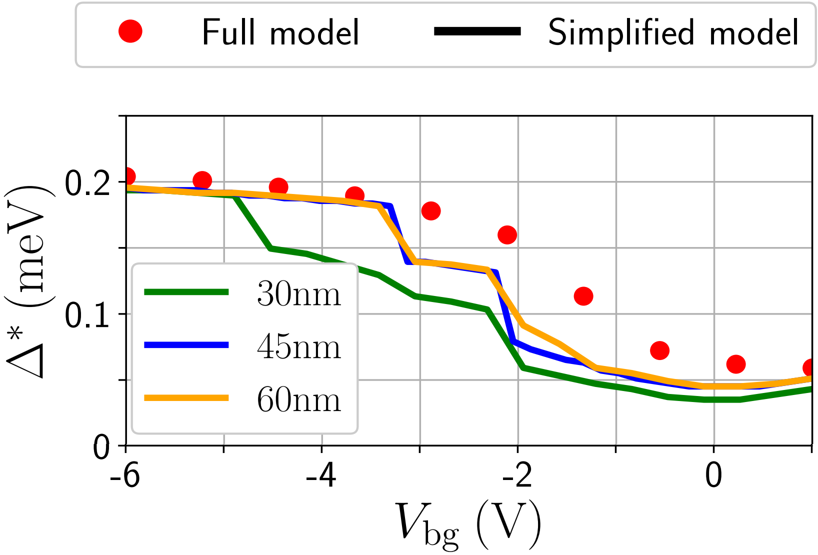
Model

To describe the superconductivity inside the semiconductor, one would need to include the superconducting layer also at a tight-binding level. But one can also describe the proximity effect directly into the superconductor.

Band schematics

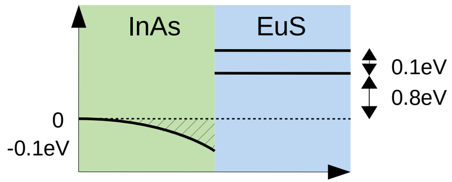




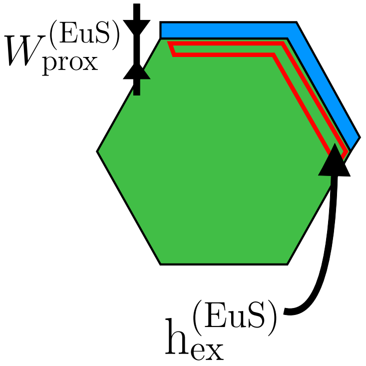


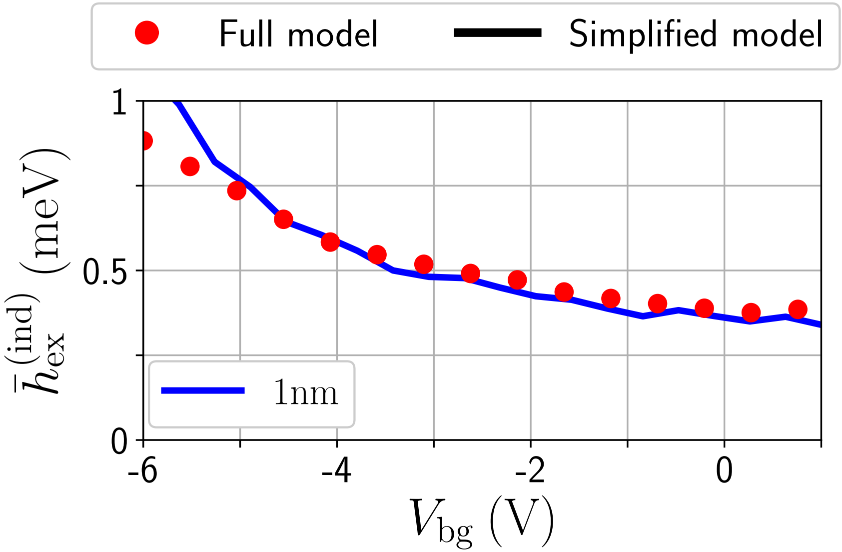
Model

Band schematics



One can do the same for the EuS layer.



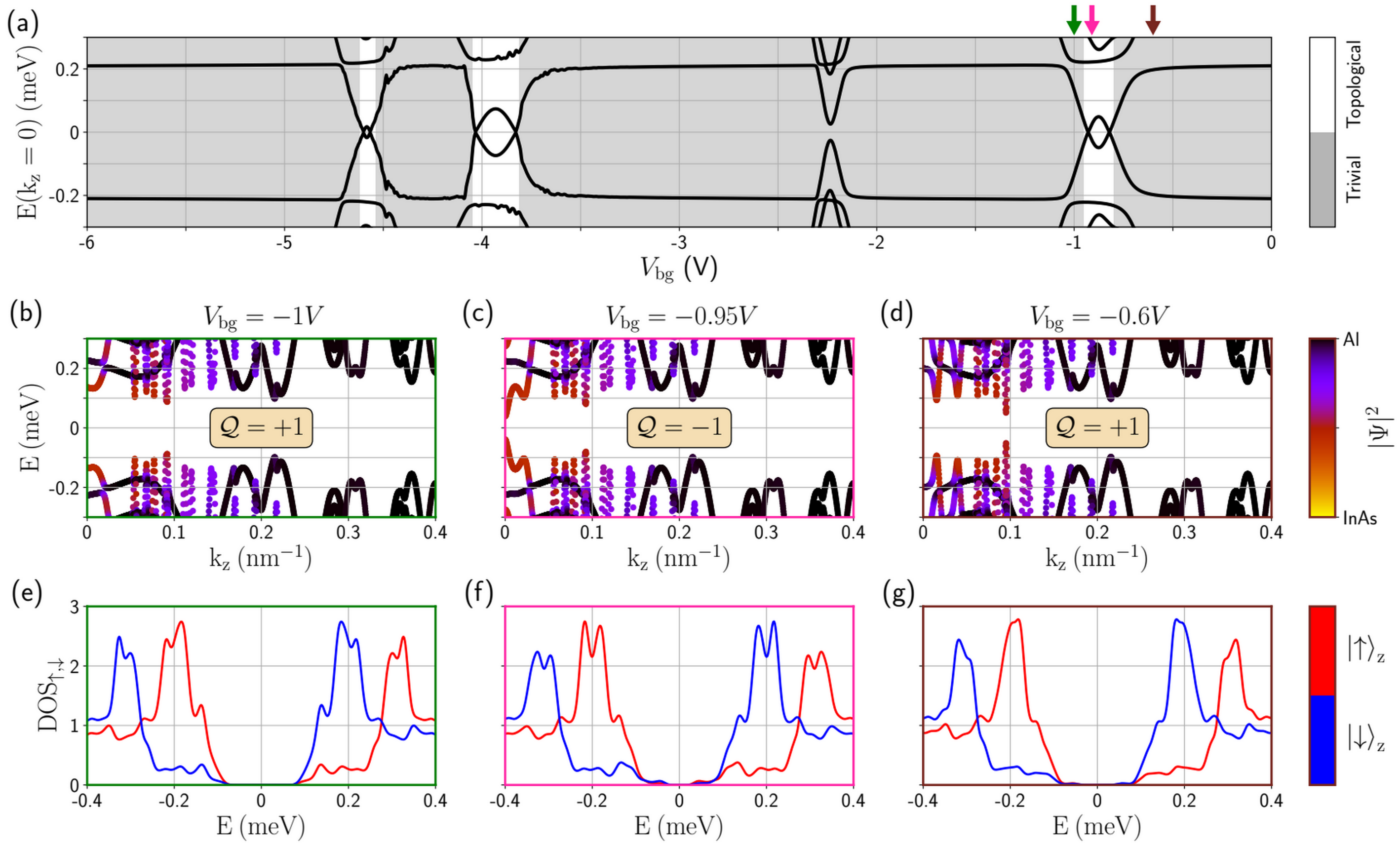


Supplementary Material

B: Further details on full-model results

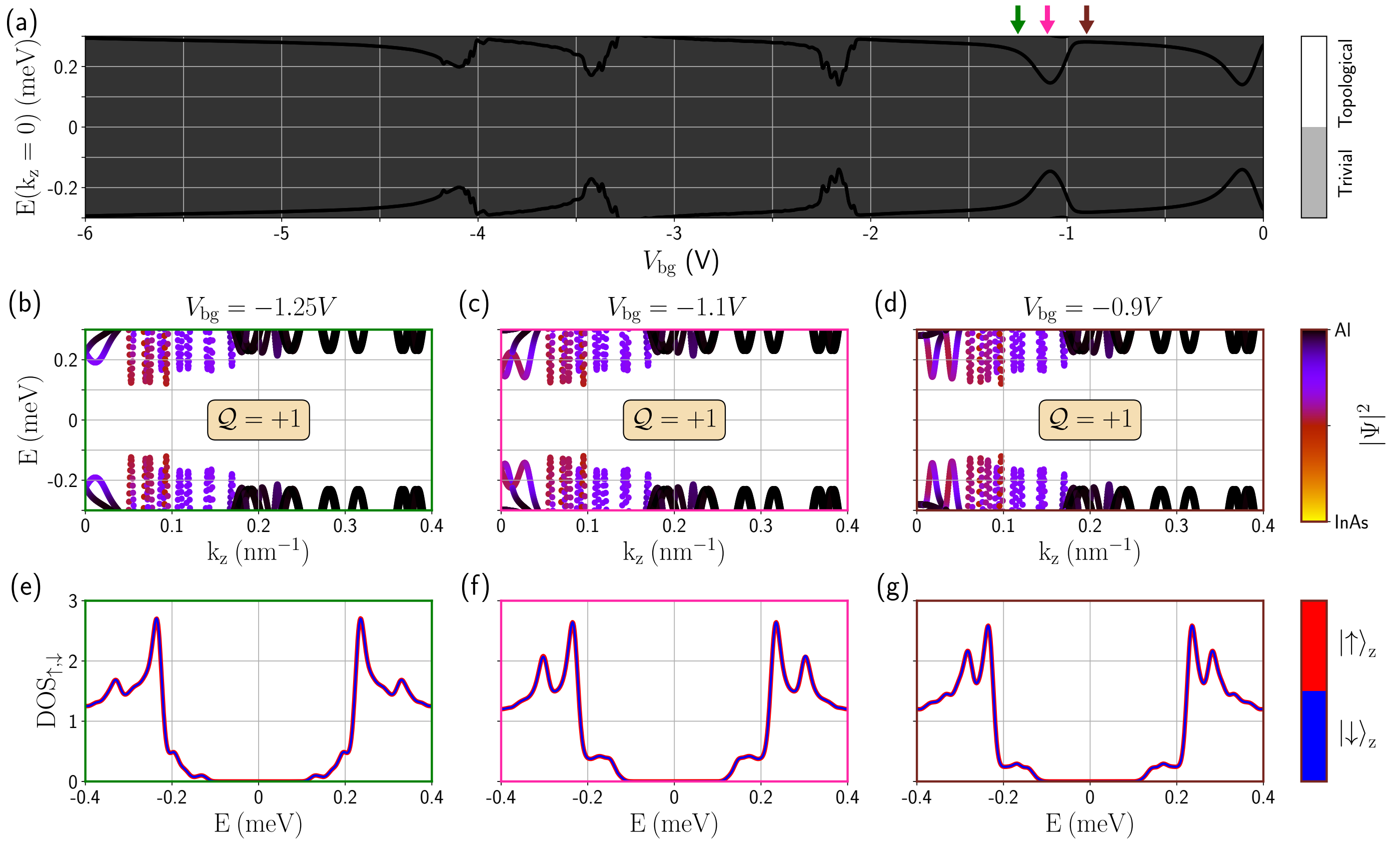
Full model

Overlapping device
Non-overlapping device
3-facet overlapping device



Full model

Overlapping device
Non-overlapping device
3-facet overlapping device



Full model

Overlapping device
Non-overlapping device
3-facet overlapping device