Conditions for Robust Majorana Bound States in Superlattice Majorana Nanowires

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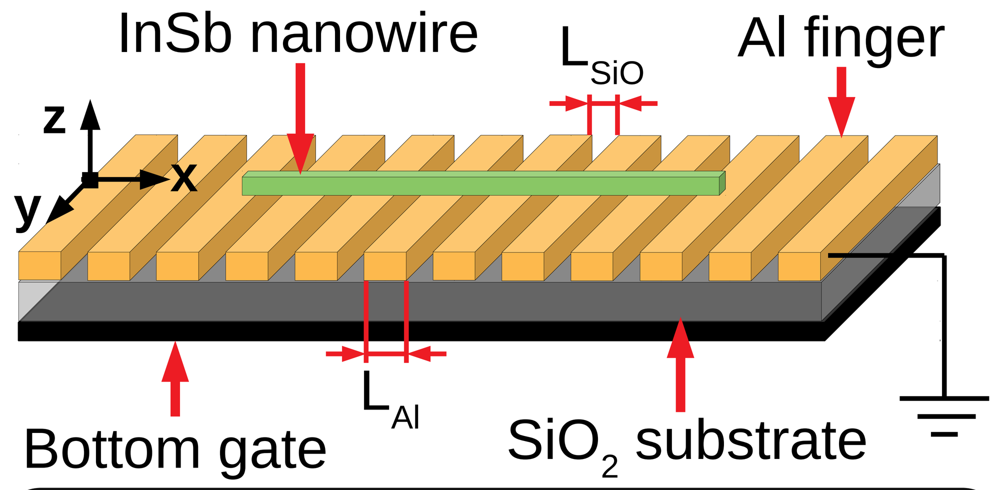
ABSTRACT: Spectroscopic measurements in recent Majorana Nanowire experiments [1] exhibit Zero Bias Peaks compatible with the existence of Majorana Bound States (MBS). However, a **proof of the non-locality** of its wavefunction **is still lacking**. In this work we study a recently proposed configuration [2] in which the semiconductor nanowire is placed over a **superlattice array of superconductor (SC) fingers**, allowing a **STM tip to measure the local dI/dV** on top of the wire, **revealing the non-local nature of the MBS**. Here, we focus on the **impact of the inhomogeneous electrostatic potential** created by this superlattice on the Nanowire spectral properties. For that purpose, we use a **3D finite model** for the Nanowire and we compute the **electrostatic profile solving self-consistently the Poisson equation**. We analyze which are the optimal superlattice parameters for **obtaining robust MBS**.

1. Model

Model



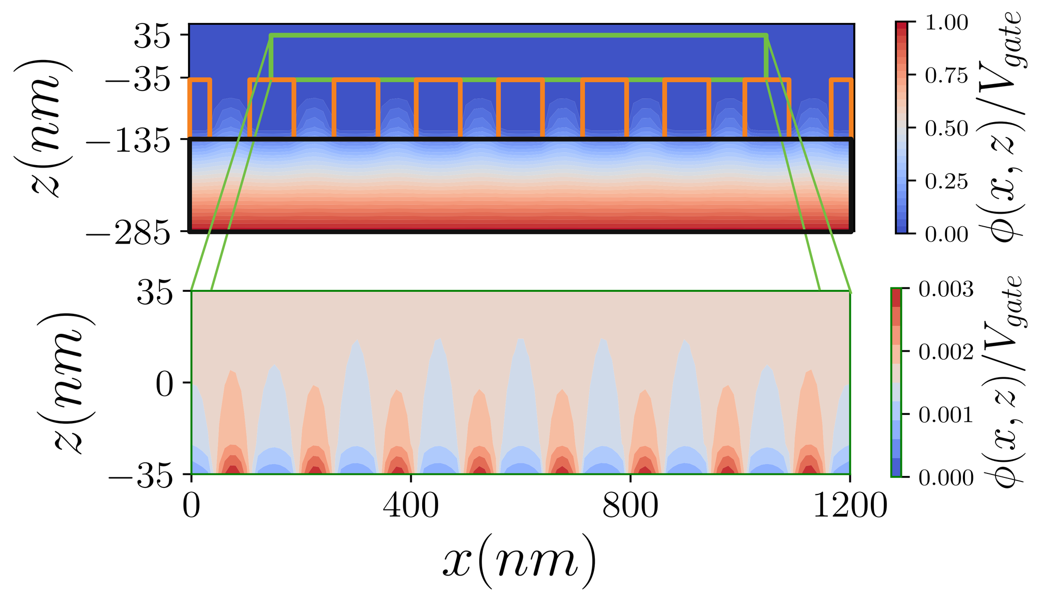
Superlattice parameters: $L_{cell}=L_{Al}+L_{SiO}$ $r_{Al}=L_{Al}/L_{cell}$

We use the effective Hamiltonian for a **3D Majorana nanowire**…

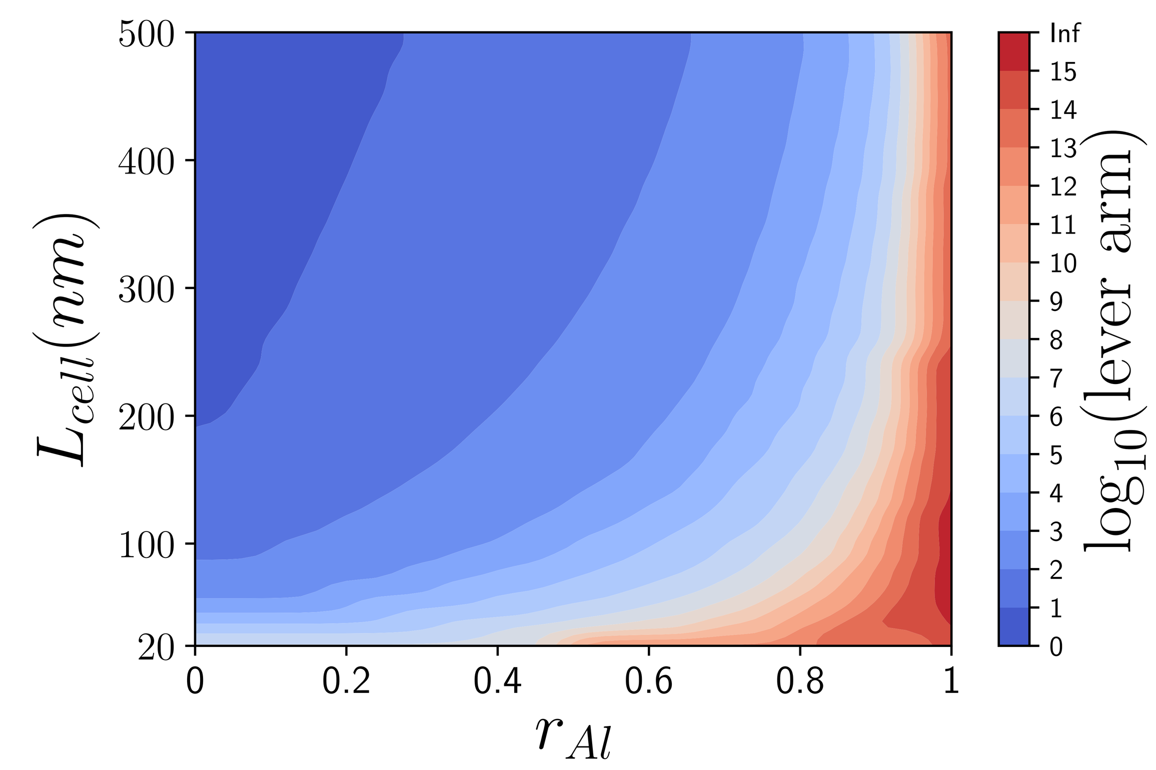
$$H=\left[\left(\frac{\hbar^2k^2}{2m^*}+E_{int}-\phi(x,y,z)\right)\sigma_0+\right.$$
$$\left.+\alpha_R(k_x\sigma_y-k_y\sigma_x)+V_Z\sigma_x\right]\tau_Z+\Delta(x,y,z)\sigma_y\tau_y$$

Where $\Delta(x,y,z)$ is given by a step-function ($\Delta(x)=\Delta_0$ when x is over a SC finger and 0 otherwise) and $\varphi(x,y,z)$ is obtained by solving the **Poisson equation** in the whole space.

Electrostatic Profile



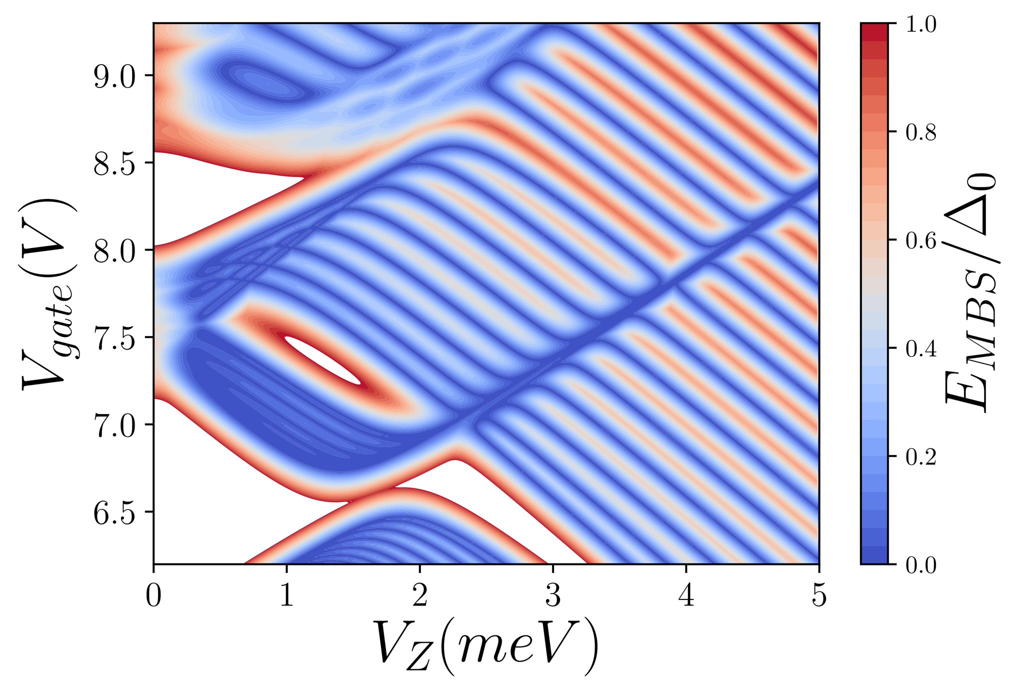
2. Lever arm



- Large lever arms also mean large potential oscillations. That could create QDs along the wire instead of extended quasiparticles.

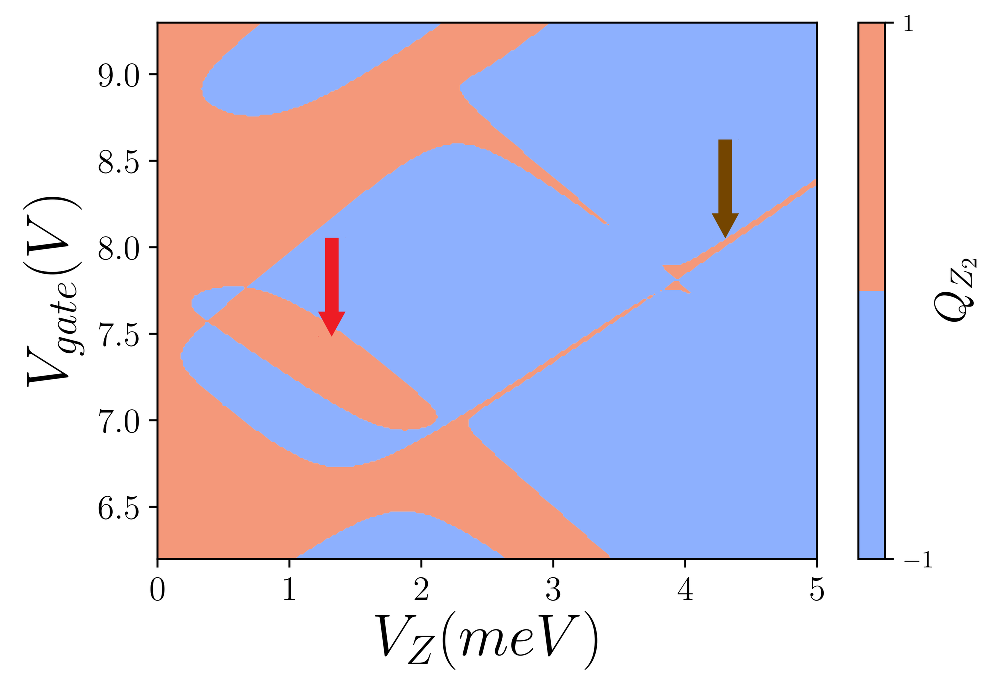
3. Impact of the superlattice on the Spectral Properties

Phase Diagram for a 1D nanowire



- The induced superconductivity is always smaller, leading to less topological protection.

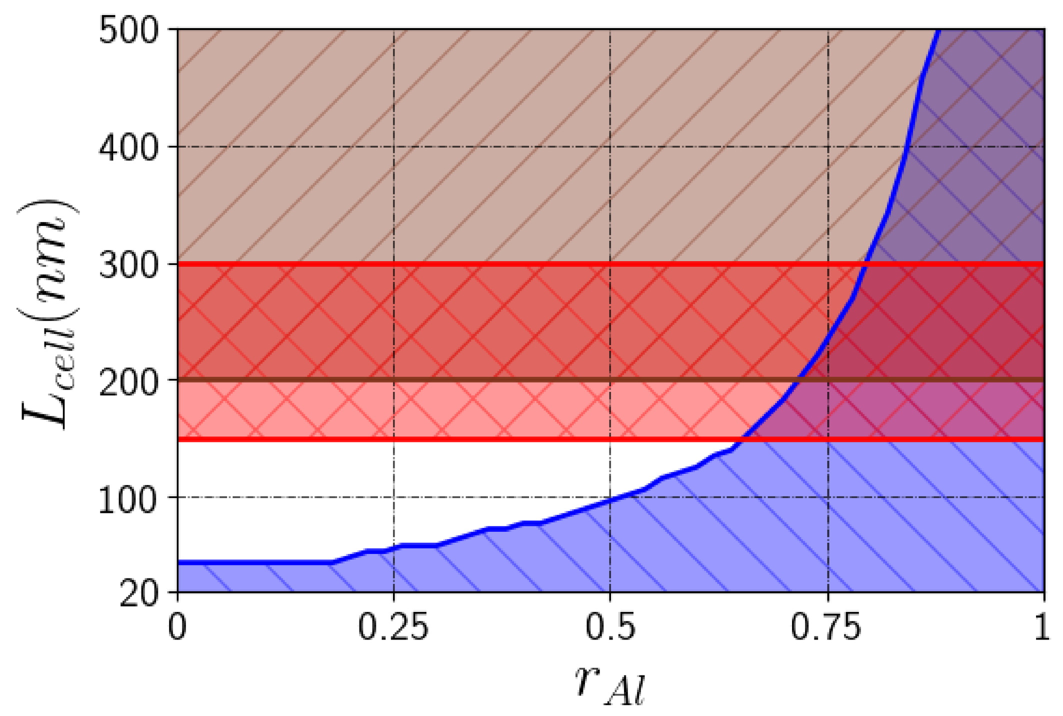
Its corresponding bulk topological phase



- Longitudinal sub-bands emerge due to the superlattice periodicity (even-odd effect).
- Trivial holes emerge when $\lambda_{MBS}=L_{cell}$.

4. Optimal Superlattice Parameters

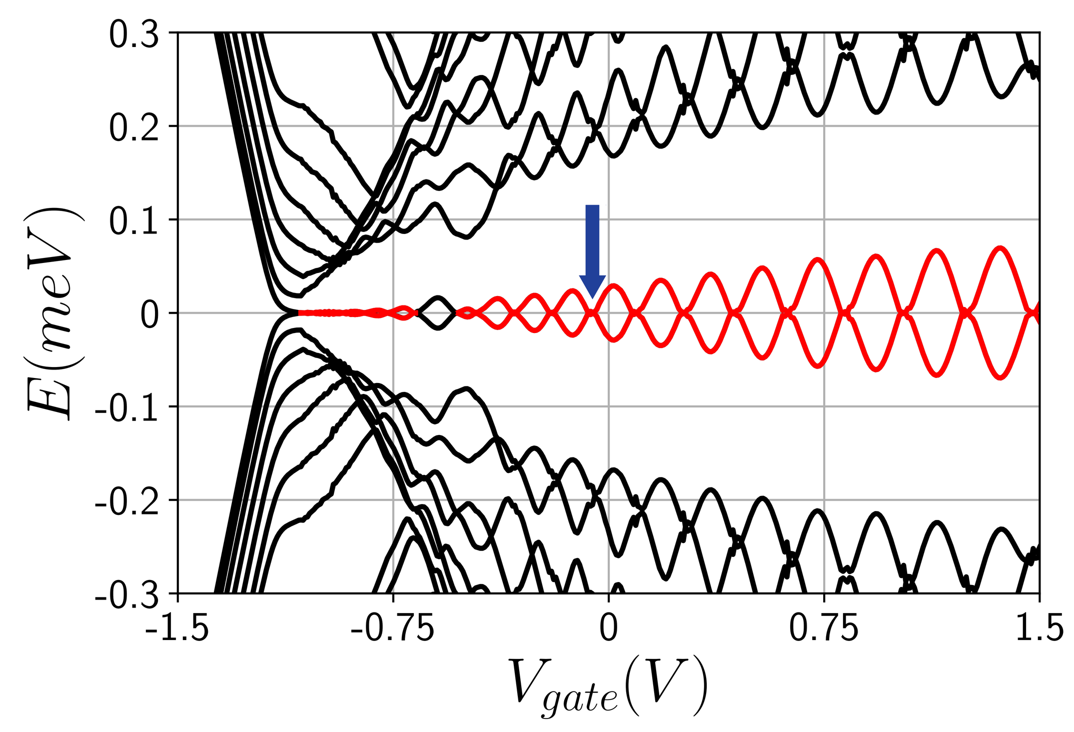
Optimal Superlattice Parameters



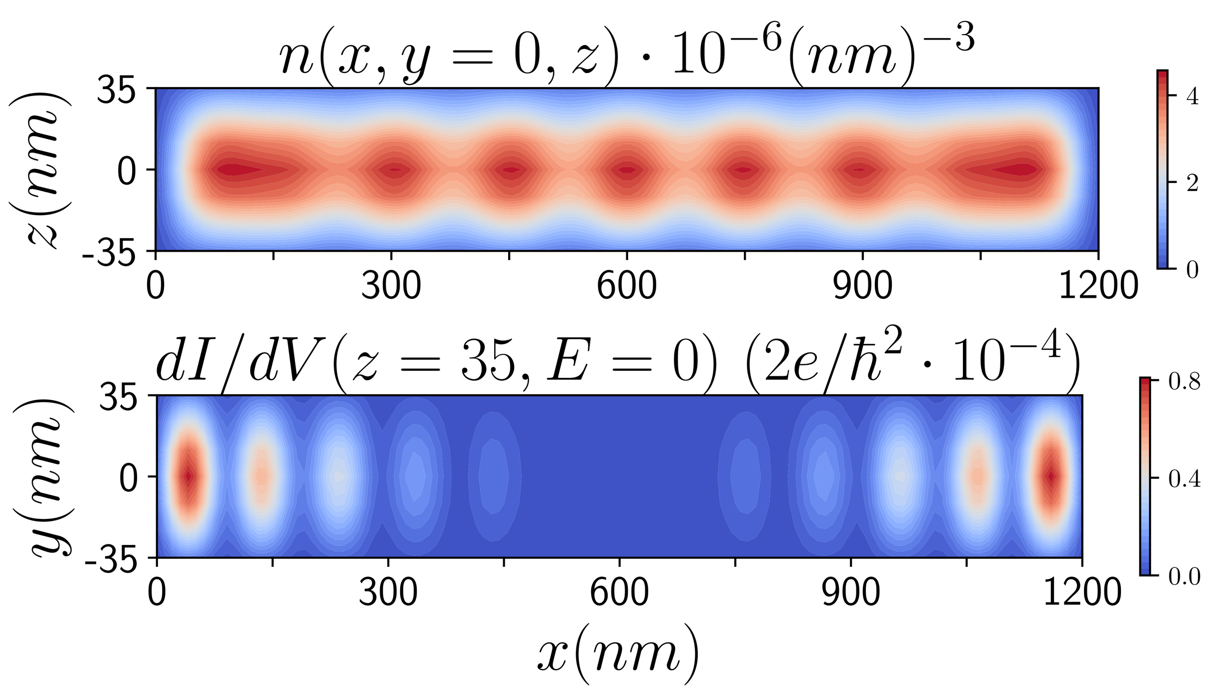
We discard those parameters for which:

- gating the wire is difficult.
- trivial holes are created.
- longitudinal sub-bands are close one to each other.

Results for a 3D nanowire with Poisson



- The energy spectrum for L_{cell}**=150nm** and r_{Al}**=0.5** shows MBSs (red). However, there is a topologically trivial hole.
- There are zero energy pinned regions.



- The charge density (top) oscillates with the periodicity of the superlattice.
- The dI/dV (bottom) shows the MBSs at zero energy, with a different periodicity.

5. Summary and Conclusions

- The inhomogeneous superconductivity lessens the topological protection.
- Depending on the superlattice parameters, the robustness of the topological phase may be weaker. That occurs when L_{cell} is either, as small that different longitudinal bands are close one to each other (compared to the other energy scales), or when L_{cell} is comparable to λ_{MBS}.
- Attending to these aspects and the capability for gating, some superlattice constants are not desirable for obtaining robust MBS.
- For the desirable superlattice constants values, we obtain topologically protected MBSs with a wavelength given by λ_{MBS}, while the charge density of the wire oscillates with the periodicity of the superlattice.

Parameters.- $m^*=0.015m_e$, $E_{int}=-10$meV, $\alpha_R=60$meV·nm, $\Delta_0=0.3$meV, $L_x=1.2$µm, $W_y=W_z=70$nm, $W_{Al}=100$nm, $W_{SiO}=150$nm, $L_{cell}=150$nm, $r_{Al}=0.5$, $V_{Al}=0$meV, $V_z=1.5$meV, T=10mK.

References.- [1] Hao Zhang *et al.*, *Nature* **556**, 7699 (2018).
[2] Yoav Levine, Arbel Haim, and Yuval Oreg, *Phys. Rev. B* **96**, 165147 (2017).