Spin-orbit coupling of holes in III-V compound semiconductor core-shell nanowires: application to full-shell Majorana physics

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Motivation

Full-shell Majorana nanowires (NWs) are predicted to host topological superconductivity[1] (TS). They have been carried out in III-V compound semiconductor (SM) NWs fully encapsulated by a superconductor (SC) shell. However, spin-orbit (SO) coupling is negligible in this geometry because, in the conduction band, it depends on the electric field, which vanishes[2].

Here, we explore to leverage the SO coupling of the hole bands instead. We find strong engouh values of the SO coupling, around 20 meV·nm, which does not depend on the electric field or the strain at the interface. This is an advantage as well with respect to Ge/Si NWs, which rely on strain at the interface to support a measurable SO coupling[3].
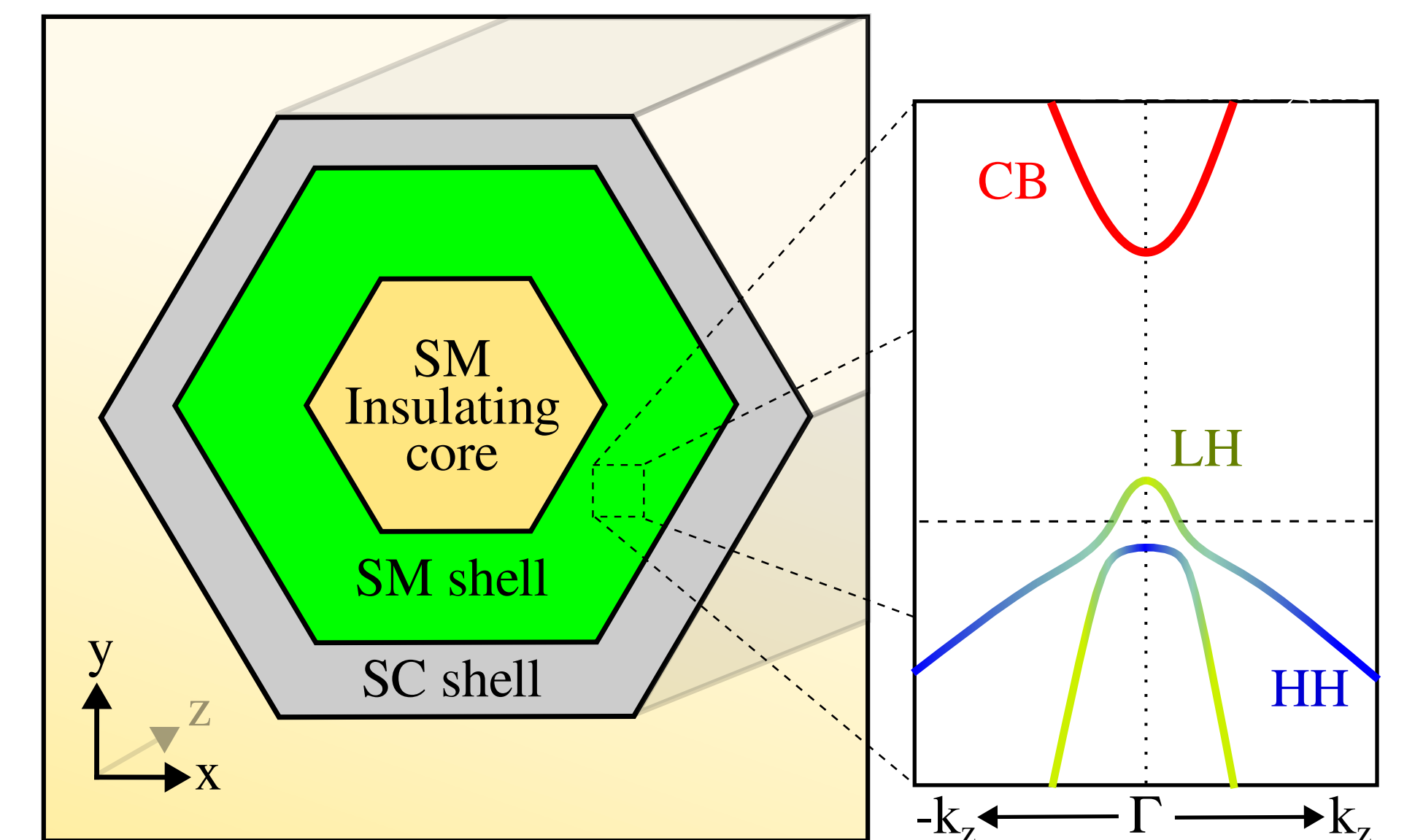

Model

We investigate InP/GaSb core-shell NWs:

- In InP/GaSb heterostructures the Fermi level may lay at the valence bands -- **hole carriers**
- The insulating core pushes the wavefunction to the outer facet -- **enhanced proximity effect**
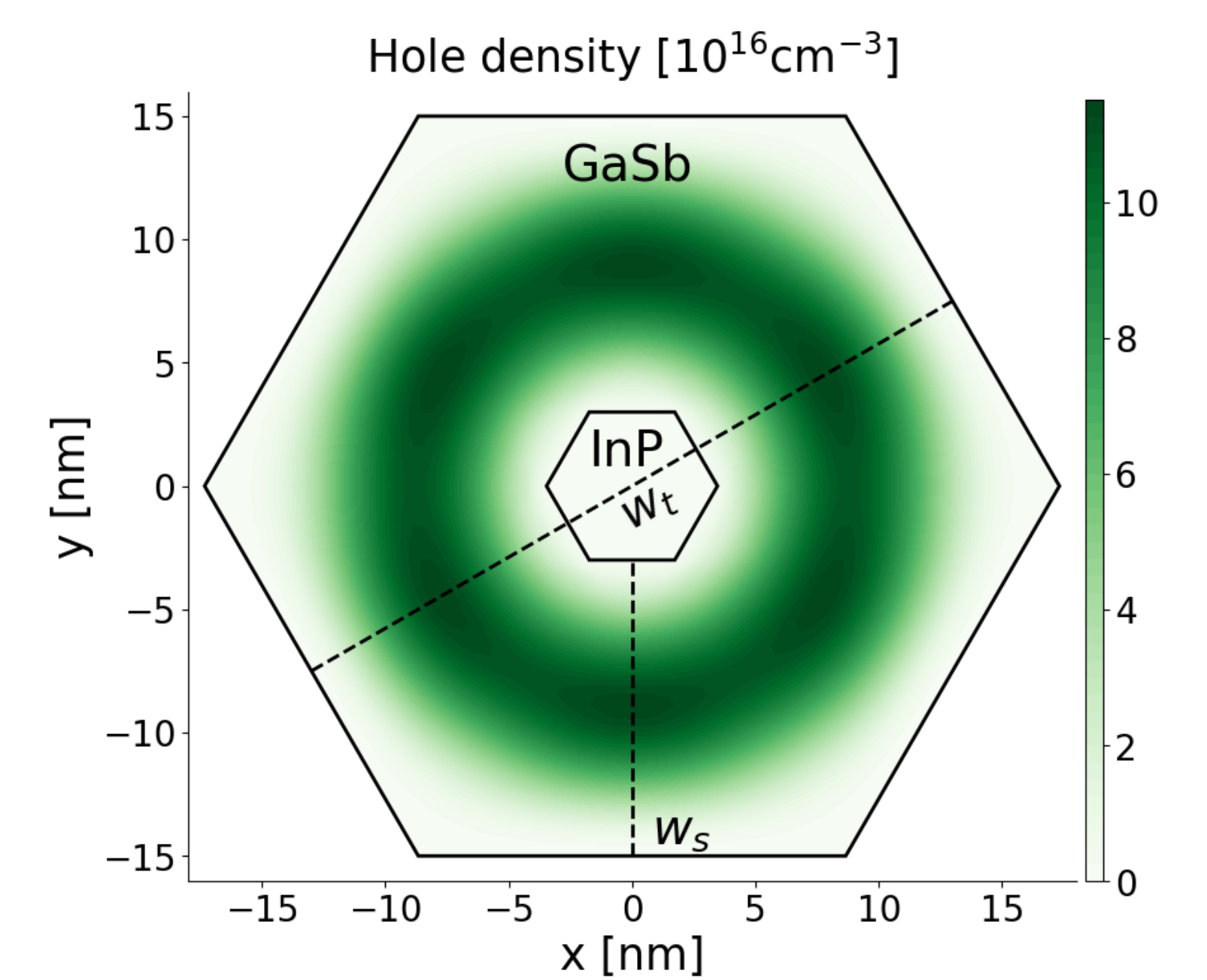- The facets are covered and the core is insulating -- **the disored is inhibited**
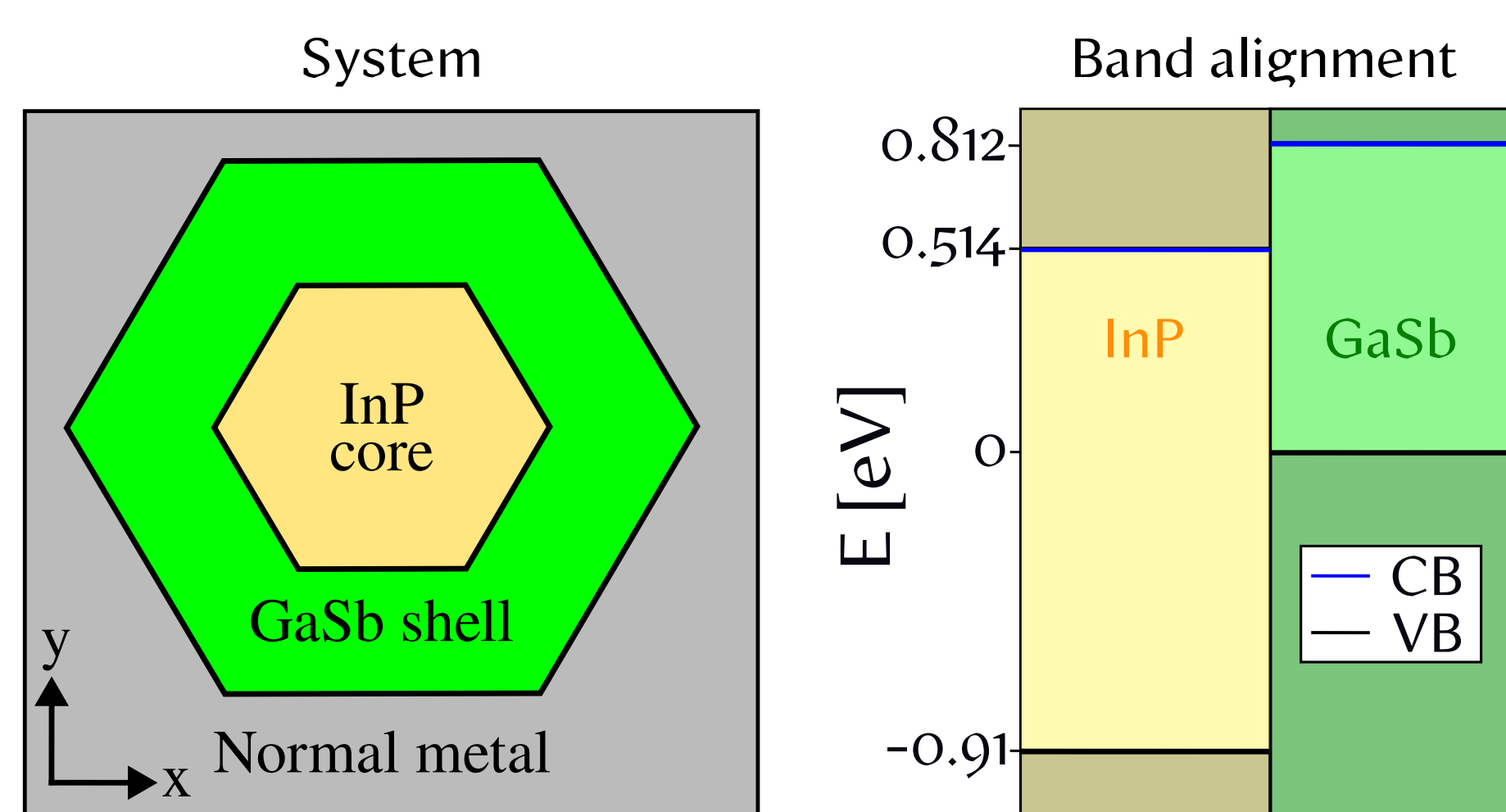
Methods

We employ a **8-band k.p Hamiltonian** to describe the NW, and we solve it self-consistently together with the Poisson equation.
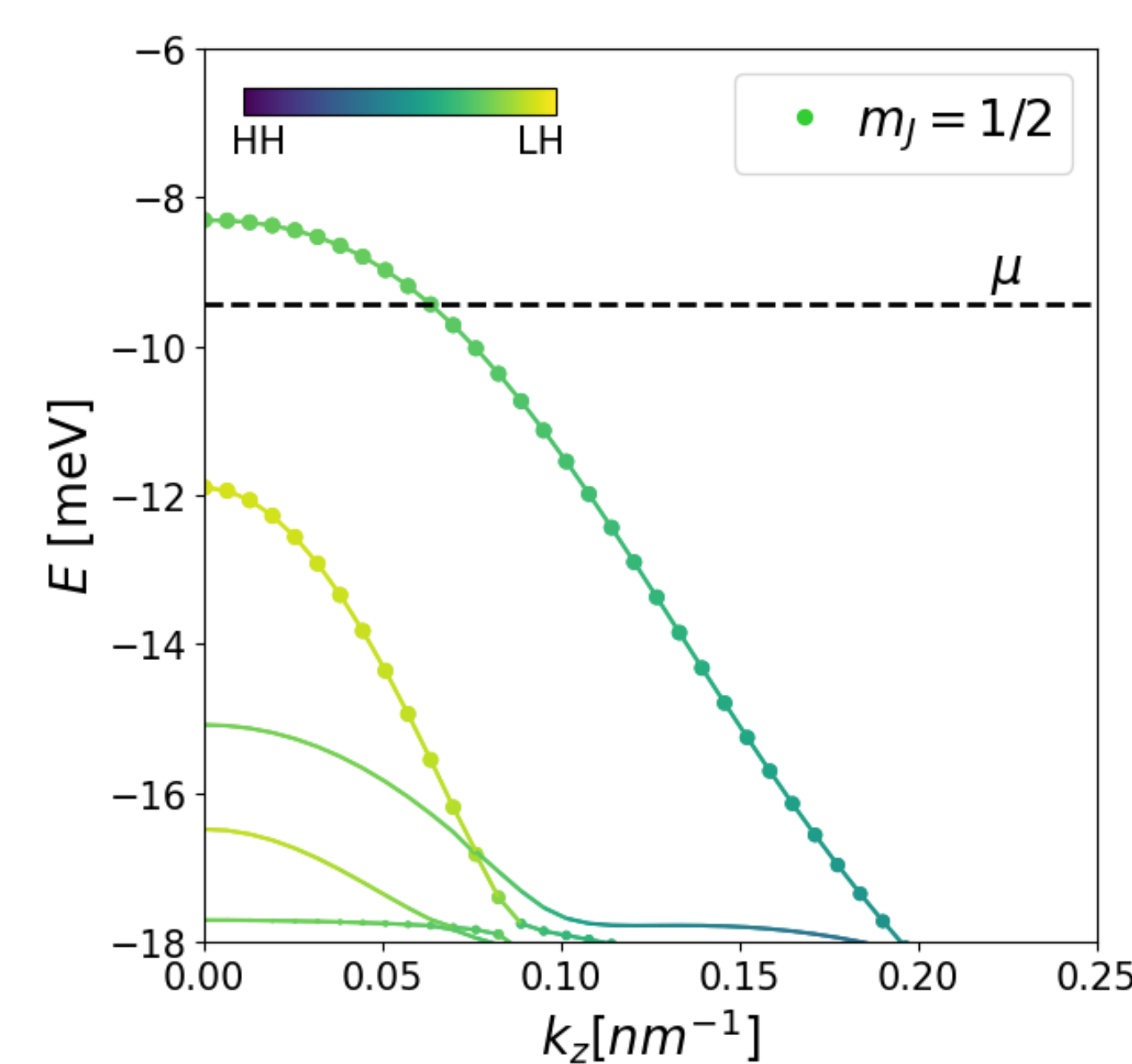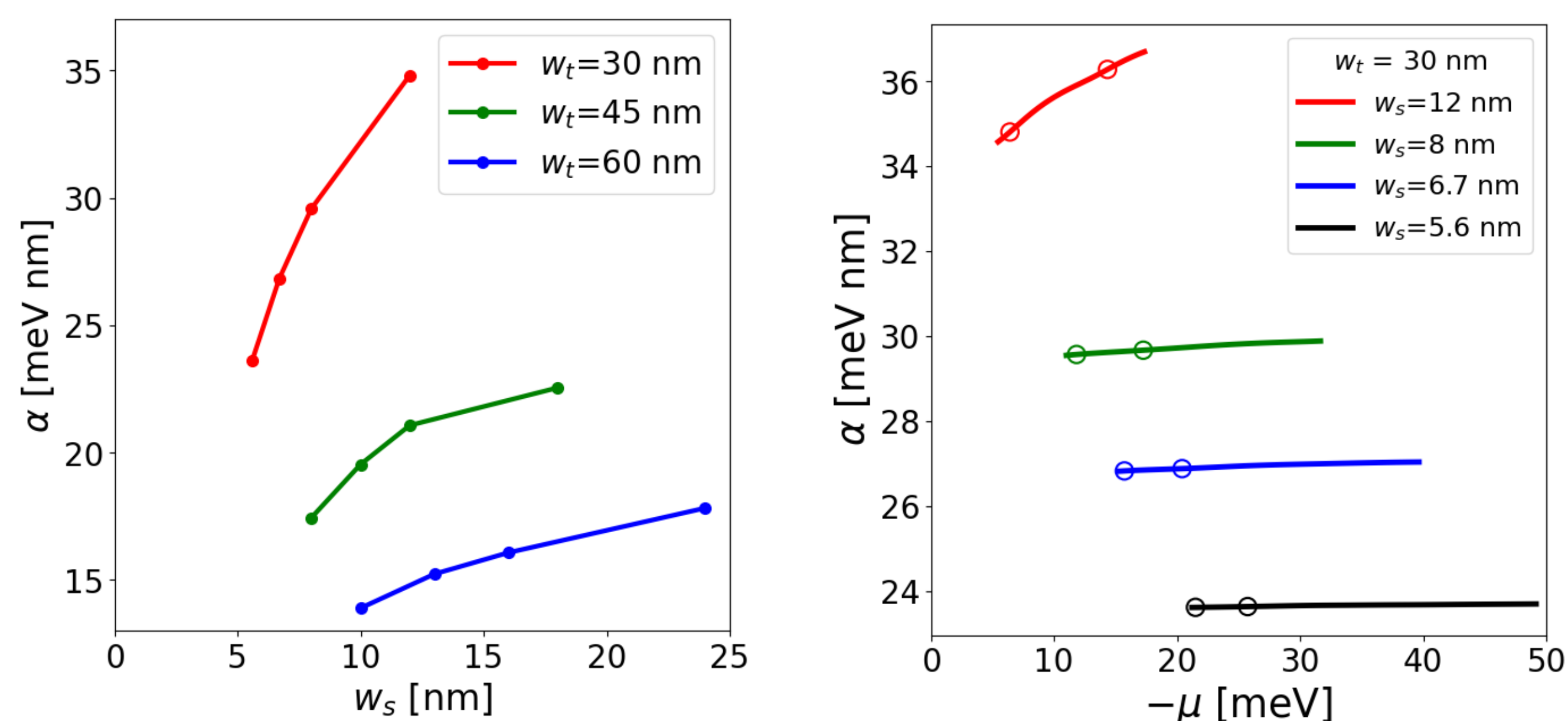

The highest-energy band is the ligh-hole band (LH) with angular momentum 1/2

Heavy-hole bands (HH) are far below

Charge is in the SM shell, with almost angular symmetry

Numerical Results

We study the SO coupling vs the shell thicknes w_s and for different wire diameters w_t, as well as vs the doping of the wire.

The SO coupling is not Rashba type, i.e., does not depend on the electric field. It depends on the wire geometry.

Analytical approximations

We numerically prove that the SO coupling only depends on the LH and HH bands. We can thus use a Wolf-Schrieffer approximation

$$H_{\text{eff}} \simeq \left(\frac{\hbar^2 k_z^2}{2m_{\text{eff}}} - \mu_{\text{eff}} \right) \sigma_0 + \alpha_{\text{eff}} k_z \sigma_+$$

where the SO coupling is given by

$$\alpha_{\text{eff}} = \frac{3}{2} \frac{\hbar^2}{m_0 R_{\text{eff}}} \gamma_s \left[1 - \frac{256}{9\pi^2 \left(10 + 3\frac{\gamma_1}{\gamma_s} \right)} \right] \qquad R_{\text{eff}} = \frac{w_t - w_s}{2}$$

The SO coupling is instrinsic, arising as a result of the bulk crystal symmetry, and it only depends on the charge distribution of the holes inside of the SM shell.

Application to Majorana physics

When proximitized with a full-shell SC, this NW is more likely to host Majorana modes, as compared to conventional InAs-Al NWs, as they exhibit sizeable SO coupling, in the appropriate direction, enhanced proximity effect, the charge density is strongly localized, and the metallization effects are supressed.

References

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[2] B. D. Woods et al., PRB 99, 161118(R) (2019).
[3] S. Bosco et al., PR Applied 18, 044038 (2022).

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