# Electron Optics in Phosphorene pn Junctions: Negative Reflection & Anti-Super-Klein Tunneling

**Thomas Stegmann**
Yonatan Betancur-Ocampo, François Leyvraz
*Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México, Cuernavaca, México*
stegmann@icf.unam.mx

Ballistic electrons in phosphorene pn junctions show optical-like phenomena. Phosphorene is modeled by a tight-binding Hamiltonian that describes its electronic structure at low energies, where the electrons behave in the armchair direction as massive Dirac fermions and in the orthogonal zigzag direction as Schrödinger electrons. Applying the continuum approximation, we derive the electron optics laws in phosphorene pn junctions, which show very particular and unusual properties [1]. Due to the anisotropy of the electronic structure, these laws depend strongly on the orientation of the junction with respect to the sublattice. Negative and anomalous reflection are observed for tilted junctions (Figure 1), while the typical specular reflection is found only, if the junction is parallel to the zigzag or armchair edges. Moreover, omni-directional total reflection, called anti-super-Klein tunneling, is observed if the junction is parallel to the armchair edge (Figure 2). Applying the nonequilibrium Green's function method on the tight-binding model, we calculate numerically the current flow. The good agreement of both approaches confirms the atypical transport properties, which can be used in nano-devices to collimate and filter the electron flow, or to switch its direction.

## REFERENCES

[1] Y. Betancur-Ocampo, F. Leyvraz, T. Stegmann, Nano Letters 19: 7760 (2019), DOI: 10.1021/acs.nanolett.9b02720

## FIGURES

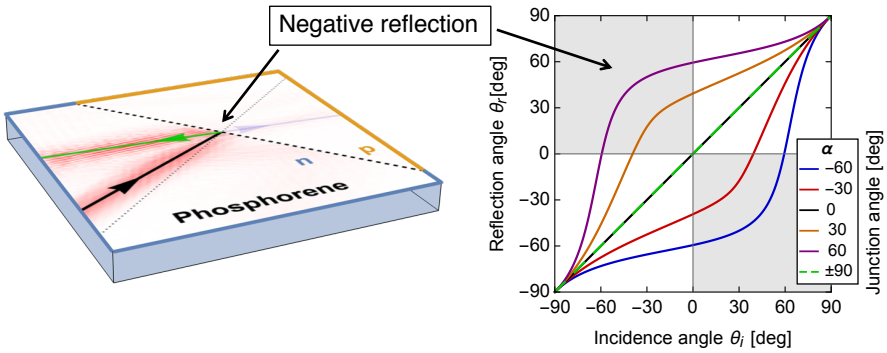


**Figure 1:** Electron optics in phosphorene pn junctions. Negative reflection is found for tilted junctions.

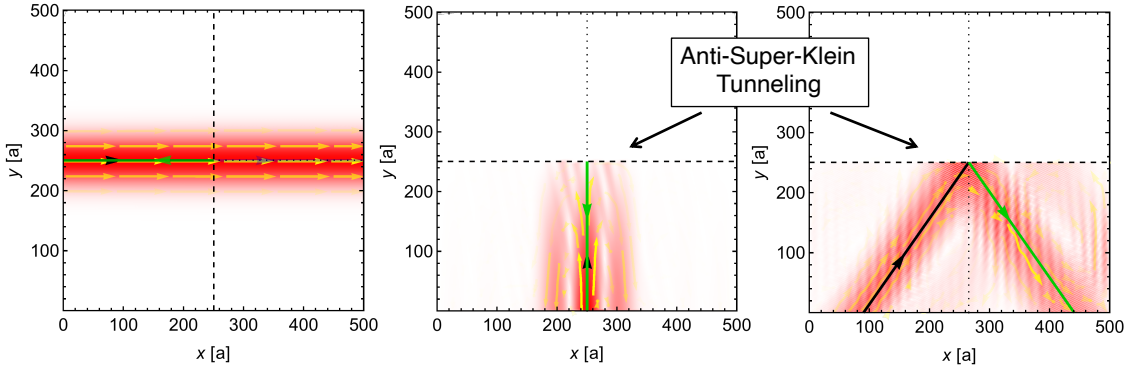


**Figure 2:** Omni-directional total reflection, called anti-super-Klein tunneling, is observed if the junction