Electron optics in bilayer graphene[1]

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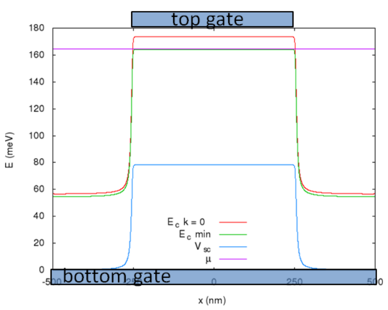
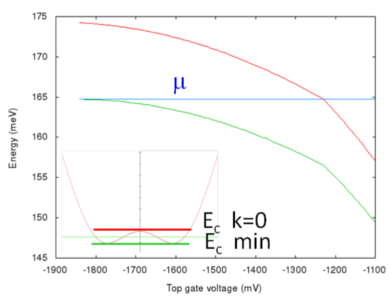
Negative refraction, electron focusing and similar electron optical effects in bilayer graphene are investigated. Recently, negative refraction has been observed at a monolayer graphene pn junction [1] but the focusing is poor because the junction has unfavourable transmission characteristics. In contrast, negative refraction in biased bilayer graphene is an intrinsic property of the material so a pn junction is not required. A simple potential barrier is all that is needed to observe electron focusing.

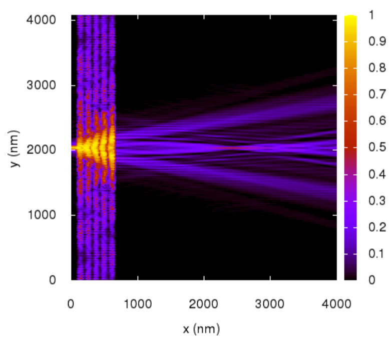
Negative refraction occurs in biased bilayer graphene in the energy regime where there is a negative group velocity. However for each energy in this regime there is a second state with positive group velocity. Consequently, bilayer graphene exhibits electronic birefringence as well as negative refraction.

The birefringent regime occurs in a narrow energy range, typically 5 - 10 meV, between the conduction band maximum and conduction band minimum. Despite the narrow energy range, this regime is easy to access experimentally. The potential barrier can be created by putting the bilayer graphene between a wide back gate and a narrow top gate (bottom left figure). Self-consistent Thomas-Fermi calculations of the potential in this device show that the Fermi level is pinned in the birefringent regime because of the large density of states at the conduction band minimum: the chemical potential stays in the birefringent regime over a top gate voltage range of about 600 meV, about 70 times the birefringent regime width (bottom centre figure).

The bottom right figure shows electron focusing in the birefringent regime. The wave function is computed numerically [2] from the potential in the left part of the figure, with the flat part extended by 75 nm. A Gaussian source is placed at $x = 0$. The negatively refracted part of the wave function converges to an image at $x \sim 2450$ nm while the positively refracted part diverges. This is consistent with geometrical optics. Other electron optical devices, for instance a beam splitter will also be discussed.







[1] Chen et al, Science **353**, 1522 (2016).

[2] P. A. Maksym and H. Aoki, in preparation.

[1] Work done at Tokyo in collaboration with H. Aoki (Tokyo and AIST).