Electron optics in graphene

P. Rickhaus[1], M.-H. Liu[2], P. Makk[1], S. Hess[1], R. Maurand[1], E. Tovari[3], M. Weiss[1], K. Richter[2] and C. Schönenberger[1]

[1]Dept. of Physics, University of Basel, Switzerland

[2]Institute of Theoretical Physics, University of Regensburg, Germany

[3]Dept. of Physics, Budapest University of Technology and Economics, Hungary

peter.rickhaus@unibas.ch

In ballistic graphene, electrons behave in many ways similar to photons. By changing the electrostatic potential locally, we realized elements in graphene that are known from optics. But in contrast to conventional optics, gapless p-n interfaces can be formed showing a negative index of refraction and the effect of Klein tunneling. Even more, electron trajectories can be bent by applying a magnetic field. The electron-optics devices that we will show were fabricated using high-mobility suspended monolayer graphene on organic lift-off resists. We extended the technology introduced by N. Tombros et al. [1] allowing to add a multitude of bottom and top gates [2]. Recently we have demonstrated that with this technique a ballistic p-n junction can be created forming a Fabry-Pérot etalon. We will go beyond our recent publication [3] and discuss the observed transition from the Fabry-Pérot to the Quantum Hall regime that is observed once a magnetic field is applied. We will show striking features that can be traced to the formation of snake state trajectories along a pn interface. By this we can guide electrons along arbitrary interfaces already at very small magnetic fields of 100 mT. Beyond that we will demonstrate that electrons in ballistic graphene can be guided by gate potentials (Fig.1a) the same way as photons in an optical fiber, and that the formation of a p-n interface increases the guiding efficiency due to Klein filtering. We will show that we can fill the electrostatic guiding channel mode by mode. A further electron-optics element that we will present is a four terminal device that involves a tilted gate structure (Fig.1b) which acts as a mirror. Theoretical calculations [4] clearly reproduce the measured features of the different electron-optics devices, and the simulated current density plots give further insight to the nature of the discussed effects.

References

[1] N. Tombros et al. Journal of Applied Physics 109, 093702 (2011).
[2] R. Maurand, P.Rickhaus, P.Makk et. al. Carbon 79, 486 (2014)
[3] P. Rickhaus, P.Makk, M.-H. Liu et al., Nature Communications 4, 2342 (2013)
[4] M.-H.Liu, P.Rickhaus, P.Makk et.al., arXiv:1407.5620 (2014)

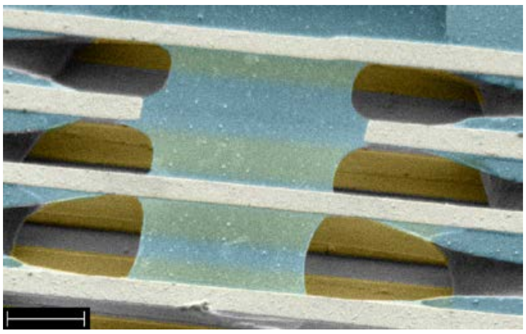
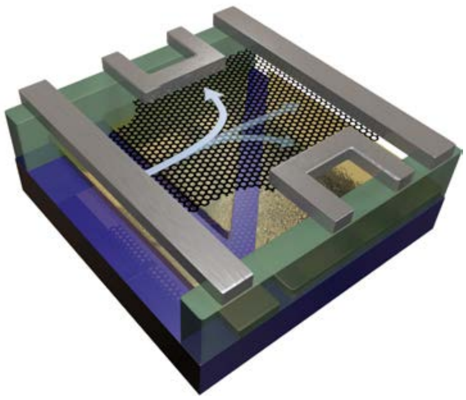
a)  b) 

Fig. 1. a) *False color image of a suspended graphene flake (blue) with side contacts (gray) and bottomgates (yellow) that can be used for electron guiding.* ***b)*** *Another four-terminal device with a tilted gate structure allows studying the reflection at the pn-interface and acts as a mirror.*