Quantum interference and Klein tunneling in graphene heterojunctions

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The extreme thinness and the possibility of tuning the carrier concentration of single layer graphene makes it a very promising material for electronic applications. Some of the best research labs in nanoelectronics worldwide are nowadays involved in designing and measuring a wide variety of devices based on graphene.

Single layer graphene is a metal where the carriers show a mobility independent of the concentration, $\mu \approx 10.000 \text{cm}^2 \text{Vs}^{-1}$ for samples on a SiO_2 substrate. The mobility is higher by an order of magnitude in suspended samples, and also in some samples grown epitaxially. It is also fairly temperature independent, which implies that it compares favorably with doped semiconductors at room temperature. At low temperatures the mobility of graphene is lower than that of other well studied two dimensional electronic systems, and, interestingly, than graphite itself, whose low temperature mobility is almost two orders of magnitude larger than that of single layer graphene in its most studied configuration, on a SiO_2 substrate.

The differences between single layer graphene and bulk graphite are attributed to extrinsic effects, like charges and other defects in the substrate, impurities absorbed above the graphene layer, and the influence of inhomogeneities and corrugations of the substrate. Intrinsic lattice defects and ripples can also play a role. Actual devices, such as p-n and p-n-p junctions, require complex geometries and different gates, which make them more susceptible to extrinsic effects. The presence of more metallic gates in close contact with the graphene layer tends to lower further the mobility.

A number of ways have been devised to minimize the influence of the environment on the carriers in graphene devices, like suspended geometries, or top gates separated by just air from the graphene layer. The goal is to obtain devices in the ballistic limit, where the elastic mean free path is longer than the dimensions of the system.

Transport of graphene in the ballistic limit is expected to show a number of unusual features. For instance, electrons incident normally on a potential barrier are transmitted with probability one, a phenomenon called Klein tunneling. Because of charge conjugation symmetry, an incoming electron always finds a state, electron or hole like, with the same energy on the side with a different potential. Moreover, quasiparticles in graphene carry an internal quantum number associated with the amplitude of the wavefunction on the two sublattices in which the honeycomb lattice can be divided. This pseudo spin is conserved when the barriers do not change appreciably on scales comparable to the lattice spacing. Quasiparticles moving in opposite directions have opposite pseudo spins, so that backscattering becomes impossible.

A direct observation of Klein tunneling would require a very flat barrier, and the accurate collimation of the velocities of the incoming electrons. As this is as present unfeasible, other features of tunneling by Dirac electrons are being studied, in order to determine the existence of ballistic transport in graphene devices.

The article cited above gives a very complete description of small graphene p-n-p junctions, where the width of the central part is $l \sim 20-60$nm. At carrier densities $n \gtrsim 10^{12}\text{cm}^{-2}$ the mean free path estimated is $l \approx 100$nm. The conductance in these devices, as function of the height of the barrier in the center shows an oscillating behavior (see also similar results in **Conductance of p-n-p graphene structures with 'air-bridge' top gates**, by R. V. Gorbachev, A. S. Mayorov, A. K. Savchenko, D. W. Horsell, F. Guinea, arXiv:0804.2081, Nano Lett. **8**, 1995 (2008)). These oscillations can be explained assuming the existence of narrow Fabry-Pérot resonances within the barrier. A mentioned above, electrons normally incident are insensitive to the existence of the barrier. For other angles, the reflection amplitude at each barrier is finite, and resonances occur at the right values of the length and height of the barrier, the Fabry-Pérot resonances. The transmission integrated over angles is enhanced when these resonances occur near normal transmission. For a theoretical analysis of the problem, see **Klein Backscattering and Fabry-Pérot Interference in Graphene Heterojunctions** by A. V. Shytov, M. S. Rudner, and L. S. Levitov, arXiv:0808.0488, Phys. Rev. Lett. **101**, 156804 (2008). The observation of Fabry-Pérot resonances is further confirmed by the shift in the oscillations by half a period in moderate magnetic fields. The coherence of the electronic wavefunctions in the central region implies that the device is indeed in the ballistic limit. The dependence of the oscillations on a weak magnetic field further confirms that this is the case. Consistently with the small temperature dependence of the mobility in diffusive samples, these oscillations are also weakly modified by the temperature, and they are observable at 60K.