Quantum pumping in graphene nanoribbons at resonant transmission

E. Grichuk[1], E. Manykin[2]

[1]National Research Nuclear University "MEPhI", 115409, Kashirskoe sh., 31, Moscow, Russia
[2]Russian Research Centre "Kurchatov Institute", 123182, pl. Kurchatova, 1, Moscow, Russia
evgeny.sg@gmail.com

In recent years graphene has been the subject of intense theoretical and experimental research mainly due to its very peculiar electronic structure and electronic properties, resulting in numerous unusual effects: Klein tunnelling "paradox", half-integer quantum Hall effect, and other effects [1]. Many authors consider graphene as a good candidate for spintronics and for future replacement of silicon-based electronics. A graphene sheet can be cut to form graphene nanoribbons (GNR) with different orientations of edges relative to the graphene crystal structure. If two (or more) independent parameters (e.g., gate voltages) of a mesoscopic system are adiabatically modulated in time, finite dc current through the device can be generated. This phenomenon is known as adiabatic quantum pump effect. Quantum pump effect in graphene was previously studied by E.Prada et al. using Dirac approximation [2]. They argued that the Klein tunnelling effect has a great impact on the properties of graphene-based pumping devices due to the unusual (in comparison with normal devices) contribution of evanescent modes. Pumping with two potential barriers, separated by a finite unbiased central region, was considered in ref. [3]. It was demonstrated that due to the high anisotropy of transmission through a potential barrier in graphene both directions of pumping can be realized for a fixed pumping contour in contrast to normal devices. Pumping with a series of barriers was considered in a recent paper by Z.Wu et al. [4].

We consider adiabatic quantum charge pumping in graphene nanoribbon double barrier structures with armchair (AGNR) and zigzag (ZGNR) edges in the resonant transmission regime [5]. The geometry of the setup is depicted in fig. 1(a). The Hamiltonian of the device is expressed using orthogonal nearest-neighbour tight-binding approximation. Pumping is achieved by periodic variation of two external gate voltages which are modelled by adding on-site energies U_1 and U_2 to the diagonal terms of the Hamiltonian. Electron-electron interactions are neglected and the spin degeneracy factor of 2 is omitted for clarity. In the adiabatic approximation the charge pumped through the device can be calculated within scattering matrix formalism using Brouwer's formula [6]. Alternatively, Green's function formalism can be used [7].

In the case of AGNR the whole resonance line of conductance contributes to the pumping of a single electron per cycle through the device. This picture is reminiscent of that of a simple 1D double barrier structure (a quantum dot separated from the leads by two point contacts with variable conductances). In fig. 2(a) the dependence of the pumped charge Q on the Fermi energy E_F in the leads is plotted. The transmission amplitude is peaked when E_F becomes equal to the energy of some quasi-bound state in the device region. When the Fermi level is far from any such state, no resonance is observed. One can see from fig. 2(a) that for some values of E_F the pumped charge tends to the electron charge value. This happens each time when the pumping contour encloses a large part of the resonance line. This charge quantization behaviour is in agreement with charge loading/unloading picture discussed in ref. [8]. The pumping contour crosses the resonance line in two resonance points A and B (see fig. 1(b)). When the point A is crossed, the quasi-bound level inside the device moves below the Fermi level in the leads and an electron tunnels from the left lead into the central region. At the point B the quasi-bound level moves up and an electron tunnels into the right lead.

The situation is qualitatively different for ZGNR due to zero-conductance resonances (dips) inherent to locally gated ZGNRs and associated with the formation of discrete quantum levels in the barrier region. [9]. In fig. 2(b) we plot the dependence of the pumped charge on the Fermi energy. The pumped charge is also quantized, but in contrast to AGNR, both directions of current are now possible for fixed direction of the pumping contour. Such behaviour can be explained within charge loading/unloading picture [8] taking into account the zero-conductance resonances. In the AGNR case at point A (fig. 1(b)) the probability of tunnelling through the right barrier is much lower than the probability of tunnelling through the left one because the right barrier is much higher. At the point B the situation is reversed. The parameters can be adjusted such that the tunnelling through the left (right) barrier at point A (B) is blocked by the zero-conductance resonance. This results in the backward direction of current. These conductance dips separate the whole resonance line into several parts, each of which corresponds to the pumping of a single electron through the device, and in contrast to AGNR, one electron can be pumped from the left lead to the right one or backwards.

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Figures

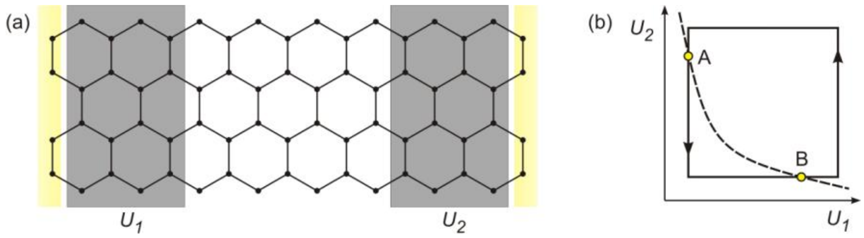

Fig. 1. (a) Schematic of the quantum pump ZGNR-based device (AGNR case is similar and not shown). Pumping is achieved by periodical variation of potentials U_1 and U_2. (b) Typical pumping contour, schematic resonance line of conductance and two resonance points A and B.

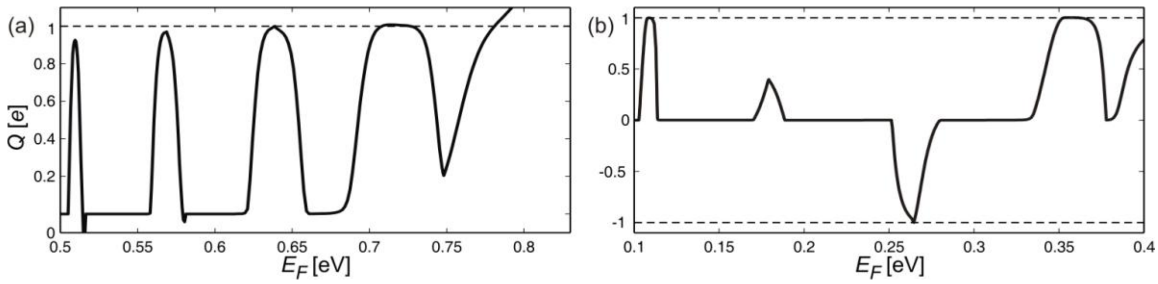

Fig 2. (a) The pumped charge per cycle Q for 10-AGNR as a function of the Fermi energy E_F in the leads for a fixed pumping contour. (b) The pumped charge per cycle Q for 10-ZGNR as a function of the Fermi energy E_F in the leads for a fixed pumping contour. See ref. [5] for the details.