Edge-states interferometers in graphene nanoribbons: a time-dependent modeling

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INTRODUCTION

Graphene has recently proved to be a reliable platform for electronic quantum optics in the integer quantum Hall regime[1], and offers promising perspectives for flying-qubit implementation of quantum computers[2]. Edge-state Mach-Zender interferometers (MZIs)[3] represents one of the simplest setups able to expose the wealth of physical phenomena stemming from the multi-valley bandstructure of graphene, as Klein tunneling and snake states in *pn* junctions. In the proposed contribution, we will present the methods and results of our time-dependent modeling of quasiparticle dynamics in graphene MZIs [4] based either on quantum point contacts or valley beam splitters (fig. 1). We will illustrate the reasons why a time-dependent approach, taking into account the real-space dispersion of the carriers, is necessary to fully assess the functional regimes of MZ devices.

MODEL AND METHOD

To obtain the exact evolution of the carrier quasiparticles injected in an edge state, we numerically integrate the corresponding time-dependent Schrödinger equation in the integer quantum Hall regime in graphene through the split-step Fourier method. We extended the latter approach to include the whole band structure in the proximity of the valleys in the first Brillouin zone, and consider the electronic wave function as a four-component spinor. This allows us to take into account the sublattice and valley degrees of freedom. The Hamiltonian is obtained within the $k{\cdot}p$ model, in which the bands are approximated by a linear dispersion near the valleys. An edge state is localized in the direction orthogonal to the nanoribbon boundary or to the *pn* junction, but it is delocalized in the transport direction. Since we aim at studying the time evolution of localized wave packets, we consider as the quasiparticle initial state a localized linear combination of edge states in the transport direction.

RESULTS

Our simulations show that it is possible to control the transport regime of single particles along graphene *pn* junctions through the interplay between the energy of the injected carrier and the height of the junction itself (fig. 2), in turn, tailored by an external electrostatic field. The tuning of the cyclotron radius of the carrier in both regions of the junction makes it possible to either observe semiclassical snake-state trajectories or edge-state behavior, with Klein tunneling through a finite potential barrier. The energy dispersion of the localized wave packet allows to observe phase averaging at the end of the MZIs, a phenomenon which does not occur for delocalized currents[4].

We also highlight a transport regime in which the Edge Channels that constitute the interferometer cross periodically along the zigzag direction perpendicular to the nanoribbon boundary (fig.3). This phenomenon affects the frequency of Aharonov-Bohm oscillations and causes the visibility to drop significantly[4].

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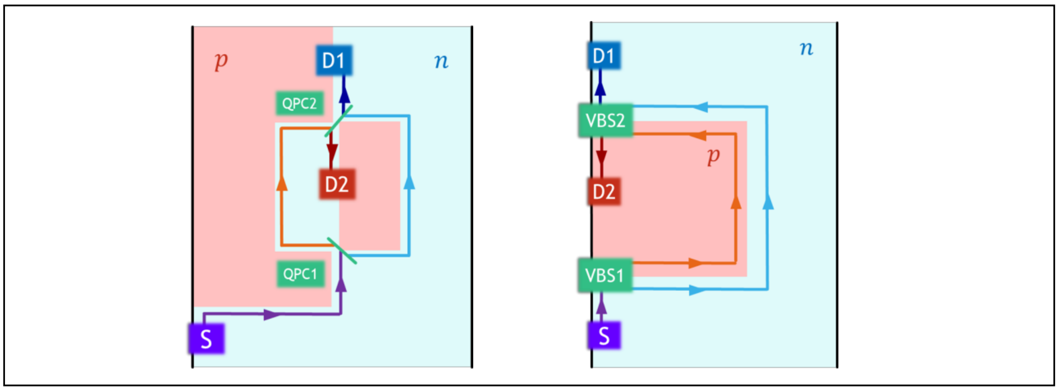

Fig. 1. MZIs for edge-states in graphene nanoribbons with armchair boundaries (black vertical lines) where the quasiparticles are injected from an excitation source (S) able to inject carriers with an energy broadening of 45 meV and detected in the two outputs of the interferometer (D1 and D2). Left panel: the two beam splitters are realized by two quantum point contacts (QPC1 and QPC2) where channels between two *n*-doped regions are quenched by the *p*-doped region. Right panel: the two valley beam splitters are realized by electrostatically aligning the electron-like and hole-like edge states where the *n* and *p* regions meet the boundary (VBS1 and VBS2) and the two edge states propagate in the same direction in the two regions with opposite doping.

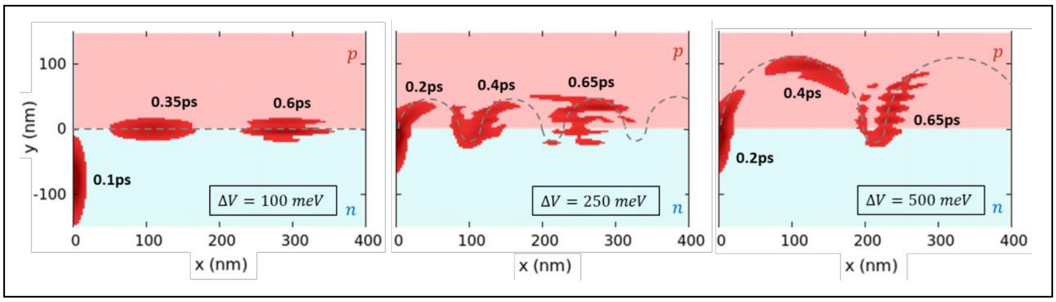

Fig. 2. Dynamics of a Gaussian wave packet of edge states at a *pn* junction of an armchair nanoribbon. The three panels show three cases, with different height ΔV of the potential step leading to different effective electrostatic doping in the two regions. The initial wave packet has an energy E=51.4 meV (left panel) and E=77.5 meV (center and right panels). The interplay between the potential energy difference among the junction and the packet energy gives rise to snake states, where electron-like and hole-like states are excited on the opposite sides of the junction.

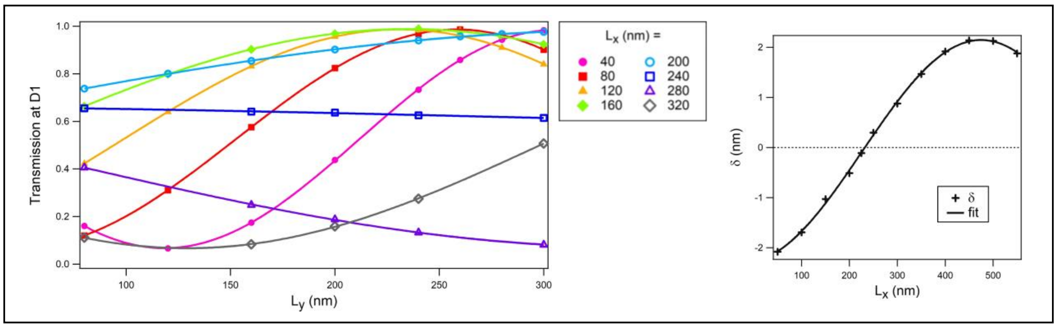

Fig. 3. Behaviour of Aharonov-Bohm oscillations in the interferometer on the right from fig. 1. The transmission probability at D1 (left panel) is reported as a function of the vertical dimension of the *p* region (L_y) for different values of the horizontal dimension (L_x). The frequency of the curves changes with L_x. The right panel shows the distance δ between the channels along L_y, which oscillates as a function of L_x.