Graphene-based Klein tunneling transistor

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INTRODUCTION

As a high mobility material, graphene is well suited for high frequency electronics [1]. However, the absence of bandgap restricts the switching off capability of graphene, which, even for microwave applications, is a strong limitation. Generating a finite bandgap in graphene is usually at the cost of a reduced mobility. Here, we investigate the opportunity offered by the Klein tunnelling effect of ballistic Dirac fermions (DFs) in graphene [2]. In this transport regime, DFs manifest optics-like properties at interfaces determined by Fresnel-like relations [3]. We consider a p-n-p transistor that exploits the internal reflection in a Klein tunnelling (KT) prism made of an n-doped triangular area controlled by a triangular gate. We show that in this KT transistor the transmission is suppressed when increasing the gate doping deep in the metallic regime, in strong contrast with conventional semiconducting transistors.

DEVICE PRINCIPLE AND MODEL

The principle of Klein tunneling prism is schematized in Fig. 1 and can be understood in terms of scattering theory. It relies on the total internal reflection in a triangular n-doped graphene region (density n, angle α), embedded in a p-doped environment (density $p \le n$) playing the role of vacuum. The refraction at the input p-n junction obeys a Snell-Descartes-like law $\sin\varphi_1 = \nu \sin\theta_1$, where $\nu = -\sqrt{n/p}$ is the negative refraction index [3]. The refracted DF beam is focussed along the junction normal within an angular opening $|\theta_1| \le \theta_C$, where $\theta_C = \arcsin 1/\nu$ is the critical angle. At the drain side, DFs impinge an n-p junction at incidence $\varphi_2 = \alpha - \theta_1$ and the Snell-Descartes law reads $\nu \sin\varphi_2 = \sin\theta_2$. For $|\nu| \gg 1$, it implies total reflection for $|\varphi_2 \ge \varphi_C|$, with $\varphi_C = \theta_C$ for symmetric drain and source with zero bias. The condition of reflection is met for any ray incident to the prism provided that $\theta_C < \alpha/2$ or $n > p/\sin^2(\alpha/2)$. Finally, the reflected beams are transmitted back across the source junction. The reflection can be controlled and transmission restored by decreasing n-doping, i.e. increasing θ_C, as shown in figure 1-b. The transmission may thus be suppressed when increasing the gate doping. This simple geometrical description leads to analytical expression of transmission but does not include size effects as diffraction which may degrade the full reflection in off-state. To include these effects we have used a tight-binding / NEGF model to describe the electron states and transport in the KT transistor schematized in Fig. 2. It consists of a series of prims to form a sawtooth gate with elementary units made of an isosceles triangle of opening angle $\pi - 2\alpha$.

RESULTS

We restrict the NEGF simulation to the structure with a single triangular unit of height L = 60 nm and prism angle α = 45°. It is compared with the case of rectangular angle of same area. The source and drain areas are doped to $p = 2.3\times10^{12}\,\mathrm{cm}^{-2}$. In Fig.4 the transmission is shown at V_{DS} = 0.2 V for the rectangular geometry (red lines) and the triangular geometry (blue lines) for the on- state of the KT transistor (dotted lines, low gate barrier, low $n \approx 2p$) and the off-state (solid lines, high $n \approx 6p$). In the on-state, two minima of transmission appear corresponding to the energy position of the charge neutrality point (CNP) in the lead (E = -0.15 eV) and in the barrier (E = 0.15 eV). A transmission maximum is observed at the Fermi energy in the source E_{FS} = 0, irrespective of the gate geometry. In the off-state (large doping) the maximum is shifted toward higher energy and scaled up. The transmission at E_{FS} remains large for rectangular gate and reduces strongly for triangular gate. From the transmission, we can deduce the currents plotted in Fig. 4. A

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significant suppression of current (below CNP minimum) is obtained with the triangular gate, which is the signature of the KT transistor. Better results could be even obtained for large devices with negligible refraction effect. In Fig. 5 that is shown the sensitivity of current to the prism angle α calculated at $V_{DS} = 10$ mV with the simple scattering theory model.

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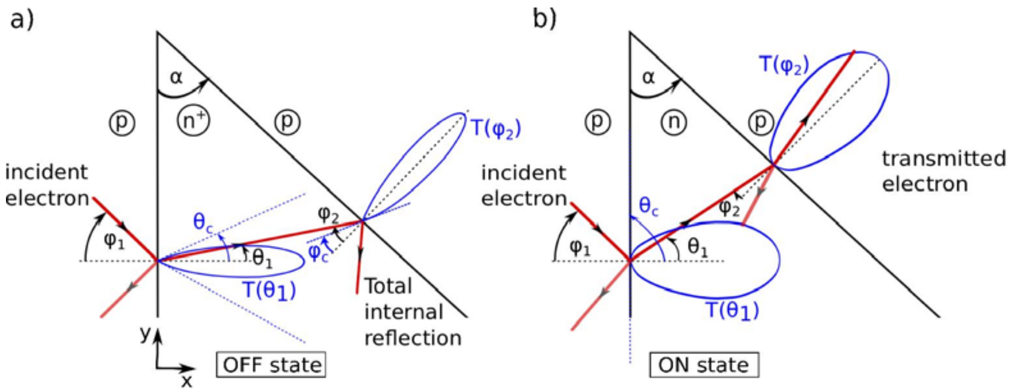

Fig. **1**. Principle of reflection in a KT prism. The refraction angle of DF beams (red lines) and their angular dependent transmission (blue lobes) are controlled by the index ratio $\nu = -\sqrt{n/p}$ of the p and n regions. (a) Off-state: $n >> p$. (b) On-state: $n \approx p$.

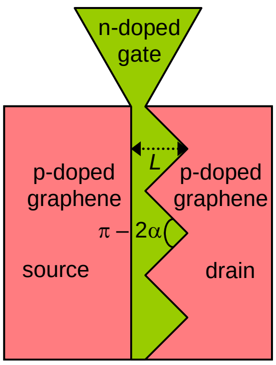

Fig. 2. Schematic view of the sawtooth gate KT transistor. The gate area (green) is n-doped ($V_{GS} > 0$).

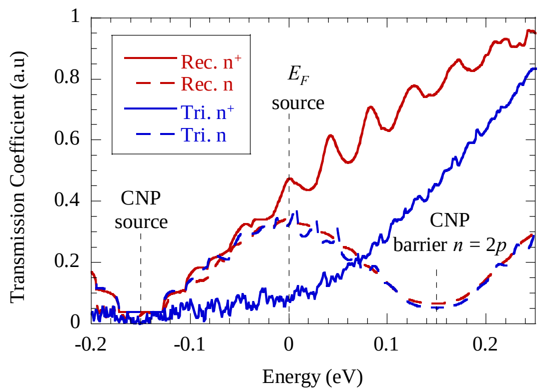

Fig. 3. Transmission coefficient in rectangular and triangular gate transistors calculated by NEGF simulation.

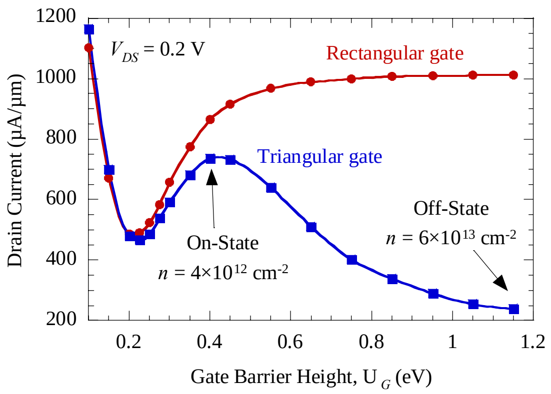

Fig. 4. Current in rectangular and triangular gate transistors.

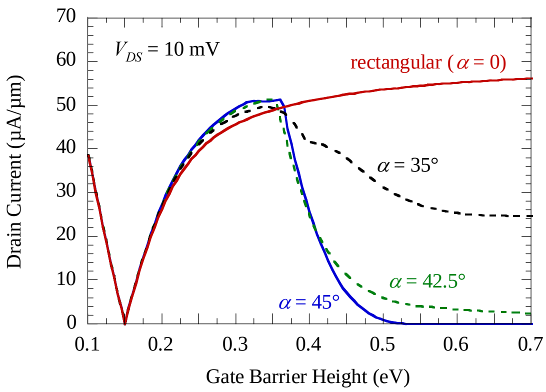

Fig. 5. Sensitivity of current to the prism angle (scat. theory).