Strong negative differential resistance in graphene devices with local strain

M. Chung Nguyen, Viet-Hung Nguyen,
Jérôme Saint-Martin, Philippe Dollfus
Institut d'Electronique Fondamentale,
CNRS, Univ Paris Sud, Université Paris-Saclay
Orsay, France
mai-chung.nguyen@u-psud.fr

Huy-Viet Nguyen
Center for Computational Physics
Institute of Physics, VAST
Hanoi, Vietnam

***Abstract*—The effects of local uniaxial strain on grapshene devices like single-barrier structure and p-n tunnel diode are investigated. The strain-induced displacement of Dirac points allows us toi suppress and/or control the Klein tunneling and the interband tunneling, which leads to strong effect of negative differential conductance. It is shown that when strain is suitably applied, the peak-to-valley ratio of the current-voltage characteristics can reach of a few hundred at room temperature.**

Keywords*—*Graphene; Strain; transport gap; Negative differential conductance

I. INTRODUCTION

The effect of negative differential resistance (NDR) has been widely investigated in devices based on conventional semiconductors. This effect is suitable for a wide range of high-frequency applications [1]. Recently, several designs of graphene structures and devices exhibiting an NDR behavior have been proposed, based on various physical mechanisms [2]. In most cases, the opening of a bandgap in the bandstructure of graphene by nanostructuring is used to make the modulation of Klein/interband tunneling possible [3-8].

Recently, the effects of uniaxial strain on 2D unstrained/strained graphene junctions were investigated and it was found that a significant conduction gap of a few hundred meV can be achieved with a small strain of a few percent [9]. This conduction gap is not due to a bandgap opening in the band structure but to the shift of the Dirac cones in the Brillouin zone of the strained side. This effect has been used to demonstrate a strong improvement of on/off current ratio in graphene transistors with local strain in the channel [10]. Here, we investigate the possibility to use local strain engineering to generate high peak-to-valley current ratio in graphene devices exhibiting negative differential resistance (NDR).

II. MODEL

We focus on two devices: (i) a single-barrier structure controlled by a gate voltage where the strain is applied on a finite area of length L_S (Fig. 1) and (ii) a PN tunnel diode where the strained area overlap the transition region of the diode where the interband tunneling occurs. Our calculations are based on an atomistic nearest neighbor tight-binding model with transport simulation performed using the Green's function formalism in the ballistic approximation [2]. Under a uniaxial strain applied along the Ox direction, the C-C bond vectors change as [11]

$$\begin{cases} r_x(\sigma) = (1+\sigma)\, r_x(0) \\ r_y(\sigma) = (1-\gamma\sigma)\, r_x(0) \end{cases} \tag{1}$$

where σ is the strain amplitude and γ = 0.165 is the Poisson's ratio [12]. The hopping parameter between neighboring atoms is given by [13]

$$t_{nm}(\sigma) = t_0 \exp\left[-3.37\left(r_{nm}(\sigma)/r_0 - 1\right)\right] \tag{2}$$

where $t_0 = -2.7$ eV and $r_{nm}(0) = r_0 = 0.142$ nm are the hopping energy and the C-C distance in unstrained graphene, respectively.

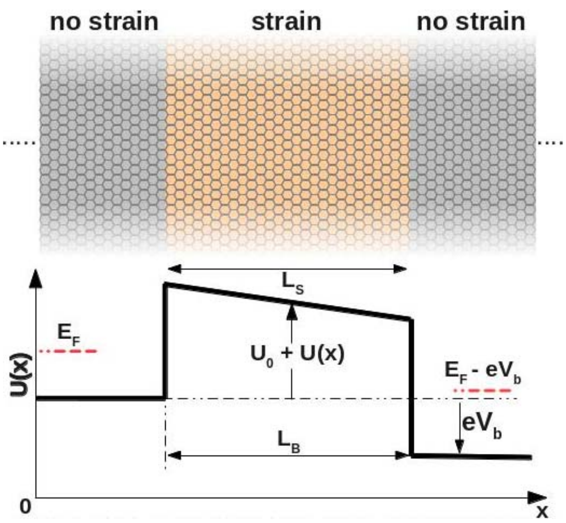

Fig. 1. Schematic of single potential barrier structure with uniaxial strain locally applied on an area of length L_S and a gate-controlled potential barrier of length L_B.

III. SINGLE-BARRIER STRUCTURE

We plot in Fig. 2 the *I-V* characteristics of the single-barrier structure, schematized in Fig. 1, for different strain amplitudes σ, with $L_S = L_B = 40$ nm and the Fermi energy $E_F = 0.25$ eV. In the unstrained device the NDR effect is very limited due the high transparency of the barrier, as a consequence of Klein tunneling [14]. When increasing the strain amplitude, Klein tunneling is suppressed and the conduction gap opening resulting from strain-induced displacement of Dirac cones [9] tends to reduce both the peak and valley currents, with an enhanced NDR effect. It is illustrated in the maps of transmission plotted in Fig. 3 for a strain $\sigma = 5\%$. In the valley area of the *I-V* characteristics ($V = 0.2$eV) the transmission is fully suppressed around the Fermi energy, which results in very low valley current.

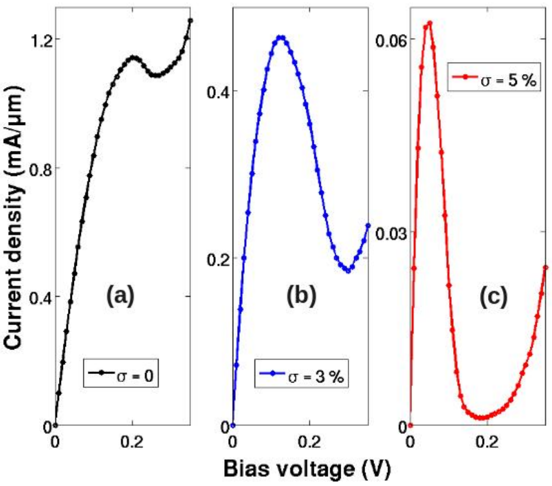

Fig. 2. I-V characteristics of the single-barrier structure for different strain amplitudes. Parameters: $L_S = L_B = 40$ nm, $U_0 = 0.45$ eV.

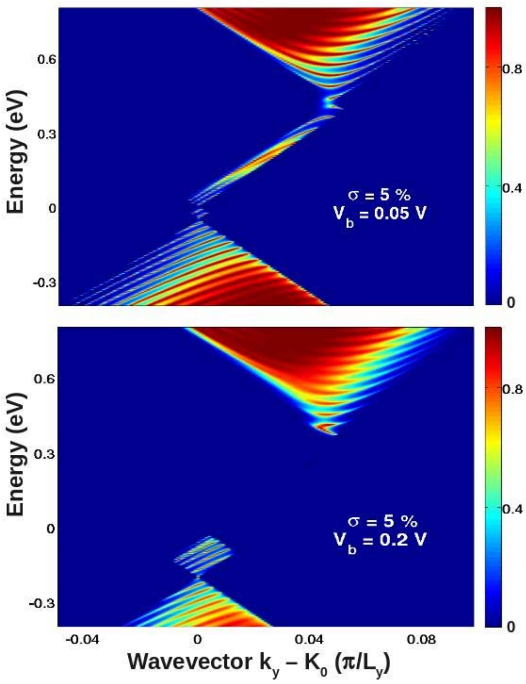

Fig. 3. (E-k_y) maps of transmission in strained device for two bias voltages for the strain $\sigma = 5\%$. K_0 is the Dirac point position in unstrained sections.

The influence of the barrier and strained area lengths on the *I-V* characteristics for a given strain amplitude $\sigma = 5\%$ is shown in Fig. 4. When increasing L_S and L_B the peak-to-valley ratio (PVR) increases up to about 250 and tends to saturate beyond $L_S = 100$ nm. Indeed, increasing LS tend to reduce the overall current, but the valley current is more strongly suppressed than the peak current because both propagating and evanescent states contribute to the latter while only evanescent states, very sensitive to the length, contribute to the former.

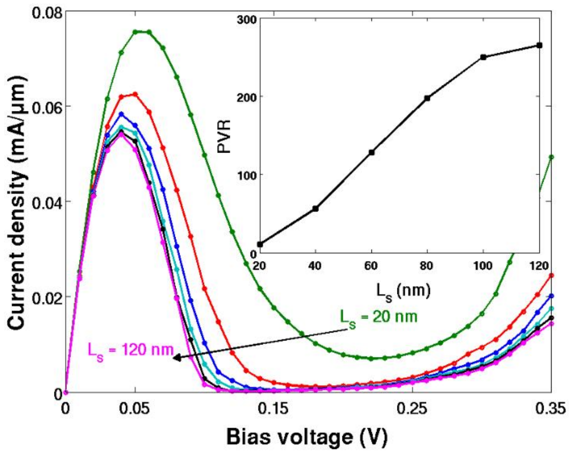

Fig. 4. *I-V* characteristics for different lengths $L_S = L_B$. Inset: peak-to-valley ratio as a function of $L_S = L_B$ ($\sigma = 5\%$).

IV. P-N TUNNEL DIODE

Similar effects are achieved in the strained PN diode schematized in Fig. 5 (top panel), where the strained-induced conduction gap allows us to control the interband tunneling.

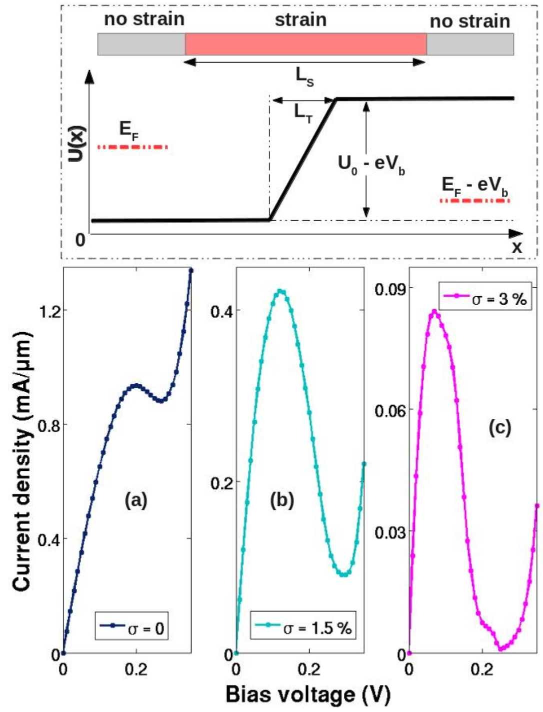

Fig. 5. Top: schematic and potential profile of a graphene p-n junction. Bottom: *I-V* characteristics for different strain amplitudes. ($U_0 = 0.5$ eV, $L_S = 40$ nm and $L_T = 10$ nm).

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In this case, a small strain amplitude of $\sigma = 3\%$ is enough to achieve high PVR of a few hundreds. However, the transmission at the peak current is strongly sensitive to the length of the transition region L_T separating N and P areas that must be smaller than L_S to get a high peak current, as shown in Fig. 6. However, the decrease of peak current in this structure is not very strong (inset of Fig. 7) compared the case of other p-n junctions [10] made of simple gapped graphene channels. Here the peak current is dominated by modes around $k_y = K_{strain}$ (the Dirac point in the strained area) for which the transition region is almost transparent, which makes the peak current and thus the PVR quite weakly sensitive to the transition length L_T.

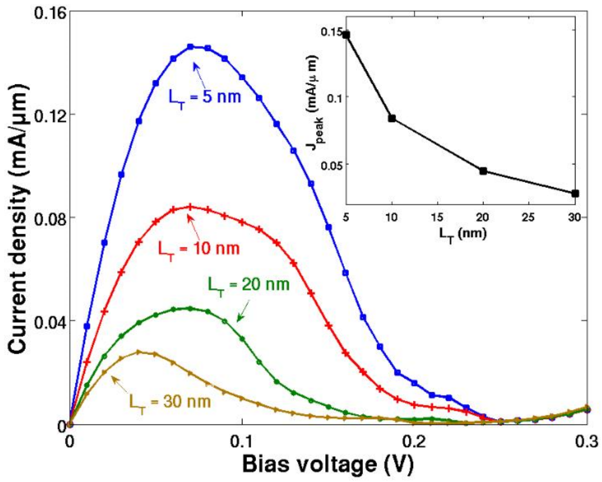

Fig. 6. *I-V* characteristics of strained device ($\sigma = 3\%$) for different lengths L_T ($L_S = 40$ nm is fixed, $U_0 = 0.5$ eV). Inset: peak current as a function of L_T.

V. CONCLUSION

In summary, we have shown that local strain engineering is effective to enhance strongly the NDR effect in graphene devices thanks to the conduction gap generated at strained/unstrained interfaces. A PVR of a few hundred is achievable at room temperature in devices where the current is controlled by a gate-induced barrier or a PN junction. In the latter case the PVR is even weakly sensitive to the length of the transition region between N-doped and P-doped areas.

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