Strong negative differential resistance in graphene devices with local strain

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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, many 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.

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 [3]. 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 graphene. This effect has been demonstrated to strongly improve on/off current ratio in graphene transistors with local strain in the channel [4].

Here, we investigate the possibility to use local strain engineering to generate high peak-to-valley current ratio of NDR behavior in graphene devices. We focus on two devices: (i) a single gate-induced potential barrier structure where the strain is applied on an area of length L_S (Fig. 1) and (ii) a PN tunnel diode where the strained area covers wide parts of two highly doped regions and the transition section between them (see the top of Fig. 5). Our calculations are based on an atomistic tight-binding model as in [4], which is solved by the Green's function formalism in the ballistic approximation.

We plot in Fig. 2 the I-V characteristics of the single-barrier structure for different strain amplitudes with $L_S = L_B = 40$ nm and the Fermi energy $E_F = 0.25$ eV. In unstrained device the NDR effect is very limited due the high transparency of the barrier. When applying strain, the misalignment (in both the k-space and the energy) of the graphene bandstructure inside (i.e., strain) and outside (i.e., no strain) the barrier results in a finite energy-gap of transmission at finite bias (see Fig. 3). Because of this effect, the overall current is reduced, especially, the valley current and hence a peak-to-valley ratio (PVR) of NDR behavior is significantly enhanced when a strain is applied (see Fig. 2). Since the effect mentioned above is strongly dependent on the length of the barrier/strained area, it is shown in Fig. 4 that the PVR increases when increasing L_S ($\equiv L_B$) and can reach a value higher than 250 beyond $L_S = 100$ nm in the ballistic limit.

Similar non-linear I-V characteristics can be achieved in the strained PN diode schematized in Fig. 5, where the strained-induced conduction gap allows us to control the interband tunneling. In this case, even a small strain amplitude of $\sigma = 3\%$ is enough to achieve high PVR of a few hundreds. Additionally, it is shown that the peak current is sensitive to the length of the transition region L_T separating N and P sections (see Fig. 6), however, the effect is much weaker than that observed in other simple gapped graphene P-N devices [2].

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 hundreds is achievable in devices where the current is controlled by a gate-induced barrier or a PN junction.

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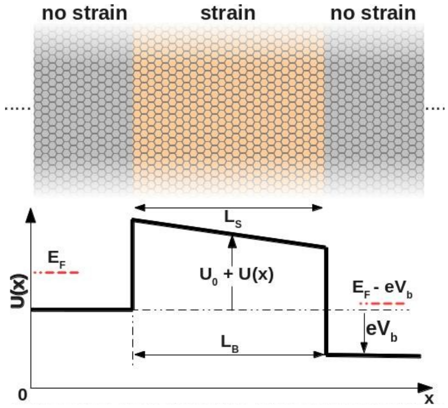

Fig. 1. Schematic of single potential barrier structure with strain is applied locally on an area of length L_S and gate-controlled potential barrier of length L_B.

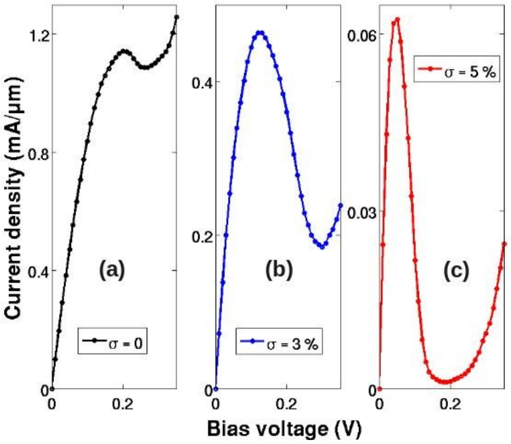

Fig. 2. I-V characteristics for different strain amplitudes (single-barrier structure with $L_S = L_B = 40$ nm, $U_0 = 0.45$ eV).

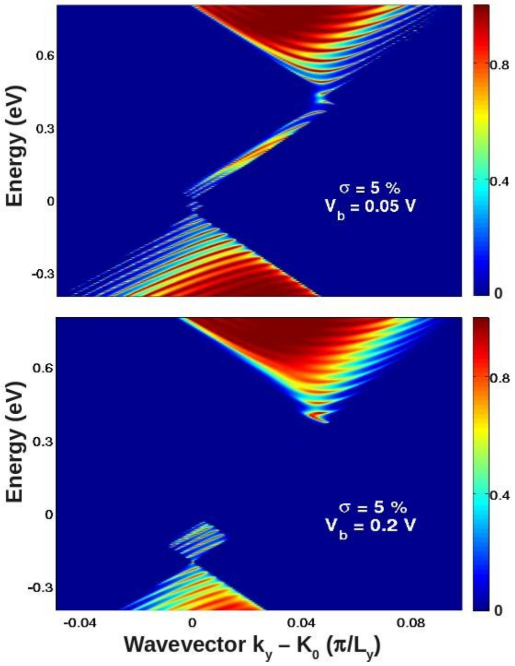

Fig. 3. (E-ky) map of transmission in strained device for two bias voltages (same U_0, K_0 = unstrained Dirac point position).

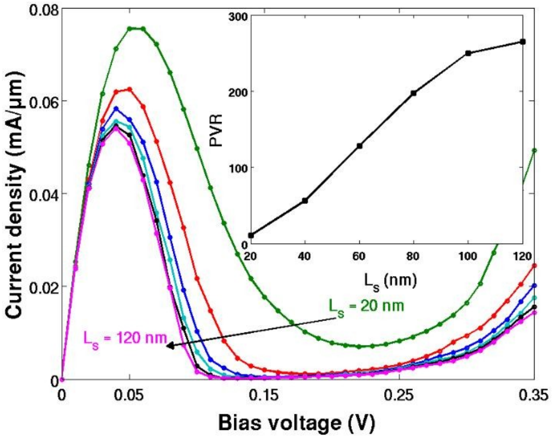

Fig. 4. I-V characteristics for different lengths $L_S = L_B$ (**σ = 5%)**. Inset: peak-to-valley ratio as a function of $L_S = L_B$.

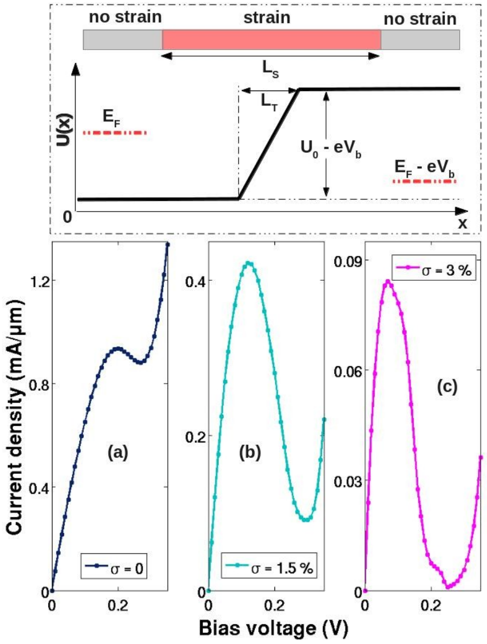

Fig. 5. Top: schematic of graphene p-n junctions. Bottom: I-V characteristics for different strain amplitudes. (U_0 = 0.5 eV, L_S = 40 nm and L_T = 10 nm.).

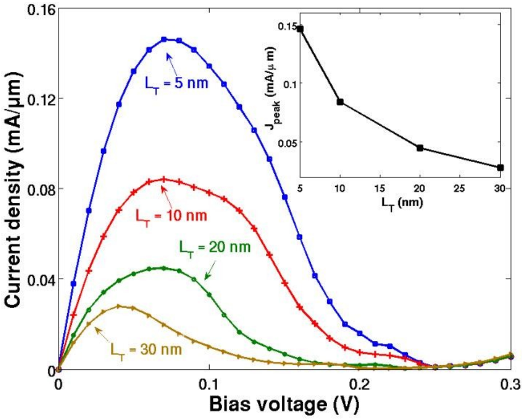

Fig. 6. I-V characteristics of strained device (σ = 3%) with different lengths L_T (L_S = 40 nm is fixed, U_0 = 0.5 eV). Inset: peak current as a function of L_T.