ROMANIAN JOURNAL OF INFORMATION SCIENCE AND TECHNOLOGY
Volume **11**, Number 1, 2008, 29–35

Graphene – A One-Atom-Thick Material for Microwave Devices

D. DRAGOMAN[1], M. DRAGOMAN[2], A. A. MÜLLER[3]

[1]University of Bucharest, Physics Dept.,
P.O. Box MG-11, 077125 Bucharest, Romania
[2]National Institute for Research and Development in Microtechnology (IMT),
P.O. Box 38-160, 023573 Bucharest, Romania
[3]Technische Univ. München, Lehrstuhl für Hochfrequenztechnik,
Theresienstr. 90, D-80333, München, Germany
E-mail: danieladragoman@yahoo.com, mircead@imt.ro,
andrei.mueller@tum.de

Abstract. The graphene is a native one-atom-thick crystal consisting of a single sheet of carbon atoms. In this material discovered in 2005, the electron transport is ballistic at room temperature and is described by a quantum relativistic-like Dirac equation rather than by the Schrödinger equation. Also, graphene has a Young modulus of 1.5 TPa. Due to these unique properties .graphene is considered to be a very promising material for high frequency nanoelectronic devices such as oscillators and switches. In this paper, we will show that a single graphene barrier acts as a switch with a very high on-off ratio and displays a significant differential negative resistance at frequencies beyond 1THz. Also, we will show that graphene can be used in a very efficient RF-NEMS switch for microwave applications.

1. Introduction

The graphene is a monolayer of graphite consisting of a repetitive honeycomb lattice in which carbon atoms bond covalently with their neighbours. The graphene is the key structure of many carbon-based materials. For example, when the graphene is stacked in a pile forms graphite and HOPG (high ordered the pyrolytic graphite), and when it is rolled up forms the carbon nanotube (CNTs) - a key material for many nanoelectronic devices.

Many years, it was supposed that graphene as a monolayer cannot exist in a free state, but experiments have succeeded to isolate such a carbon monolayer using mechanical exfoliation [1] from HOPG and to deposit it on a SiO_2 layer grown on a doped Si substrate. Micromechanical manipulation techniques are also used to fabricate graphene of various dimensions [2]. These methods are able to produce large graphene sheets, up to 100 μm in size. In graphene the electron and hole states are correlated through charge-conjugation symmetry, their transport being described by a Dirac-like equation, which is a relativistic-like quantum equation for particles with spin $1/2$. This is an astonishing situation since in common semiconductors and the heterostructures based on them two unrelated Schrödinger equations describe the electron and hole transport, respectively. There are also other striking differences between physicals effects in graphene and common semiconductors, such as Landau levels and Hall conductivity [3]. The dispersion relation in graphene is linear for both electrons and holes: $E = \pm|\hbar\mathbf{k}|\, v_F$, where v_F is the Fermi velocity and the positive sign corresponds to electrons, while the negative sign is assigned to holes. This unusual dispersion relation indicates that graphene is a gapless semiconductor because the conduction and valence bands touch in one point, often termed Dirac point. The linear dispersion relation in graphene is analogous to that of photons. However, the linearity of the dispersion relation for electrons in graphene and photons, has very different physical significances. In the case of electrons transported through graphene, the linearity of the dispersion relation indicates that the effective mass of electron and holes is zero meaning that there is no interaction between electrons and holes and the graphene lattice, so that electrons propagate balistically through graphene with the velocity $v_F \cong c/300$, where c is the speed of light. In the case of photons, the linearity of the dispersion relation e.g. $E = \hbar\omega = hc/\lambda$ means that the photon is propagating in vacuum with the speed of light c. Thus, graphene is a slow-wave structure in which electrons and holes propagate with a velocity that is much smaller than c.

2. Tunneling in graphene

It is well known that in semiconductor heterostructures the transmission through a barrier is strongly dependent on (in fact, decays exponentially with) the barrier width and height, because inside the barrier the wavenumber is purely imaginary and corresponds to evanescent propagation.The transmission can equal 1 only in the particular case of resonant tunnelling heterostructures which have very important applications in high-speed devices such as resonant tunnelling diodes and semiconductor cascade lasers [4].

The tunnelling through a barrier in graphene is described by the Klein tunnelling mechanism since the Dirac equation is describing the transport of massless fermions in graphene. In graphene, in deep contrast with semiconductor heterostructures, if the ballistic electrons are normally incident on the barrier, the transmission is 1 irrespective of the barrier height and width since electron propagation is not evanescent inside the barrier region [5]. This is happens because the holes take the role of electrons as charge carriers in barriers. Thus, a single graphene barrier is equivalent to resonant tunnelling based on common semiconductor heterostructures. We will further demonstrate that a graphene barrier displays a differential negative resistance, like any resonant tunnelling structure.The Dirac spinors Ψ_1 and Ψ_2 for an electron wave incident from region 1 on a barrier of height V_0 and width D and propagating at an angle φ_1 with respect to the x axis are given by:

$$\Psi_1(x,y) = \begin{cases} [\exp(ik_1x) + r\exp(-ik_1x)]\exp(ik_yy), & x \le 0 \\ [a\exp(ik_2x) + b\exp(-ik_2x)]\exp(ik_yy), & 0 < x < D \\ t\exp(ik_3x)\exp(ik_yy), & x \ge D \end{cases},$$

$$\Psi_2(x,y) = \begin{cases} s_1[\exp(ik_1x + i\varphi_1) - r\exp(-ik_1x - i\varphi_1)]\exp(ik_yy), & x \le 0 \\ s_2[a\exp(ik_2x + i\varphi_2) - b\exp(-ik_2x - i\varphi_2)]\exp(ik_yy), & 0 < x < D \\ s_3t\exp(ik_3x + i\varphi_3)\exp(ik_yy), & x \ge D \end{cases}.$$

In these expressions, which generalize those in [5] for the case when a bias V is applied over the structure, $k_y = k_F \sin\varphi_1$ with k_F the Fermi wavenumber, $k_1 = k_F \cos\varphi_1$, $k_2 = [(E - V_0 + eV/2)^2/\hbar^2 v_F^2 - k_y^2]^{1/2}$, $k_3 = [(E + eV)^2/\hbar^2 v_F^2 - k_y^2]^{1/2}$, $\varphi_{2,3} = \tan^{-1}(k_y/k_{2,3})$, $s_1 = sgnE$, $s_2 = sgn(E - V_0 + eV/2)$, and $s_3 = sgn(E + eV)$, with E the electron energy. The transmission coefficient through the barrier $T = s_3\cos(\varphi_3)|t|^2/s_1\cos(\varphi_1)$ is determined by imposing the requirement of wavefunction continuity at the $x = 0$ and $x = D$ interfaces. The barrier can be created by p-doping or, simpler, by gating [5]. The potential energy diagram of the biased barrier surrounded by non-gated regions is illustrated in Fig. 1.

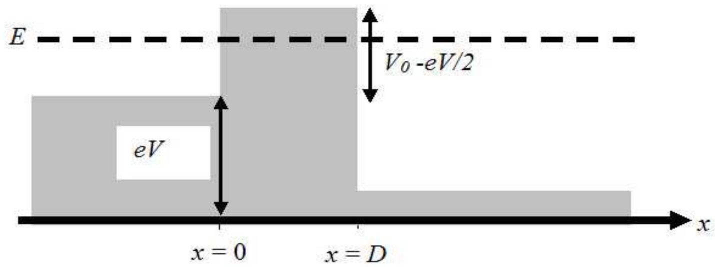

Fig. 1. Energy band diagram for a biased graphene. barrier.

The transport mechanism in the graphene tunnelling structure represented in Fig. 1 is unique i.e. in the regions where the electron energy E is higher than the potential energy, as is the case in left and right regions surrounding the barrier, the charge transport is assured only by electrons, whereas in the barrier region, when the electron energy is lower than the potential energy, only holes are participating to the transport. Thus, the term “barrier” does not mean in this case a region of evanescent propagation, as in common semiconductors, but a region in which charge transport is replaced by holes instead of electrons.

The transmission of the graphene barrier is represented in Fig. 2 as a function of voltage and at various Fermi wavenumbers $k_F = \alpha k_{F0}$, where α is 0.25, 0.3 and

0.35 when $\varphi_1 = 15°$ and $D = 100$ nm, where $k_{F0} = 50$ nm. A noticeable feature of these curves is the fact that the transmission has a gap, which increases when k_F is increasing. This happens because the transmission of the incident wavefunction is forbidden in the barrier because otherwise k_2 would be imaginary, fact that is not allowed by the gapless band energy diagram of the graphene. This means that graphene is a native quantum switch of ballistic electrons. Such an abrupt ON-OFF characteristic is unprecedented in nanoelectronic devices.

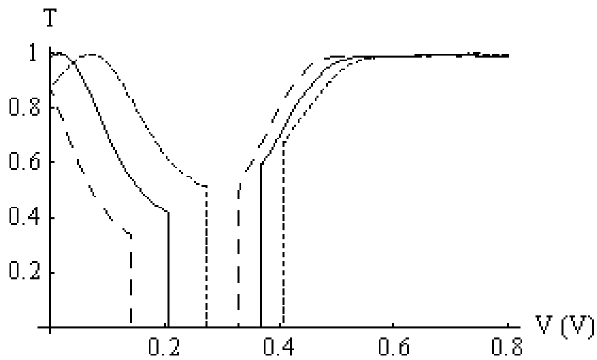

Fig. 2. Transmission of the graphene barrier as a function of the applied voltage at various Fermi wavenumbers: $k_F = 0.25k_{F0}$ (dotted line), $k_F = 0.3k_{F0}$ (solid line) and $k_F = 0.35k_{F0}$ (dashed line).

Further, in Fig. 3 the $I - V$ characteristics of the graphene barrier calculated using the Landauer formula at room temperature are represented for the structures considered in Fig. 2: curves are plotted at various Fermi wavenumbers k_F, when $\varphi_1 = 15°$ and $D = 100$ nm. A very pronounced negative differential resistance region is occurring. Increasing k_F, the peak-to-valley ratio of this region is increasing in the range 2.5–4 in our simulations, but the maximum value of current is decreasing.

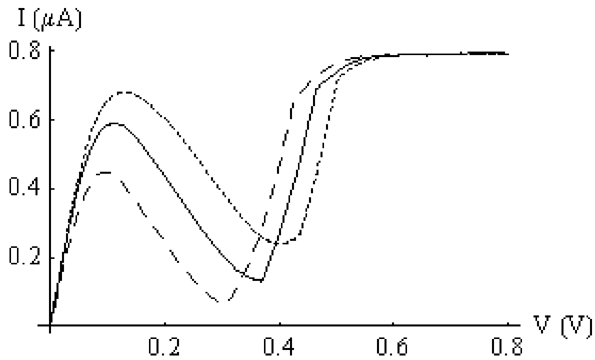

Fig. 3. The $I - V$ characteristics of graphene barrier at various Fermi wavenumbers: $k_F = 0.25k_{F0}$ (dotted line), $k_F = 0.3k_{F0}$ (solid line) and $k_F = 0.35k_{F0}$ (dashed line).

The occurrence of the negative differential resistance region is due to the gap in the transmission coefficient. This is exactly the opposite situation to resonant tunnelling diodes made of semiconductor heterostructures, where the physical origin of the peak in the current is due to a narrow peak in transmission. The negative differential resistance is the physical mechanism of generation of monochromatic signals of high frequencies, up to THz, as described in [4]. An oscillator consists of the negative differential resistance device loaded with a load, which selects the desired oscillation frequency. Considering that the transport in graphene is ballistic, the cut-off frequency of such a device is $f_c = v_F/2\pi D \cong c/600\pi D$, which for $D = 100$ nm gives 1.6 THz. This cut-off frequency could be increased decreasing the barrier width.

3. RF NEMS switches based on graphene

Graphene is not only a unique material for new nanoelectronic devices but also find astounding applications in the area of nanoelectromechanical (NEMS) devices due to its huge Young modulus. In this respect, it was recently demonstrated that a NEMS resonator consisting in a single atom-thick graphene suspended over a gated trench in SiO_2 working at room temperature is able to detect forces smaller then 0.9 fN [6]. Such high sensitivity is unprecedented for two-dimensional NEMS. Based on these facts we have simulated a RF NEMS switch as is displayed in Figs. 4a and 4b.

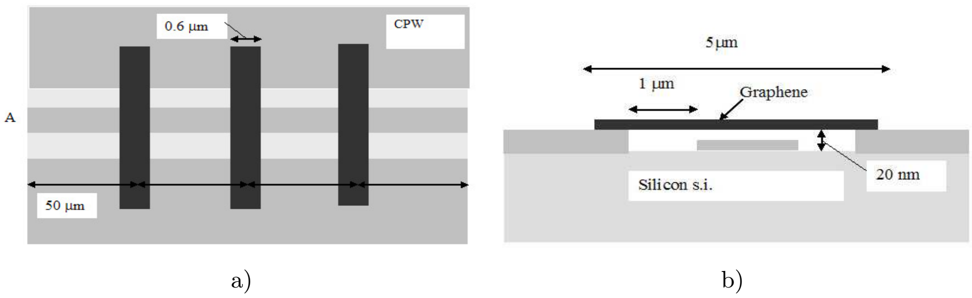

Fig. 4. The RF-NEMS graphene switch: a) top view, b) cross-section view.

The metallic graphene nanomembranes (a single graphene monolayer with a thickness of 1 nm) are loading periodically a coplanar waveguide. All relevant dimensions are indicated in Fig. 4. In practice this loading of CPW with graphene flakes is done manually, or using electrostatic self-assembly techniques. Graphene flakes remain suspended over the CPW only due to van der Waals forces [5], but metallic contacts could be also made using electron-beam techniques. In Fig. 5 we have represented the current flow at 10 GHz through the RF NEMS switch when a single graphene beam is actuated by the central electrode of CPW (ON state of the switch) and located at 50 µm from the left microwave excitation point (A). This electrostatic actuation is possible when a bias is applied between the central CPW electrode and the grounds. In our case the actuation voltage is 2 V. We can see that the current is suppressed near the graphene beam.

Further, we have considered that we add successively graphene sheets distanced at 50 µm and we have computed the S_{21} parameters with the help of IE3D simulator in the ON (graphene actuated) and OFF state (graphene not actuated). The results are displayed in Fig. 6.

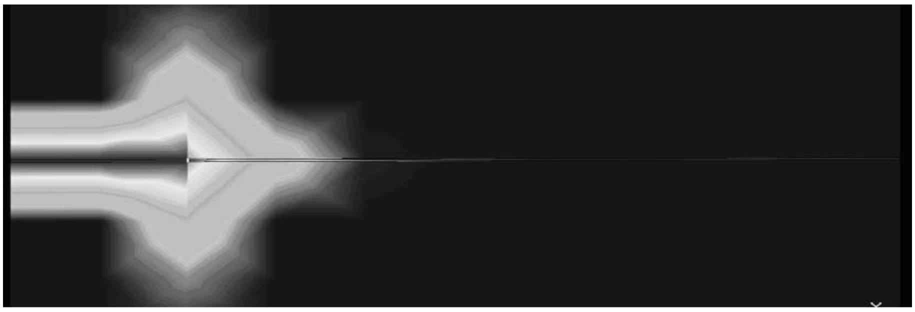

Fig. 5. The current distribution in RF NEMS switch based on graphene.

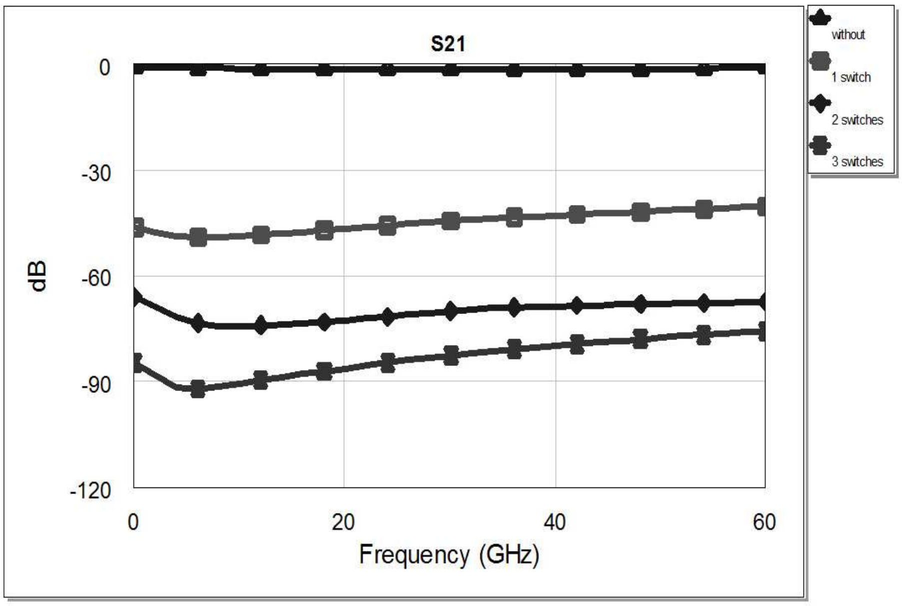

Fig. 6. S_{21} for the RF NEMS based on graphene.

From Fig. 6 we can observe we can observe that the RF MEMS switch is working very well in wide range of frequencies u to 60 GHz. Adding more graphene beams has the result of substantial improving of isolation of the switch while the losses are very low.

4. Conclusions

The paper has demonstrated that graphene plays in important role in new innovative high frequencies nanoelectronic devices. The unique transport properties of graphene make that a barrier made on graphene to act as a resonant tunnelling device able to oscillate beyond 1 THz. It is worth noting that a resonant tunnelling device implemented with AIII-BV semiconductors needs a heterostructure formed by several semiconductor layers grown by MBE techniques while in the case of graphene the same devices consists of a single gated nanomembrane of semiconducting graphene. The mechanical properties of graphene are exploited for RF-NEMS switches working with good performances over a very wide band of frequencies.

References

[1] NOVOSELOV K.S., GEIM A.K., JIANG D., ZHANG Y., DUBONS S.V., GROGORIEVA I.V., FIRSOV A.A., *Electric field effect in atomically thin carbon films*, Science **306**, pp. 666–669, 2004.

[2] ZHANG Y., SMALL J.P., PONTIUS W.V., KIM P., *Fabrication and Electric Field Dependent Transport Measurements of Mesoscopic Graphite Devices*, Appl. Phys. Lett. **86**, 073104, 2005.

[3] A.K. GEIM, K.S. NOVOSELOV, *The rise of graphene*, Nature Materials **6**, pp. 181–183, 2007.

[4] DRAGOMAN M., DRAGOMAN D., *Nanoelectronics Principles and Devices*, Chapter 5, Artech House, Boston, 2006.

[5] KATSNELSON M.I., NOVOSELOV K.S., GEIM A.K., *Chiral tunnelling and the Klein paradox in graphene*, Nature Physics **2**, pp. 620–622, 2006.

[6] BUNCH J.S., VAN DER ZANDE A.M., VERBRODGE S.S., FRANK I.W., TANENBAUM D.M., PARPIA J.M., CRAIGHEAD H.G., MC. EUEN P., *Electromechanical resonators from graphene sheets*, Science **315**, pp. 490–493, 2007.