RF NEMS BASED ON CARBON NANOTUBES AND GRAPHENE

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Abstract–*This paper presents RF- NEMS devices (resonators, oscillators and switches) for microwave applications based on carbon nanotube and graphene. We have demonstrated that innovative and cost-effective devices with good performances can be produced combining the NEMS principles and microwave techniques.*

1. INTRODUCTION

Nanoelectromechanical systems (NEMS) are simple mechanical systems such cantilevers, and double-clamped beams having at least one dimension of the order of few nanometers and which are electrostatically actuated by an external electrode [1]. NEMS displays mechanical resonance frequencies in the range 100 MHz-5 GHz, so coinciding with the electromagnetic microwave spectrum [1-2]. NEMS have also very high mechanical quality factors of $10^2 – 10^3$ at room temperature, in the GHz range.

The correspondence between the electromagnetic GHz spectrum and NEMS mechanical frequency oscillations can be used for new innovative devices in the area of high frequency NEMS [3]. Further, we will demonstrate that simple NEMS configurations based on carbon nanotubes (CNTs) have important applications for signal processing in the GHz range.

2. MICROWAVE RESONATOR BASED ON AN ARRAY OF FEW MILLIONS OF CARBON NANOTUBES.

When microwave signal frequencies are tuned near the mechanical resonant frequency of an array of metallic cantilevered carbon nanotubes (CNTs) sandwiched between two coplanar waveguide (CPW) lines (see Fig. 1 a), the CNTs array displays a notch in the microwave transmission coefficient due to a metal-dielectric transition of the carbon nanotube array at the mechanical resonant frequency of the cantilever. Thus, the CNTs array acts like a resonator. We have used a CNT array having 10^9 CNTs/cm^2.The measured quality factor of such an array of millions of CNTs cantilevers has a quality factor of 800 at room temperature at the fundamental resonance frequency of 1.4 GHz (see Fig. 1b) [4].

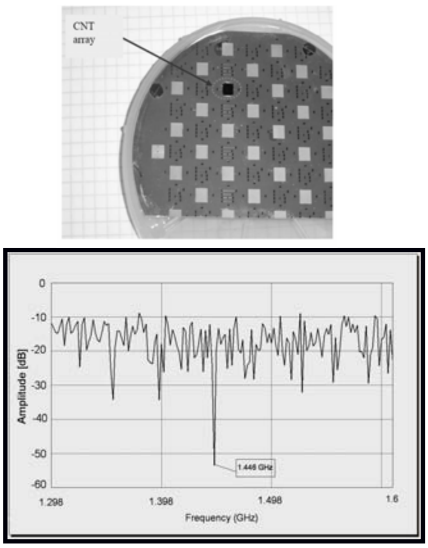

Fig. 1. The CNT resonator (a) The CNT array on the wafer (b) $|S_{21}|$ dependence on frequency.

3. OSCILLATIONS AND AMPLIFICATION WITH SUSPENDED NANOTUBES

In what follows, we present a double-clamped CNT bundle suspended over a metallized trench which is 1 μm wide and micromachined in GaAs substrate. In this configuration, this NEMS is behaving as FET-like device (see Fig.2, and 3). The drain and source contacts are made on the each side of the trench, while the gate is the metallized electrode of the gate located at 1.5 μm below the CNT bundle. The device is biased as FET transistor and low V_G is acting as variable resistor controlled by gate as any FET, but at certain gate voltage in the range 15-18 V, this structure displays a S shaped negative – differential resistance (NDR). Further, applying equal V_{DS} steps of 0.2 V the NDR is displaying multiple branches, which are parallel between them. In this way, the entire structure is working as a high speed switch with multiple levels which are very useful for multi-valued logic applications.

The I_D–V_D curve displayed in Fig. 4 shows that at low drain-source voltages V_D and for low gate voltages V_G the device is FET-like, i.e. a tunable resistor controlled by the gate voltage. However, at higher voltages, i.e. for V_D > 18 V and V_G > 12 V, the I_D–V_D characteristics considerably changes, and shows a multiple NDR behavior, as shown in Fig. 5. An S-shaped characteristics appears initially and then, at constant V_D steps of 0.2 V, the upper branch of the NDR is jumping and produces almost parallel 5–8 branches, depending on the V_D value.

The jumps in the I_D–V_D characteristics are most probably due to charge accumulation followed by potential lowering at the potential step discontinuities between different CNTs in the bundle. A similar mechanism has been evidenced in [5]. After overcoming the potential barrier at the electrode–CNT interface, which is responsible for the initial low-current region, the electrons in the CNT that is in direct contact with the electrode must overcome a potential barrier in order to penetrate in an adjacent CNT in the bundle (the potential barrier between adjacent CNTs is about 50 meV in height and 4 Å in width [6]). Charge accumulation at this potential barrier and the subsequent potential lowering, i.e. the jump in the I_D–V_D curve, means that electron transport is producing through another conduction channel/CNT each time such a jump is observed.

The traversal time τ of electrons across the potential barrier between adjacent CNTs was estimated at 10 fs and represents the switching time between two consecutive branches of the NDR characteristic. This signifies that our device is an ultrafast electric switch.

This traversal time was calculated as $\tau = \int dx / v_g$, where the group velocity of electrons in the x direction (across the barrier) is defined as $v_g = J / |\Psi(x)|^2$, with ψ(x) the electron wavefunction in the barrier region and J the probability current.

The microwave measurements of our device were performed using a vector network analyzer (VNA) and a probe station. The probe-tip test structure connected to the FET-like architecture of our device is displayed in Fig. 6a. The maximum stable gain MSG = $|S_{21}|/|S_{12}|$ of a CNT-FET structure is shown in Fig. 6b for V_D = 1.6 V, V_G = 8 V and I_D = 2.25 mA. The measurements were performed in air and at room temperature. Microwave "on wafer" measurements were made using an Anritsu 37397D Network Analyzer in the 0.04–4 GHz range, a SOLT calibration procedure and the Picoprobe Calibration Substrate. The response includes the parasitics of the test structure. The results show that the active behavior of the CNT-FET structure is up to 3.25 GHz. The fact that S_{21} differs from S_{12} reveals the unilateral behavior of the device. Similar results were reported in [7], but at a much lower frequency (below 80 MHz). This device needs further matching networks and a minimization of parasitic capacitances in order to amplify in microwaves.

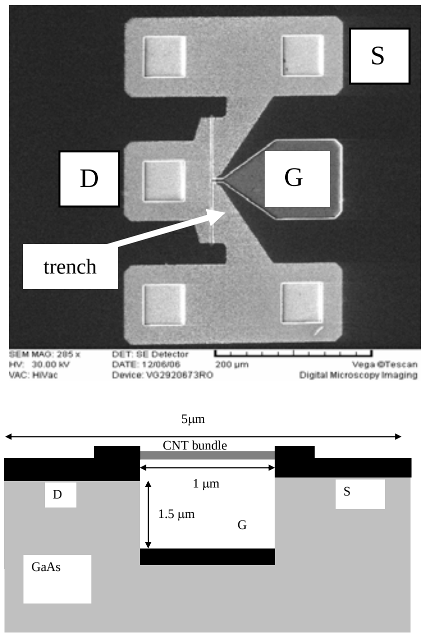

Fig. 2. The double clamped CNT bundle FET-like device.

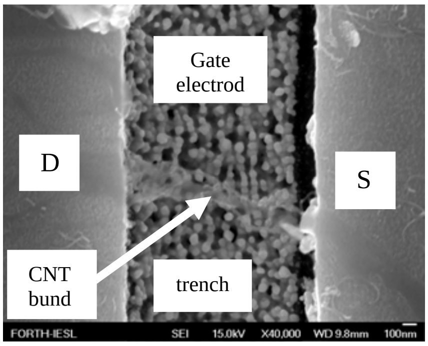

Fig. 3. The detail of the above device to evidence the CNT bundle.

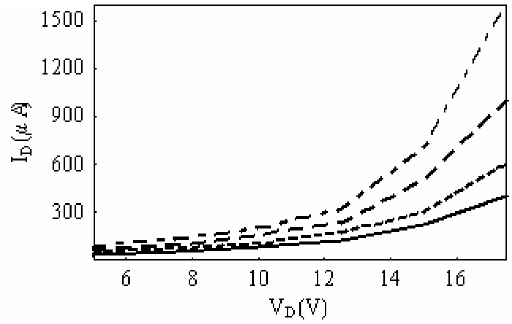

Fig. 4. The I_D–V_D dependence on the gate voltage for V_G = 0 (solid line), 4 V (dotted line), 8 V (dashed line), and 12 V (dashed-dotted line).

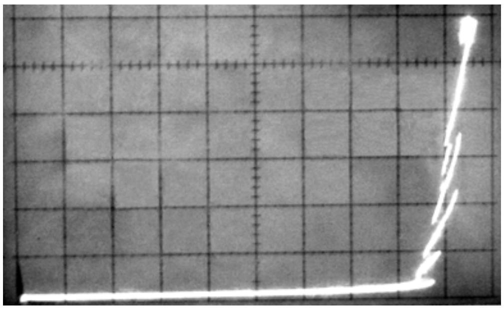

Fig. 5. Multiple NDR of the device (V_G =14 V; I_D - 500μA/div and V_D -2V/div).

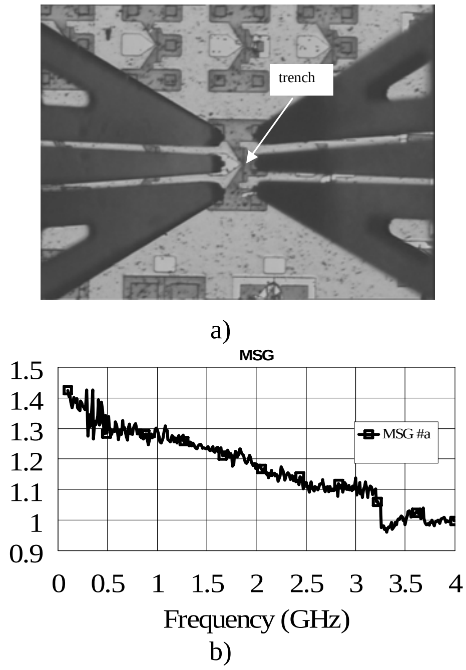

Fig. 6. (a) The probe-tip mounted on the CNT FET -like structure, and (b) the MSG characteristics.

4. RF GRAPHENE DEVICES

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 relativistic-like quantum Dirac equation instead of a Schrödinger equation [8]. Also, graphene has a Young modulus of 1.5 TPa. Due to these unique properties, graphene is very promising for high frequency nanoelectronic devices, such as oscillators and switches working at high frequencies. We will demonstrate that graphene is a very efficient RF switch for microwave applications, tuning its resistivity from high values to low values with the help of a gate voltage.

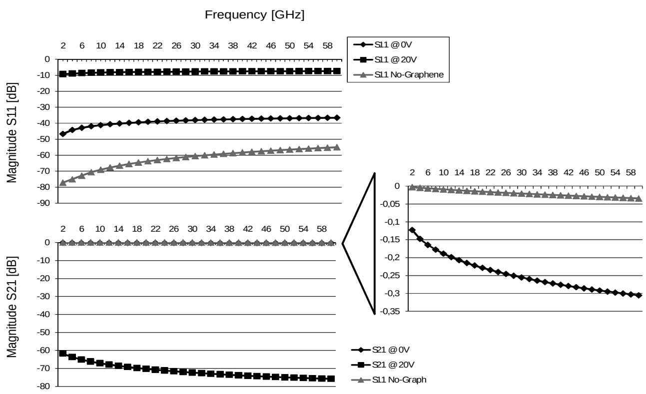

Fig. 7. Graphene switch up to 60 GHz.

The switch is formed by a metallic CPW patterned over a graphene sheet grown over 300 nm of SiO_2. The SiO_2 is grown on a doped Si substrate playing the role of the gate. The results of the simulations are displayed in Fig.7.

The switching characteristics are also evidenced in the current distribution at 60 GHz displayed in Fig. 8.

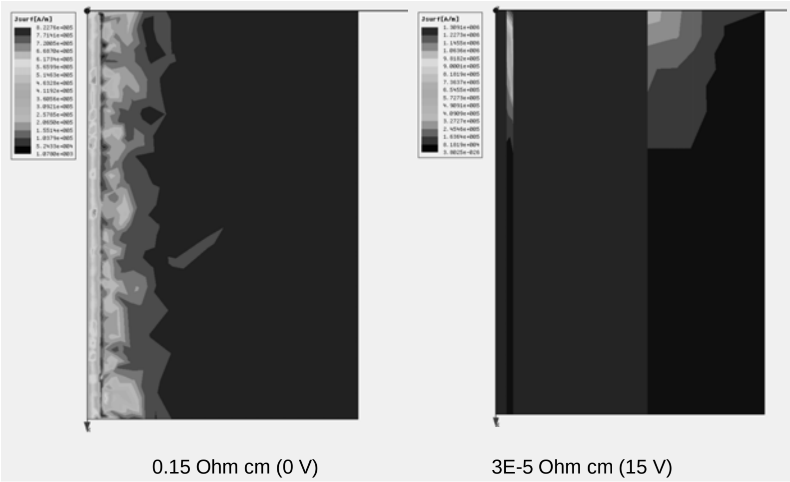

Fig. 8. The current distribution of CPW patterned over a graphene sheet when the gate voltage is tuned in the range 0-15 V.

5. CONCLUSIONS

The new materials originating from the accelerated development of the nanotechnologies and nanoelectronics have a large impact in the RF devices conferring them miniaturization, reconfigurability, and new functionalities.

References

[1] K.L. Ekinci and M.L. Roukes, "Nanoelectro-mechanical systems", *Rev. Sci. Instr.*, vol. **76**, 2005, pp. 061101/1-4.

[2] M. Dragoman and D. Dragoman, *Nanoelectronics: Principles and Devices*, Boston, USA: Artech House, 2006.

[3] H.B. Peng, C.W. Chang, S. Aloni, T.D. Yuzvinsky, and A. Zettl, "Ultrahigh frequency nanotube resonators", *Phys. Rev. Lett.*, vol. **97**, 2006, pp. 087203/1-4.

[4] M. Dragoman, D. Neculoiu, A. Cismaru, K. Grenier, S. Pacchini, L. Masenq, and R. Plana, "High quality nanoelectromechanical microwave resonator based on a carbon nanotube array", *Appl. Phys. Lett.*, vol. **92**, 2008, pp. 063118/1-3.

[5] W.-C. Liu, L.-W. Laih, S.-Y. Cheng, W.-L. Chang, W.-C. Wang, J.-Y. Chen, and P.-H. Lin, "Multiple negative-differential-resistance (MNDR) phenomena of a metal-insulator-semicon-ductor-insulator-metal (MISIM)-like structure with step-compositioned $In_xGa_{1-x}As$ quantum wells", IEEE Trans. Electron Dev., vol. **45**, 1998, pp. 373-379.

[6] S.K. Biswas, L.J. Schowalter, Y.J. Jung, A. Vijayaraghavan, P.M. Ajayan, and R. Vajtai, "Room-temperature resonant tunneling of electrons in carbon nanotube junction quantum wells", Appl. Phys. Lett., vol. **86**, 2005, pp. 183101.

[7] A.J.-M. Bethoux, H. Happy, A. Siligaris, G. Dambrine, J. Borghetti, V. Derycke, and J.-P. Bourgoin, "Active properties of carbon nanotube field-effect transistors deduced from S Parameters Measurements", IEEE Trans. Nanotechnology, vol. **5**, 2006, pp. 335-342.

[8] A. K. Geim and K. S. Novoselov, "The rise of graphene", *Nature Materials*, vol. **6**, 2007, pp. 181-183.