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Low Frequency Noise of Carbon Nanotubes THz detectors

A. Rehman¹, A. Krajewska¹, S. Smirnov², B. Stonio^{1,3}, D.B. But^{1,3}, K. Pavlov³, G. Cywinski^{1,3},
D. Lioubtchenko^{1,2}, W. Knap^{1,3}, S. Rumyantsev¹

¹CENTERA Laboratories, Institute of High Pressure Physics PAS, Warsaw, Poland

²Division of Micro and Nano systems, KTH Royal Institute of Technology, Stockholm, Sweden

³Centre for Adv. Materials and Technologies CEZAMAT, Warsaw University of Technology, Warsaw, Poland

Abstract—We report studies of noise properties of carbon nanotube (CNT) networks-based devices used for the terahertz detectors. Low-frequency noise characteristics of CNTs as a function of temperature, UV illumination, and back-gate voltages were examined. Our results demonstrated the existence of at least two important resistance components of nanotubes rather than generally accepted dominant tube-to-tube junction resistance. We showed that noise spectroscopy can be employed to probe the structural quality of nanotube networks. Measurements as a function of back gate voltages revealed the existence of generation-recombination noise, related to deep traps, which play a significant role in the performances of CNT networks-based terahertz detectors.

I. INTRODUCTION

Carbon nanotubes (CNTs) having high Seebeck coefficient and absorption over a wide range of electromagnetic spectra are effective materials for room temperature terahertz detectors. Efficient single detectors and CNTs based terahertz cameras are already demonstrated [1-3]. The responsivity of the detectors can be improved via alignment of nanotube networks [4] and by overcoming several instabilities factors that exist in CNTs based transistors [5].

Noise is one of the most important parameters of the detectors, which defines the Noise Equivalent Power (NEP). On the other hand, noise is an effective tool for the material and device characterization [6]. It allows to study the properties of the specific defects, material quality, reliability and degradation at early stages [7]. It also allows to explore the hidden defects, which are not seen in the regular DC characteristics [8]. Noise is also an effective tool for gas and biological sensing [9-11].

Here, we study the effect of UV illumination, temperature, and back gate voltage on the low-frequency noise in CNT network transistors and demonstrate that noise spectroscopy is an effective tool to probe the structural quality of the material and characterize CNTs for their potential applications in THz detectors.

II. RESULTS

We have deposited a randomly oriented network of CNTs on glass and oxidized Si substrates. Inset in Fig. 1 shows the schematic view of one of the CNTs devices on a glass substrate. Transmission line model (TLM) geometry was employed to understand the relative contributions of the contacts to total device resistance and noise. Resistance as a function of length for one of the studied nanotube networks is shown in Fig. 1. It was found that in all studied devices, the contact resistance is negligible in comparison with total device resistance.

The scanning electron microscope (SEM) and Raman microscope were used for the structural characterization of CNTs. The lower inset in Fig. 1 shows the SEM image of one of the studied CNT networks. Fig. 2 shows the Raman spectra of two of the other studied CNT networks. The peaks at ~130, 1350, and 1580 cm⁻¹ are referred to as radial breathing mode (RBM) peak, defects related D peak and graphitic G peak,

Fig. 1. Resistance of CNTs as function of length. Red dashed line is drawn to guide the eye. The contribution of contacts to total device resistance is negligible. Upper inset shows the schematic view of CNTs on glass substrate. Lower inset shows the SEM image of one of the studied nanotube networks.

respectively. The ratio of Raman G to D peak estimates the quality of CNTs (i.e. the higher is the G/D ratio, the higher is the structural quality of the nanotubes). The Raman RBM peak provides information about the diameter of CNTs via relation $d = A/\omega - B$ [12]. Here, $A = 217.8 \text{ cm}^{-1}$, $B = 15.7 \text{ cm}^{-1}$ and ω is the wavenumber of the peak in cm⁻¹. Insets in Fig. 2 show the Raman RBM peak decomposition to Lorentzian peak functions and diameters on nanotubes which composed the studied networks.

Fig. 2. Raman spectra of two of the studied CNTs along with zoom in view of RBM peak. Lorentzian peak fitting was used to estimate diameter of nanotubes. The G/D peak ratio indicates that lower (black) studied nanotubes has higher defects compare to upper (red).

The low-frequency noise was measured in the frequency range from 1 Hz to 100 Hz. The detailed procedure of noise measurement protocols can be found elsewhere [6, 7]. All of our studied devices exhibit $1/f^\gamma$ noise spectra shapes with the exponent γ varying from device to device. The measurement of CNTs under UV illumination increases the resistance (inset in Fig. 3) and noise amplitude ($S_f/I^2 \times f$) while preserving the spectral noise shape (Fig. 3). Measurements at elevated

Fig. 3. Noise spectra of one of the CNTs device under UV illumination. It can be seen that UV illumination increase the noise amplitude and shift the spectra upwards (from black to red line), while preserving the spectral shape. Lower inset shows the resistance of the same device as function of UV illumination.

temperature affect the shape of the noise spectra and have a minor effect on the noise amplitude (Fig. 4). The effect of UV light and temperature on noise can be explained via simple equivalent circuit model consisted of two parallel resistors. The spectral noise density in such conditions can be given as $\frac{S_f}{I^2} = \frac{R_0^2}{(R_0 + R_n)^2} \frac{S_{Rn}}{R_n^2}$. Here, R_0 and R_n are the noiseless and fluctuating resistances, respectively and $\frac{S_{Rn}}{R_n^2}$ is the spectral noise density of R_n fluctuations. Assumptions that UV illumination does not affect the fluctuating resistor R_n but increases the resistance R_0 and $R_n \geq R_0$, allow us to explain the effect of UV light on noise. The effect of temperature on noise can be explained by the temperature dependence of $\frac{S_{Rn}}{R_n^2}$. These reveal at least two important components of nanotube networks resistance rather than generally accepted dominance of tube-to-tube-junction resistance.

We have also witnessed that noise is very sensitive to the structural quality of nanotubes determined by Raman spectroscopy. The upper inset in Fig. 4 shows the correlation of the area and fill-factor normalized noise amplitude $\tilde{A} = S_f/I^2 \times f \times \text{Area} \times \text{fill-factor}$ for samples with different Raman G/D peak values as shown in Fig. 2 (the higher G/D ratio is an indication of the higher quality of nanotubes). It can be seen that the sample with the higher G/D peak ratio demonstrates a low noise level. This signifies that noise is sensitive to the quality of CNTs and can be used to probe the structural quality of carbon nanotube-based devices.

We have further extended our study to as-fabricated and aged CNTs based transistors. As-fabricated devices demonstrated the existence of generation-recombination (GR) noise, whereas, GR noise component was suppressed along with the reduction of noise level in aged devices, (lower inset in Fig. 4). This effect can be explained by the effect of the humid laboratory air environment.

The results of noise measurements allow us to estimate the best values of the CNTs based THz detectors NEP. Following published data [1-3], we found that CNTs detectors can have responsivity typically from 1 V/W up to 10 V/W. This gives us the estimate of the NEP ranging from 10 pW/Hz^{0.5} to 100 pW/Hz^{0.5} for the detectors operating in the photovoltaic regime (no drain current). Noise at non-zero current was found

Fig. 4. Noise spectra of CNTs device at room and at high temperature indicate the change in spectral shape. Upper inset of the figure shows the area and fill-factor normalized noise amplitude (i.e., $\tilde{A} = S_f/I^2 \times f \times \text{Area} \times \text{fill-factor}$) as function of area along with Raman G/D peak values of studied devices. Lower inset shows the noise spectra of aged and as fabricated CNTs transistor.

to be relatively high. This results in at least one order of magnitude higher NEP for biased detectors.

III. SUMMARY

The low-frequency noise characteristics of randomly oriented network of CNTs were studied. Noise measurements under UV illumination and at elevated temperature revealed at least two important components of nanotube networks resistance rather than generally accepted dominance of tube-to-tube-junction resistance. It was also found that noise spectroscopy allows to estimate the quality of nanotubes devices as terahertz detectors. Measurements of CNTs transistors revealed GR noise and its dependence on the environment. Estimates for the NEP yielded competitive values for detectors operating in photovoltaic mode but strongly degrading in the case of biased detectors.

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