Use of Carbon Nanotubes as radiation detectors

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Carbon Nanotubes are one-dimensional structures with diameters ranging between 2 and 100 nm and lengths up to hundreds of microns. They are characterized by a large variety of peculiar characteristics such as a semiconductive or metallic behaviour, a ballistic electrical conductivity and enhanced field emission capabilities. Among these characteristics their sensitivity to the radiation is very peculiar depending on their diameter and chirality. The energy gap varies from 0.4 to ~6 eV leading to sensitivity to the electromagnetic radiation, potentially from UV to IR. This opens the possibility to build a wide sensitive range radiation detector for space researches and environmental controls.
Main characteristics of Carbon Nanotubes allowing the detection of radiation will be reported together with first results obtained exposing first detectors prototypes to UV, visible and IR radiation.

1. INTRODUCTION

Carbon nanotubes (CNT) are empty cylinders made of carbon atoms [1,2]. They are neither semiconductor nor metals, and are classified as semimetals [3]. The physical mechanism describing the conduction in nanotubes is ruled by the laws of quantum mechanics rather than by classical electromagnetism. The geometrical parameters of nanotubes, fixed by the (n, m) chiral vectors of the structure, set the electronic states of the structure [4]. Only one geometrical arrangement results into a metal-like behaviour. All the other configurations lead to semiconductor nanotubes [5].
There are two different structures for nanotubes: Single Wall Carbon NanoTubes (SWCNT) and Multi Walls Carbon NanoTubes (MWCNT). MWCNTs appear as several concentric SWCNTs with different tube diameter and/or with different values of the chiral vectors. MWCNTs exhibit a conductor-like behaviour while SWCNTs can be either conductors or semiconductors depending on their chiral vectors. Several experiments have already shown that semiconductor carbon nanotubes exhibit fluorescence properties in the near-infrared wavelength region (between ~ 1 and ~ 1.5 μm) [6]. This property is due to the electronic configuration of semiconductor carbon nanotubes and seems promising for applications in devices used in biophysics and in physics in general. Carbon nanotubes characterized by n-m=3p (p positive or null integer) behave like metallic conductors. Nanotubes corresponding to other combinations of *n* and *m* indexes are semiconductors having an energy band gap depending on the tube diameter following the relation: $E_{gap} = 2y_0acc/d$, where $y_0 = 0.1$ eV, acc = 0.142 nm and d is the tube diameter. Thus, in semiconductor nanotubes, the energy band gap ranges between 0.4 and 0.7 eV.

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Results presented in this paper have been obtained in the frame of GINT *(Gruppo INFN per le Nano Tecnologie)* program [7], funded by INFN. The GINT's research scientific program is addressed to study the possibility to build a nano-patterned photocathode working in a wide radiation range using carbon nanotubes. For this purpose MWCNTs have been produced and their response to the incident laser radiation has been studied.

2. The CNT used device

The device used for this investigation is shown in Fig. 1. MWCNT are grown in the chinks of two platinum combs deposited on a 500 micron silicon substrate insulated by means of 30 nm Si_3N_4 layer. A drain voltage applied between platinum electrodes collects drift charges through the nanotube layer. Under pulsed laser illumination, charges can be generated in the CNT layer and collected with the electrical applied field. The corresponding signal on the oscilloscope can be registered and studied to evaluate the charge amount generated as a function of the laser wavelength and intensity. The comparison with the device response in the absence of laser light allows the study of dynamic properties of CNTs. In particular the I-V characteristic has been measured by the oscilloscope in the absence of laser (dark current) and compared with that obtained with traditional amperometric measurements.

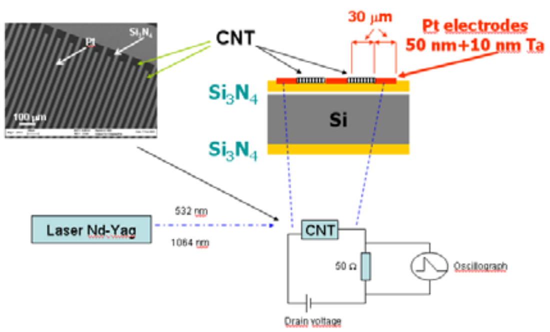

Figure 1: The CNT device realized. A Q-Switched Nd-YAG laser is used as exciting source.

Fig. 2 shows the I-V characteristics of two different CNT productions. The first sample, labelled as "Old CNT", has been obtained at 500 °C and presents a strong metallic behaviour (dashed line in Fig. 2), while the second one, labelled as "New CNT", obtained at 700 °C, shows a semi metallic behaviour (continuous line in Fig. 2). That means that CNT layer characteristics can be varied according their production process.

Measurements reported in the following have been obtained with the last device using a Q-Switched Nd-YAG laser (10 ns pulse duration, 10 Hz repetition rate) as exciting source.

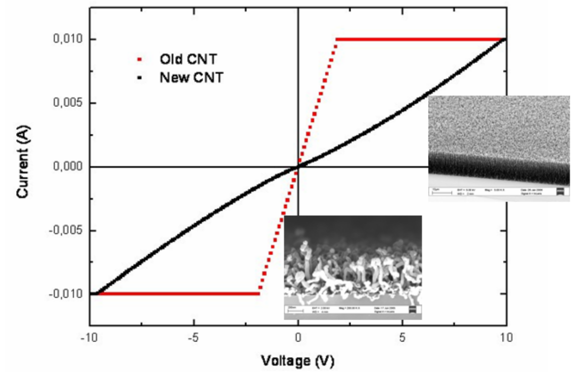

Figure 2: I-V plot for two different CNT productions. Insets show the corresponding SEM images.

3. CNT dynamic characteristics

Fig. 3 shows the signals obtained firing a 532 nm, 76 μJ laser pulses on the nanotube carpet, varying the drain voltage from 0 to 10 V. Oscilloscope trace between 0 to 200 ns shows the dark current level, from which the I-V plot of Fig. 2 has been obtained. A laser signal trigger, indicated by the blue line, starts at 200 ns. The CNT signals follow immediately this trigger. Maximum signal at 10 V is about 1.2 V.

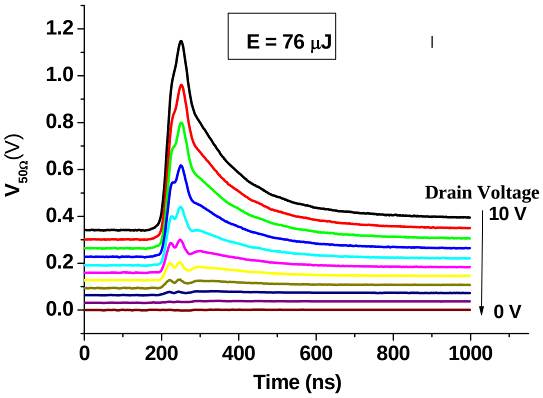

Figure 3: Signal observed as answer to a pulsed laser radiation 532 nm wavelength and 76 μJ intensity.

Fig. 4 shows signal characteristics and comparison between different drain voltages. Structures are observed on the peak and a long tail is evident at all voltages. This tail is probably due to the photo-generated charge that relaxes over the capacitance of the device structure.

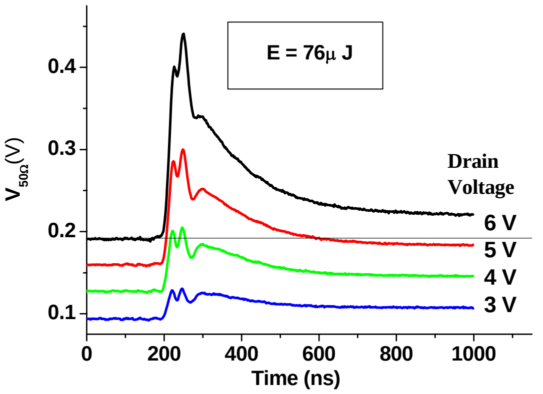

Figure 4: Signal characteristics at different drain voltages.

This effect is still evident in Fig. 5, where comparison between signals obtained at various wavelengths with a drain voltage of 10 V is shown. Sensitivity to the radiation depends on the radiation wavelength, but the long tail is observed in all cases: in fact Fig.5 indicates maximum intensity of the signal in the UV region, and a decrease to higher wavelengths

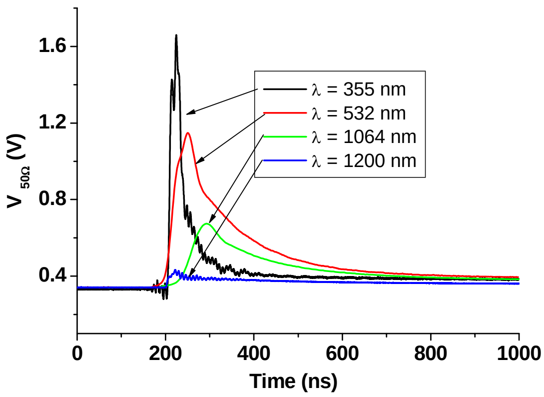

Figure 5: Comparison between signals obtained at different wavelengths.

The integrated area of signals is proportional to the drained current. In Fig. 6 the plot shows the charge collected at different drain voltages for two radiation wavelengths. About 1 billion of electrons are collected for each laser pulse.

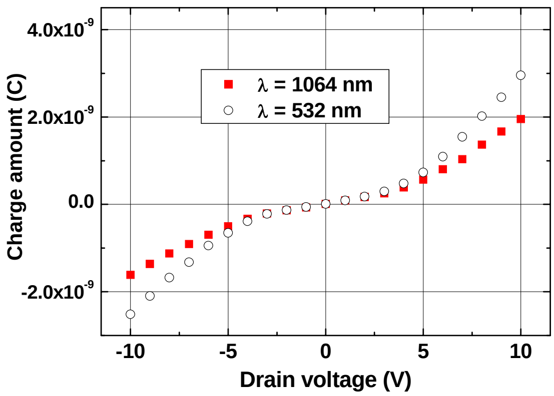

Figure 6: Charge Drained as a function of the drain voltage at two different wavelength of the exciting radiation.

In order to estimate the quantum efficiency of this device, the number of collected electrons has been normalized to the number of photons in the laser pulse. Unfortunately the device layout does not allow a precise measurement of CNT illuminated area, and then an estimate may be made only in arbitrary units. Nevertheless it is worth noting from Fig. 7 that the quantum efficiency strongly depends on the radiation wavelength, and it assumes the maximum value in the UV region at 355 nm while monotonically decreases in the infrared region. In the graph the quantum efficiency for the silicon substrate only is also reported.

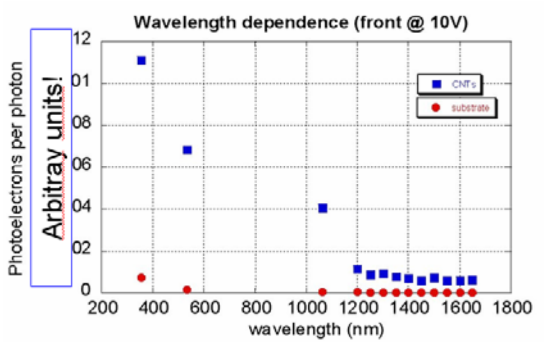

Figure 7: Quantum efficiency in arbitrary unit.

4. CONCLUSIONS

Carbon nanotubes thin films promise to have in the next years important applications in the field of radiation detectors. In this paper we have approached the problem to build a large area, large wavelength range radiation detector with the use of CNT. First results are very encouraging showing:

1. Aligned MWCNT have been produced with the CVD technique;
2. the films have shown important photo-conversion effect as a function of the wavelength in a large spectral interval
3. An accurate analysis on CNT photoconductivity properties is still in progress to understand the solid state mechanisms at base of the observed effect also with the help of the ab initio modelling methods;
4. CNT patternization in nanometric scale to make efficient devices is in progress.

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