Progress on the development of a silicon-carbon nanotube photodetector

SinPhoNIA
Single Photon Nanotechnology Innovative Approach

Carla Aramo for the Sinphonia Collaboration
INFN – Sezione di Napoli – Italy
aramo@na.infn.it

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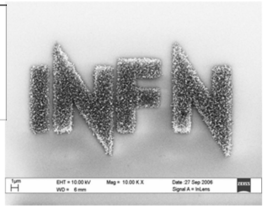


Abstract: The properties of Carbon Nanotubes (CNTs), the new allotropic status of carbon discovered in 1991, have been widely investigated in all possible application field. This new material in fact can be easily obtained chemically by CVD (Chemical Vapour Deposition) as a layer of nanotubes growth on a wide variety of materials. When growth on a silicon surface, CNTs create a semiconductor heterojunction with peculiar photoresponsivity properties. We studied this heterojunction with the purpose to realize a large photocathode with high quantum efficiency in a large wavelength range from UV to IR. Results obtained up to day allowed us to build a new kind of photodetector very cheap, stable and easy to manage. Recently this new device has been proposed as one of candidates for the beam monitor system of SuperB.

Introduction

The development of new technologies and nanotechnology over the last decade made possible the discovery of new materials or new allotropic form of known materials with surprising and unexpected properties. One of the most promising new materials is carbon nanotube (CNT), an allotropic form of carbon. A lot of interesting aspects of CNTs are yet to be studied and exploited: his affinity with silicon can open new channels for the development of nanoelectronics and nanodetectors. In particular large area heterojunctions can be realized by growing multiwall carbon nanotubes (MWCNTs) on the surface of a silicon substrate creating a new hybrid material with very interesting properties for photodetection. MWCNTs consist of multiple layers of graphite sheets forming concentric cylinders, from two to many tens. Some MWCNT properties made them an attractive material for UV photodetector [1,2] and photosensor applications, when associated their response to light stimulus.

Hereinafter we present a novel large area detector featuring low noise, high efficiency and great surface uniformity. This detector has been obtained by coupling the optoelectronic characteristics of carbon nanostructures (CNs) with the well-known optoelectronic properties of silicon. The proposed device mimics the behaviour of a p-n-p phototransistor where the CN-silicon interface acts as base, while the emitter is Metal-Insulator-Semiconductor (MIS) junction between the back electrode and the silicon substrate and the collector is the CN layer itself.

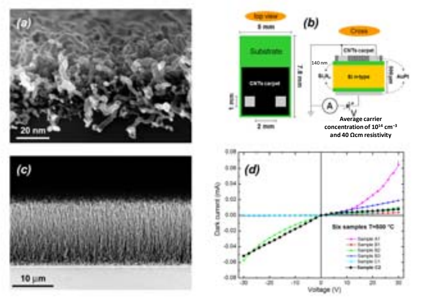


Figure 1| SEM images and dark current. **a, b, c**, SEM images of CN grown at a temperature of 500 °C (**a**) and 700 °C (**c**) on the substrate schematized in (**b**). See the morphological differences between carbon nanofibers (**a**) and the MWCNTs (**c**), induced by the growth temperature. **d**, Dark current-voltage characteristic of six Si-CN devices.

CN-Si based device

Figure 1a shows a SEM image of CN device grown at a CVD temperature of 500 °C, which behaves as bunches of ropes of carbon nanofibres (CNFs) with variable diameter along the tubes. The average diameter of these nanostructures is 48 nm with a length of ~ 0.2 microns.

By using a higher CVD growing temperature, 700°C, (Fig. 1b) vertically aligned carbon nanotubes are obtained, with an average diameter of 19 nm and a length greater than 16 microns.

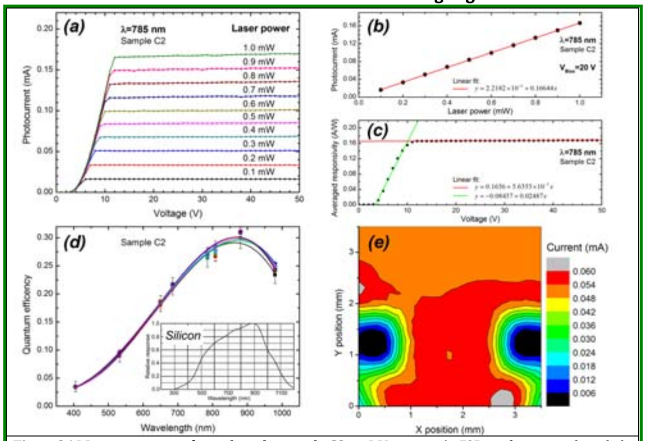
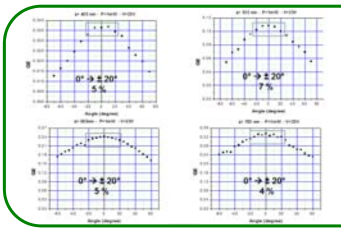


Figure 2 | Measurements performed on the sample C2. **a**, I-V curve at λ=785 nm for various laser light intensities. **b**, Linearity plot at λ=785 nm for an applied drain voltage of 20 V. **c**, Averaged responsivity at λ=785 nm. In the plot linear fit curves are superimposed fitting the signal rise and the current plateau. **d**, Quantum efficiency (QE) of detector C2 as a function of the wavelength ranging from 405 to 980 nm fitted with a four order polynomial curve. In the inset the spectral response of silicon. **e**, Detector surface photocurrent map demonstrating the uniformity of sensitive area covered by CNFs.

Figure 2a shows the photocurrent measured when the device is illuminated with a 785 nm continuous laser beam at various light power intensities. The rectifying behaviour is confirmed also in the presence of high intensity of illumination and in a large range of drain voltage. This is due to the particular structure of substrate in which the electrode on the back forms a MIS junction with the silicon substrate, whereas CNs form a carbon nanostructure–silicon heterojunction [3].

It must be noted that no electronic amplification has been applied: the measured current is the one directly generated by photons impacting the CNF layer.



The quantum efficiency (QE) is a function of angle of incidence of the laser beam but in the range 0°-20° the QE changes only few % for all used wavelengths. This allow the use of this kind of detector also for inclined incident light.

The MWCNT-Si based device

The same measurements have been repeated for the devices based on vertically aligned MWCNTs (Fig. 1b). It is evident that, despite the different nanostructure morphologies, the heterojunction between CNs and silicon is always strongly sensitive to the radiation in a wide range of wavelengths. The QE is four times higher than that measured for CNF-based device in the UV energy region. The present result paves the road to the use of MWCNT-based detectors in the UV region.

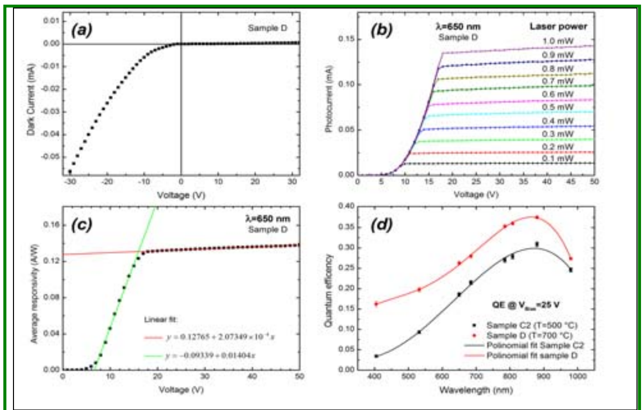


Figure 3 | Measurements performed on sample D. **a**, Dark current. **b**, I-V curve at λ=650 nm for various laser light intensities. **c**, Averaged responsivity at λ=650 nm. In the curves are superimposed fitting the signal rise and the current plateau. **d,** quantum efficiency as a function of the wavelength ranging from 405 to 980 nm of detector C2 compared with that of detector D fitted with a four order polynomial function.

Discussion

In absence of CNs the device can be schematized as a double Schottky junction polarized back-to-back (Fig. 5a). The presence of the CNs overbalances the system: a heterojunction is created between the CN layer and the silicon (Fig. 5b). The presence of the insulator (silicon nitrite) is bypassed by the formation of permanent low resistivity conduction channels inside this film, favouring the charge flow through the silicon substrate. The channels are created as an external voltage is applied to the device thanks to the peculiar characteristics of CNs. In addition CNs are semi-transparent to the radiation. The device shows the characteristics of a p-n-p photo-transistor, where the metallic contact on the back acts as the emitter, the upper CN layer is the collector and the CN-silicon depletion area plays the role of the transistor base. The performance of this detector depends on the carbon nanostructure morphology and ultimately on their electronic properties. We have found that MWCNT-based devices show a higher junction thresholds and a higher sensitivity to the UV radiation.

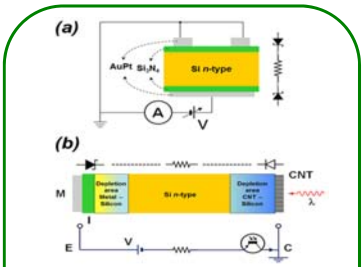


Figure 5 | Layout of CN-Si with the junctions.
a, In absence of CNs the device can be schematized as a double Schottky junction polarized back-to-back.
b, The presence of the CNs overbalances the system: a heterojunction is created between the CN layer and the silicon.

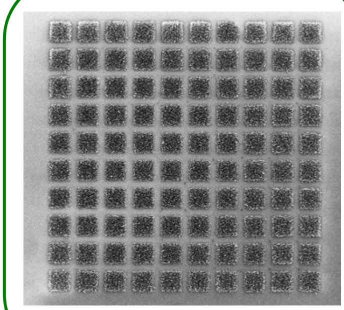


Figure 6 | 100 pixels of 4x4 μm each obtained with micro lithography.

Conclusion

The device is extremely promising in a future use in high energy physic experiments and medical applications. Highly pixelled surfaces can be obtained by means of micro or nano lithography (Fig. 6) [5] permitting the coupling of detector with external lighting devices such as scintillators and optical fibres.

Pixelled large area photocathode can be used for the medical imaging or to manufacture fluorescence light detectors or to detect Cerenkov light cone with high accuracy. Due to its peculiar characteristics this detector has been considered for beam monitoring at SuperB *(Large Angle Beamstrahlung Detector).*

References

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