Carbon Nanotube Multi-spectra Sensor Development

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The sensor was designed and developed 100% from the institutes of INPP and INN of NCSR "DEMOKRITOS"

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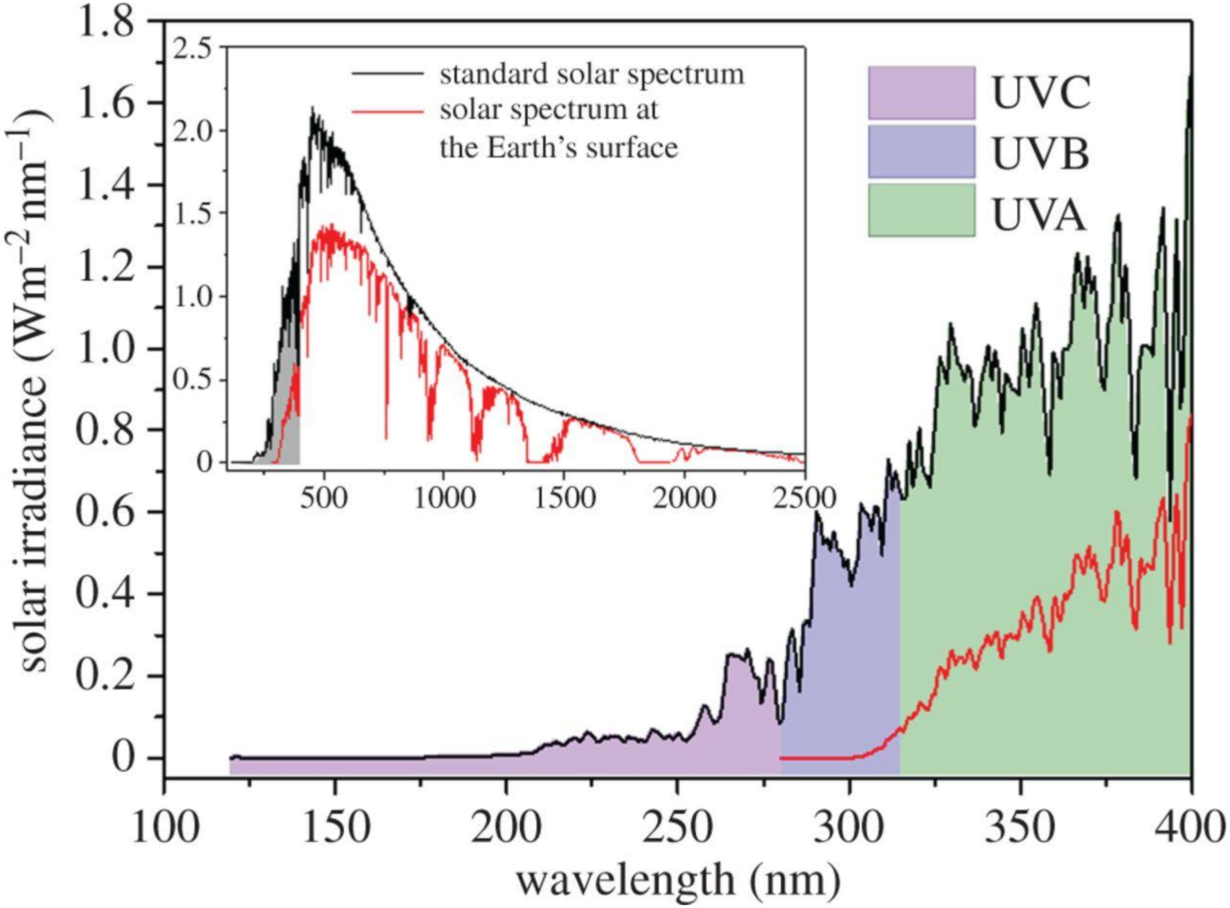
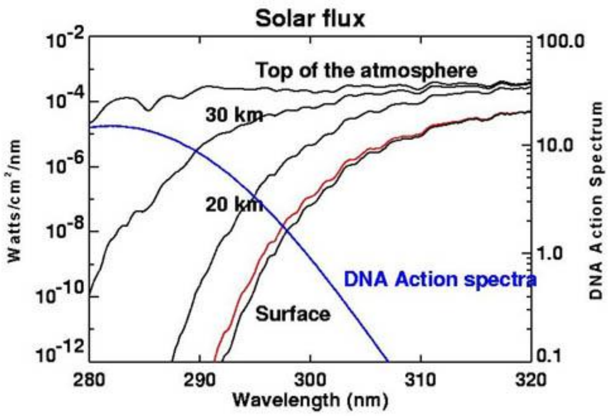
Solar Spectrum



UV reduction caused by the ozon layer 20 and 40 Km above earth's surface.

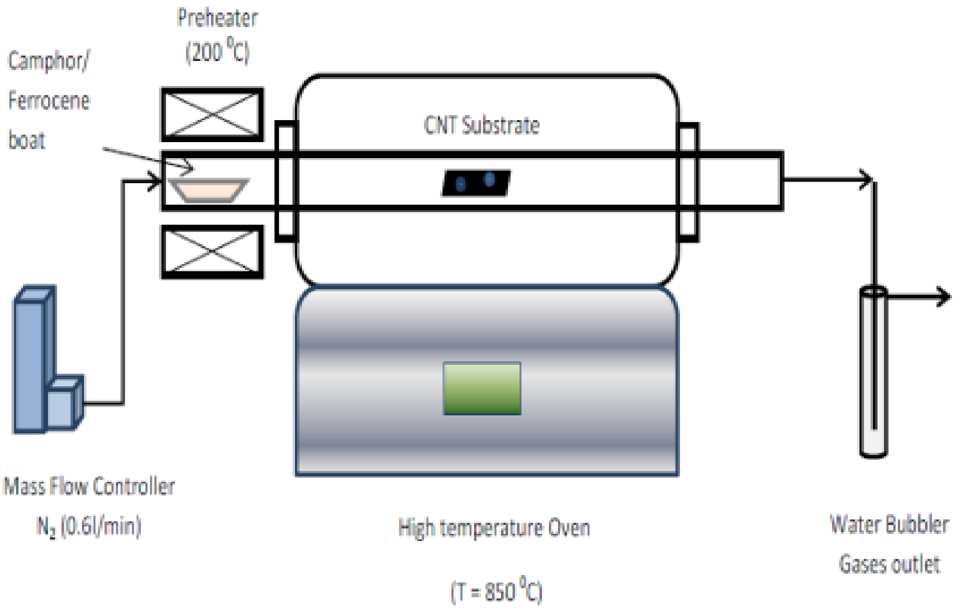


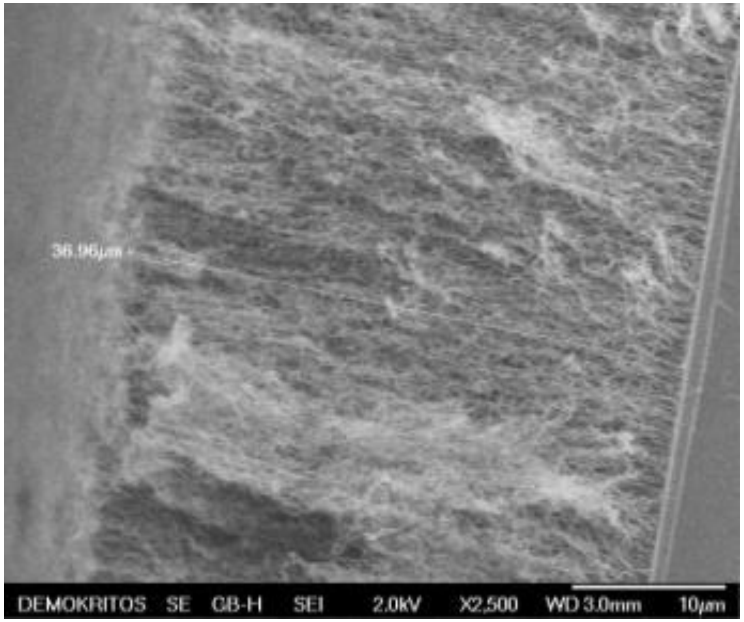
Introduction-Main Idea

- Many types of Ultra Violet (UV) detectors are used up to now.
- UV spectrum is of particular interest not only in particle physics where Cherenkov light and scintillators emit in this region but also in other fields like agriculture, food industry or medicine.
- The main idea of this proposal is to build low cost and low operating voltage UV, sensors based on arrays of well-aligned Carbon Nano Tubes (CNT) in the form of Multi Wall CNT (MWNT)

CNT Development Facility

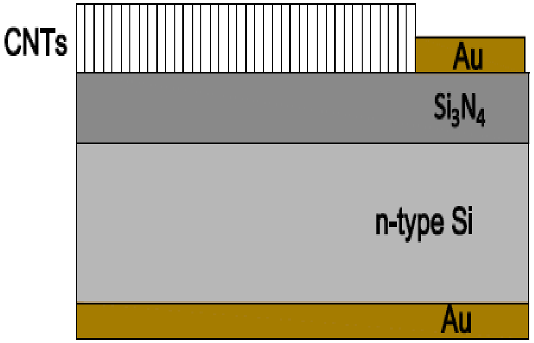
- A mixture of 2g of Camphor with 0.1g of Ferrocene as a catalyst .
- Preheating phase at T = 200 ^{0}C and main high temperature oven at T = 850 ^{0}C.
- The whole process lasts about 40min.
- Achieved to control the length in the CNT array below 40μm.

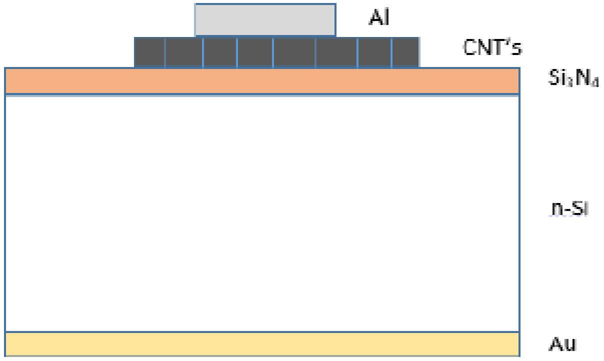


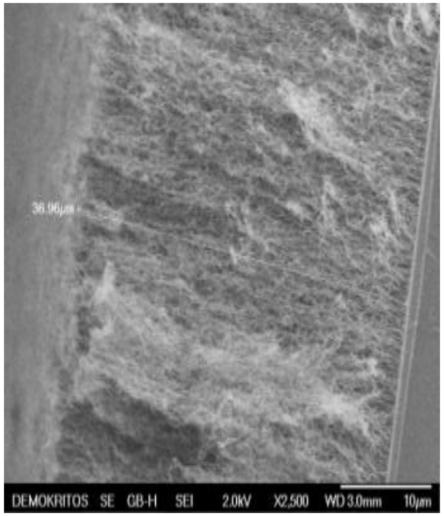


Sensor Fabrication

- n-type Si (450μm width) of 100 orientation and ρ = 10Ω.cm.
- The back plain of the Si is covered with a thin layer (30μm) of gold (Au) to serve as Ohmic contact.
- 140μm Si_3N_4 layer is deposited on the top plain to serve as a diffusion barrier (i.e. Fe from Ferrocene during CNT development) as well as a dark current reducer.
- The CNTs were deposited using CVD process at 850 ^{0}C

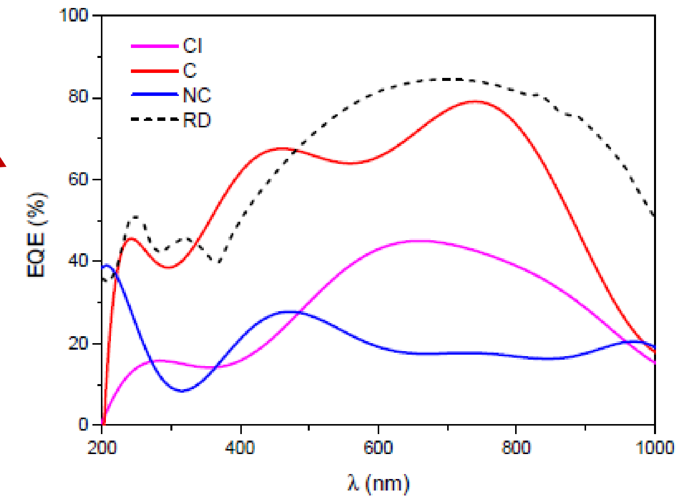






Sensor Performance (I)

➢Effective Quantum Efficiency (EQE) of the fabricated sensor for 9V bias voltage.
➢Good performance in UV (200nm – 400nm).
➢Peak EQE in IR (750nm).

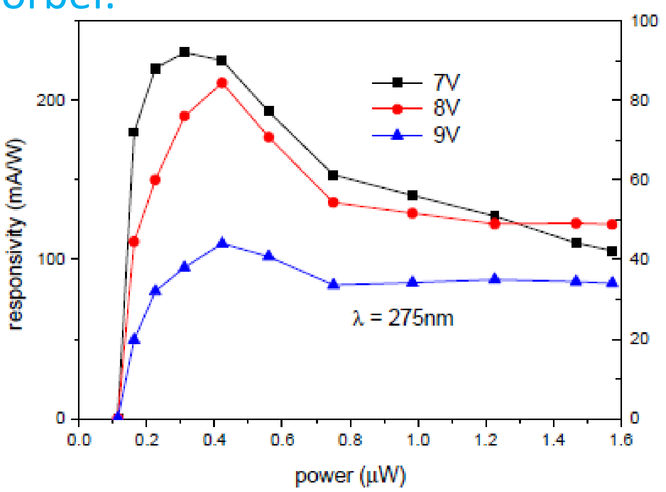


The UV response of the device is attributed to:

➢The presence of the nitride layer which has a bandgap of ~5.2eV (238nm).

➢CNT act as a UV photon absorber.

➢Responsivity(R) /EQE as a function of the bias voltage and irradiation power from a LED emitting at λ = 275nm



Responsivity of same level of the best performing Schottky or MSM type GaN, UV detectors

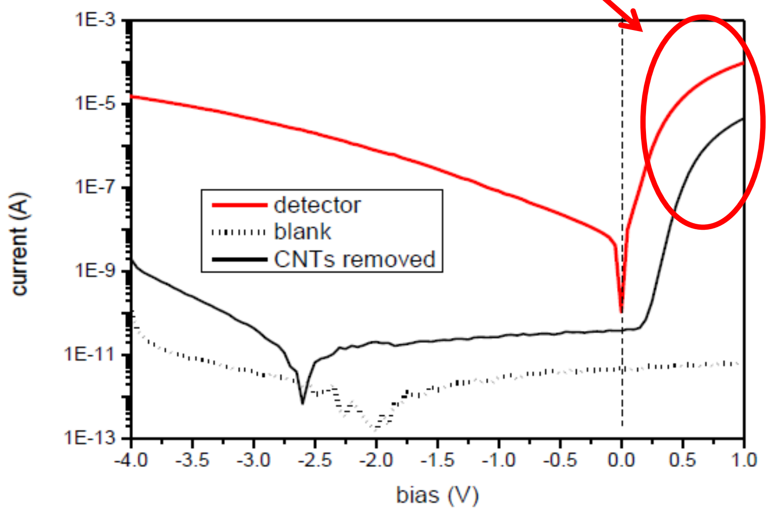
$R(\lambda) = I_{PD} / P_{opt}$, I_{PD} : generated photocurrent, P_{opt} : incident light power at a given wavelength (λ)

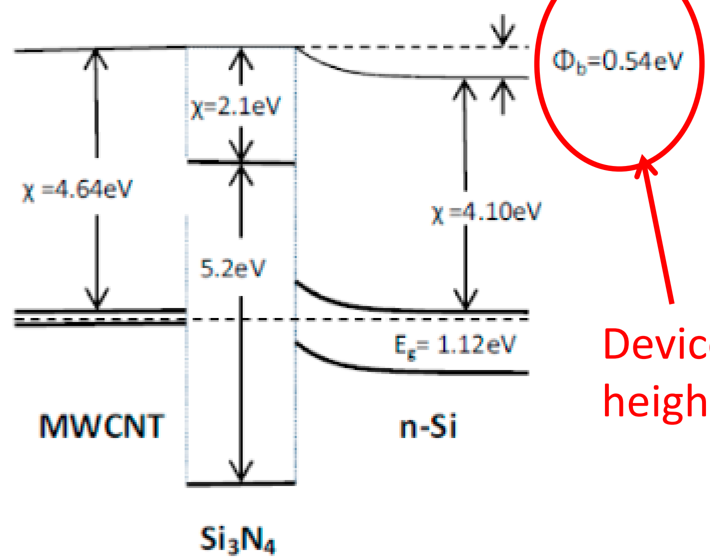
Sensor Performance (II)

➢Thermally treatment in the stage of CNT deposition causes Fe catalyst atoms contamination of the Si_3N_4 layer and the conductance behavior completely changes.

➢The fabricated detector behaves as a Schottky diode (red solid line) that depends upon the MWCNT/n-Si barrier.

➢The Si_3N_4 layer, due to the addition of the Fe traps, becomes a series resistance (~10-30kΩ) manifesting itself as a bending of the forward characteristic (bias >0.5V).





Device Barrier height

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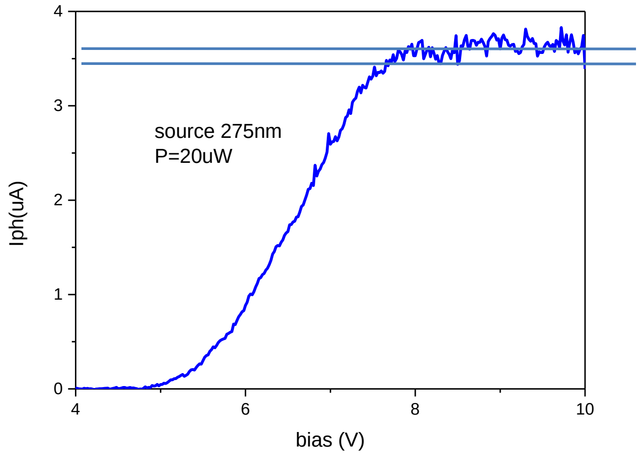
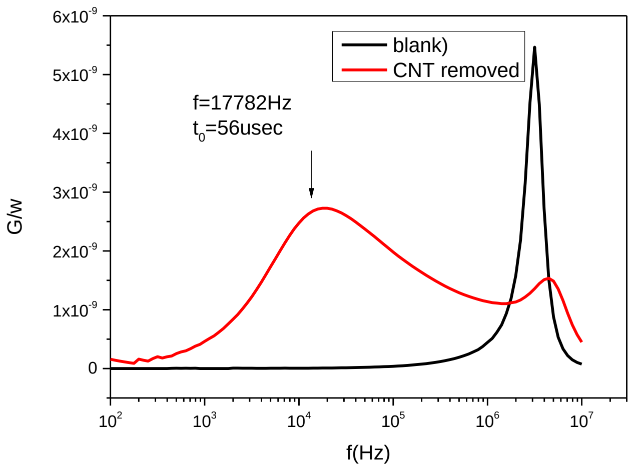
Sensor Performance (III)



UV response of the device vs Bias Voltage

Current Noise level (I_n)at Bias Voltage = 8V, I_n ~ 0.08μA



Sensor Specific Detectivity(defines the resolving power):

$$D^* = R\frac{\sqrt{A\,\Delta f}}{I_n}$$

For A = 0.04cm^2, Δf = 17782Hz, I_n=0.08μA, R = 140mA/W for V=8Volts → D* = 4.7x10^7 cm Hz$^{1/2}$/W

- Trapping role of the Fe atoms demonstrated in admittance over omega (G/ω) vs frequency (f) plot in the case of the “blank” and the “CNT removed” references.
- The Fe traps contribute by a time constant of 56μsec affecting the performance of the device. → *flicker noise*, or *1/f*

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A UV photodetector based on ordered free standing MWCNT

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Summary: Multiple Wall Carbon Nanotubes (MWCNT) present advantages for optoelectronic applications such as the large effective photo-collector surface as well as the possibility to tune their band gap and absorbance through the growth parameters[1]. In this work, we demonstrate a hybrid MWCNT/Si_3N_4/n-Si photodetector based on ordered MWCNTs and evaluate its performance in the UV, visual and near IR spectrum (200-1000nm). Depending on the application the absorbing nanotube layer can be made thick enough (e.g. several millimetres) to enhance radiation absorption and electron-hole pair generation. The best result obtained so far as a UV detector is a 90% Equivalent Quantum Efficiency @275nm for a 20μm CNT layer thickness[2].

Device Fabrication

The device structure is presented in figure 1. Fabrication starts with a n-type (100) Si wafer (450μm thickness) of ρ = 10 Ω*cm. The back plain of the Si is covered with a thin (100nm) of gold (Au) electrode, while a 150μm Si_3N_4 layer is deposited via Chemical Vapor Deposition (CVD) to serve as an anti-reflecting coating as well as a dark current reducer. This is followed by the development of the Carbon Nanotubes (CNT) layer via Catalytic CVD and the thermal evaporation of an aluminum (Al) thin (100nm) electrode.

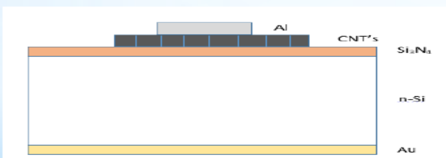


Figure 1: *Device Structure*

The reactor used for the CNT development is displayed in figure 2. A mixture of 2g of Camphore with 0.1g of Ferrocene as a catalyst was injected into the deposition chamber with the use of N_2 gas flow (0.6l/min), after preheating at 200°C. The mixture gas travels through the main high temperature oven, which is kept at θ = 850°C and MWCNTs are formed on the "cold" substrate. The whole process lasts about 40min and produces well-ordered MWCNTs (Figure 3).

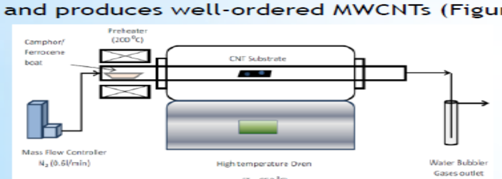


Figure 2: *The CNT development facility with the High Temperature Oven*

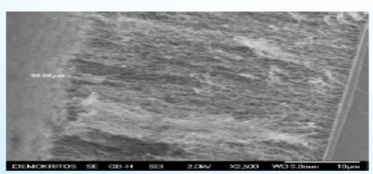


Figure 3: *MWCNTs of 20μm length and 15nm diameter*

Operation

When used as a photodetector, the device is biased in the inverse direction (n-Si substrate positive) and behaves as a Schottky diode with an intermediate dielectric barrier layer. Figure 4 shows the band scheme of the device. The Si_3N_4 layer acts as a wave guide for UV photons and as a diffusion barrier for the Fe ions introduced during MWCNT fabrication (Figure 5)

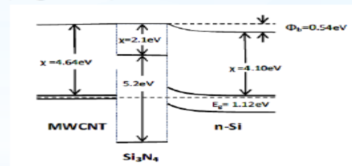
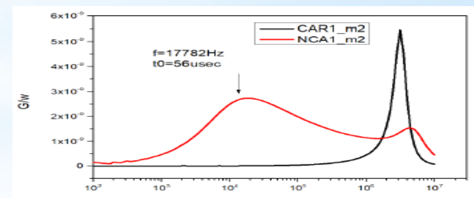


Figure 4: *The MWCNT/Si_3N_4/Si heterojunction an be considered as a Schottky diode (0.54eV barrier) with an intermediate dielectric layer carrying Fe traps.*

Figure 5: *The CNT formation procedure requires the presence of Fe catalyst. This is blocked by the Si_3N_4 layer resulting in donor/acceptor traps with a characteristic time of 56μsec.*



Performance

The device has excellent performance in the UV and the visual part of the spectrum. Responsivity and EQE exceed 100mA/W and 50% for a selected operation bias. The UV response is shown in figure 6.

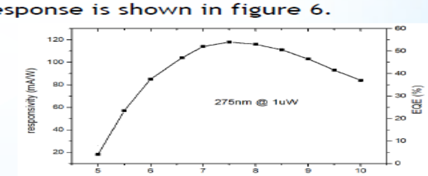


Figure 6: *Responsivity and EQE for a 275nm source vs device bias [2]*

References

[1] C. Aramo *et al.*, "Progress in the realization of a silicon-CNT photodetector," *Nucl. Inst.*
[2] A. Filatzikioti *et al.*, "Carbon nanotube Schottky type photodetectors for UV applications," *Solid. State. Electron.*, vol. 151, pp. 27-35, 2019.

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Carbon Nanotube Schottky type UV Sensor

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Carbon nanotube Schottky type photodetectors for UV applications

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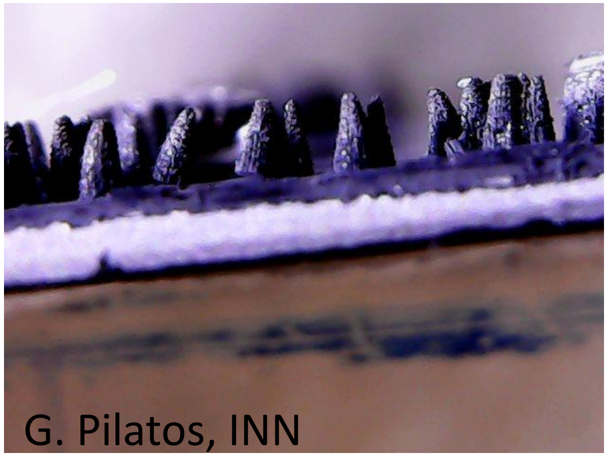
Future Plans

- Try to tune the various parameters of the sensor i.e. CNT height, and Si_3N_4 layer width.
- Try to reduce the size of the sensor to ~0.5mm in diameter and construct an array of such sensors. First results are promising.



- Try to combine CNT development procedure with lithographic techniques to produce a SiPM type device in possible collaboration with KETEK GmbH.

Conclusions for CNT Sensors

•We developed CNT sensors with high added value (fully constructed in NCSR) that can operate:

- In a wide range of the UV spectrum(200nm – 400nm)
- Have large Responsivity ~200mA/W for UVC band
- Reasonable Detectivity ~ 4.7×10^{7} cm $Hz^{1/2}/W$
- They can operate in low voltage < 10V.
- The development process and production is cheap.
- They are promising UV radiation sensors