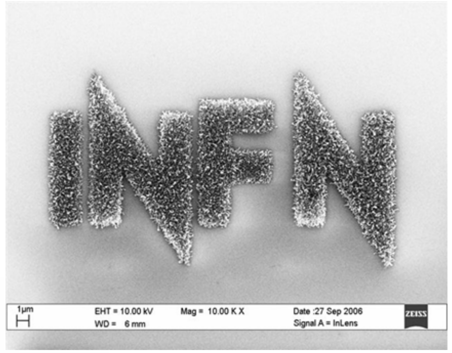
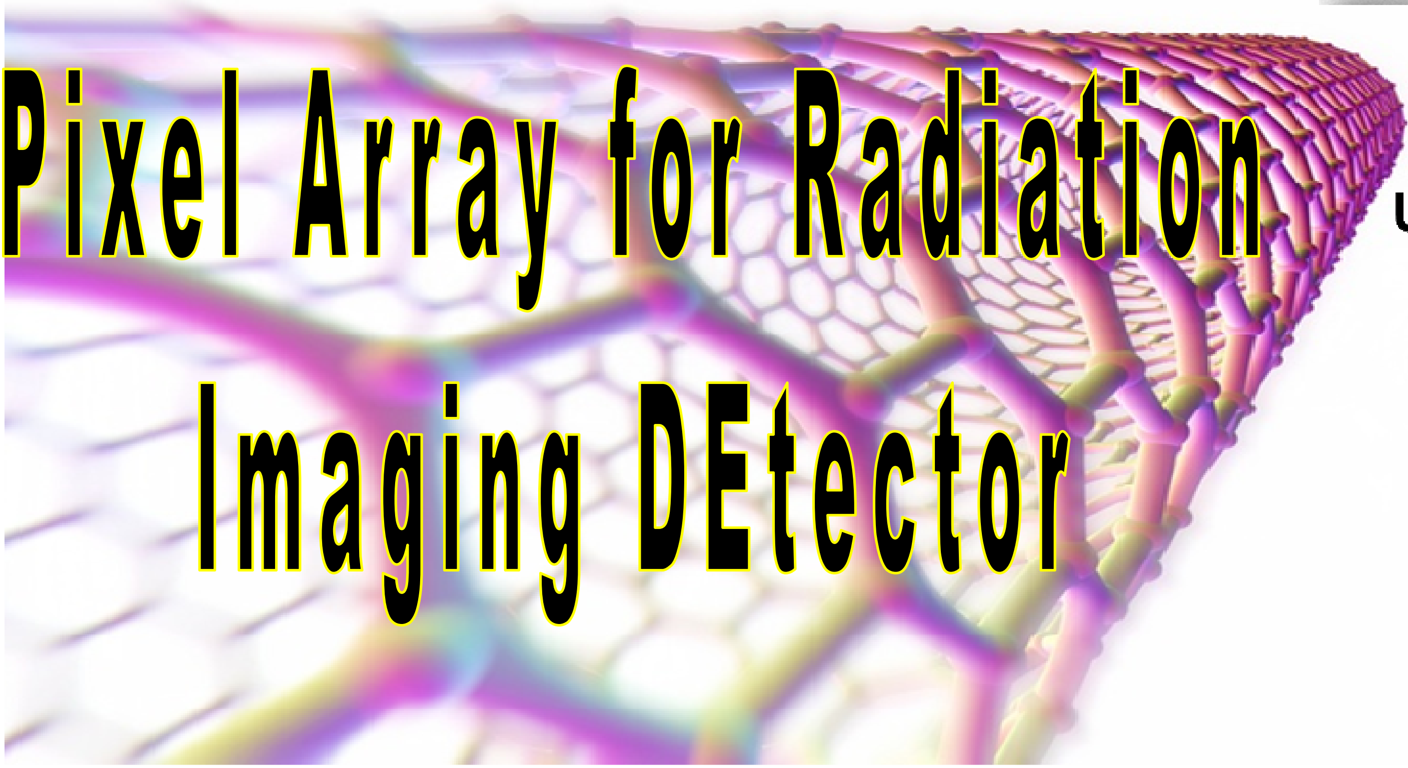
PARIDE



Pixel Array for Radiation Imaging DEtector



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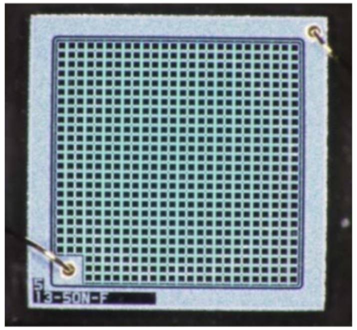
+ FBK

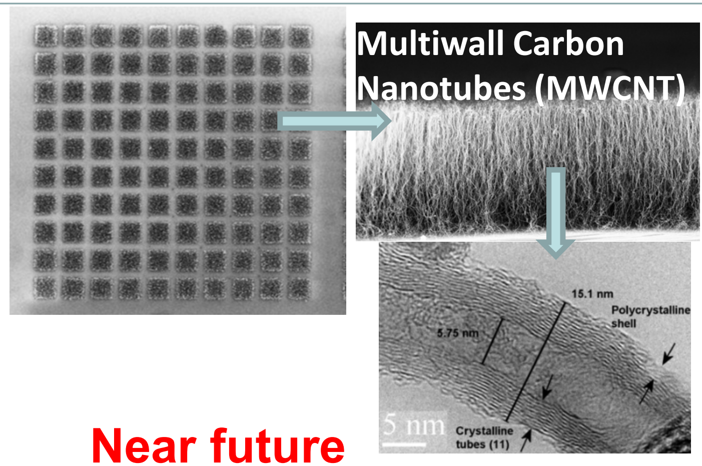
Large area CNT-Si heterojunction for photodetection

Carla Aramo for PARIDE Collaboration

Micro&Nano for photon detection

MACRO | MICRO | NANO





'30

Issues

- Intrinsic limit QE < 40%
- high voltage, bulky, fragile
- influenced by B, E fields
- damaged by high-level light
- ageing (eg. He)
- radiopurity

'90

Issues

- Dark noise still the most limiting factor → active area
- Low T: perform ideally in the range 100K < T < 200K
- QE in near-UV region ~ 40% and PDE ~ 30%

Near future

Advantages

- Lower dark noise at room temperature
- Large area and highly segmented → linearity
- Higher QE in the near-UV region

from Vacuum to Silicon to Carbon

Carbon Nanotubes (CNTs)

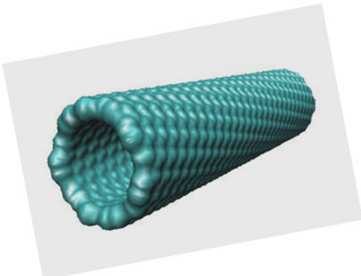
Molecular Nanowires (d ~ 1 nm, l ~ 1 μm)

SWNTs

Single Graphene Sheets ($d \approx 0.7 \div 3$ nm, $l \approx$ μ-range)

$\notin$ N — |n-m|/3 — $\in$ N

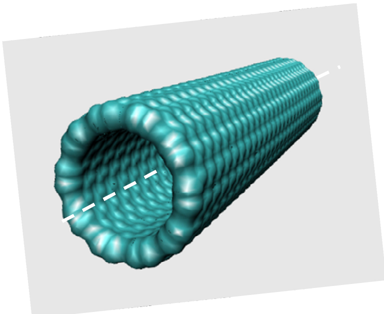
Semiconductor



Channel (FETs),

Luminescence

Metal



Ballistic Conduction,

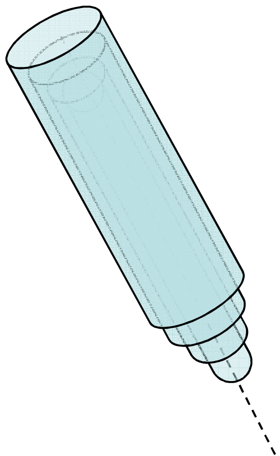
e-wave guides, SETs

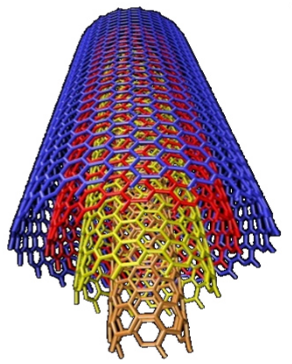
MWNTs

Coaxial graphene sheets
($d \approx 2 \div 100$ nm, $l \approx$ μ-range
($d^{out} \approx 20_{AD}$, 100_{CVD} nm)

Vias

Nanocomposites

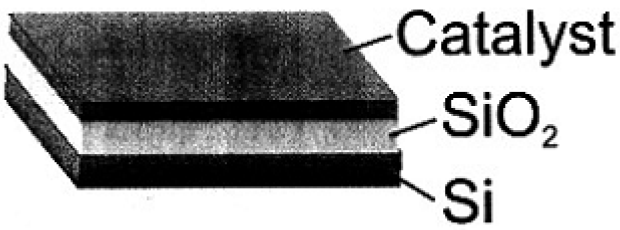


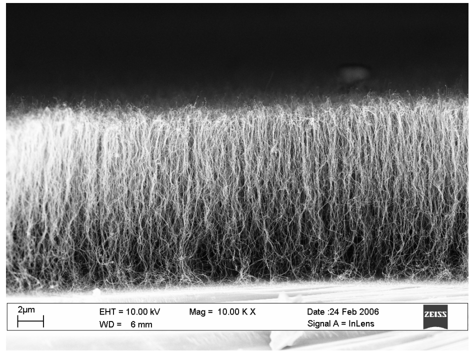


Growth Mechanism of Carbon Nanotubes (CVD)

Substrate

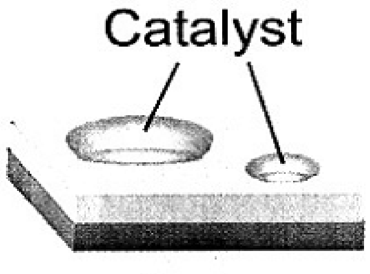
Ni or Fe Catalyst deposition

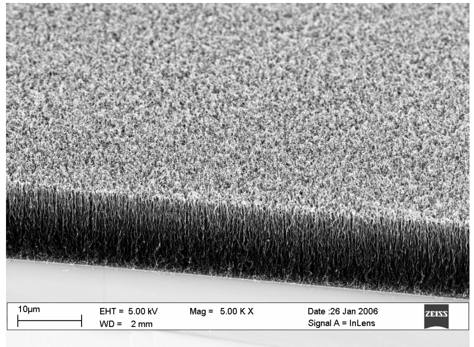




Ni or Fe Clusters formation

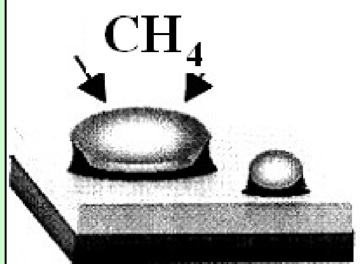
480 - 650 C°
10^{-5} torr
10 - 45 min

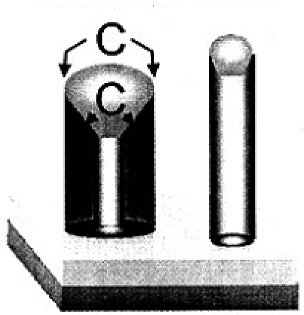


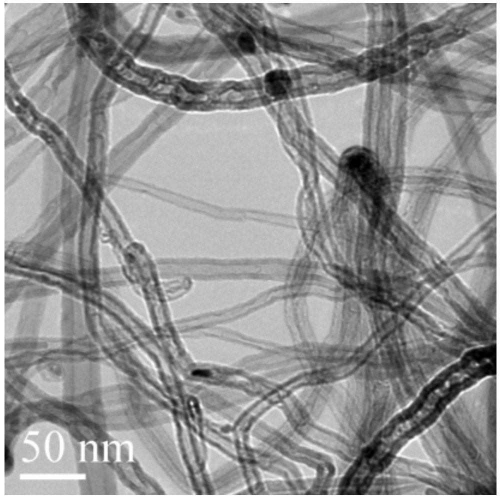


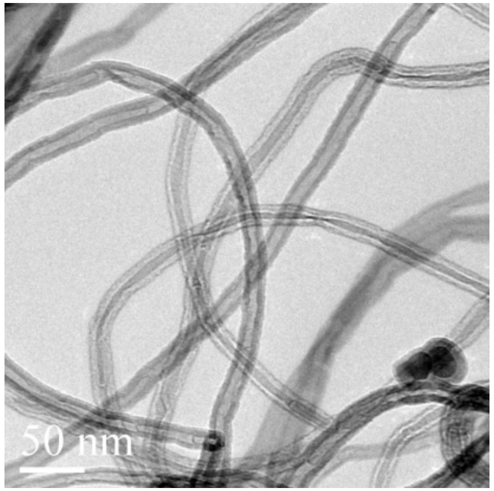
CVD

400!! - 800 C°
1 torr
C_2H_2
or
CH_4
+ NH_3



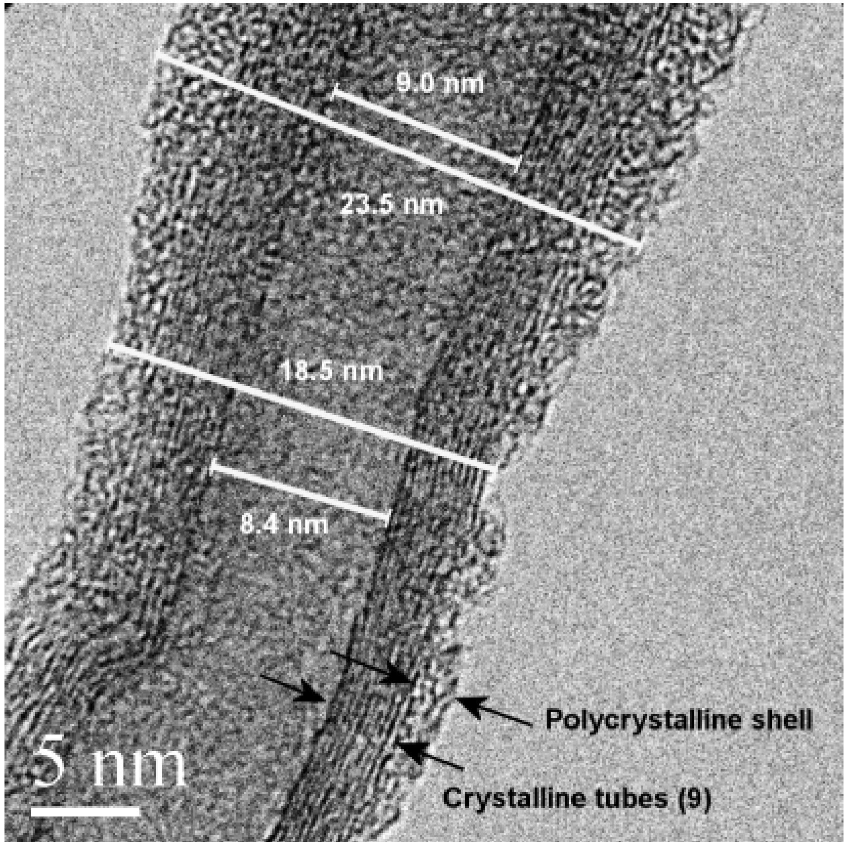


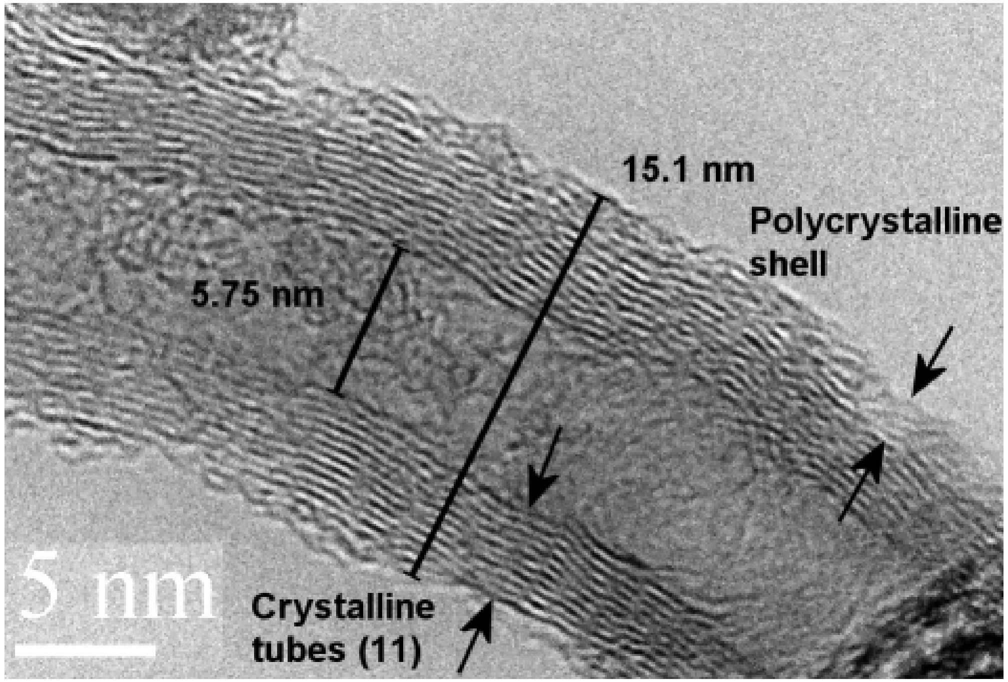




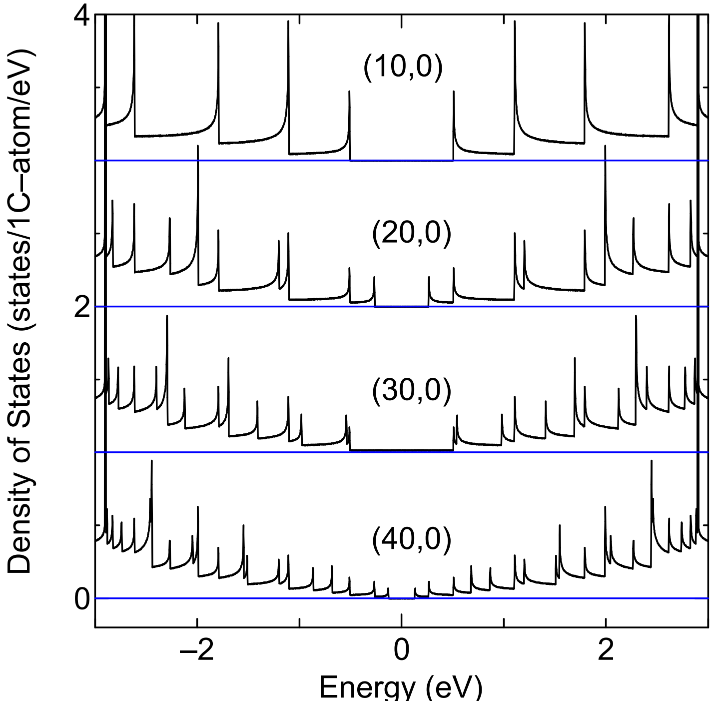
CNT Characteristics

- External diameter: 15 – 25 nm
- Internal diameter: 5 – 10 nm
- Average number of nanotubes: 10 – 15



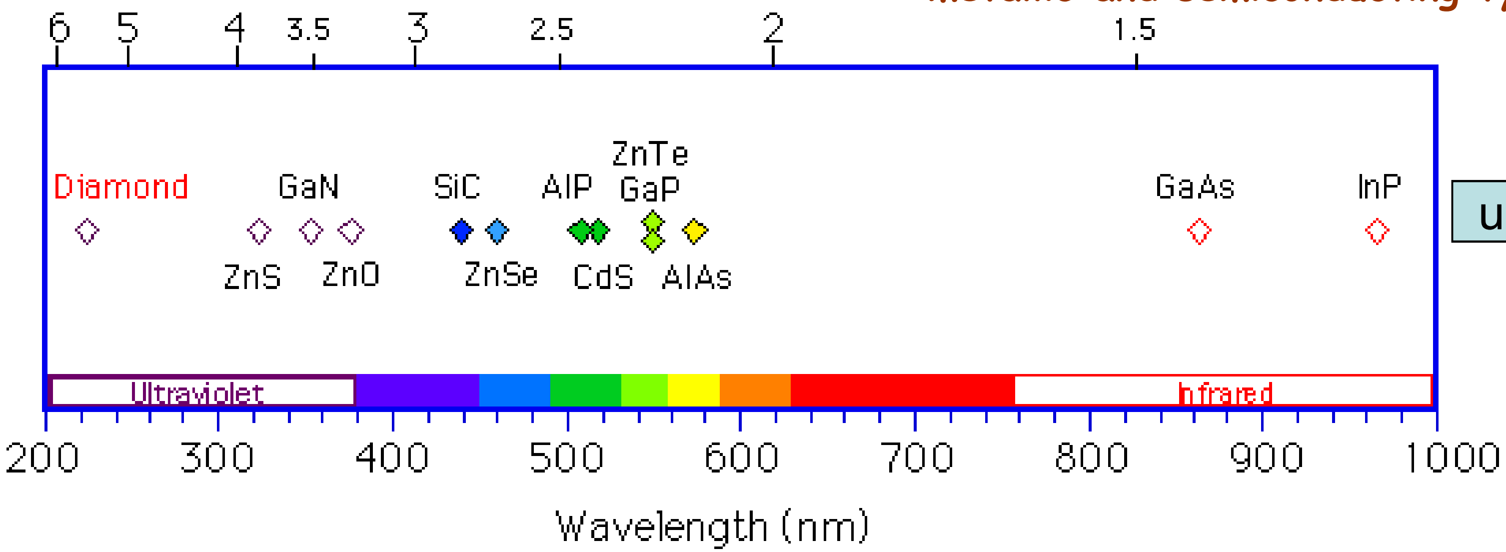


May CNT be used as photodetectors?



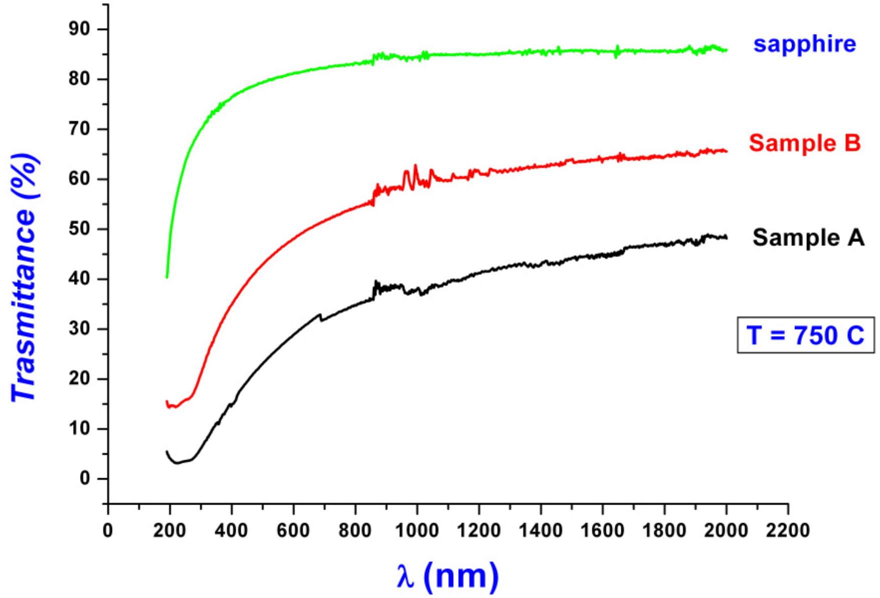
A layer of Multiwall Carbon Nanotubes covers a wide range of diameters and chirality, offering a device sensitive to a wide range of radiation frequencies. In addition the CNT density is very high, allowing, even in a small area, a great number of tubes sensitive to the radiation: ≈ $10^8 - 10^{10}$ MWCNT / 1 mm^2

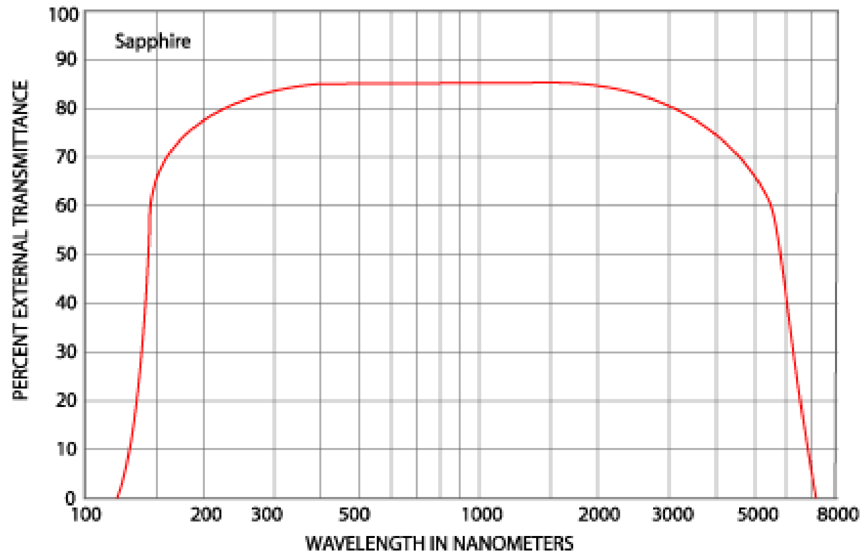
A multiwall carbon nanotube typically consists of a concentric set of nanotubes of both metallic and semiconducting types

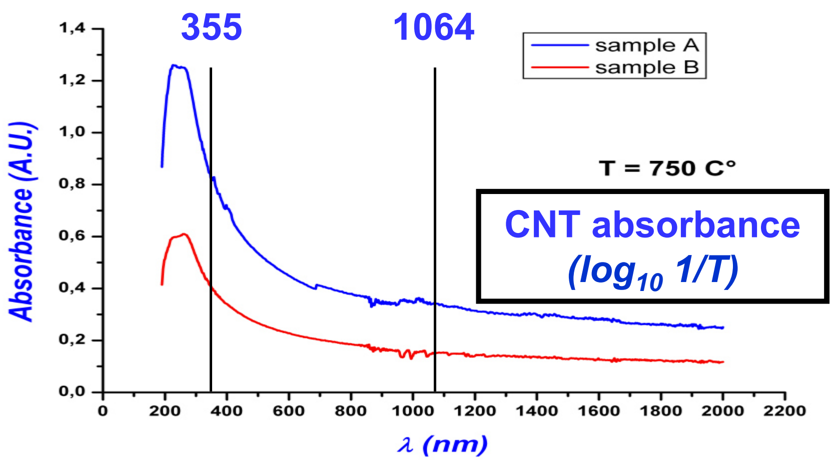


up to 3 μm (0.4 eV)

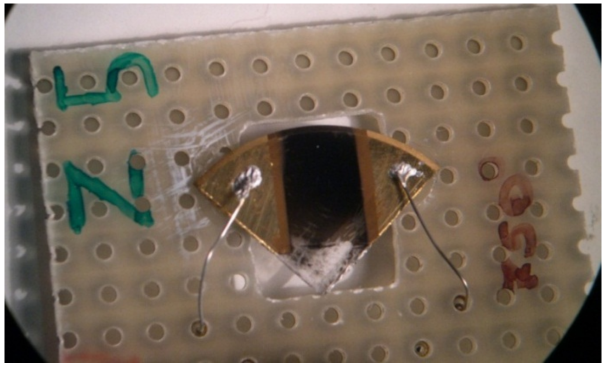
MWCNT photo absorbance





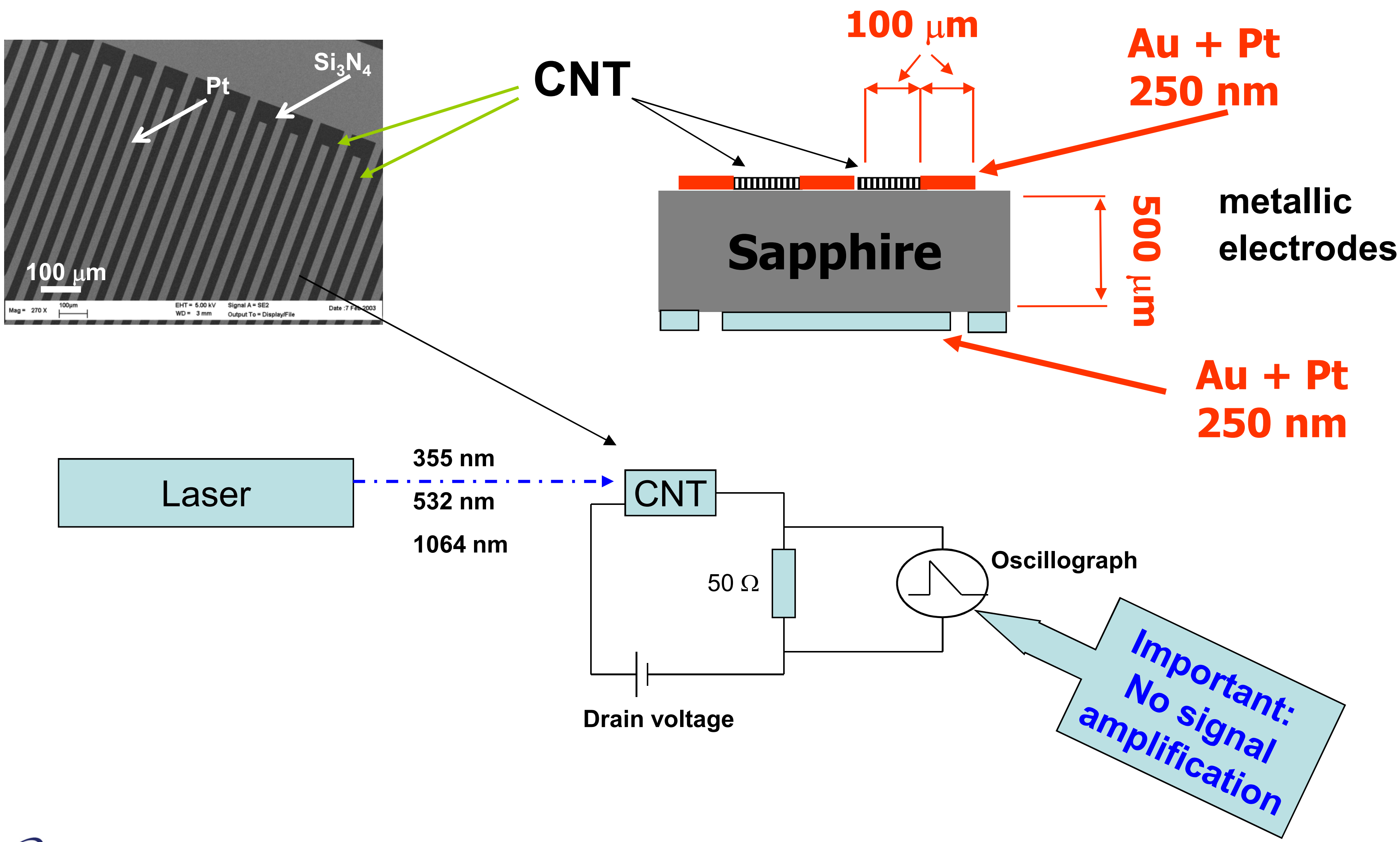


The UV radiation appears more absorbed than the visible and infrared (IR) photons.

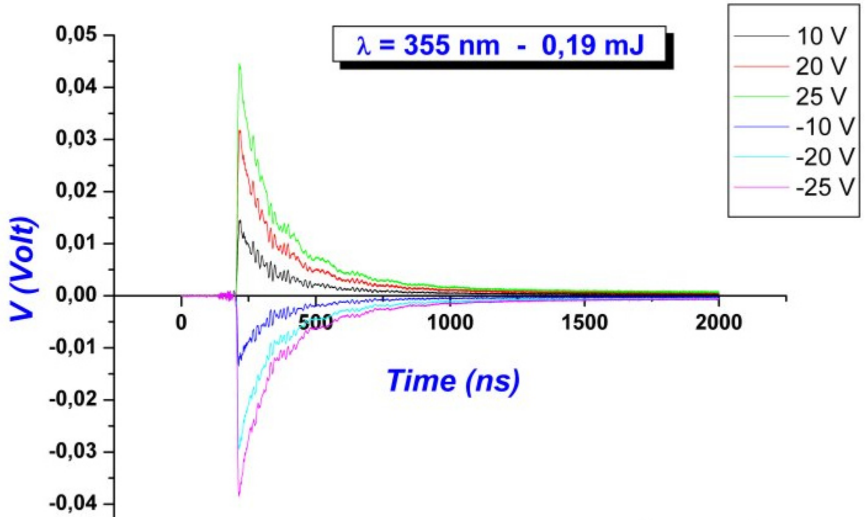


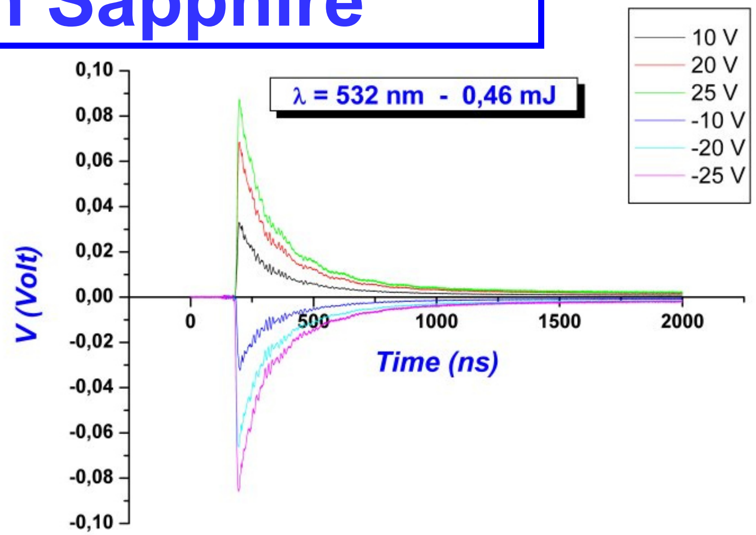
CNTs on sapphire

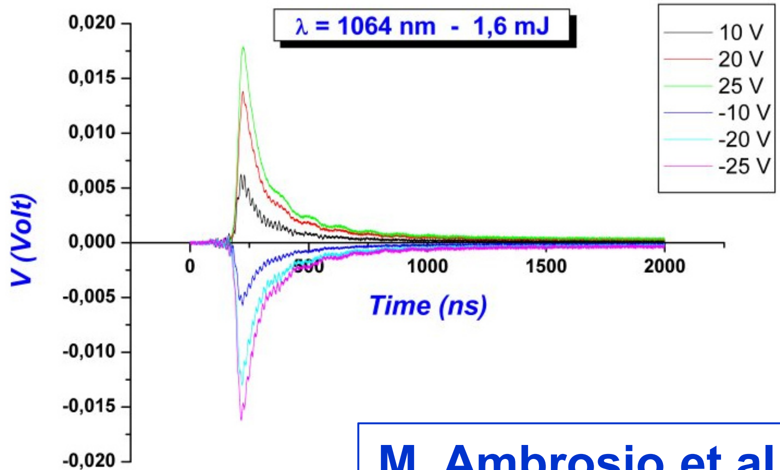
Sapphire prototype detector



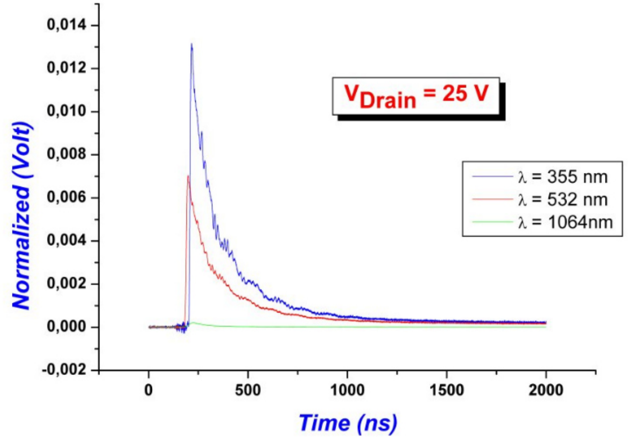
Detected Signals on Sapphire







Comparison at different λ

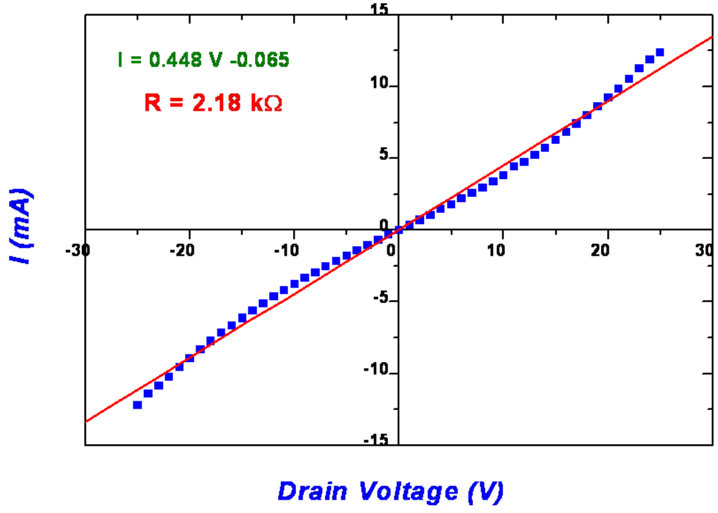


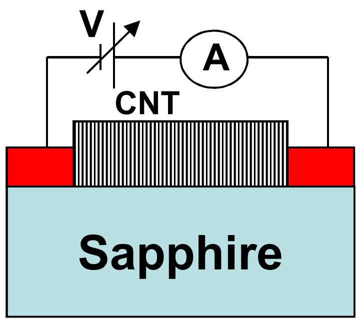
M. Ambrosio et al. VCI 2007

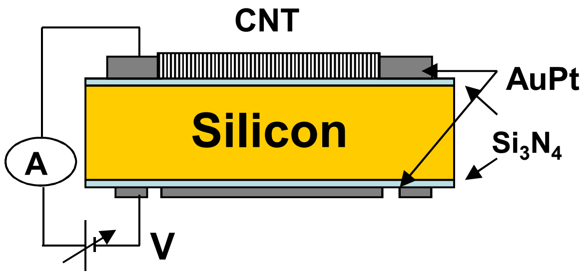
The response of the MWCNT carpet to a monochromatic pulsed light, showing the highest and faster detection efficiency for the UV light. These characteristics make the material highly interesting for UV photodetection.

Main problems with sapphire photodetector

1. **High dark current between metallic electrodes;**
2. **Low level of photocurrent (no signal amplification can be applied without amplifying the dark current also).**



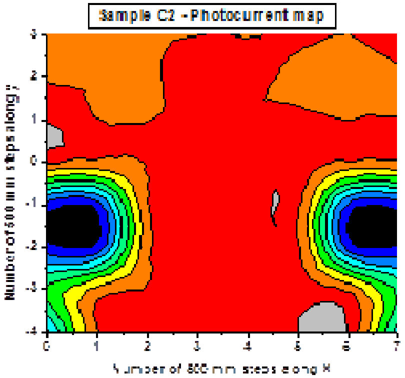


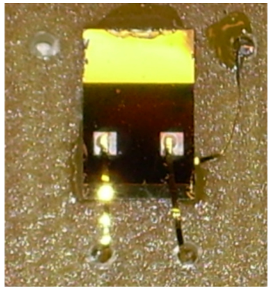


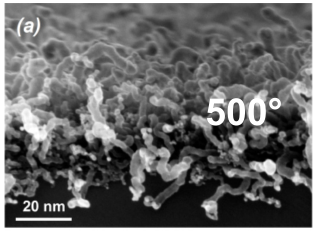
The use of a layered silicon substrate permits to collect the generated photocurrent through the silicon avoiding the surface dark current.

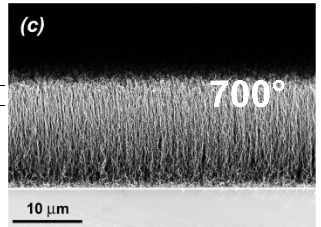
Solution: create a MWCNT-Si photosensitive heterojunction in which CNTs film converts photons into electrons and the layered silicon substrate amplify the signal by means of a secondary dicharge.

The results of first MWCNT-Si device





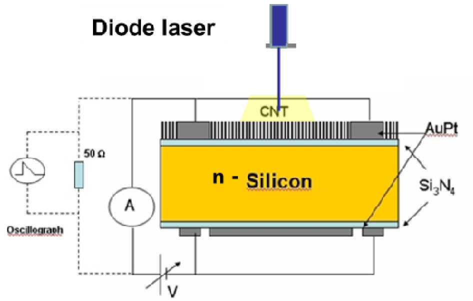


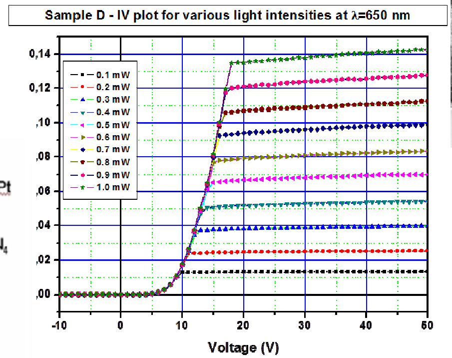


Ni Catalyst deposition

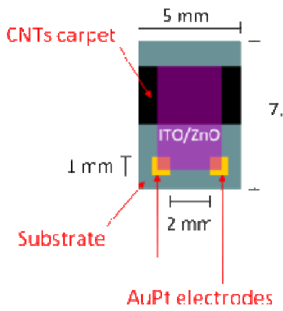
***Electrical analysis of carbon nanostructures/silicon heterojunctions designed for radiation detection*, NIM A 629, 377–381 (2011)**

***Innovative carbon nanotube – silicon large area photodetector*, 2012 JINST 7 P08013 2012.**

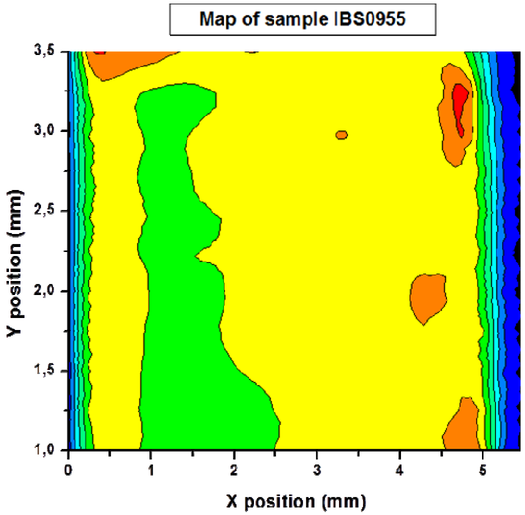


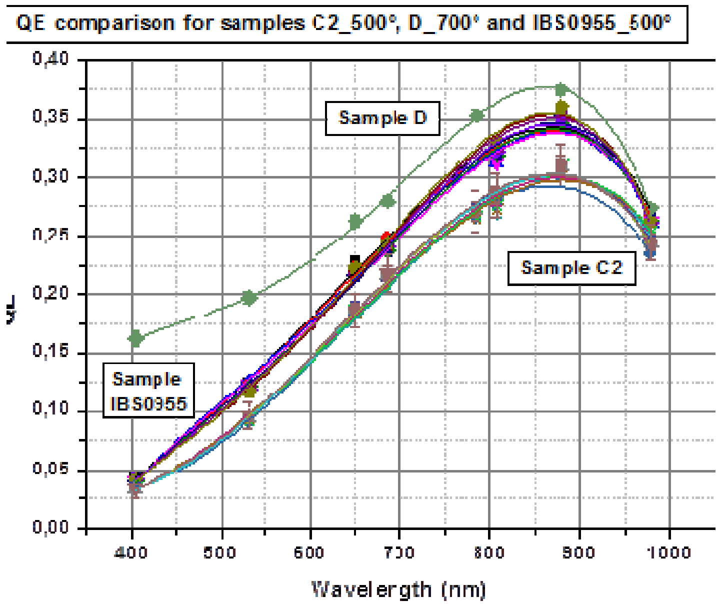


Coating

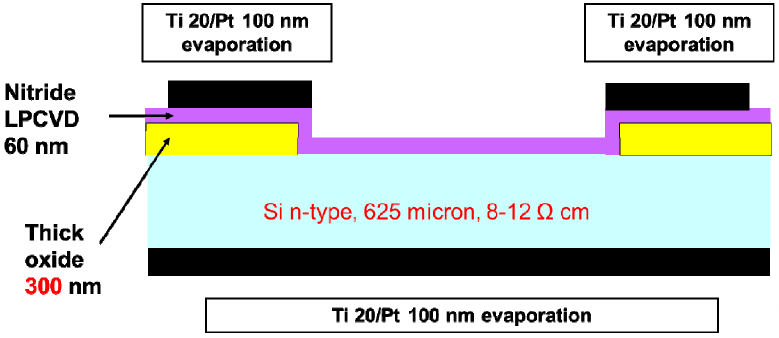


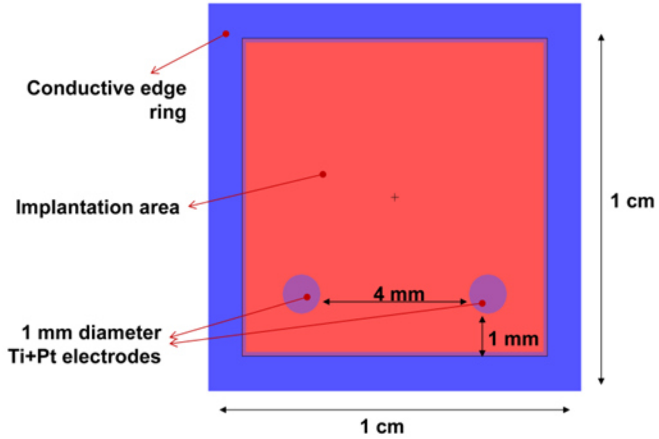
Great uniformity over large area

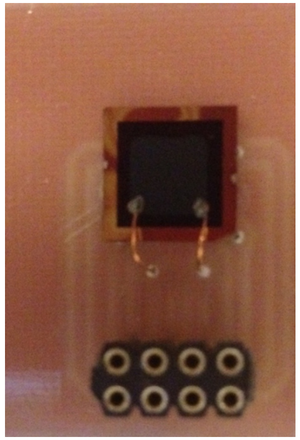




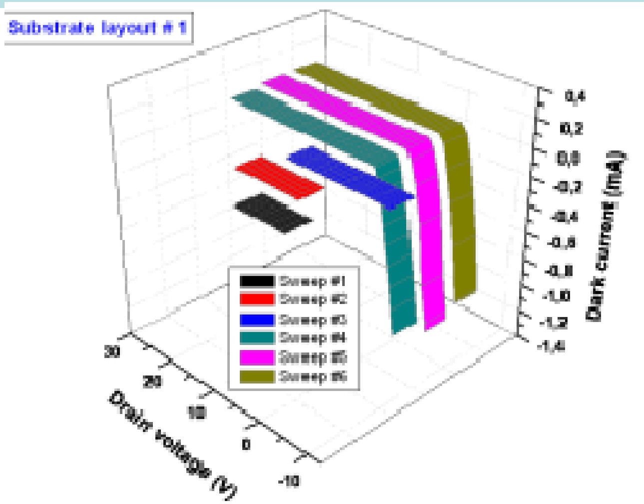
The FBK substrate

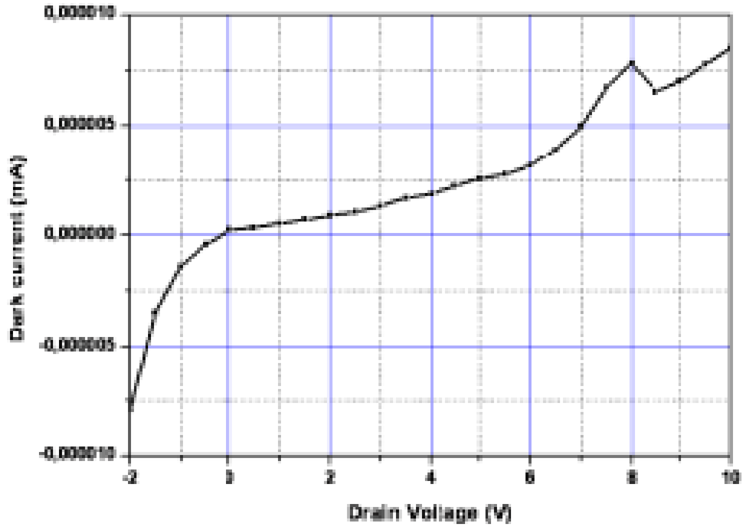




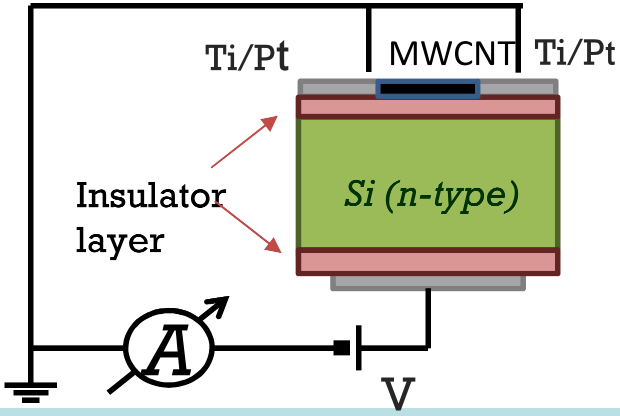


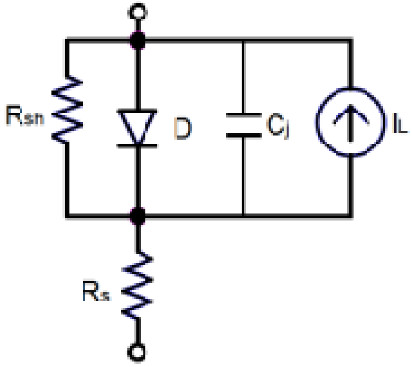
The device substrate has the structure of a Metal-Insulator-Silicon (MIS) photodiode: applying an external electrical field between the two electrodes on the front and on the back of silicon layer and operating voltage sweeps the dark current assumes a straighten behavior typical of a diode .





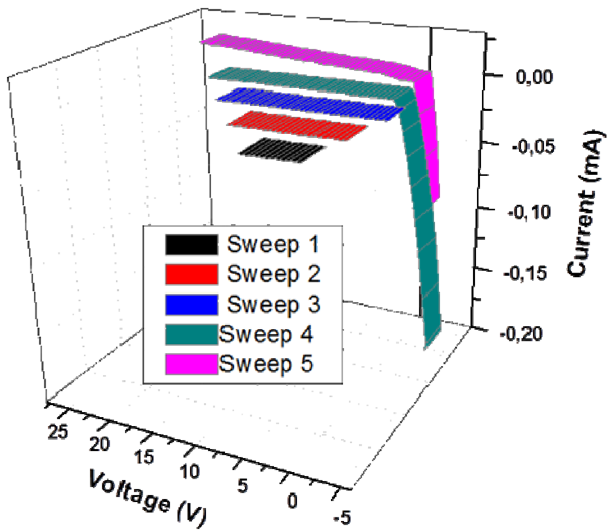
Large area MWCNT-Si radiation detector

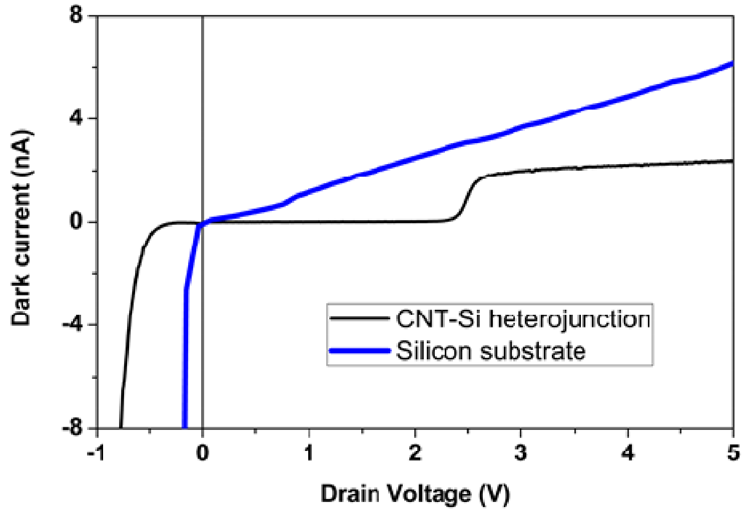




An electrical field can be applied between the two sides of device obtaining a large area photodiode whose equivalent circuit is depicted in figure, where D is the device, I_L is the photocurrent generated by the incident light, Cj is the heterojunction capacity, R_{sh} the shunt resistance and R_s the circuit resistance.

The application of voltage sweeps to the device generates the heterojunction between CNT and silicon substrate: the dark current measured between electrodes in the front and in the back of device assumes a threshold behavior.

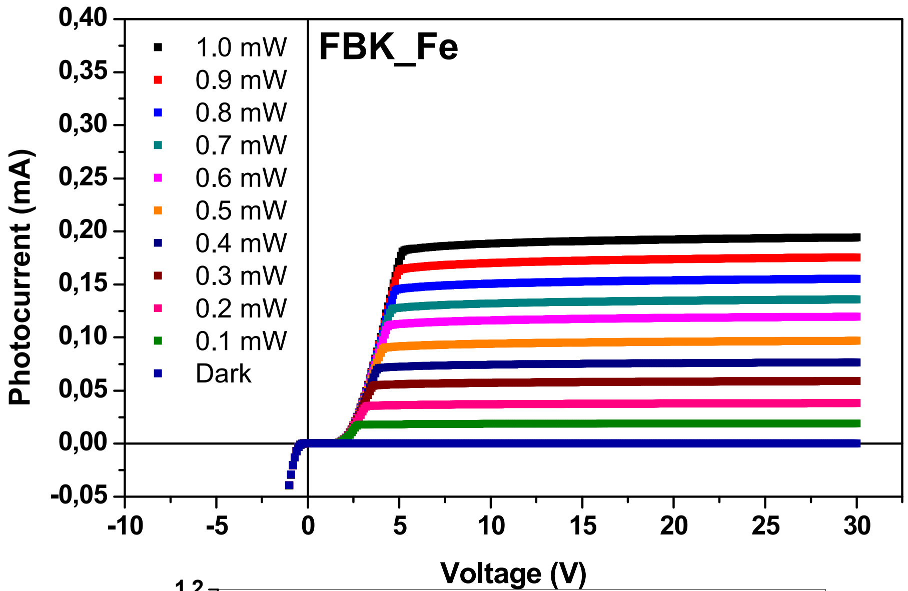


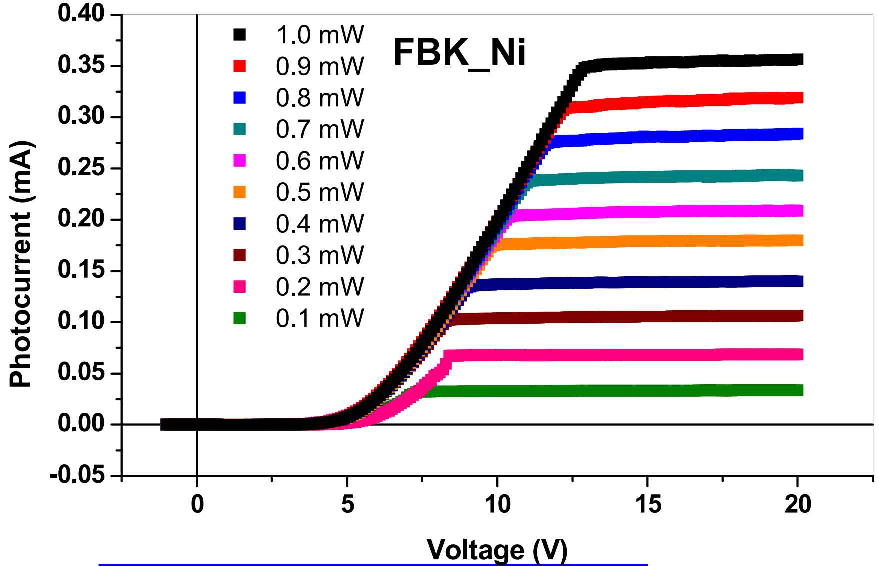


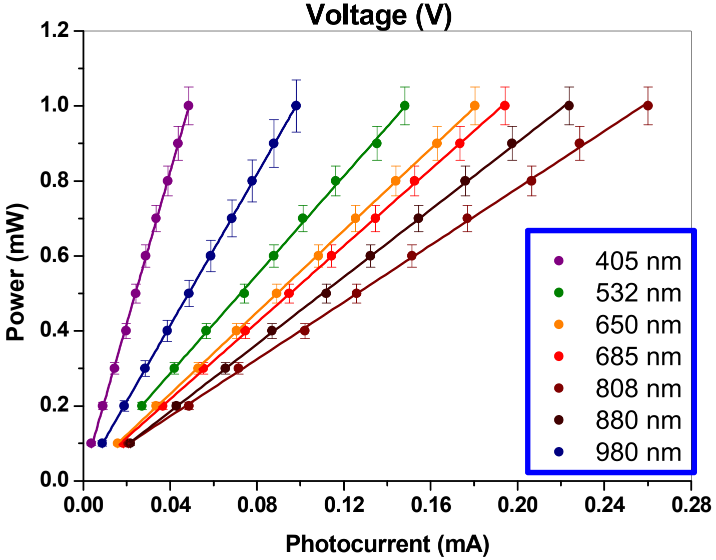
The heterojunction is characterized by a well defined threshold at 2.4 V completely absent in the substrate without CNTs. Dark current is about 2 nA for a surface of 0.5 cm^2

Photocurrent and linearity

685 nm light emitting diode (LED) laser





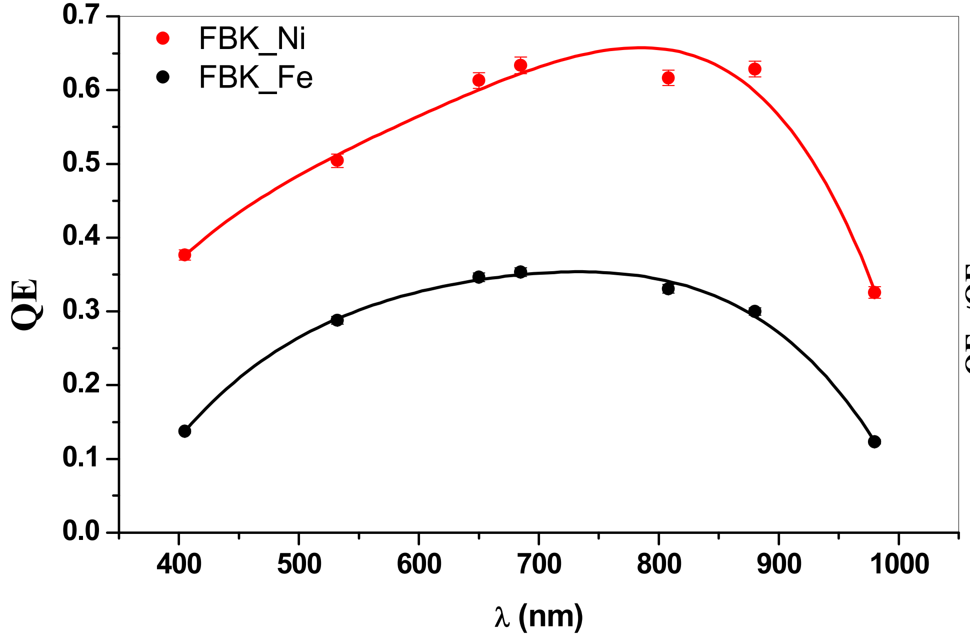


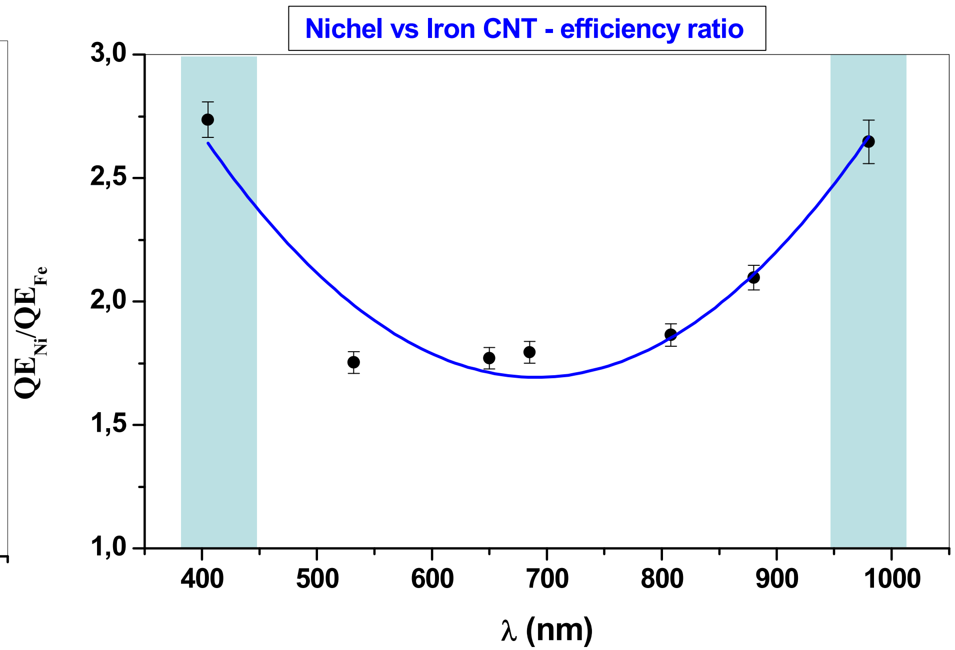
- Room temperature
- No electronics
- No signal amplification
- Long and stable plateau
- Linearity I vs P
- Threshold
- No saturation observed
- Uniformity on all the CNT surface
- Long term stability (>8 years)
- Breakdrown @ >100 V

Quantum Efficiency

The quantum efficiency (QE) of the device was estimated as the ratio of the number of electrons collected at plateau (I) to the number of incident photons according to the relation:

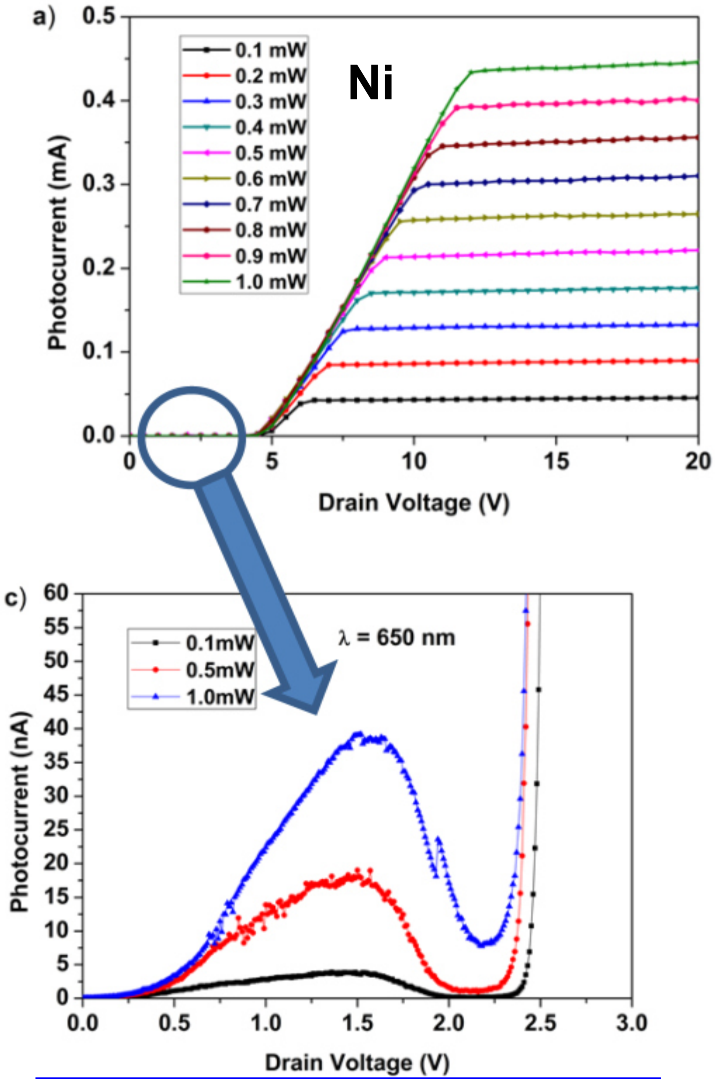
$$QE \pm \sigma_{QE} = \frac{hcI}{\lambda e P} \pm \frac{hc}{e}\sqrt{\left(\frac{1}{\lambda P}\right)^2 \sigma_I^2 + \left(\frac{I}{\lambda^2 P}\right)^2 \sigma_\lambda^2 + \left(\frac{I}{P^2 \lambda}\right)^2 \sigma_P^2}$$





Quantum efficiency of CNTs with Ni catalyst appears much higher than that of CNTs with Fe catalyst, especially in the UV and IR regions.

Tunnel effect



Aramo C. et al: *Beilstein J. Nanotechnol.* 2015, *6,* 704–710

The shape of the current-voltage curve presents a negative differential resistance and resembles that of a resonant tunneling junction.

These observations clearly indicate that impinging light and, as a consequence, the photogenerated charges play a fundamental role in the heterojunction behaviour.

The current shape similarity with that of typical resonant tunneling junction suggests that a kind of electronic resonance process induced by the photogenerated charges may be present.

Resonant tunnel-like current is generated only under light radiation and it is function of the wavelength as well as of the power intensity

Study of heterojunction MWCNT-Si

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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Electrical analysis of carbon nanostructures/silicon heterojunctions designed for radiation detection

A. Tinti [a,*], F. Righetti [a], T. Ligonzo [a], A. Valentini [a], E. Nappi [a], A. Ambrosio [b], M. Ambrosio [c], C. Aramo [c], P. Maddalena [b], P. Castrucci [d], M. Scarselli [d], M. De Crescenzi [d], E. Fiandrini [e], V. Grossi [f], S. Santucci [f], M. Passacantando [f]

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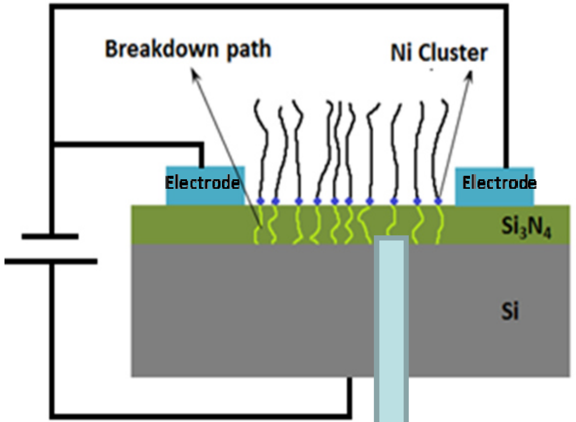
Nuclear Instruments and Methods in Physics Research A 629 (2011), 377-381

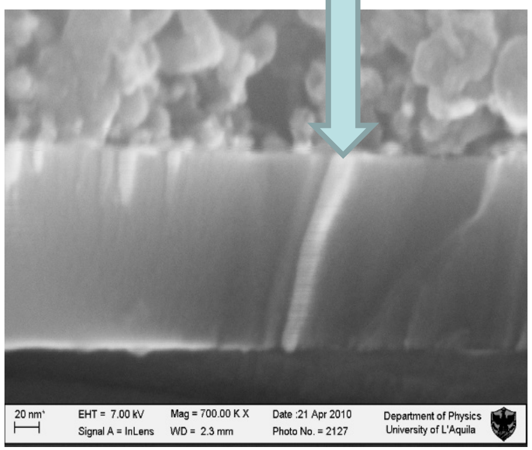
A B S T R A C T

A new class of radiation detectors based on carbon nanostructures as the active photosensitive element has been recently developed. In this scenario the optimization of the device, both in dark and on light irradiation, is a crucial point. Here, we report on electrical measurements performed in dark conditions on carbon nanofibers and nanotubes deposited on silicon substrates. Our experimental results were interpreted in terms of a multistep tunneling process occurring at the carbon nanostructures/silicon interface.

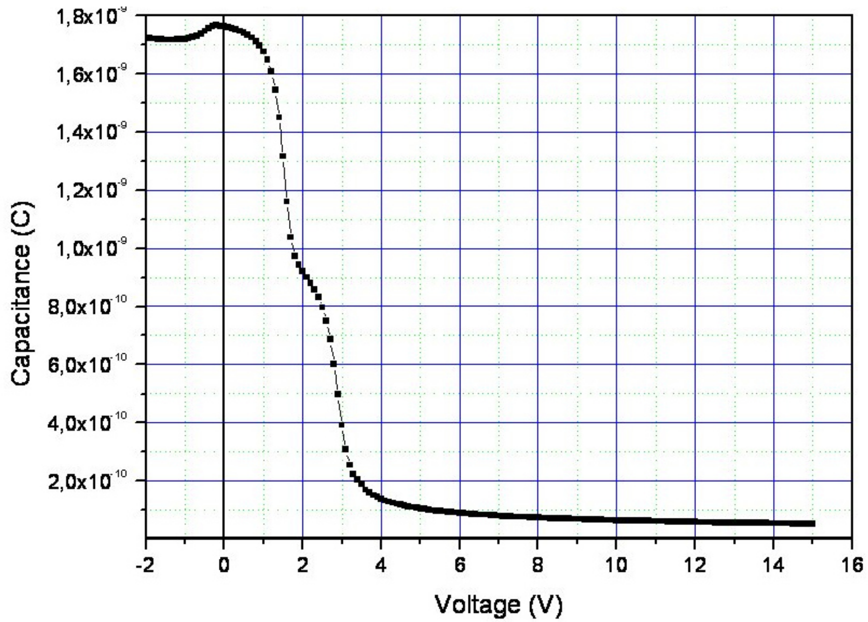
Keywords:
Carbon nanotubes

Key point → how the hetero-junction creates?



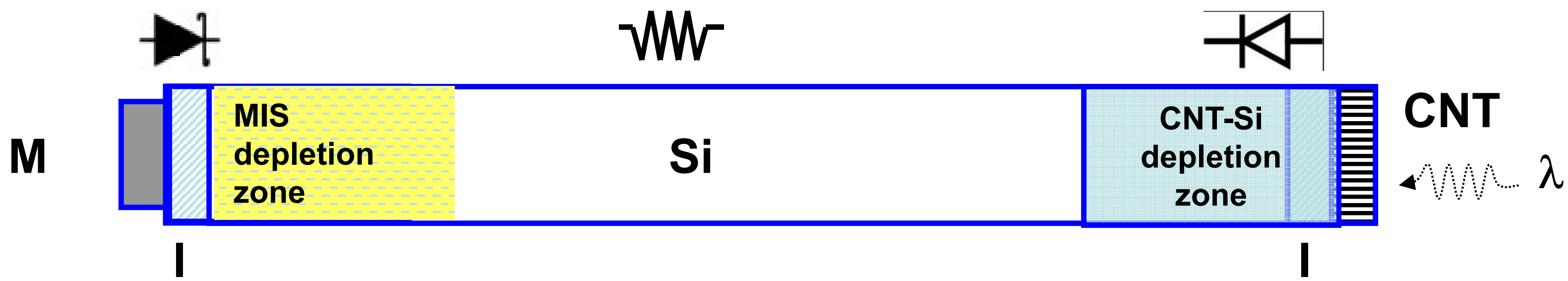


The presence of the insulator is bypassed by the formation of permanent low resistivity conduction channels which are created as an external voltage is applied to the device thanks to the peculiar characteristics of the nanotubes to appear as uni-dimensional elements.



The C-V plot indicates the change of capacitance at the same drain voltage threshold of 2.4 V. The MWCNTs act as a semi-metallic layer, the silicon substrate is n-doped and the nitrite layer is the pierced insulating dielectric.

Phototransistor-like device configuration



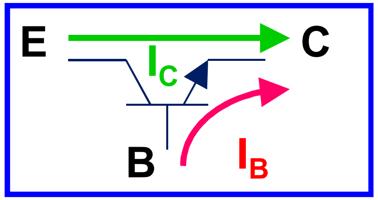
Depletion regions amplitude depends on the applied voltage. The silicon bulk, 625 μm thick, can be considered as a passive resistance except in the depletion areas.

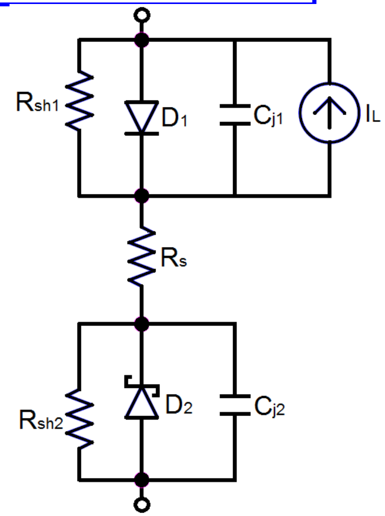
The MIS depletion area cannot be reached from optical radiation because of the presence of metal.

Instead the depletion area created by the CNT-Si heterojunction can be reached and activated by the radiation due to the nanotube characteristics. A light's fraction is absorbed inside CNT and converted in hole-electron pairs or excitons. The other reaches silicon and is converted inside.

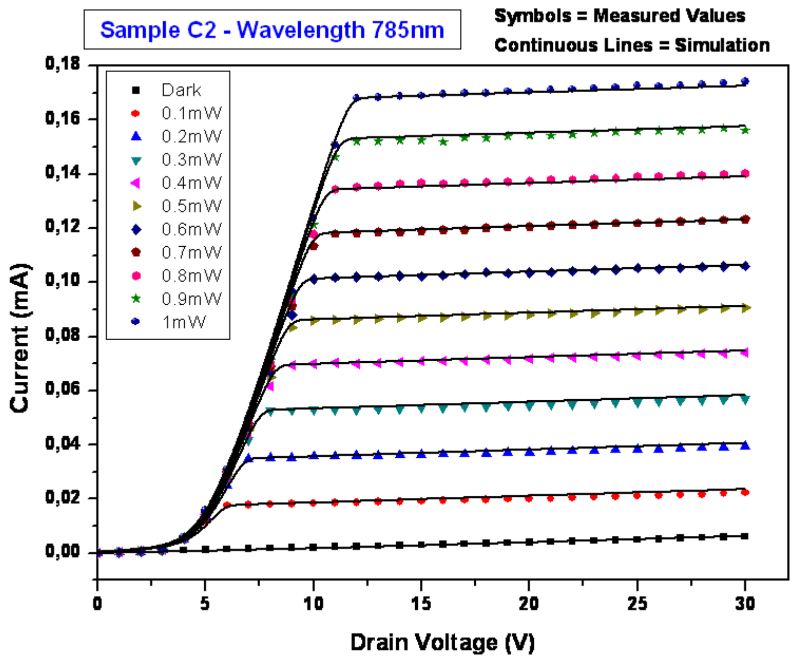
The described device can be considered as a "phototransistor"

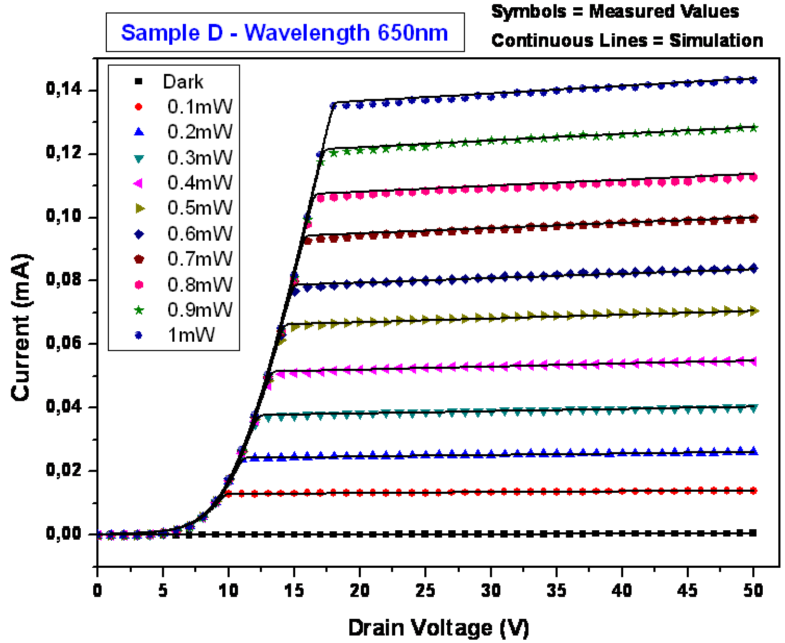
The p-n-p Phototransistor



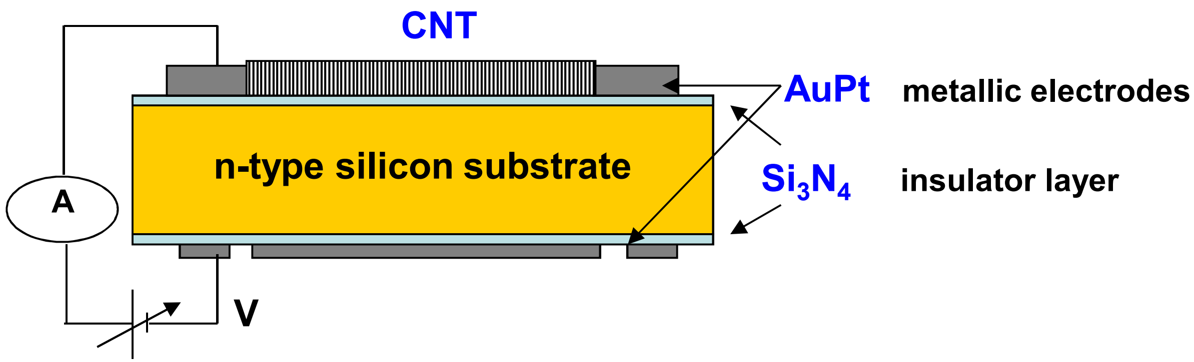


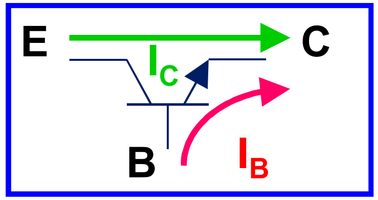
PSpice Model Editor





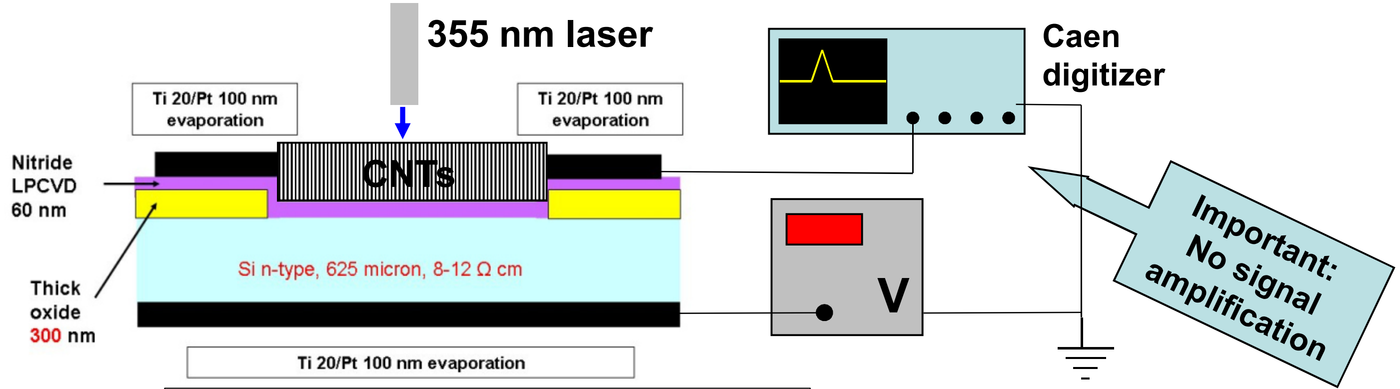
Key points of a CNT-Si photodetector

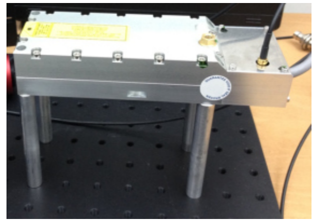




1. A large area photodetector build by simply growing CNTs on a n-type silicon substrate;
2. a CNT-Si heterojunction is created applying voltage sweeps to the electrodes;
3. the device presents a great uniformity over all the sensitive area;
4. QE and photoresponsivity are comparable to that of commercial photodiode;
5. charge collected presents a great linearity and saturation effects have been observed;
6. photosensistivity extends in a wide wavelength range, from UV to IR;
7. the device can be used both to detect continuous and pulses light;
8. at present no amplification – can detect light pulses with large number of photons ($>10^4$)

355 nm pulsed laser

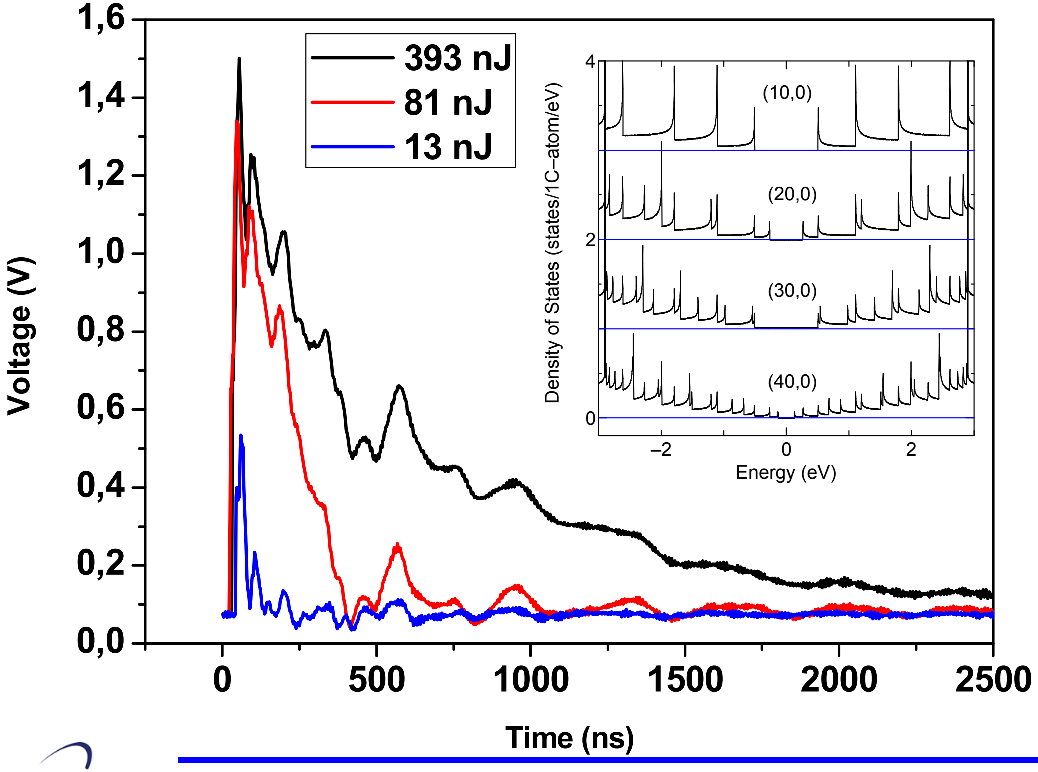




Teem Photonics

Q switched laser
mod. STV-01E-030
2 microJ at 355 nm
1KHz trigger
pulse width < 400 ps

FBK_Ni @ 20 V vs Laser pulse energy



The signal of Ni catalysed CNT-Si detector due to pulsed signals @ 355 nm is fast, with a rise time of few ns.

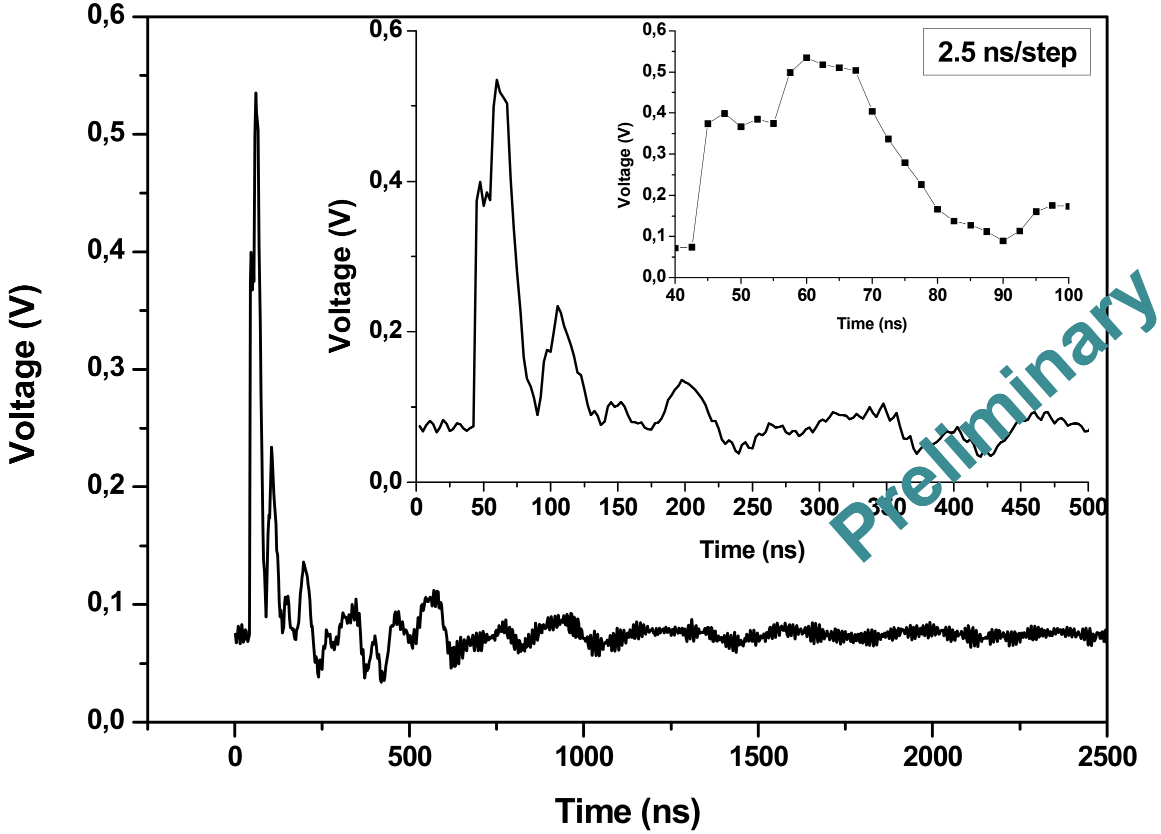
The signal peak, charge and length depend from the laser intensity.
At 13 nJ the peak is ≈ 0.5 V over 50 Ω.

As the laser energy beam increases the photodetector signal heigth raises and its duration becomes larger.

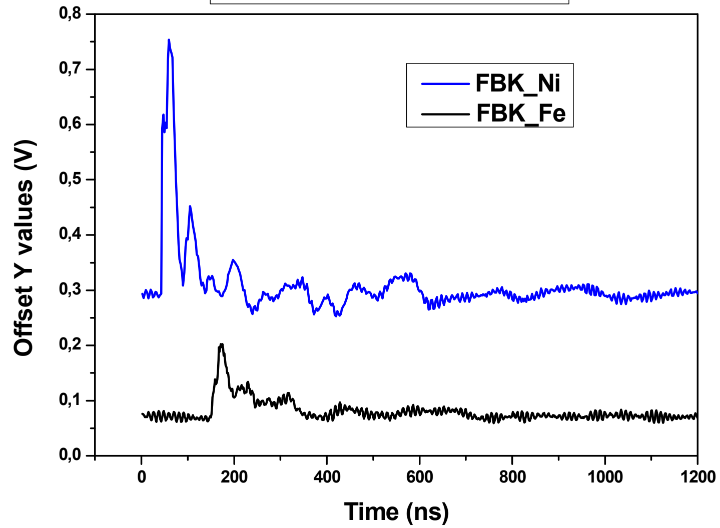
The great signal duration at higher energy probably is due to long time decay metastable states of CNTs excited by beam, whose peaks are well visible as the energy increases.

Details of photodetector signal

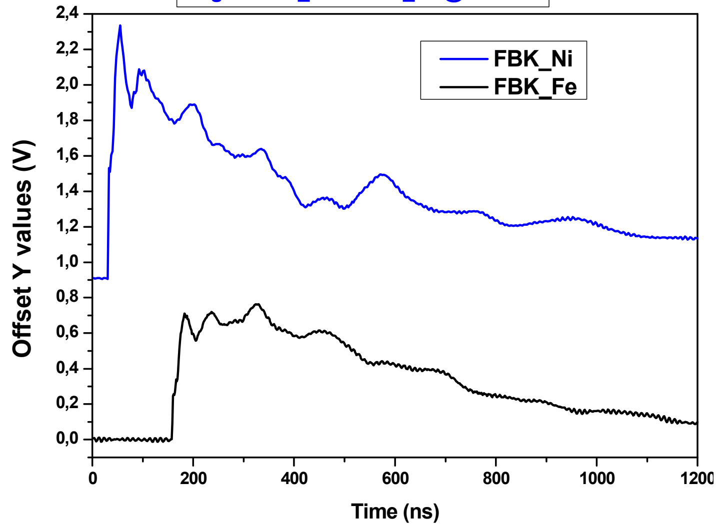
FBK_Ni @ 20 V - Laser energy = 13 nJ



Signal FBK_Ni vs FBK_Fe @ 13 nJ

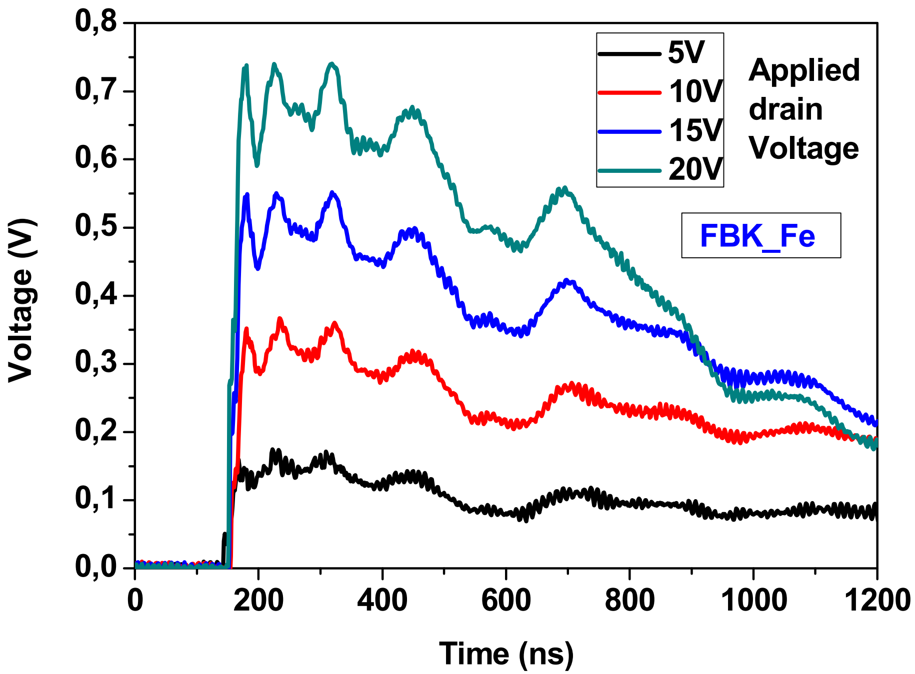


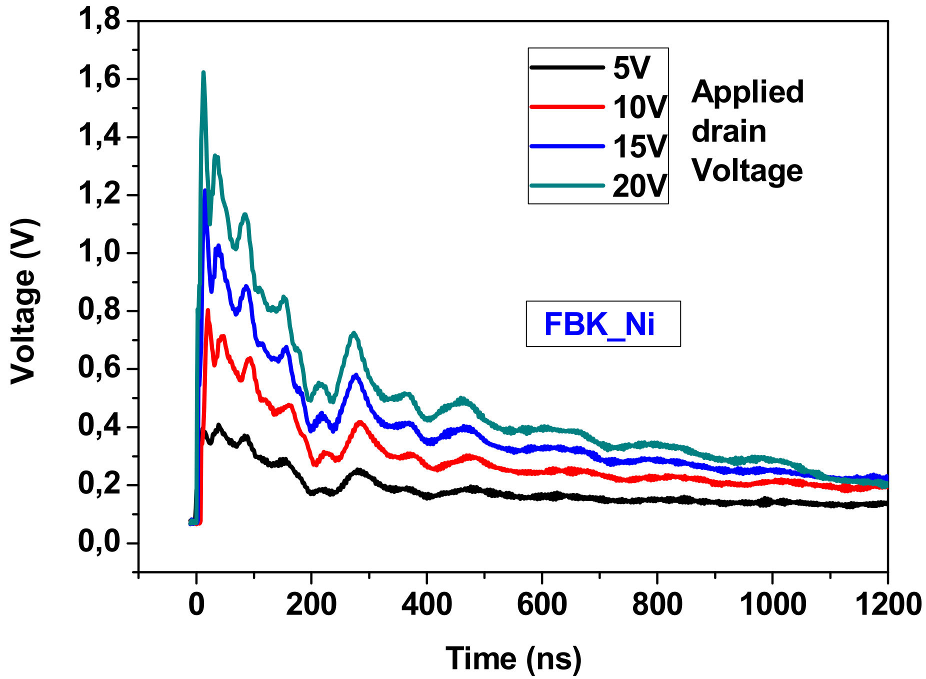
Signal FBK_Ni vs FBK_Fe @ 393 nJ



- Rise time of first peak less than 2.5 ns @ 13 nJ
- Signal from Ni catalysed CNTs larger and faster than Fe
- As the laser power increases the number of secondary delayed peaks increases also enlarging the photodetector signal

Signal vs drain voltage @ 81nJ

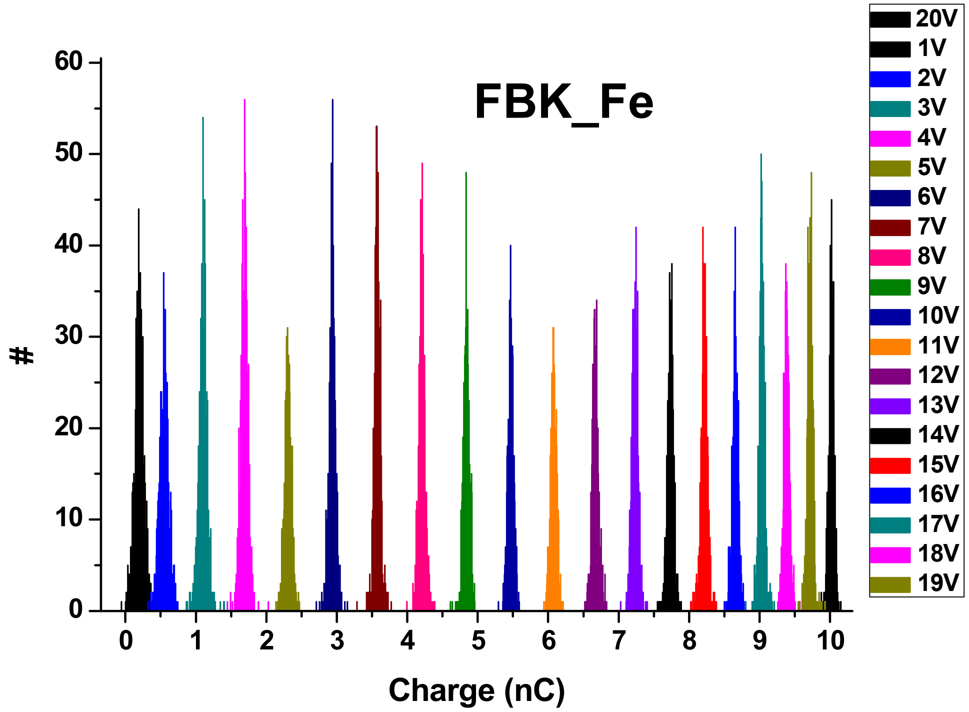


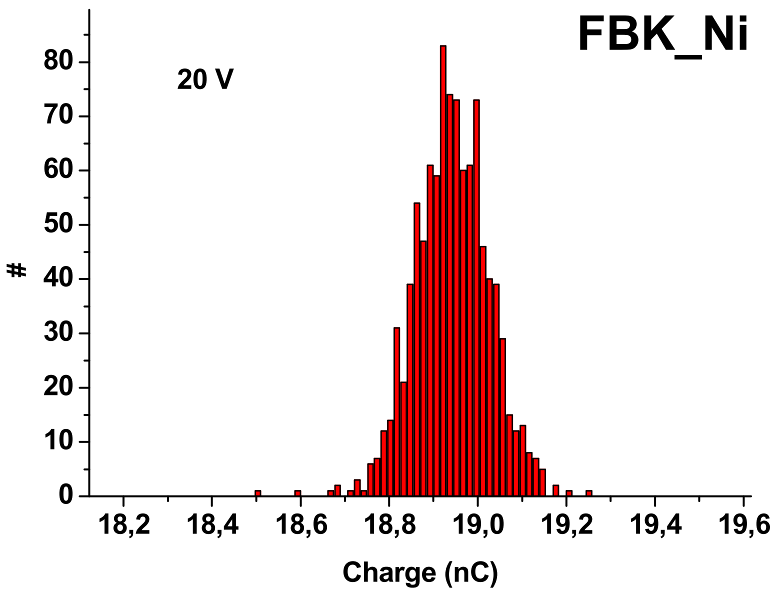


The signal shape strongly depends from the CNT catalyst and from the laser light intensity, less from the drain voltage applied.

The incident radiation excites CNTs energetic levels and the drain voltage collects the generated charge. No saturation effects have been observed.

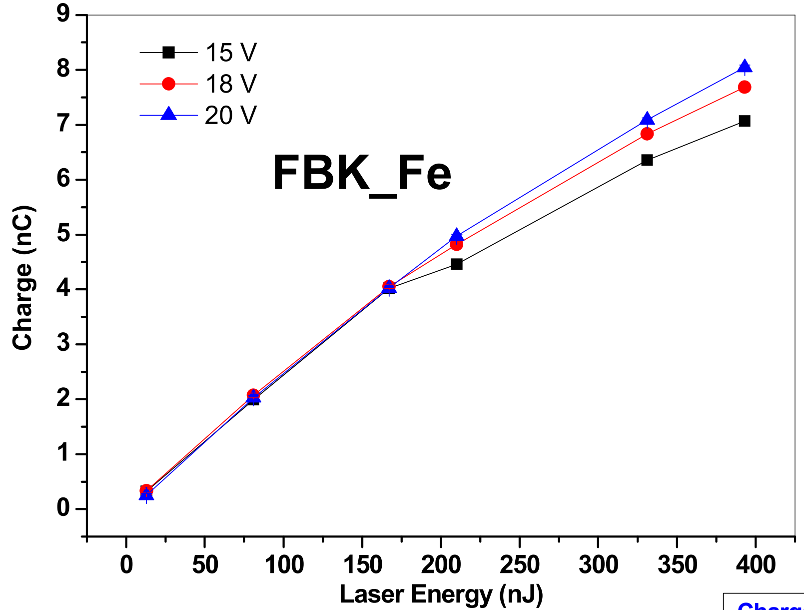
Charge vs drain voltage

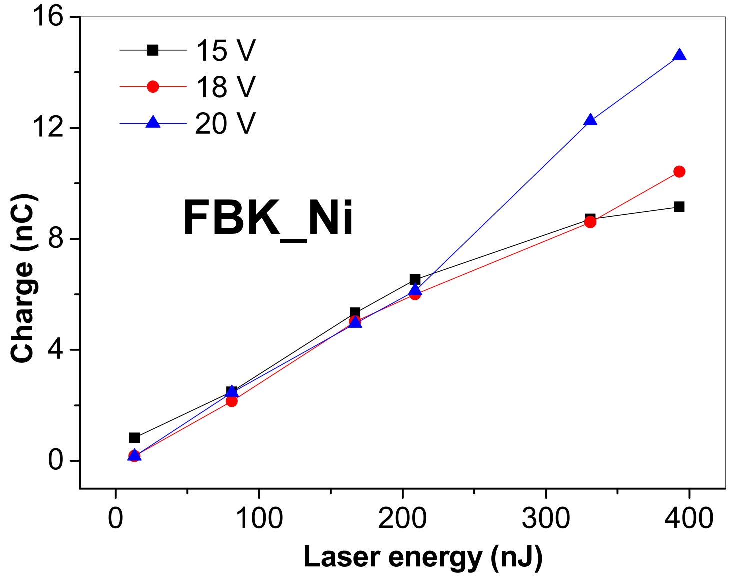


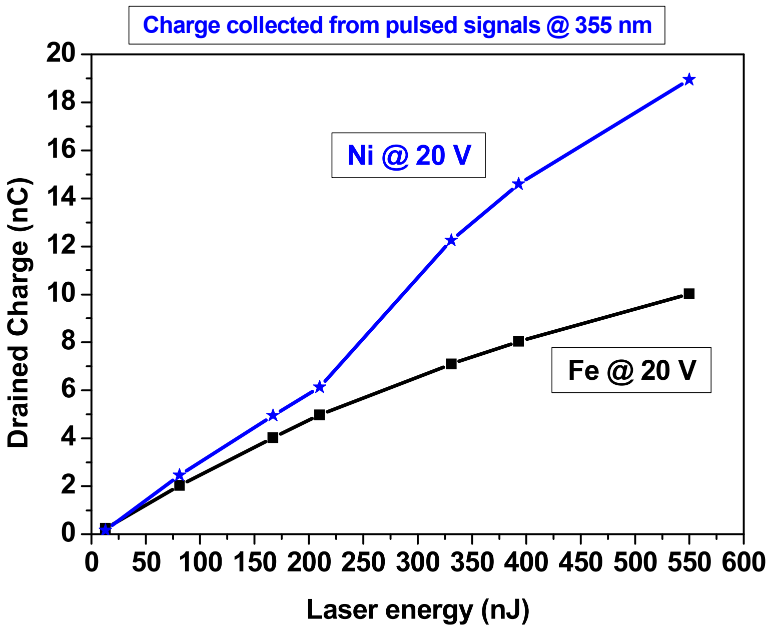


- **The MWCNTs with Ni catalyst shows an higher charge generation than Fe.**
- **In spite of the high light intensity the photodetector charge is linear for all drain voltage range and not in saturation.**
- **The charge distributions are well separeted for all drain voltage range.**

Charge vs voltage and laser energy







- **For higher intensities a higher drain voltage is requested to avoid the charge recombination inside CNTs.**
- **For Ni_CNTs it is need a bigger drain voltage due to a bigger amount of charge generated inside the device**

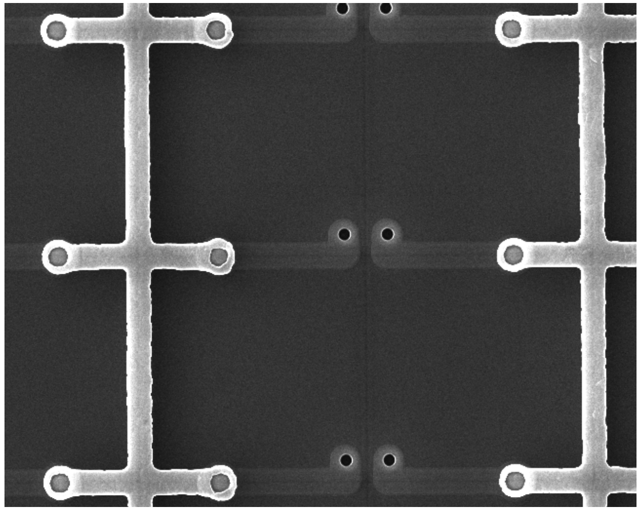
The collected charge from pulsed signals increases quite linearly with laser energy, that means no saturation effects are observed.

SiPM_CNT Project

- SiPMs based on FBK NUV-HD technology and specifically designed for CNT

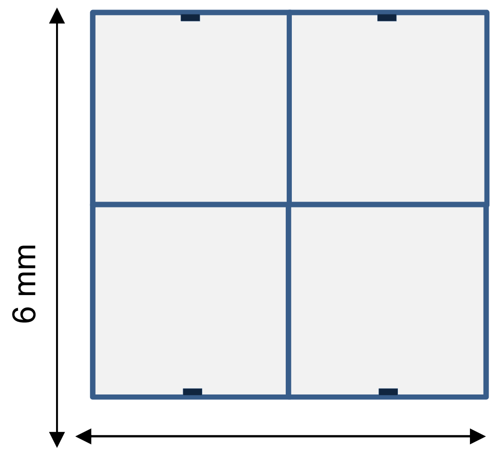
Typical specs of the standard NUV-HD SiPMs

Typical Parameters (@ room T)	NUV-HD CS = 25um
Cell Size	25 µm
Fill Factor	73%
Breakdown Voltage	26.5 V
Max PDE	50%
Peak PDE λ	410 nm
DCR (20°C)	< 150 kHz/mm^2
DiCT	25%
DeCT + AP	2%

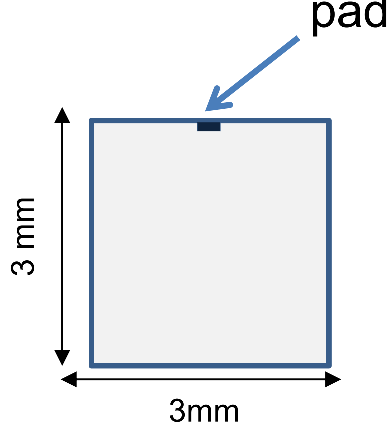


SEM Image of the single cell composing the SiPM (cell size = 25um)

4 SiPMs Array



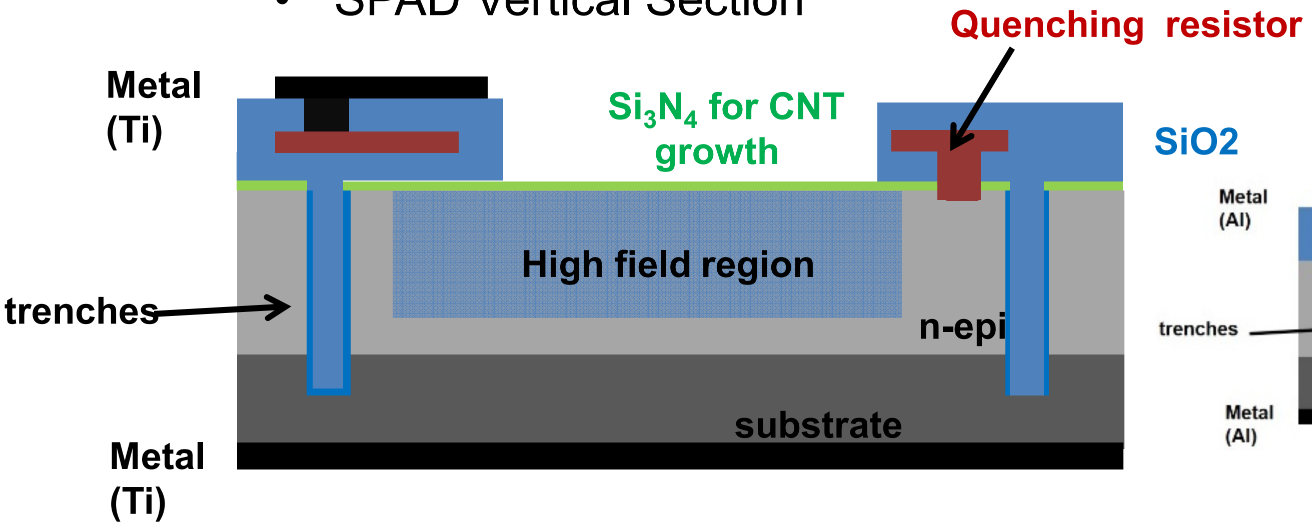
QUAD

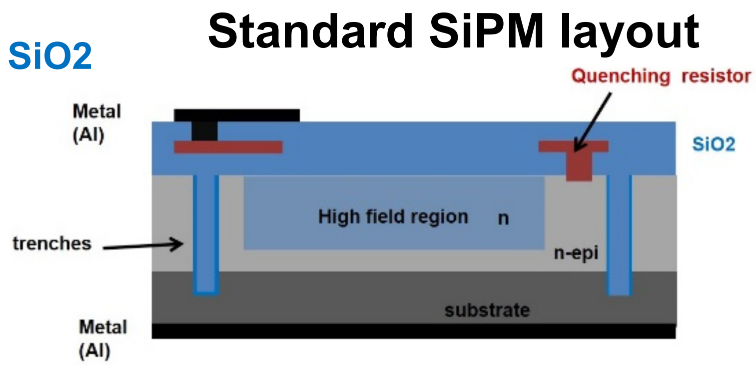


Single SiPM

SiPM_CNT Layout

- SPAD Vertical Section





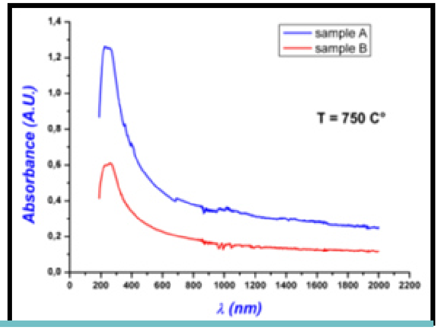
- Spad Size = 30 x 30 um^2
- SPAD Fill factor = 78%

SiPM_CNT

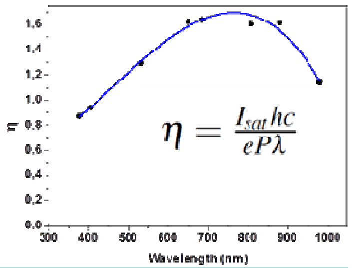
- **New SiPM structure for high temperature tolerance**
- **The CNT grown directly on the device surface**
- **Sensitive surface for every pixel constituted by MWCNT-Si hetero-junction**

Main Scientific Challenges

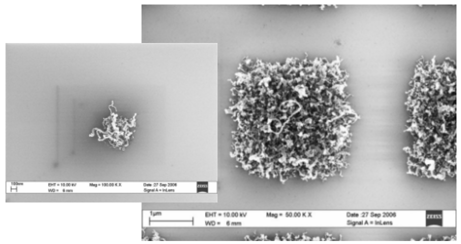
- ✓ **Increase quantum efficiency** due to the photoresponsivity enhancement from MWCNT absorbance, in the wavelength range 200-400 nm.



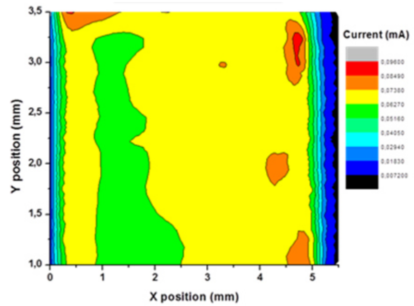
- ✓ **Decrease dark noise** thanks to hetero-junction MWCNT/Si → increase the device area (cm^2 or more VS mm^2 SiPM).



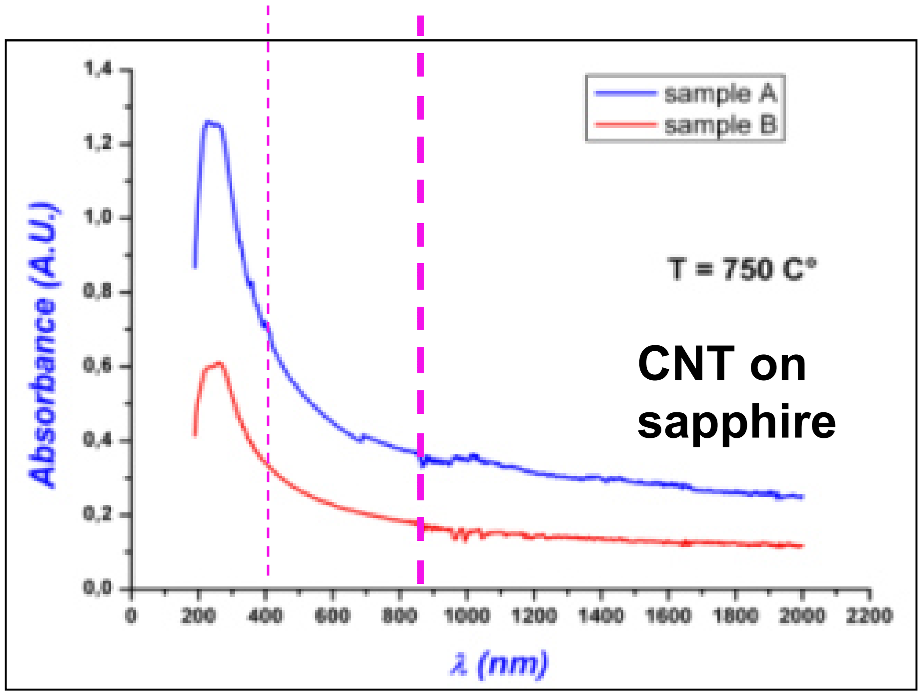
- ✓ **MWCNT bottom-up technology** → cells (pad or strip) hundreds of nm up to mm VS 15 μm up to 100 μm for SiPM.

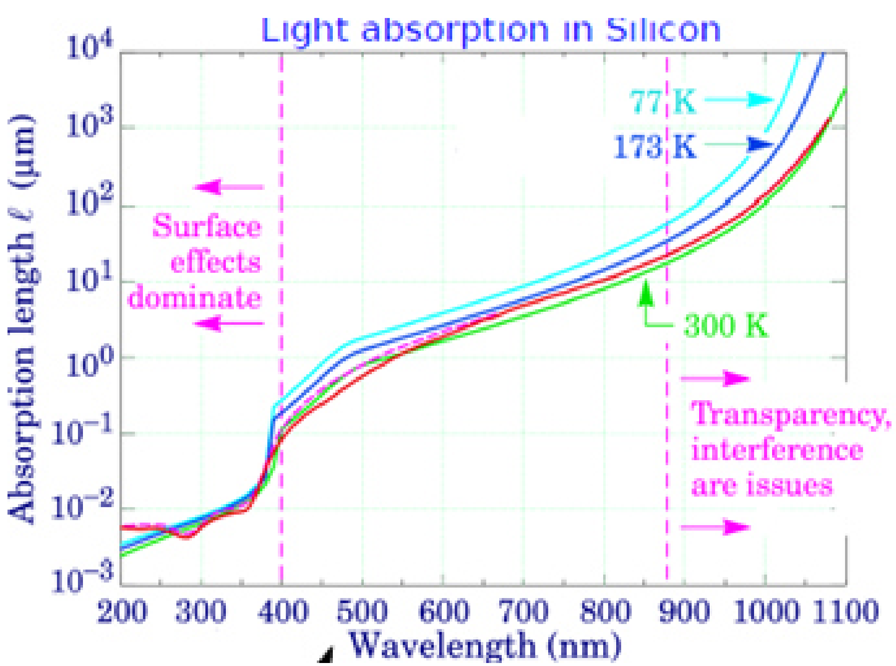


- ✓ **Maximizes the sensitive area for photo-conversion and its uniformity** → Electric field applied via a conductive coating.



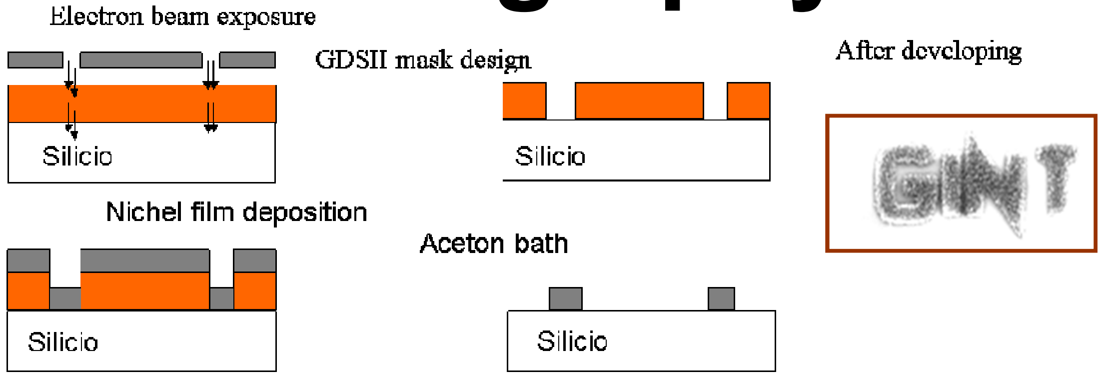
Light absorption

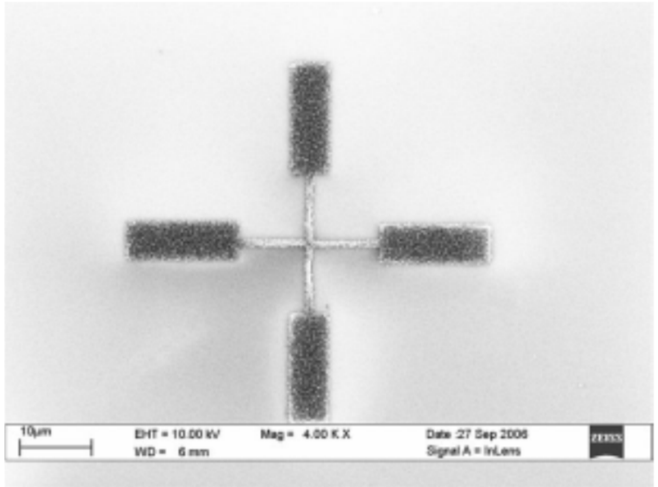


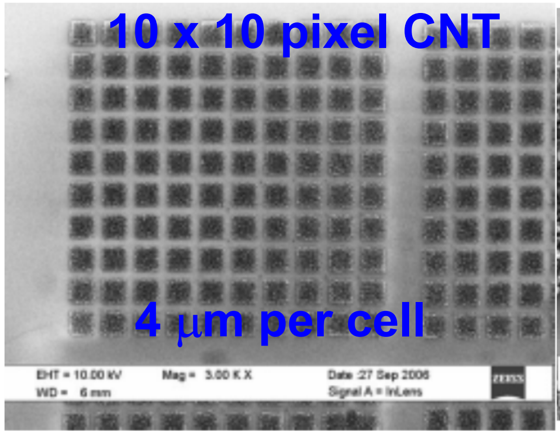


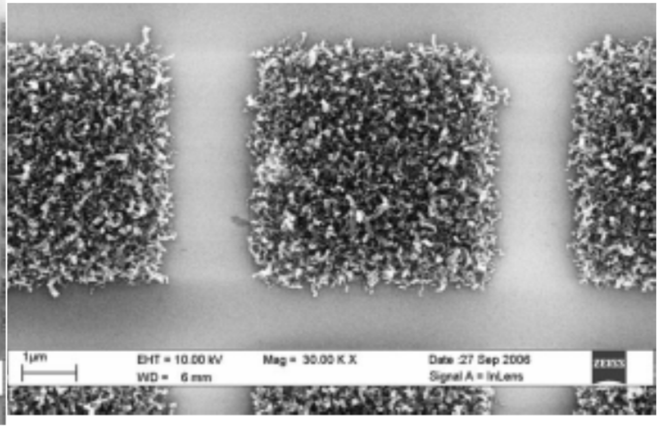
The CNT layer absorbs UV photons producing photoelectrons that can be transferred by means of an external electrical field inside the depletion zone of the hetero-junction. Therefore the charge induces a photocurrent drained out by the applied voltage.

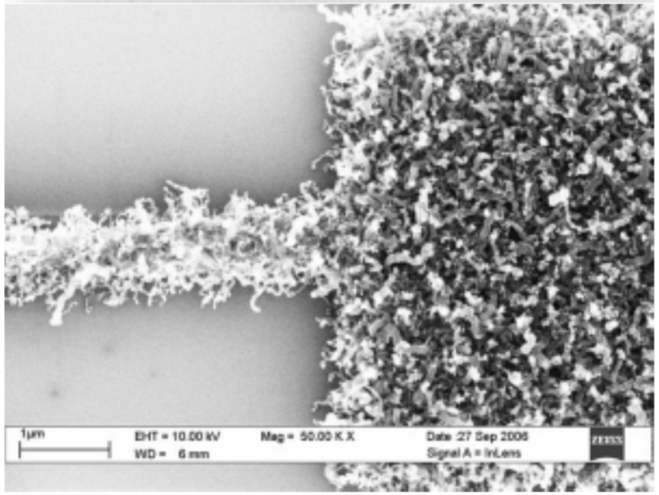
Nanolithography and patternization





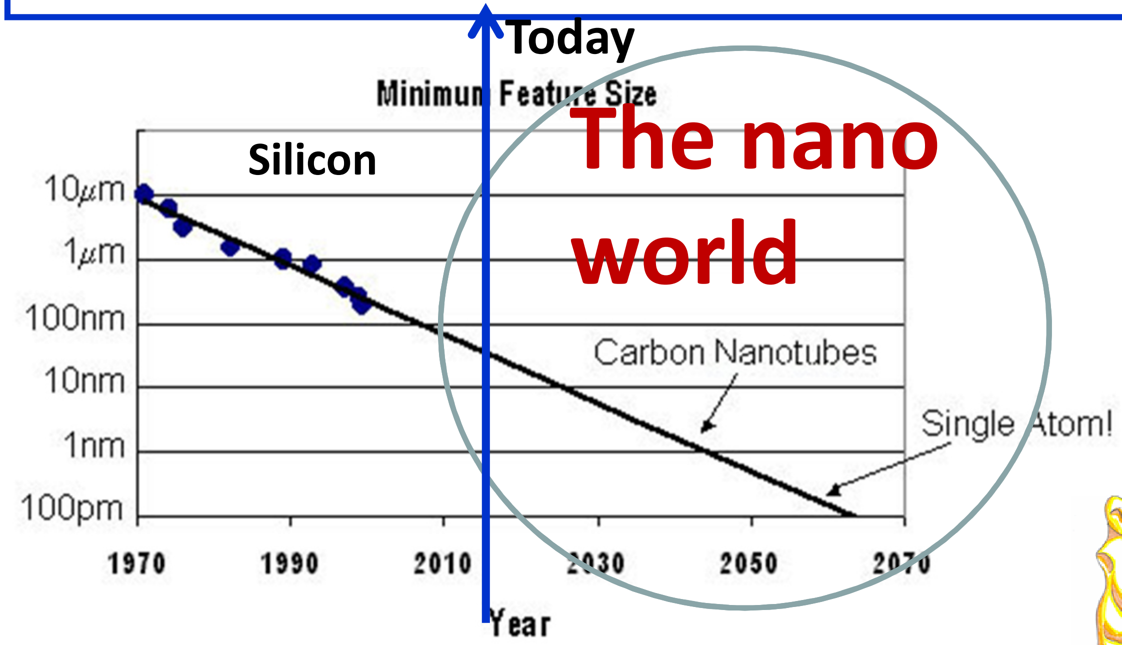






Nano-pixelled photocathodes sensitive to the UV radiation may be obtained by means of nanolithography in a very cheap and easy way!

From micro to nano world



How long we can continue with the Moore's law?

Top - Down

Bottom - Up

The ability of silicon semiconductor to efficiently conduct electric current is lost at a few nanometers →carbon nanotubes.

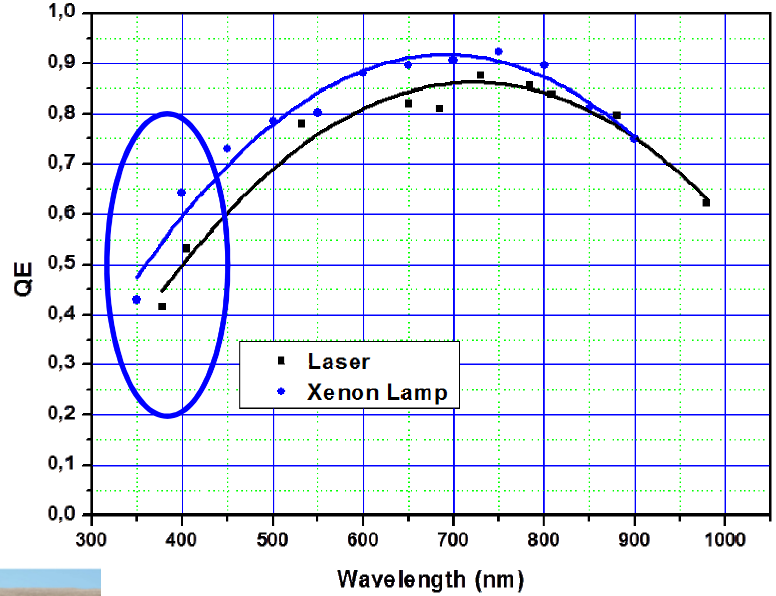
Building nano - detecting micro

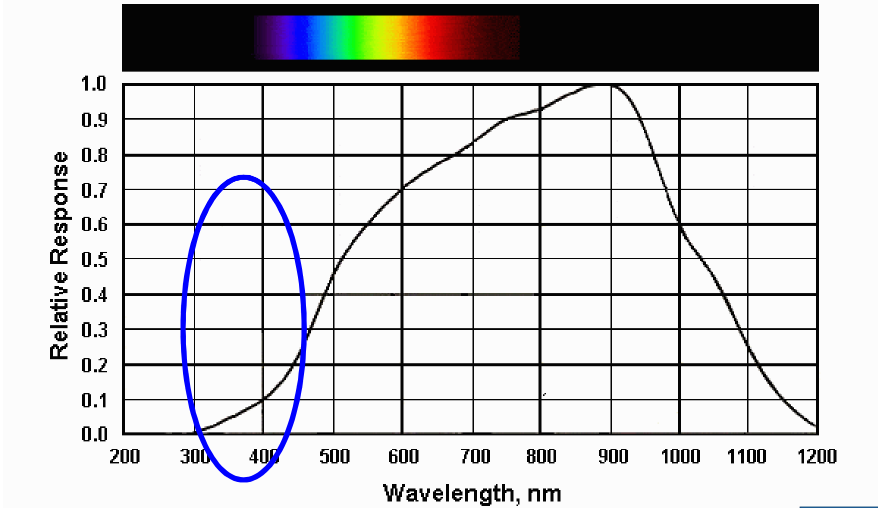
PARIDE

Pixel Array for Radiation Imaging DEtector

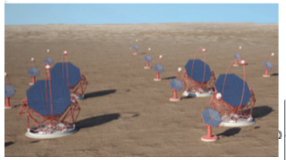
Thank you for attention

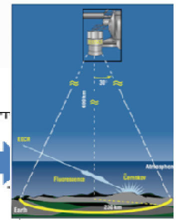
Why a MWCNT-Si photodetector?

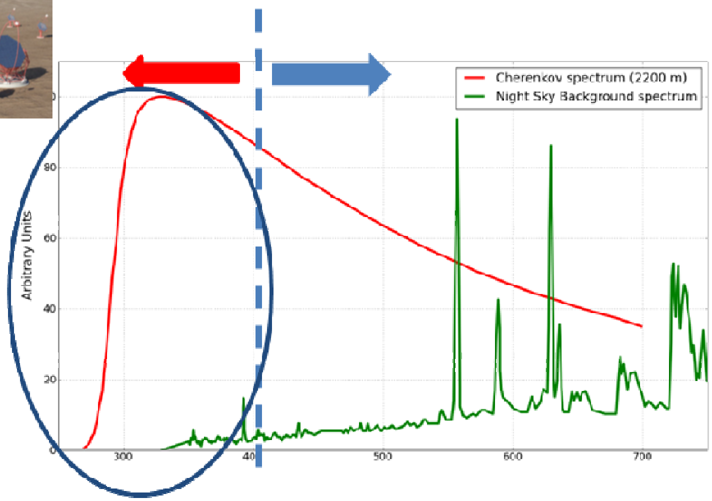




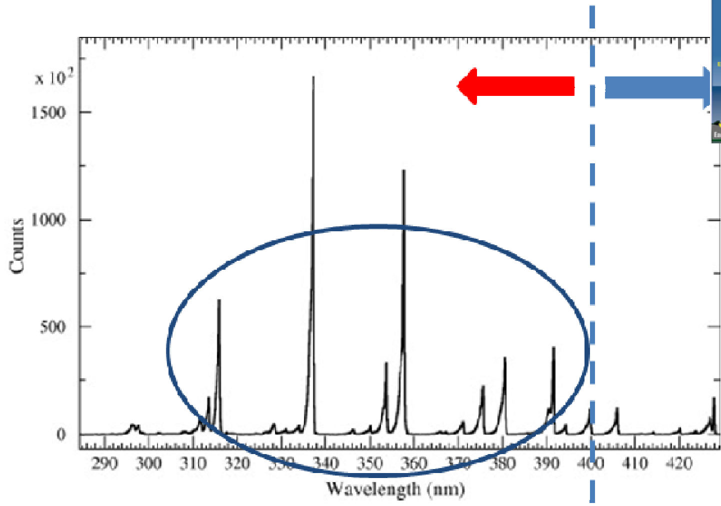
Typical Silicon Photodiode Spectral Response





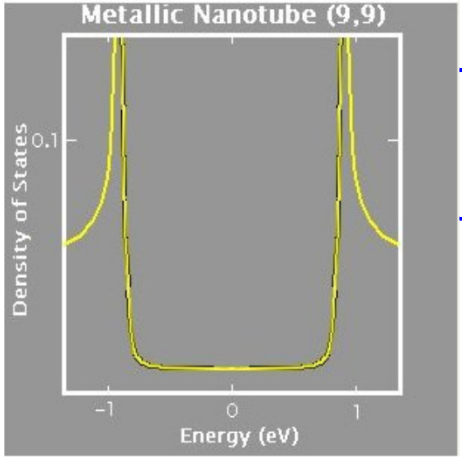


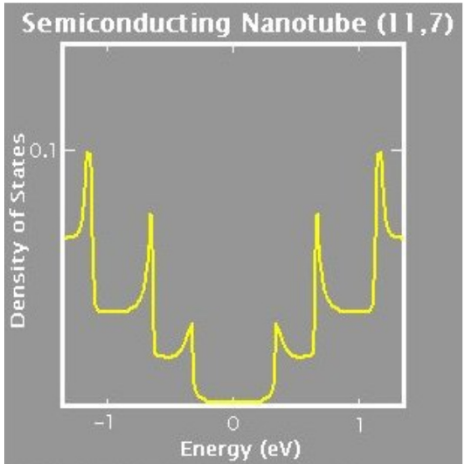
Cerenkov radiation



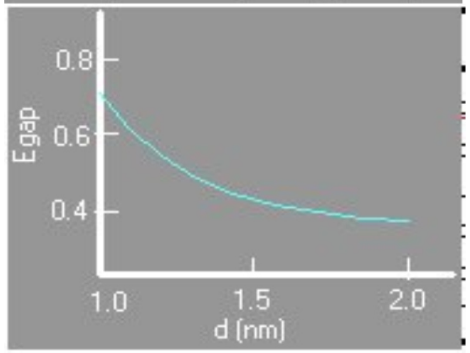
Fluorescence radiation

CNT energetic levels





Above: The Van Hove singularities in metallic and semiconducting nanotubes. Adapted from [19].



Semiconductors nanotubes show interesting fluorescence properties in the region of close infrared (from ~ 1 to ~ 15 μm) tied to their electronic characteristics. *Nanotubes of type n-m=3p with p entire positive or null are metallic conductors*.

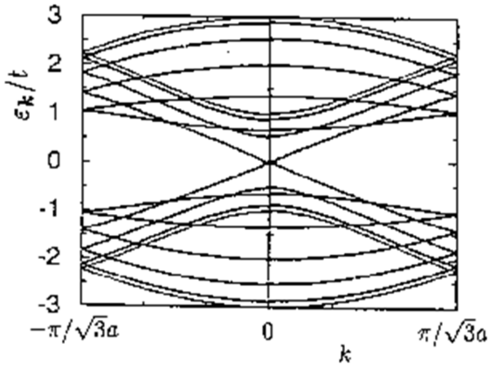
All the others are semiconductors whose gap is function of the diameter, and are approximated from the function:

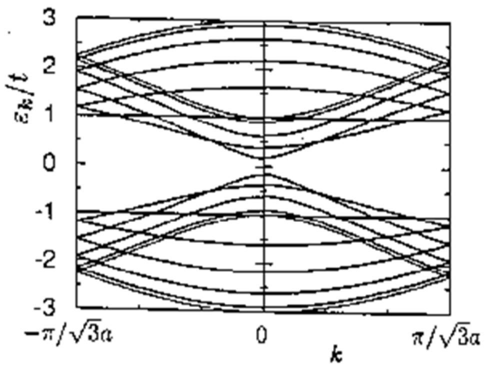
$$E_{gap}=2\ y_0\ acc/d$$

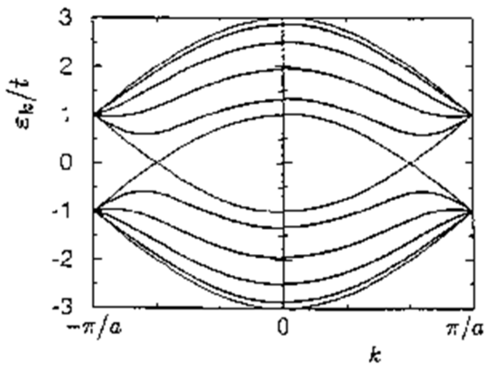
where y_0=0.1 eV, acc=0.142 nm and d is the diameter. This implies that for the Single Wall CNT the fundamental gap varies from 0.4 to 0.7 eV.

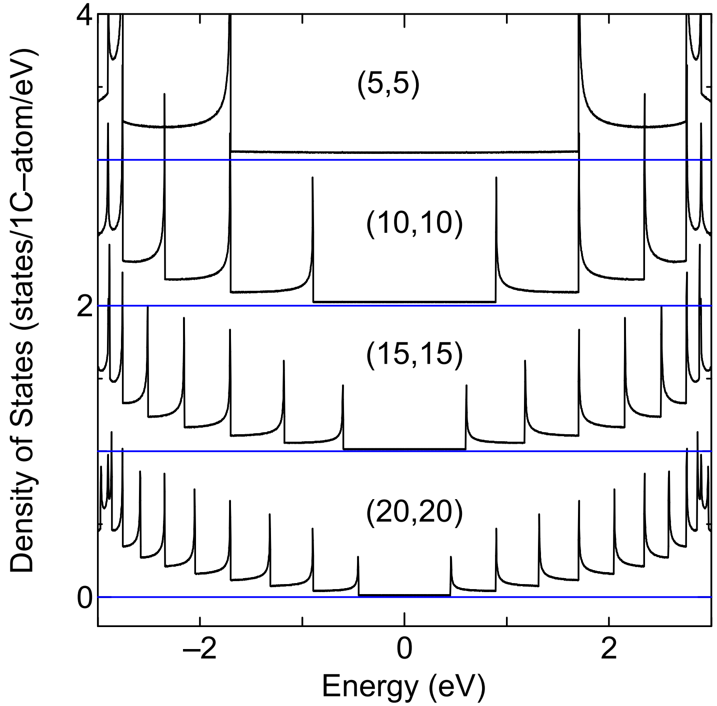
Multi Wall CNT instead present a wider range of energy gap.

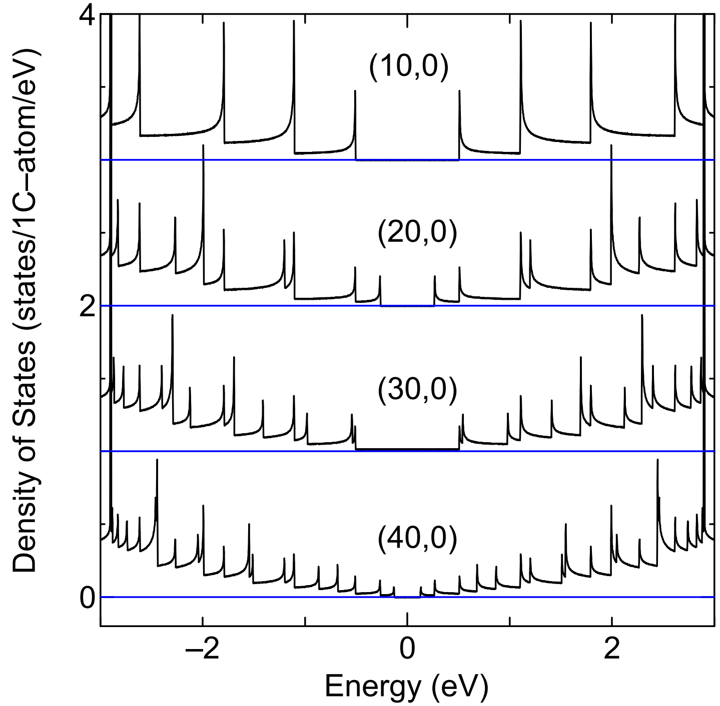
Metallic Zig-zag   Semiconducting Zig-zag   Armchair











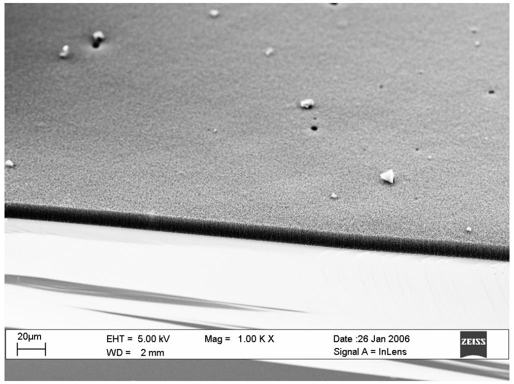
$c \cdot K = 2\pi m$

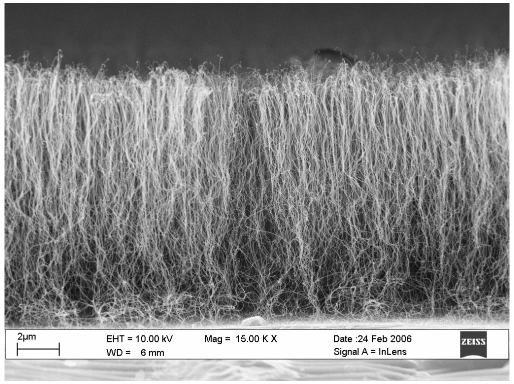
$m = 1 \ldots q$

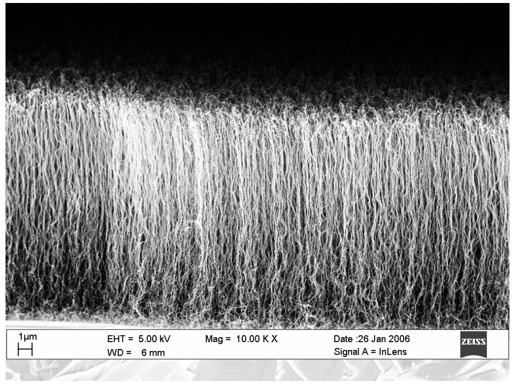
A multiwall carbon nanotube typically consists of a concentric set of nanotubes of both metallic and semiconducting types

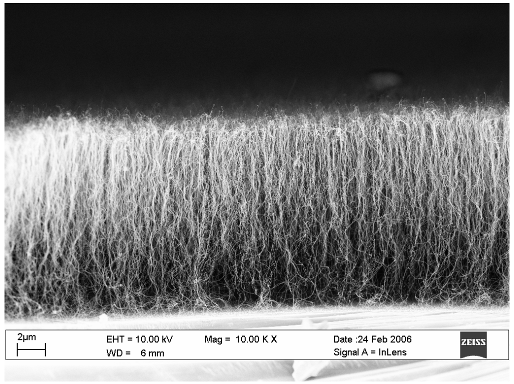
R. Saito, G. Dresselhaus and M.S. Dresselhaus, *Physical Properties of Carbon Nanotubes*, Imperial College Press (2003)

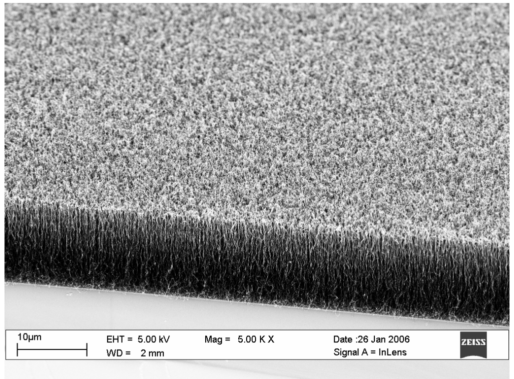
SEM Images

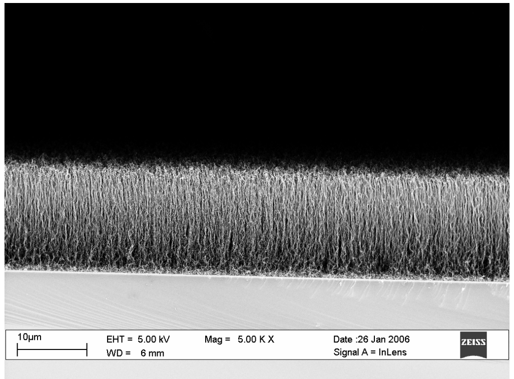

20µm
EHT = 5.00 kV
WD = 2 mm
Mag = 1.00 K X
Date :26 Jan 2006
Signal A = InLens

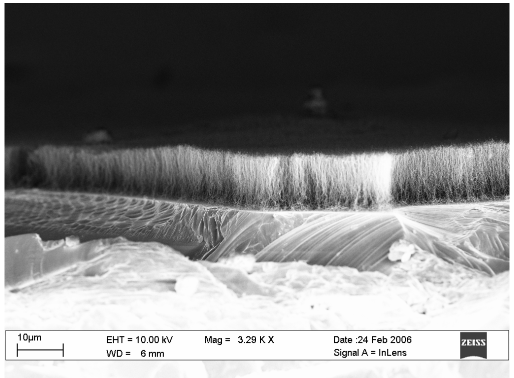

2µm
EHT = 10.00 kV
WD = 6 mm
Mag = 15.00 K X
Date :24 Feb 2006
Signal A = InLens

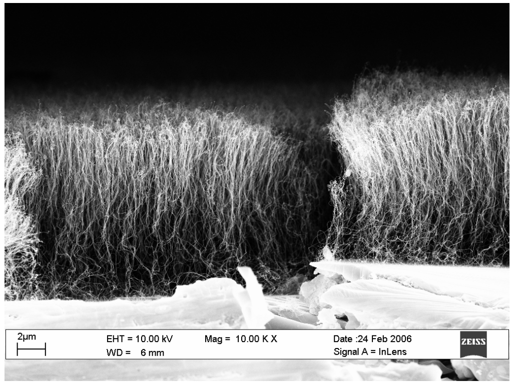

1µm
EHT = 5.00 kV
WD = 6 mm
Mag = 10.00 K X
Date :26 Jan 2006
Signal A = InLens

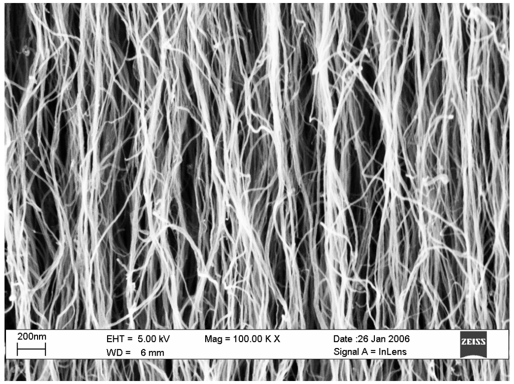

2µm
EHT = 10.00 kV
WD = 6 mm
Mag = 10.00 K X
Date :24 Feb 2006
Signal A = InLens


10µm
EHT = 5.00 kV
WD = 2 mm
Mag = 5.00 K X
Date :26 Jan 2006
Signal A = InLens

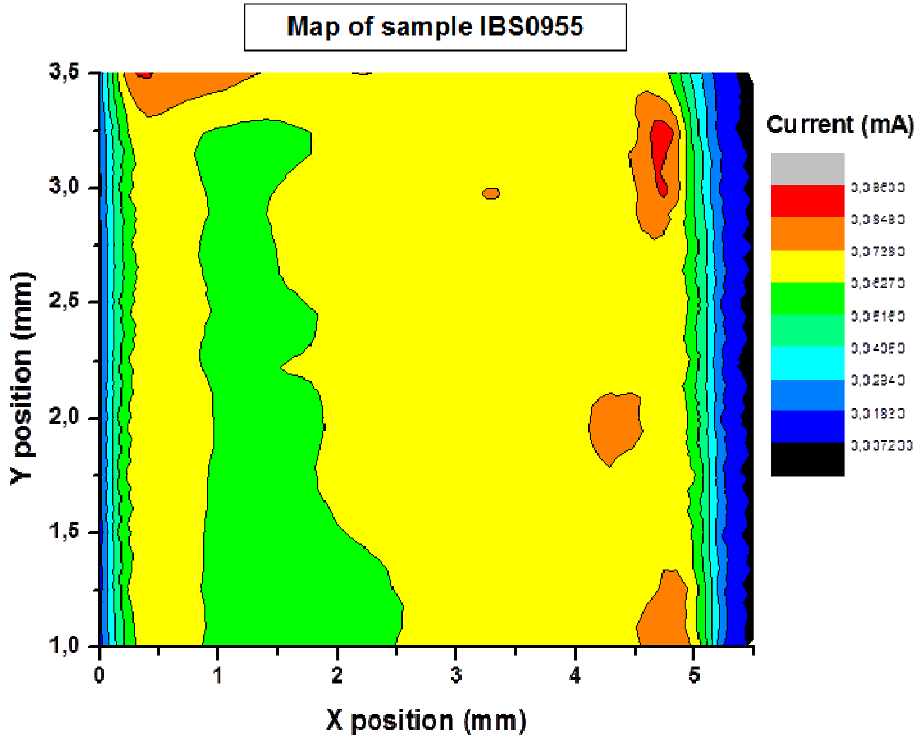

10µm
EHT = 5.00 kV
WD = 6 mm
Mag = 5.00 K X
Date :26 Jan 2006
Signal A = InLens


10µm
EHT = 10.00 kV
WD = 6 mm
Mag = 3.29 K X
Date :24 Feb 2006
Signal A = InLens


2µm
EHT = 10.00 kV
WD = 6 mm
Mag = 10.00 K X
Date :24 Feb 2006
Signal A = InLens


200nm
EHT = 5.00 kV
WD = 6 mm
Mag = 100.00 K X
Date :26 Jan 2006
Signal A = InLens

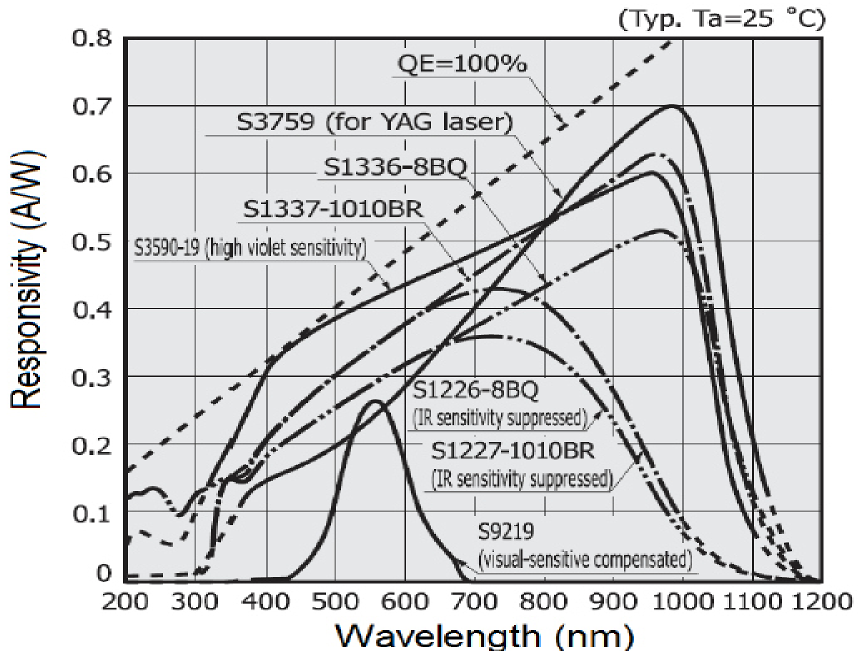
Great uniformity over large area

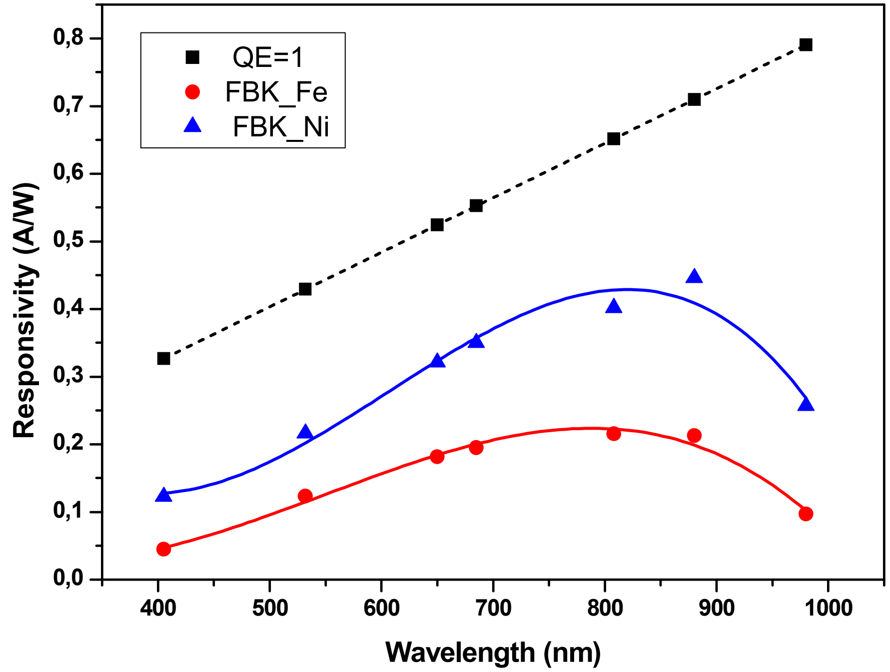


The electric field applied uniformly over the entire CNT surface plays a fundamental rule making uniform the charge electrodes.

The signal generated everywhere in the sample can be collected to the metallic electrodes through the ITO layer, whose resistivity is very low.

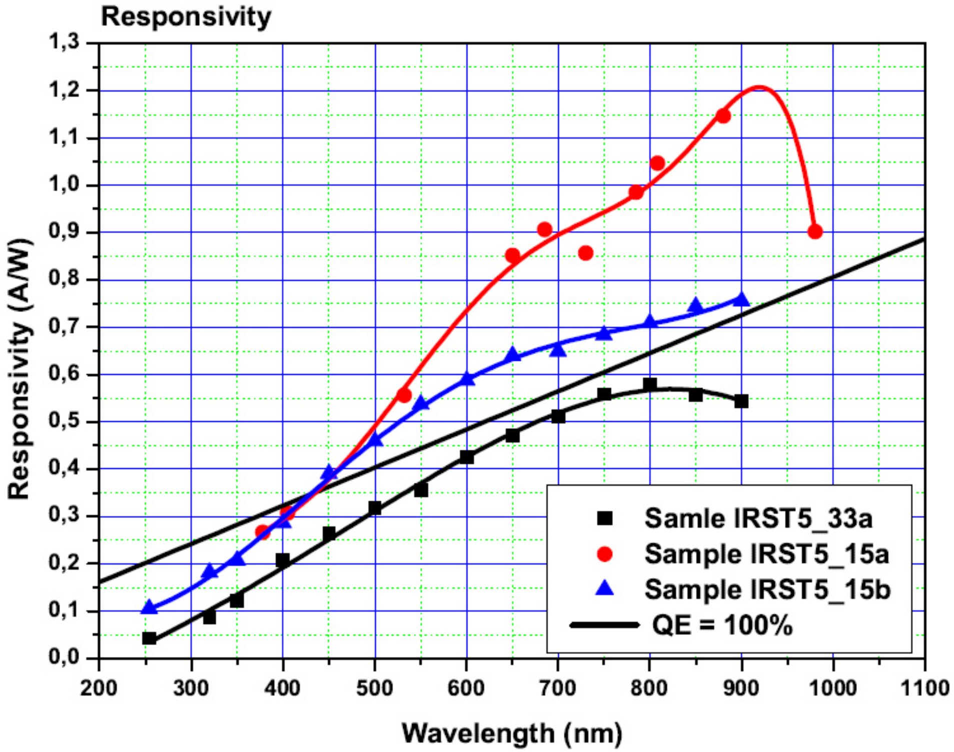
Si-CNT photodetector responsivity

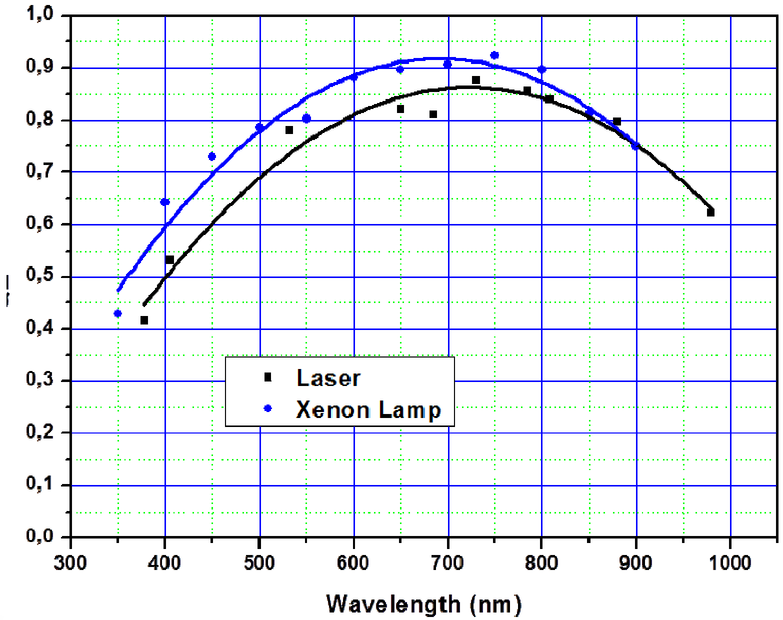




Responsivity comparison between Si-CNT prototype and commercial photodiode

Si-CNT photoresponsivity





A particular layered substrate without the schottky junction on the back shows very peculiar characteristics: high quantum efficency in all the wide wavelength range, a hetero-junction threshold at 2.5 V and a well defined tunnel effect under this voltage. Work on this substrate is still in progress.