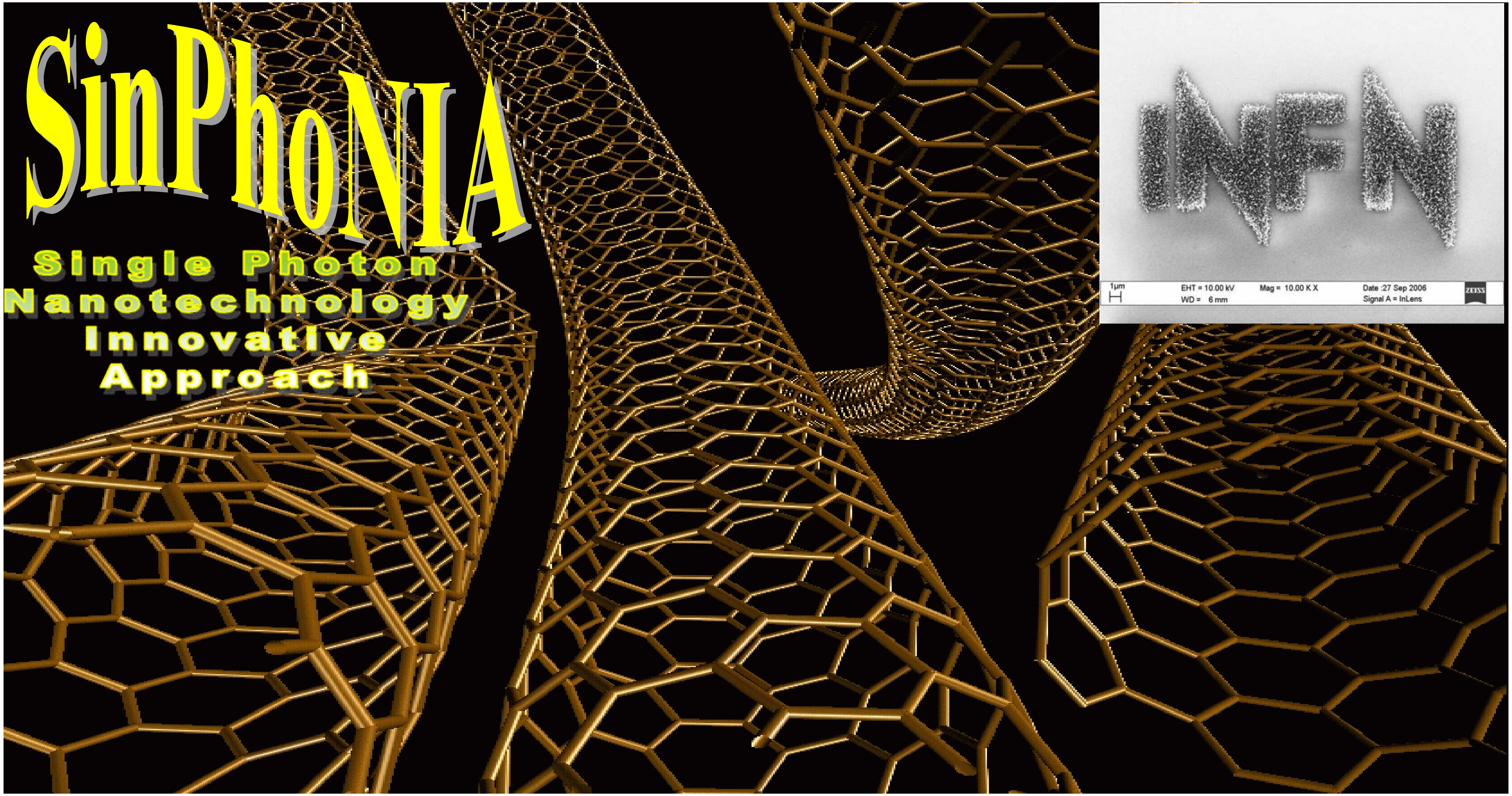


Istituto Nazionale di Fisica Nucleare

http://sinphonia.na.infn.it/index.htm

A new Si-CNT large area photodetector

ambrosio@na.infn.it

INFN Istituto Nazionale di Fisica Nucleare

Michelangelo Ambrosio

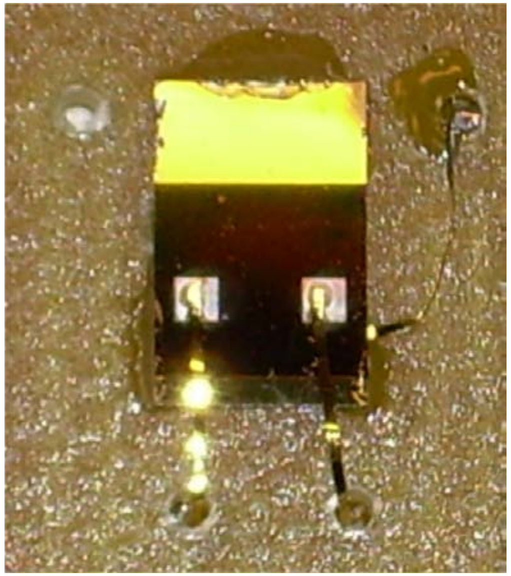
Outline

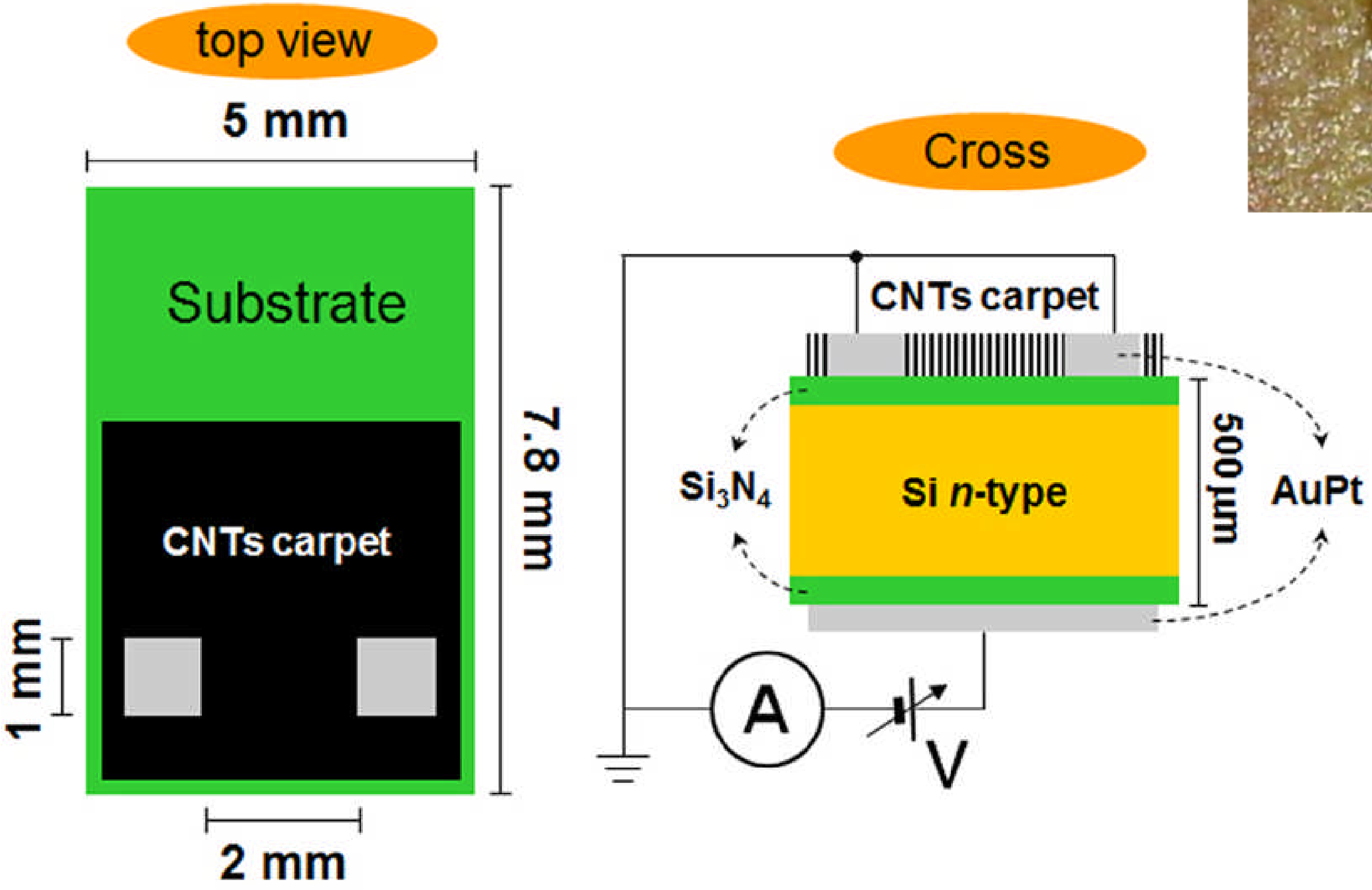
- Layout of a Si-CNT photodetector
- Measurements with CNT growth @ 500 °C.
- Comparison with CNT growth @ 700°C
- Surface coating with ITO
- More useful information
- Future developments.
- Applications.

The SinPhoNIA collaboration:

INFN, CNR and University of Bari, L'Aquila, Naples, Perugia, Roma2

The Si-CNT detector layout





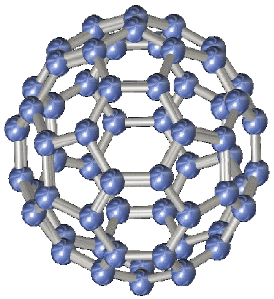
…from Fullerene to Carbon Nanotubes (CNTs)

New Carbon Allotropes

Fullerene: C_{60}

C_{60} is a "tiny-droplet" of graphene sheet

- radius of 7.10 Å
- produced by arc-discharge



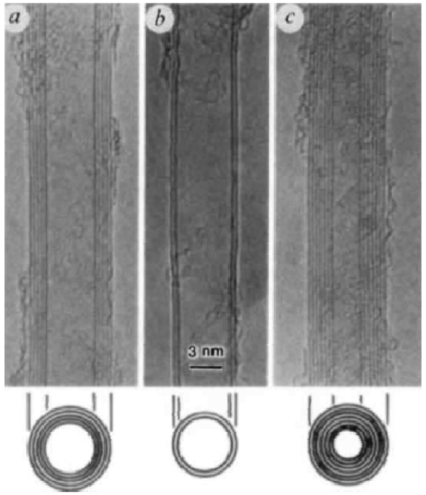
H. W. Kroto, R. F. Curl and R. E. Smalley 1985 Rice University

…the evolution of the experiments for the synthesis of C_{60} by Arc-Discharge has led to Carbon Nanotubes discovery

Carbon Nanotubes: CNTs

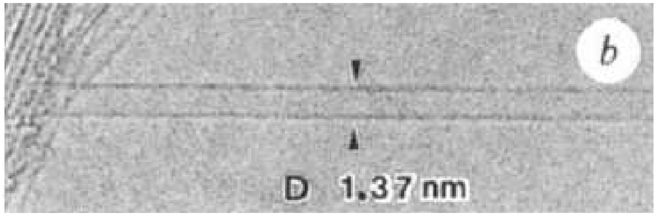
CNTs are rolled up graphene sheets

MWNTs



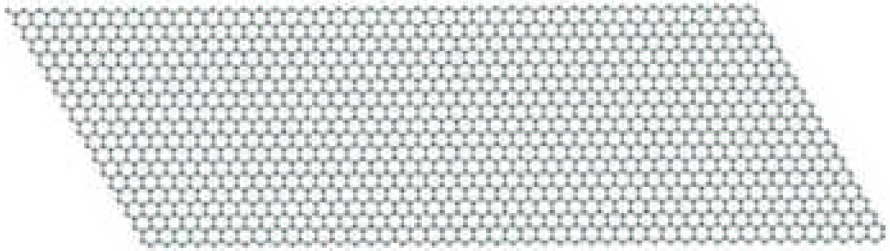
S. Iijima, Nature 354, 56 (1991) NEC Laboratories

SWNTs



S. Iijima e T. Ichihashi Nature, 363, 603 (1993)

What is a CNT?



A graphene sheet can be rolled only one and more than one way, producing single walled and multiwalled carbon nanotubes.

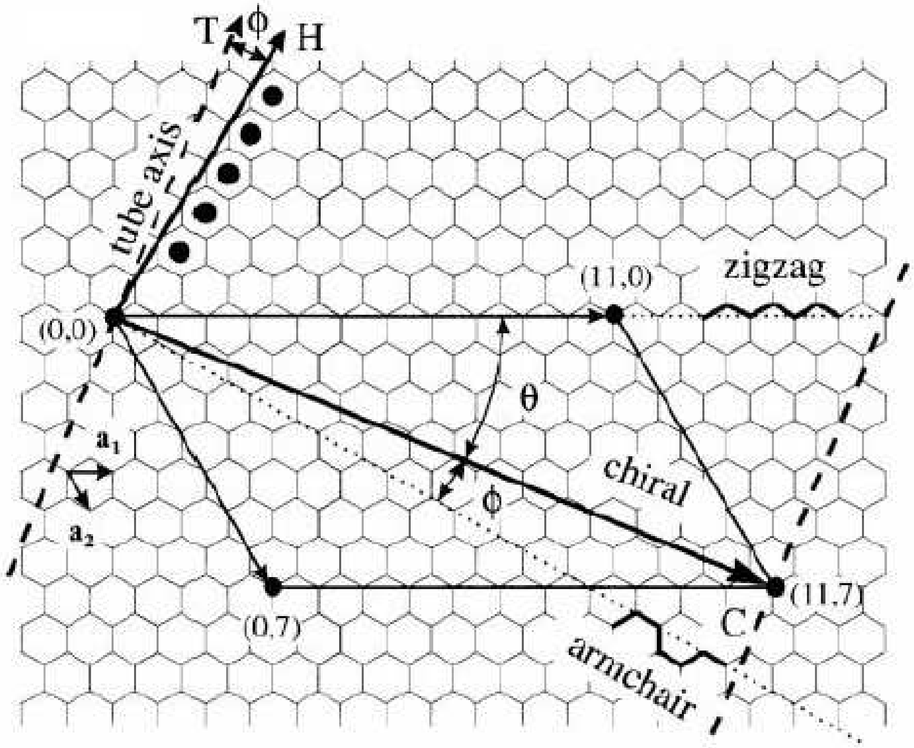
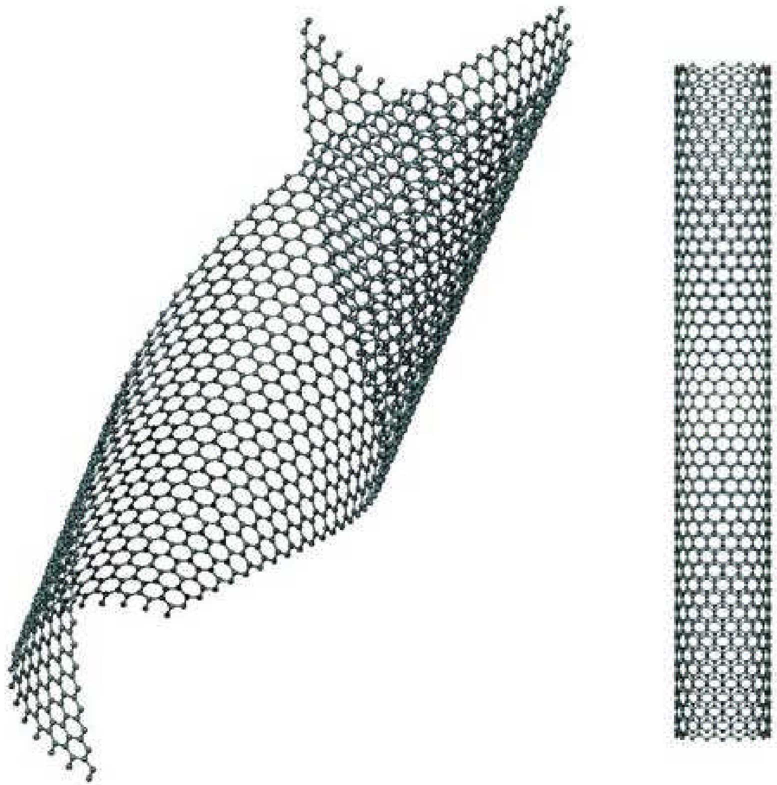


Figure 5. Chiral vector for CNT characterization (adapted from Wildoer, 1998, p. 59)



Carbon Nanotubes (CNTs)

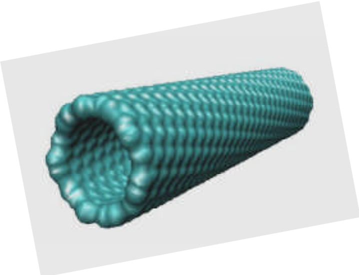
Molecular Nanowires ($d \sim 1$ nm, $l \sim 1$ μm)

SWNTs

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

$\notin$ N — |n-m|/3 — $\in$ N

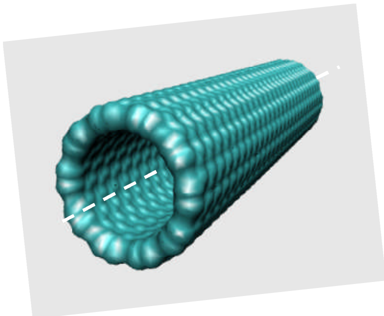
Semiconductor



Channel (FETs),

Luminescence

Metal



Ballistic Conduction,

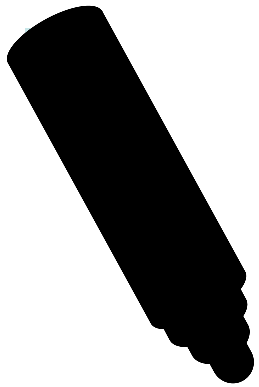
e-wave guides, SETs

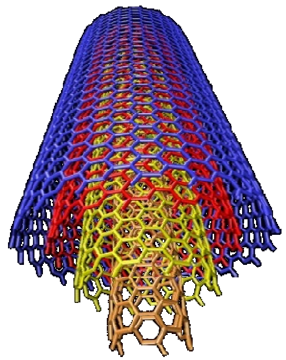
MWNTs

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

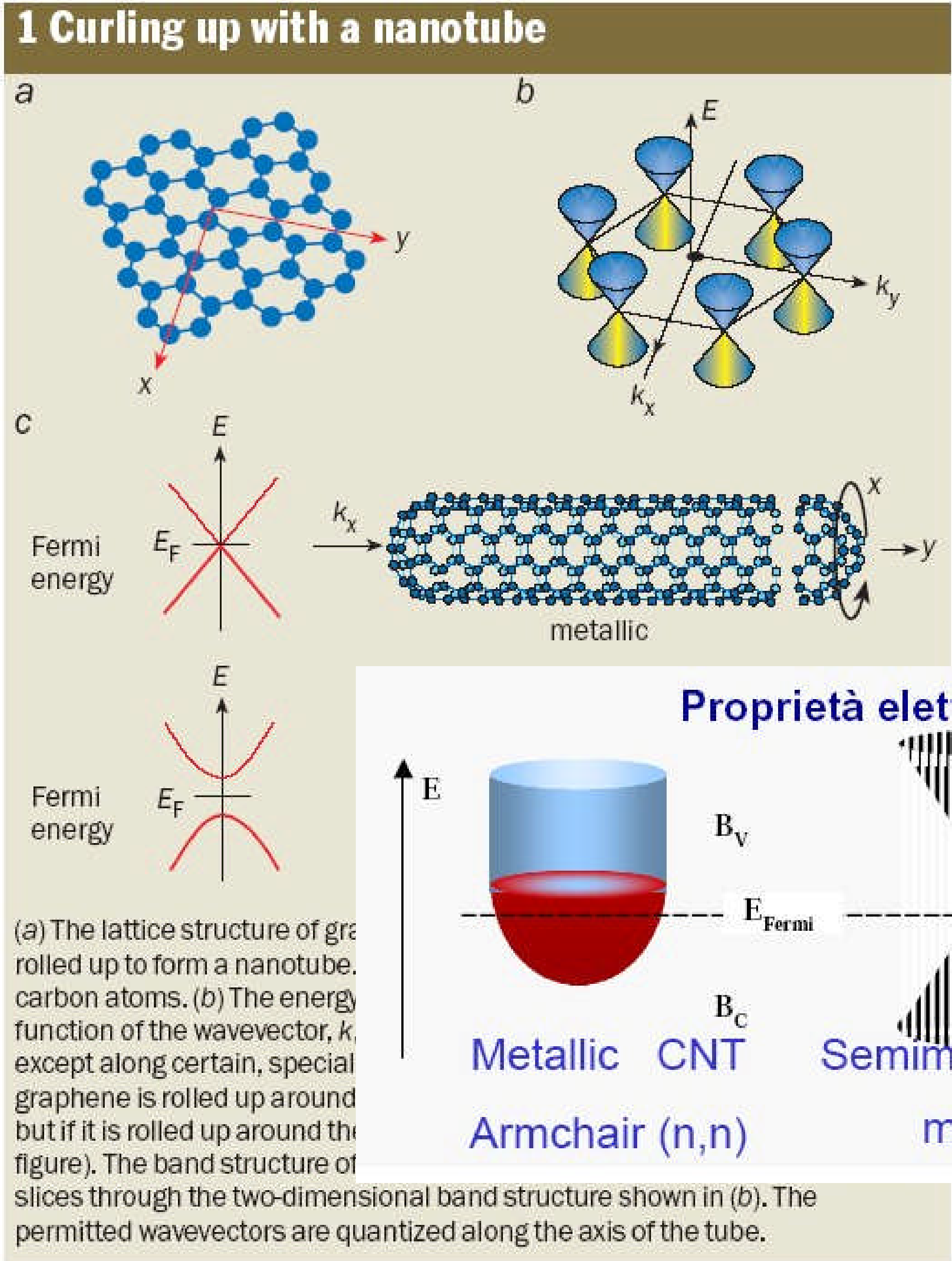
Vias

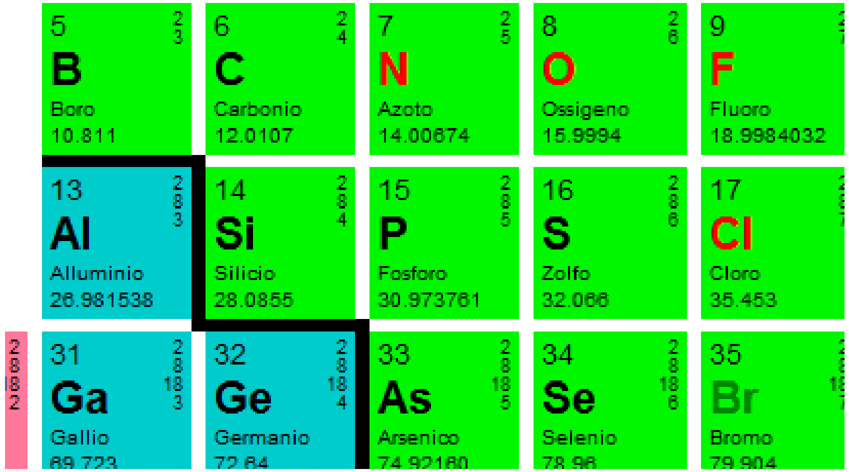
Nanocomposites

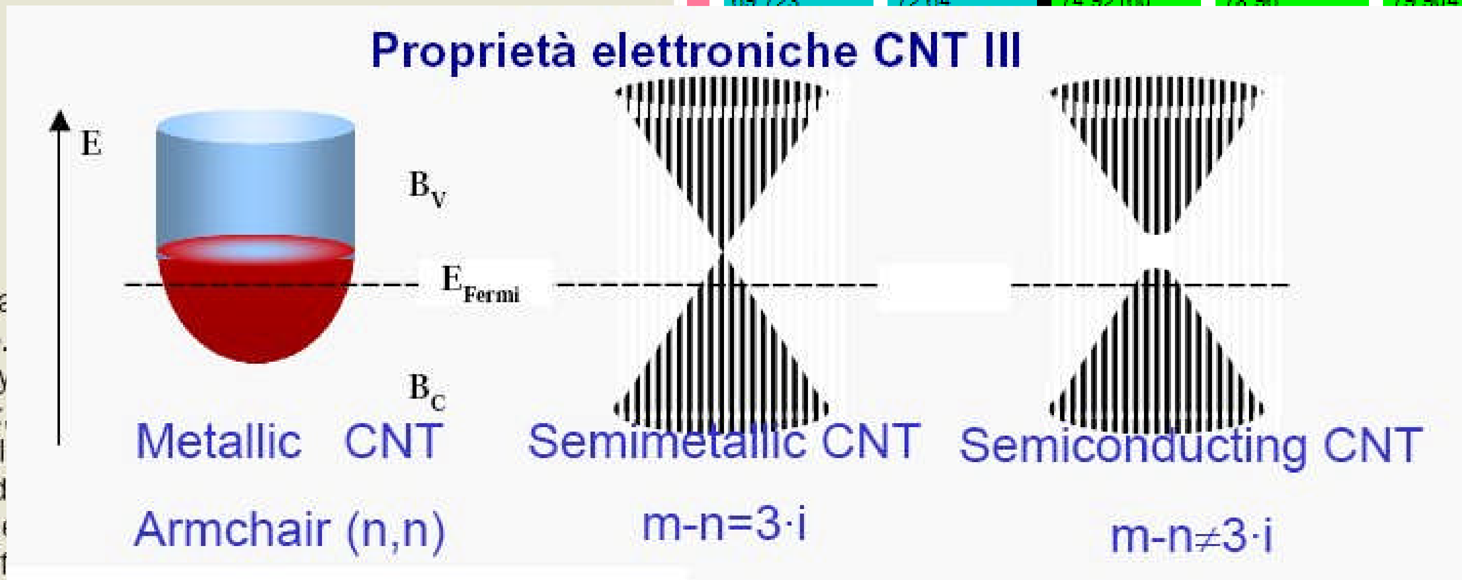




Electronics characteristics







Electronic structure of SWNTs

- Band structure predicts three types:
  - semiconductor if *(2n+m)/3* not integer; band gap:

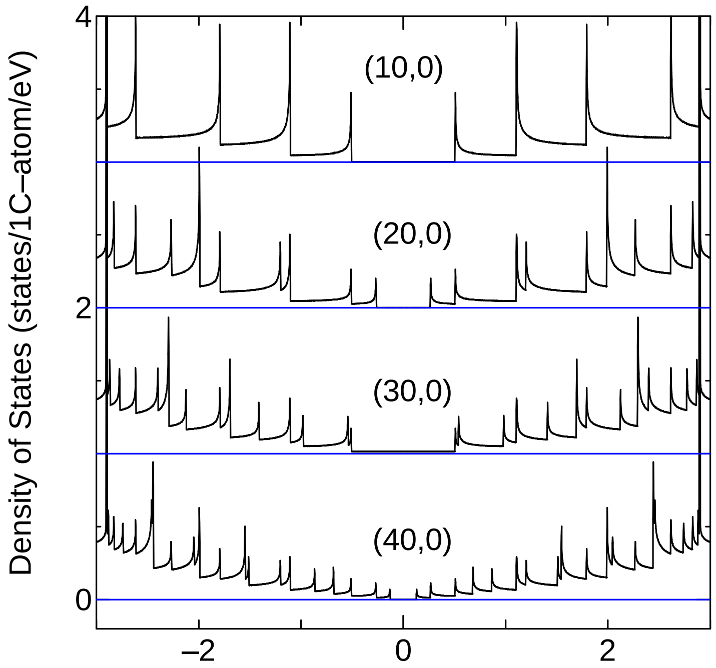
$$\Delta E = \frac{2\hbar v_F}{3R} \approx 1\,\mathrm{eV}$$

  - metal if *n=m* (armchair nanotubes)
  - small-gap semiconductor otherwise (curvature-induced gap)

- Experimentally observed: STM map plus conductance measurement on same SWNT

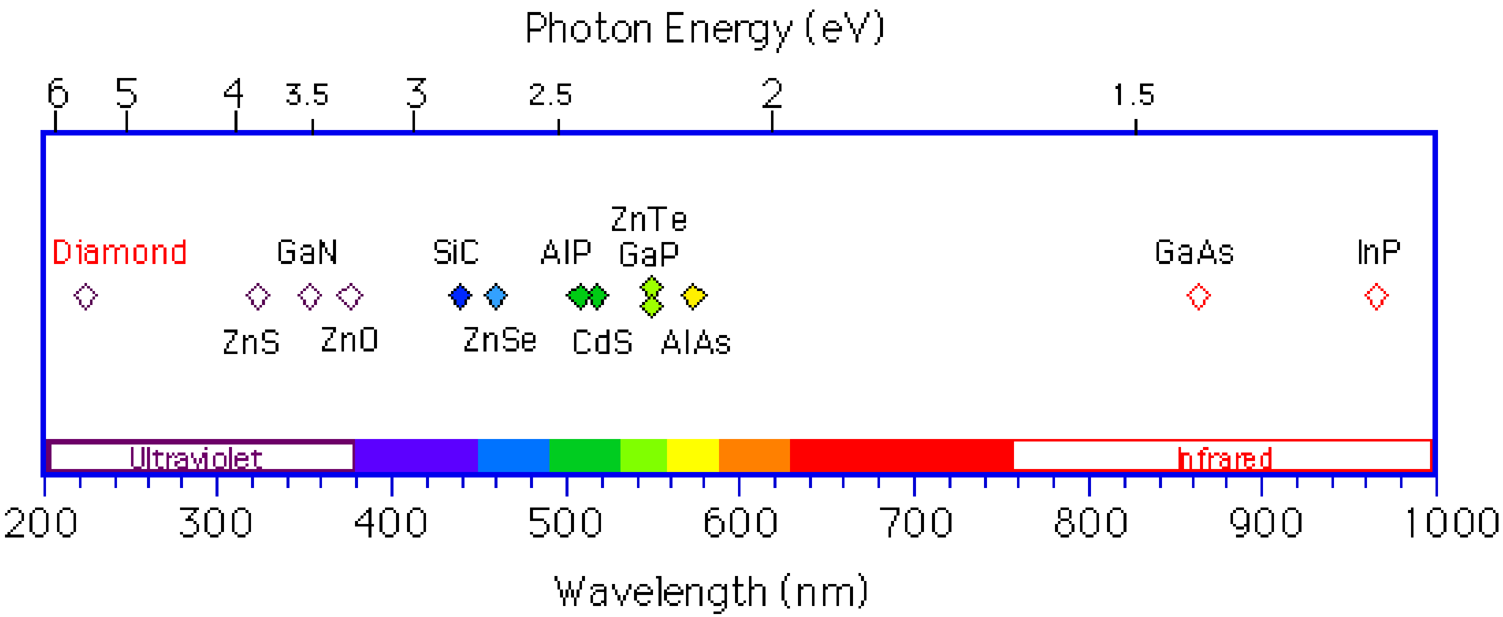
- In practice intrinsic doping, Fermi energy typically 0.2 to 0.5 eV

CNT as detectors



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, every in a small area, a great number of tubes sensitive to the radiation.

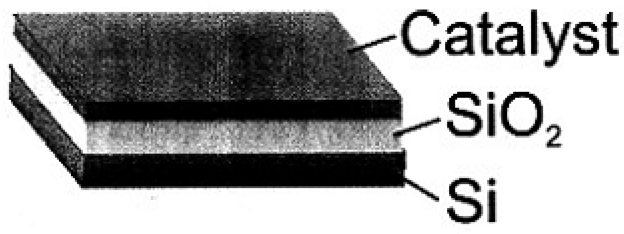
≈ 10^8 – 10^{10} MWCNT / 1 mm^2



Growth Mechanism of Carbon Nanotubes (CVD and PECVD)

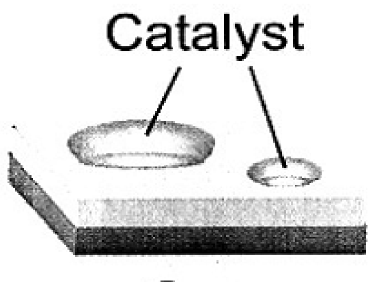
Substrate

Ni Catalyst deposition



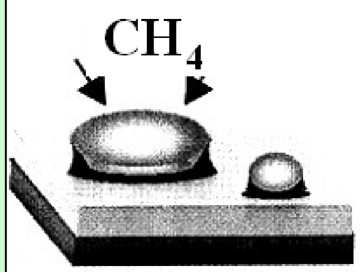
Ni Clusters formation

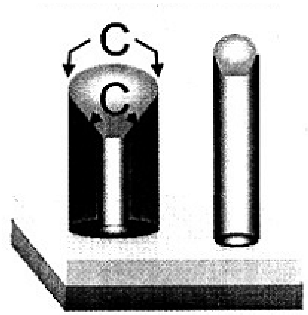
480 - 650 C°
10^{-5} torr
10 - 45 min



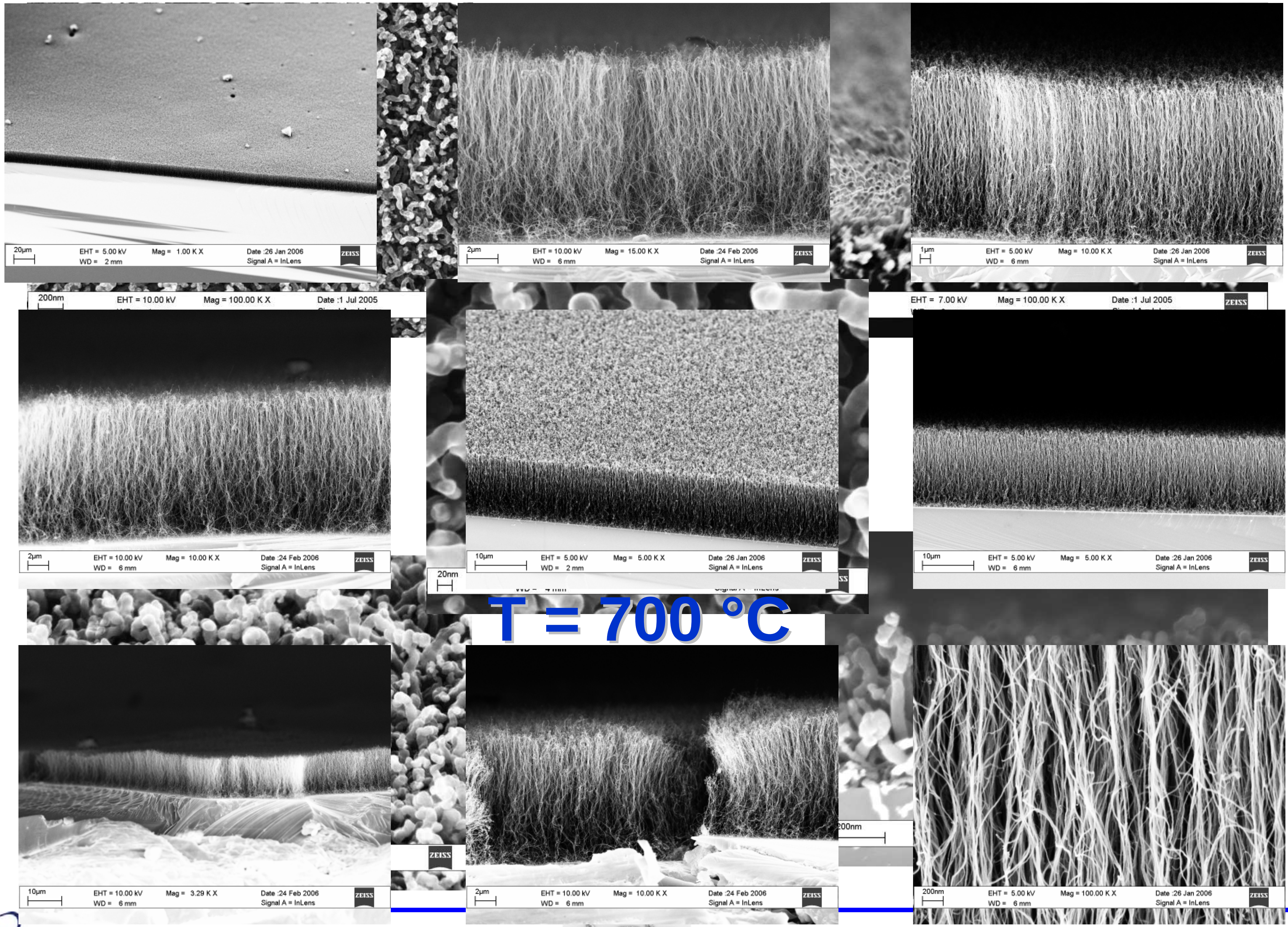
CVD or
rf PECVD

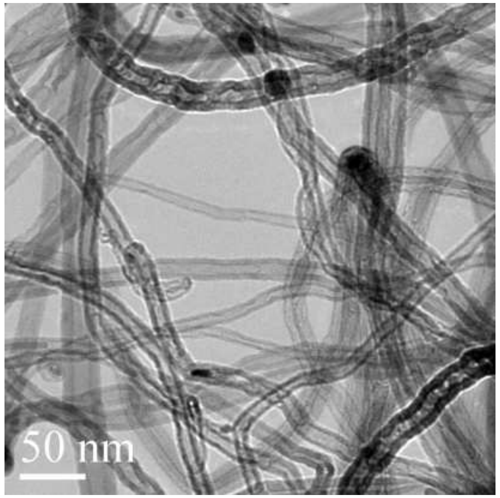
500 - 750 C°
1 torr
C_2H_2
or
CH_4
+ NH_3

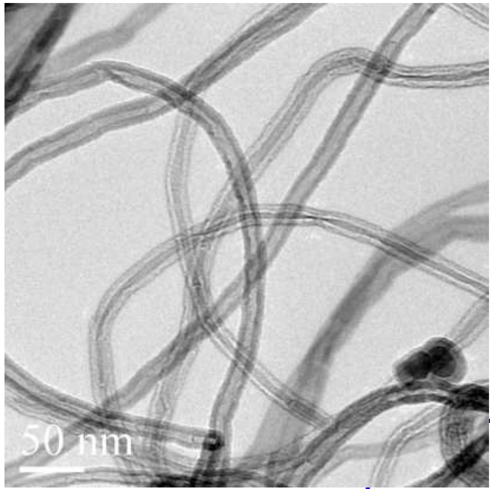




Nanotube production: SEM images

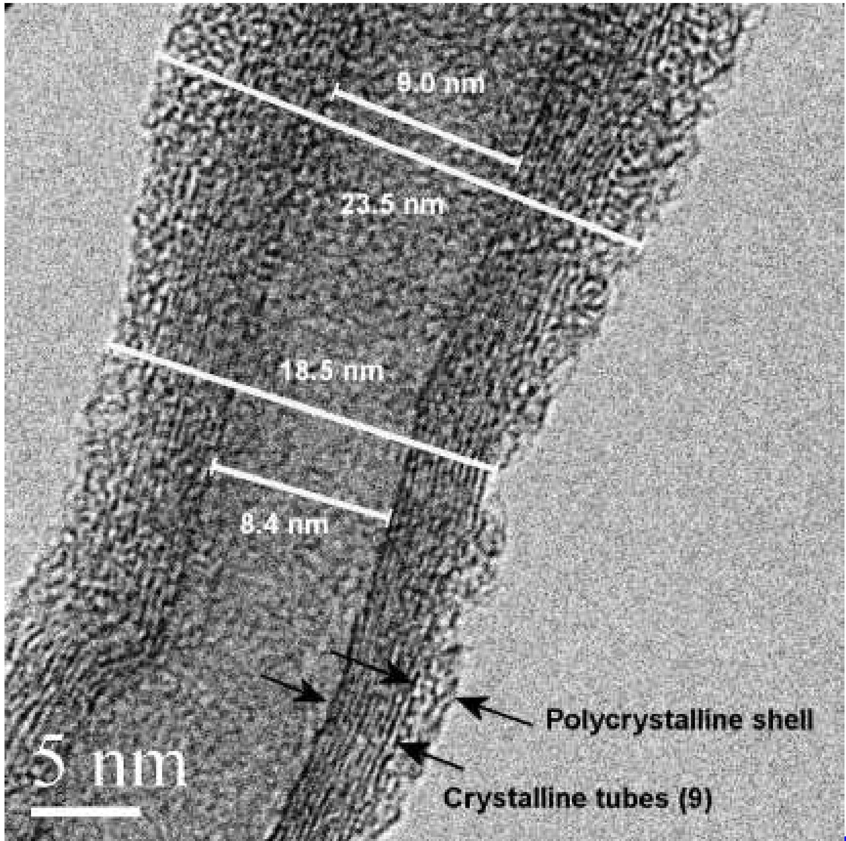


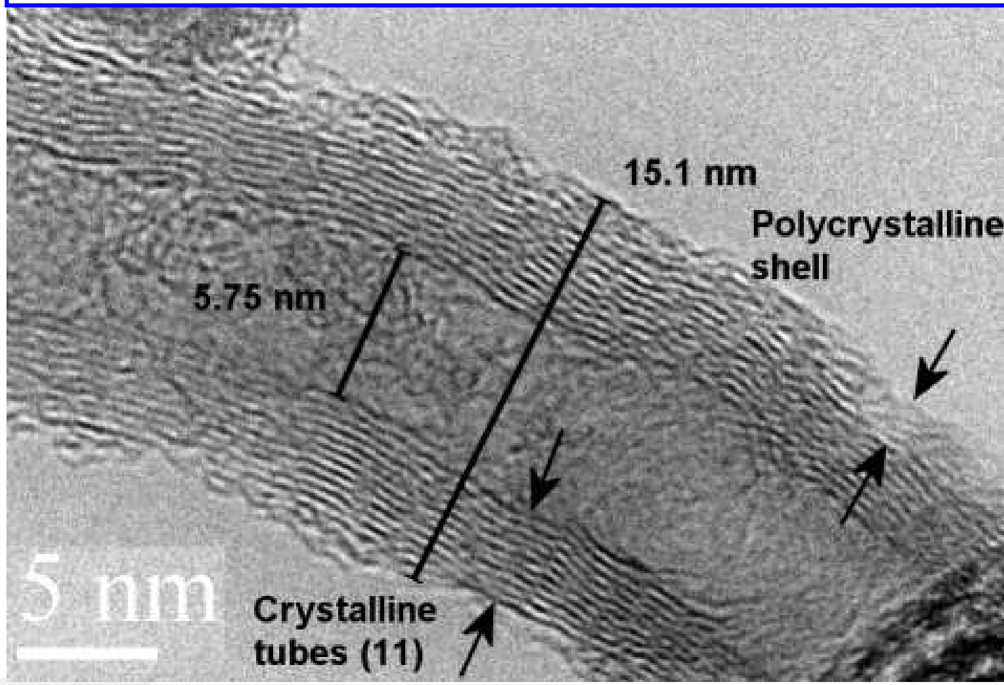




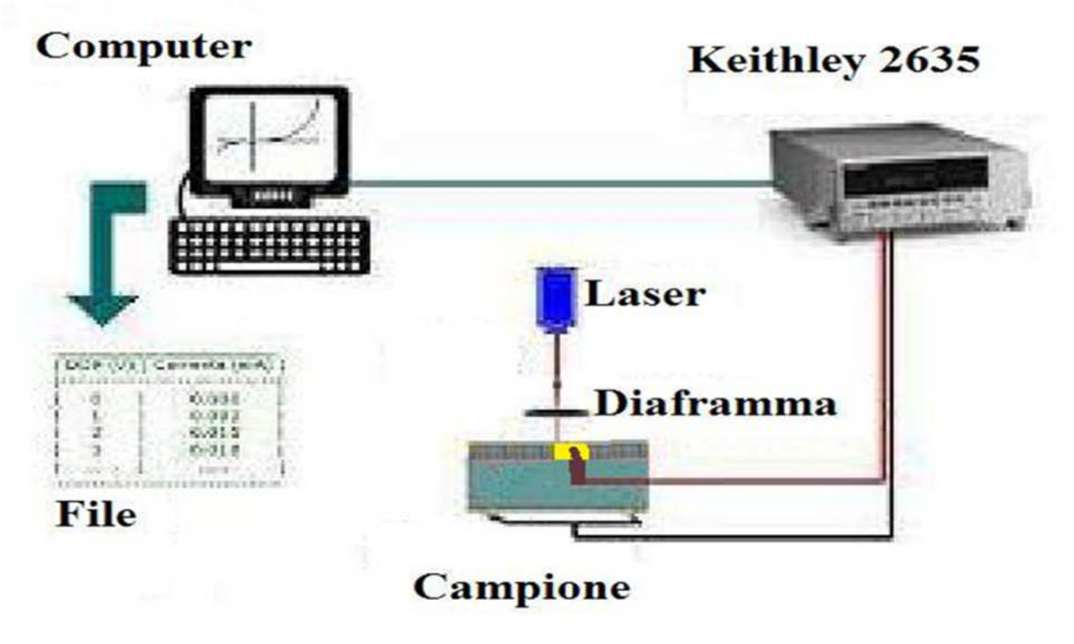
- External diameter: 15 – 25 nm
- Internal diameter: 5 – 10 nm
- Average number of nanotubes: 10 – 15

CNT Characteristics





Si-CNT detector test layout



Low power (up to 5 mW) laser diode.

Wavelengths (nm):

405
532
650
685
785
880
980

Measurements at laser light intensities of:

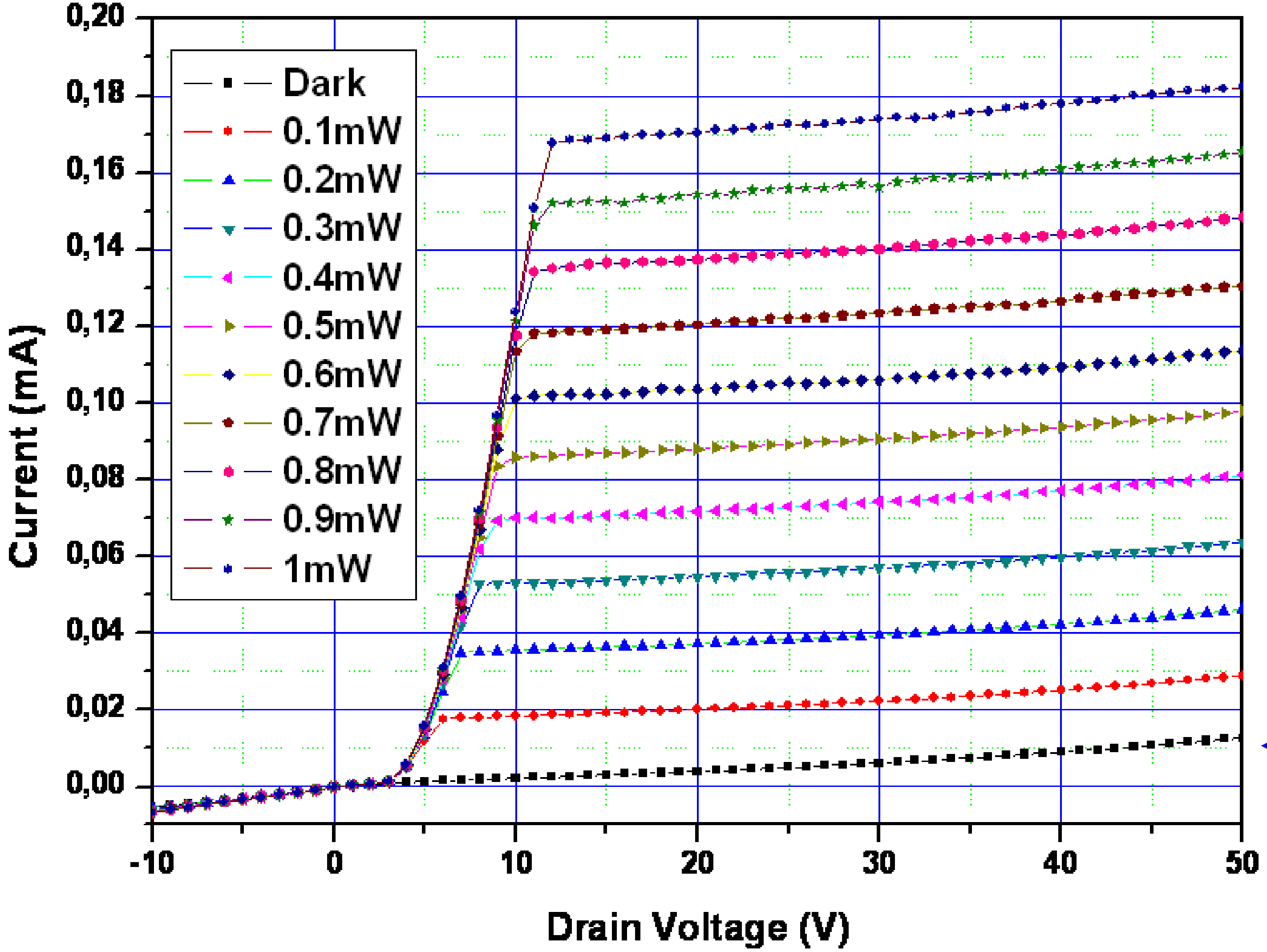
0.1 - 1.0 mW, step 0.1 mW

Drain voltage ranges from -30 to 50 V, step 1 V

Typical response of a SiCNT photodetector

$T_{CNT\ growth}$ = 500 °C

I-V plot of sample C2 @ λ=785 nm



Room temperature

No electronics

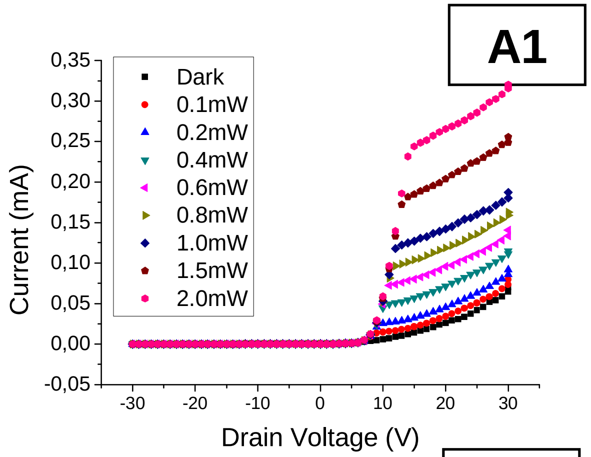
No signal amplification

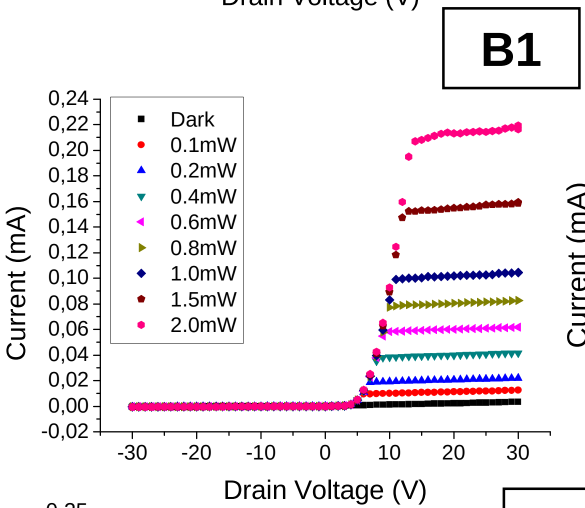
Breakdrown @ >100 V

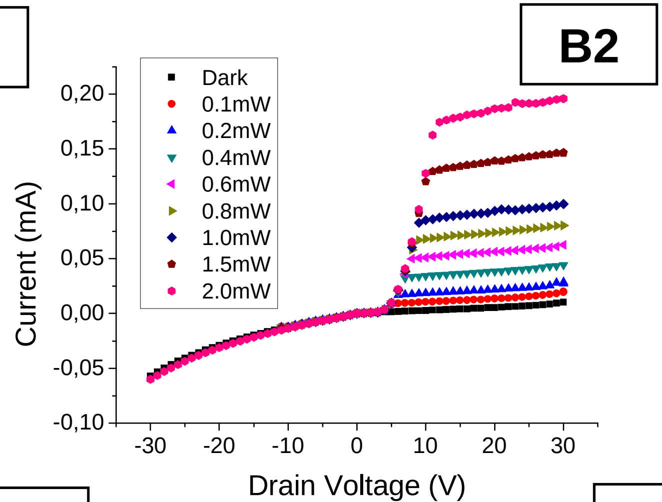
Dark current

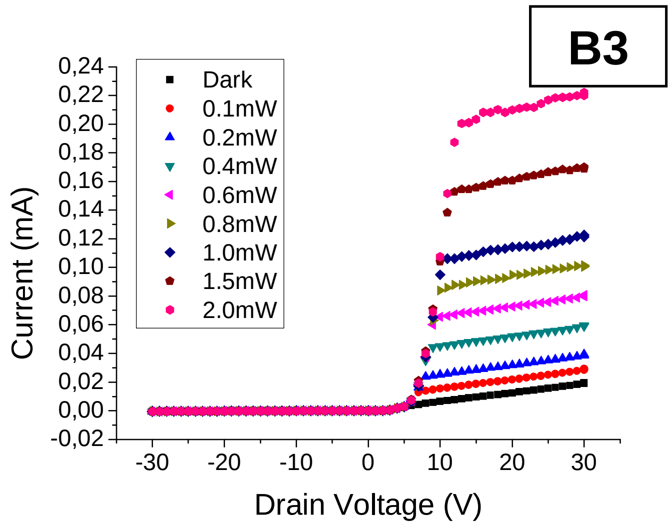
T_{CVD} = 500 °C

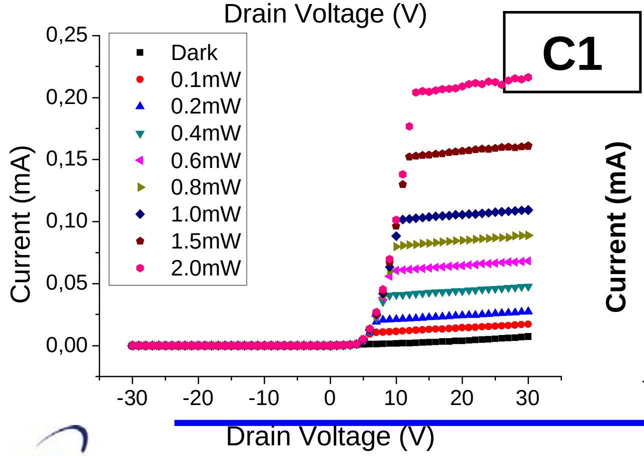
Room temperature

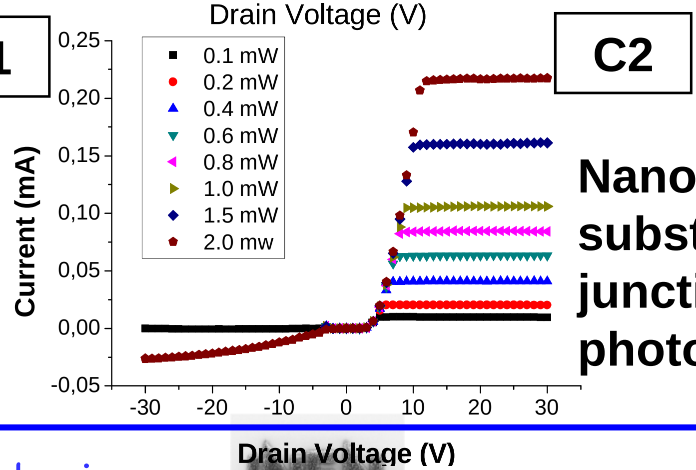






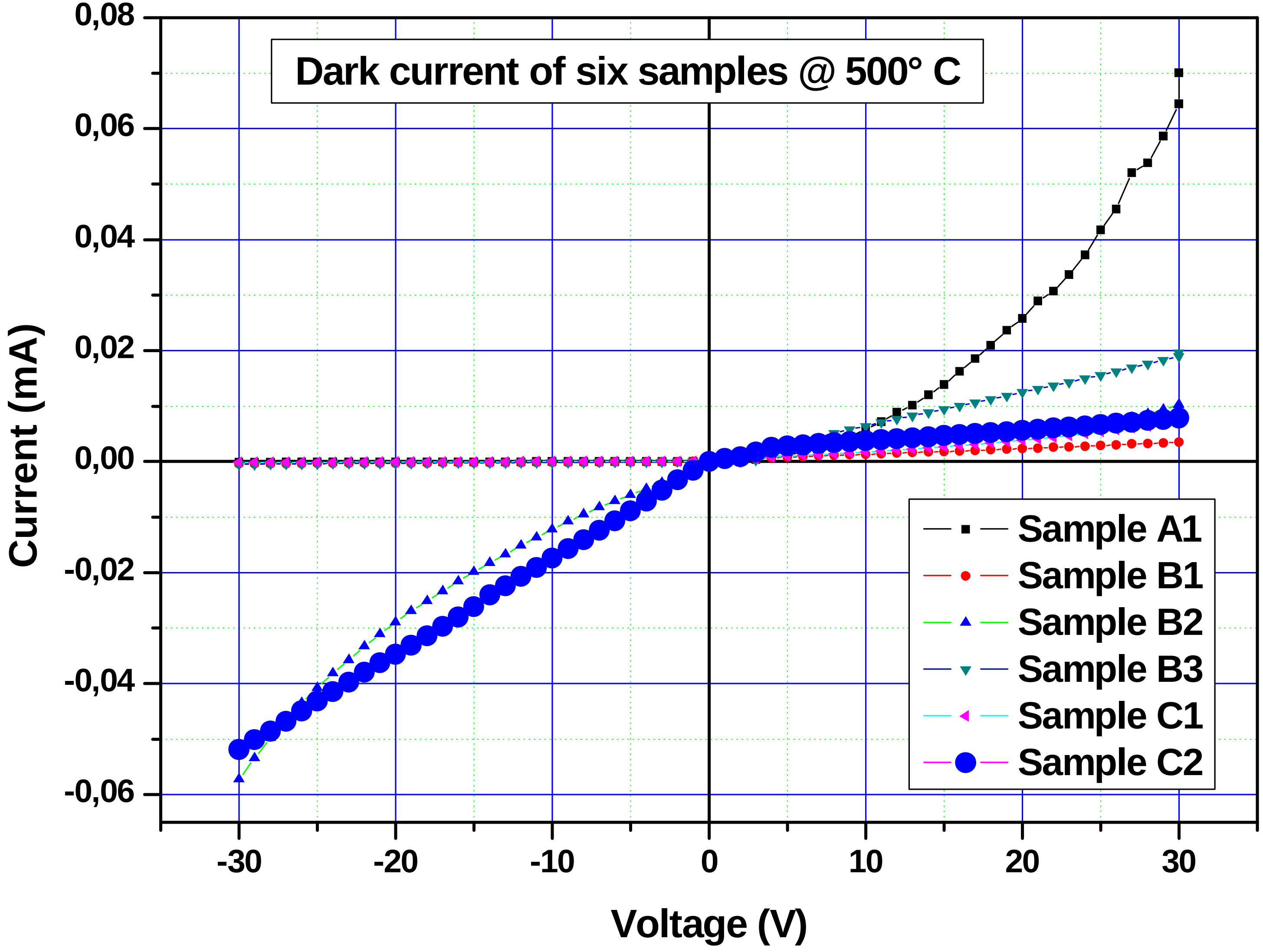






Nanotubes grown on a silicon substrate create an hetero-junction with surprising photoresponsivity properties.

Si-CNT junction characteristics



Study of heterojunction Si-CNT

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

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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[b] *CNR-SPIN U.O.S. di Napoli e Dipartimento di Scienze Fisiche, Università degli Studi di Napoli Federico II, Via Cintia 2, 80126 Napoli, Italy*
[c] *INFN, Sezione di Napoli, Via Cintia 2, 80125 Napoli, Italy*
[d] *Dipartimento di Fisica, Università degli Studi di Roma Tor Vergata, Via della Ricerca Scientifica 1, 00133 Roma, Italy*
[e] *INFN, Sezione di Perugia e Dipartimento di Fisica, Università degli Studi di Perugia, Piazza Università 1, 06100 Perugia, Italy*
[f] *Dipartimento di Fisica, Università degli Studi dell'Aquila, Via Vetoio 10, 67100 Coppito, L'Aquila, Italy*

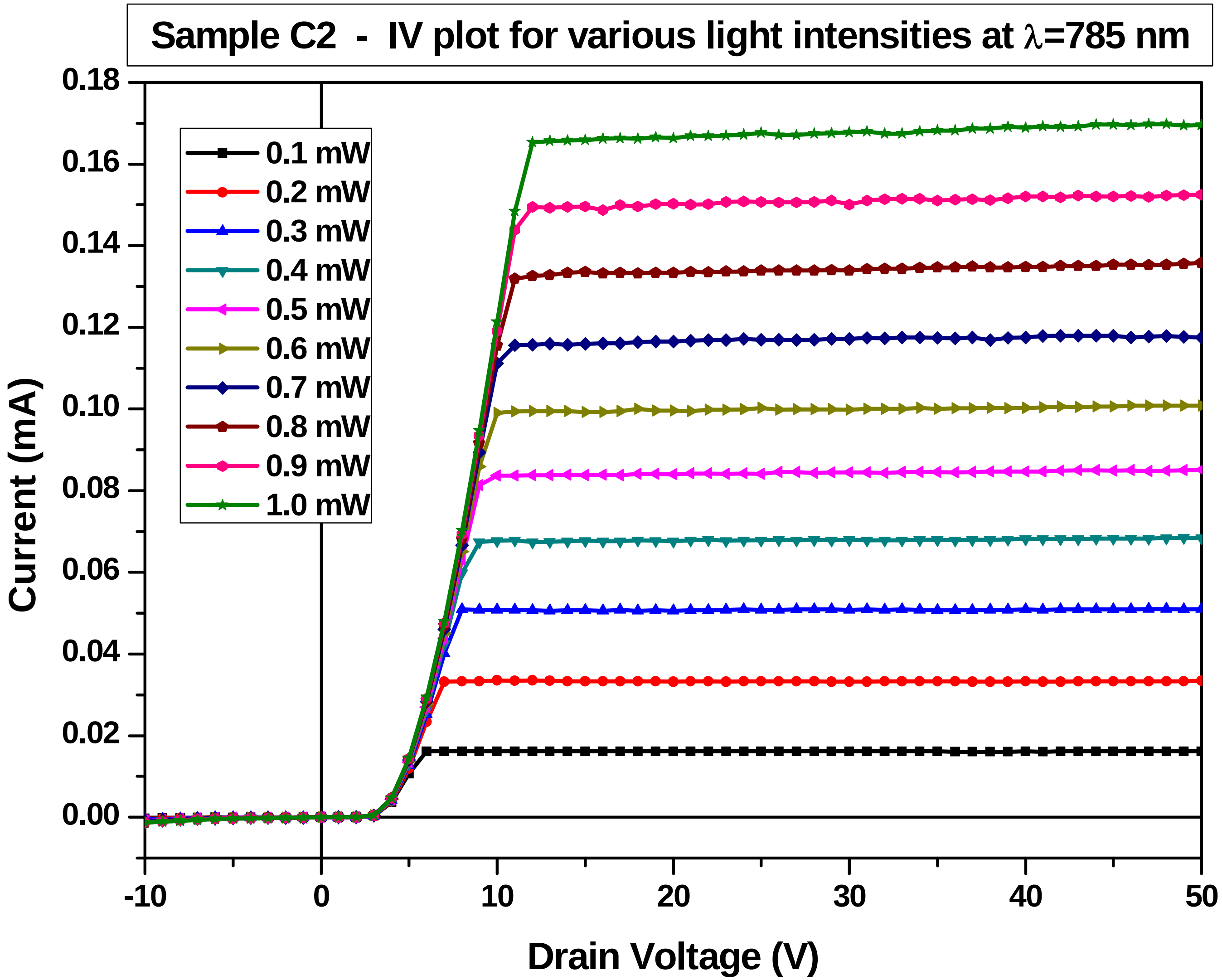
Nuclear Instruments and Methods in Physics Research A 629 (2011), 377-381

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

I-V plot of C2 detector @ λ=785 nm



Room temperature

No electronics

No signal amplification

Long and stable plateau

Linearity I vs P

Threshold 3.55 V

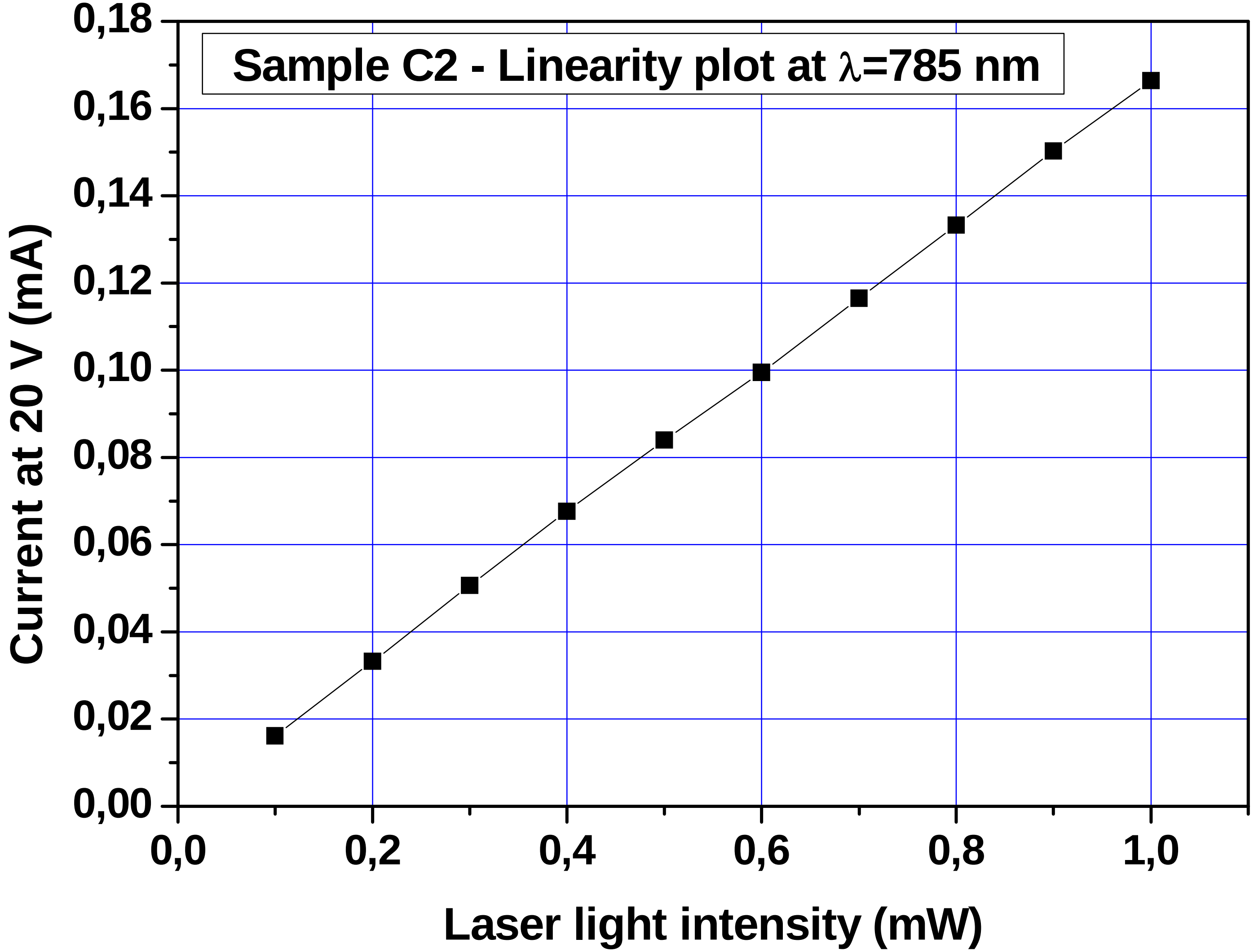
No saturation observed

No aging in two years

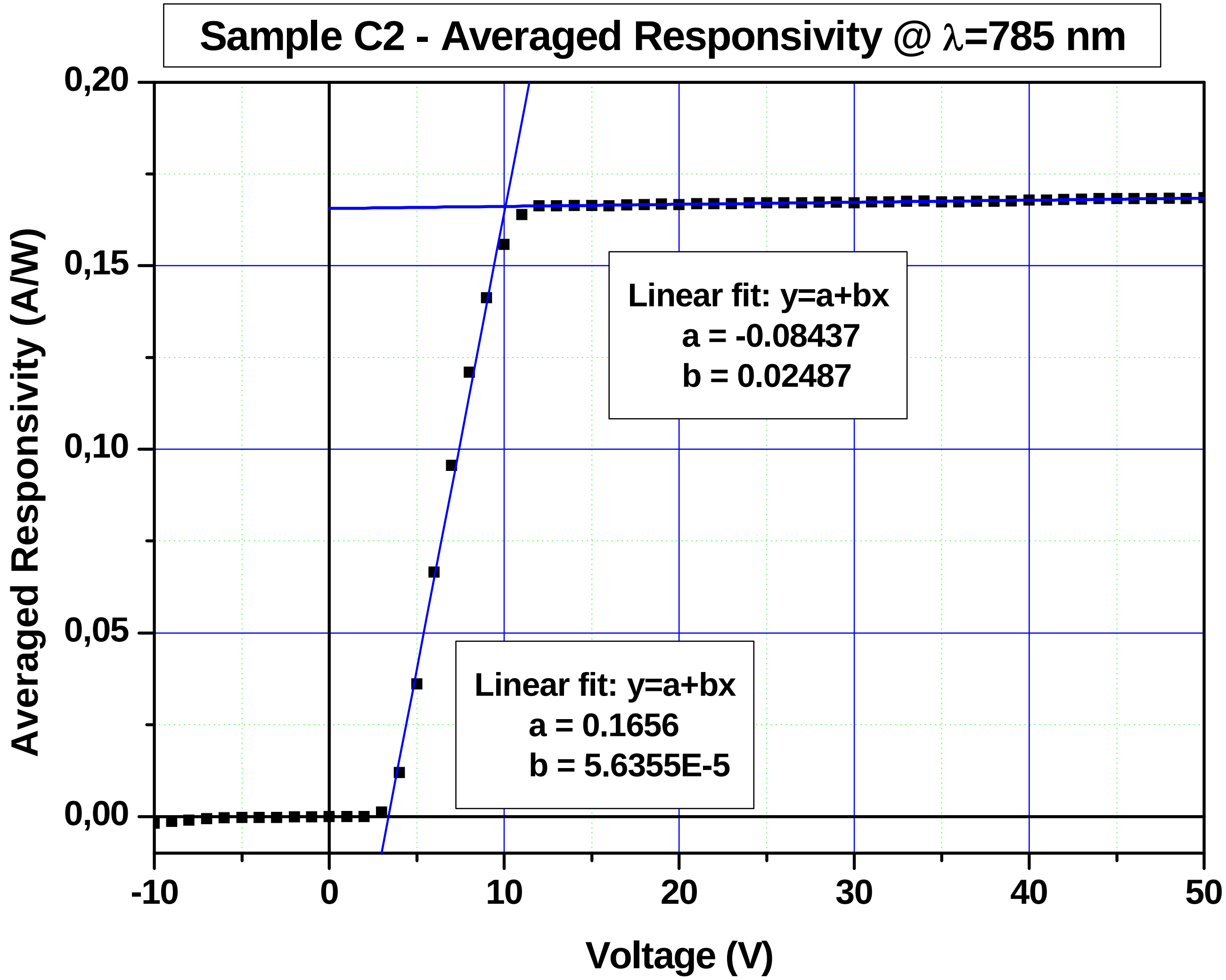
Uniformity on all the CNT surface

Breakdrown @ >100 V

Photocurrent Linearity

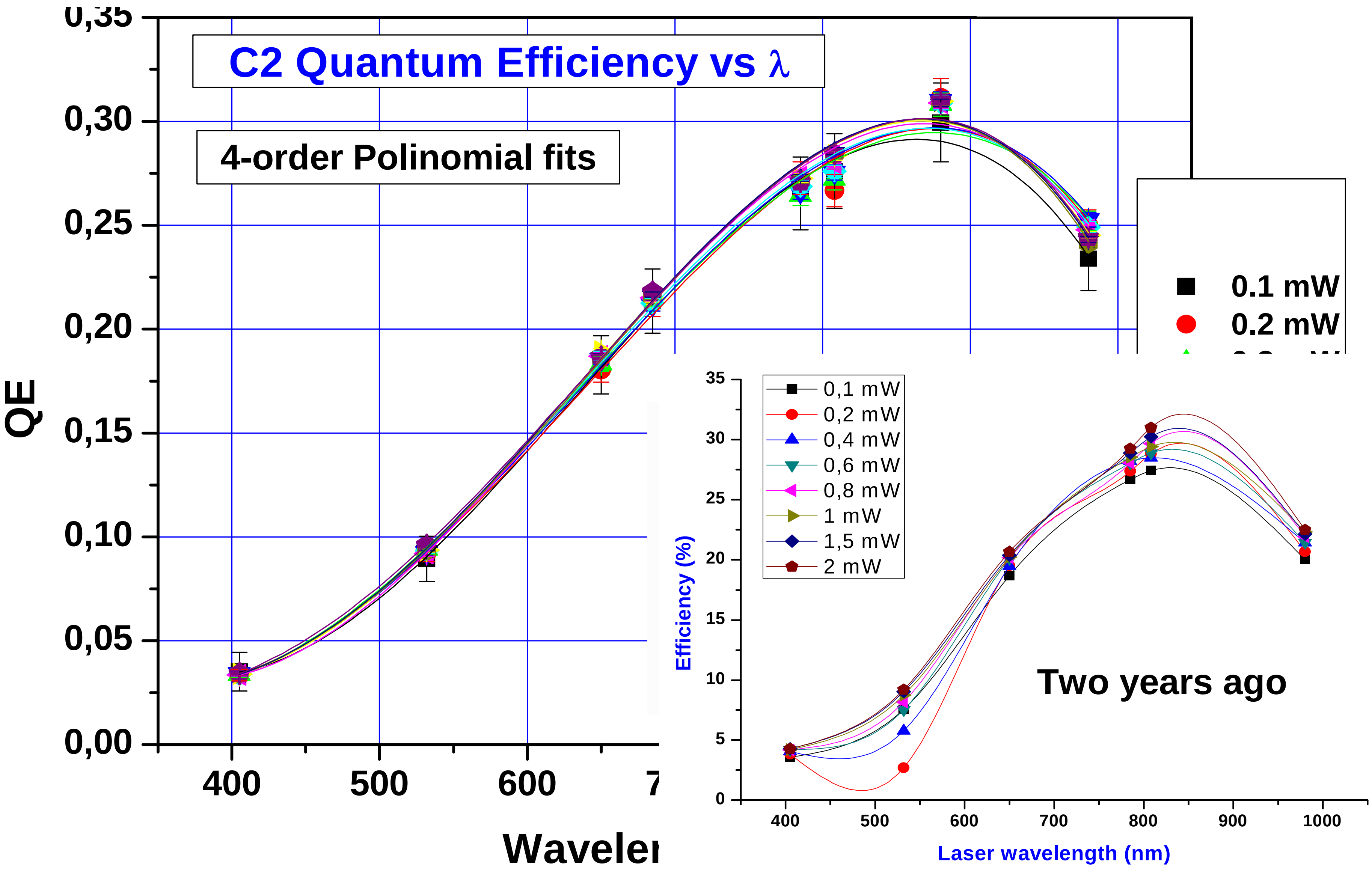


Responsivity

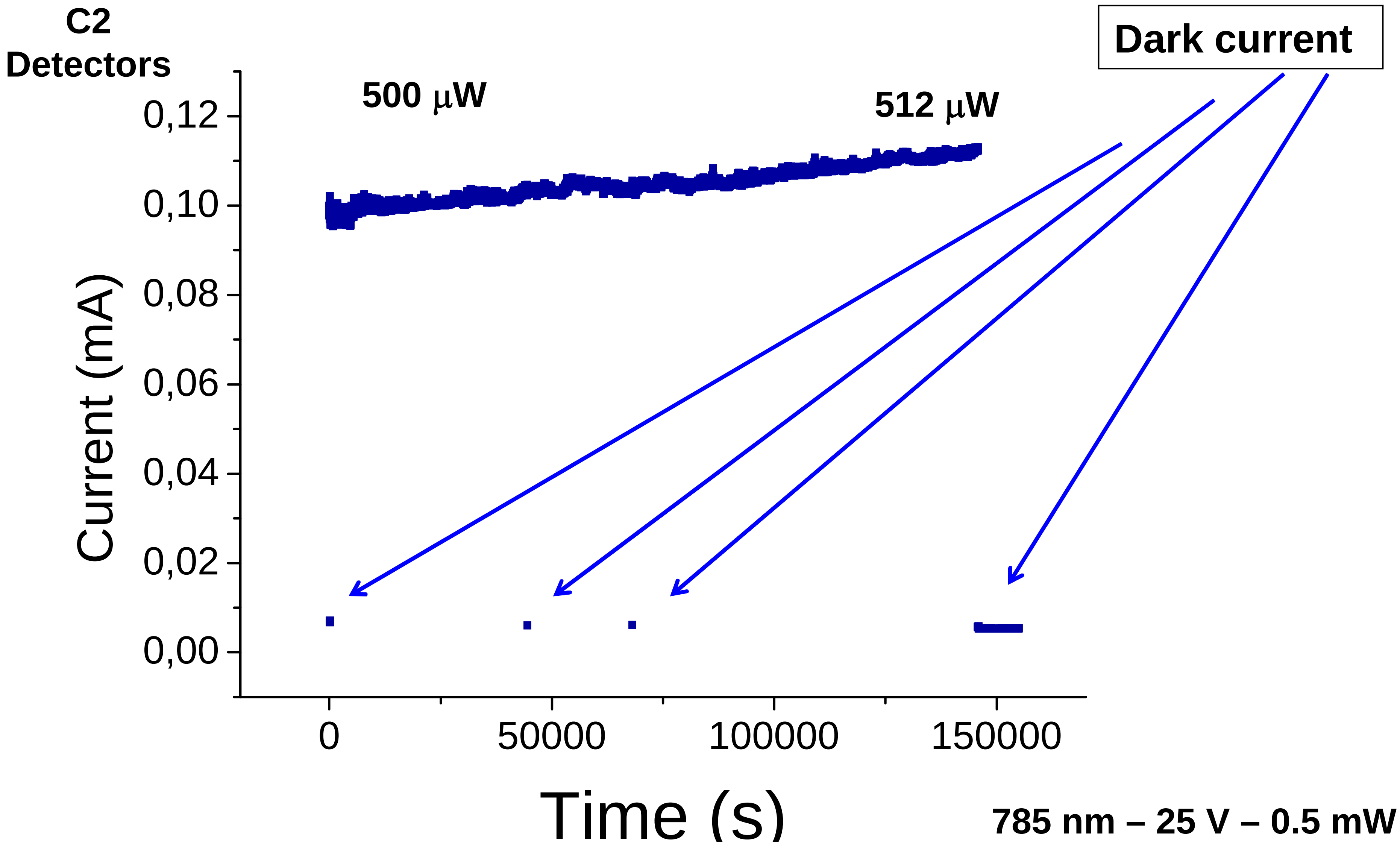


QE

$$\eta = \frac{I_{sat} hc}{eP\lambda}$$



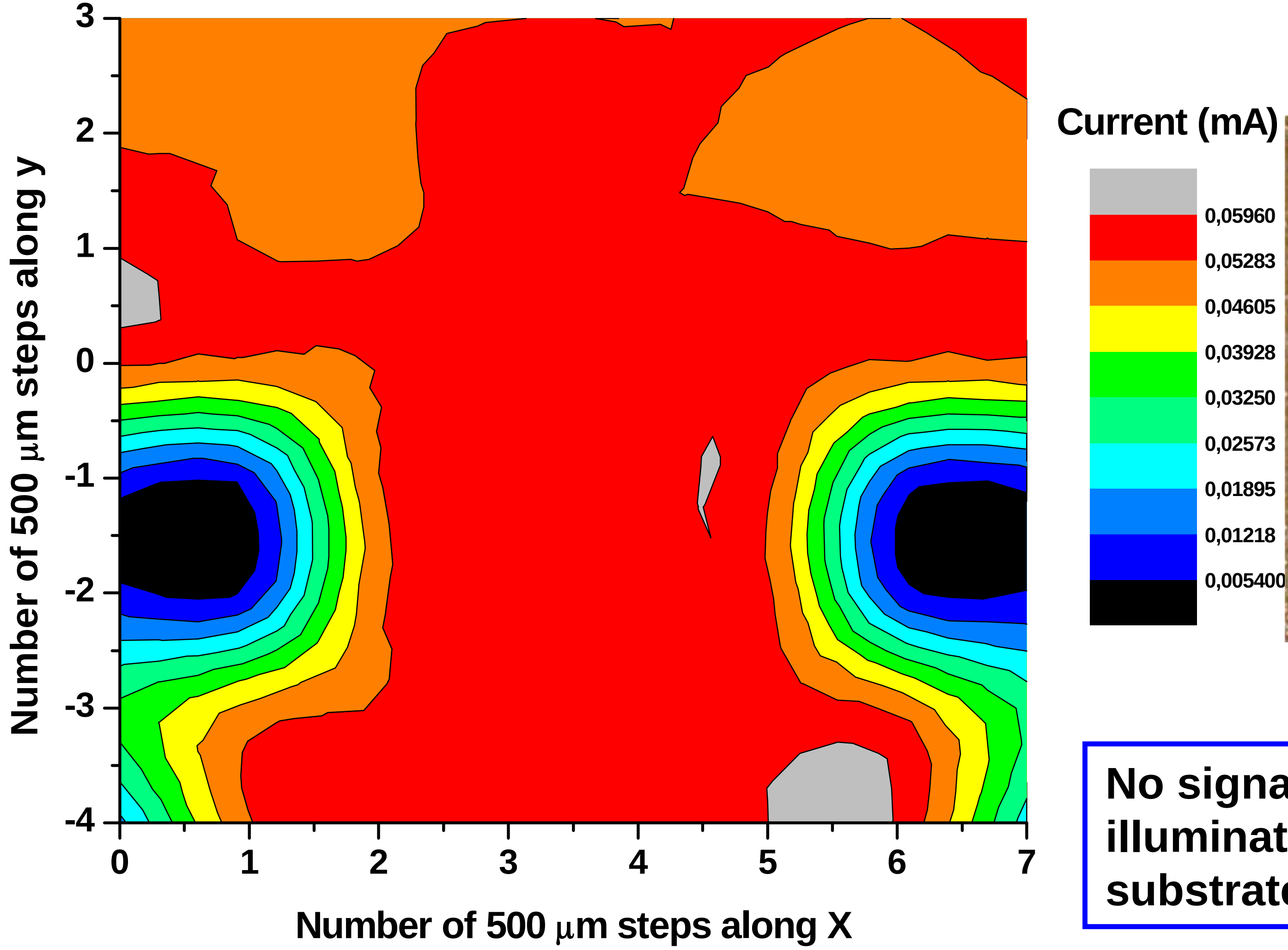
Long term stability – 40 hours

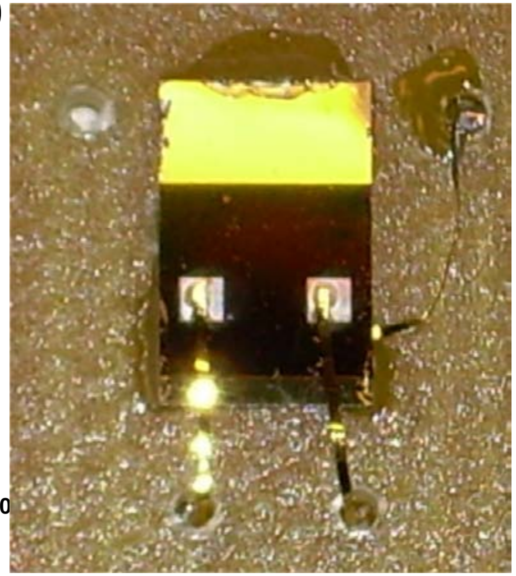


785 nm – 25 V – 0.5 mW

Photocathode uniformity

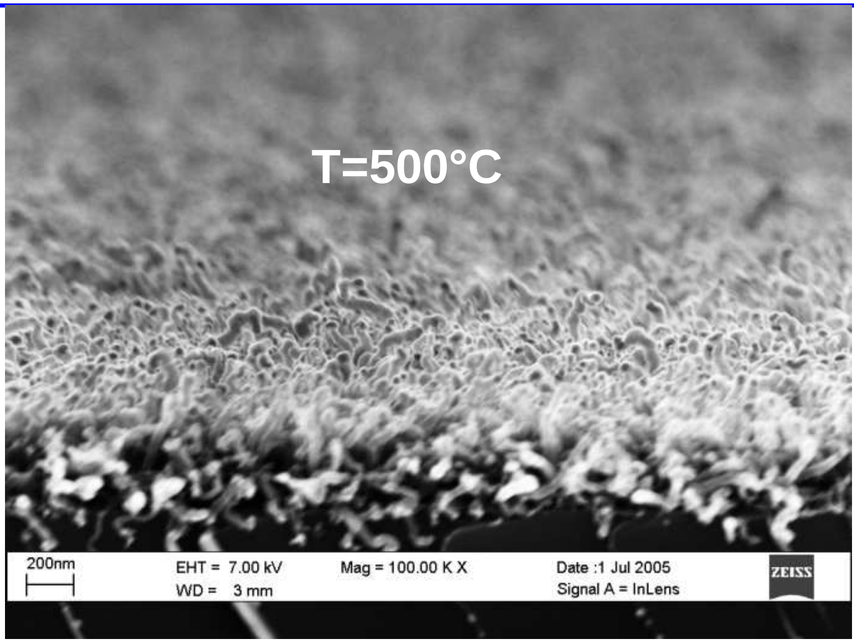
Sample C2 - Photocurrent map

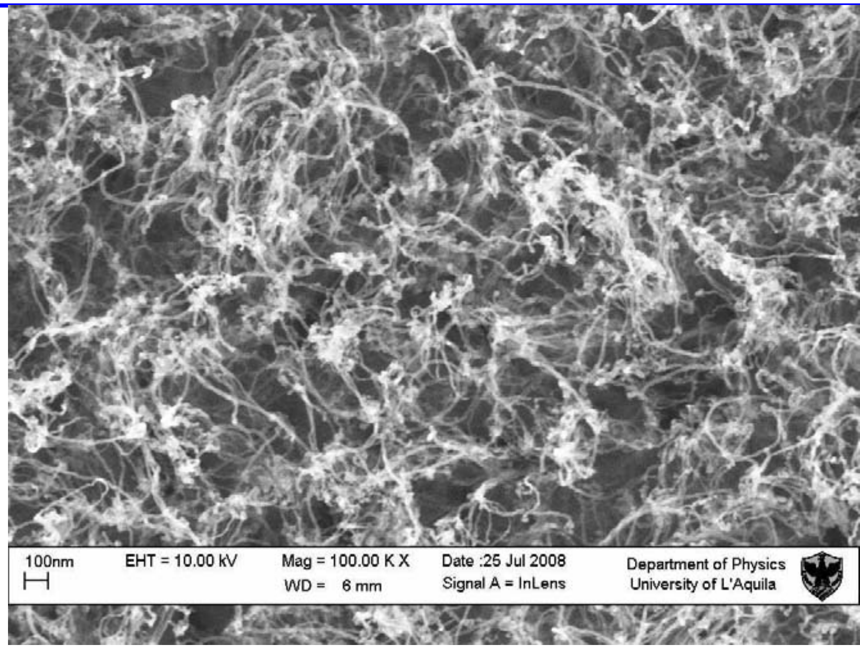


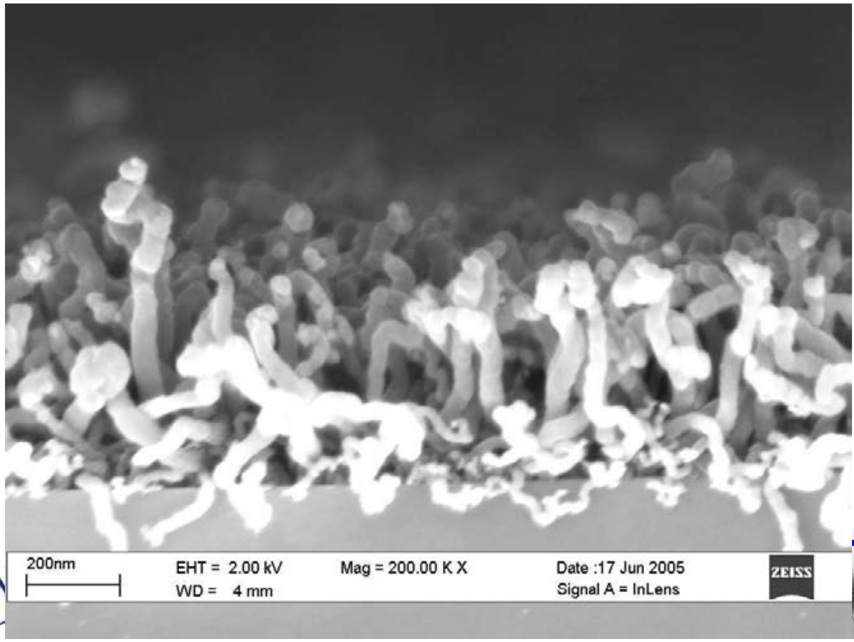


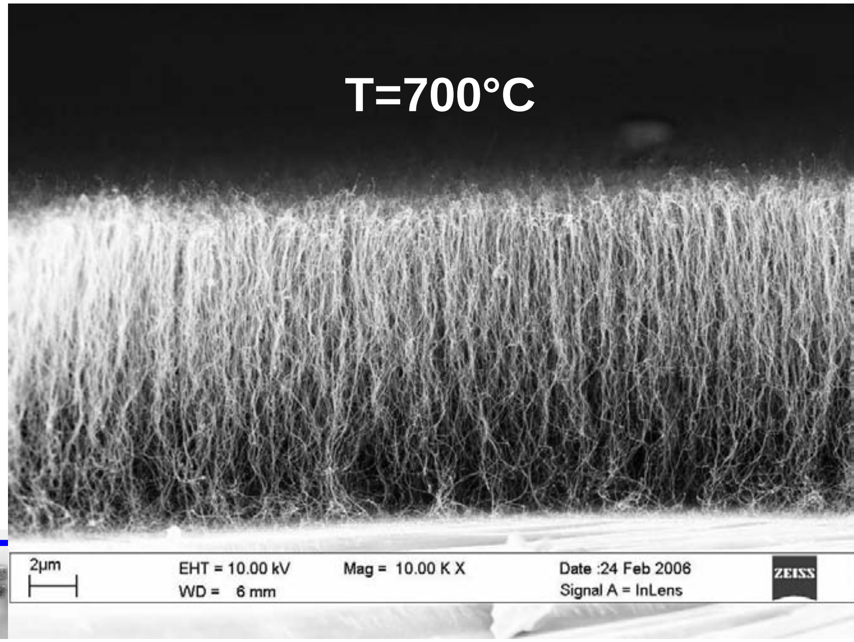
No signal appears illuminating the silicon substrate.

Comparison between CNT growth at 500 and 700 °C

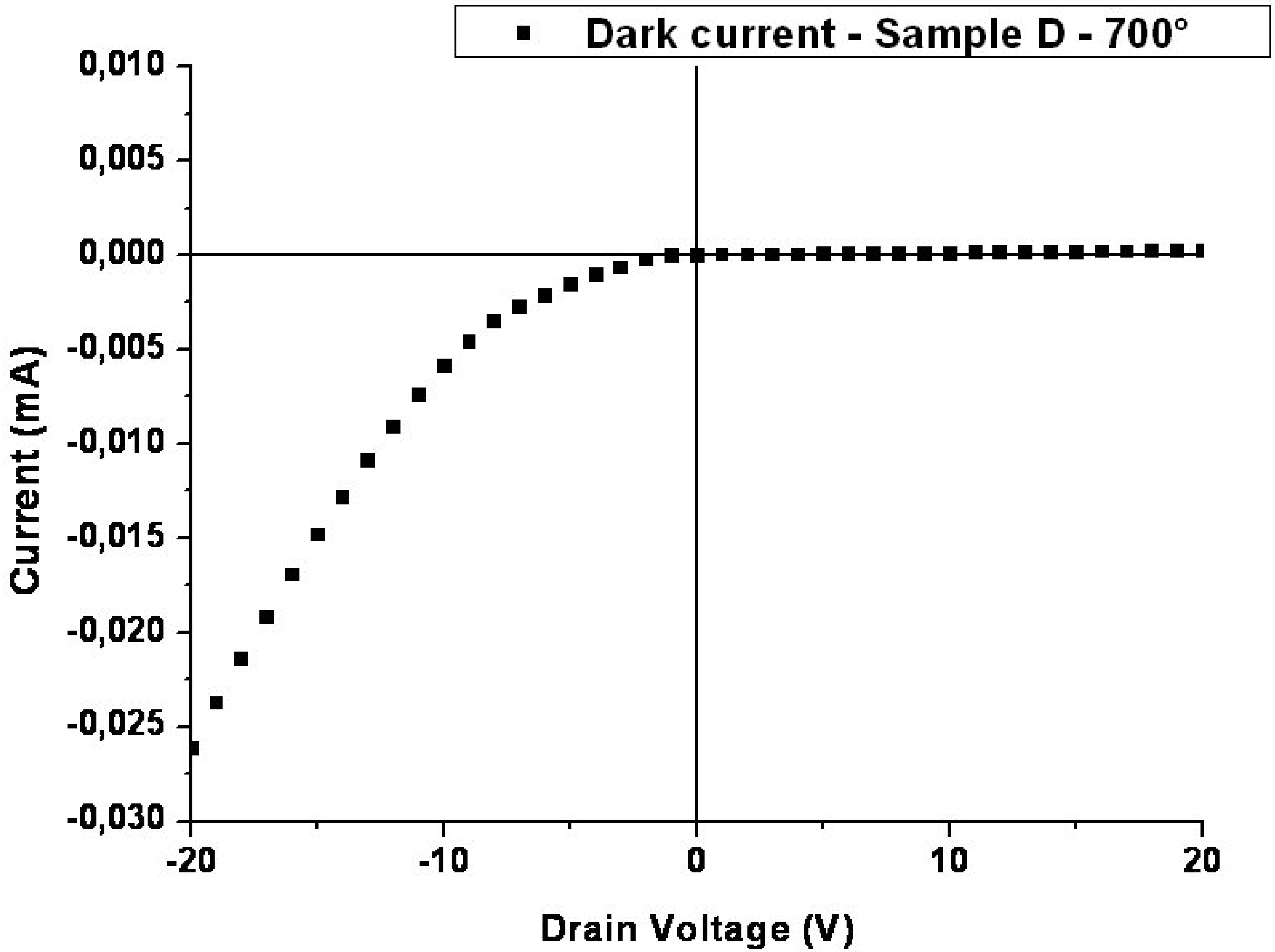




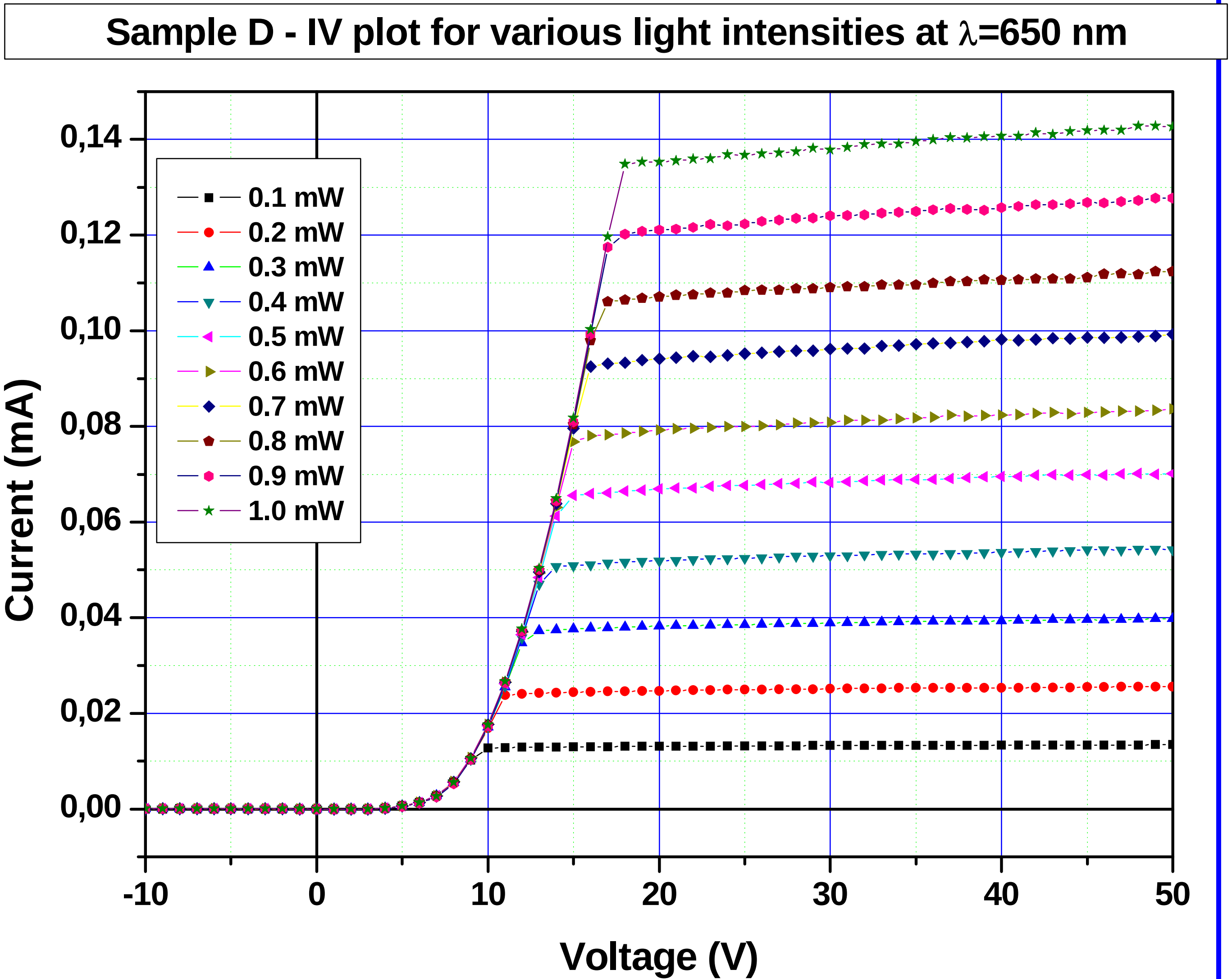




700 °C samples

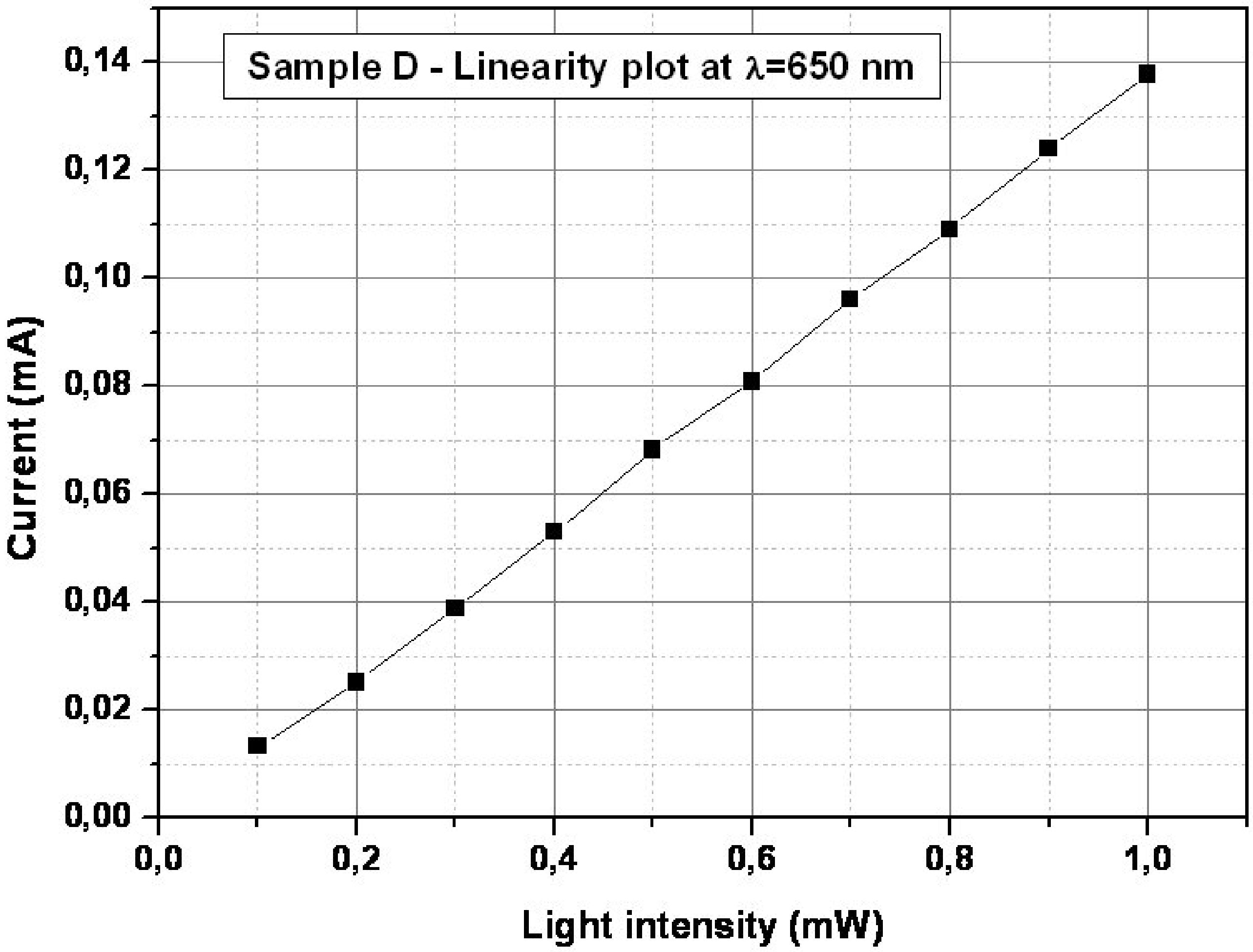


700 °C - D detector @ λ=650 nm

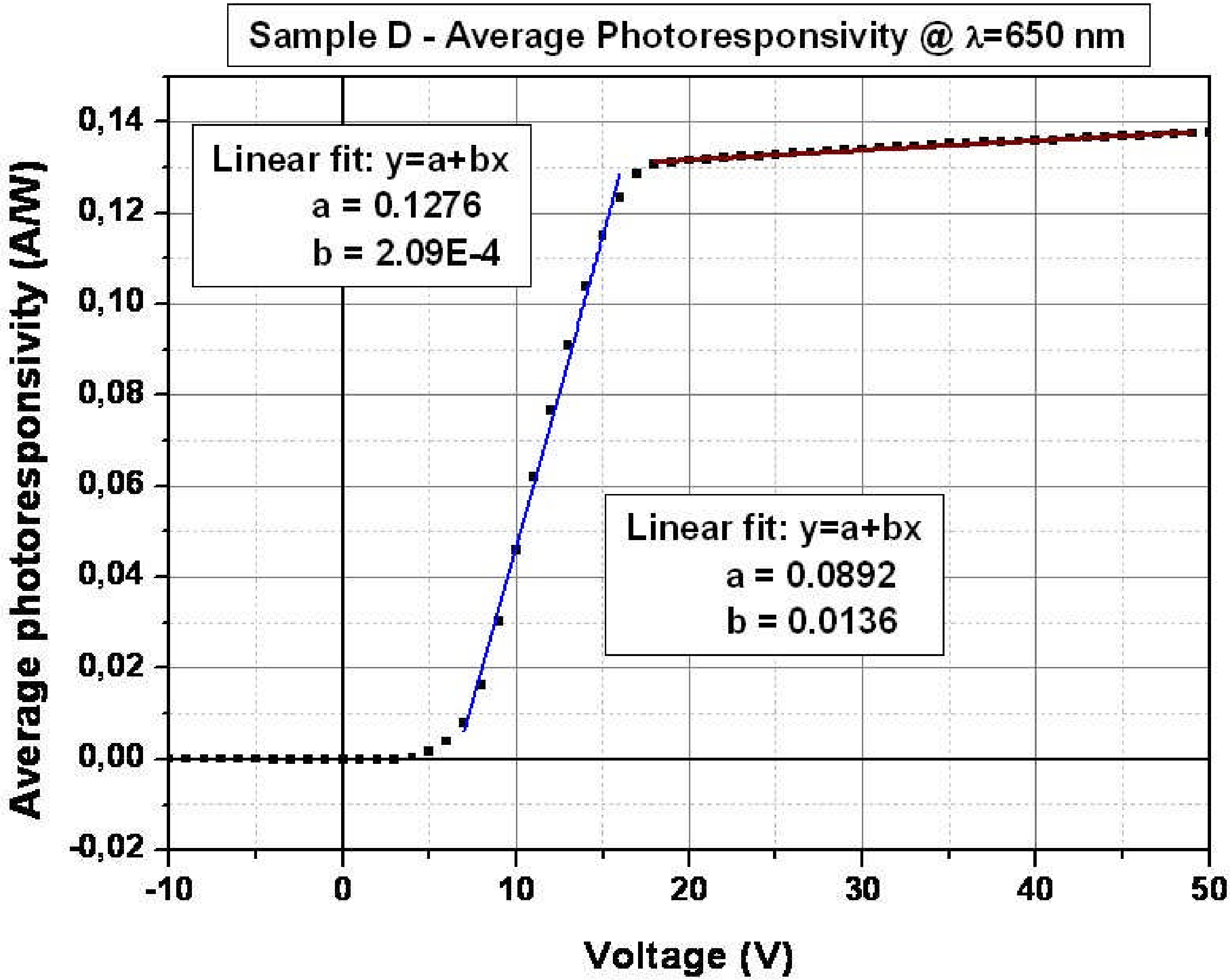


- Room temperature
- No electronics
- No signal amplification
- Long and stable plateau
- Linearity I vs W
- Threshold 3.55 V
- No saturation observed
- No aging in two years
- Uniformity on all the CNT surface
- Breakdrown @ >100 V

Photocurrent Linearity

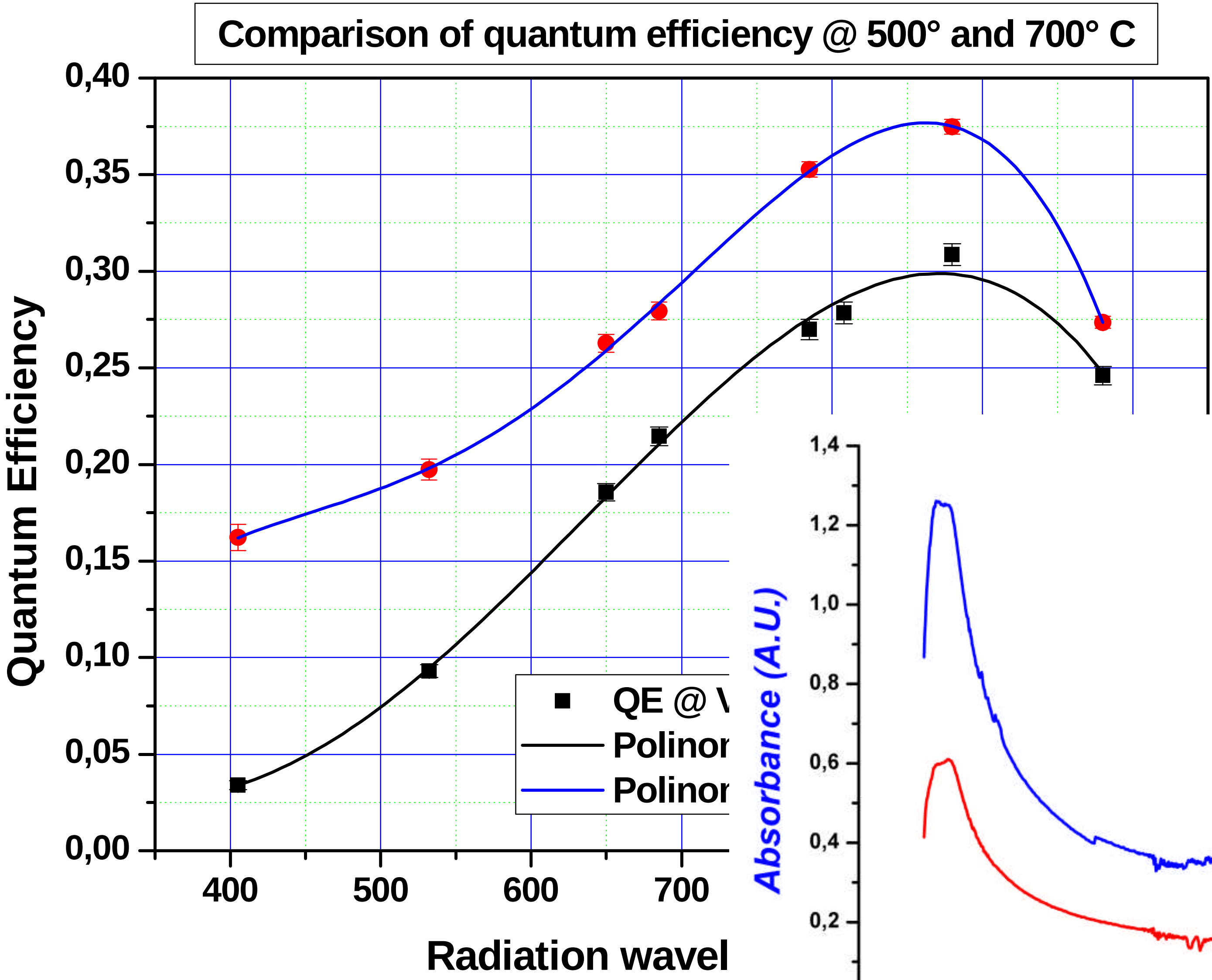


Responsivity



QE

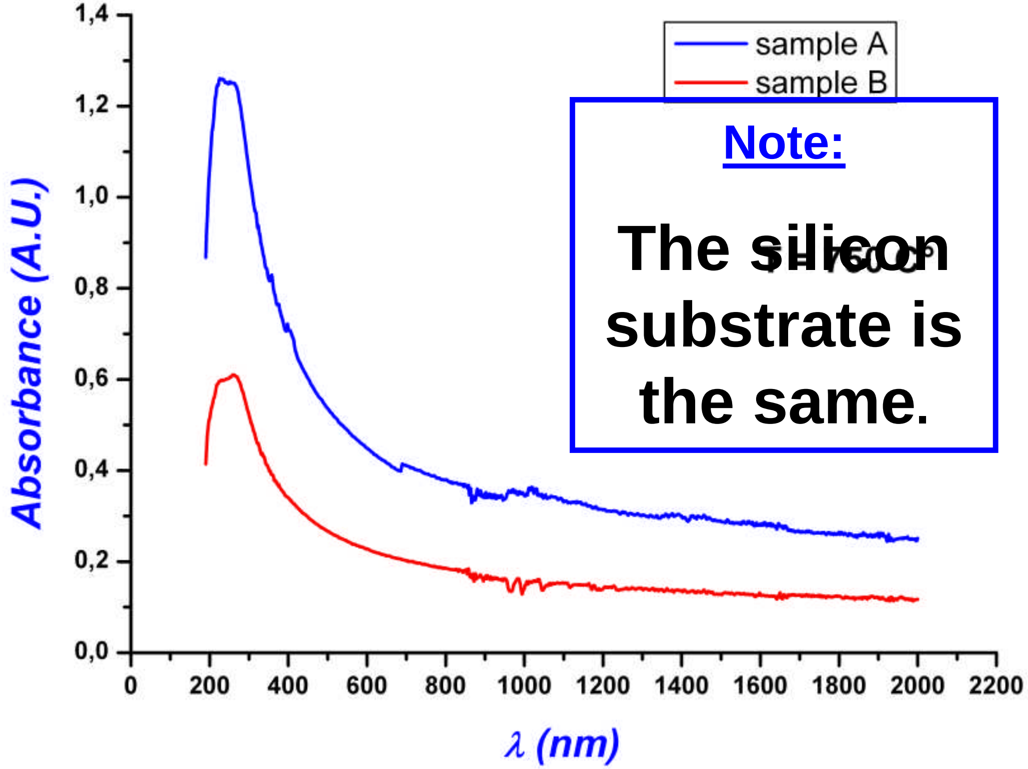
$$\eta = \frac{I_{sat} hc}{eP\lambda}$$



Higher T

⇩

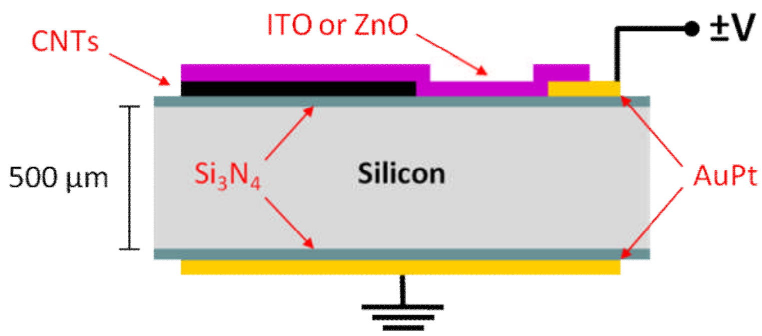
Higher UV photosensitivity

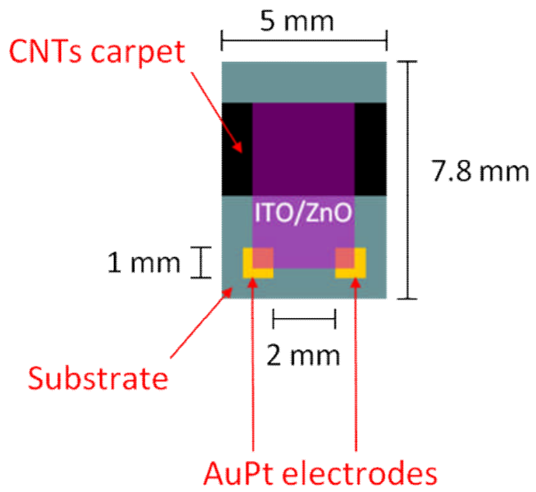


Note:

The silicon substrate is the same.

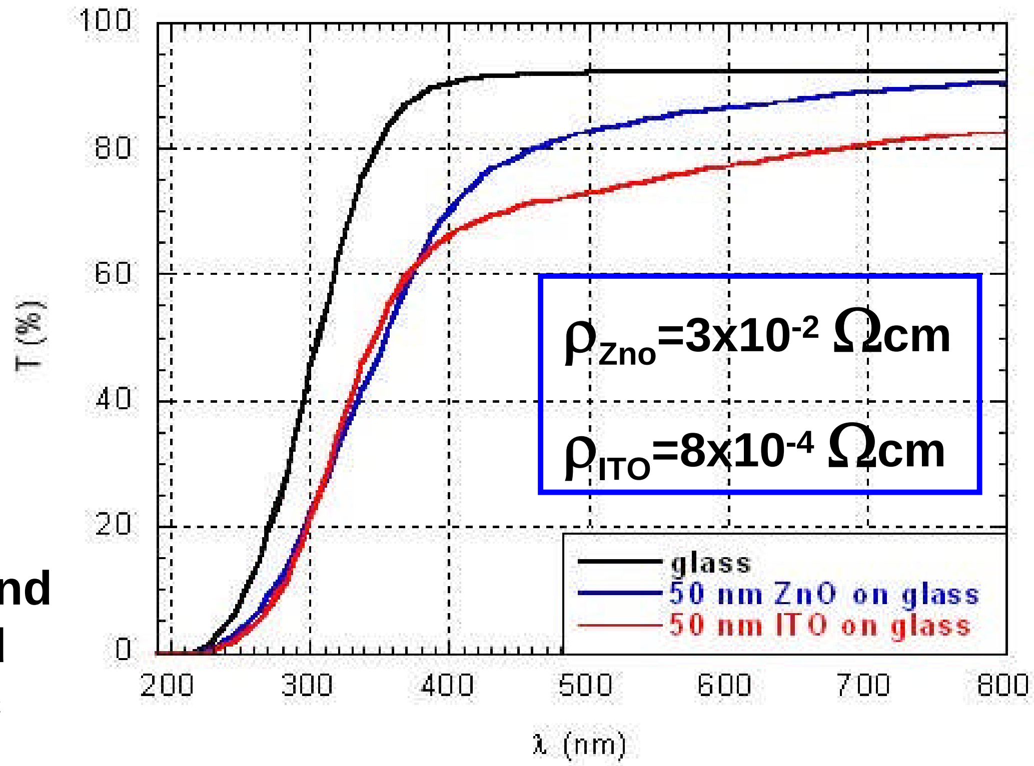
Coating - Sample IBS0955 @ 500°





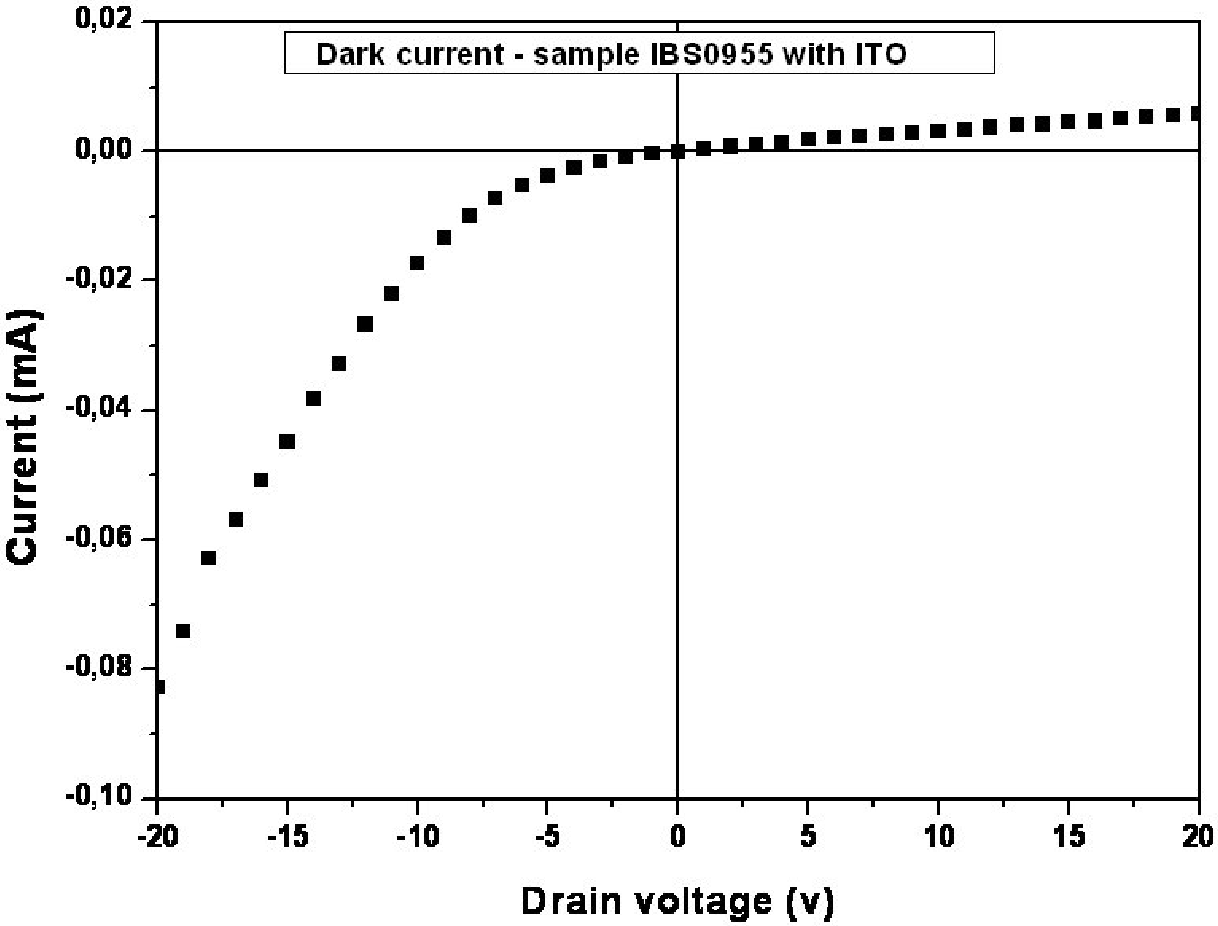
(a)

In order to obtain a CNTs coating, a thin film of a transparent conductive oxide (TCO), namely indium tin oxide (ITO) or zinc oxide (ZnO), is sputtered on the CNTs network so to partially cover the Au/Pt pads.



Optical properties of TCO films and their electrical resistivity ensured the formation of near ideal ohmic contact.

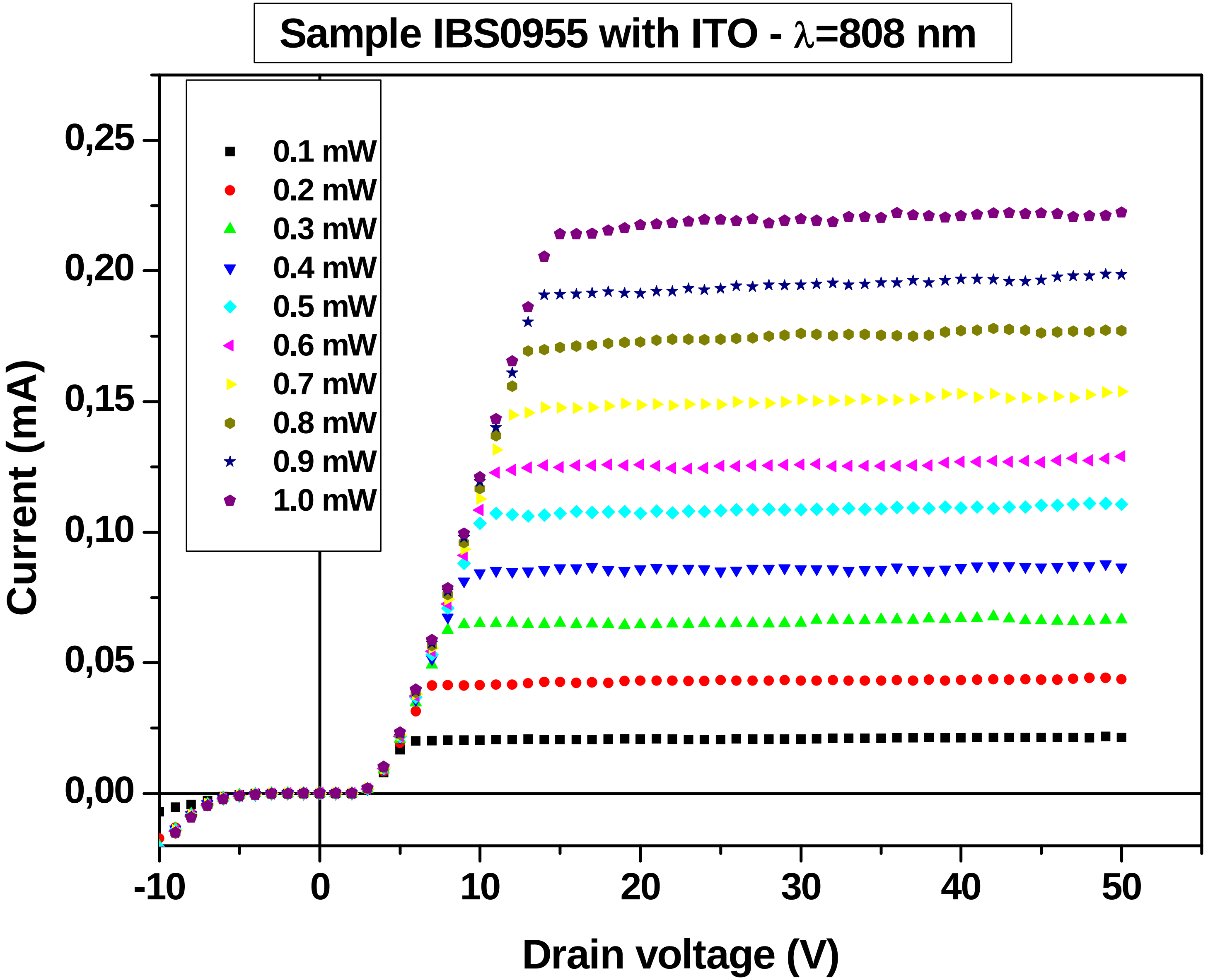
Sample IBS0955 – Dark Current



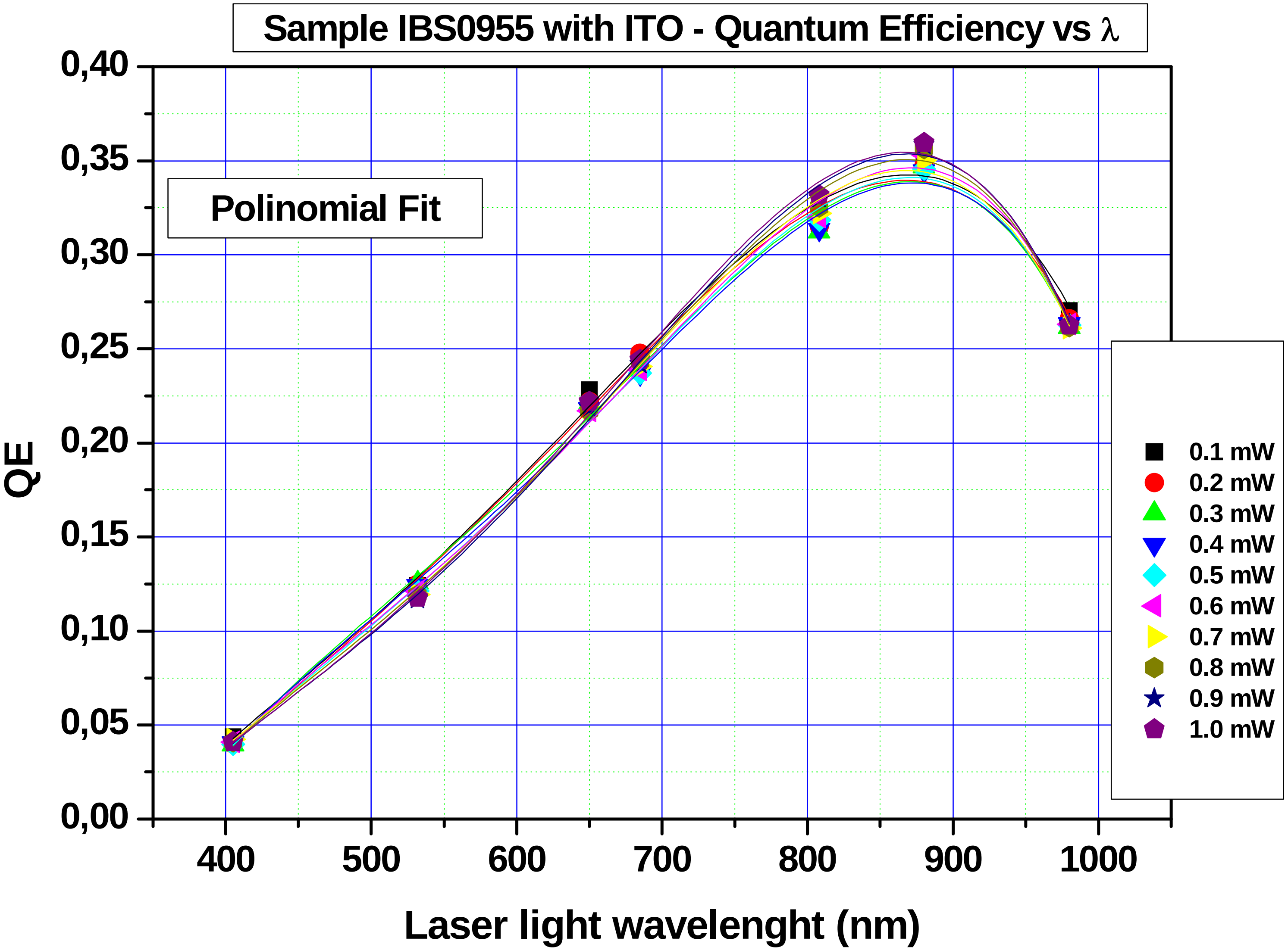
The rectifying behavior of CNT-Si heterojunction is clearly visible.

(Shottky + hetero)

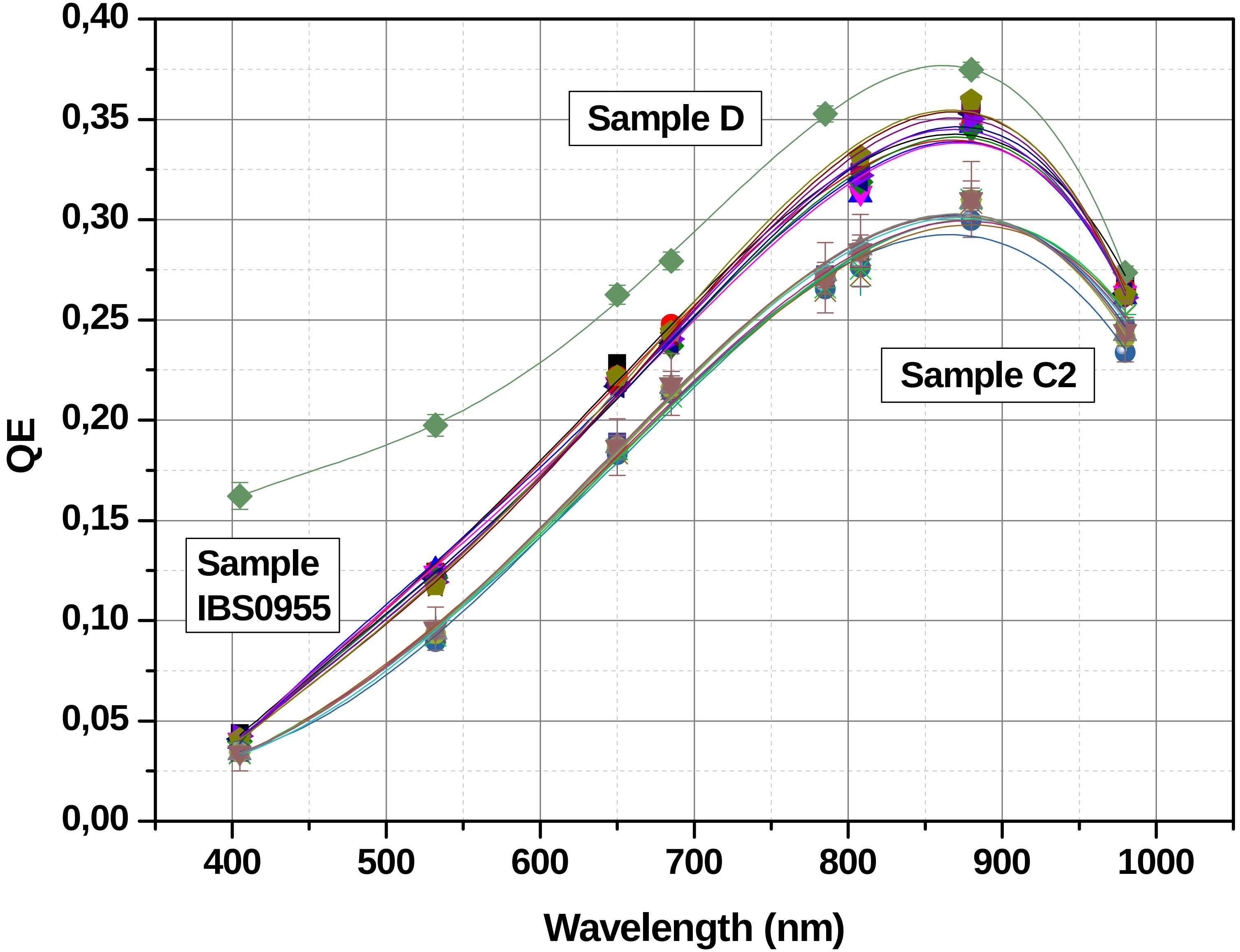
Sample ITO photocurrent

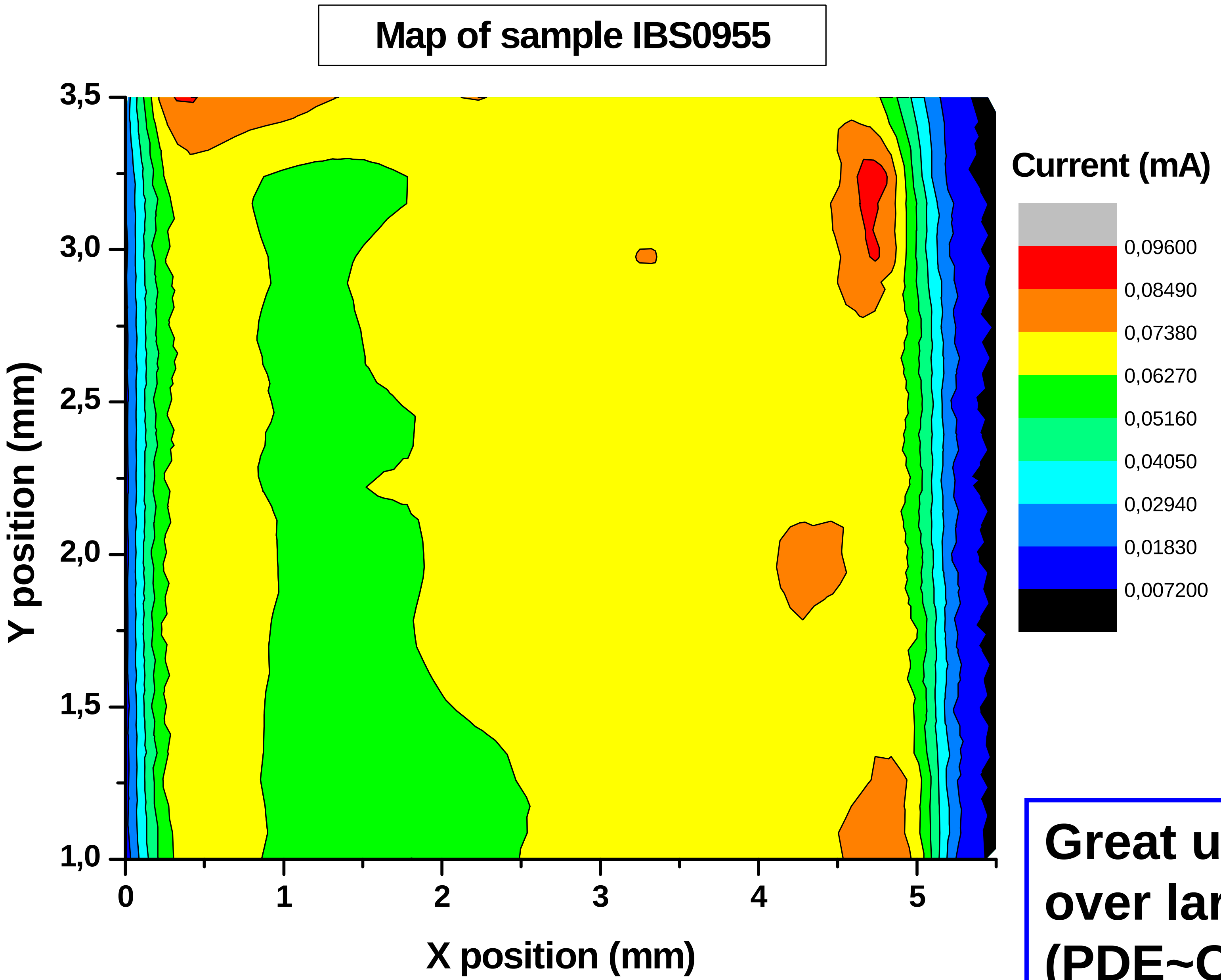


Sample ITO - QE



QE comparison for samples C2_500°, D_700° and IBS0955_500°





Great uniformity over large area (PDE~QE)

Summary of measurements

A novel photon detector made of Silicon and CNT has been realized .

The main characteristics of this detector are:

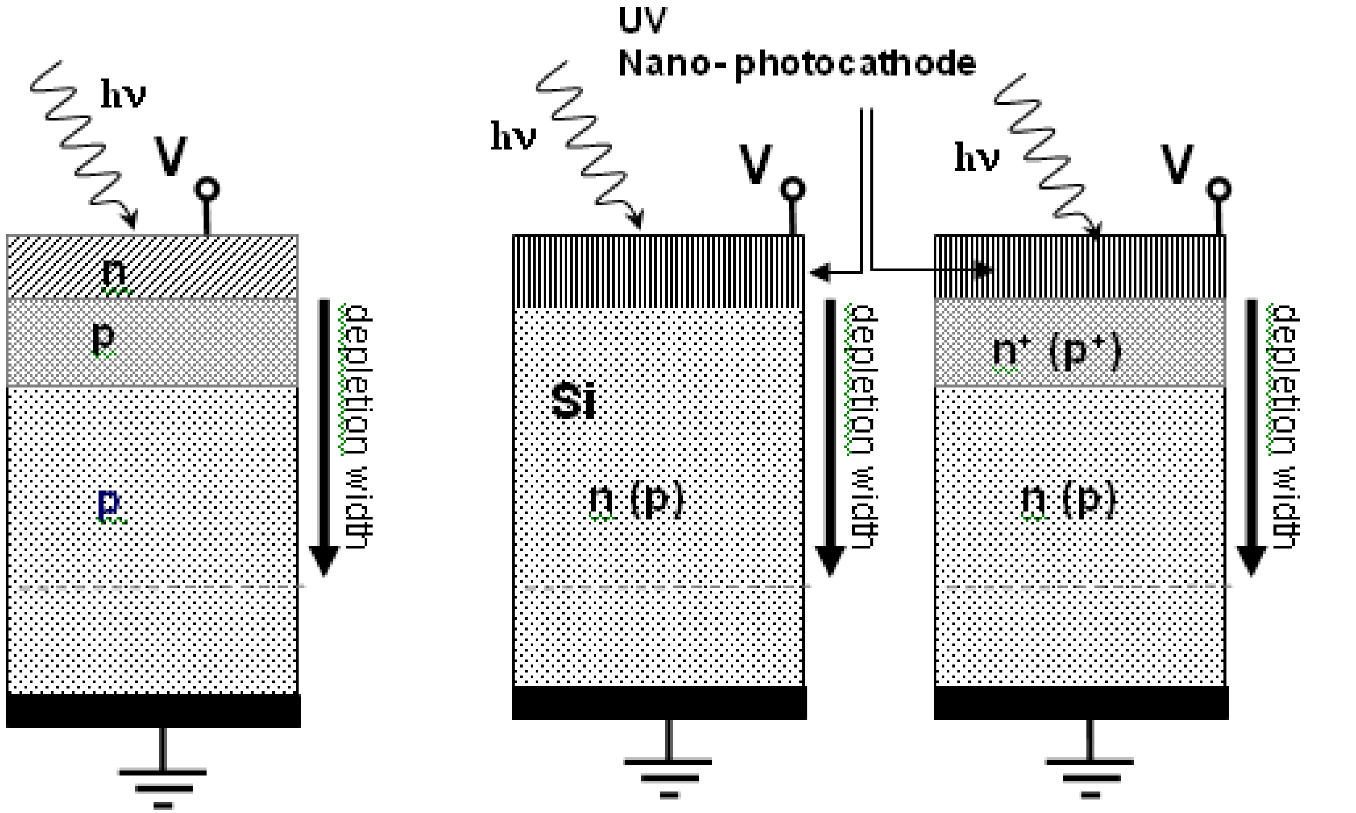
- Low cost and large area / Photocathode's area can be increased up to m^2
- Low threshold / Low dark current
- Large and stable plateau region / High linearity
- Stable at room temperature and for high intensity current
- Aging verifyed over two years of operations
- High QE depending from light wavelength and from CVD temperature

Coating of CNTs surface has been obtained with a conductive layer of ITO, making the detector usable as light sensor.

OUTLOOK

Collaboration with FBK-IRST is in progress to obtain amplifying Silicon substrates structured as SiPM. The final purpose is to realize a highly pixelled single photon detector sensitive from UV to near IR.

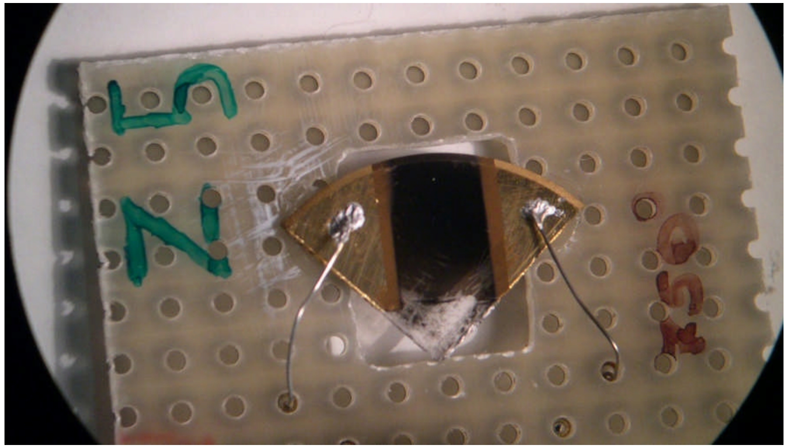
A possible final layout:
Si-CNT single photon detector



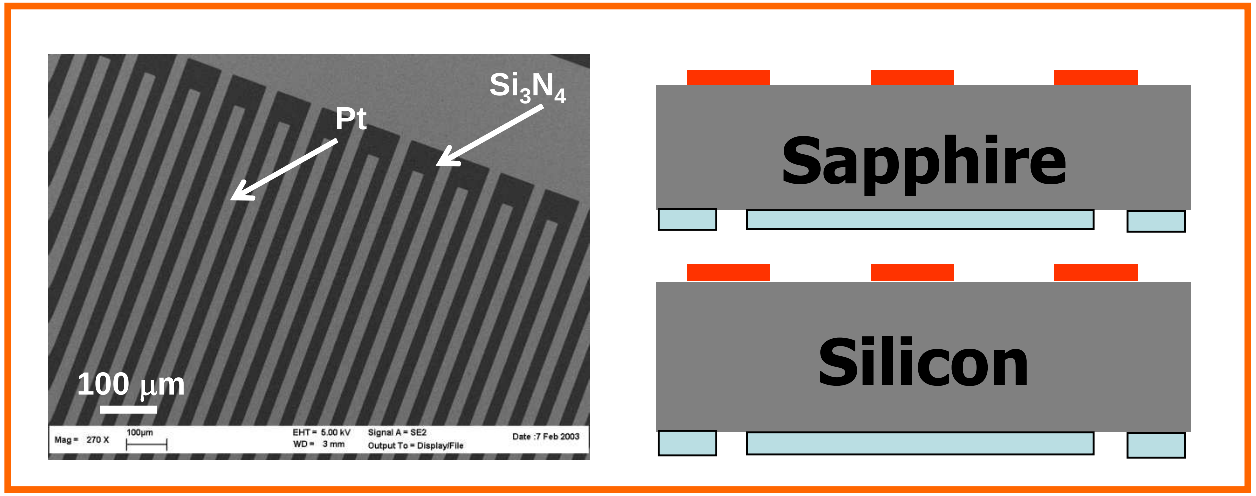
a) 2009- Silicon photomultiplier
(Principle structure)

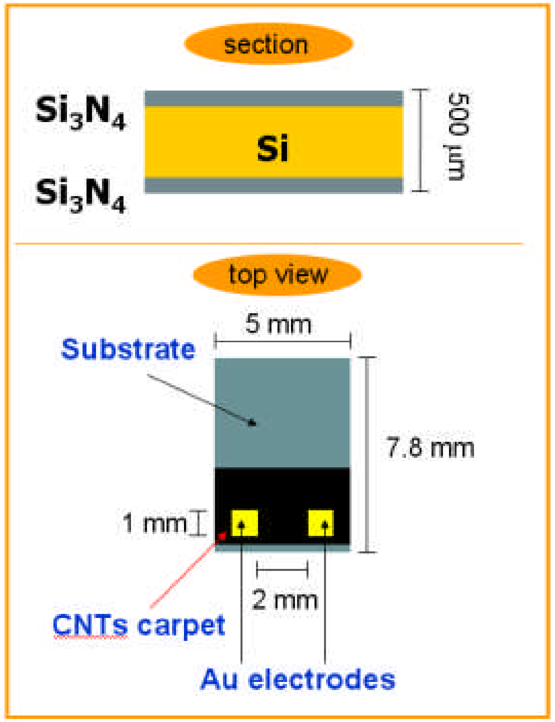
b) Nano-Silicon diode
(base structure for study)

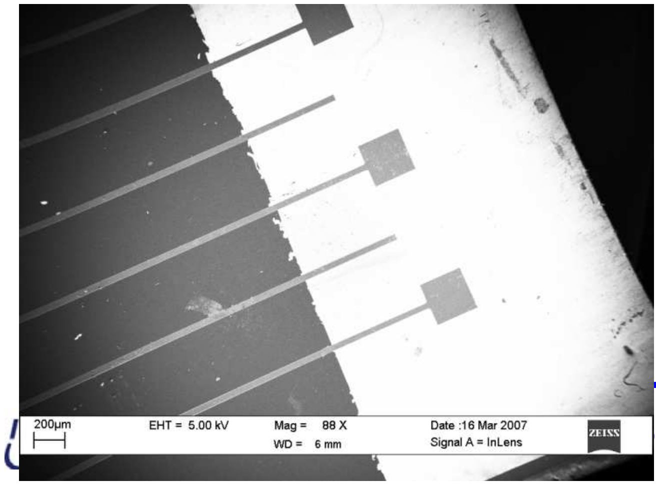
c) N-SiPM → 201(1?)
(final structure – main objective)

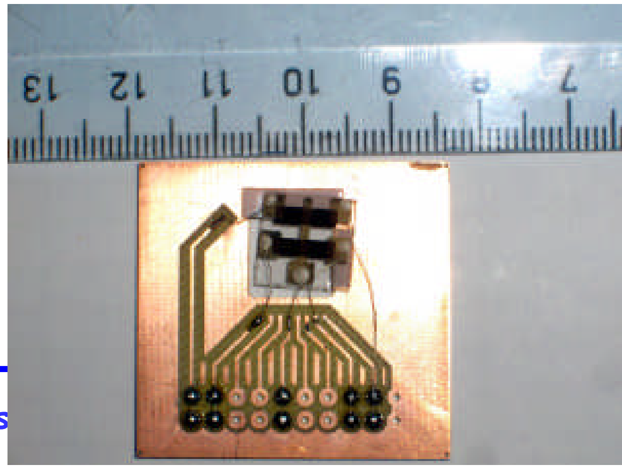


GINT
(Gruppo INFN per le NanoTecnologie)



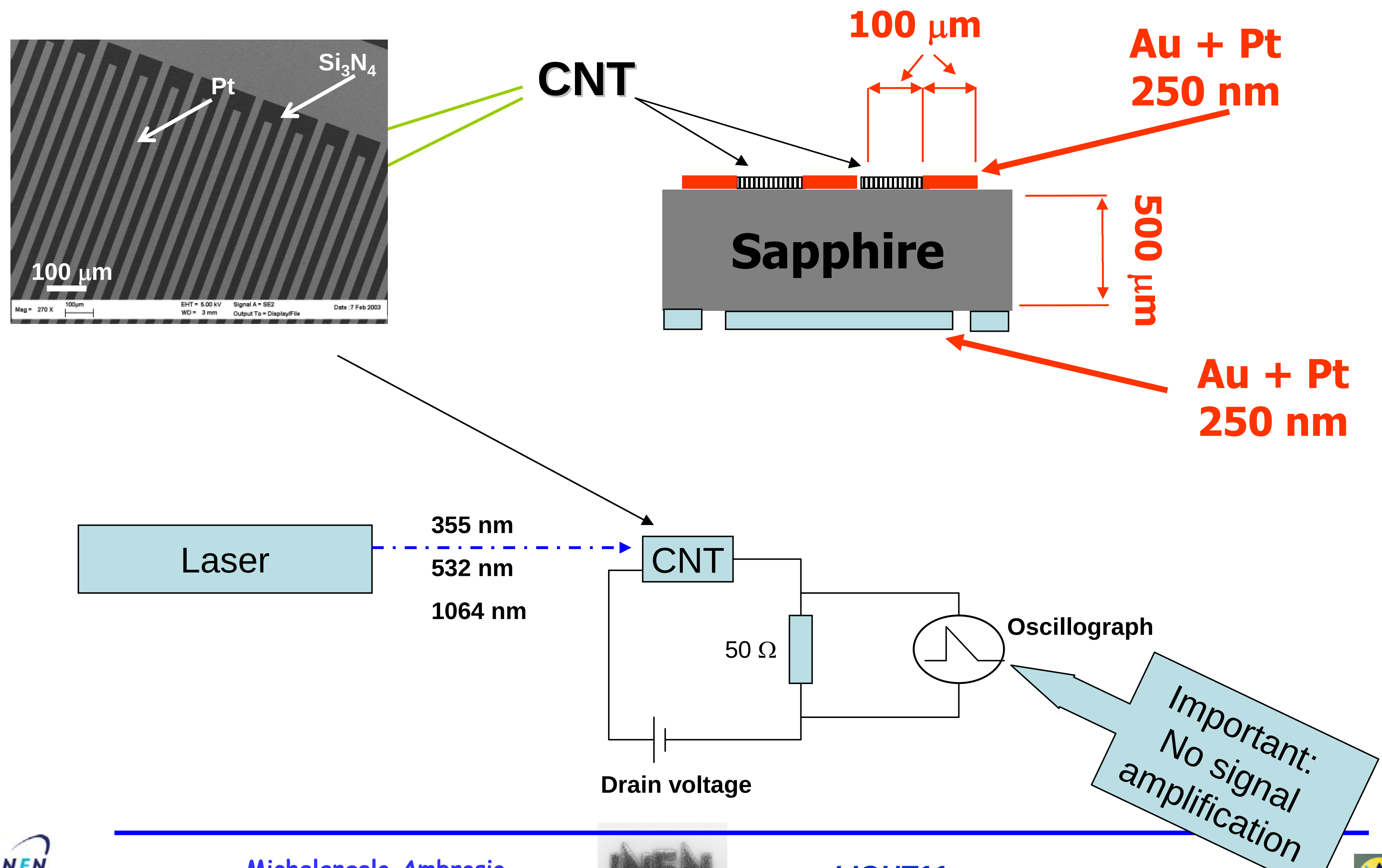




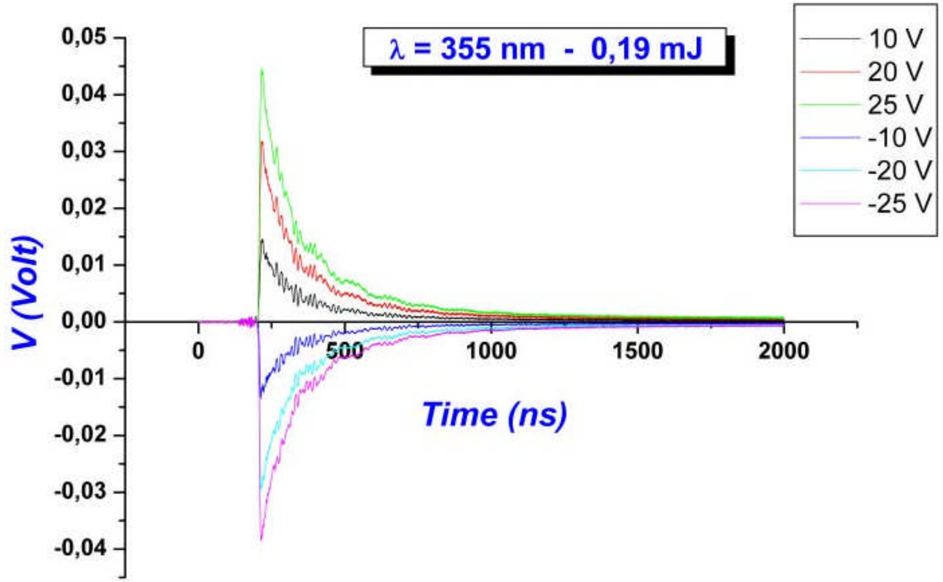


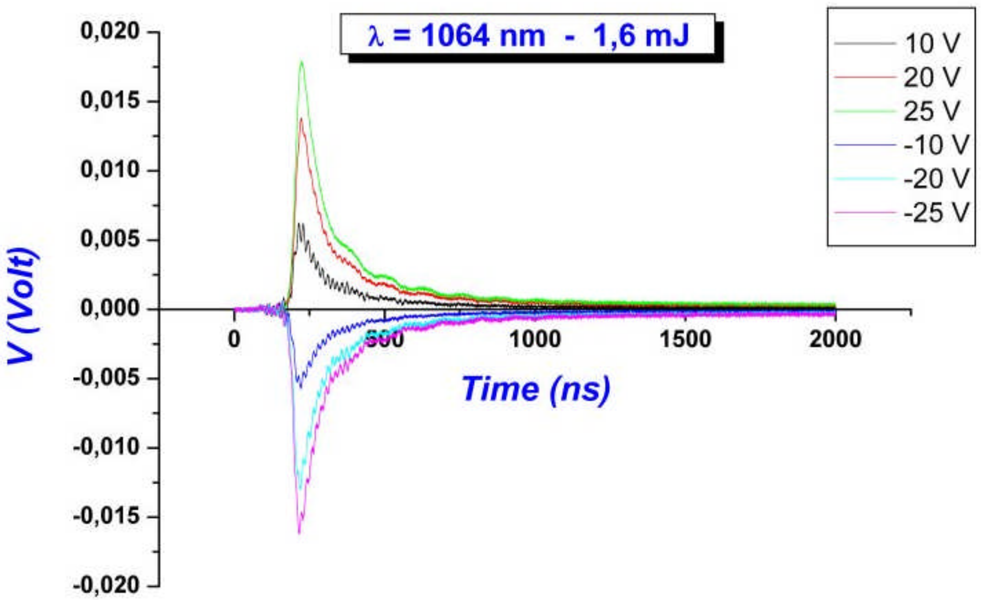
Various kind of substrates

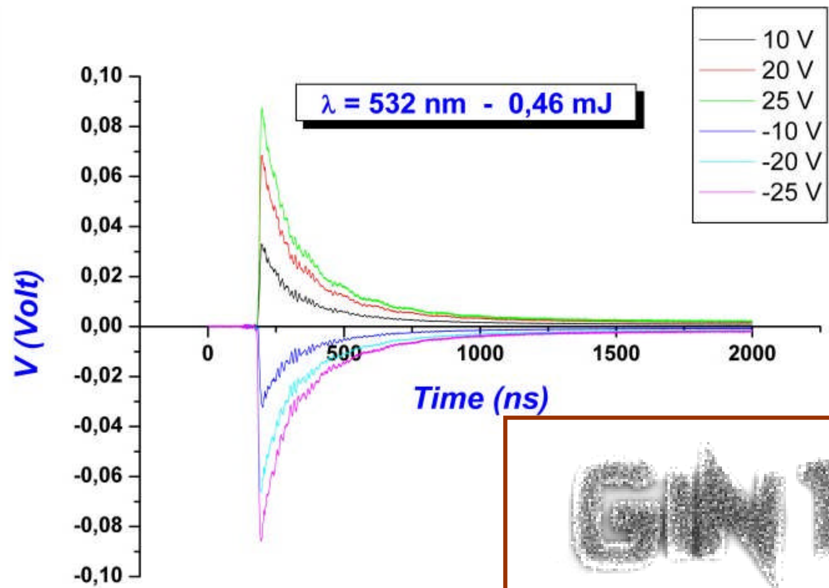
Sapphire prototype detector



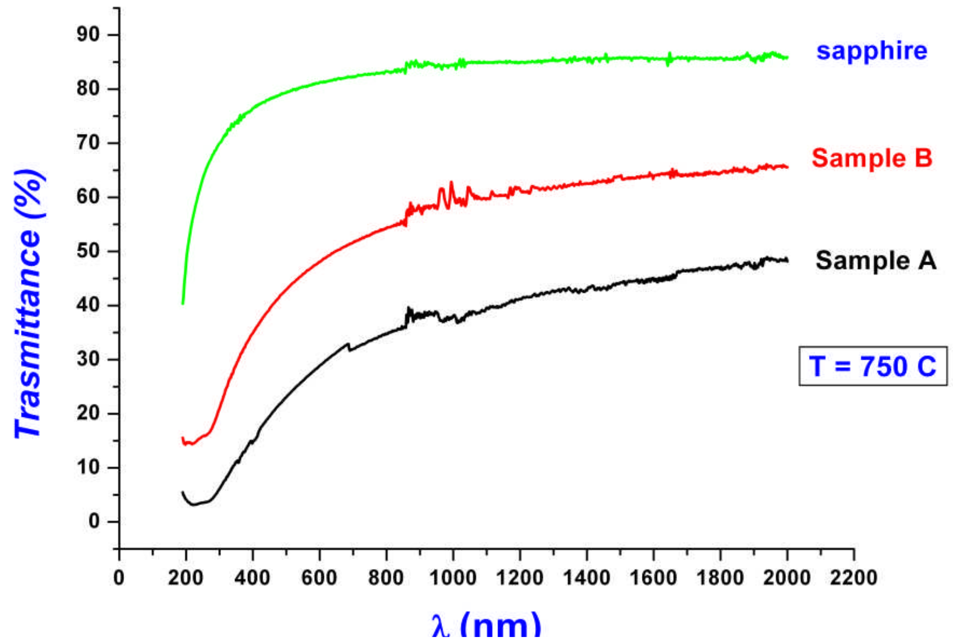
Signals detected with the first carbon nanotube radiation detector

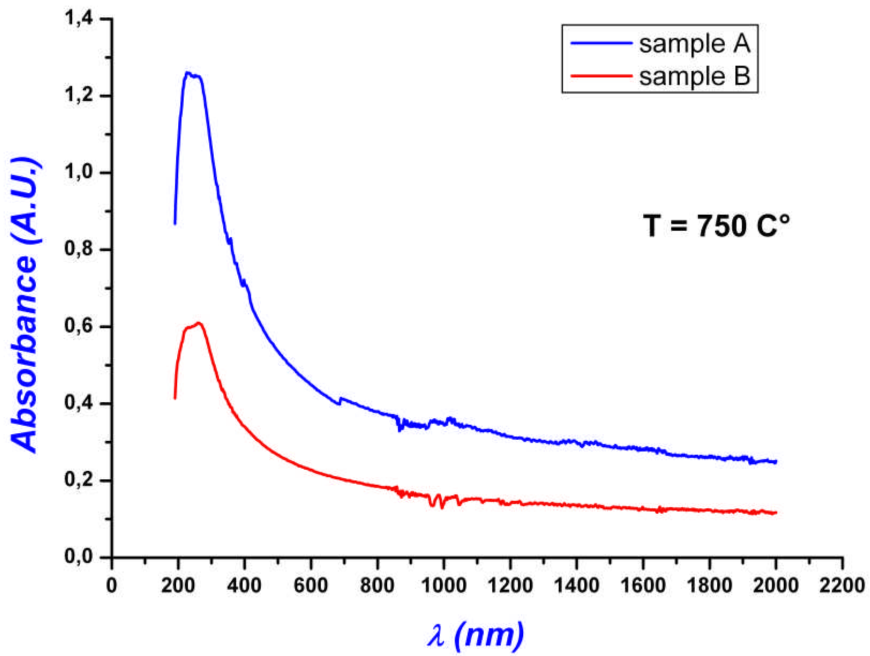




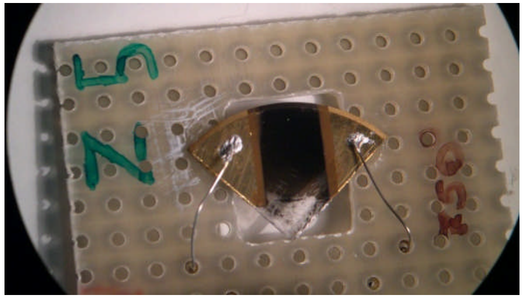


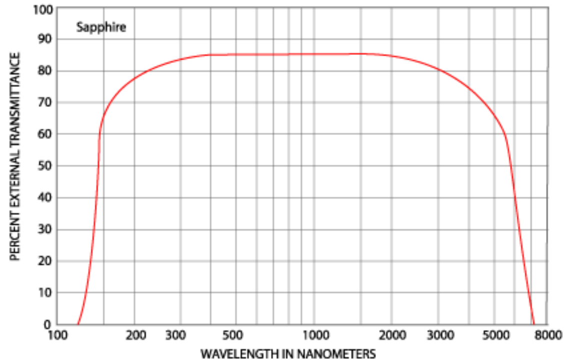
A. Ambrosio et al: ***"A prototype of a Carbon Nanotube microstrip radiation detector"***, **Nuclear Instruments and Methods in Physics Research A 589 (2008) 398–403**





GINT
(Gruppo INFN per le NanoTecnologie)





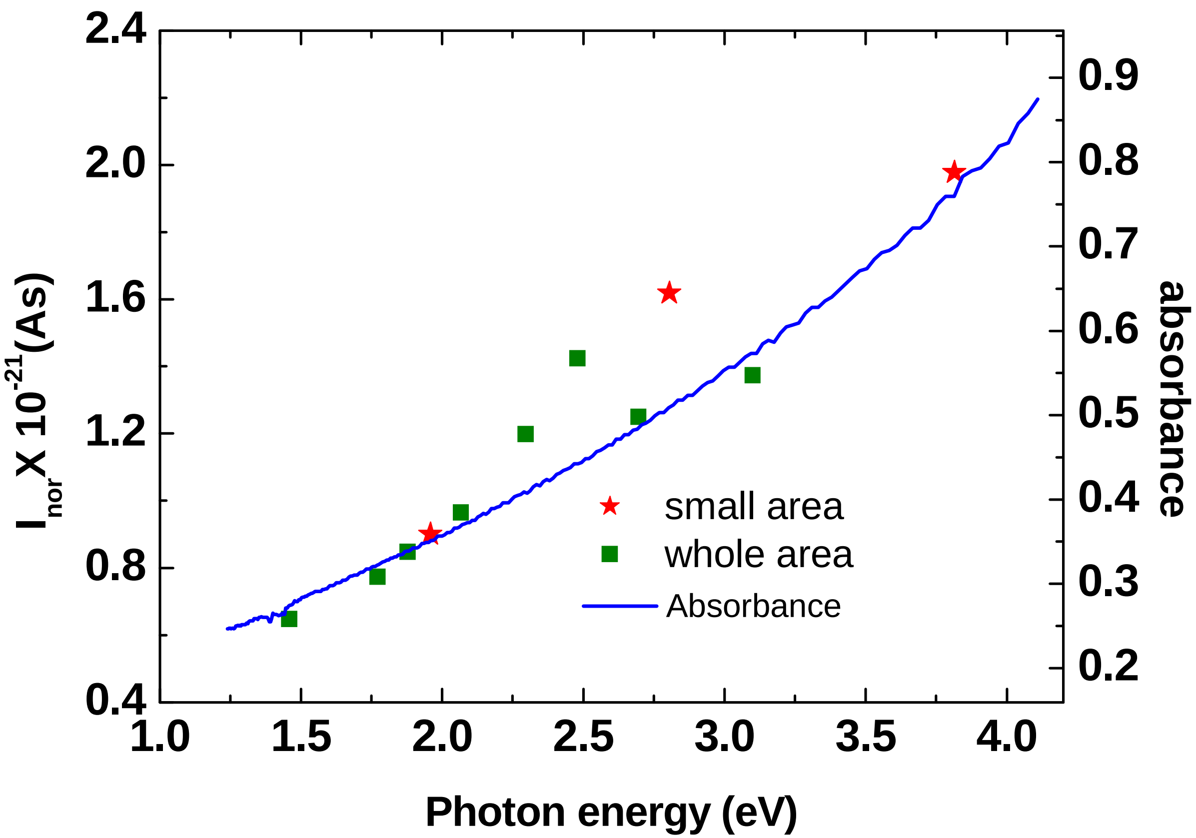
CNT absorbance

(log_{10} 1/T)

Photocurrent vs λ

GINT

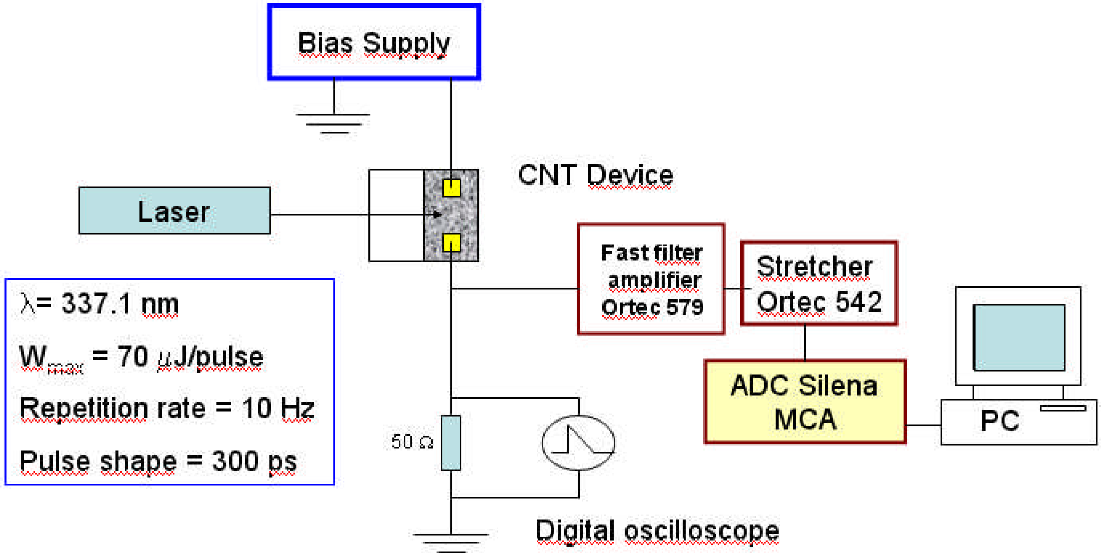
(Gruppo INFN per le NanoTecnologie)

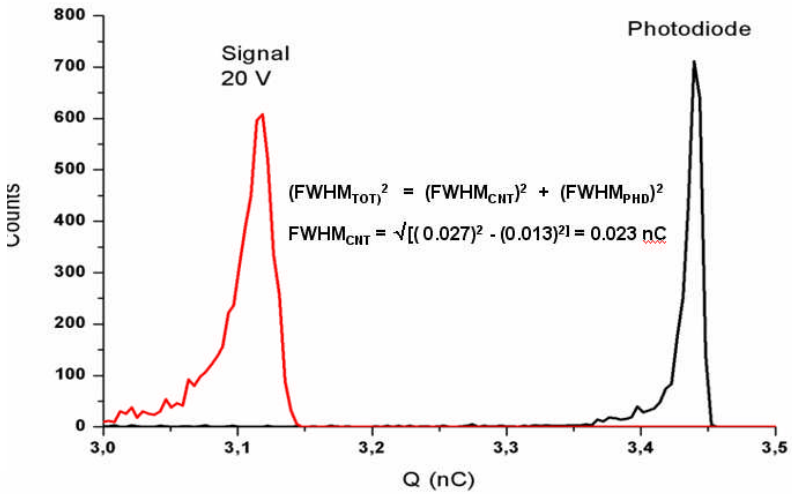


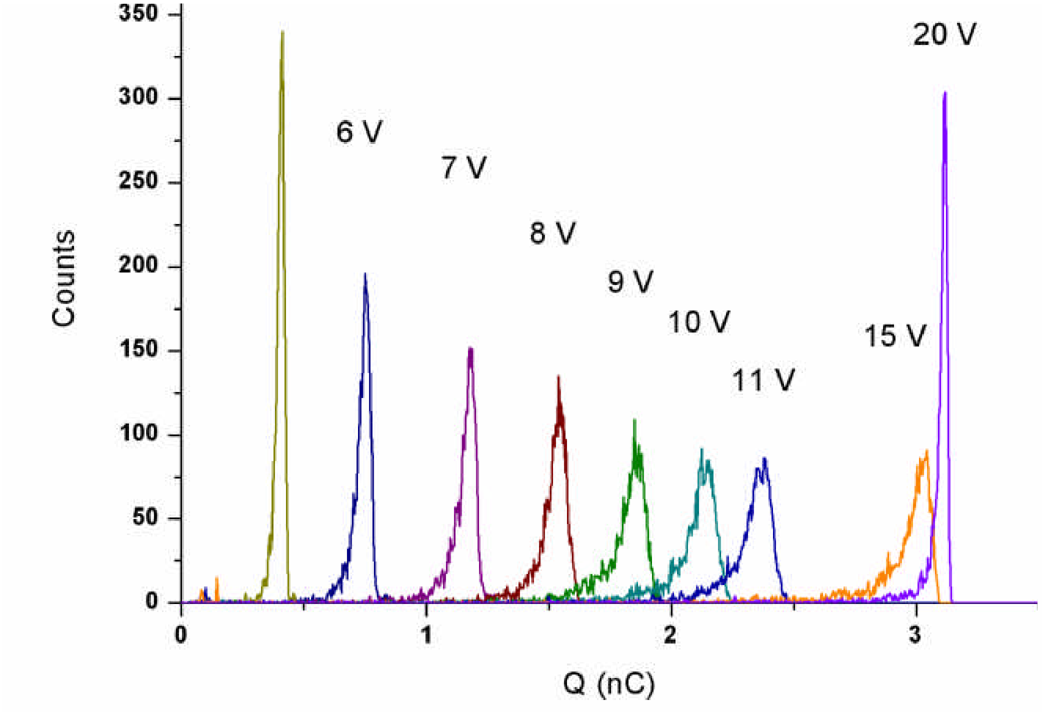
Photocurrent normalized to the number of photons I_{nor} vs photon energy, obtained illuminating the whole surface of a MWCNT sample with filtered light (■) as well as small part of the surface with laser spots (*). Continuous line indicates the absorbance spectrum of the same MWCNT sample

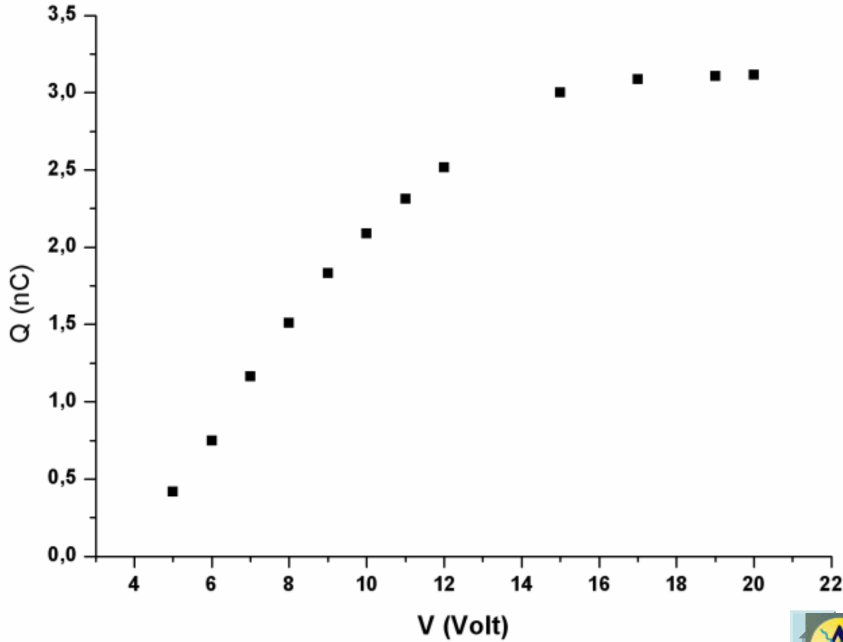
M. Passacantando et al: *"Photoconductivity in defective carbon nanotube sheets under ultraviolet–visible–near infrared radiation"*, APPLIED PHYSICS LETTERS 93, 051911 2008

Photoresponsivity UV

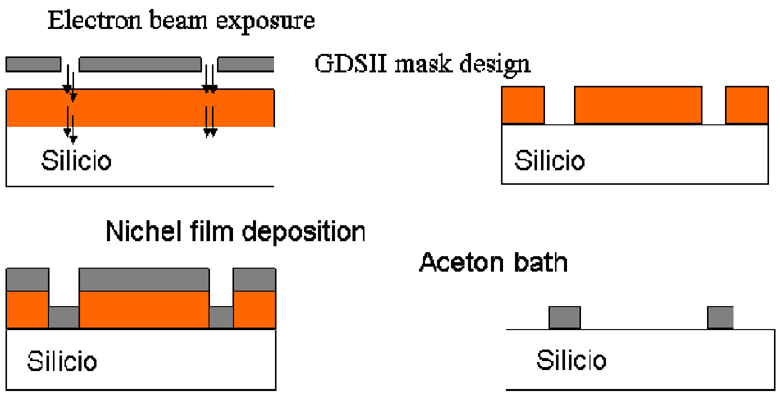




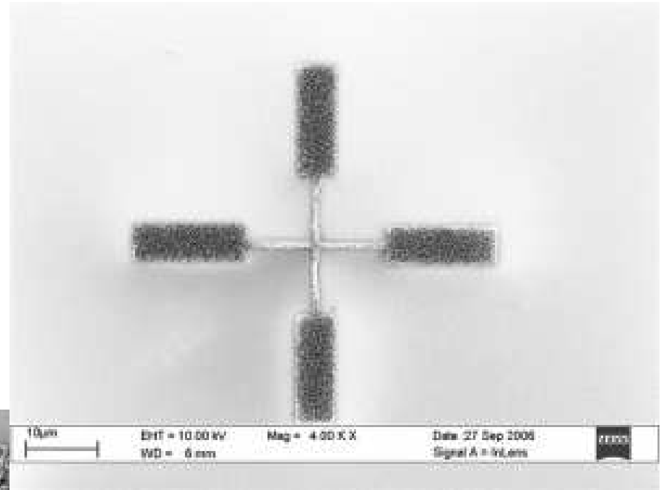


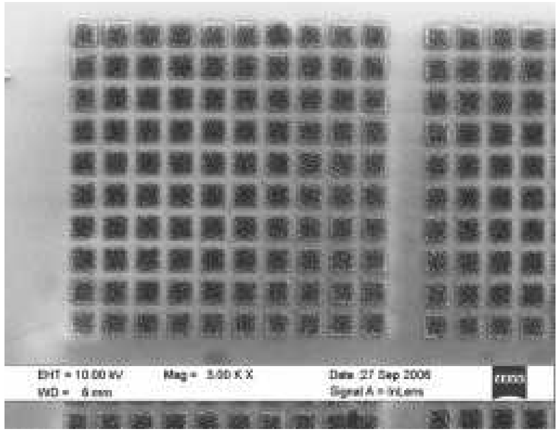


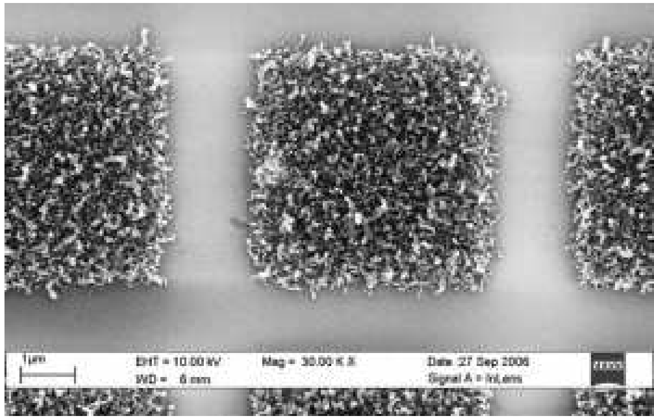
Nanolithography and patternization

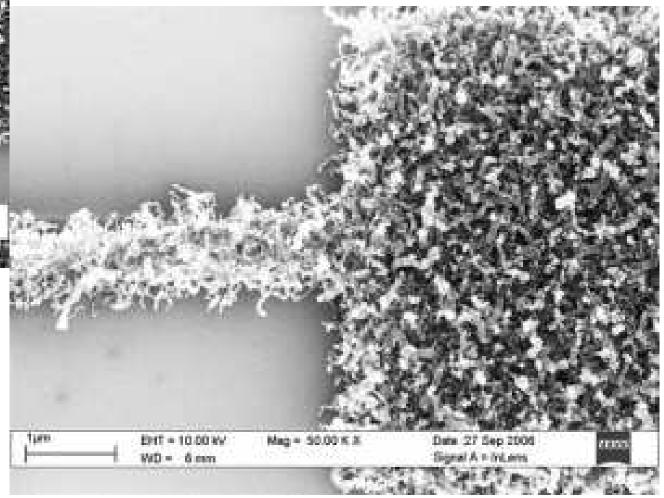


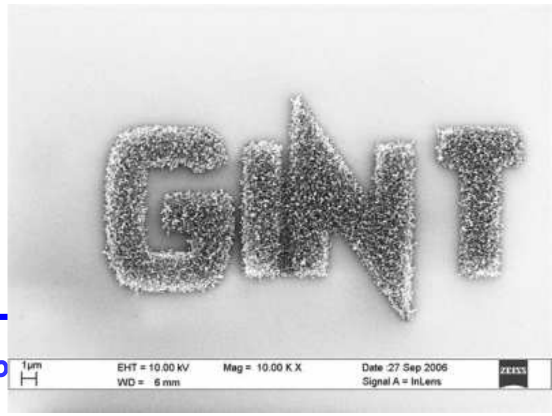
After developing



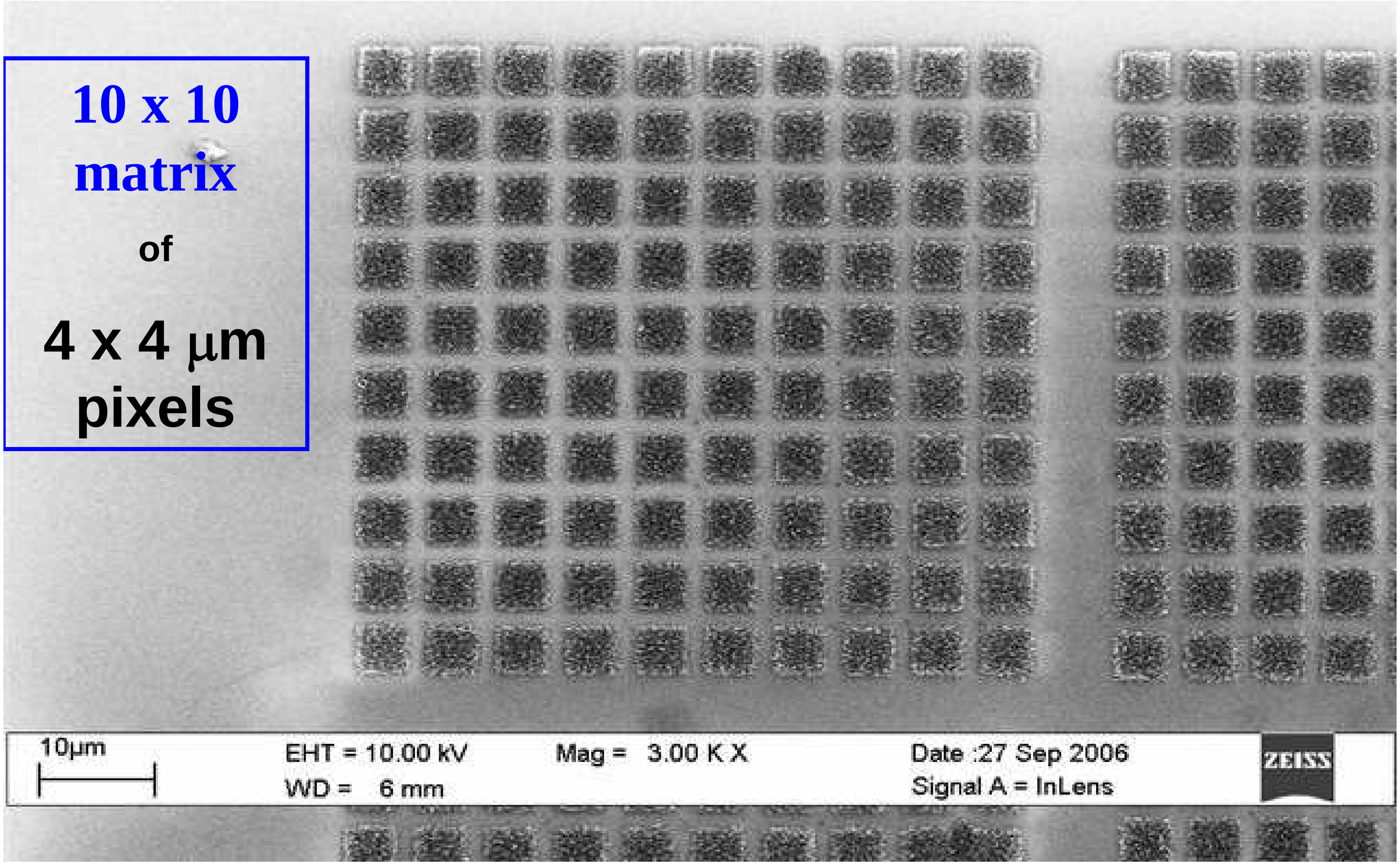








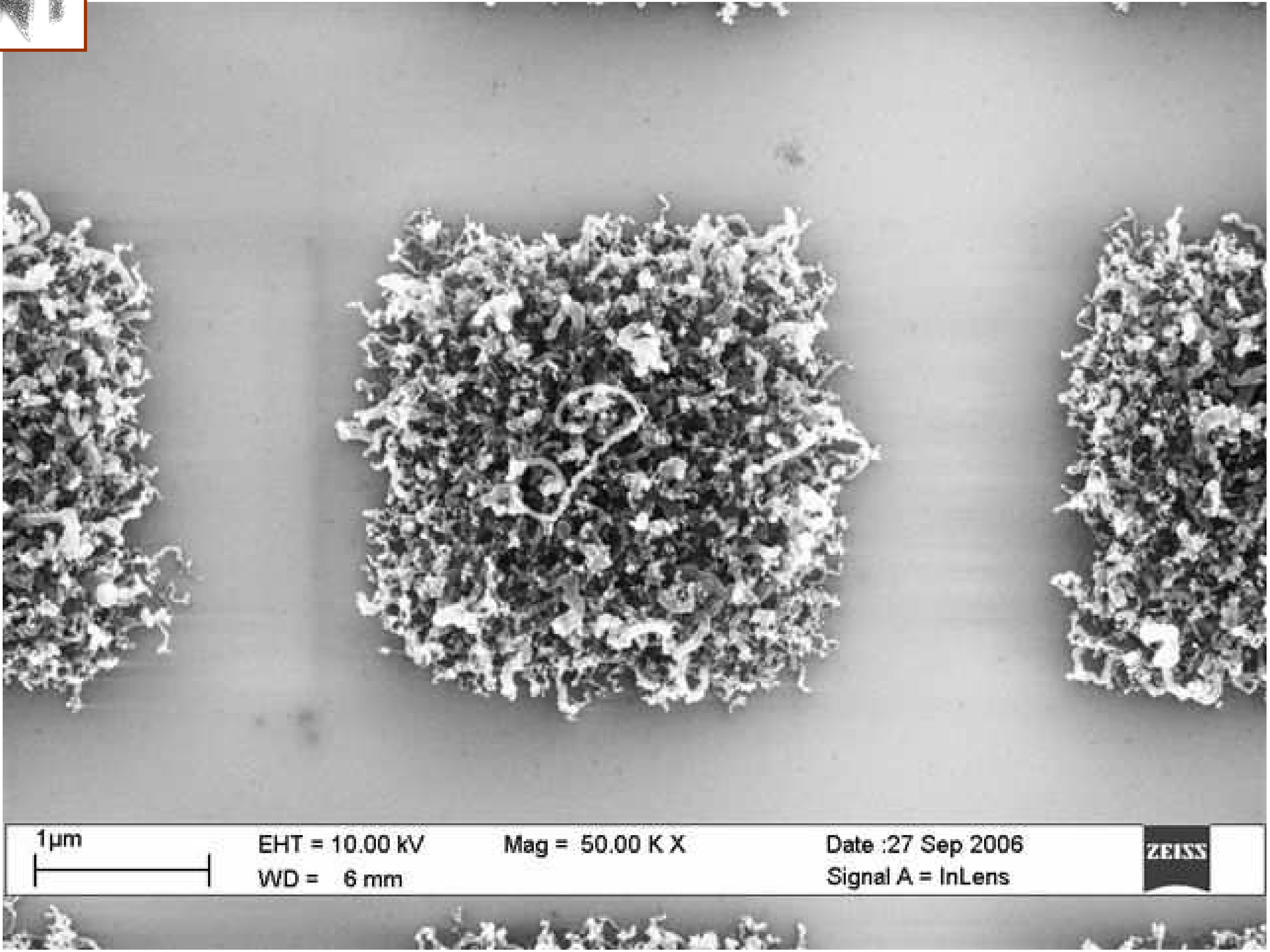
Pixelled photocathode



10 x 10 matrix

of

4 x 4 μm pixels


1µm
EHT = 10.00 kV
WD = 6 mm
Mag = 50.00 K X
Date :27 Sep 2006
Signal A = InLens
ZEISS

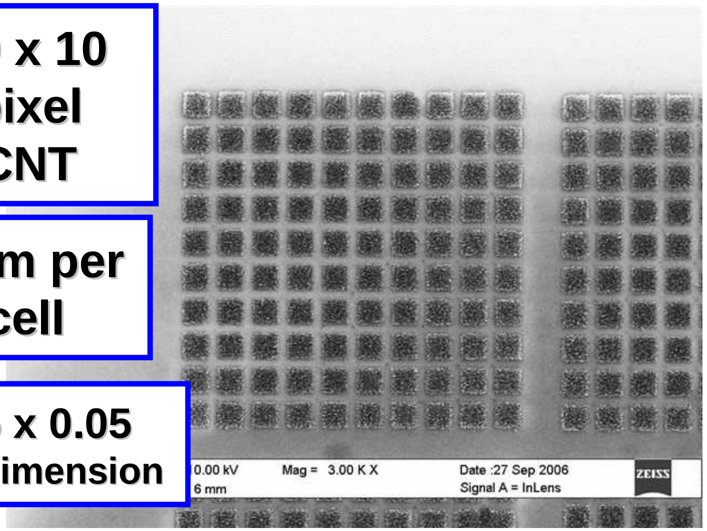
Nano-pixelled photocathodes

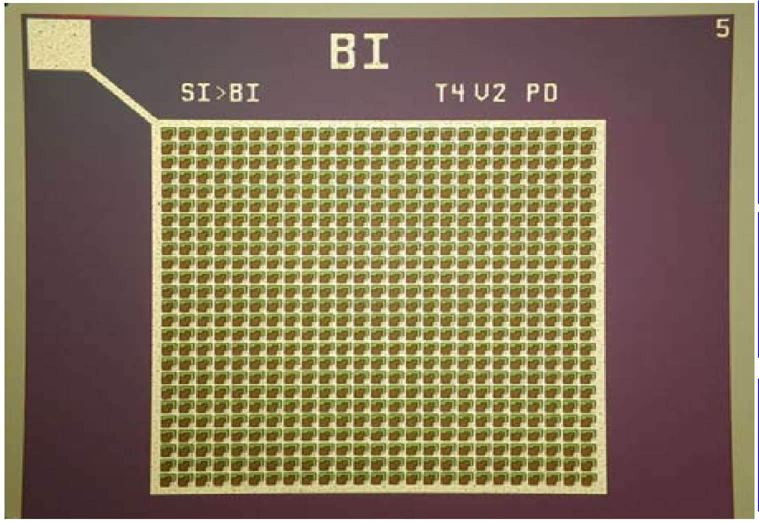
MWCNTs can be grown on different kind of substrates according the desired geometry. Nanolithography process allows to obtain finely pixelled elements over large surfaces.

10 x 10 pixel CNT

4 μm per cell

0.05 x 0.05 mm^2 dimension





25 x 25 pixel SiPM

40 μm per cell

1 x 1 mm^2 dimension

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

Scientific production – Main papers

A. Ambrosio et al: ***"Development of Carbon Nanotube based radiation detectors"***, V C I 2007 , The **11th Vienna Conference on Instrumentation**, Vienna, Austria – February 19-24, 2007

M. Ambrosio et al: ***"Nanotechnology: a New ERA for Photodetection?",*** OPENING TALK della 5th **NDIP Conference, Aix-Les-Bains**, 15-20 June 2008

M. Ambrosio et al: "***New Photon Detectors made of Multi Wall Carbon Nanotubes",*** **IEEE Dresden** 2008, 19-25 October 2008, Germany

A. Ambrosio et al: ***"A prototype of a Carbon Nanotube microstrip radiation detector"***, **Nuclear Instruments and Methods in Physics Research A 589 (2008) 398–403**

M. Passacantando et al: "***Photoconductivity in defective carbon nanotube sheets under ultraviolet–visible–near infrared radiation",*** **Applied Physics Letters 93, 051911 2008**

A. Tinti et al: **"*Electrical analysis of carbon nanostructures/silicon heterojunctions designed for radiation detection",*** **Nuclear Instruments and Methods in Physics Research A 629 (2011), 377-381**

Possible applications

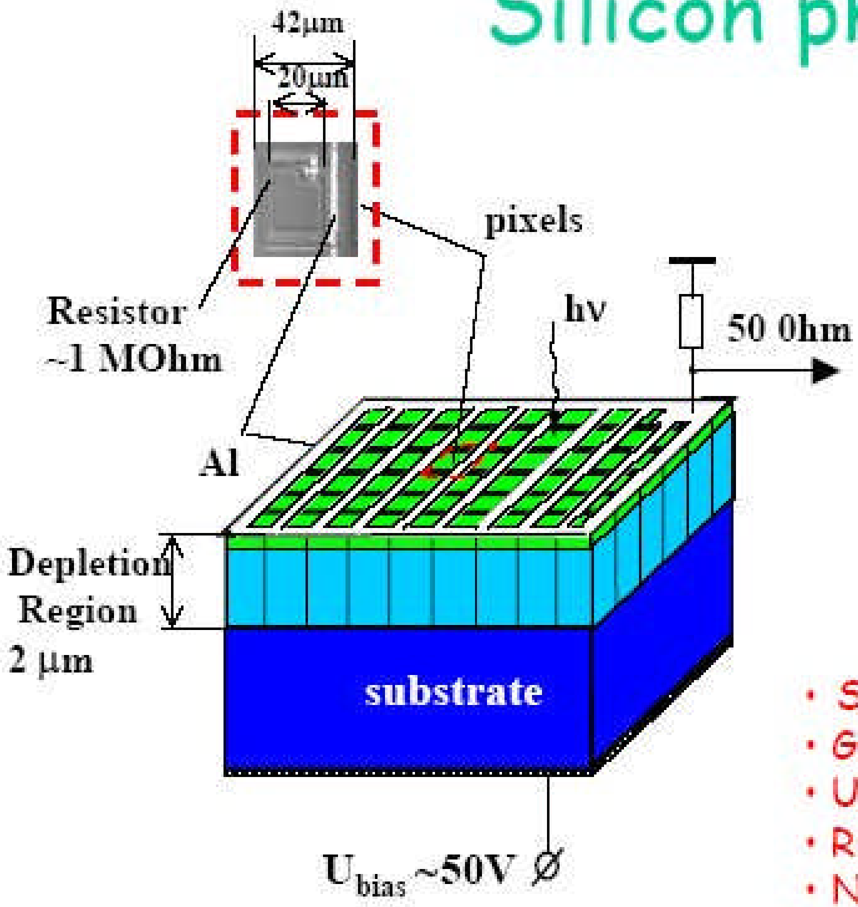
The ITO coating makes the present version of the Si-CNT detector usable as photodetector despite the absence of a signal amplification. Sensitive area can be enlarged to mqs. The responsitivity at the peack is of about 200 μA/mW and QE of about 35%. It permits to detect intense and/or large area light sources for long time with great stability and sensitivity without apparent aging. This is actually a challenge for detecting intense beams as those generated from bremsstralhung emission in SuperB. Pulsed signals are also detected.

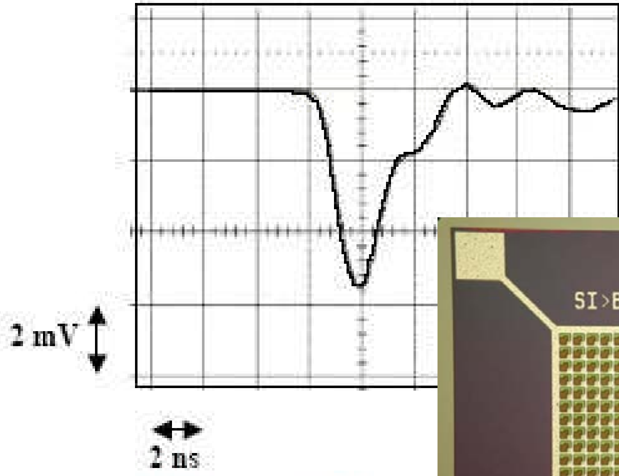
Looking at a next future the present photodetector is extremely promising for high energy physic experiments. Highly pixelled surfaces can be obtained with micro or nano lithography permitting the coupling of detector with external lighting devices such as scintillators and optical fibres.

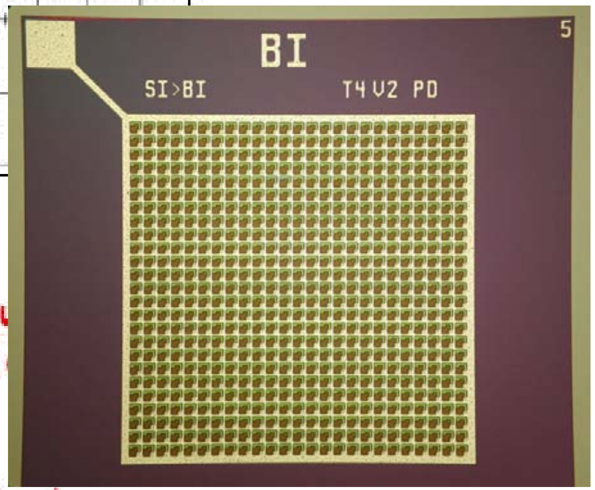
Pixelled large area photocathode can be used for medical imaging or fluorescence light detectors or to detect Cerenkov light cone with high accuracy (CTA, RICH, etc. - Astroparticle physics, space physics, etc.)


I have a dream …
Innovations are due to funny ideas or to visionary dreams.

Silicon photomultiplier (SiPM)







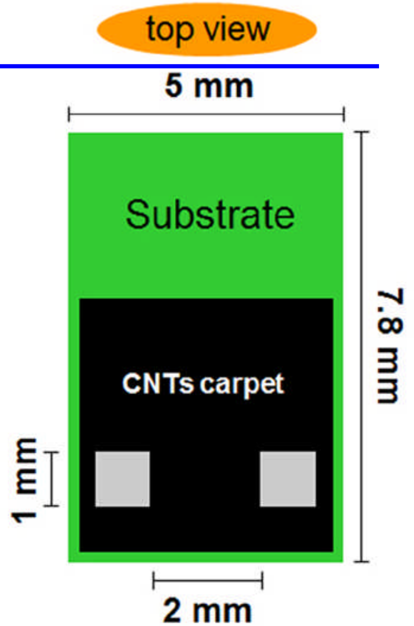
SiPM main featu

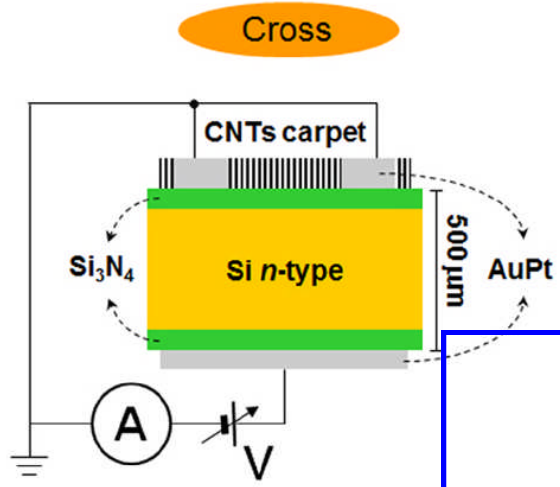
- Sensitive size 1x1mm^2 on
- Gain $2{\cdot}10^6$
- U_{bias}~50V
- Recovery time < 100 ns/pixel
- Number of pixels: ~ 1000/mm^2
- Nuclear counter effect: negligible (due to Geiger mode
- Insensitive to magnetic field
- Dynamic range ~10^3/mm^2

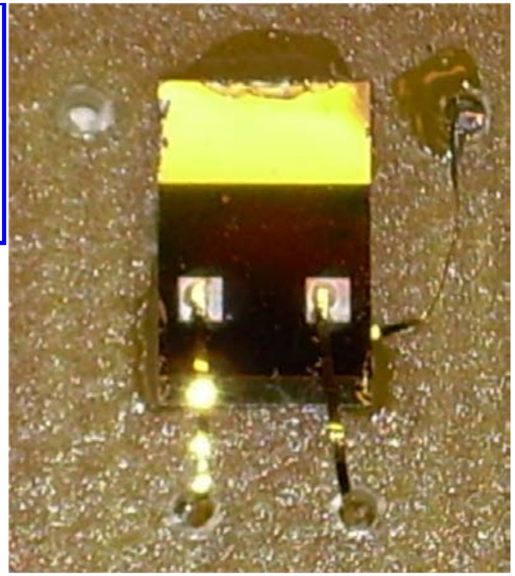
for details: NIMA 504(2003)48

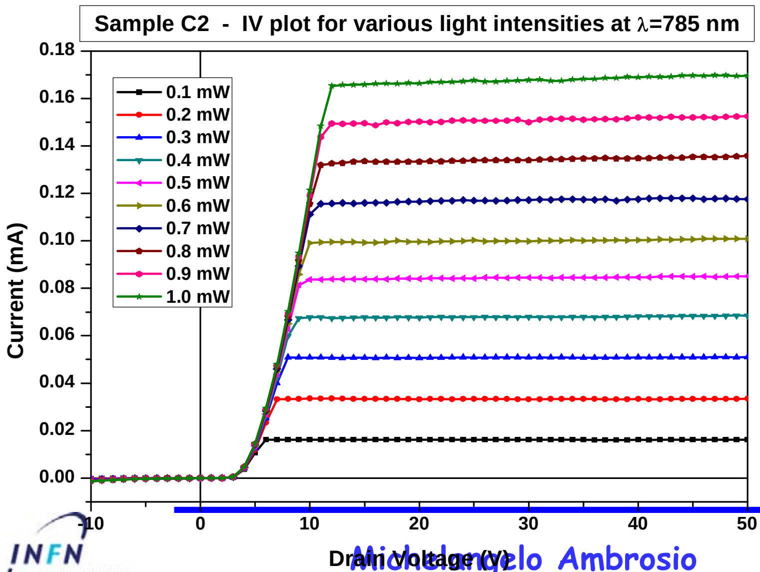
Dolgoshein_Beaune 2002

The Si-CNT detector layout









My dream

LIGHT14 ?

Single photon Silicon-Carbon Nanotube detector

Search for collaboration

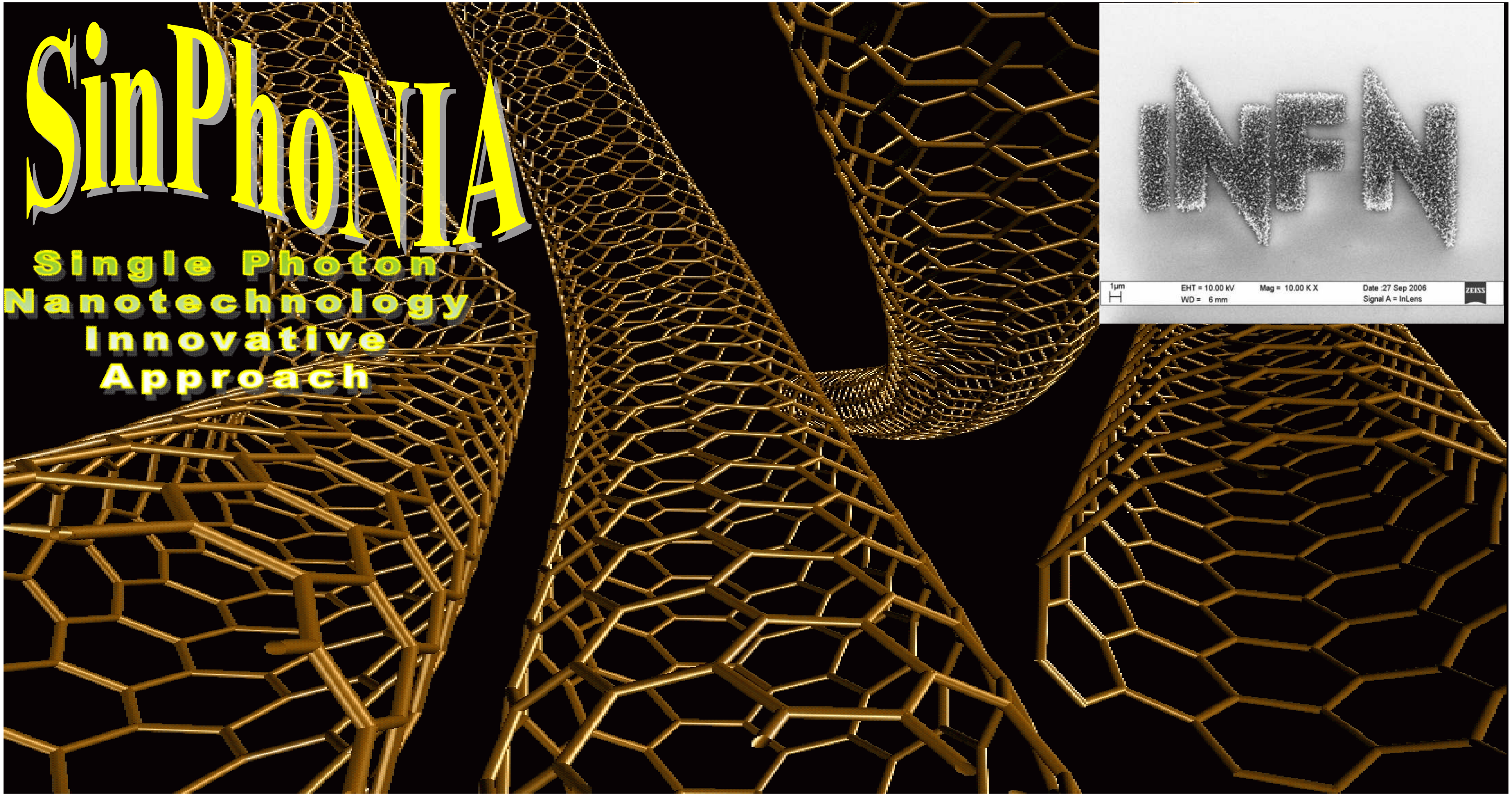
For this reason we are open to all useful collaborations with scientists and industries.

Applications as photosensors are ready to be produced.

Applications to medical imaging are not far. It’s necessary only to amplify the signal and develop readout electronics for specific investigation.

Applications to physics experiments need development of geiger-mode charge multiplication.

Nanoelectronics and opto-nano-electronics knock at the door.



Istituto Nazionale di Fisica Nucleare

http://sinphonia.na.infn.it/index.htm

Thank you for your attention

ambrosio@na.infn.it