Development of Carbon Nanotube radiation detectors

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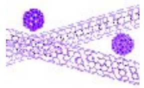
GINT collaboration

http://gint.na.infn.it/



What is a CNT?

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

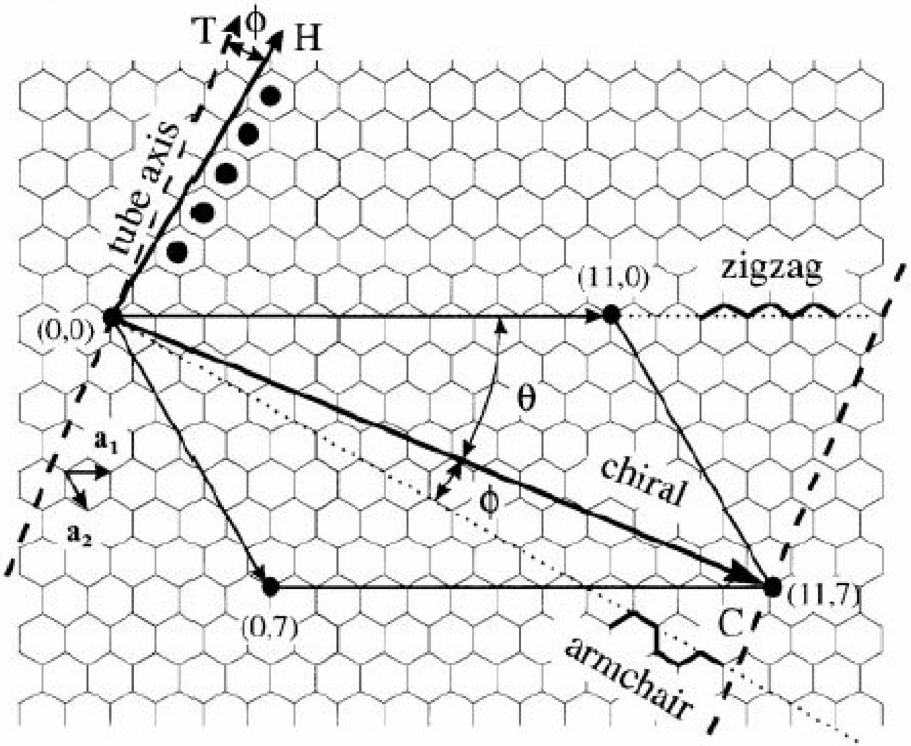
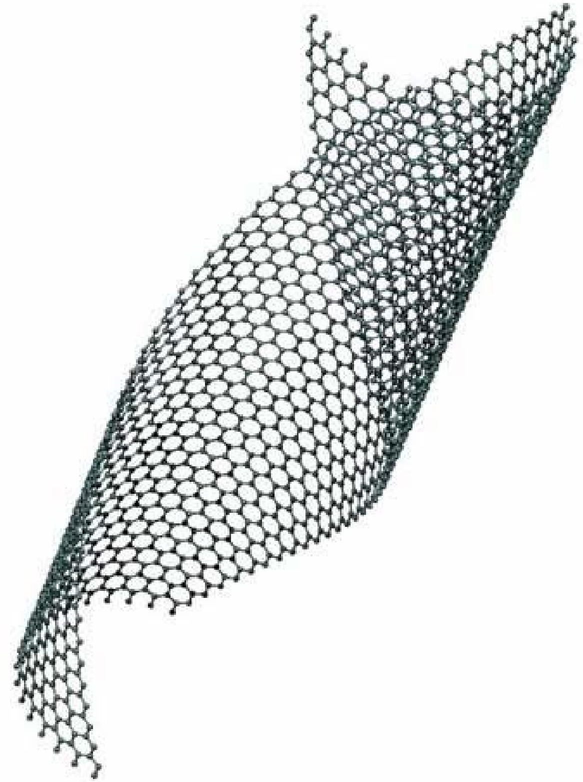
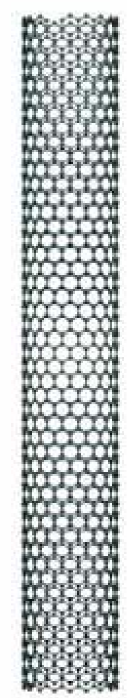
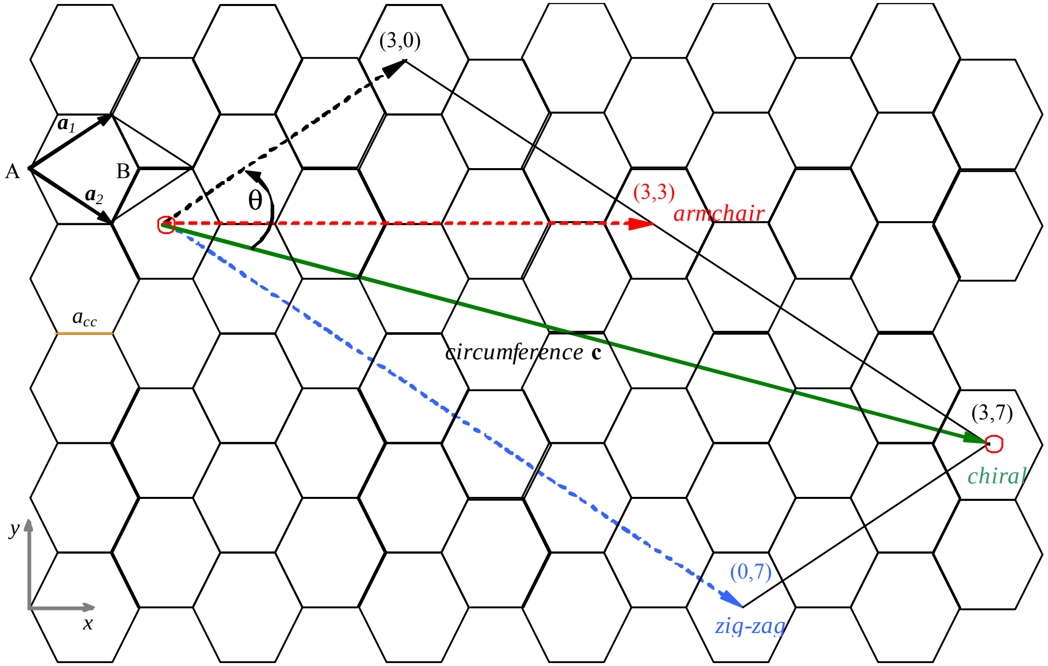


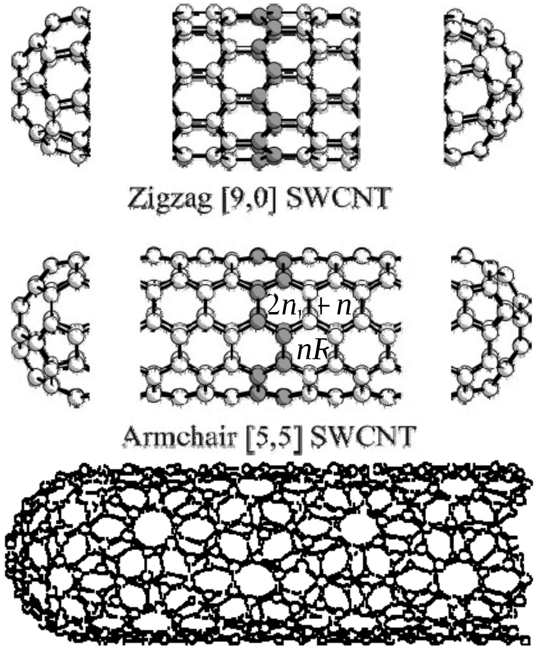
Figure 5. Chiral vector for CNT characterization (adapted from Wildoer, 1998, p. 59)





Carbon Nanotubes: *lattice parameters*





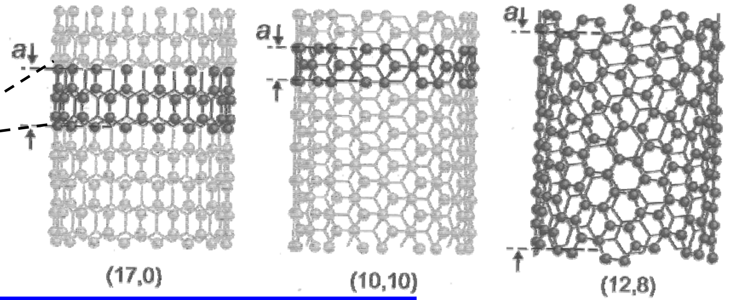
(n,0)
zig-zag

(n,n)

(n,m)
chiral

$$\boldsymbol{c} = n\boldsymbol{a}_1 + m\boldsymbol{a}_2 \qquad n, m \in \mathbb{N}$$
$$\boldsymbol{a} = t_1\boldsymbol{a}_1 + t_2\boldsymbol{a}_2 \qquad t_1, t_2 \in \mathbb{N}$$

Unit cell of CNTs



$$\boldsymbol{a}_1 \equiv \left(\frac{\sqrt{3}}{2}a_0, \frac{a_0}{2}\right)$$
$$\boldsymbol{a}_2 \equiv \left(\frac{\sqrt{3}}{2}a_0, -\frac{a_0}{2}\right)$$

$a_0 = 2.49$ Å

$$t_1 = -\frac{2n_2+n_1}{nR} \qquad t_2 = \frac{2n_1+n_2}{nR}$$

$$d = \frac{|c|}{\pi} = \frac{a_0}{\pi}\sqrt{n^2 + nm + m^2}$$

Carbon Nanotubes (CNTs)

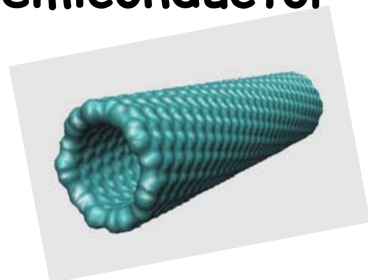
Molecular Nanowires (d ~ 1 nm, l ~ 1 μm)

SWNTs

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

$\notin$ **N** | **|n-m|/3** | $\in$ **N**

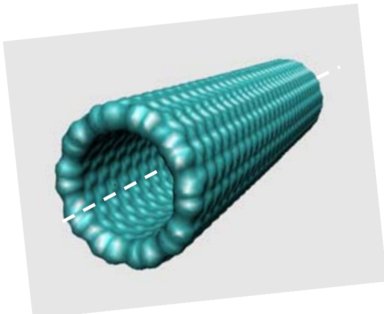
Semiconductor



Channel (FETs),

Luminescence

Metal



Ballistic Conduction,

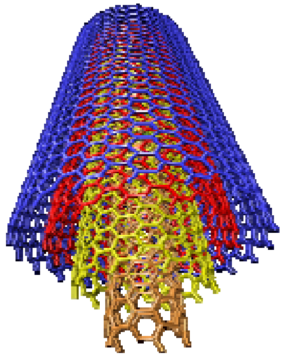
e-wave guides, SETs

MWNTs

Coaxial graphene sheets
(d ≈ 2 ÷ 100 nm,
($d^{out} \approx 20_{AD}$, 100_{CVD} nm)
$L \approx$ μm-range

Vias

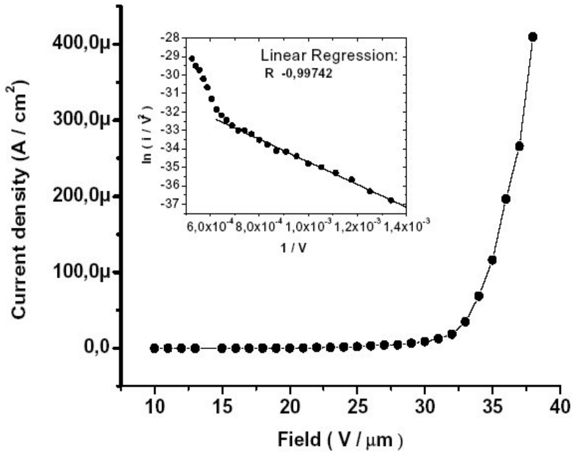
Nanocomposites



Physical Properties of Carbon Nanotubes

- Superior stiffness and strength to all other materials
- Extraordinary electric properties
- Reported to be thermally stable in a vacuum up to 2800 ^{o}C
- Capacity to carry an electric current 1000 times better than copper wires
- Twice the thermal conductivity of diamonds
- Pressing or stretching nanotubes can change their electrical properties by changing the quantum states of the electrons in the carbon bonds
- They are either conducting or semi-conducting depending on the their structure

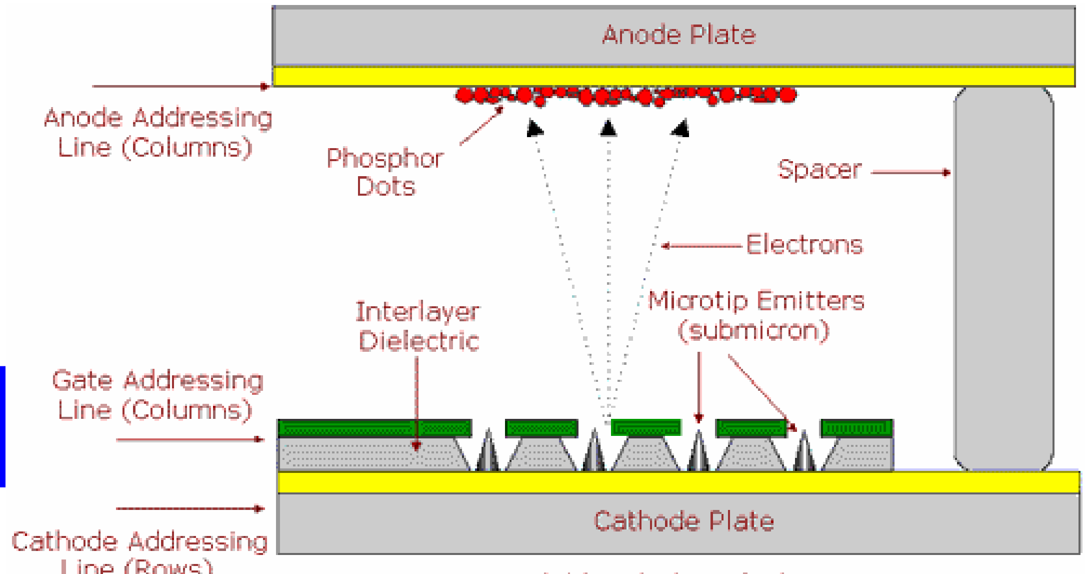
Field Emission of CNTs



Field Emission from tunneling of electrons from a metal into vacuum

$$I = \alpha E_{eff}^2 \exp(-\beta / E_{eff})$$

Fowler-Nordheim equation



Field Emission Display

β is a constant, proportional to the work function
E_{eff} is the effective field at the emitter tip
α is a constant related to the geometry

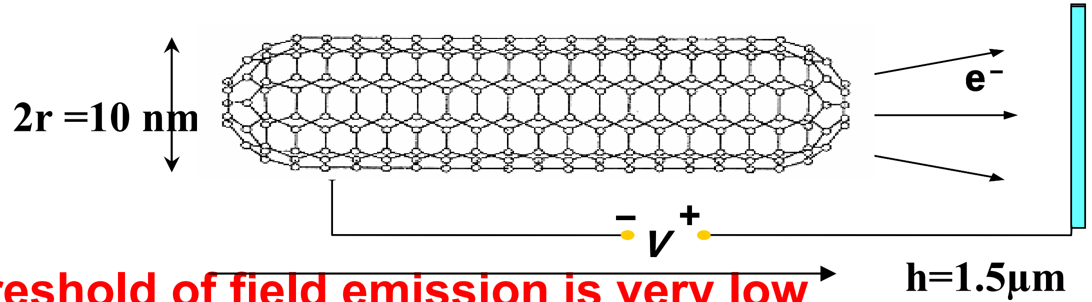
Maximum Current from a single MWNT = 0.2 mA

Emission from well defined energy levels, corresponding to localized states at the tube tip

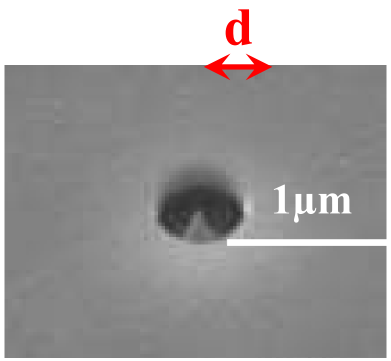
Closed and well-ordered tips are better than opened and disordered tips

Why CNT as emitters?

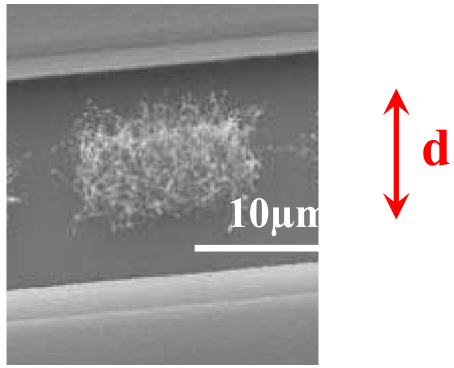
- The aspect ratio h/r produce enormous field amplification factor β



- The threshold of field emission is very low



µTips β =30 V=100 d=1µm

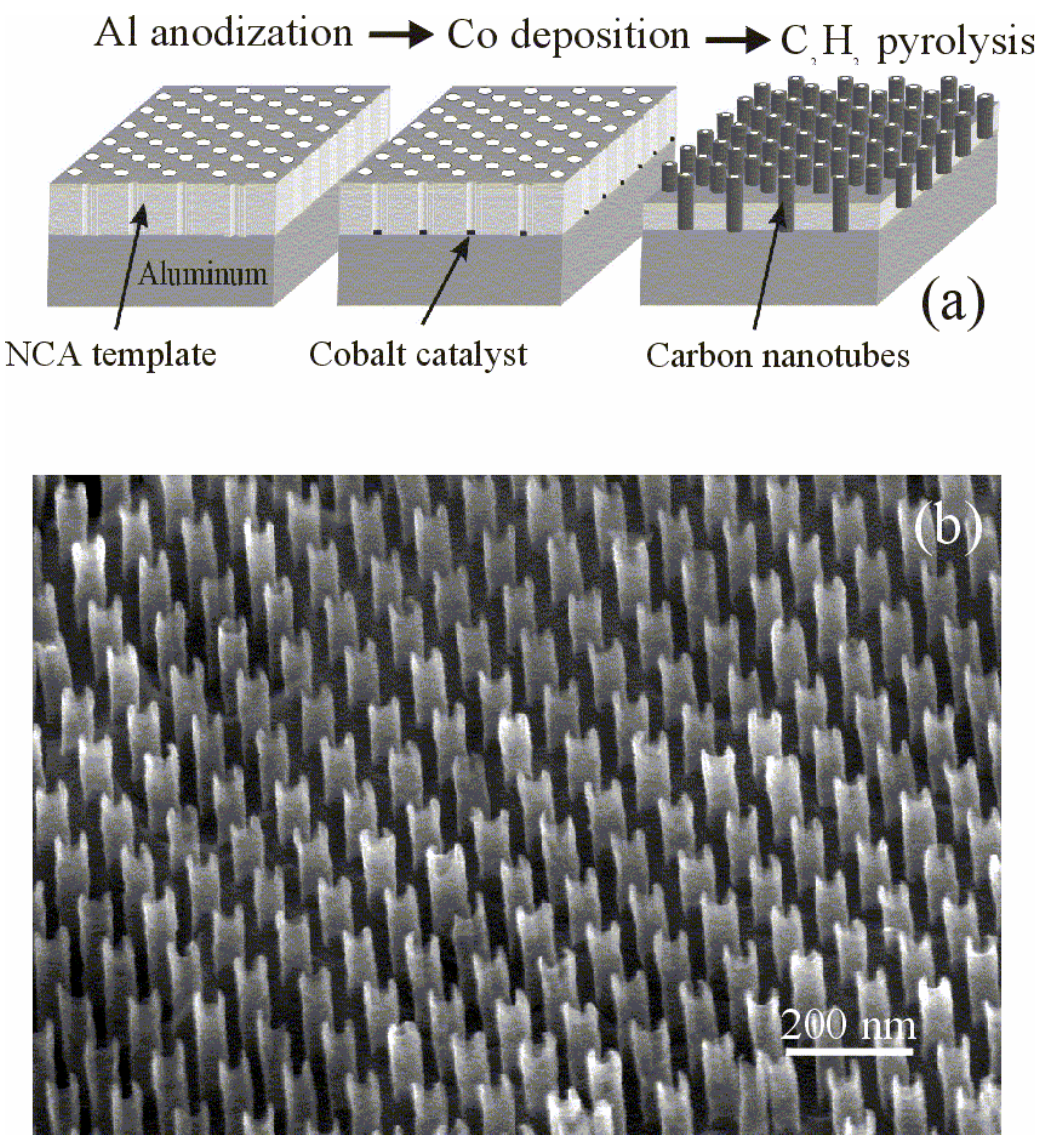


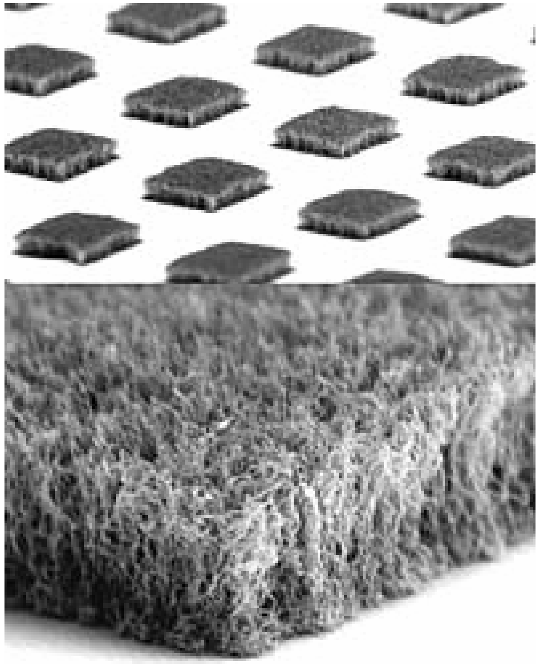
CNT β =300 V=100 d=10µm

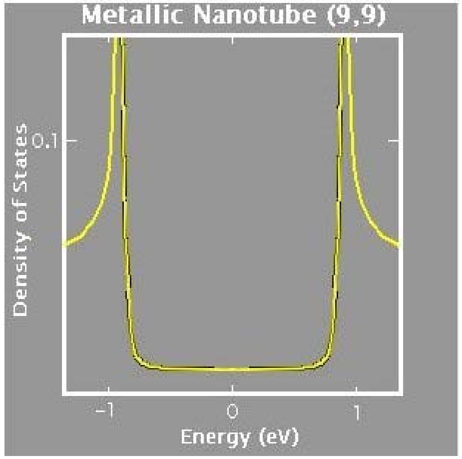
CNT devices allow the manufacturing of displays with large design rules

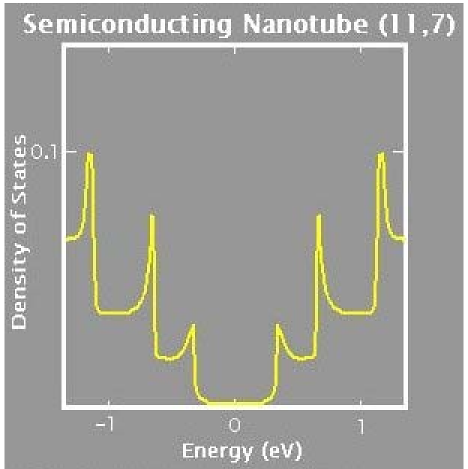
High beta CNT materials are needed
MWCNT electrically connected

CNT patternization

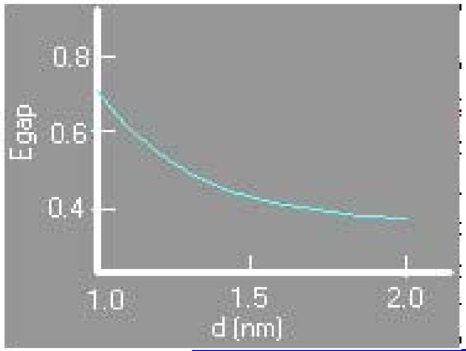








Above: The Van Hove singularities in metallic and semiconducting nanotubes. Adapted from [19].



CNT energetic levels

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*.

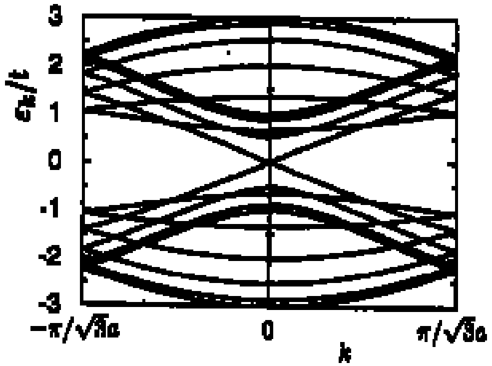
All the others are semiconductors whose gap is function of the diameter, and are approximated from the function:

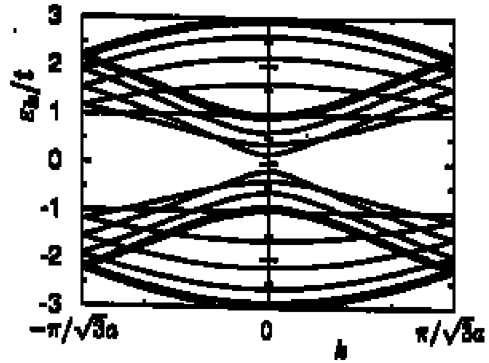
$$E_{gap}=2\ y_0\ acc/d$$

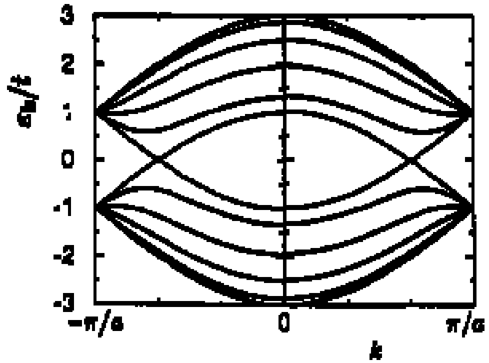
where y_0=0.1 eV, acc=0.142 nm and d is the diameter. This implies that for the Single Wall CNT the fundamental gap varies from 0.4 to 0.7 eV.

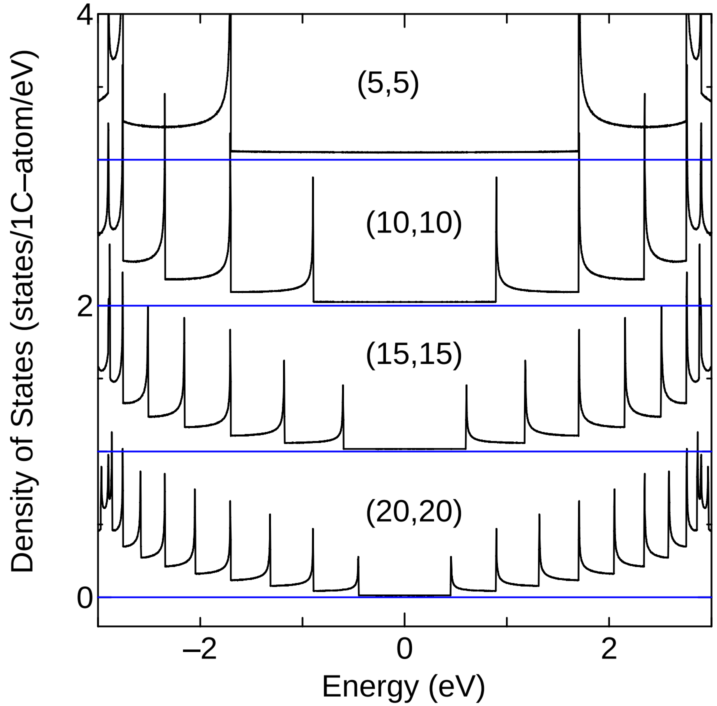
Multi Wall CNT instead present a wider range of energy gap.

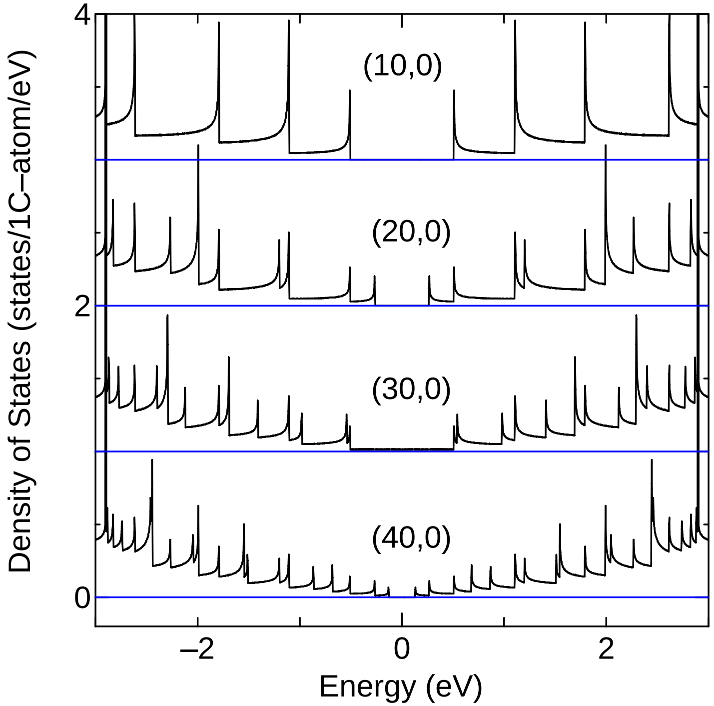
Metallic Zig-zag Semiconducting Zig-zag Armchair









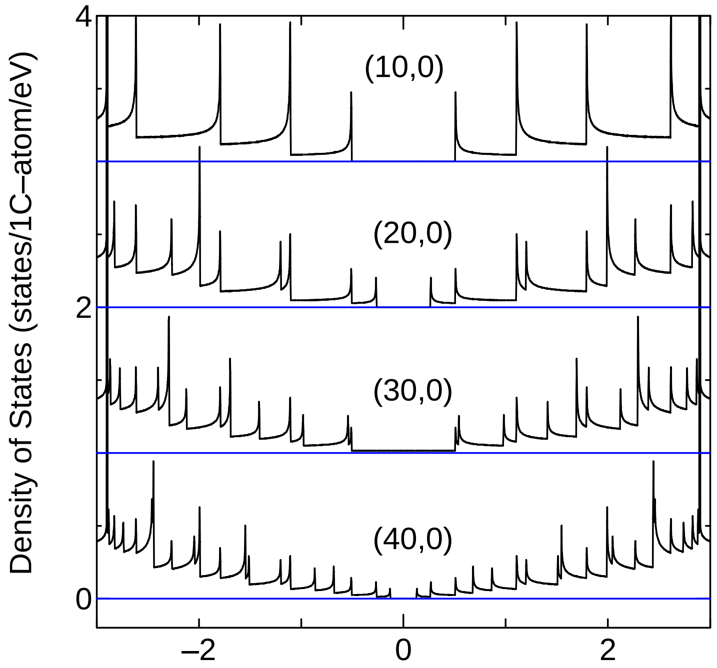


$c \cdot K = 2\pi m$

$m = 1 \ldots q$

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

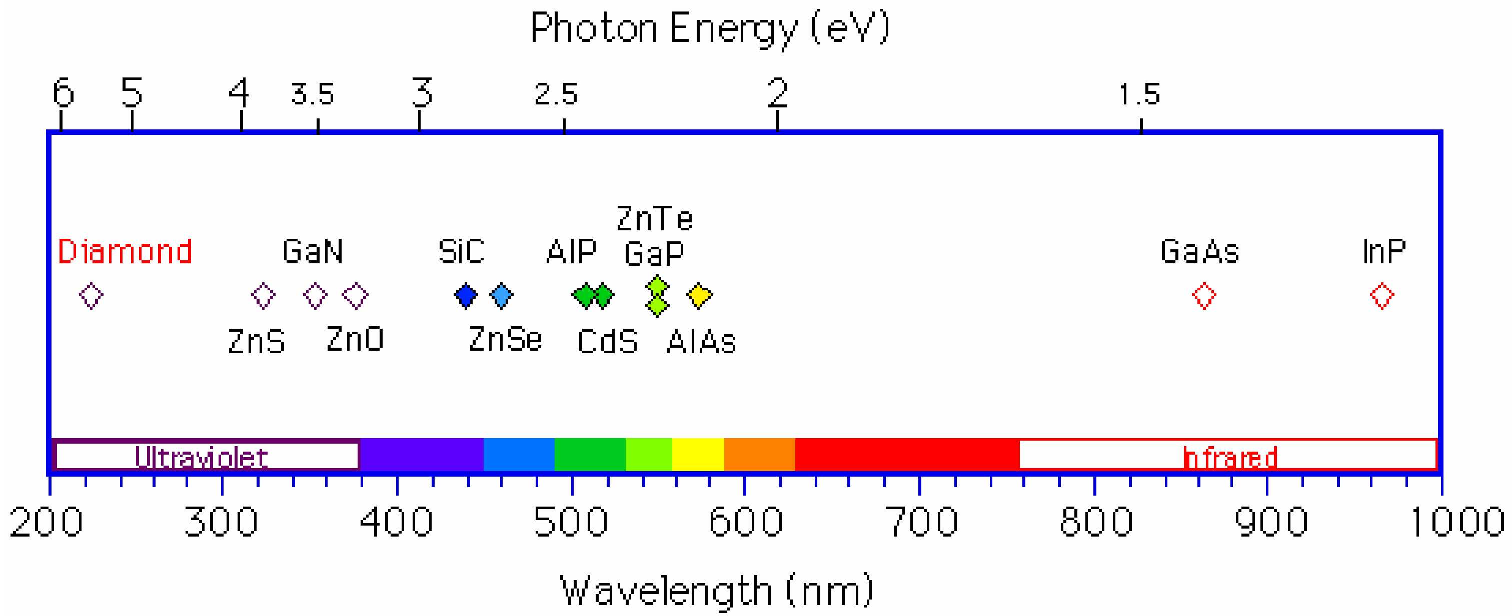
R. Saito, G. Dresselhaus and M.S. Dresselhaus, *Physical Properties of Carbon Nanotubes*, **Imperial College Press (2003)**



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



Photocathods with nanometric resolution

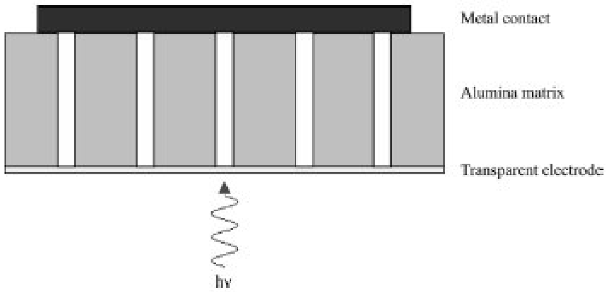


Fig. 4. Basic element of CNT IR detector array. The light is incident on the transparent electrode and is absorbed by the nanotube array. A bias applied to the metal contact allows the change in conductivity to be detected.

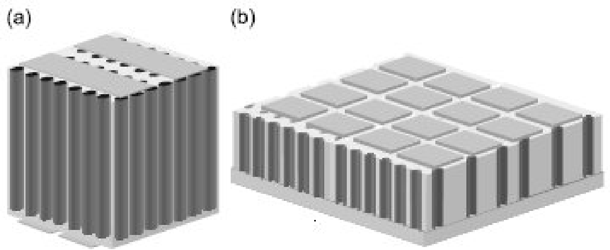


Fig. 5. (a) CNT IR detector configuration using crossed top and bottom electrodes for XY addressing. (b) CNT IR detector array with transparent bottom electrode and square grid pixel array for readout.

Nanotubes have been used as IR detectors.
(I.M.Xu: Highly ordered carbon nanotube arrays and IR detection – Infrared Physics and Technology 42 (2001) 485 – 491)
(M.E. Itkis: Bolometric Infrared Photoresponse of suspended Single-Walled Carbon Nanotube Film – SCIENCE Vol. 312 (2006) 413 – 416)

The realization of large area *uncooled* detectors for the infrared radiation covers a particular importance for the physics space researches to detect galactic and extragalactic sources

The problem: how to collect and amplify the signal generated in individual or “islands” of CNT’s?

Our objective: a CNT_PMT

A possible cathode + amplifier layout

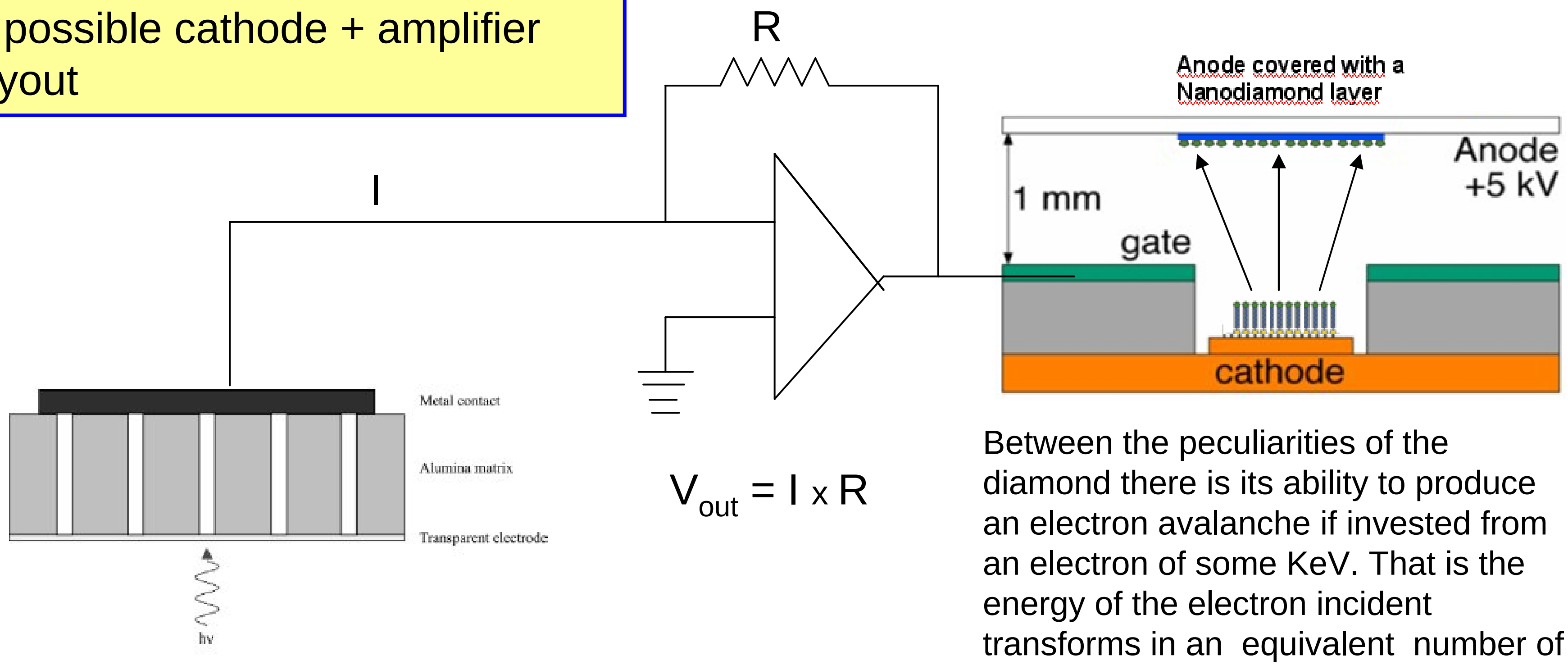


Fig. 4. Basic element of CNT IR detector array. The light is incident on the transparent electrode and is absorbed by the nanotube array. A bias applied to the metal contact allows the change in conductivity to be detected.

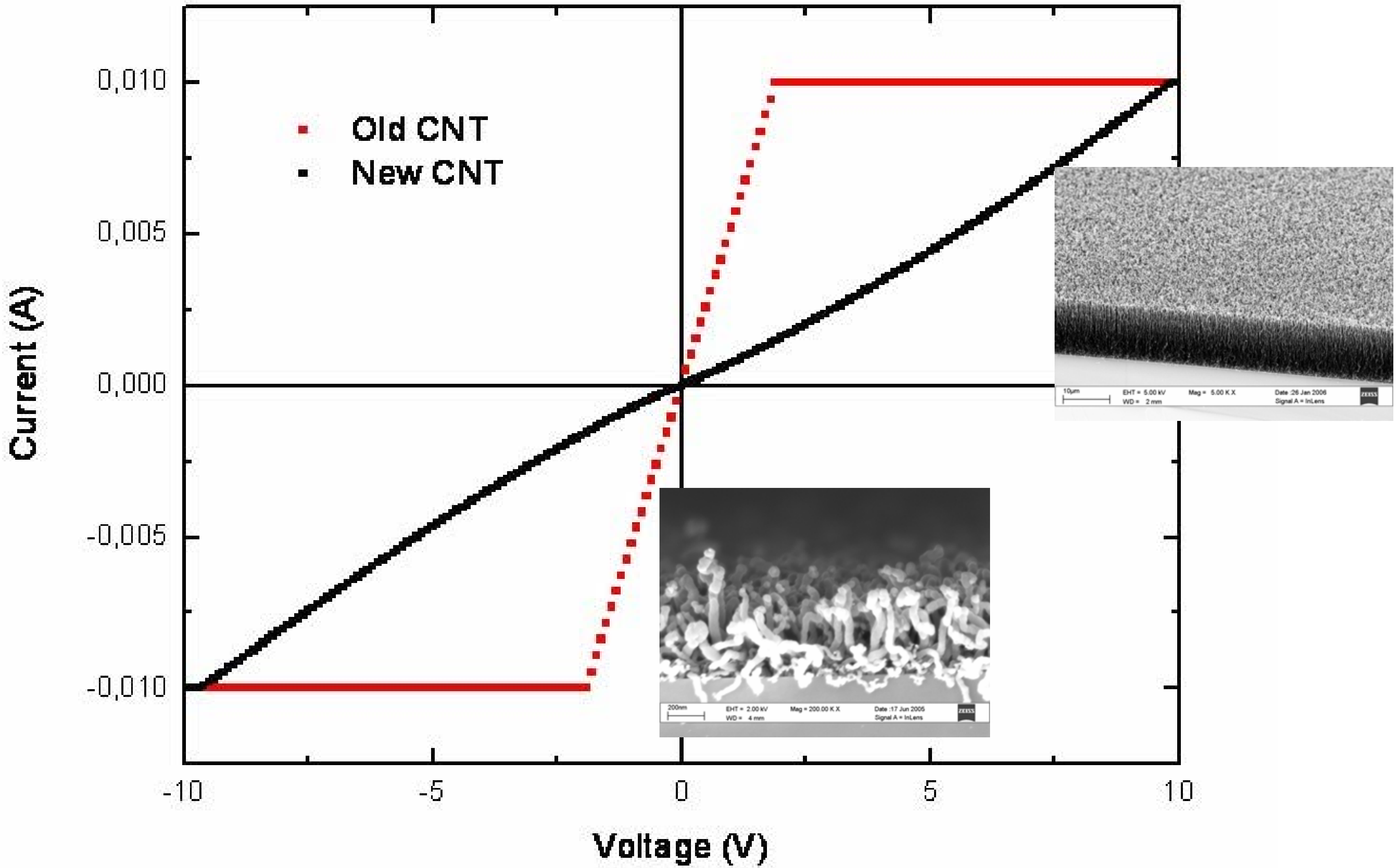
$V_{out} = I \times R$

Between the peculiarities of the diamond there is its ability to produce an electron avalanche if invested from an electron of some KeV. That is the energy of the electron incident transforms in an equivalent number of electrons inside the nanodiamond.

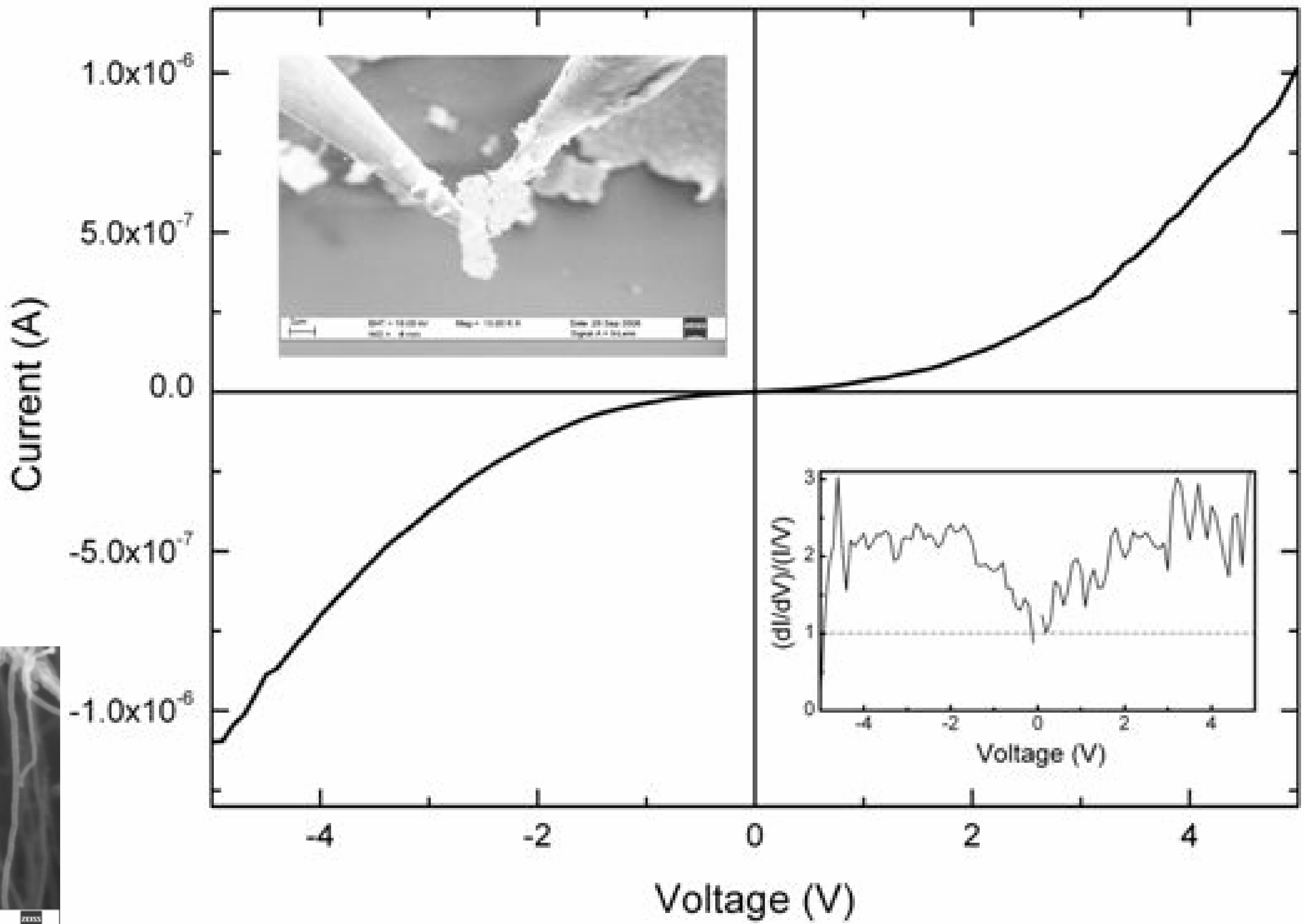
[*I. Ben−Zvi et al. "Secondary emission enhanced photoinjector" Report Brookhaven National Lab Upton NY, C−A/AP\#149*].

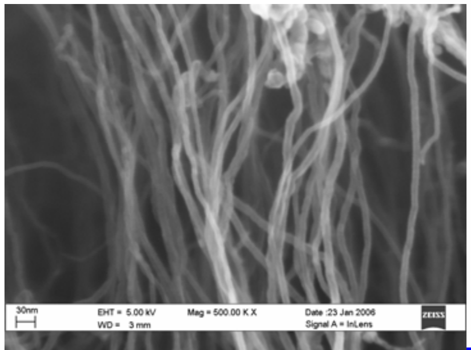
The GINT collaboration: first results

I-V Plot

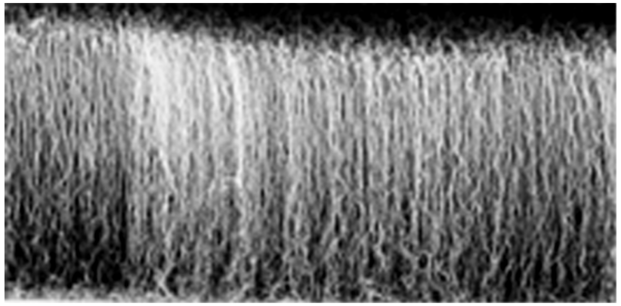


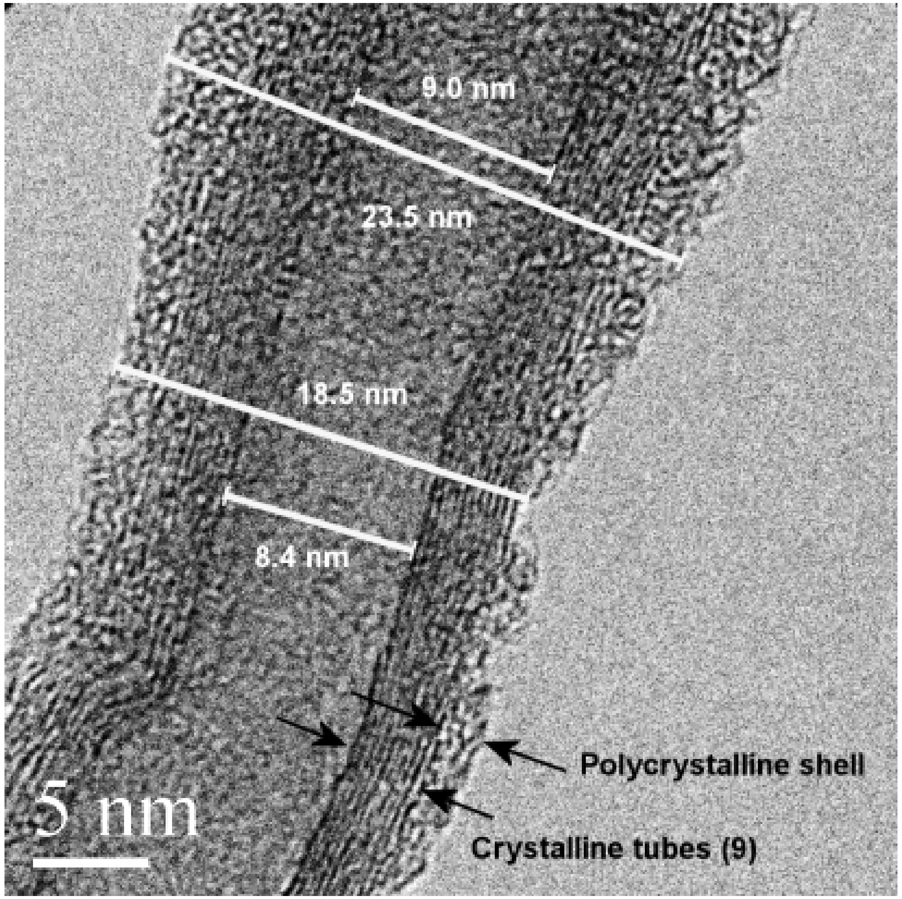
Last production: I – V plot

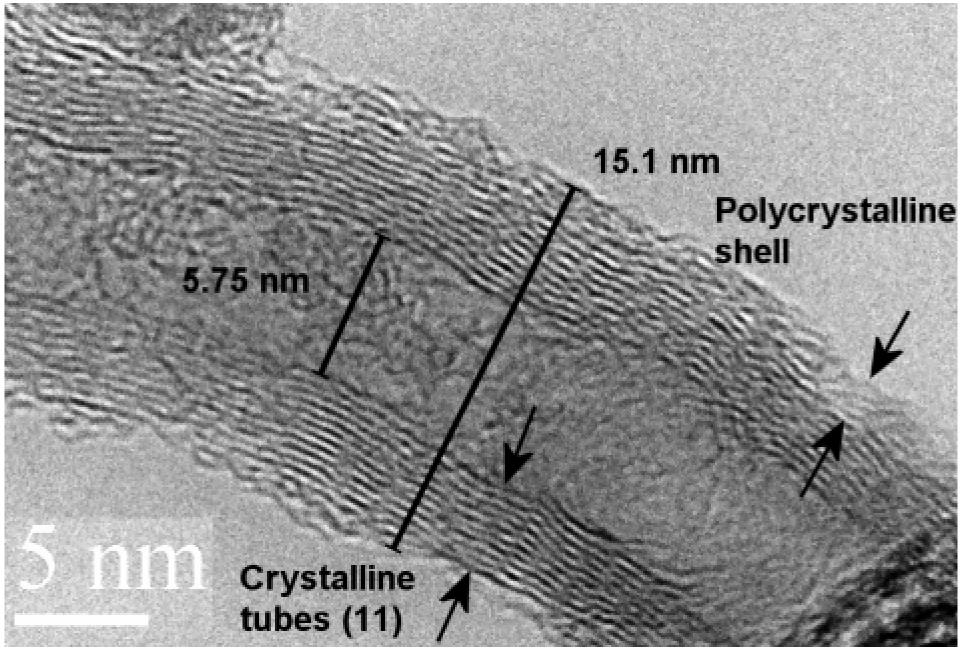




TEM image of MWCNT



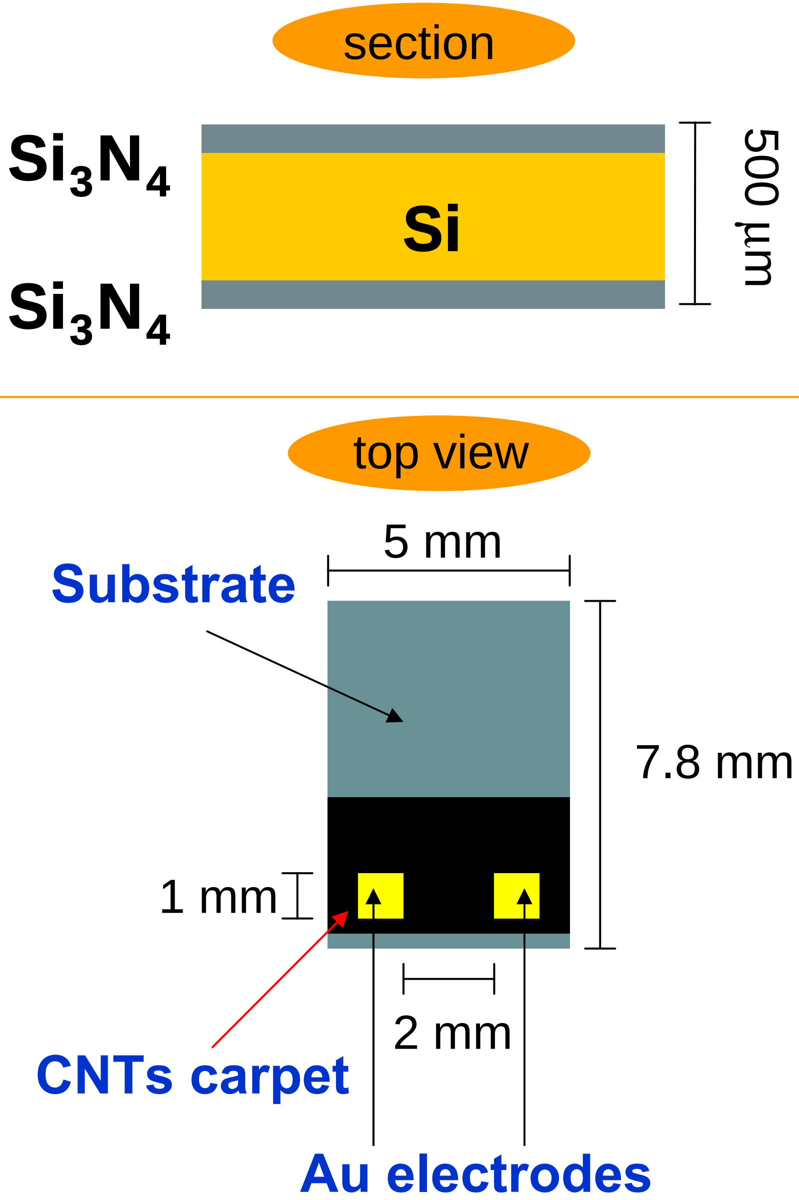




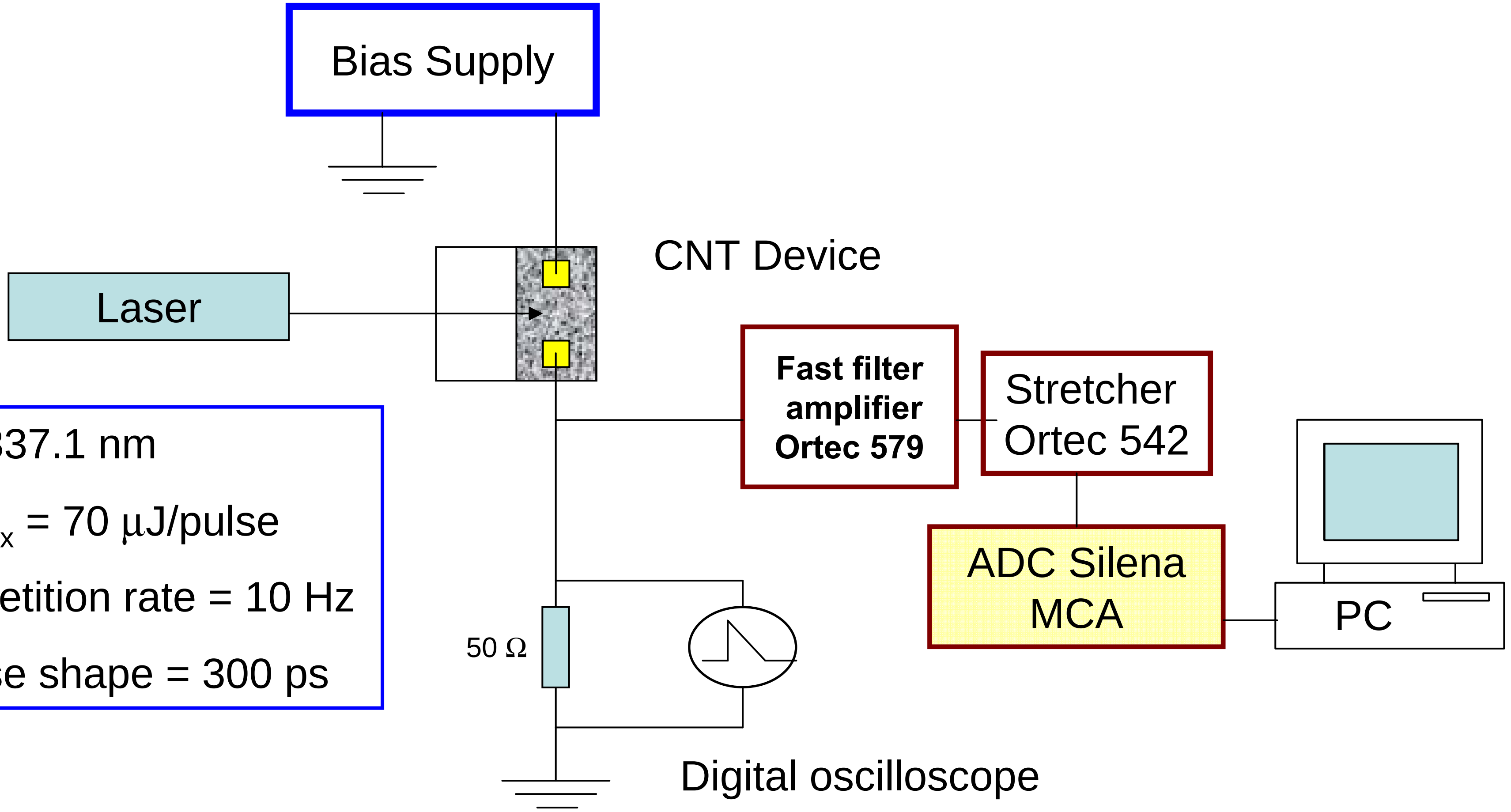
- Outer diameter: 15 – 25 nm
- Inner diameter: 5 – 10 nm
- Average # of tubes: 10 – 15

Sample sketch

Sample picture



Apparatus layout



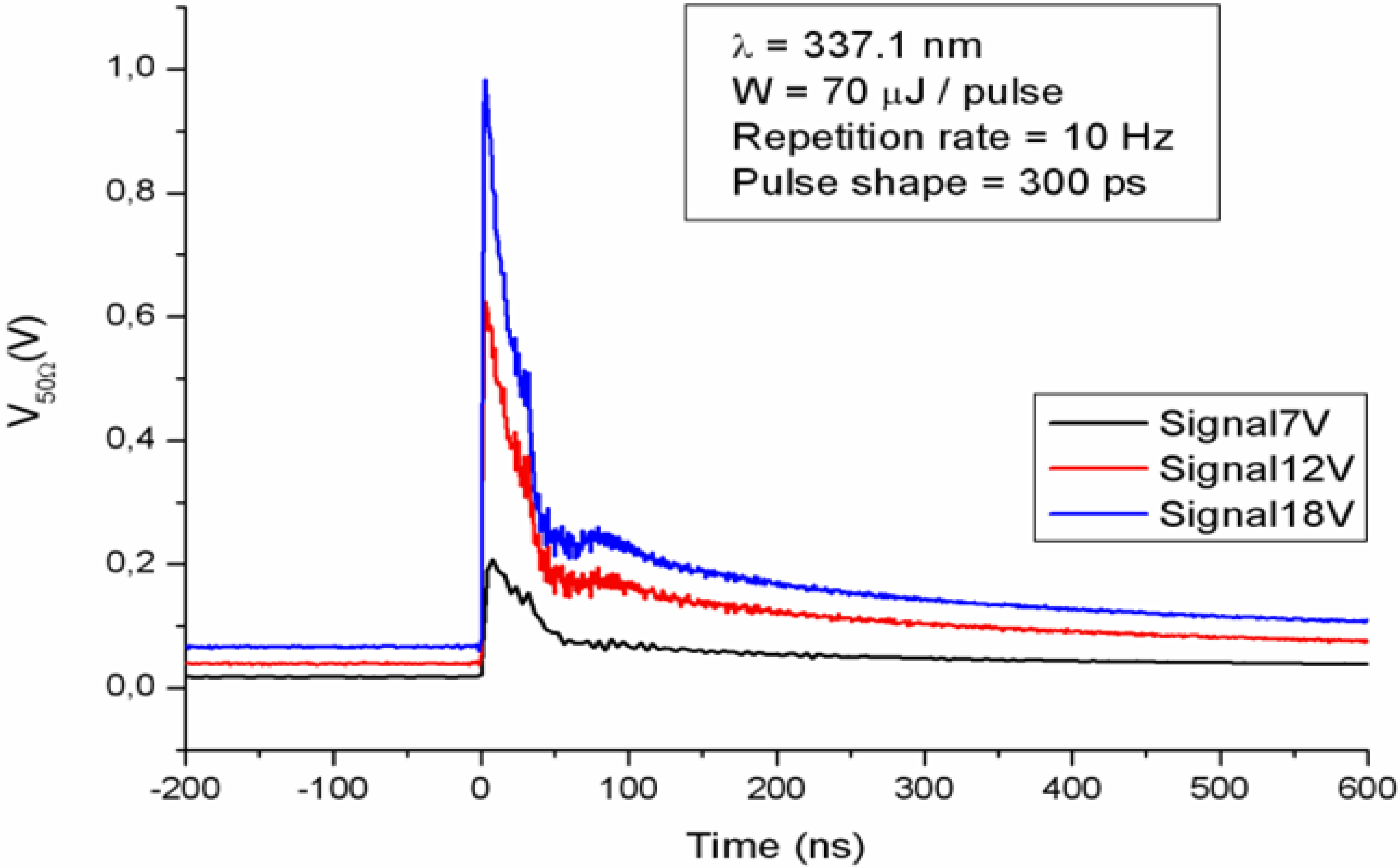
λ= 337.1 nm

W_{max} = 70 μJ/pulse

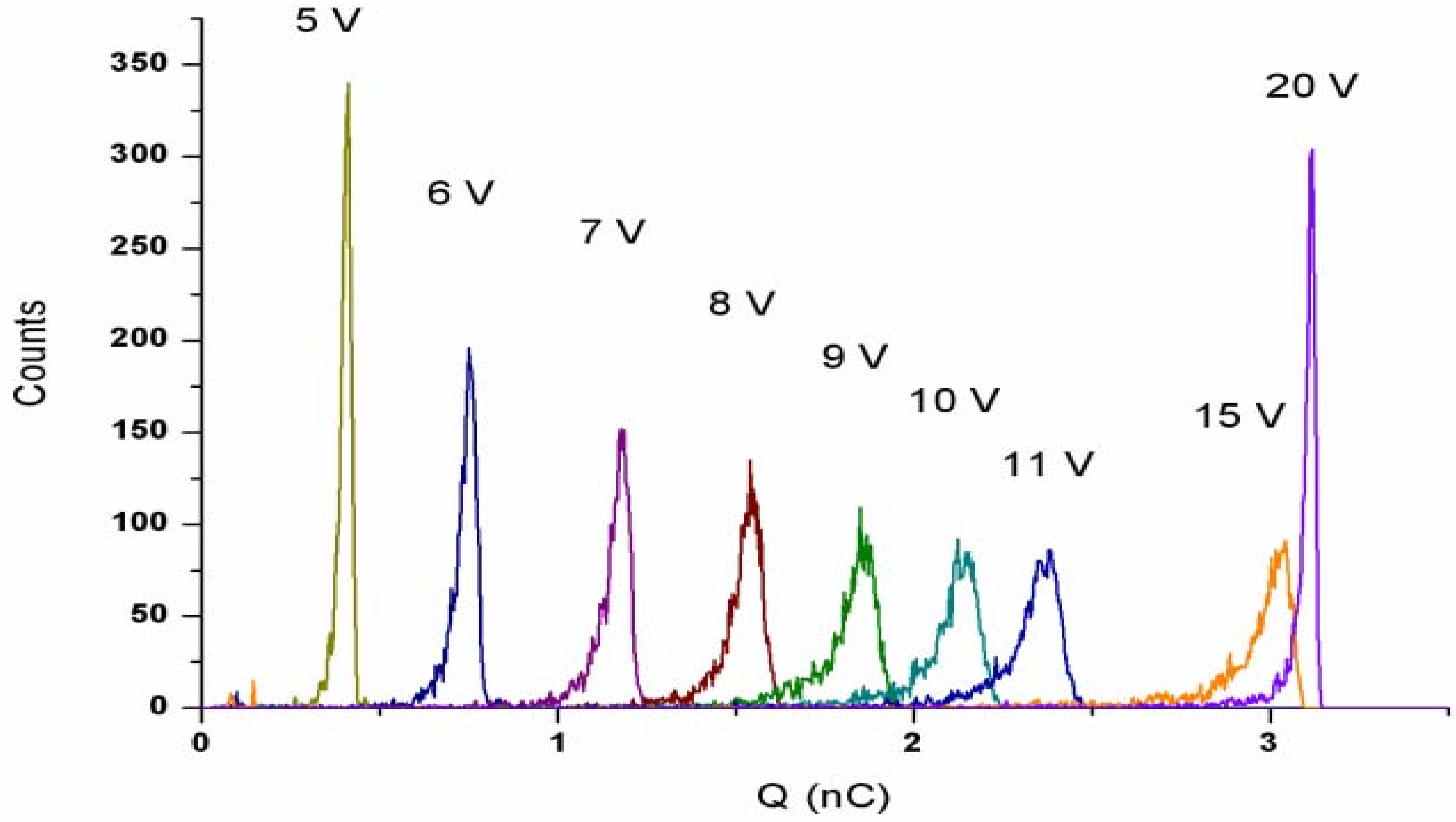
Repetition rate = 10 Hz

Pulse shape = 300 ps

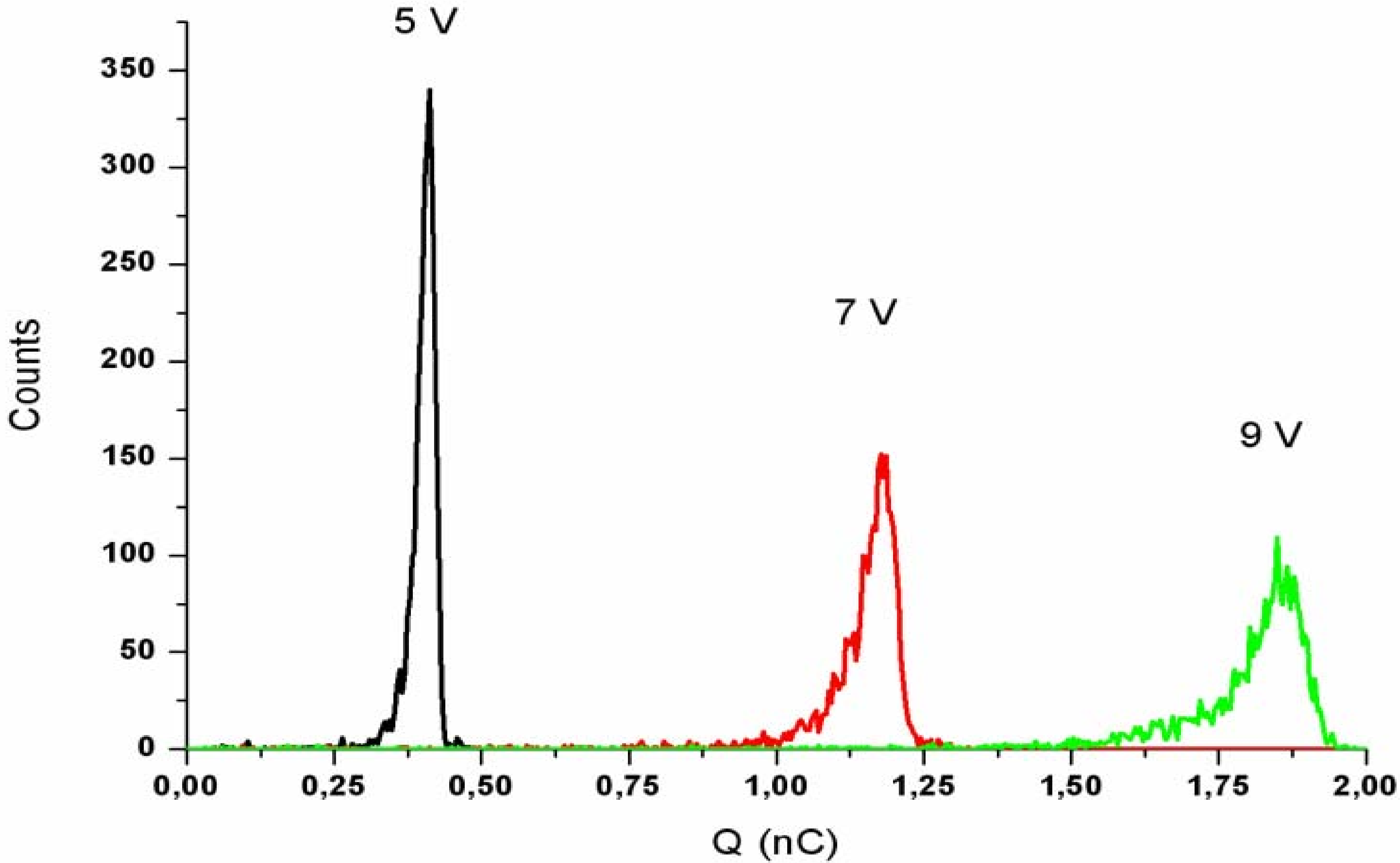
Signal characteristics



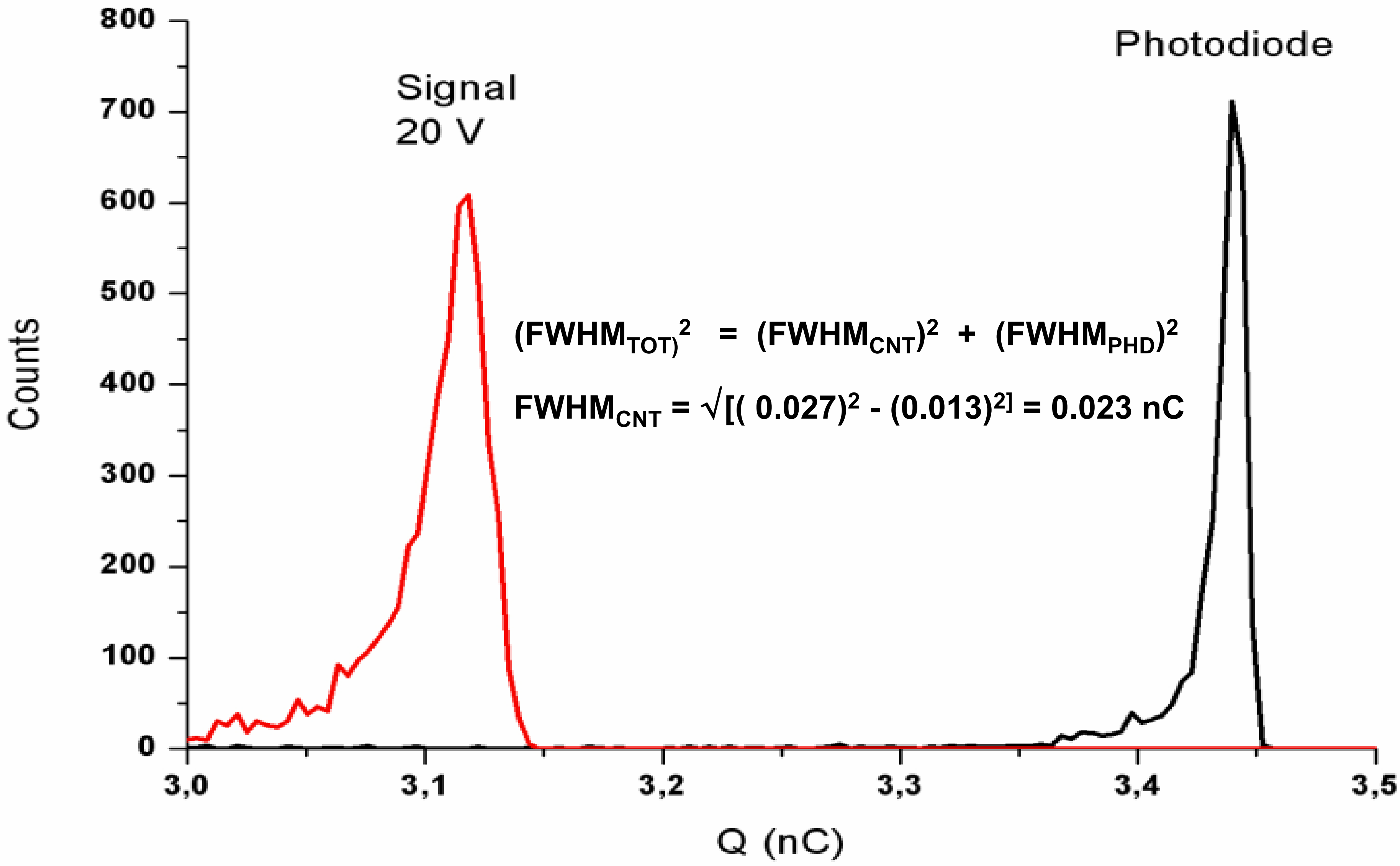
Charge spectra at variuous voltages



Some particular charge spectra



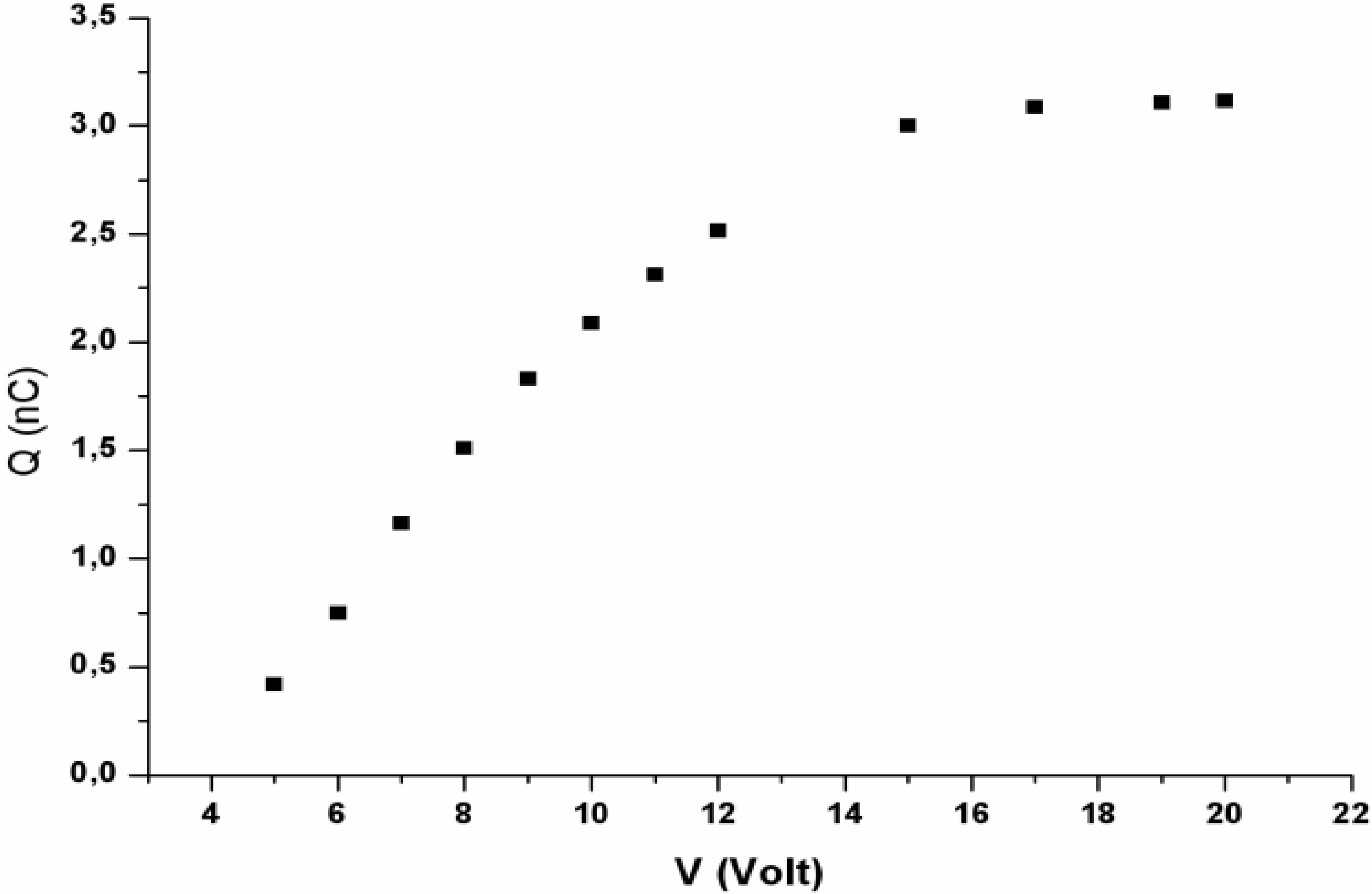
Laser beam spread



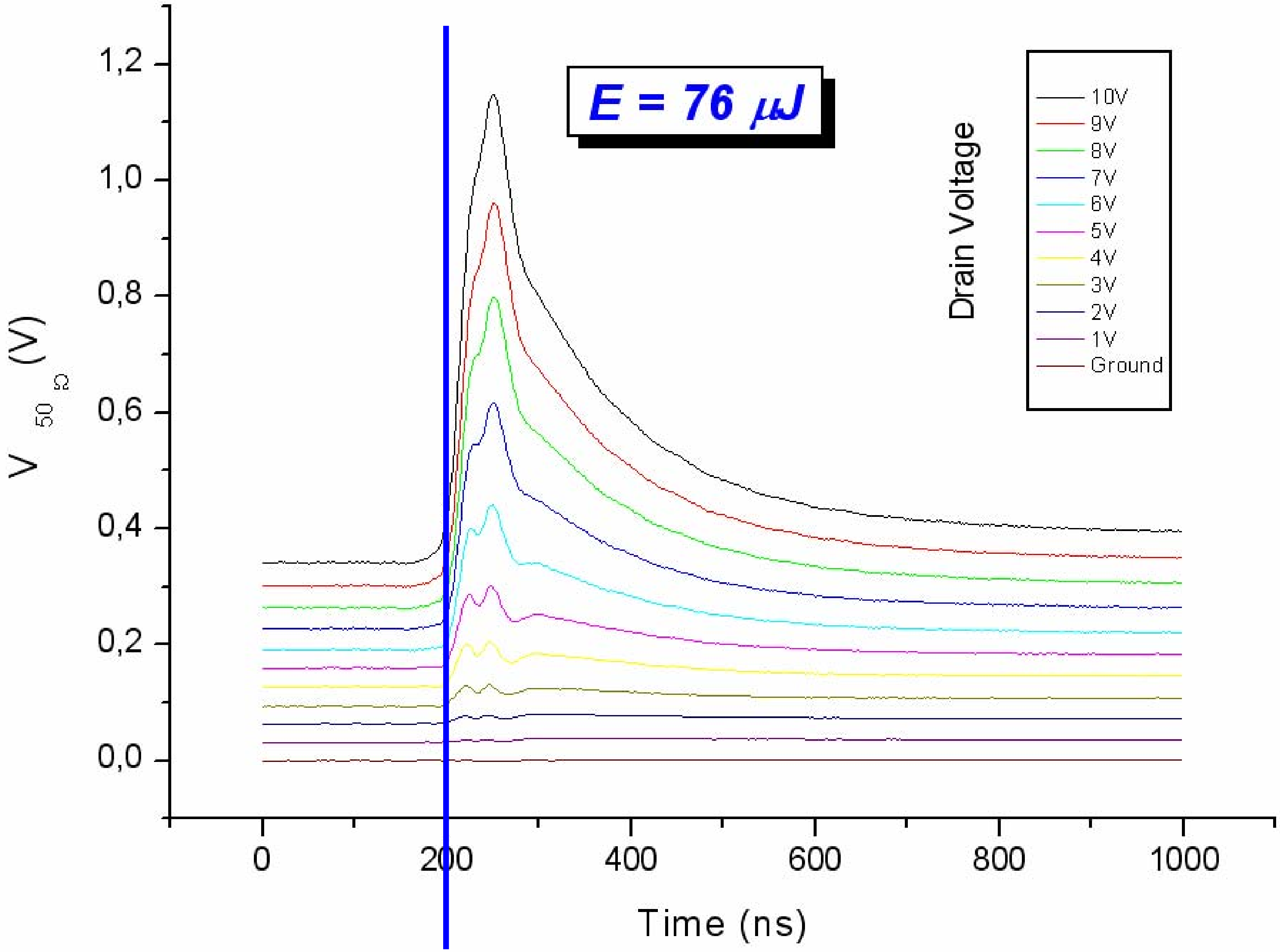
$$(FWHM_{TOT})^2 = (FWHM_{CNT})^2 + (FWHM_{PHD})^2$$

$$FWHM_{CNT} = \sqrt{[(0.027)^2 - (0.013)^2]} = 0.023 \text{ nC}$$

Drained charge vs V_{drain}

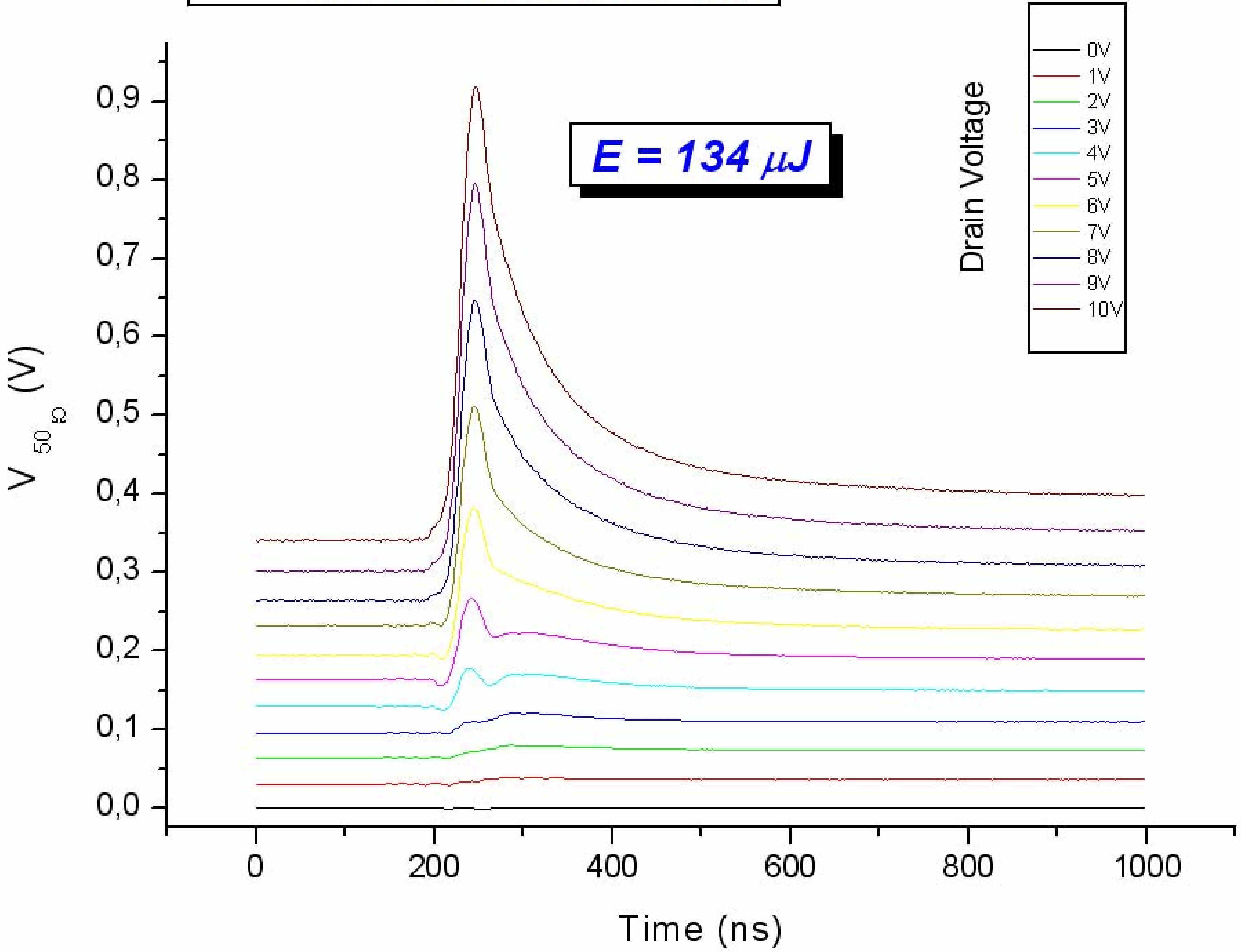


Laser 532 nm on CNT

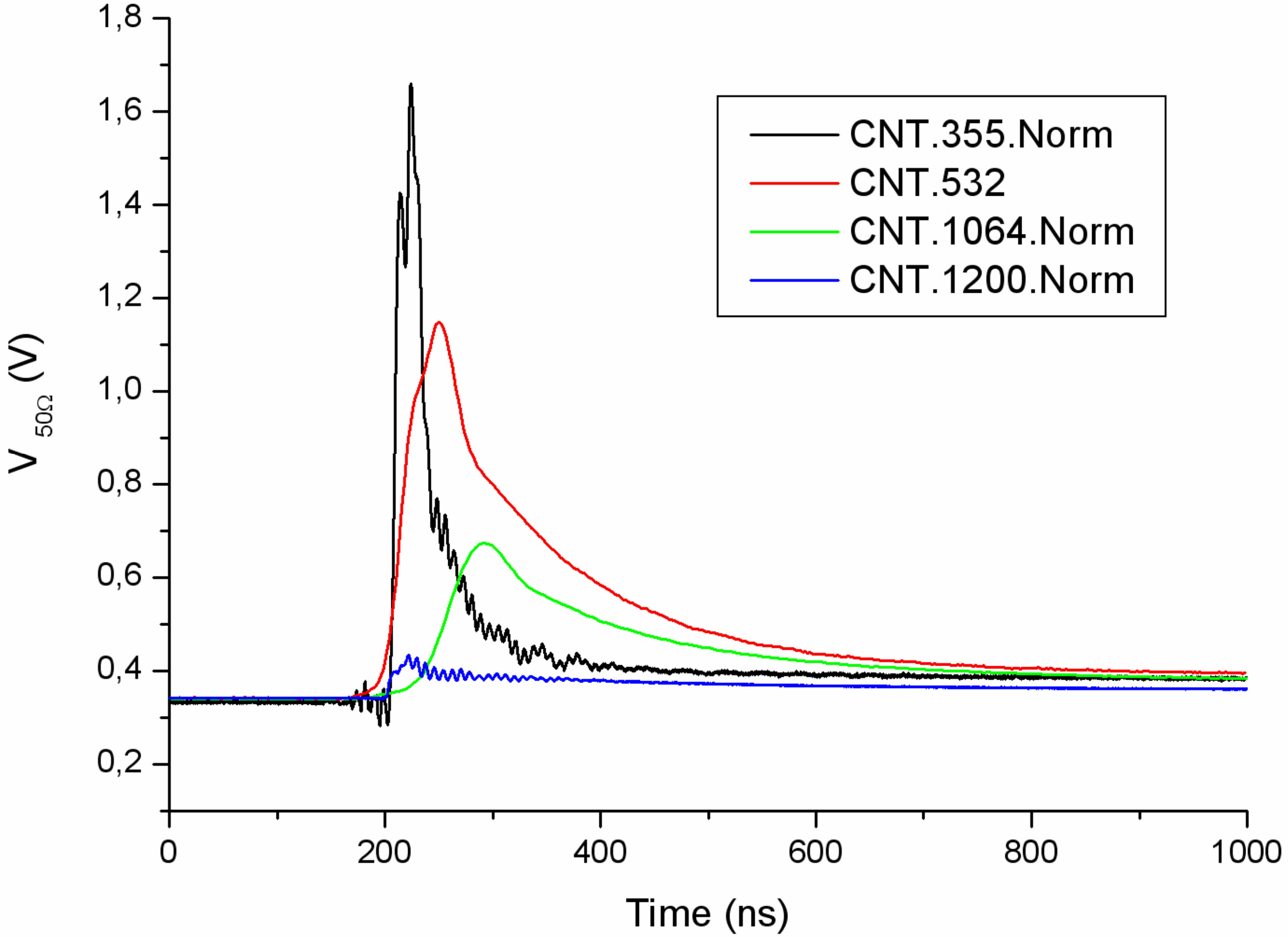


Trigger signal

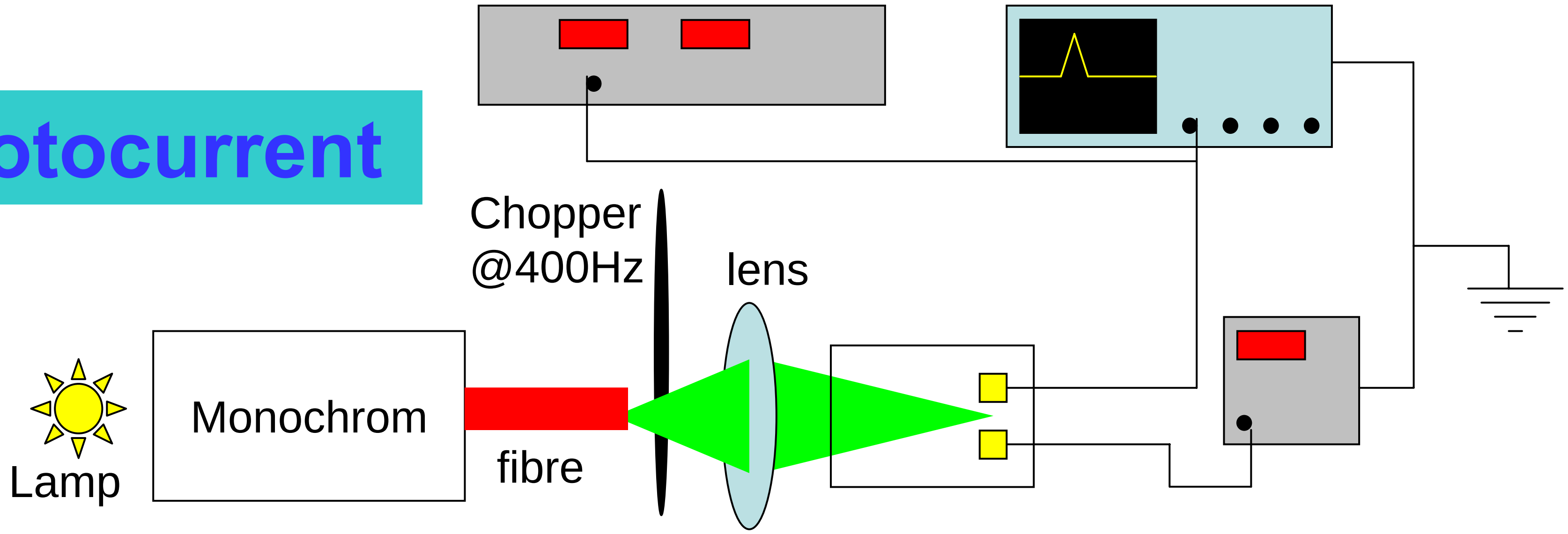
Laser 1064 nm on CNT



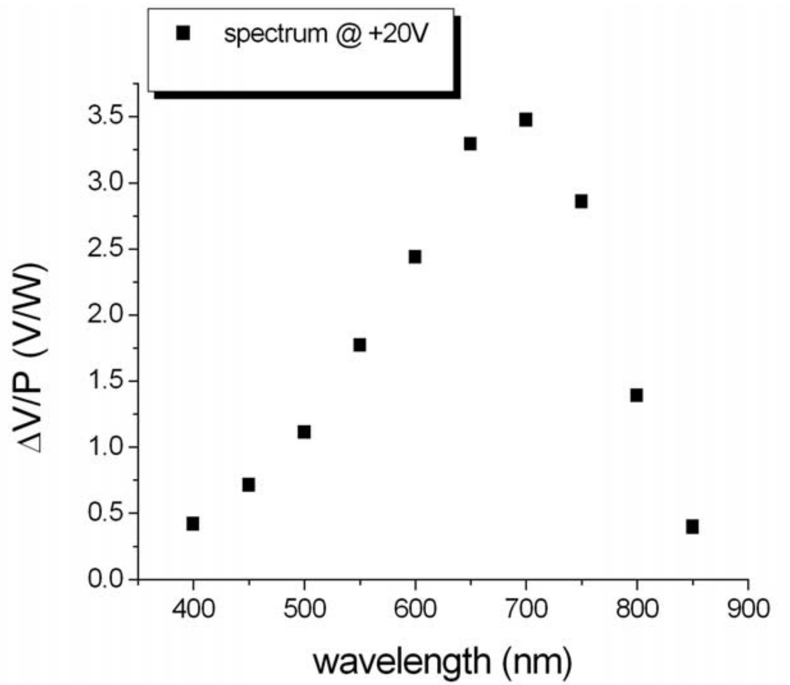
Comparison at different λ

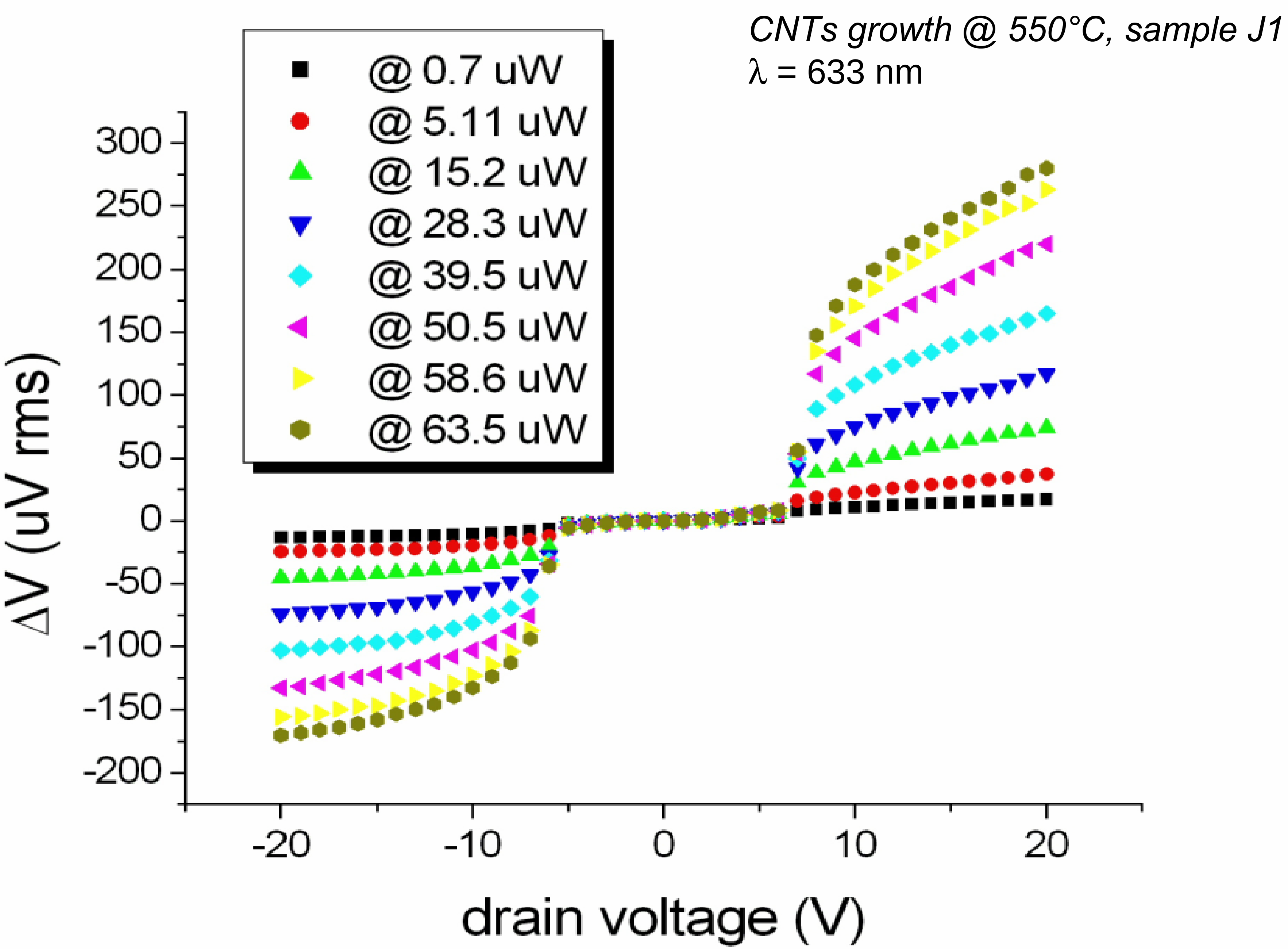


Photocurrent

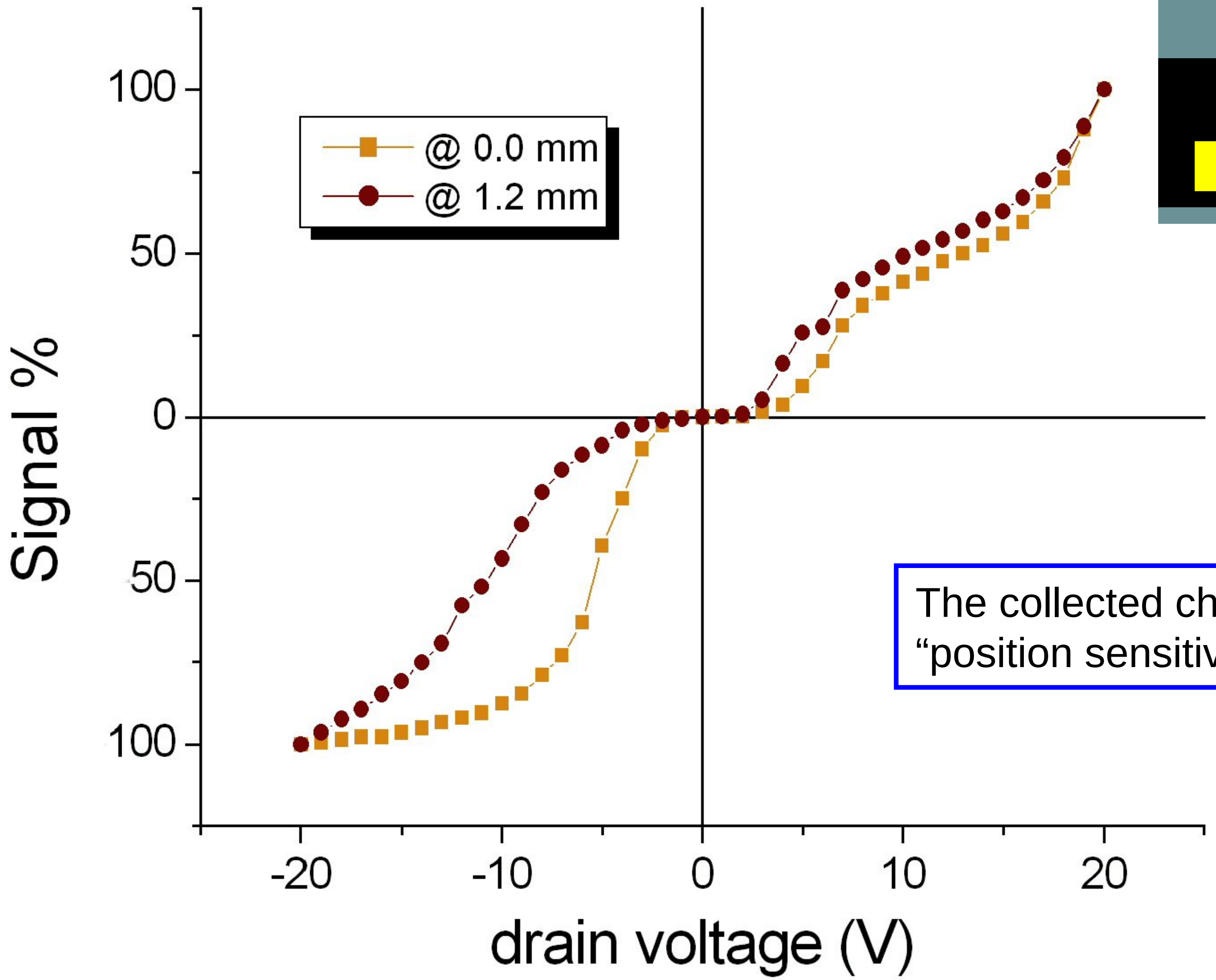


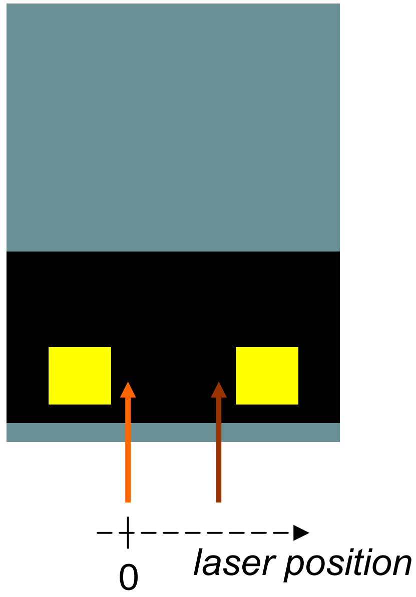
CNTs 550°C
@+20V drain voltage





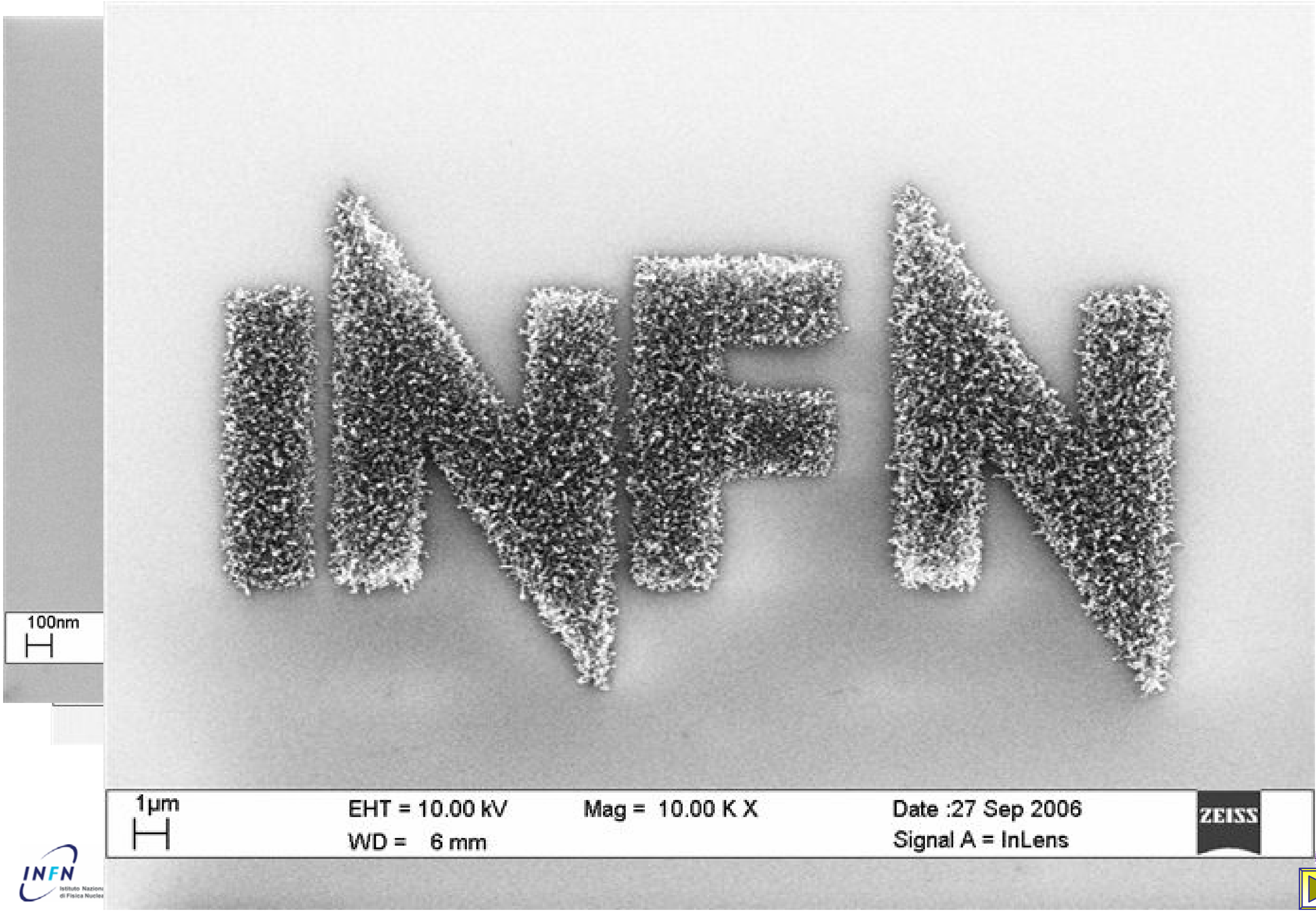
CNTs growth @ 550°C, sample J1
λ = 633 nm
@ 0.7 uW
@ 5.11 uW
@ 15.2 uW
@ 28.3 uW
@ 39.5 uW
@ 50.5 uW
@ 58.6 uW
@ 63.5 uW
ΔV (uV rms)
300
250
200
150
100
50
0
-50
-100
-150
-200
-20
-10
0
10
20
drain voltage (V)





The collected charge is "position sensitive"

Patternization



Conclusions

Carbon nanotubes promise to be very important in the next years as material with unique mechanical, optical and electrical properties

The possible application area of CNT is extremely large: idrogen cell, DNA manipulation, medical application, electronics, etc.

We can reasonably claim that we are at the beginning of the

POST SILICON ERA

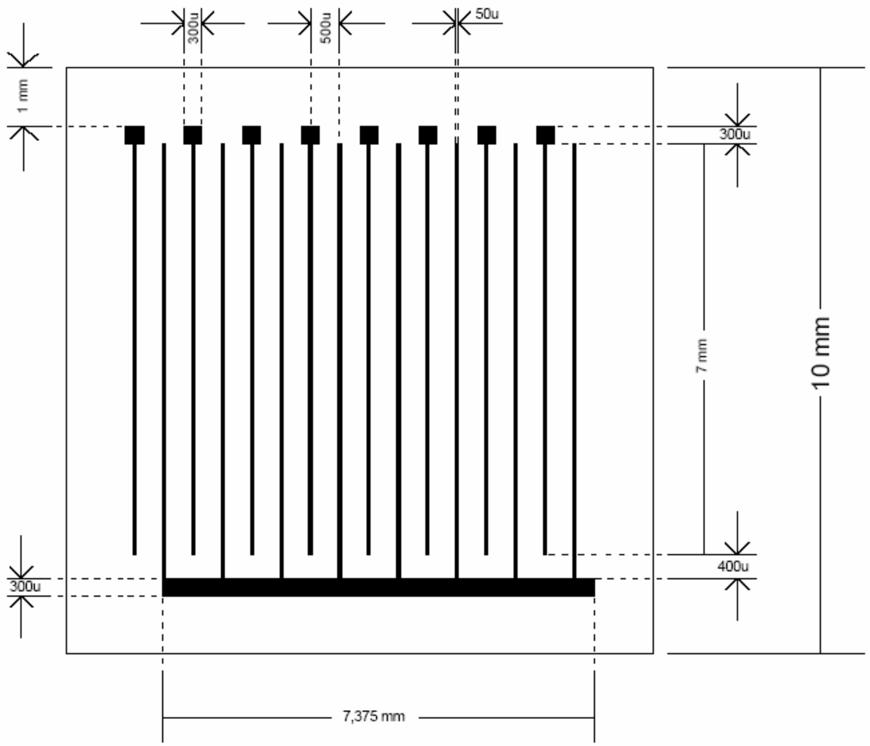
Conclusion (2)

The GINT collaboration is approaching the problem to build a large area, large frequency range, nano-pixelled, radiation detector with the use of CNT.

First results are very encouraging:

1. The CNT production has been strongly improved: MWCNT of quite good quality are now availables;
2. CNTs are analysed with optical methods (FTIR, TEM, SEM, SNOM, Raman) and electronics (I-V plot, field emission)
3. Analysis on CNT fotoconductivity properties is in progress;
4. CNT patternization in nanometric scale has been realized successfully;
5. CNT modelling is in progress.

We hope to rapidly address the work in the construction of a nano-pixelled large area radiation detector with nanometric accuracy



Thank you for your attention