Università degli Studi di Torino

Facoltà di Scienze MM.FF.NN.

Corso di Laurea in Fisica

## Tesi di Laurea Triennale in Fisica
## B.Sc in Physics - Degree Thesis

# “Definizione di un protocollo di caratterizzazione di semiconduttori per lo studio della loro resistenza da radiazione”

**“Definition of an experimental protocol for the characterization of semiconductors to study their radiation hardness”**

***Candidate: Nicolò Barbero***
***Supervisor: Prof. Ettore Vittone***

# The frequent problem of ionizing radiation induced damages

*Solar cells, environmental studies*

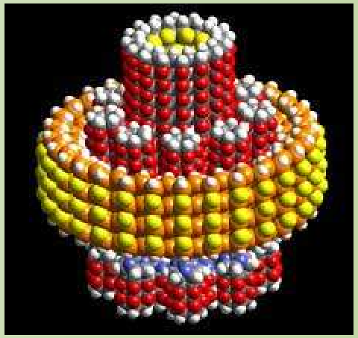
*Integrated circuits technology*

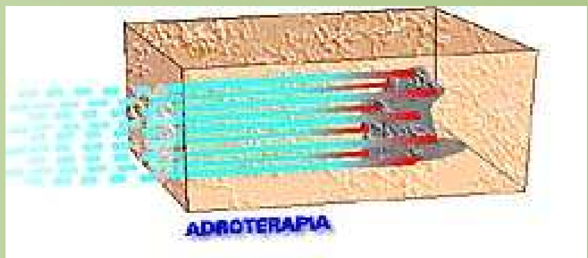
*ISS, Space technologies*

*AUGER, cosmic rays Physics*

***A better knowledge dealing with radiation hardness of several materials is a many-sided enrichment for science… from the upgrade of the particle detectors until the space tech. In many fields we have to face the problem of radiation induced damage.***

*Nanotechnologies*






*Hadron therapy*

*C ERN, high energy Physics*

# Electrical consequences of the ionizing radiation-induced defects

**RECOMBINATION MODEL (bulk generation rate contributions):**

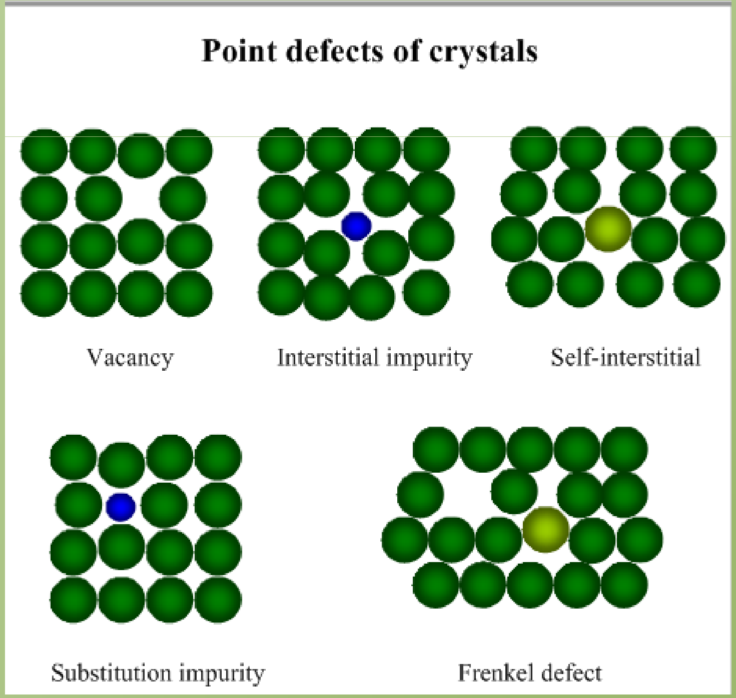
•Shockley-Read-Hall recombination
•Radiative recombination
•Auger recombination

**CONSEQUENCES OF DEFECTS**

•they act as recombination-generation centers (increase of reverse-bias voltage, volume-generated leakage current ∝ fluence Φ);

• they act as trapping centers where electrons and holes are captured but afterwards re-emitted with a certain delay;

• they can change the charge density in the depletion region ⇒ change of the electrostatics of the device as function of the fluence Φ.




*Source: SUBSTECH*

# We miss a definition of "radiation hardness"

The effects of radiation in semiconductors materials and devices have been studied for fifty years but there are still significant gaps dealing with:

•their effects on the electrical properties of the materials;

•the features of the radiation induced defects;

•a comprehensive definition of the radiation hardness.

**INTERNATIONAL ATOMIC ENERGY AGENCY INITIATED A PROJECT**

•established as an autonomous organization on 29 July 1957. Headquarters in Wien. Reports to the UN General Assembly and Security Council;

•151 member States;

*1.(right): IAEA (International Atomic Energy Agency) flag*
*2.(left): IAEA headquarters in Wien*

## Why an IAEA Coordinated Research Project (CRP) ?

**IAEA missions:**
**(from the IAEA statute)**

**•to accelerate and enlarge the contribution of atomic energy and its practical applications to peace, health and prosperity throughout the world;**
**•to implement safeguards to verify that nuclear energy is not used for any military purpose;**
**•to promote high standards for nuclear safety.**

**WHY A CRP?**

**The CRPs are projects coordinated by the IAEA to lead to:**
**•new knowledge and technologies in applied physics;**
**• the sharing of research results and facilities among the scientists and the institutes;**
**•the transfer of knowledge between developed and developing countries;**
**•the synergy with the on-going national and international activities.**

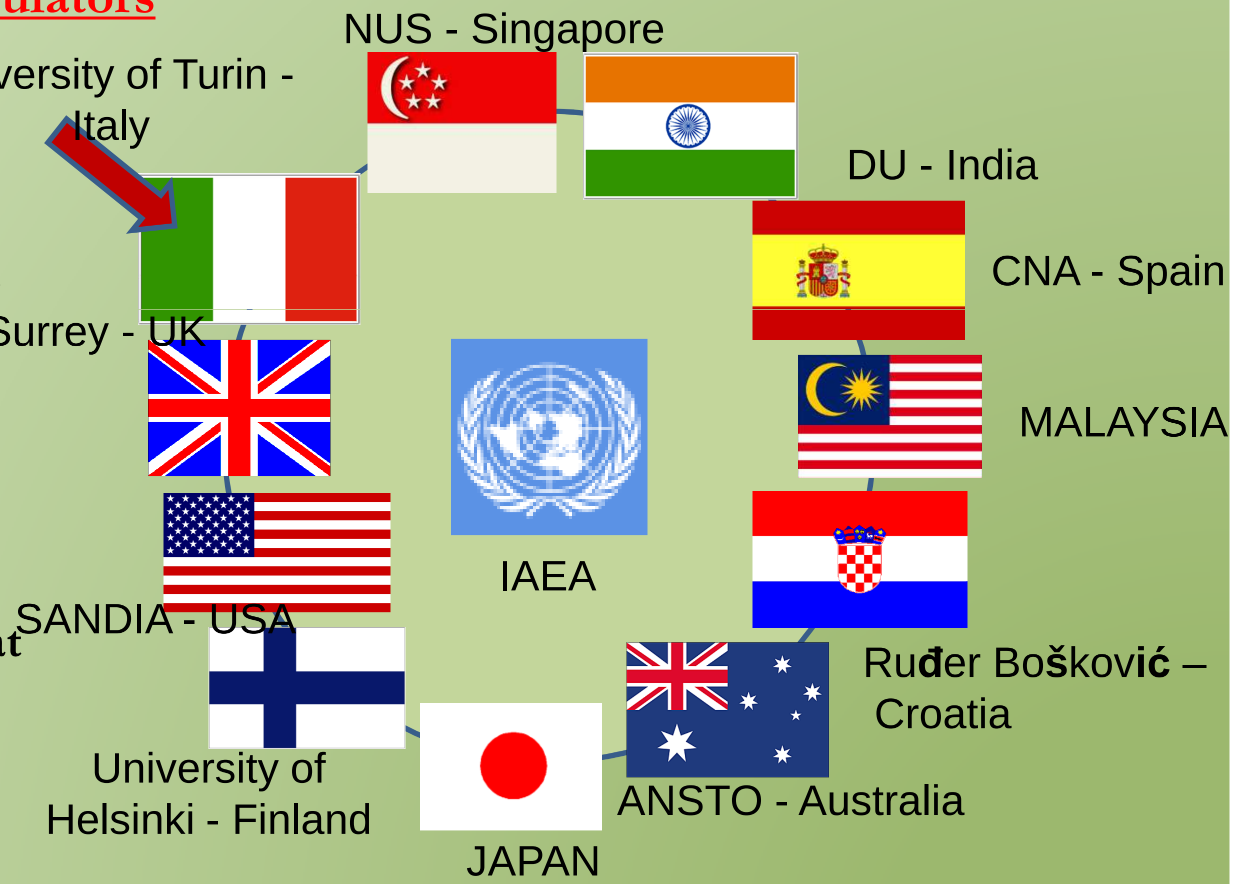
# The CRP n. F11016 about Radiation Hardness (2011-2015)

"Utilization of ion accelerators for studying and modeling of radiation induced defects in semiconductors and insulators"

COOPERATION AND MUTUAL UNDERSTANDING LEAD TO GROWTH AND GLOBAL ENRICHMENT

**MAIN FEATURES**

- MeV ions (from H until U): easily controllable fluence;
- thanks to CRP many facilities are available;
- MeV ions results can be extended to many situation where radiation damages happen as previously seen;
- anyone should be able to repeat the experiments ⇒ **EASY FABRICATION AND CHARACTERIZATION METHODS**



# Our goal: to define the "radiation hardness"

We would like to define an experimental protocol and a suitable theoretical model in order to evaluate the radiation hardness of <u>any semiconductor material and device (beginning from silicon).</u>

<u>THE STRATEGY WITHIN UniTo</u>

- a well known material → Silicon;
- a simple device → a Schottky diode as detector;
- a well defined cleaning procedure → RCA;
- a simple fabrication technique → thermal evaporation;
- a well defined set of characterization techniques → SPV,…
- a well defined procedure for device irradiation (ion type, energy, fluence)
- suitable computational tools for ion-matter interactions (SRIM or Marlowe);
- the development of a suitable model to interpret the performance degradation as function of radiation damage.

<u>EXTENSION TO OTHER MATERIALS</u>

# My activity

**0. Theoretical studies: extra contents available in COMPLEMENTS;**
**1. design and fabrication of Schottky diodes as a detectors;**
**2. XPS characterization of the original Silicon wafer;**
**4. electric characterization of the diode;**
**5. SPV characterization;**
**6. conclusions.**

**In collaboration with:**

**•NIS, Nanostructured Interfaces and Surfaces, Centre of Excellence in Turin (wafer cleaning);**
**•INRiM, National Institute of Metrological Research (microbonding);**
**•Vishay Corporation (wafers).**

*The "Mole Antonelliana", Turin*

## Wafer cleaning: a RCA modified protocol at NIS*

•the RCA (Radio Corporation of America) standard silicon cleaning protocol was modified according to the Italian safety law and to the quality needed for getting acceptable experimental results;

•WAFERS I1-2 (from INRIM**, n-type, ρ=3-6 Ωcm) and WAFER V1-25 (from VISHAY Corporation, n/n+ type, ρ(epi)=20-25 Ωcm).

PROTOCOL

• dip for 15 min the silicon samples in a 110°C boiling piranha solution (the sulfuric acid/hydrogen peroxide ratio 5). The oxidant effect will remove the organic residuals;

• rinse in DI water;

• dip dynamically the samples in a HF (2%, diluted with DI water) solution for some minutes (3-15 mins) to remove the silicon oxide on the surface;

• rinse for some seconds in DI water and then in methanol;

• finally dip in methanol.

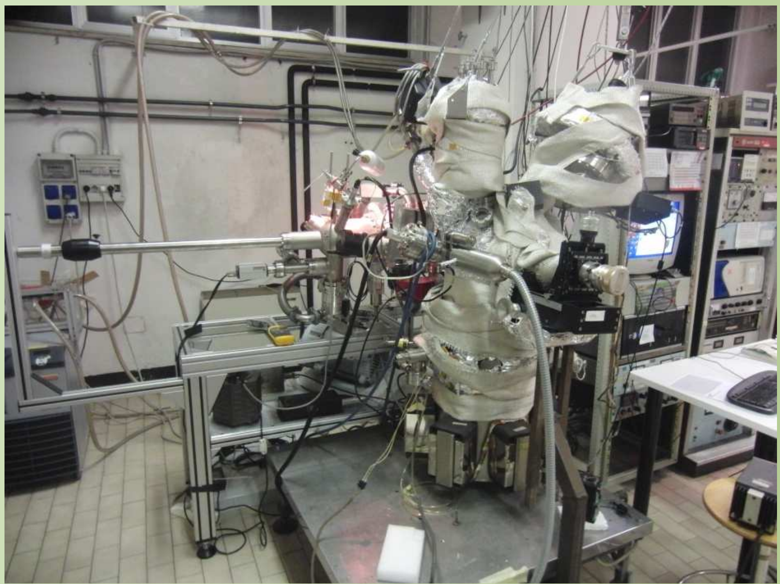

*Nanostructured Interfaces and Surfaces Centre, Turin

**National Institute of Metrology, Turin

# The XPS analysis at Solid State Physics Lab. (UniTo - Turin)

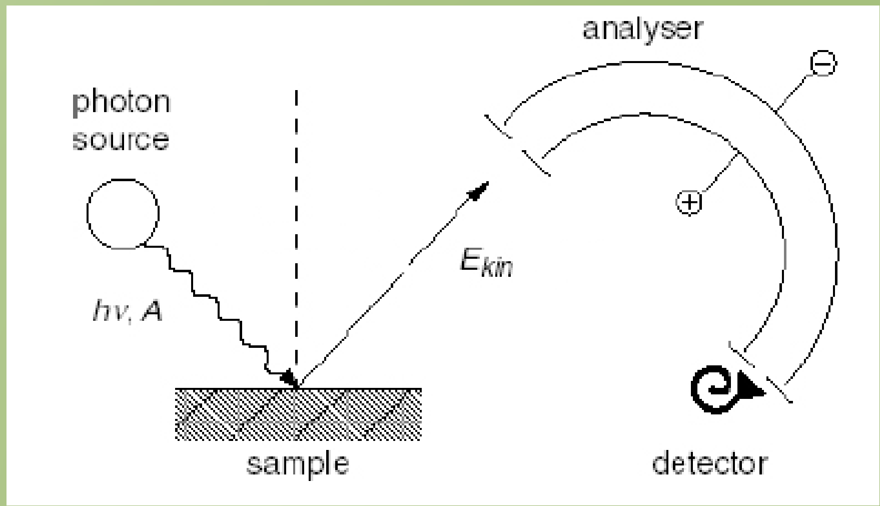
- The X-ray photoelectron spectroscopy is a surface characterization method.
- This photoelectric effect is due to the X-rays from a Al-Kα source (1486.6 eV).
- The observable measured by a CHA (concentric hemispherical analyzer) is the kinetic energy $E_{kin}$ of the emitted electrons. Auger peaks are excluded from the analysis.
- The setup operates in UHV (ultra-high vacuum, i.e.≈$10^{-9}$ mbar).
- The SAMPLING DEPTH is about three times the mean free path of the probe rays.
- The binding energies spectra is calculated from the kinetic energies of photoelectrons:

$$E_B = h\nu - E_k - e\phi_s$$

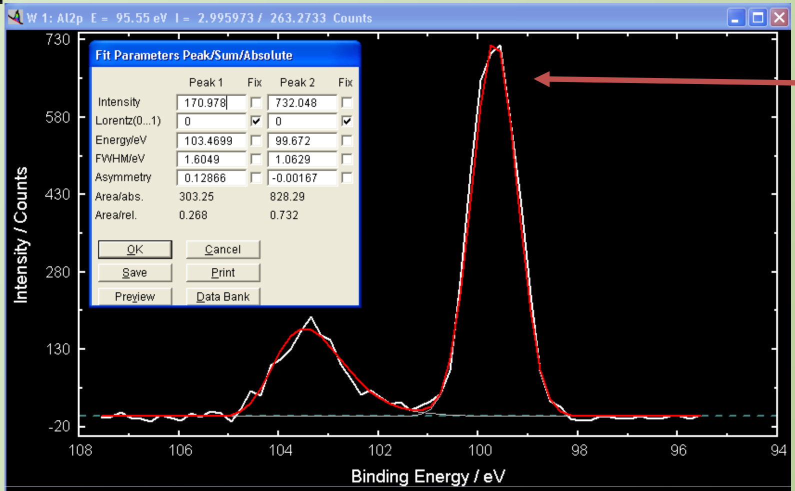


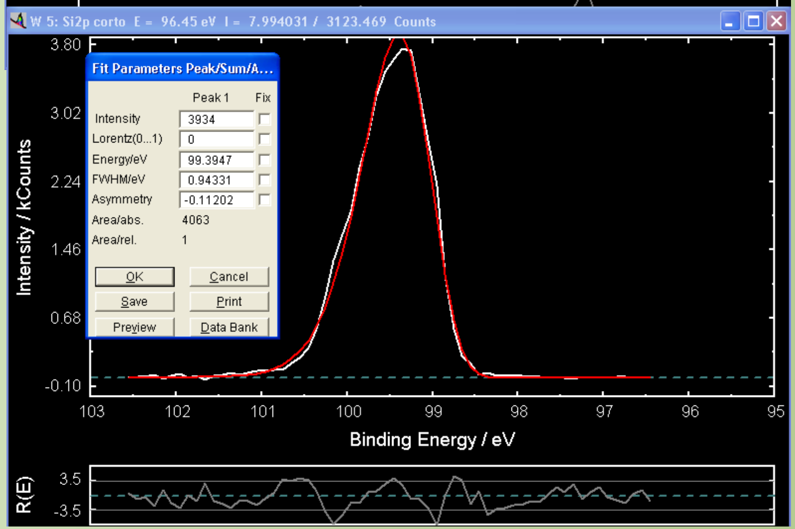
*Left: The XPS experimental setup;*

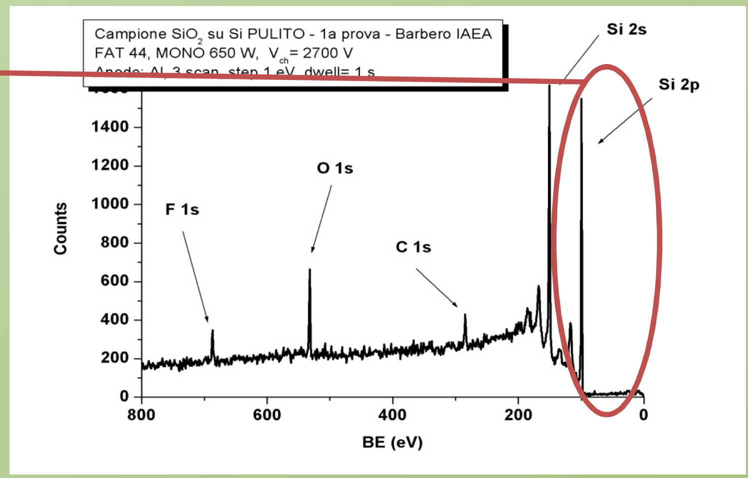
*Right: How does XPS work?*



# The XPS spectrum




**TOP**

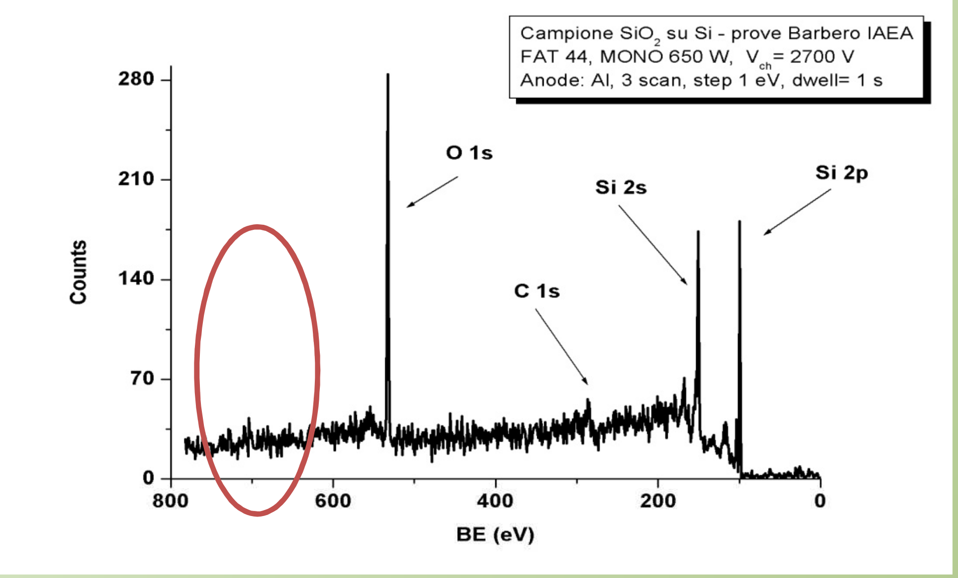
**2p-Si spectrum before cleaning protocol; chemical shift due to $SiO_2$.**

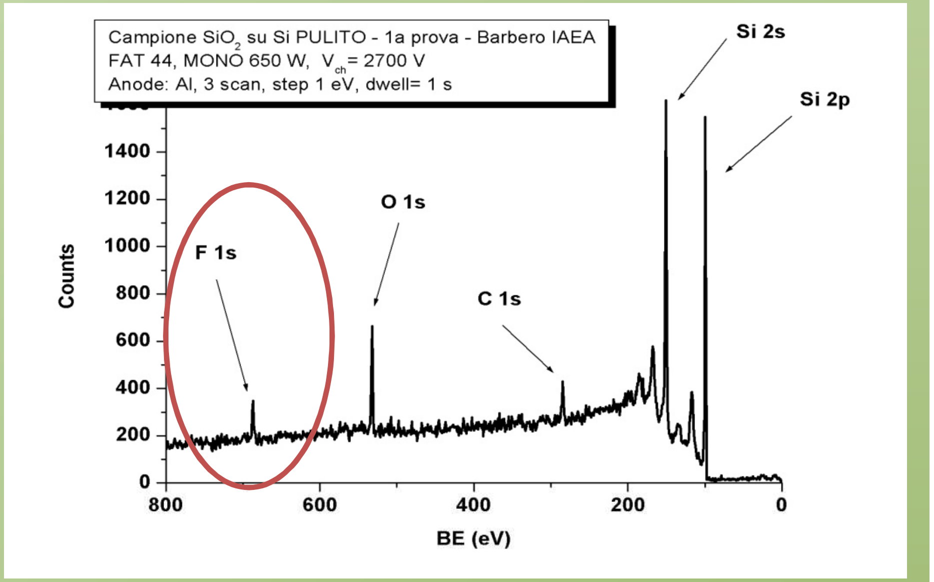
**BOTTOM**

**2p-Si spectrum after cleaning protocol; $SiO_2$ removed from the surface.**

*Special thanks to Alfio Battiato for the XPS measurements*

# The XPS surface analysis




**Above XPS spectra**

**Left: Before cleaning**

**Right: After cleaning**

FLUORINE ON THE SURFACE AFTER CLEANING

| SURFACE ANALYSIS | F (%) | Si (%) | O (%) | C (%) |
|---|---|---|---|---|
| **$SiO_2$ / Si** | 0.0 | 59.1 | 31.0 | 9.9 |
| **Si cleaned 1:10 HF** | 4.9 | 54.7 | 12.8 | 27.6 |
| **Si cleaned 1:10 HF, heated** | 2.7 | 75.5 | 11.2 | 10.7 |
| **Si cleaned 1:5 HF** | 1.9 | 79.2 | 8.8 | 10.1 |
| **Si cleaned 1:5 HF, heated** | 1.9 | 78.4 | 10.0 | 9.7 |

# Contact deposition: the thermal evaporator

The contacts were deposited by thermal evaporation, based on Joule effect.

*jack*

*high-vacuum chamber*

*porthole*

*cooling system (by water)*

*valve*

*turbomolecular pump*

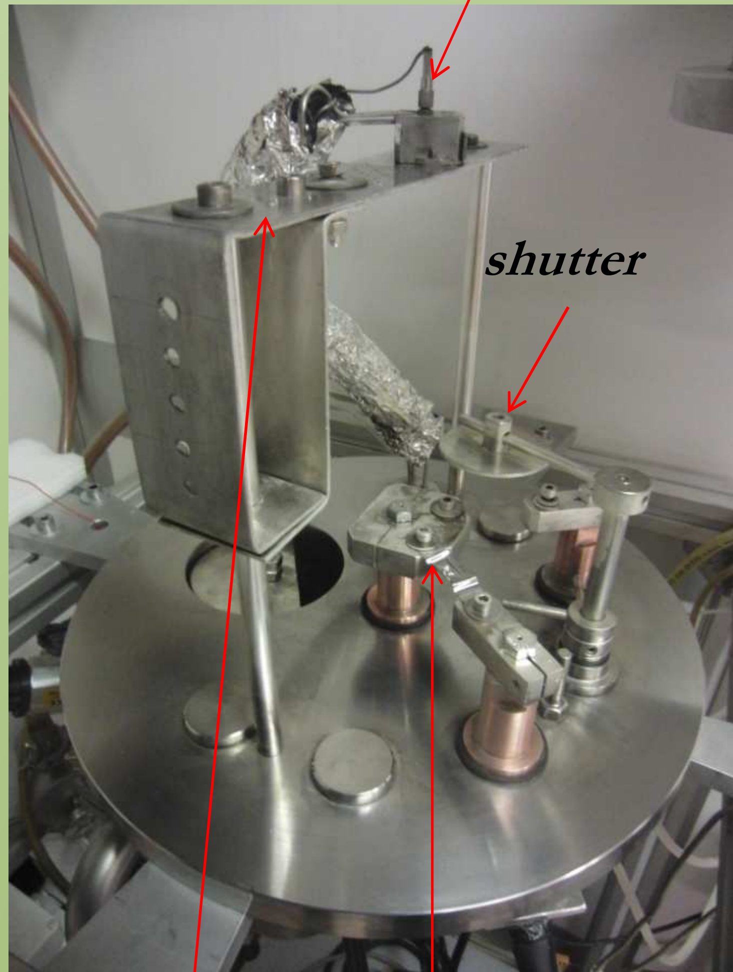
*vacuum gauge*

*displacement pump*

*power supply*

***quartz lattice vibration sensor for thickness measurements***

***shutter***

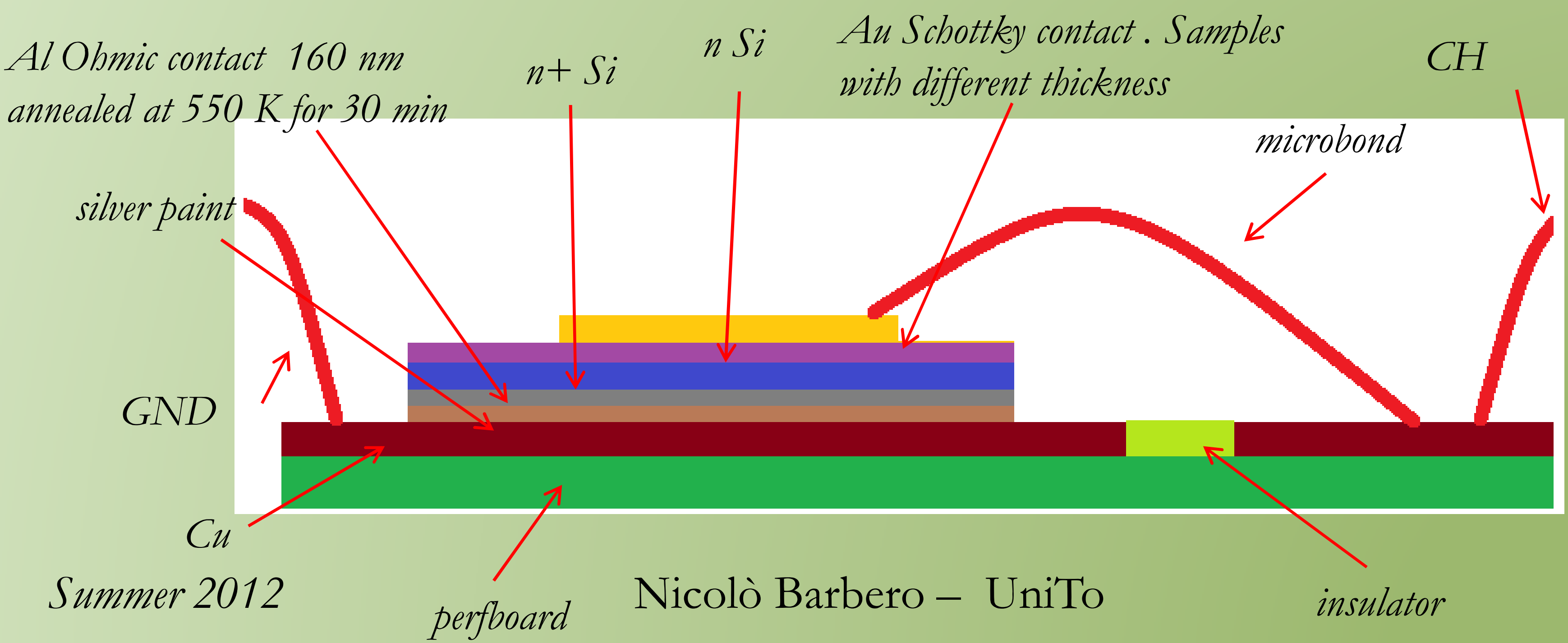


*sample holder* *boat with metal*

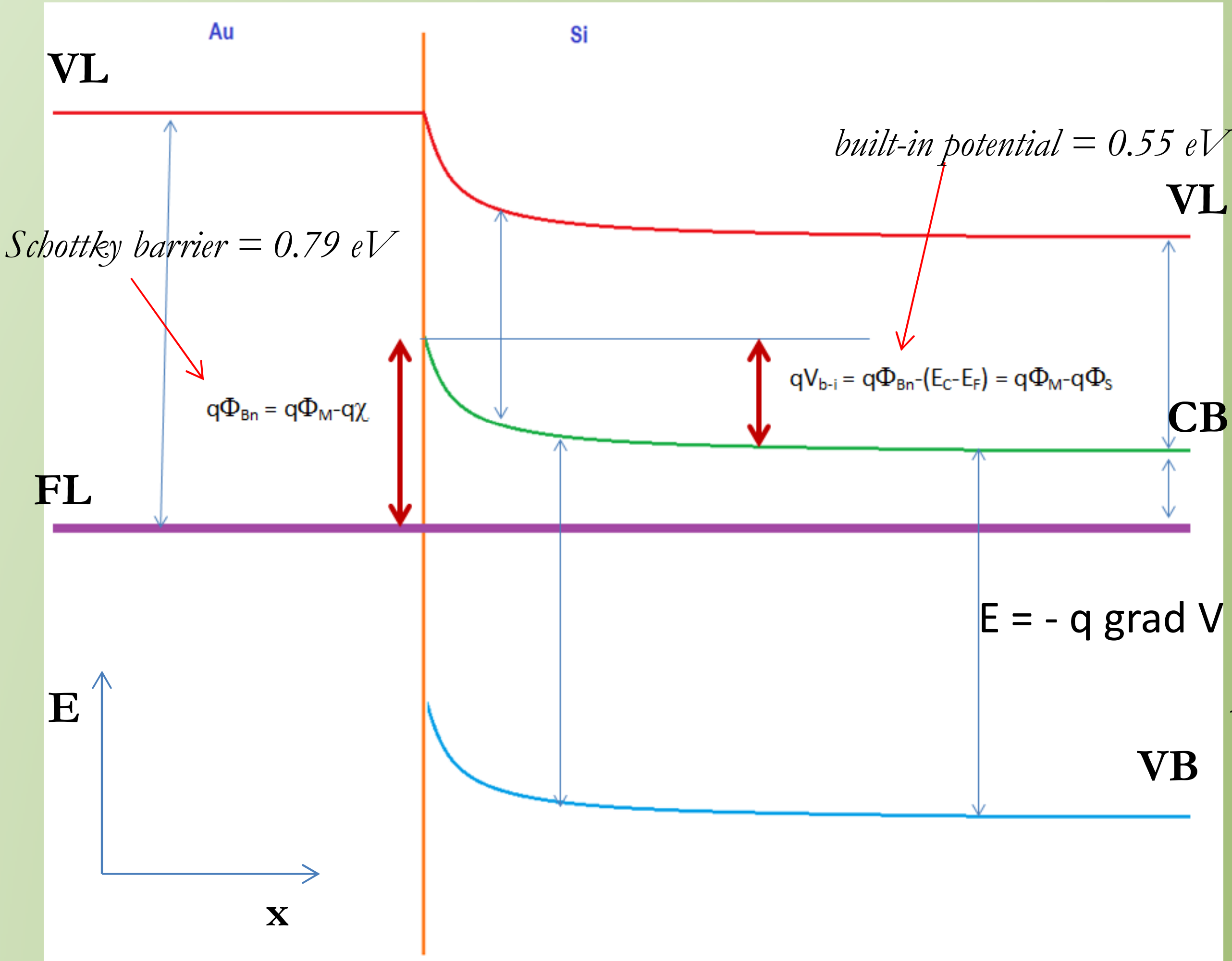
# Prototypes: the design

- Schottky contact: Pd, Au, Ag; Schottky barrier heights BH almost constant ⇒ theory of surfaces. The surface has more energy level than bulk;
- Ohmic contact: Al with annealing treatment;
- I prepared 15 samples called Star plus a progressive number;
- The best compromise is Au/n/Al (saturation current, BH,…).

*Star 3*



# Schottky diodes as detectors: the m-s junction




*Conservation of the three intrinsic properties*

↓

*Bands distortion*

$$\frac{dE}{dx} \qquad \frac{d^2E}{dx^2}$$

E = - q grad V = q $\mathcal{E}$ | div $\mathcal{E}$ = -ρ/ε

***POTENTIAL BARRIER, ELECTRIC FIELD***

***SPACE CHARGE***

FIXED DONORS (+)

$\varepsilon_{Si}$ = 1.03 pF/cm

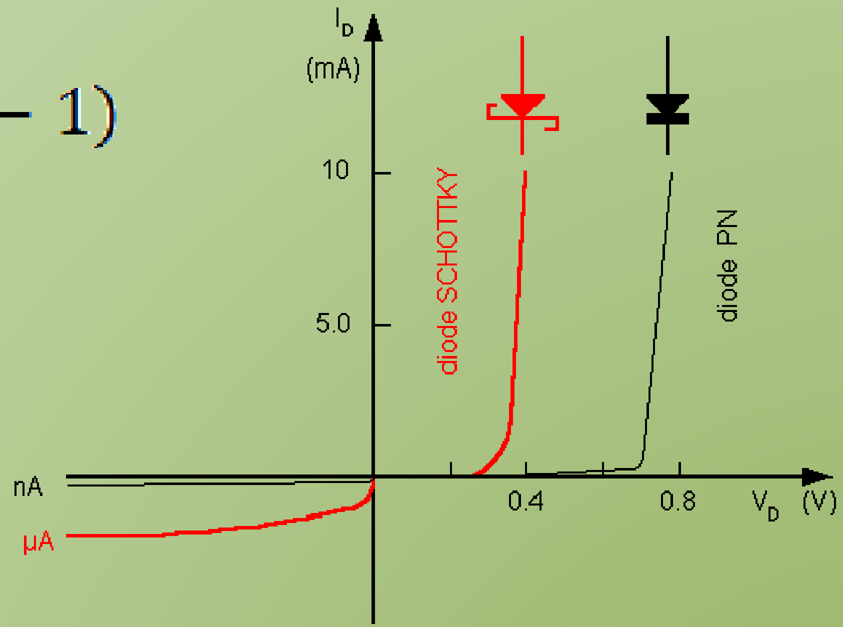
# Schottky diodes as detectors: The I-V characteristic

**Schottky diode: lower voltage drop and higher switching speed. The Shockley equation expresses the I-V characteristic:**

$$I = I_S\left(e^{\frac{eV}{\eta k_B T}} - 1\right)$$

**The law of Richardson-Dushmann shows that the saturation current is exponentially dependent upon the barrier height:**

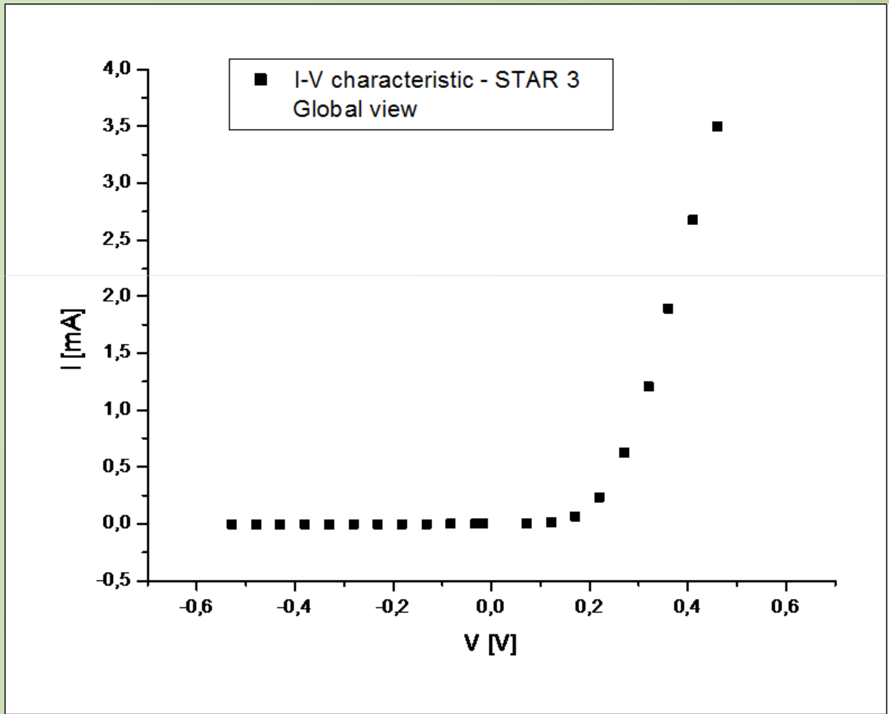
$$J_S = A^* T^2 e^{\frac{-e\Phi_{Bn}}{k_B T}}$$



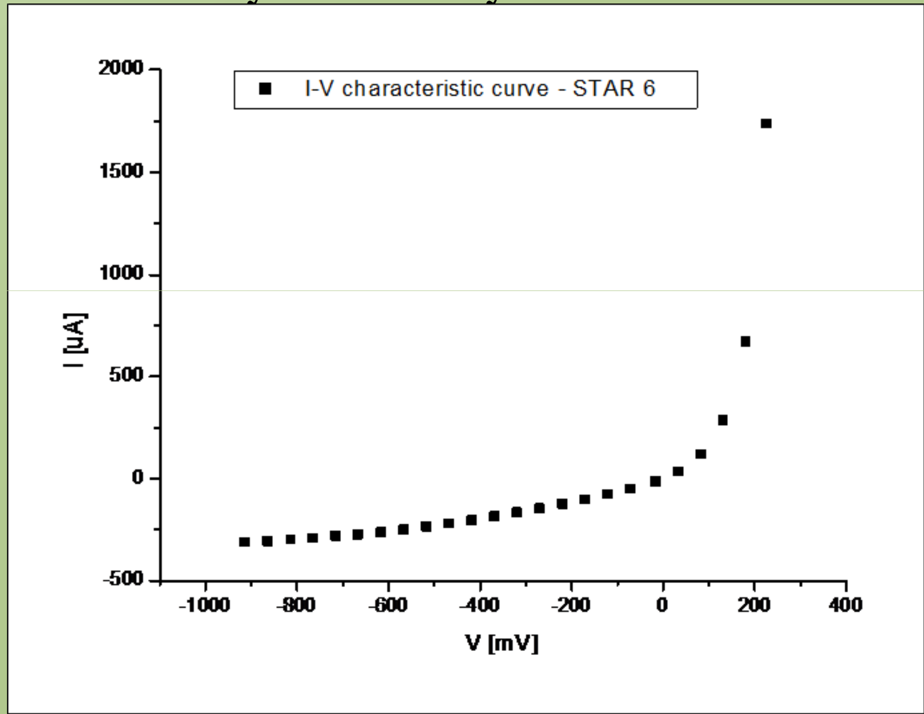

**•In a NP diode the order of magnitude of saturation current is ~nA while in a Schottky diode is µA.**

# Electric characterization of the diodes: I-V, global view

**Diode Star 3 (Au[250nm]/Si[n]/Al[160nm]) and Star 6 (Au[160nm]/Si[n/n+]/Al[160nm]) - biased with a Keithley 617 picoamperometer and the voltage was measured by a Keithley 177.**

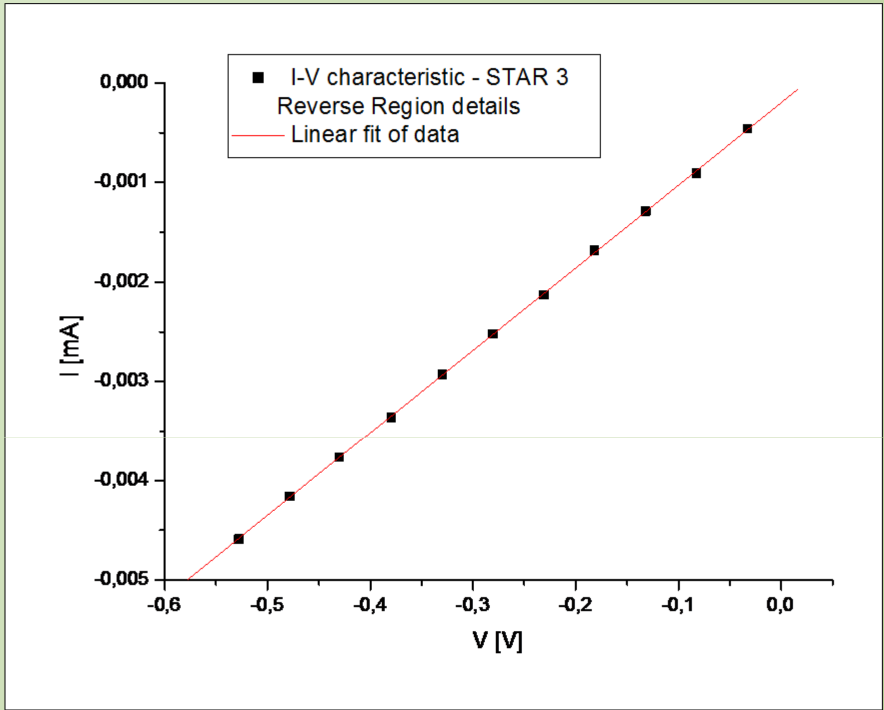


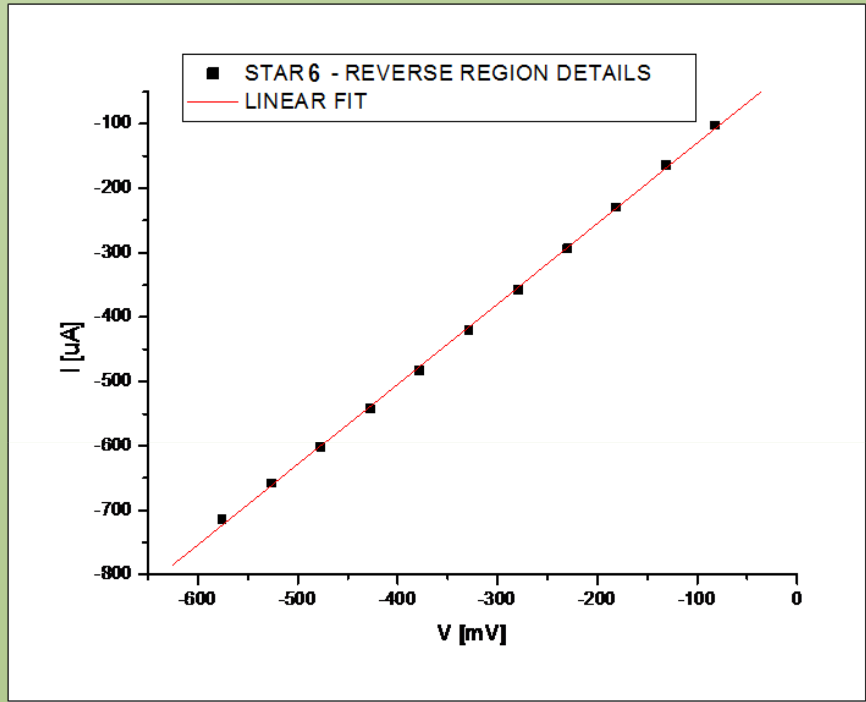

STAR 3, Schottky contact thickness: 250 nm




STAR 6, Schottky contact thickness: 160 nm

# Electric characterization of the diode: I-V, reverse region




**SLOPE = 8.3±0.3 uA/V**
**⇒ R = (120±10) kΩ**

**SLOPE = 12.41±0.07 uA/V**
**⇒ R = (81±3) kΩ**

**WHAT DOES IT MEAN?**

## Problems and a possible model

- High reverse saturation current ⇒ high noise for nuclear measurements…
  - Shunt resistance (f-b leakage (passivation needed), defects…)
  - Tunnel transmission ? The tunnel resistivity can be expressed as:

$$\xi \propto e^{\frac{4\pi\sqrt{m^{*}\varepsilon_S}\Phi_{Bn}}{w\sqrt{N_D}}}$$

MODEL×

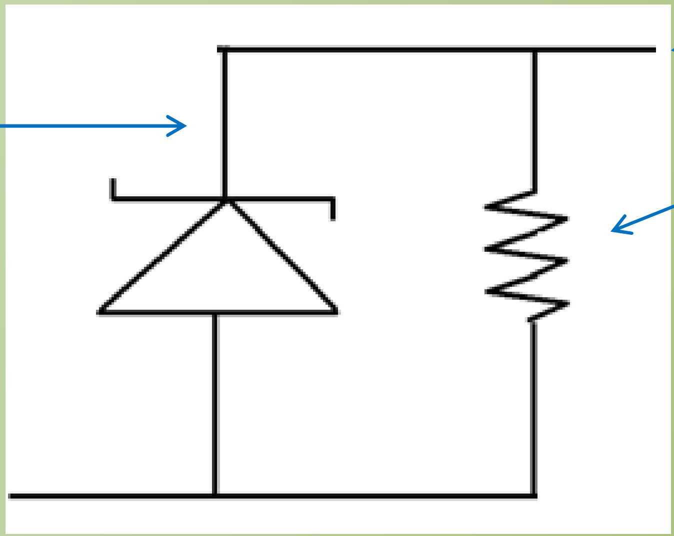
***the real diode is the effect of mutual interactions of these structures due the deposition and surface irregularities.**

*Ideal Schottky diode: themionic current + (?) tunnel current*

*INPUT*

*Shunt Resistance due to defects, and conductive films (fluorine?)*

*OUTPUT*



*WITHOUT PASSIVATION:*

## The SPV (Surface PhotoVoltage) characterization method

**The SPV method was adopted to evaluate the quality of the material, expressing it by the diffusion length L, i.e. strictly related to the mean minority charge carrier lifetime.**

$$L_n = \sqrt{D\,\tau_R} \quad \leftarrow \quad D = \mu k_B T$$

**This quantity well estimates the quality of the material because, according to the Shockley-Read-Hall model, L is inversely proportional to the trapping centers density, i.e. impurities and defects.**

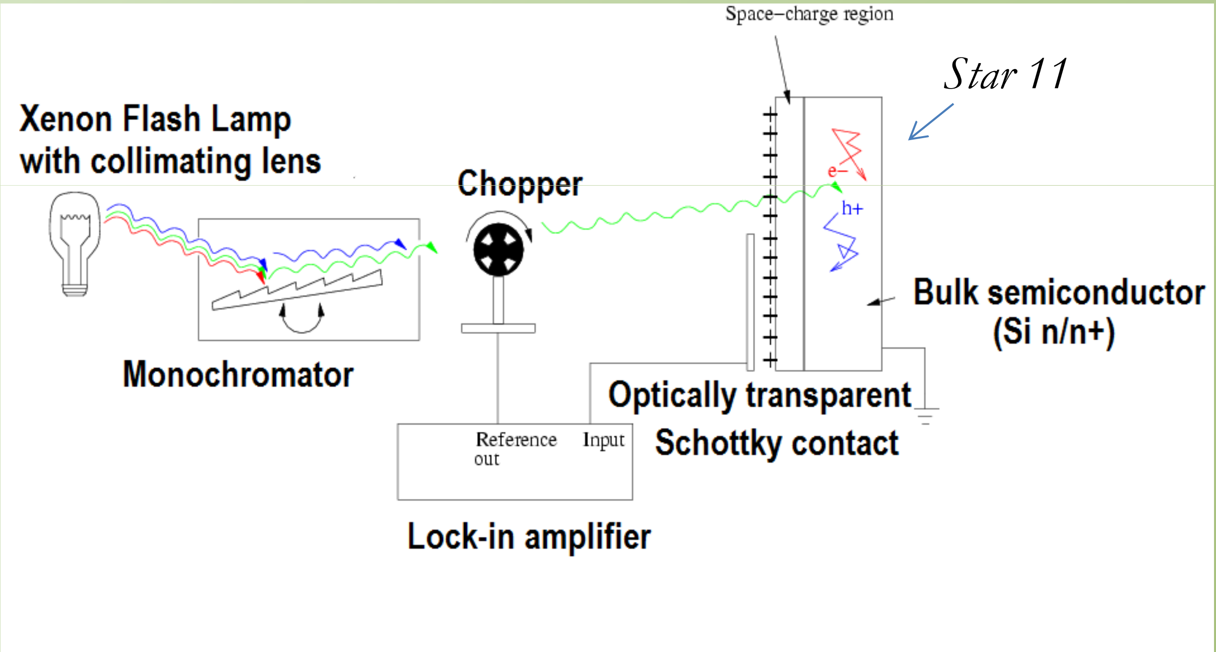
**For electronic grade materials the order of magnitude is of micrometers' tens.**

**THE EXPERIMENTAL SETUP**

# SPV theory and experimental setup

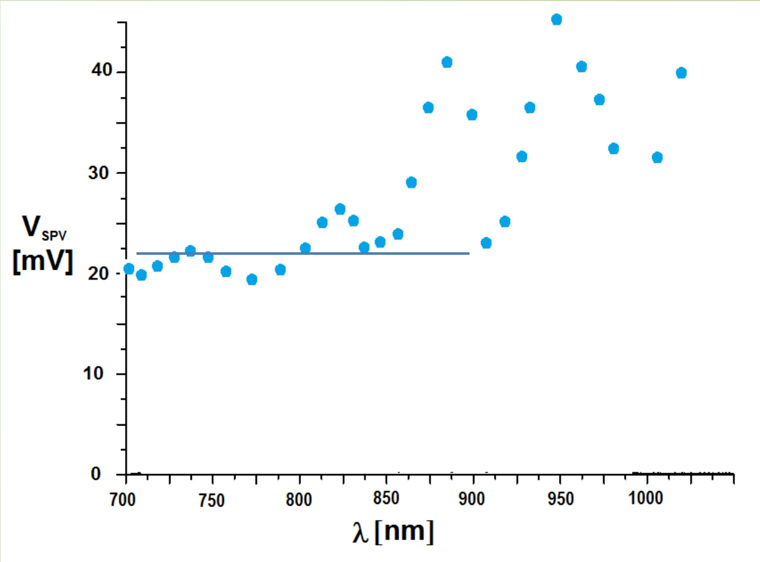
**The Surface PhotoVoltage $V_{SPV}$ can be expressed as:**

$$V_{SPV} = A \frac{(1-R)\Phi L_n}{\left(v_{SR} + \frac{D_n}{L_n}\right)\left(L_n + \frac{1}{\alpha}\right)}$$




**L: diffusion length**
**Φ: flux**
**R: reflectivity**
**v: surface recombination velocity**
**D: diffusion coefficient**
**α: absorption coefficient**

# SPV: Modus Operandi




$$800nm < \lambda < 1100nm$$

**Valid for silicon. See bibliography**

$$\alpha = \left(\frac{84.732}{\lambda} - 76.417\right)^2$$

**IMPORTANT OBSERVATION:**

**$V_{SPV}$ constant ⇒ R, D, v ≅ const**

$$V_{SPV} = A\frac{(1-R)\Phi L_n}{\left(v_{SR}+\frac{D_n}{L_n}\right)\left(L_n+\frac{1}{\alpha}\right)}$$

$$\Phi = B\frac{1}{\alpha} + BL_n$$

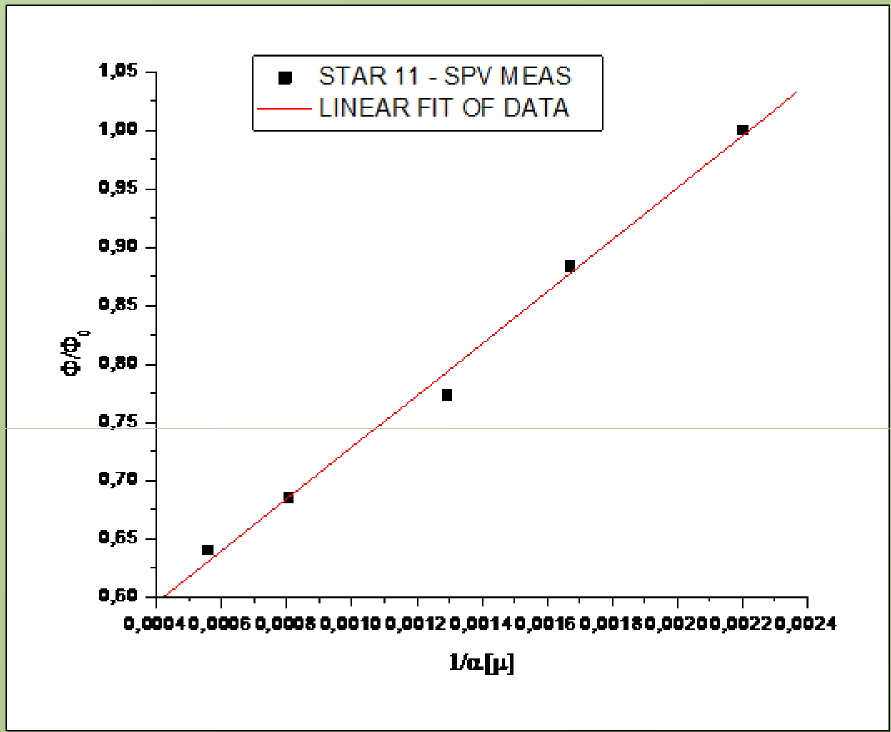
# SPV: data acquisition and analysis

$$\Phi = B\frac{1}{\alpha} + BL_n$$

$\propto$ **Power x ( λ/Sensitivity)**

**Photodiode with multimeter (reverse-biased)**

**Photodiode calibration curve**




**L = (23.9±1.4) μm**

## Conclusions

**What I did:**

- **definition of an experimental protocol for cleaning the silicon wafers;**
- **XPS characterization of the wafer before and after cleaning it;**
- **definition of a metallization protocol (for Schottky diodes' fabrication);**
- **electrical characterization of the devices;**
- **analysis and discussion of the data and of the problems involved;**
- **SPV characterization of the devices: definition of the experiment and of the procedure to determine the charge carrier lifetime.**

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**I think that everybody can teach us something. What today may seem uncorrelated to it, tomorrow might be its main explanation. I will try my best to contribute to the great and ambitious dream that Physics expresses: the knowledge of nature.**

## Acknowledgments

**I'm very grateful to all the people who with their love, esteem, knowledge and wisdom helped me during the B.Sc degree studies and thesis.**

**Many thanks to Prof. Shyama Rath (DU – India) and Prof. Mark Breese (NUS – Singapore) for the attention given to me.**

# Thanks for your kind attention!

**All data and more details in this paper are available… please send a message to my e-mail: arist.atin@yahoo.it or nicolo.barbero@studenti.unito.it.**

# Fundamental Bibliography and Sources


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