

Electrical activation of implanted dopants: statistical mechanical aspects of defect recovery and Hall effect characterization.

Virginia Boldrini ^{a)} and Marco Pieruccini ^{b)}

National Research Council (CNR) - Institute for Microelectronics and Microsystems (IMM)

a) E-mail: boldrini@bo.imm.cnr.it

b) E-mail: marco.pieruccini@cnr.it



 Institute for
Microelectronics
and Microsystems

Consiglio Nazionale delle Ricerche

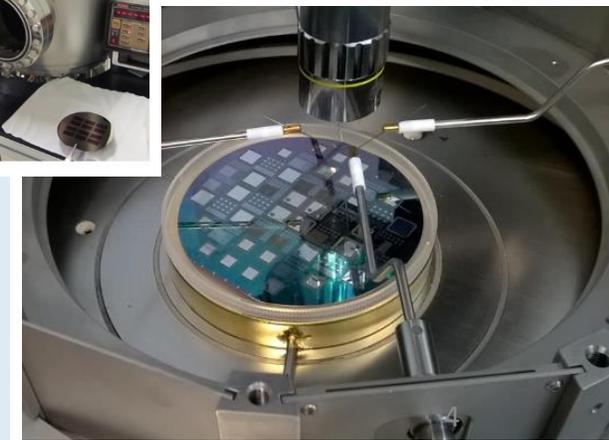
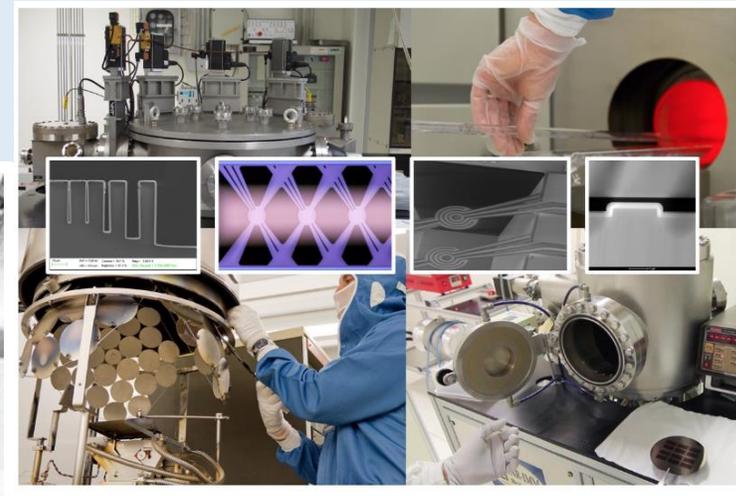
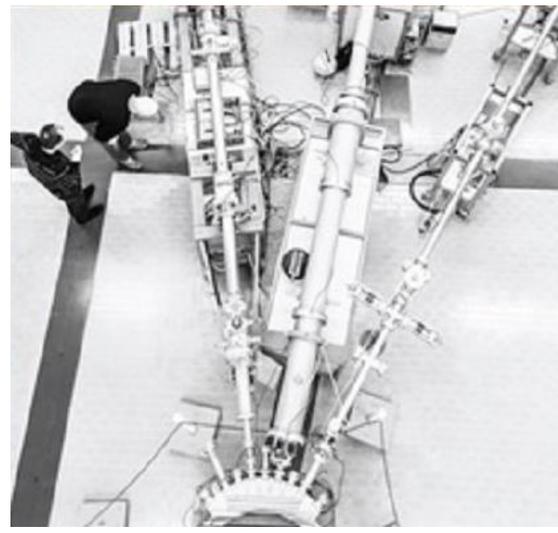
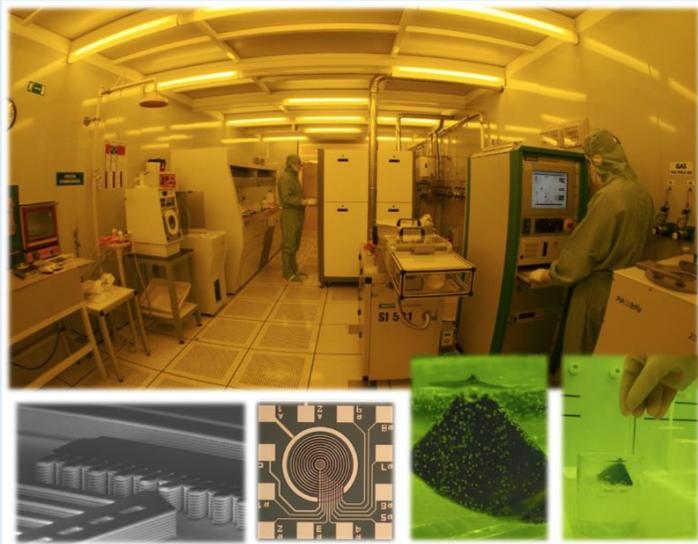
Electrical activation of implanted dopants: statistical mechanical aspects of defect recovery and Hall effect characterization.

Virginia Boldrini ^{a)} and Marco Pieruccini ^{b)}

National Research Council (CNR) - Institute for Microelectronics and Microsystems (IMM)

a) E-mail: boldrini@bo.imm.cnr.it

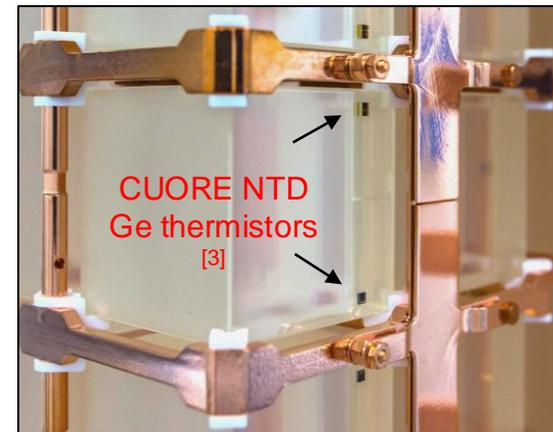
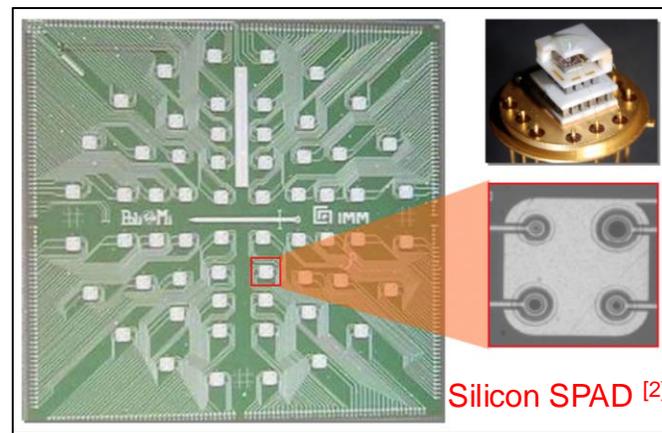
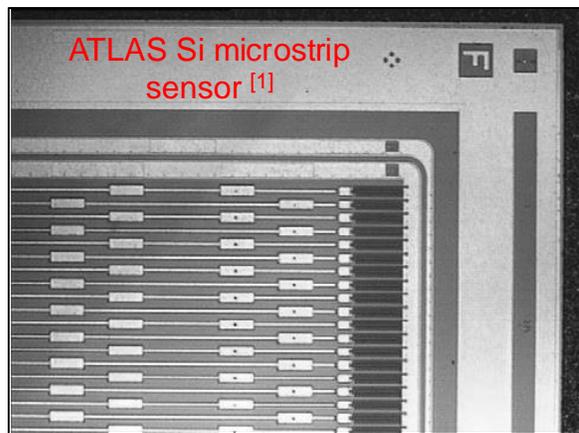
b) E-mail: marco.pieruccini@cnr.it



Nuclear and particle physics need electronic devices

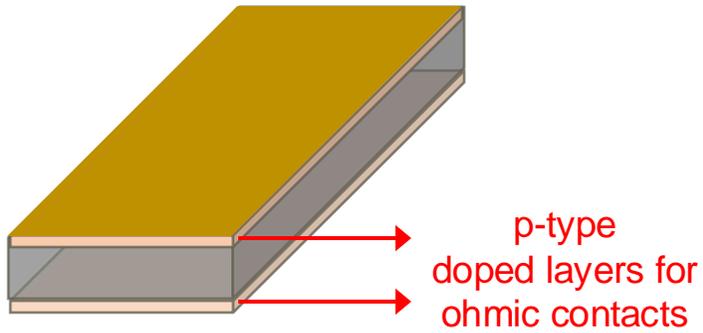
During a nuclear or particle physics experiment, it is often necessary to measure several quantities such as the particle energy, momentum, position, count, or environmental parameters. The **electrical transduction** mechanism is one of the most commonly used to carry out this type of measurements.

Hence, it is crucial to pursue a continuous **R&D activity** on electronic devices, gaining more and more knowledge on the functioning of the materials that mostly compose them: **semiconductor materials**.

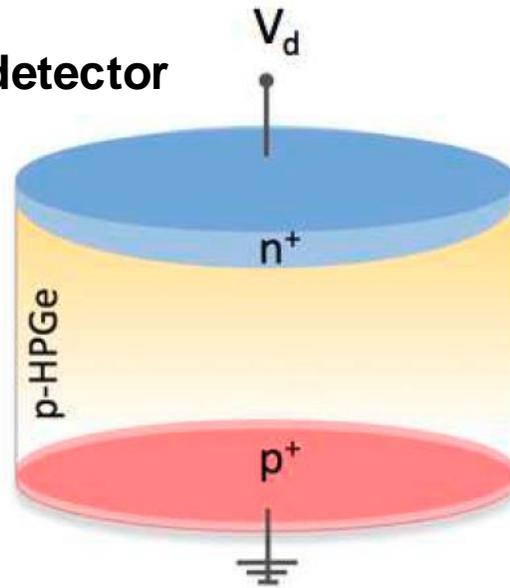


Most of the electronic devices contains doped layers

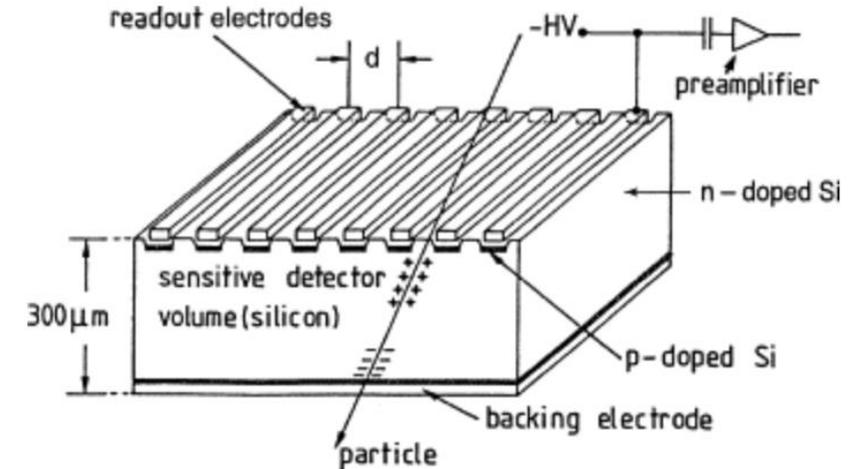
Ge bolometer



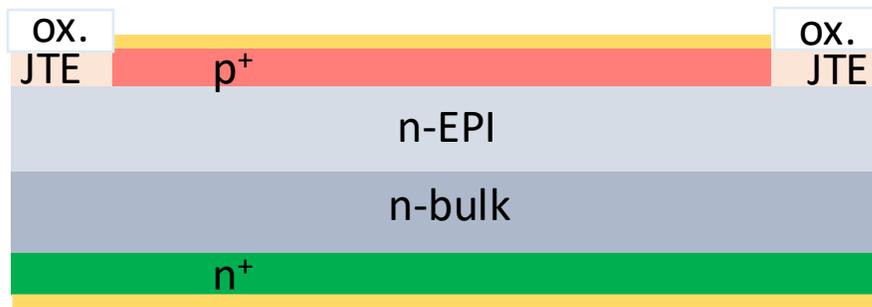
HPGe detector



Si microstrip detector



SiC PiN diode



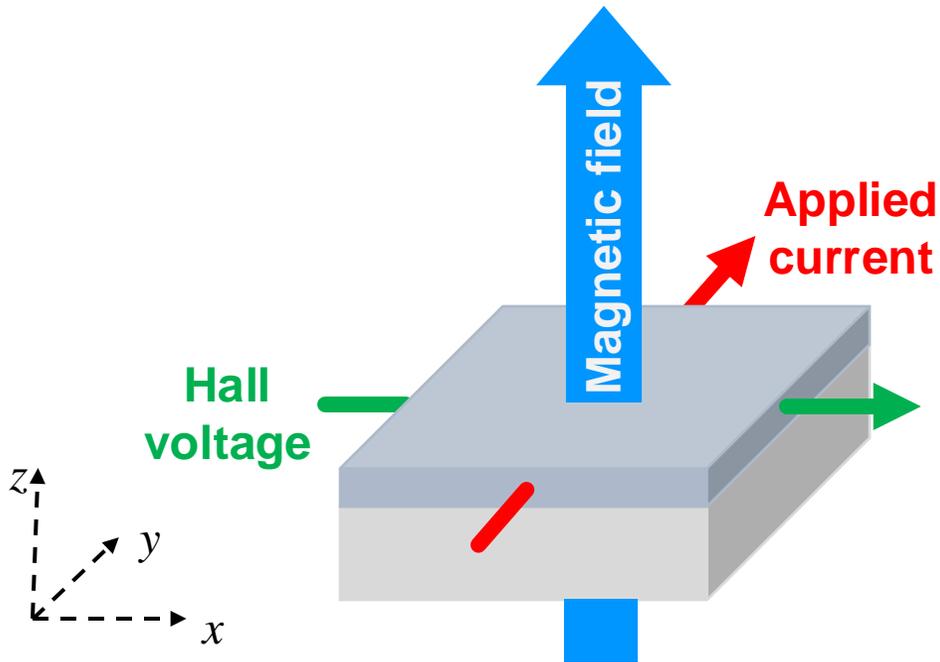
Doping techniques:

- ion implantation;
- equilibrium or quasi-equilibrium thermal diffusion;
- out-of-equilibrium laser thermal annealing (LTA);
- epitaxy.

... whatever technique you use, electrical activation is not guaranteed

ELECTRICAL ACTIVATION of a dopant = when the impurity atom locates substitutional in a reticular site being able to share its excess carrier, which will take part to the electrical transport in the extended states of conduction or valence band. To quantify the electrical activation we have to probe the electrical transport.

Hall-effect characterization:

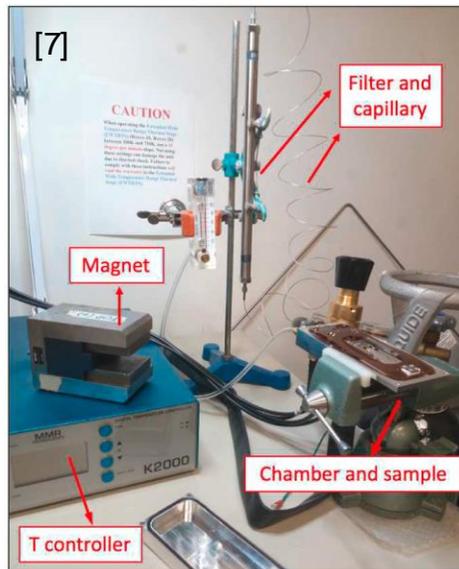
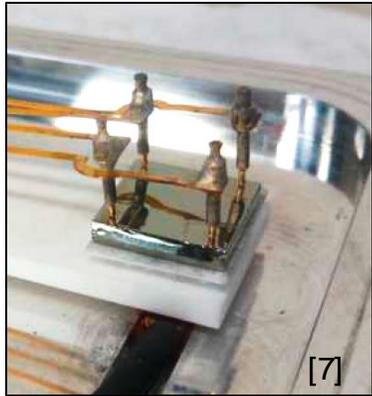


It is a technique for the electrical characterization of doped semiconductor layers. It allows to measure the density of free charge carriers available for the conduction and their sign: - for electrons and + for holes.

Based on the Lorentz force: $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B})$

At the steady state along the \hat{x} direction:
$$V_{Hall} = \frac{I \cdot B}{n \cdot t \cdot e}$$

Experimental setup for resistivity and Hall-effect measurements



For room temperature measurements:

- permanent or variable magnet in the range 0.5 – 1 Tesla;
- sample holder and 4 point probe system;
- current source and voltmeter, or source-measure unit (IMPORTANT! high voltmeter sensitivity μV or nV);
- switch matrix;
- computer with a software for automated measurements and data acquisition.

For low and high temperature measurements you need also:

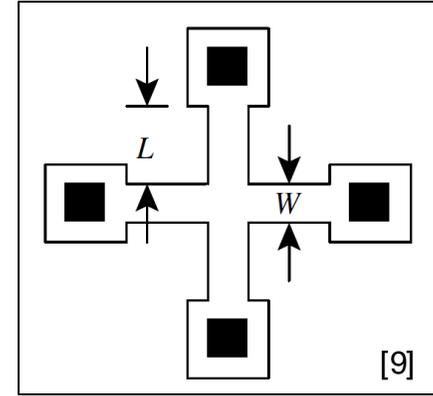
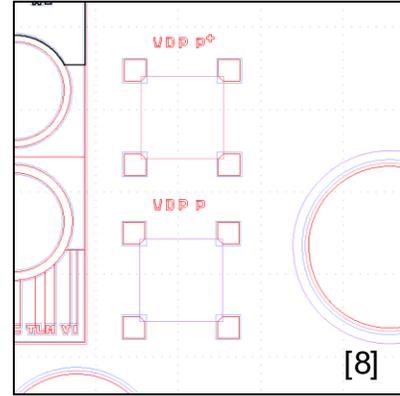
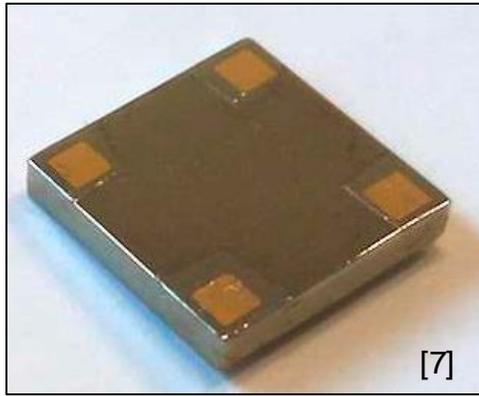
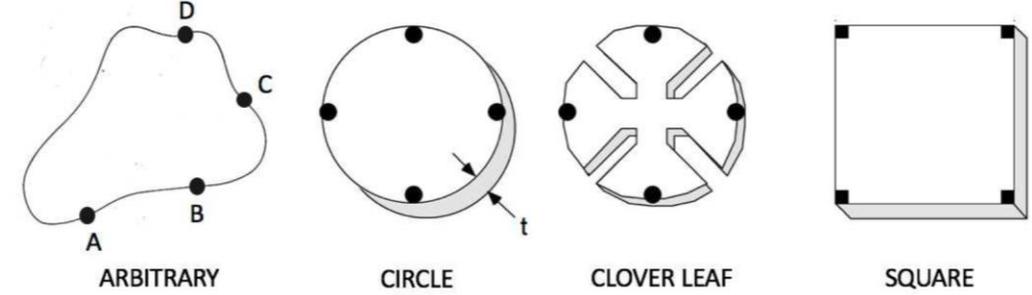
- vacuum chamber and vacuum pump;
- sample holder with a refrigerating circuit and a heater;
- hardware and software for temperature control.



1958/59 Van der Pauw papers for Hall measurements on flat samples [5,6]

Resistivity and Hall-type measurements can be done contacting the surface of a flat sample if:

- the four contacts are at the perimeter;
- each contact area is small;
- isn't there any isolated discontinuity in the doped layer;
- the layer thickness is homogeneous.

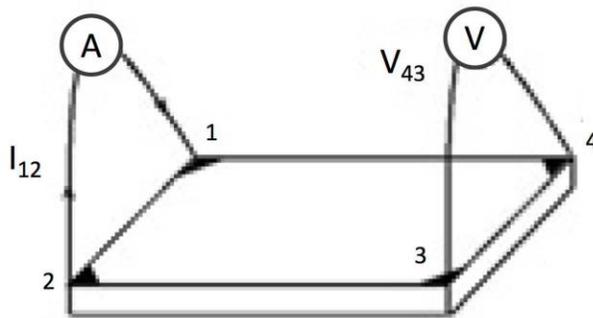


Finite contact size correction factors: [R. Chwang et al., Solid State Electronics, 17 (1974) 1217].

Four point probe method for resistivity and Hall characterization

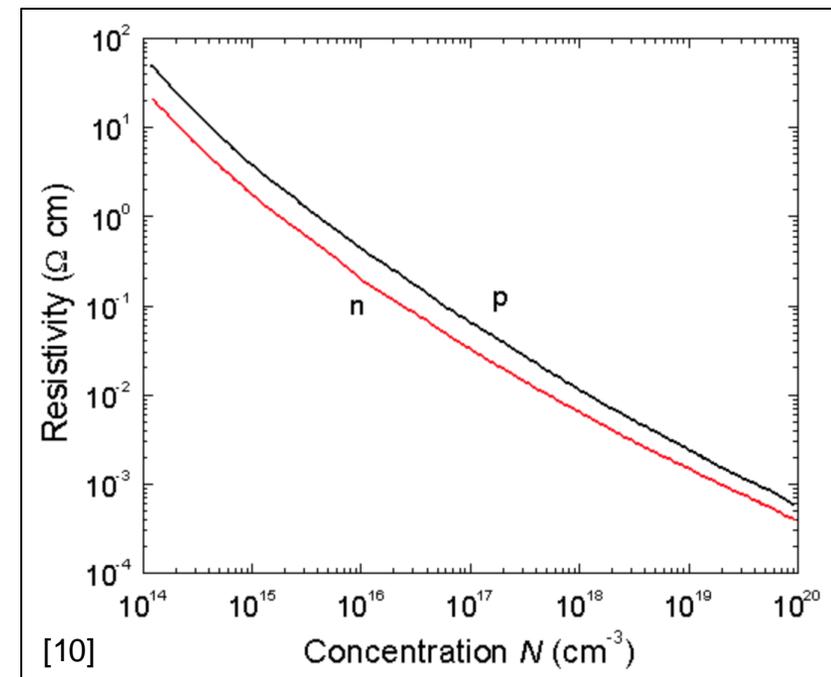
The importance to use four probes/wires: an extremely low current passes through the V-measuring probes, so the contact and probe resistances don't affect the measurement.

Sheet resistance measurement is done with two pairs of **parallel contacts** for I supply and V measure.



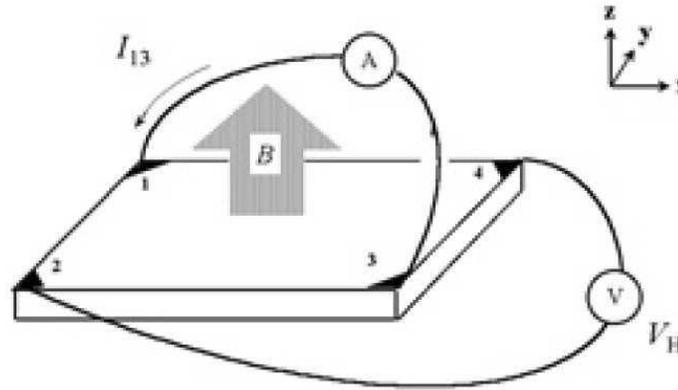
For a symmetrical sample:

$$\left\{ \begin{array}{l} R_{sheet} = \frac{\pi}{\ln 2} \cdot \frac{V_{43}}{I_{12}} \\ \rho = R_{sheet} \cdot t \\ \sigma = \frac{1}{\rho} \end{array} \right.$$



Four point probe method for resistivity and Hall characterization

Hall measurement is done with two pairs of **crossed contacts** for I supply and V measure, when \vec{B} is applied.

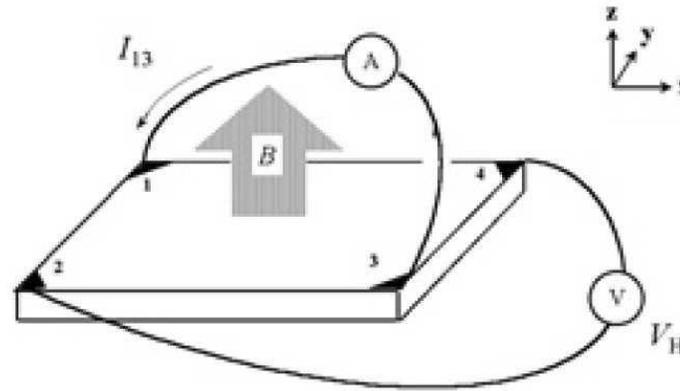


For a symmetrical sample:

$$\left\{ \begin{array}{l}
 \text{From } V_H \text{ sign you know the sign of charge carriers} \\
 R_H = \frac{V_H \cdot t}{I \cdot B}, \quad R_H = \frac{r_H}{n \cdot e} \longrightarrow n = \frac{r_H \cdot I \cdot B}{e \cdot V_H \cdot t} \\
 \mu = \frac{\sigma}{n \cdot e}
 \end{array} \right.$$

Four point probe method for resistivity and Hall characterization

Hall measurement is done with two pairs of **crossed contacts** for I supply and V measure, when \vec{B} is applied.



For a symmetrical sample: {

From V_H sign you know the **sign** of charge carriers

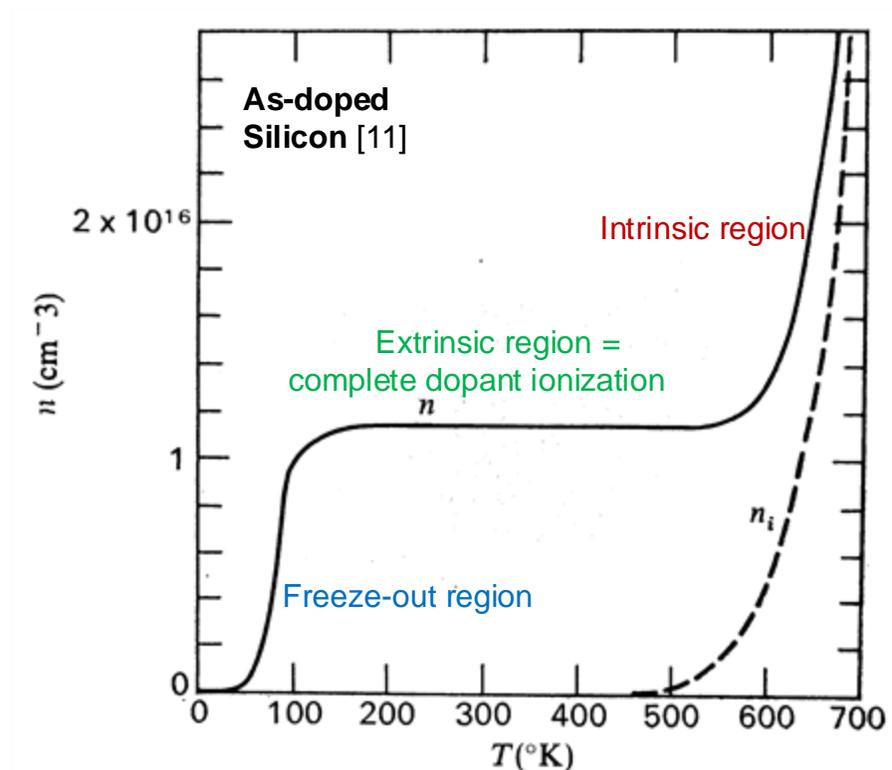
$$R_H = \frac{V_H \cdot t}{I \cdot B}, \quad R_H = \frac{r_H}{n \cdot e} \quad \longrightarrow \quad n = \frac{r_H \cdot I \cdot B}{e \cdot V_H \cdot t}$$

$$\mu = \frac{\sigma}{n \cdot e}$$

$$\frac{n_{free}}{N_{impl}} = \%_{ACT}$$

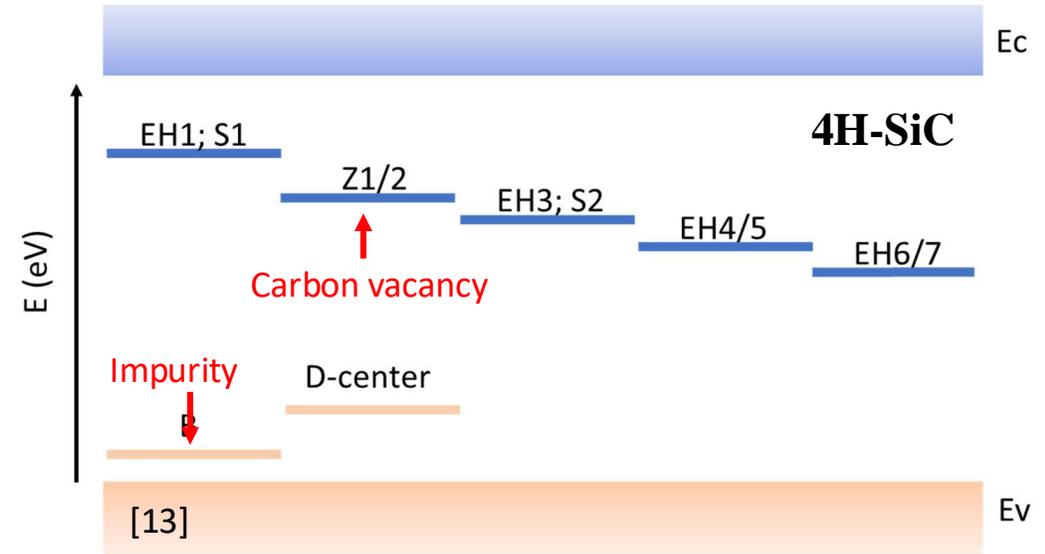
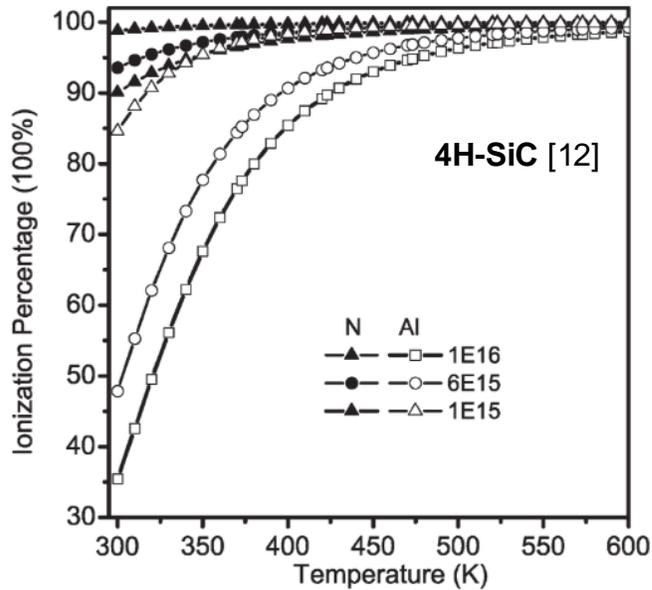
Measurements at variable temperature → different use depending on the semiconductor bandgap

In the case of **narrow bandgap** semiconductors ($E_g^{\text{Si}} = 1.12 \text{ eV}$, $E_g^{\text{Ge}} = 0.66 \text{ eV}$), a complete ionization of impurities is already reached at room temperature, thus measurements at variable T could be useful for special purposes (such as Arrhenius plots construction for defects or contaminants analyses).



In wide bandgap semiconductors carrier compensation is significant

In **wide bandgap** semiconductors ($E_g^{4H-SiC} = 3.26 \text{ eV}$) things are different.



COMPENSATION: it happens when lattice defects or impurities introduce an energy state inside the forbidden gap, getting charge carriers trapped there.

PROBLEM! free charge carriers (thus dopant activation) would be more than what you measure, because some of them are trapped by compensating centres.

In wide bandgap semiconductors carrier compensation is significant

When we deal with such materials it is fundamental to collect resistivity and Hall-effect data at variable temperature, in order to perform an accurate data analysis with the **charge neutrality equation**:

$$p(T) = \left(\sum_i N_{A_i}^- \right) - N_D^+$$

Measured free charge-carrier density

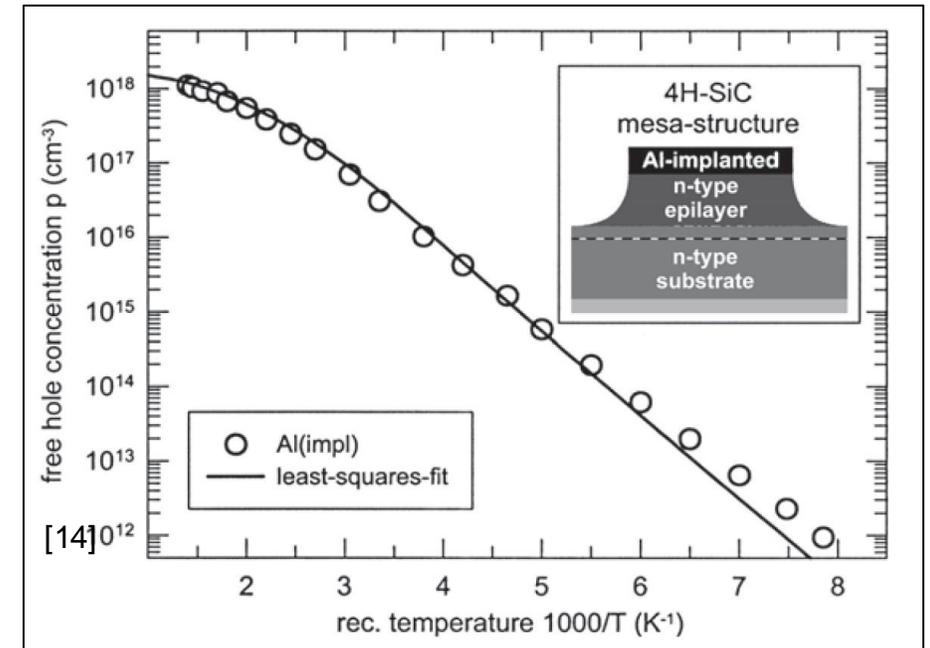
Density of ionized acceptors

Density of ionized compensating donors

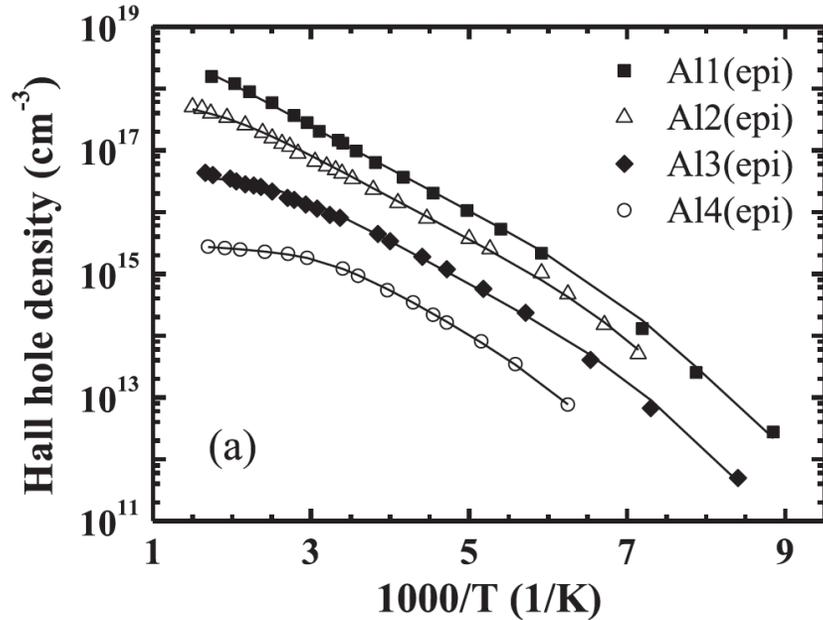
$$p(T) = \sum_i \frac{N_{A_i}}{1 + g_i \exp[(E_{A_i} - E_F)/k_B T]} - N_D$$

Least squares fitting, but many parameters to fix

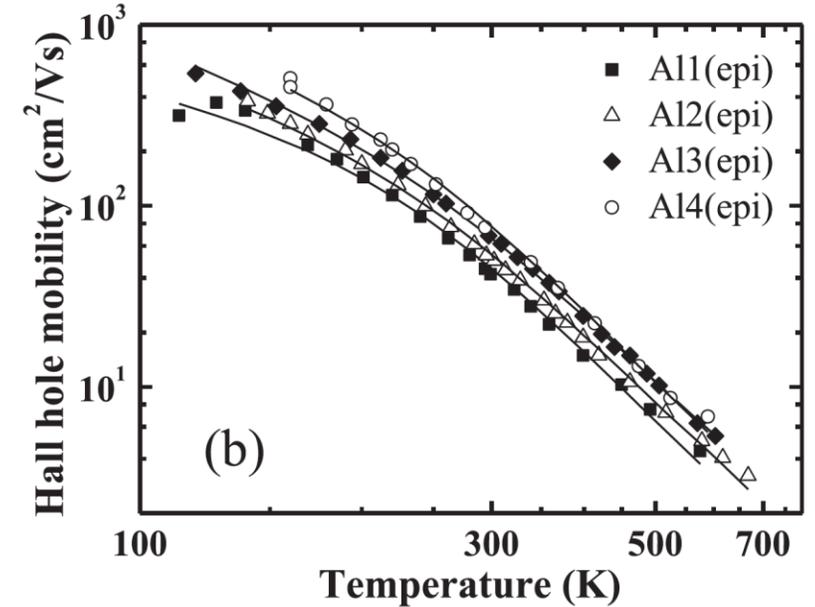
Acceptor ionization energy



A self-consistent fitting procedure of p and μ : the case of 4H-SiC



$p(T), R_{sheet}(T) \rightarrow \mu(T)$



Charge neutrality equation:

$$p(T) = \sum_i \frac{N_{A_i}}{1 + g_i \exp[(E_{A_i} - E_F)/k_B T]} - N_D$$

Equation describing mobility, derived from the relaxation time approximation:

$$\mu = \frac{e \langle \tau(E) \rangle}{m_{drift}}$$

$\tau(E)$ is the relaxation time of the total scattering momentum

$$\frac{1}{\tau(E)} = \sum_n \frac{1}{\tau_n(E)}$$

Conclusions:

Hall-effect characterization allows you to measure:

- the resistivity ρ of your doped layer;
- the volume concentration n of free charge carriers;
- their sign $+/-$ and mobility μ .

Then, with the right data analysis you can derive the percentage of active dopants, their ionization energy and the density of compensating centers.

Conclusions:

Hall-effect characterization allows you to measure:

- the resistivity ρ of your doped layer;
- the volume concentration n of free charge carriers;
- their sign $+/-$ and mobility μ .

Then, with the right data analysis you can derive the percentage of active dopants, their ionization energy and the density of compensating centers.

Thank you!

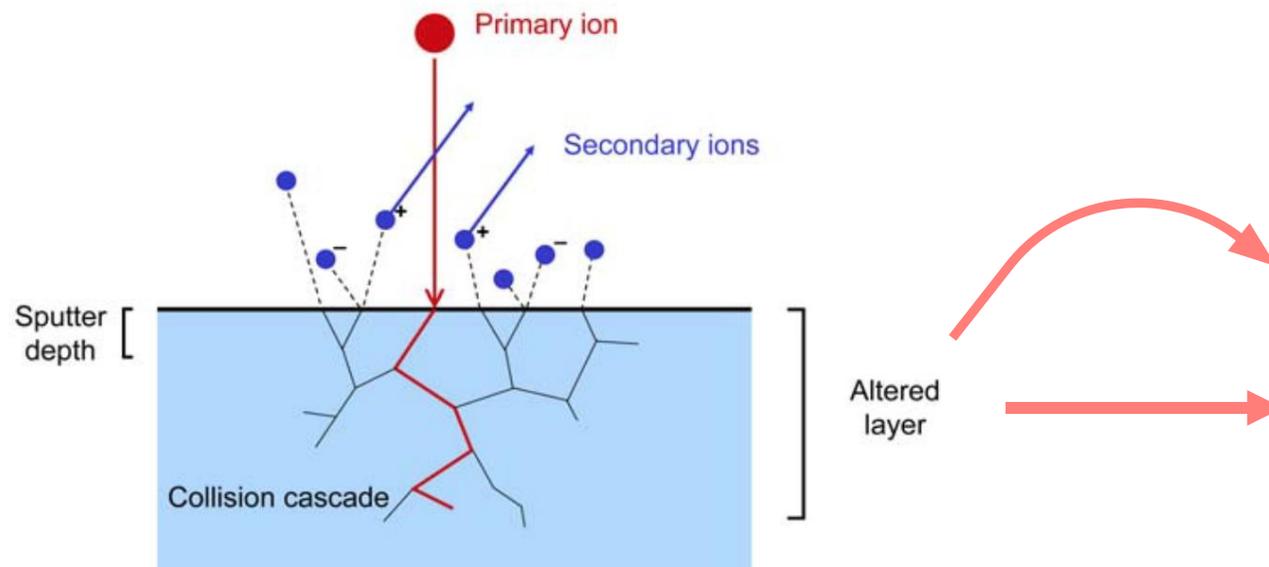
Bibliography

- [1] The silicon microstrip sensors of the ATLAS semiconductor tracker
- [2] <https://www.bo.imm.cnr.it/unit/articles/development-spad-detector-improved-performances>
- [3] <https://cuore.lngs.infn.it/en>
- [4] «AGATA - Advanced Gamma Tracking Array»
- [5] L.J. Van der Pauw, Philips Technical Review 20 (1958/59).
- [6] L.J. Van der Pauw, Philips Research Reports 13 (1958).
- [7] V. Boldrini, PhD thesis, University of Padova (2018).
- [8] Photolithography mask, ASBeST PRIN project (2023).
- [9] D.K Schroder, «Semiconductor material and device characterization», John Wiley & Sons, Inc. (2006).
- [10] <https://ioffe.ru/SVA/NSM/Semicond/Ge/electric.html#Basic>
- [11] A.S. Grove, «Physics and technology of semiconductor devices», John Wiley & Sons , Inc.(1997) pag. 106.
- [12] E.X. Zhang et al., IEEE TRANSACTIONS ON DEVICE AND MATERIALS RELIABILITY, 12 (2012).
- [13] I. Capan and T. Brodar, Electron. Mater. 3 (2022) 115.
- [14] F. Schmid et al., Silicon Carbide. Recent Major Advances, edited by W. J. Choyke, H. Matsunami, and G. Pensl (Springer, 2004), p. 517.

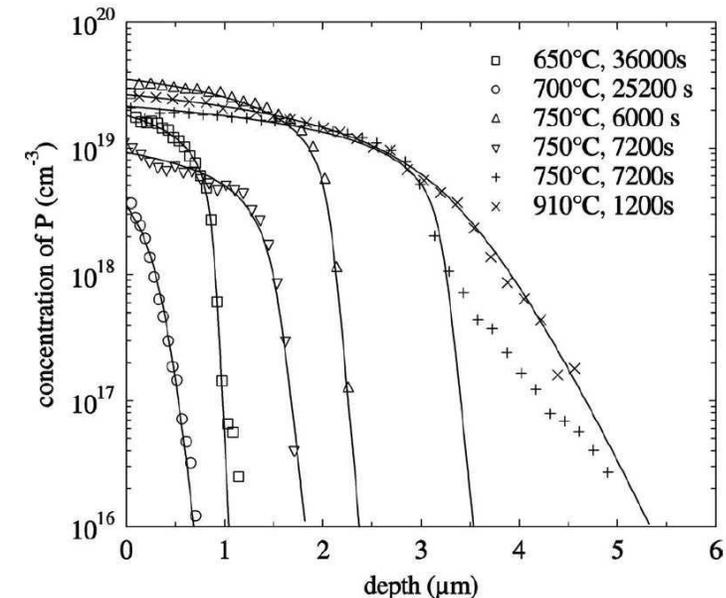
The electrical properties should be optimized and predictable

Whatever doping technique is used (equilibrium thermal diffusion, ion-implantation + thermal annealing, out-of-equilibrium Laser Thermal Annealing), for most devices it is crucial to obtain a homogeneous dopant concentration in the layer of recommended thickness.

After the doping process, it is a good practice to check the shape of the impurity concentration distribution across the layer thickness. This is done through SIMS (Secondary Ion Mass Spectrometry).



[R.A. De Souza and M. Martin, Phys. Stat. Sol. (C) 4, 6 (2007)]

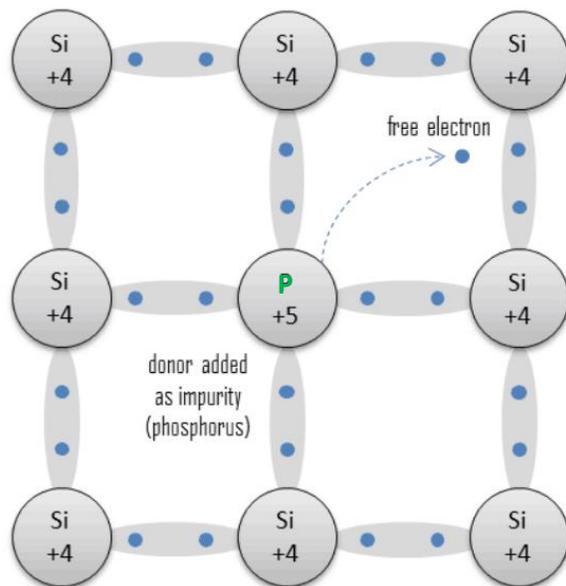


[S. Brotzmann and H. Bracht, JAP 103 (2008)]

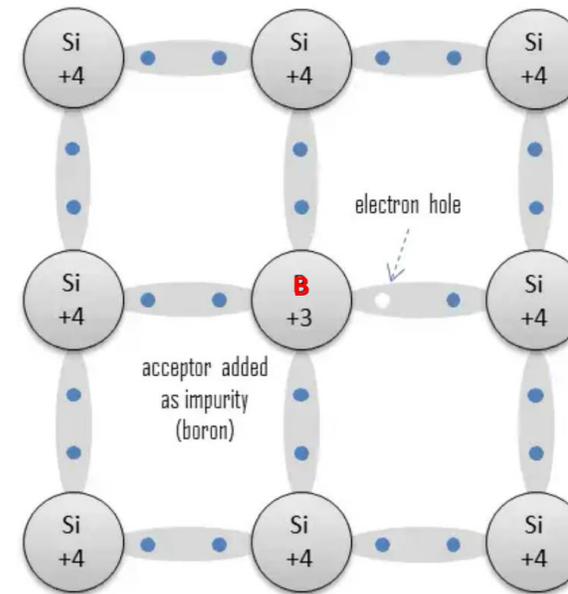
There is no semiconductor electronics without doping

It is by enriching some regions of a semiconductor material with more charge carriers (electrons or holes) than there are intrinsically present in the crystal, that the desired electrical transport can be obtained. This is achieved with the process called "doping", i.e. the insertion into the lattice sites of a certain concentration of atoms belonging to other elements of the periodic table called "impurities", which can act as donors (making an electron available) or acceptors (trap an electron and thus make a hole available).

n-type doping



p-type doping



4H-SiC band structure

