ESIPAP School 2022 — SSD Online Lab-Session
Radiation Damage in Silicon Pad Sensors:
CV-IV & TCT Characterization

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Introduction

The lab session illustrates the operation of silicon particle sensors as detectors for ionising radiation. These sensors are based on a diode structure consisting of n- and p-doped silicon layers forming a pn-junction. The test structures basically consist of heavily doped electrodes (n^+ and p^+) implanted in a low-doped silicon bulk material.

For the operation of a silicon sensor an external reverse bias voltage is applied to form a space charge region. The bias voltage necessary to extend the space charge region over the full thickness of the device is the so-called full depletion voltage V_{dep}. With increasing bias voltage also the electric field within the depletion region increases.

The first part of the lab session (CV/IV measurement) demonstrates the development of the depletion region and the sensors capacitance as a function of the bias voltage. Furthermore, this part includes the determination and calculation of intrinsic sensor parameters relevant for the operation of the sensor such as the effective doping concentration and the electrical resistivity. The second part of the lab session (Transient Current Technique measurement) demonstrates how size and shape of the induced signal vary with bias voltage for front and back side illumination using a red laser with a wavelength of 660 nm. Based on the measurement it becomes possible to calculate the mean velocity of the generated charge carriers.

Devices Under Test

The devices used in the lab session are simple pad sensors illustrated in Fig. 1. They are based on p-in-n diodes with a thickness of 300 µm and implants penetrating the material less than 2 µm.

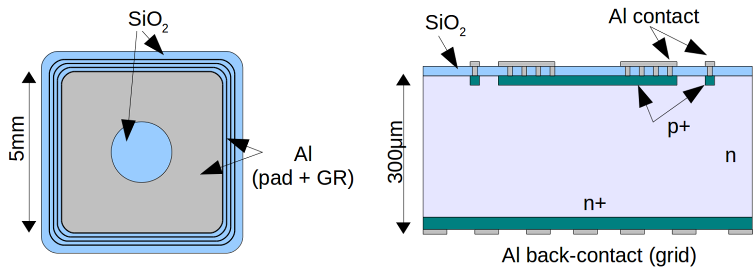


Figure 1: *Layout of a p-in-n pad diode showing the top view (left) and the cross section (right). The pad structure includes the guard ring and the optical window on the top and the grid structure on the back.*

The heavily p^+-doped ($\approx 10^{18}$atoms/cm^3) front implant forms the pn-junction with the n-doped

($\approx 10^{11} - 10^{12}$atoms/cm^3) bulk. The back side is heavily n^+-doped ($\approx 10^{18}$atoms/cm^3) to build an ohmic contact. Front and back contacts are covered with a metal layer to build electrical connections for biasing and read-out. The front side contact comes with an optical window while the backside is covered with a grid to provide access for the illumination with a laser. To reduce surface currents across the conductive sensor edge, the front pad is surrounded by one p^+ guard ring. If this guard ring is grounded it can be used to define the active area of the device to be 0.5x0.5 cm.

Table 1: *Devices under test and fluence*

CV/IV	TCT	fluence
W324-H3	W324-N8	unirradiated
W331-D10	W331-C10	unirradiated
W331-D6	W331-Q4	$1 \cdot 10^{13}$ p/cm^2
W331-P8	W331-Q3	$1 \cdot 10^{14}$ p/cm^2

The samples which are studied during the lab session consist of 2 batches of 3 pad detectors fabricated by STMicroelectronics. These sample parameters are summarized in Tab. 1. While the samples for the CV/IV part are the bare pad sensors, the ones for the TCT part are already wire-bonded to PCBs. In order to investigate the radiation damage, four samples were irradiated with 24 GeV/c protons at the CERN Proton Synchrotron (PS). The corresponding fluence can also be found in Tab. 1.

1 Capacitance and Current Characterization

The CV/IV set-up is used to investigate the operational parameters of silicon sensors. It is based on the voltage-dependent measurement of the capacitance and the leakage current of a device.

For the measurement a bias voltage is applied to the back side of the sample while the capacitance or leakage current are measured between the pad and the back electrode using a LCR meter or a picoamperemeter, respectively. The so-called cold chuck to mount the device under test (DUT) and to control the temperature is depicted in Fig. 2 including the micro-manipulators ending with the probe needles. A more detailed description is given by the supervisor, take appropriate notes if necessary. Starting from Poisson's equation given in Eq. 1 it is possible to calculate the electric field E and the electrostatic potential V inside an abrupt pn-junction, where N_{eff} is the effective space charge density of the semiconductor.

$$\frac{dE}{dx} = \frac{d^2V}{dx^2} = -\frac{\rho}{\epsilon} = \frac{q}{\epsilon_{Si}\epsilon_0} N_{eff} \quad (1)$$

Solving Poisson's equation by integration gives the potential as a function of the depletion depth x as given in Eq. 2.

$$V(x) = \frac{q}{2\epsilon_{Si}\epsilon_0} |N_{eff}| x^2 \quad (2)$$

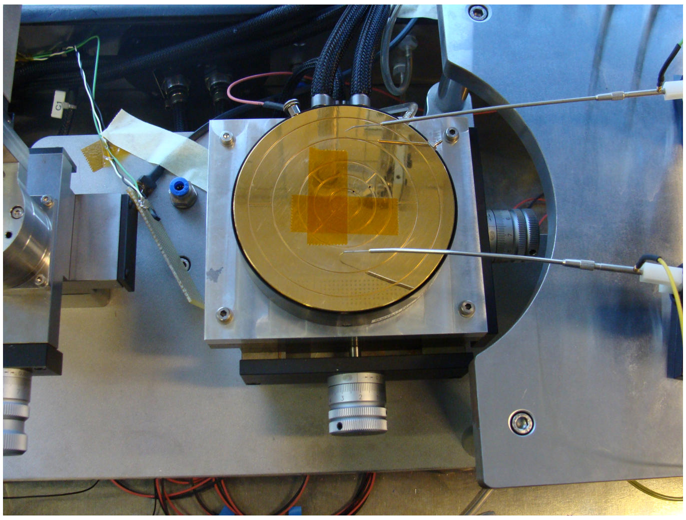


Figure 2: *Cold chuck and probe needles of the CV/IV setup*

The depletion voltage V_{dep} of the diode is the voltage at which the depletion depth is equal to the thickness of the device (300 µm). The corresponding depletion width w given in Eq. 3 can be expressed as a function of the applied potential.

$$w(V_{dep}) = \sqrt{\frac{2\epsilon_{Si}\epsilon_0}{q|N_{eff}|}V_{dep}} \quad (3)$$

Above full depletion the sensor capacitance can be expressed as the capacitance of a plate capacitor given in Eq. 4 with a plate area A.

$$C(w) = \frac{\epsilon_{Si}\epsilon_0 A}{w} \quad (4)$$

The electrical resistivity ρ_{el} of the semiconductor given in Eq. 5 is defined as the inverse conductivity σ and given by the product of the effective doping concentration N_{eff} and the mobility μ of the majority carriers.

$$\rho_{el} = \frac{1}{\sigma} = \frac{1}{q\mu|N_{eff}|} \quad (5)$$

Table 2: *Constants needed to calculate silicon properties*

$\epsilon_{Si} = 11.9$	amu $= u = 1.66054 \cdot 10^{-27}$ kg (atomic mass unit)
$\epsilon_0 = 8.854 \cdot 10^{-14}\,\mathrm{A\,s\,V^{-1}\,cm^{-1}}$	$\rho_{Si} = 2.33\,\mathrm{g/cm^3}$
$q = 1.602 \cdot 10^{-19}\,\mathrm{C}$	atomic weight/mass $= 28\,u$
$\mu_e = 1350\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$	$N_A = 6.022 \cdot 10^{23}\,\mathrm{mol^{-1}}$ (Avogadro constant)
$\mu_h = 480\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$	

Aim of the CV/IV lab session

Observe the capacitance (CV) and current (IV) characteristics of silicon pad sensors before and after irradiation as function of the applied bias voltage. Acquire the key parameters of the sensor, i.e. depletion voltage, leakage current, effective doping concentration and electrical resistivity. Learn how these properties and the performance of silicon sensors change due to damage caused by radiation.
Get familiar with the physical principles of semiconductors and pn-junctions. Discuss the definition of semiconductors and the working principle of a pn-junction.

Measurement procedure

Since this lab-session will be online, the following measurements - usually performed by the students - will be performed by the supervisor in close discussion with the students.

- Check the connections for HV, pad and ground.
- Place the sample on the cold chuck and fix it with the vacuum. Use the microscope to position and connect the probe needles to the pad sensor and the guard ring using the corresponding screws on the micropositioner.
- Remove the microscope and close the Faraday cage.
- Check the polarity of the setup by applying $\pm 1\,\mathrm{V}$ to your sensor.
- Set up the DAQ software (based on LabView) according to your needs - provide information about the voltage range, the maximum current and the temperature.
- For the CV measurement do the "open correction" to eliminate stray capacitance from the set-up instruments and cables.
- For the IV measurement choose "IV with two I-meter"

Tasks for the report

- Give a general description of the setup.
- Which polarity of bias voltage was applied and why? How can you safely check the polarity?
- Plot $1/C^2$ and the leakage current as function of applied bias voltage for all measurements (two plots).
- What are the variations between the different samples concerning the fluence? Discuss your observations in respect to the impact of radiation damage.
- Explain how you can extract the full depletion voltage V_{dep} and the end capacitance C_{end}.
- Extract the full depletion voltage V_{dep} and the end capacitance C_{end} from your measurements. Plot V_{dep} vs. fluence.

- Compare the leakage current at a fixed voltage (e.g. 300 V) for the different samples in one plot.
- How does the leakage current at 300 V change with fluence?
- Calculate the thickness d of the sample, the effective doping concentration N_{eff} of the bulk material and the ratio between phosphorus and silicon atoms.
- Comment on the sensitivity of your phosphorus concentration measurement.
- Determine the resistivity of the bulk material.

2 Transient Current Technique (TCT)

Charge carriers generated by ionizing radiation within the active sensor region of a silicon particle detector get separated by the electric field and start to drift towards the electrodes (holes travelling towards the negative electrode and electrons towards the positive one). The movement of these charge carriers in the electric field induces a current signal which is used to determine the path of a particle in a high energy physics experiment (tracking). In the case of a low electric field strength, the drift velocity v of the charge carriers is proportional to the local electric field strength E and the mobility μ of the charge carrier.

$$v = \mu \cdot E \tag{6}$$

As the induced signal is related to the electric field configuration in the sensor it became necessary to develop means to determine the exact shape of the electric field. Especially for the characterization of particle detector properties after irradiation these measurement techniques provide the possibility to understand the formation of the field. Furthermore, this information makes it possible to modify the sensor layout to increase charge collection properties after irradiation and to improve the sensor performance. One of these techniques is the Transient Current Technique (TCT) which injects e/h-pairs by irradiating the sensor surface with a laser.

2.1 Signal generation fundamentals

The movement of a charged particle inside a detector induces a current signal on the electrodes, which is defined by the Ramo theorem given in Eq. 7. This signal can be used to study the electric field profile within a sensor.

$$\vec{I}(\vec{r}) = -q \cdot \vec{v}(\vec{r}) \cdot \vec{E}_w(\vec{r}) \tag{7}$$

Here, q corresponds to the charge of the particle, $\vec{v}$ to its velocity and $\vec{E}_w$ to the weighting field of the electrode. The equation is given as a function of the particle position vector $\vec{r}$.

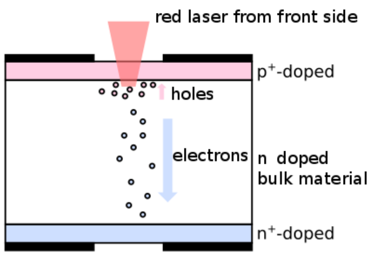
The weighting field concept, introduced by Ramo [1], is not a physical field but a mathematical construction used for this calculation, and it depends exclusively on the geometry of the detector. In the case of sensors with parallel plate geometries such as the diodes in Tab. 1, $E_w = 1/d$. Presuming a low electric field strength ($< 10\,\mathrm{V\,\mu m^{-1}}$) and replacing the weighting field makes it possible to combine Eq. 6 and Eq. 7 to see the correlation between the induced current and the electric field within the sensor.

$$\vec{I}(\vec{r}) = -\frac{q\mu\vec{E}(\vec{r})}{d} \tag{8}$$

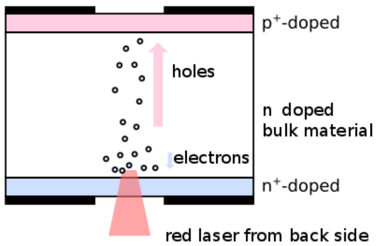
In the case of multiple particles moving at the same time, the total current is obtained as the sum of all individual contributions. Note that, since the current is induced by the movement of the charges (and not by the carriers reaching the electrode), the signal is generated right after the interaction when the electron-hole pairs start to separate due to the electric field. Also note that both holes and electrons contribute to the induced current.

2.2 Study of the electric field profile using TCT measurements

A red laser (λ = 660 nm) is used in the laboratory for injection of electron-hole pairs. At this wavelength, the absorption length in silicon is of the order of $3\,\mu\mathrm{m}$. This is about 1% of the detector thickness, so in practice all charge carriers are generated very close to the surface. In consequence, charges of one polarity (holes or electrons depending of the side of illumination) reach their electrode immediately after being generated, and do not contribute to the measured signal. Charges of the opposite polarity, on the contrary, have to drift all the way through the detector bulk until stopping at the far side electrode. This drift is of the order of a few nanoseconds and induces signal on the readout electrode (Eq. 8). Thus, depending on the illumination direction, the signal generated by the movement of the holes or electrons can be investigated. Both measurement configurations are illustrated in Fig. 3.



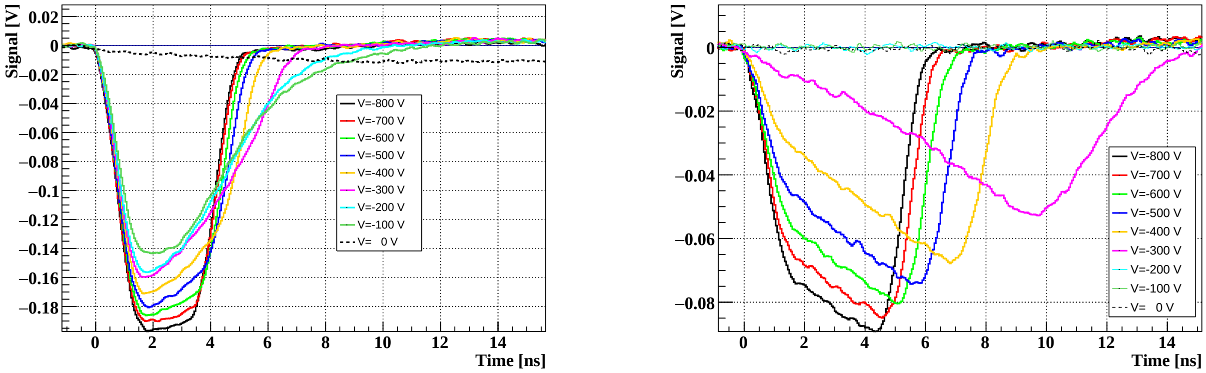
(a) *front illumination*



(b) *back illumination*

Figure 3: *TCT measurements illustrating the two illumination methods and the corresponding charge movement in the sensor bulk.*

The laser is focused with a beam spot diameter of few micro meters, and is operated in pulsed mode, with a pulse duration of a few picoseconds. At each laser shot, a current pulse is induced on the readout electrode of the detector, which is converted to a voltage pulse using a dedicated amplifier,



(a) *front illumination*

(b) *back illumination*

Figure 4: *TCT signal for electrons Fig. 4(a) and holes Fig. 4(b), respectively. Remarkable is the variation of the signal width and shape for the different charge carriers.*

and observed in an oscilloscope.

Since the pulse duration is short compared with the total drift time, the dispersion of the generated charge cloud is small compared to the detector thickness. Thus, as a first order approximation we can assume a point-like charge "sweeping" the detector in the depth direction. Taking into account Eq. 8, the current generated at the electrode over time is

$$\vec{I}(t) = -\frac{nq\mu\vec{E}(\vec{r}(t))}{d} \tag{9}$$

where n is the number of photons injected by the laser. $\vec{I}(t)$ is given as a function of time to stress the fact that the temporal signal that is observed at the oscilloscope is a "snapshot" of the electric field profile along the detector depth

$$\vec{I}(t) \propto \vec{E}(\vec{r}) \tag{10}$$

Due to the non-constant electric field inside the silicon diode, the induced current is not constant but varies while the charge cloud drifts through the material. This behaviour is illustrated in Fig. 4 showing laser induced signal pulses for electron and hole movement in a diode. Due to the different drift velocity of electrons and holes the signal width varies, as shown in Fig. 4.

Aim of the TCT lab session

The aim of this session is to get a general understanding of the Transient Current Technique and to learn how to extract sensor properties from the measurements.
In a first step we will discuss together the TCT setup to get an introduction to the different com-

ponents and the readout circuit. This discussion will also focus on the development of the electric field in the diode and its impact on the performance of the sensor and the measurement.
In order to determine the sensor properties in function of the applied bias voltage and fluence two of the diodes given in Tab. 1 need to be measured with the TCT setup. The measurements will be performed for different bias voltages and with illumination from the front as well as the back side. The measured signal will be directly compared and discussed. Finally you will use the obtained data to extract the mean velocity and mean mobility of the different charge carries.

Measurement procedure

Since this lab-session will be online, the following measurements will also be performed by the supervisor in close discussion with the students.

1. Check that all power supplies are ramped down to 0 V and the laser is turned off before modifying the setup.
2. Mount the PCB with the sensor and connect the readout and temperature control.
3. Check that the readout circuit inside the shielded box is correctly set up.
4. Close the shielded box before switching on the laser.
5. Ramp up to the desired bias voltage and select the illumination direction.
6. Save the measurement shown in the scope.
7. Turn off the laser and ramp down the bias voltage before you swap the samples.

Measurement tasks are:

- Perform a bias scan with the unirradiated sample (at least three voltages, front illumination).
- If time: Repeat the bias scan with back illumination.
- Mount an irradiated sample and perform measurements for front and back illumination.
- If time: Perform a bias scan with the irradiated sample.

Tasks for the report

- Give a general description of the setup and the Transient Current Technique.
- Plot the measured signals and discuss the signal shape. Focus on the differences between electron and hole movement and explain how the signal changes with irradiation.
- Which signal shape would you expect for a n-in-p-type diode structure being illuminated from the front or the back side?
- Explain how to calculate the mean velocity of charge carriers.

- For each performed bias scan: Calculate the mean velocity for electrons and holes. Plot your results in function of the applied bias voltage. Also summarize your results in a table. Calculate the mobility and summarize it in a table. Compare the results with the mobility given in Sec. 1.

References

[1] S. Ramo, *Currents Induced by Electron Motion*, Proceedings of the IRE, vol. 27, p. 584, 1939.

[2] H. Spieler, *Semiconductor Detector Systems*, Oxford University Press, 2005.

[3] F. Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, Springer International Publishing AG 2017.

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