Laboratory exercise

Measurements of electrical properties (current-voltage and capacitance-voltage) of irradiated and non-irradiated silicon detectors

Facilities:
HIP CV-IV probe station located in the cleanroom AK10; laboratories B304 and B307

Checklist:

- ✓ Instruction to the laboratory exercise (this document)
- ✓ CV-IV probe station operational manual (also located near probe station)
- ✓ Set of 3 samples containing n-type diode, p-type passivated diode, and irradiated diode.
- ✓ Memory stick for data transfers

If something is missed ask course assistants for the help.

What to do:

1. Read the instructions carefully. You are not allowed to take paper with you to the cleanroom.

2. Go to cleanroom and measure your set of samples. Download the data from probe station PC.

3. Proceed the data and make necessary plots. Write the final report and submit it to Eija.Tuominen@helsinki.fi and Ivan.Kassamakov@helsinki.fi . The deadline for submitting the report is 6.11.2015.

1. Depletion region and depletion voltage.

Silicon belongs to group IV at the periodic table of the elements. Materials from III and V group contain three or five valence electrons respectively, and considered as doping elements for silicon. After replacing silicon atom with the atom of phosphorus (V group) an additional electron becomes an additional negative charge carrier. This turns intrinsic silicon into **n-type semiconductor**. After replacing a silicon atom with the atom of Boron (III group) an additional electron should be accepted to form covalence bond around the boron atom. Adding an acceptor creates a positive charge carrier in a valence band - a hole, and turns intrinsic silicon into the **p-type semiconductor**.

After joining p-type and n-type semiconductors (pn-junction) charge carriers (electrons and holes) will diffuse through the border, recombine and form a region without any free charge carriers – **depletion region**. Diffusing charge carriers leave charged ions (space charge) behind and due to the different densities of space charge on different sides of interface the electric field E will appear in this area (Fig.1).

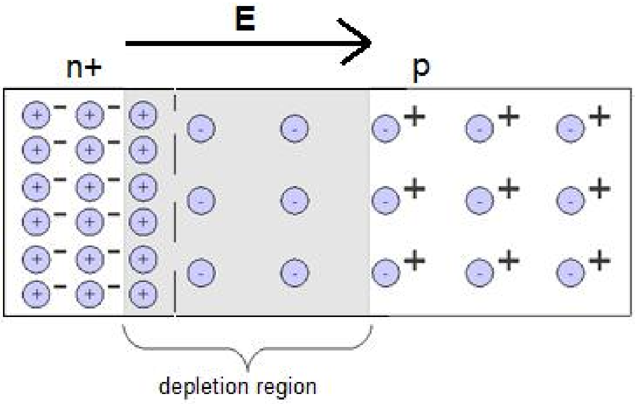

Fig.1. Depletion region.

Poisson equation for this case

$$-\frac{d^2}{dx}\varphi(x) = \frac{\rho}{\varepsilon} = \frac{q}{\varepsilon}\cdot N_{eff} \qquad \text{(Eq.1)}$$

where ρ is the charge density, q is the charge ($q = 1{,}6\cdot10^{-19}$), N_{eff} is the effective space charge density, ε is a permittivity, $\varepsilon=\varepsilon_r\cdot\varepsilon_0$ ($\varepsilon_0=8{,}85\cdot10^{12}$ F/m is a vacuum permittivity, ε is the relative permittivity of material (11,68 for silicon)).

Size of depletion region can be extended through the entire thickness of the semiconductor by applying external reverse bias potential V.

Full **depletion voltage V_{fd}** is the voltage needed to deplete the entire volume of semiconductor of free charge carriers. Vfd can be obtained by solving the Poisson equation taking into account potential and boundary conditions:

$$V_{fd} = \frac{qN_{eff}d^2}{2\varepsilon} \qquad \text{(Eq. 2)}$$

where d is the thickness of the material.

2. Operational principle of silicon detector

Silicon particle detector is a microscopic ionization chamber with the semiconductor bulk in the role of particle detecting medium. Charged particles traversing through the semiconducting medium produce electron-hole pairs (Fig. 2). The applied electric field separates electrons and holes, and moves them to the collecting electrodes which are connected to the readout electronics. Without full depletion, the bulk would contain its own free charge carriers, and it would be not possible to dissipate electron-hole pairs generated by traversing charged particle from this “noise”.

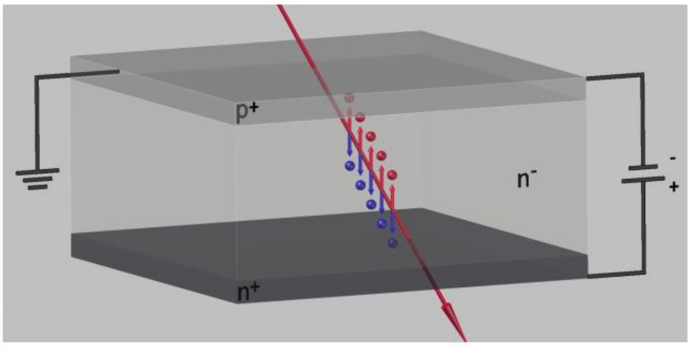

Fig. 2.Principle of particle detector. Layer heavily doped with acceptor impurities is marked with p+, layer heavily doped with donor impurities – as n^+, and lightly doped bulk material as n-. Incident charge particle (red arrow) creates electron-hole pairs (shown as blue and red spheres). Holes are collected at the negative electrode and the electrons at the positive.

3. CV measurements

The depletion voltage can be determined experimentally by measuring the capacitance as a function of applied voltage (CV). The pn-junction in the semiconductor bulk can be considered as a parallel plate capacitor of size of the depletion region (Fig. 3).

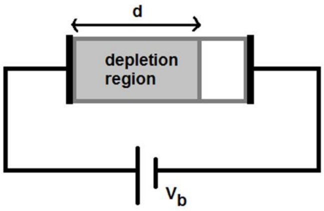

Fig. 3. Depletion region and applied voltage as simple electrical scheme

Geometrical capacitance C for parallel plate capacitor:

$$C = \frac{\varepsilon A}{d} \qquad \text{(Eq. 3)}$$

where A is the is a square of a capacitor’s plate and d is the thickness of the capacitor (=depletion region). On the other hand, using Eq.1 capacitance can be defined as

$$C = A\sqrt{\frac{\varepsilon q N_{\mathrm{eff}}}{2V}} \qquad \text{(Eq. 4)}$$

This function will describe the behaviour of the capacitance until full depletion will happen, after that it become constant (saturation of the capacitance).

The full depletion voltage is the value of voltage when the capacitance becomes constant. Measured CV data should be plotted as C^2 vs. V and the crossing point of two linear fits will give the value of the depletion voltage (Fig. 4).

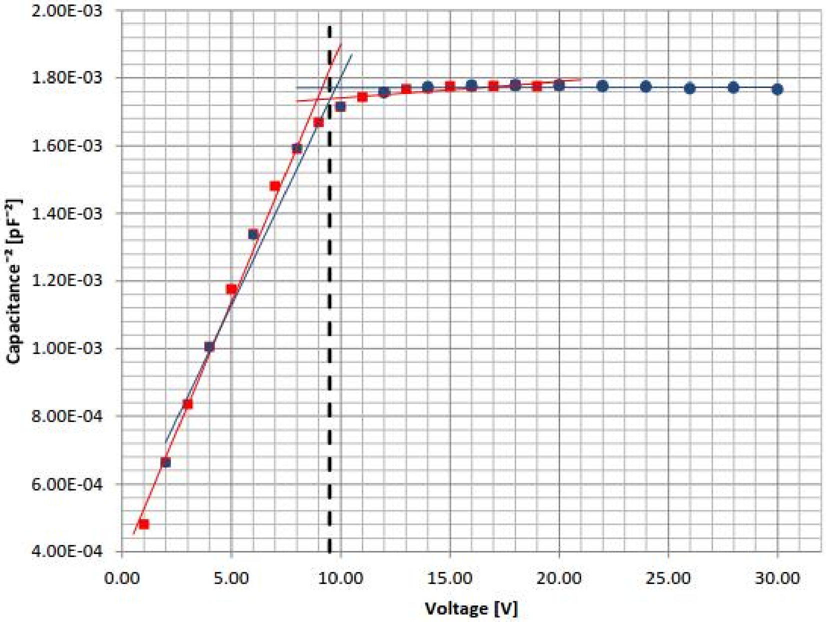

Fig. 4. C^2 vs. V plot and depletion voltage

4. IV measurements

In reality even in the fully depleted region some phenomena leading to the movement of charge carriers can occur. It silicon it is mainly thermal pair production resulting in existence of **leakage current**.

$$I_{\text{leak}} \approx qGd = \frac{qn_i d}{\tau_g} \tag{Eq.5}$$

where G is generation rate, n_i is intrinsic carrier concentration and $\tau_g$is the lifetime of generated electron-hole pairs.

Primary generated electrons enquired enough kinetic energy begin to create more electron-hole pairs, and this process escalates as multiplication of charge carriers and result in fast significant increase of leakage current. This phenomenon is called avalanche breakdown.

It is possible to find the leakage current at full depletion voltage using the value of V_{fd} determined during CV measurements (Fig. 5).

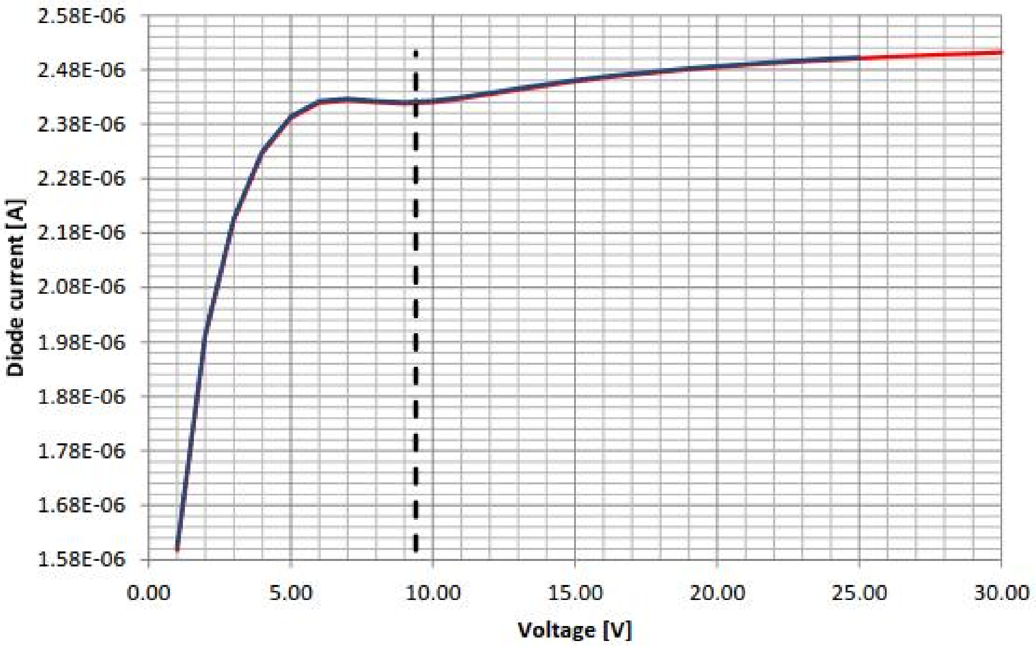

Fig.5. Determining the leakage current at full depletion

5. Sample layout

Silicon sensors for this laboratory exercise are based on a diode structure consisting of n- and p-doped silicon layers forming a pn-junction.

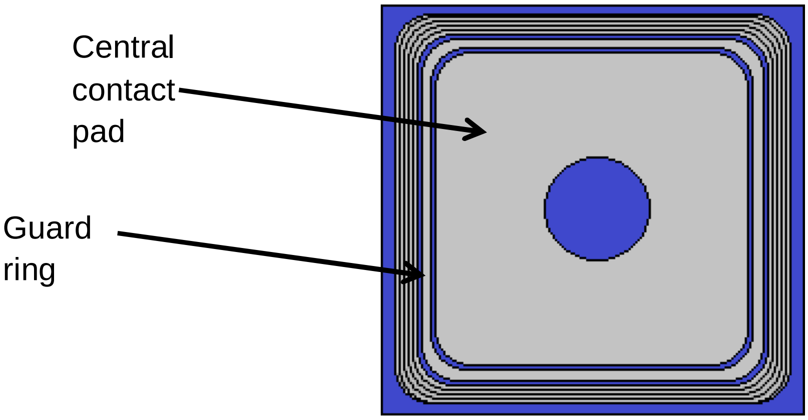

Fig. 6: Layout of diode (top view).

The pad structure (Fig.6) includes the main contact pad with round optical window and the metal layer on the back. To reduce surface currents across the conductive sensor edge the front pad is surrounded by the guard ring. In n-type samples heavily p-doped front implant forms the pn-junction with the n-doped bulk (Fig. 7). The back side is also heavily n-doped to build an ohmic contact.

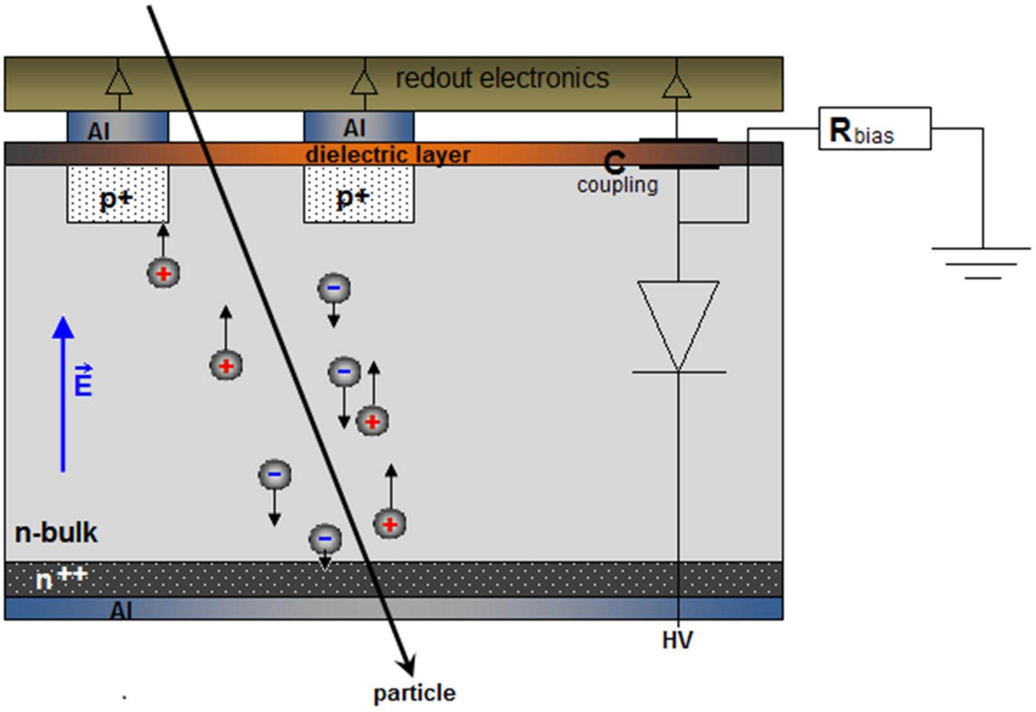

Fig. 7. Layout of diode (cross-sectional view).

P-type sample have similar structure but based on usage of p-doped silicon bulk with n-doped implants. Their front surface is covered with a dielectric layer (aluminium dioxide) for additional protection ("passivation"). Small rectangular windows – contact openings - are developed through this layer to provide the access to metal contacts beneath.

6. Measurements and data acquisition

The set of samples for measurements consists of n-type diode, p-type passivated diode, and irradiated diode. Use plastic tweezers to hold the diodes. Be especially careful with irradiated sample, do not touch it with hand.

As reverse bias voltage **positive voltage for n-type** and **negative voltage for p-type** detectors should be applied. Maximum applied voltage for n-type sample is 100V, and for p-type samples is 200V.

Measure CV and IV characteristics for each sample. Each measurement should be performed 3 times in order to minimize stochastic mistakes, and the average values should be calculated and used for analysis.

For IV measurements the CV-IV software creates a data file with two sets of current values noted as "diode current" and "total current". "Diode current" is the current through active area of the diode; "total current" is the current through the whole structure.

7. Task for final report:

1. Give a brief description of the setup and measurements.
2. Plot capacitance and leakage current in function of applied bias voltage for all samples.
3. Determine depletion voltage for all samples.
4. Compare the leakage current at a fixed voltage (e.g. 50 V) for all samples in one plot.
5. Describe the changes in behaviour of the irradiated detector.
6. Why it is important to measure leakage current?
7. What kind of information about the detector can be obtained from the CV data? From IV data?
8. Which polarity of bias voltage do you apply and why?