Appendix: Semiconductor physics

In this Appendix basic concepts of semiconductor physics are collected. For a more detailed description, the reader is addressed to [3].

Space-charge region

If homogeneously doped *p* and *n* regions initially separated are brought into contact, mobile charge carriers (electrons and holes) are sweeped away in the region around the boundary. This region is called space-charge region, where the excess nuclear charge from the doping atoms is not neutralized by the movable carriers. N_{eff} is the effective doping concentration, which is given by the difference between the concentration of ionized donors and acceptors in the space charge region.

Charge collection efficiency

The charge collection efficiency is defined as the fraction:

$$\eta = \frac{\text{collected charge}}{\text{maximum collected charge}} \quad . \tag{A.1}$$

The collected charge in pad detectors is the charge resulting from the integration of the current signal *i(t)*, which is the one circulating in the input circuit, calculable using Ramo's theorem:

$$i(t) = \frac{1}{d} \cdot \sum_i q_i \cdot v_i(t) \quad , \tag{A.2}$$

where v_i the velocity of the charge q_i and d is the detector thickness.

Depletion depth

The depletion depth (W) in a diode junction is defined by:

$$W(V) = \sqrt{\frac{2\varepsilon\varepsilon_0}{q_0|N_{\text{eff}}|}(V + V_{\text{bi}})} \qquad \text{for } W \le d \quad , \tag{A.3}$$

where q_0 is the elementary charge (1.60 10^{-19} C), d the thickness of the substrate, ε_0 the dielectric constant of the vacuum (8.85 10^{-14} F/cm), ε the relative dielectric constant of silicon (1.19), N_{eff} is the effective doping concentration and V_{bi} the built-in potential in a junction. Therefore, the potential needed to fully deplete a silicon detector (full-depletion potential) is:

$$V_{\mathrm{dep}} = \frac{q_0}{2\varepsilon\varepsilon_0}|N_{\mathrm{eff}}|d^2 - V_{\mathrm{bi}} \quad . \tag{A.4}$$

Dynamic capacitance

The dynamic junction capacitance is defined as the incremental change in the depletion layer charge for an incremental change in the applied potential and is defined by

$$C(V) = \varepsilon\varepsilon_0 \frac{A}{W(V)} = A\sqrt{\frac{\varepsilon\varepsilon_0 q_0 |N_{\mathrm{eff}}|}{2(V + V_{\mathrm{bi}})}} \qquad \text{for } W \leq d \ , \tag{A.5}$$

where A is the area of the diode.

Therefore, the capacitance reaches with full-depletion a final value of:

$$C = \frac{\varepsilon\varepsilon_0 A}{d} \quad . \tag{A.6}$$

This capacitance is called the geometrical capacitance since it only depends on the geometrical size of the diode.

Leakage current

The current of a reverse biased diode is called leakage current. While the reverse current of an ideal diode consists only of a diffusion current, in real devices, impurities, contaminations and process-induced defects in the silicon contribute to the current, making it difficult to produce sensors with leakage currents lower than 1 nA/cm^2.

The radiation induced leakage current can be divided into two basic components: the bulk generation current (I_{bulk}), which arises from electron-hole pair generation at radiation induced defects in the silicon bulk which are located close to the middle of the band gap; and the surface generation current, due to radiation induced Si-SiO$_2$ interface states. Since only defects located in the space charge region contribute to the bulk generation current, it depends on the potential in the same way as the width W of the depleted zone ($I_{\mathrm{bulk}} \propto W \propto \sqrt{V}$).

The bulk generation current temperature dependence can be described by:

$$I(T_0) = I(T) \cdot R(T) \ , \tag{A.7}$$

with

$$R(T) = \left(\frac{T_0}{T}\right)^2 \exp\left(-\frac{E_{\mathrm{g}}}{2\kappa_{\mathrm{B}}}\left[\frac{1}{T_0} - \frac{1}{T}\right]\right) \ , \tag{A.8}$$

where E_g is the band gap (1.12 eV for Silicon), T_0 is a reference temperature and κ_B is Boltzmann's constant.

Annealing and reverse annealing

Observing a radiation-damaged detector after the end of the irradiation process, one notices that the observed damage to the detector diminuishes with time. The rate of damage decrease is strongly dependent on the temperature at which the detector is kept. Annealing is a rather complicated process involving many different and only partially understood processes between defects and defect complexes.

Defects and defect complexes are stable only up to a characteristic temperature. It is determined by observing the disappearance of some defect-characteristic properties with time and temperature. The annealing temperature is not very precisely defined since even below this temperature some annealing occurs). One assumes an exponential behaviour of the annealing of the form:

$$N_d(t) = N_d(0)e^{-\frac{t}{\tau}} \qquad \text{with } \tau(t) \propto e^{\frac{E_a}{kT}}, \tag{A.9}$$

where N_d is the defect concentration, E_a is the activation energy, T is temperature and k is the Boltzmann's constant.

As new defect complexes are produced, the effect of annealing may not always be beneficial for detector performance. An example of such a detrimental effect is the increase in space charge after initial annealing of intensely irradiated detectors. This effect has been called reverse annealing.

Type inversion

The effective doping of an initially *n*-type silicon wafer decreases with irradiation fluence, and the material becomes intrinsic at an irradiation fluence of a few times 10^{12} n/cm^2 (the fluence at which type inversion occurs depends on the original doping). Above this value, the doping becomes effectively *p*-type (type inversion) and eventually rises linearly with fluence.