LECTURE 26

The action of ionizing radiation in Semiconductors

The ionization energy:

- The ionization energy (ε) is the average energy expended by the primary charged particle to produce one electron-hole pair
- This value is largely independent of the radiation type (e.g. 2.2 % difference between a proton and an alpha particle); fission fragments and heavy ions have significantly higher ε than an alpha particle
- $\varepsilon \sim 3$ eV for Si or Ge as opposed to 30 eV for a gas
- ε increases with decreasing temperature , approx 3% from room temp to liquid nitrogen ($\Delta T \sim 223$ K)
- it should be noted that the % of material used to dope *n* or *p* type materials play no role in determining the nature of the radiation interactions
- one should also note there is a dependence of the ionization energy on the energy of an incoming particle in the soft x-ray region

Fano factor:

- still defined as the difference (ratio) between the observed statistical variance and that predicted by the Poisson model

$$F \equiv \text{observed statistical variance} / (E/\varepsilon)$$

- for good energy resolution one would like E to be as small as possible, some values of Si and Ge are listed in Table 11.1

Semiconductors as radiation detectors:

Pulse formation:

- Fig 11.7 illustrates an idealized representation of the electron and hole currents flowing in a semiconductor following the creation of N_0 electron hole pairs. In the (b) plot note the contribution from the collection of each of the carriers (electrons or holes can fill either of the carrier slots). Note that if all carriers are collected a signal of eN_0 is induced, where e is the electronic charge.
- In either Si or Ge semiconductor detectors, the $\mu_n \sim 3\text{-}4 \times \mu_e$ so both are generally collected for pulse detection, since the collection times are close to being equivalent.

Electrical contacts:

- Ohmic contact – a nonrectifying electrode through which charges of either sign can flow freely
- Non injecting or blacking electrode – charge carriers initially removed by the application of an electric field are not replaced at the opposite electrode, and their overall concentration within the semiconductor will drop after the application of an electric field; hence reducing the leakage current.

Leakage Current:

- All semiconductor detectors will show some finite leakage conductivity and therefore a steady state leakage current will be observed with applied voltage
- As an example for pure Si: ρ = 50 kΩ.cm, t = 1mm, A = 1 cm^2 with ohmic contact R = 5000 Ω, apply a voltage V = 500 V, and the leakage current I_l = 0.1 A
- If we now compare this to the current produced by a radiation pulse providing 10^5 radiation induced charge carriers, yielding a current of 10^{-6} A
- We need a way to remove this overriding leakage value from our measurement.

The semiconductor junction:

Basic junction properties:

- A junction starts with having a *p* type (doped with acceptor impurities) and an *n* type (doped with donor impurities) in good thermodynamic contact.
- Good thermodynamic contact generally is formed by producing both *p*-type and *n*- type materials on either side of a single crystal. This change in impurity type from one side of the crystal to the other causes charge carriers to migrate across the junction through diffusion.
- Electrons from the *n* type region diffuse to the *p* type region while holes diffuse from the *p* type to the n type region
- Equilibrium hole concentration (*p*) and electron concentration (*n*) are plotted in Fig 11.8. Note how the electron migration leaves a net positive charge density while the electrons fill the acceptor sites leaving a now "immobile" negative charge and negative charge density fixed in the crystal
- This migration is limited by a charge density effect where the build up of charge results in stopping like charges to continue diffusing through the crystal.
- Fig 11.8 shows the spatial charge distribution in the top plot. N_A is shown as a horizontal line and the donor electrons (N_D) is the falling line illustrating the diffusion of an n type impurity from the left surface. The effects of carrier diffusion are shown in the lower plots, giving rise to the profiles for the space charge ($p(x)$), electric potential ($\psi(x)$) and the electric field ($\mathscr{E}(x)$).
- The accumulated space charge creates the electric field that diminishes the tendency for diffusion.
- The volume over which the charge imbalance exists is called the depletion region.
- One can find the value of the potential (at any point) by solving Poisson's equation:

$$\nabla^2\varphi = -\frac{\rho}{\varepsilon},$$

where ρ is the net charge density in the region and ε is the dielectric constant (permittivity) of the material in the region. In one dimension Poisson takes the form of:

$$\frac{\partial^2\varphi}{\partial x^2} = -\frac{\rho(x)}{\varepsilon}$$

- We can then integrate the equation two times and arrive at $\psi(x)$ the potential.
- We define the contact as the potential difference across the junction (nearly the full band energy of the semiconductor material)

- We can then derive our electric field, ($\mathcal{E}(x)$) by taking:

$$\mathcal{E}(x) = -grad\,\varphi = -\nabla\,\varphi(x)$$

which for one dimension is:

$$\mathcal{E}(x) = -\frac{\partial\varphi(x)}{\partial x}$$

- The electric field causes and electrons formed from a radiation event to be swept back towards the *n* type material and any holes toward the *p* type material
- The removal of charge carriers is advantageous to detection since the only charges left are bound donor and acceptor site charges. Thus any radiation event causes the flow of the excited electron hole pairs from the depleted region constituting a current.
- Having no charge carriers which are free also means the depleted region has a very high resistance
- Since there is still the possibility of thermally generated charge carriers to be created there may still exist this so called "generation current". Due to the $\mathcal{E}(x)$ field, these carriers tend to be swept away within ns and can be neglected since this time is much faster than the time required to reach equilibrium (removal is much faster than creation) and thus the small radiation generated current is easily detectable over the highly suppressed thermally generated concentration.

Reverse biasing:

- What we have discussed above is the most common use of the *p-n* junction, the diode
- If we apply a voltage in the forward direction (+V @ *p* and –V at the *n* end) a current will flow. The higher potential applied to the *p* side of the junction will attract the conduction electrons from the *n* side as well as holes from the *p* side across the junction.
- The contact potential is decreased by the voltage applied in this forward configuration, and once the contact voltage is reduced to 0 the current will begin to flow.
- If the voltage is applied in reverse with the potential lower on the *p* side and higher on the *n* side, the minority carriers (holes on the *n* side and electrons on *p* side) are attracted across the junction. Due to the low concentration of the minority carriers limits this current.
- Fig 11.9 illustrates the variation of the potential (electric) across an *n-p* junction. The lower plots show the electric energy levels (bands) across the junction. The curvature is reversed because the increase in electron energy corresponds to a decrease in the electric potential (conventional definition is for a positive charge). Fig 11.9 c shows the change in the bands adding a displacement caused by the application of a reverse bias V across the junction.

Properties of the Reverse bias junction:

- Reverse biasing increases the depletion region
- Detectors can be either partially or fully depleted where the completeness of depletion varies from a portion of the water to the entire wafer. The following

discussion will apply to the depleted regions of the various degrees of detector depletion

- For a partially depleted detector, consider the following idealized charge density distribution: $\rho(x) = \begin{cases} eN_D(-a < x < 0) \\ -eN_A(0 < x \le b) \end{cases}$; note the net charge is zero, $N_D a = N_A b$
- We go back to Poisson:

$$\frac{\partial^2 \varphi}{\partial x^2} = -\frac{\rho(x)}{\varepsilon}$$

- By substitution:

$$\frac{\partial^2 \varphi}{\partial x^2} = \begin{cases} -eN_D/\varepsilon & (-a < x \le 0) \\ eN_A/\varepsilon & (0 < x \le b) \end{cases}$$

- Our boundary conditions are that the electric field vanishes at the edges of the charge distribution
- We integrate the equation and apply the BC to get the first derivative, i.e. the negative of the electric field

$$\frac{\partial \varphi}{\partial x} = \begin{cases} -eN_D/\varepsilon(x+a) & (-a < x \le 0) \\ eN_A/\varepsilon(x-b) & (0 < x \le b) \end{cases}$$

- The figure on the middle of page 374 shows a sketch of $\mathcal{E}(x)$
- At $x = -a$ (the n side) the potential is V and at $x=b$ (the p side), the potential is 0 for our application of reverse bias.
- We integrate again and apply the BC, we get:

$$\varphi(x) = \begin{cases} \dfrac{-eN_D}{2\varepsilon}(x+a)^2 + V & (-a < x \le 0) \\ \dfrac{eN_A}{2\varepsilon}(x-b)^2 & (0 < x \le b) \end{cases}$$

- Our solutions must match at either side of the junction for $x = 0$:

$$V - \frac{eN_D a^2}{2\varepsilon} = eN_A b^2 / 2\varepsilon$$

$$N_A b^2 + N_D a^2 = \frac{2\varepsilon V}{e}$$

From the condition of $N_D a = N_A$b we get:

$$\boldsymbol{(a+b)\, b = 2\varepsilon V/eN_A}$$

- The total width of the depletion region d is the entire distance over which the space charge extends, $d = a+b = b\,(a/b + 1)$
- Suppose n side doping level is much higher than the p side ($N_D >> N_A$) then: $N_D a = N_A b \rightarrow a/b = N_A / N_D << 1$, we can then approximate the equation for d: $d \approx b$
- Our solution then can be simplified:

$$(a+b)b = db = 2\varepsilon V / eN_A$$

$$d^2 \approx 2\varepsilon V / eN_A \Rightarrow d \approx \sqrt{\frac{2\varepsilon V}{eN_A}}$$

- If the *p* side doping level is dominant instead we have $d \approx \sqrt{\frac{2\varepsilon V}{eN_D}}$
- In general we get: $d \approx \sqrt{\frac{2\varepsilon V}{eN}}$
- We can now replace this with the resistivity of the material $\rho_d = 1/e\mu N$:

$$d \cong (2\varepsilon V \mu \rho_d)^{1/2}$$

- We would like to have the largest depletion zone possible, so having the largest ρ_d would facilitate this. Thus we are in general interested in the purity material possible prior to doping.
- As we increase the reverse bias we also cause an increase in the separation of the charges, this act as a charged capacitor for the thickening depletion layer, decreasing the capacitance represented by the charged particles.
- The capacitance can be represented by: $C = \frac{\varepsilon}{d} = \left(\frac{e\varepsilon N}{2V}\right)^{1/2}$
- Good energy resolution is dependent on the capacitance in electronic noise dominant situations, specifically by obtaining the smallest capacitance possible.
- We reach this minimum capacitance by increasing the applied voltage up to the point where the detector becomes fully depleted
- The maximum electric field occurs at the point of transition between the *n* and *p* type material, with a magnitude of:

$$\mathscr{E}_{\max} \cong \frac{2V}{d} = \left(\frac{2VNe}{\varepsilon}\right)^{1/2}$$

which can easily reach 10^6-10^7 V/m for typical conditions.

- The depletion layer thickness *d* is proportional to $\sqrt{V}$ so that the value of $\mathscr{E}_{max}$ increases with applied voltage as $\sqrt{V}$.
- The interaction of parameters listed above is illustrated by the nomogram for Si detectors in Fig 11.10. The figure also shows the scales corresponding to the ranges of various charged particles to allow the selection of conditions required to produce a depletion depth that exceeds the range.
- The maximum operating voltage for any diode detector must be kept below the breakdown voltage to avoid a catastrophic deterioration of detector properties.