Semiconductor Detector Configurations

Diffused Junction Detectors:

- Fabricate by the common method of starting with a homogeneous crystal of *p*-type material.
- One surface is treating it to a vapor of *n*-type impurity (generally phosphorous).
- This causes the *p*-type to transform to an *n*-type material and the junction is formed some distance from the surface where the *n*- and *p*-type concentrations reverse.
- Typical depths of the diffused *n*-type range from 0.1 to 2.0 µm.
- Since the depletion later extends primarily toward the *p*-side of the junction, much of the surface layer remains outside the depletion layer; this is called a dead layer.
- The dead layer will tend to absorb some of the energy of a particle before reaching the depleted layer (active layer) and so other designs have been developed the reduce this disadvantage.
- This configuration does have the advantage of being more rugged than the surface barrier detectors, since oil or foreign matter accumulation on the surface will not affect the detector (since this is a dead region anyway).

Surface Barrier Detectors:

- The role of the p-type material in forming the junctions can be assumed by a high density of electron traps formed on the surface of an *n*-type crystal.
- This behaves in much the same way as a diffused junction detector, but with a much thinner depletion region.
- A potential disadvantage is a high sensitivity to light since the thin entrance windows are optically transparent.
- A high noise level is generated from ambient light, but the vacuum enclosure required for most charged particle applications reduce the noise to insignificant levels.
- A cross sectional diagram for the detector is shown in Fig. 11.11a, note that the outer housing and front surface are normally grounded and an electrical lead from the back surface of the semiconductor wafer attaches to the center electrode of the coaxial connector at the rear.
- Due to the creation of most surface barrier diodes on *n*-type crystals, a positive polarity voltage is required to reverse bias the junction.

Ion implanted layers:

- An alternate method of introducing doping impurities at the surface of the semiconductor is to expose the surface to a beam of ions produced by an accelerator.
- This method is called ion implantation and can be used to form either n^+ or p^+-type layers by selection of the ion (phosphorus or boron respectively).
- Selection of the accelerating potential (10 kV in general) or the incident energy of the ions, the concentration profile of the added impurity can be closely controlled.
- Annealing is then performed to reduce the radiation damage to the wafer (T~500 C)

- These detectors tend to be more stable and less subject to ambient conditions than surface barrier detectors.

Fully Depleted Detectors:

- The width of the depletion region associated with a *p-n* junction increases as the reverse bias is increased, eventually this region can extend across the entire thickness of the wafer, resulting in a fully depleted detector.
- Usually, one side of the detector is a heavily doped n^+ or p^+-type layer, and the other side is a mildly doped n or p-type material of very high purity (the purity requirement is reflected in the thickness of the depletion zone-eq. 11.18) and the detectors with the largest depletion zones start with the materials that leave the lowest impurity concentrations.
- The large difference in concentrations then has the depletion zone extending into the high purity areas, and there is a very thin entrance window from the heavily doped layer for weakly penetrating radiations.
- Fig. 11.12 illustrates the reverse bias voltage setup for a depleted detector, where increasing the voltage from 0 extends the depleted region from the p^+-layer into the bulk of the detector.
- Areas that are not depleted from a dead layer, until higher voltages can continue to deplete the detector.
- With enough voltage the detector reaches full depletion (sometimes called the depletion voltage). For a given thickness of a detector, T, the voltage required for a complete depletion is:

$$V_d = \frac{eNT^2}{z\varepsilon}$$

Once this voltage is reached, increasing the voltage just raises the $\mathscr{E}$-field through the entire detector.

- Fig. 11.3 shows several configurations for fully depleted detectors with field profiles in the detectors. Note the reversal of roles for the rectifying contact and blocking contacts for either the *p* or *n* base material.
- Fully depleted detectors are useful for transmission work, where a particle passes fully through the detector, the pulse height is then proportional to the energy lost by the particle as it passes through the detector. Thicknesses of these detectors range from 50-2000 μm.
- Several properties are important for these detectors:
  1. The dead layers for both surfaces must be as small as possible
  2. The thickness of the wafers must be kept uniform to avoid energy loss variations across the surface of the detector
- Other advantages of fully depleted detectors are the reduction in Johnson noise (finite electrical resistance in the dead layer), better timing properties, and added stability by removing the capacitance value from the applied voltage dependence.

Passivated Planar Detectors:

- Produced using a combination of silicon junction fabrication, ion implantation, and photolithography
- These detectors generally have superior operating characteristics and lower leakage currents
- Fig. 11.4 illustrates the steps involved with forming the layers of the passivated detector
- The passivation of the detector is the formation of a highly resistive oxide layer, reducing the leakage current

Operation Characteristics

Leakage Current:

- When a voltage is applied to a junction detector in a normal way (reversed biased) a small current of the order of a fraction of a μA is observed the leakage current
- The majority carriers will be repelled from the junction, but minority carriers will be conducted across the junction
- The minority carriers are continuously generated and free to diffuse; a steady state current is sustained
- A second source is the thermally generated electron pole pairs. These may be reduced by cooling the detector
- Surface conduction can take place at the edges where high voltage gradients reside
- The use of clean encapsulation techniques and introduction of edges in the silicon wafer design, reduce this leakage to manageable amounts
- Leakage current is generally monitored (by an ammeter in series with the voltage source) to evaluate the detector for abnormal behavior. Changes in the current may indicate loss of energy resolution, bias voltage irregularities and radiation damage

Detector Noise and Energy Resolution:

- Electronic noise falls into two categories, series noise and parallel noise
- Contributions to noise are from these sources:
    1. Fluctuation from the bulk leakage current (parallel)
    2. Fluctuations in the surface leakage current (parallel)
    3. Noise associated with the electrical contacts and other series resistance (series)
- The noise width divides in quadrature with other sources of peak broadening (charge carrier statistics and fluctuations in particle energy loss and dead layers) to determine actual peak widths
- Trapping effects will be noticed in the appearance of low energy tails

Changes with detector bias voltage:

- With low bias voltage and electric field, the pulse height increases with increasing voltage due to the increasing number of electron hole pairs that recombine before measurement. This is similar to a gas filled ion chamber. This is the result of partial charge collection

- Once significant voltages (and fields) are reached, the detector reaches the saturation region and pulse height becomes independent of voltage
- With sufficiently high voltages, multiplication may be induced, where excited electrons have sufficient energy to excite more electron hole pairs, similar to a proportional counter or G-M tube

Pulse Time Rise:

- Semiconductor are generally among the fastest of commonly used radiation detectors
- Under normal conditions pulse rise time is on the order of ten ns or less, and is composed of two components. Charge transit time and plasma time.
- Charge transit time corresponds to the migration of electrons and holes formed from instant radiation across the region of high electric fields in the depletion region.
- The time is minimized in detectors with high electric fields and small depletion regions
- The plasma time is from interactions with heavy charged particles, where their interaction create enough electron hole pairs to form a plasma-like cloud of charge that shields the electric field
- Only carriers on the exterior of the cloud are affected by the field and the erosion of charges from the cloud limits the rise time of the pulse (and charge collection)
- Rise time may also be affected by detector-preamplifier combination, including the series resistance of the undeleted region in partially depleted detectors
- Fully depleted detectors with a virtually eliminated series resistance are favored for fast timing applications.

Entrance Window and Dead Layer

- Charged radiations (or weakly penetrating) may lose much of their energy in the dead layer prior to reaching the active volume
- This layer may be bias voltage dependent and accurate measurement of the thickness must be made to compensate
- For perpendicular orientation (angle of incidence is 0) with respect to the dead layer, the energy loss is given by:

$$\Delta E_0 = \frac{dE_0}{dx} t$$

Where t is the thickness of the dead layer.
The energy loss for an angle of incidence, θ is:

$$\Delta E(\theta) = \frac{\Delta E_0}{\cos\theta}$$

The difference between the measured pulse height between 0 and θ is:

$$E' = (E_0 - \Delta E_0) - \left(E_0 - \Delta E(\theta)\right) = \Delta E_0 \left(\frac{1}{\cos\theta} - 1\right)$$

Where measurements are made with varying incident angle, and a plot of $E' \ vs. \left(\frac{1}{\cos\theta} - 1 \right)$ should be a straight line with slope ΔE_0; using tabular data for dE_0/dx we can determine t.

- There is assumption that the energy loss through the dead layer only depends on the path length
- Ion implanted detectors have the thinnest dead layers (100 nm) and produce an energy loss approximately 4 keV for a 1MeV proton or 14 keV for 5 MeV alpha particles

Channeling

- The reducing interaction (and therefore absorption) of radiation along principle crystal direction
- Affects our primarily y significant in thin totally depleted detectors
- Detectors are generally cut so the <1,1,1> crystal direction is perpendicular to the wafer source

Radiation Damage

- The proper operation of semiconductor detectors depend on the near perfection of the crystalline lattice to prevent charge collection defects (traps)
- Over time, heavy charge particles will damage the lattice and create irreversible effects that degrade the detector characteristics (light particles may also cause damage but at much slower rates)
- Radiation induced damage falls into two categories, bulk and surface defects

Bulk

- Frenkel defects are from the displacement of an atom from a lattice sight. The combination of the displaced atom and corresponding vacancy create trapping centers for normal charge carriers
- The single occurrence of these sites are called point defects and are generally caused by γ ($E \leq$ few MeV), while defects formed along the path of a heavy charged particle are more complex (clusters)
- Annealing may migrate these affects but generally they are permanent
- Effects of bulk damage include reduction of carrier lifetime and charge collection and degradation of energy resolution

Surface

- Effect is generally associated with an increase in a leakage current and loss of detector resolution
- Type of radiation can affect the distribution of damage, γ-rays and neutrons damage the entire detector, while electrons and charge particles will damage the incidence side more than the rest of the detector and levels require to damage the incidence side may be orders of magnitude less than required to damage the trailing side

Energy Calibration

- Semiconductor diodes respond with reasonable linearity for light particles (electrons, neutrons, protons or alpha) and energy calibration will be similar when a radiation of a different type is used
- However, for measurements where the absolute energy calibration is desired to be less than 1%, the particle of interest should be used
- The most common calibration source is ^{241}Am which emits two alphas (5.486 MeV-85%) and (5.443 MeV-13%), the spectrum is shown in Fig. 11.15

- Calibration should take into account energy loss from the source itself, from intervening materials in the window or dead layer

Pulse Height Defect

- Response of the detector to very heavy ions (like fission fragments) is more complicated, and produces pulse heights less than what is seen for equivalent energy light radiations
- This is illustrated in Fig. 11.16 where defects of 15 MeV can be seen, for an average energy of 80 MeV
- Research has shown three separate reasons for the defect:
    1. Energy loss at the entrance window and dead layer due to high *dE/dx* delivered at the beginning of their range
    2. Tendency for heavy ions to lose energy to other means than simple electronic collisions. Nuclear interactions become important with nuclei recoil taking energy from producing electron hole pairs
    3. The high rate of electron hole recombination in the plasma along the ion track. One can migrate this phenomena by using the largest electric field within the detector, by increasing the bias voltage
- Since trapping and recombination are affected by radiation damage, increases in the pulse height defect should be expected with use
- Fig. 11.17 shows the measured pulse height defect for a silicon heavy ion detector as a function of integrated fission fragment flux. The increase of pulse height defect is evident as well as partial correction through annealing at room temperature outside of the radiation flux.