University of Liverpool
Department of Physics

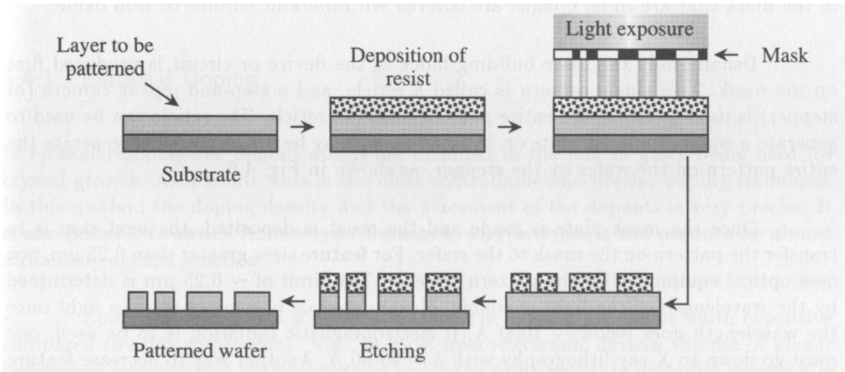
Semiconductor Applications, PHYS389

Tutorial 2: Solutions

1. Bulk crystal growth is a well developed technique. What is the reason for utilising lithographic methods? Describe the three primary processes used in lithography, with the aid of diagrams.

Answer

Lithography is required because crystal growth processes do not produce any controlled lateral variations in the material properties.
The three primary processes: Photoresist coating, Mask generation/Image transfer and etching.
In order to transfer an image to a wafer, the surface has to be made sensitive to light. Spin coating transfers photoresist onto the wafer. The wafer is spun at 2000-8000rpm to ensure a uniform thickness (1.0µm) and then soft baked. The resist is exposed to an optical image though a mask. A resist becomes more soluable when exposed to light. The mask is used to repeatedly transfer patterns to different wafers. Once the image is transferred the image is developed and etching is carried out. The etchants must be able to remove a layer of material from the region where there is no resist and not attack the resist. Wet chemical etching is often used.



2. What are the principle differences between the operation of the Bipolar Junction Transistor and the Field Effect Transistor? What advantages do Schottky contacts offer over traditional p-n junctions?

Answer:

BJT: A three contact device having an emitter, base and collector contact. The base-emitter voltage controls the flow of electrons from emitter to collector.

FET: A three contact device having a source, gate and drain contact. It consists of an active channel through which electrons flow from source to drain. The gate potential alters the charge drifting from the source to the drain.

Answer:

Schottky contacts:

p-n Diode	**Schottky Diode**
Reverse current due to minority carriers diffusing to the depletion layer $\rightarrow$ strong temperature dependence	Reverse current due to majority carriers that overcome the barrier $\rightarrow$ less temperature dependence
Forward current due to minority carrier injection from n- and p-sides	Forward current due to majority injection from the semiconductor
Forward bias needed to make the device conducting (the cut-in voltage) is large	The cut-in voltage is quite small
Switching speed controlled by recombination of minority charge carriers	Switching speed controlled by thermalisation of "hot" injected electrons across the barrier ~ps (majority carrier device).

3. Describe the three primary methods by which gamma-rays interact with matter. How does the cross-section for interaction of these three processes vary with energy?

Answer:

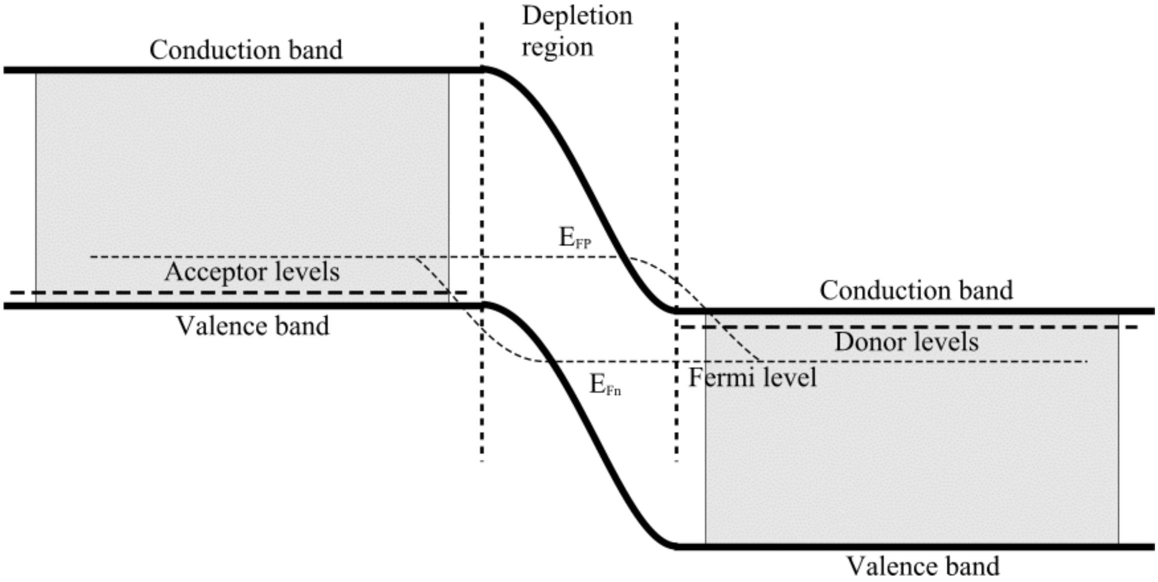
Photoelectric absorption, Compton Scattering and Pair Production.
Photoelectric absorption: The gamma-ray interacts with a bound atomic electron. The photon completely disappears and is replaced by an energetic photoelectron which has an energy $E_e = E_\gamma - E_b$, the energy of the incident gamma-ray photon minus that of the binding energy of the electron (12eV in germanium). A discrete energy signal is produced.

Compton Scattering: The gamma-ray interacts with a loosely bound atomic electron. The incoming gamma-ray is scattered through an angle θ with respect to its original direction. The photon transfers a proportion of its energy to a recoil electron. The expression that relates the energy of the scattered photon to the energy of the incident photon is: $E_s = \dfrac{E_\gamma}{1 + \dfrac{E_\gamma}{m_0 c^2}(1 - \cos\theta)}$. A continuous distribution of energies is produced.

Pair production: If the energy of a gamma-ray exceeds twice the rest mass energy of an electron (1.02MeV) the process of pair production is possible. A gamma-ray disappears in the Coulomb field of the nucleus and is replaced by an electron-positron pair. The excess energy above 1.02MeV goes to the kinetic energy of the electron and the positron. The position will subsequently annihilate after slowing down in the absorbing medium, producing two annihilation photons (511keV) which may be subsequently detected.

Draw an energy level diagram showing the variation of the energy bands across a reverse biased p-n junction. Indicate the semiconductor bands, Fermi level, and depletion region.

Answer:



Write down the expression for the overall energy resolution achievable in a germanium detector, describe the origin of each of the terms. If the value of the Fano factor is 0.06 calculate the contribution to the final energy resolution for a gamma-ray of energy 511keV.

Answer:

The expression is:

$$W_T^2 = W_D^2 + W_X^2 + W_E^2$$

W_D is the inherent statistical fluctuation in the number of charge carriers created.
W_X is due to incomplete charge collection (important in large volume detectors).
W_E is from the broadening effects of all electronic components following the detector.

$$W_D^2 = (2.35)^2 F\varepsilon E$$

F is the Fano factor (observed statistical variance/(ionisation energy/energy)), ε is the ionisation energy (2.96eV), E is the gamma-ray energy and 2.35 scaling factor

Therefore:

$$W_D = \sqrt{(2.35)^2 \times 0.06 \times (2.96 \times 1.6 \times 10^{-19}) \times 511 \times (10^3 \times 1.6 \times 10^{-19})}$$

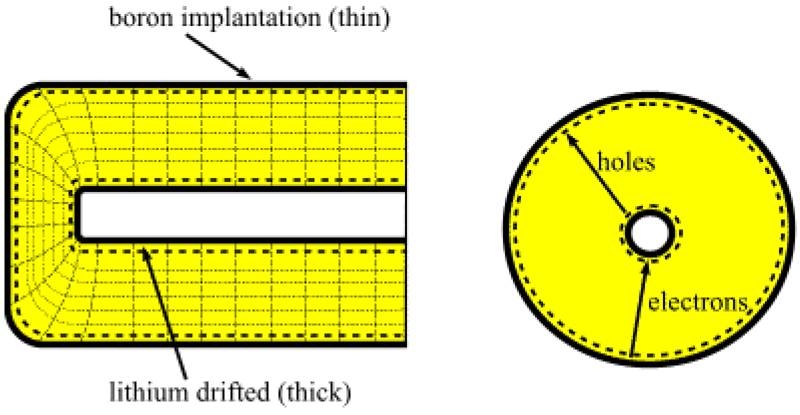
$$= 7.096 \times 10^{-17} / 1.6 \times 10^{-19}$$

$$= 708 eV$$

$$W_T^2 = 0.708^2 + W_X^2 + W_E^2$$

4. Draw a schematic diagram of a bulletised n-type closed end coaxial germanium detector used for high resolution gamma-ray spectroscopy. Label the respective contacts.

Answer:



Describe the main principles of operation for this device.

Answer:

The detector crystal is reverse biased to ensure that the whole crystal volume is depleted (full depletion). This is achieved by apply high voltage to the central anode and by grounding the outer contact. The shape of the detector maximises this volume, therefore maximising the detection efficiency. This typically requires ~2-4kV. When a gamma-ray photon interacts the associated electron-hole pairs are collected along the E-field lines. The charge is collected from the central anode is read out through an associated FET and charge sensitive preamplifier.

The voltage required to fully deplete a true coaxial germanium detector is:

$$V_d = \frac{\rho}{2\varepsilon}\left[r_1^2 \ln\left(\frac{r_2}{r_1}\right) - \frac{1}{2}(r_2^2 - r_1^2)\right]$$

For a detector of 8cm outer diameter and 1.5cm inner diameter calculate the voltage required for full depletion.

<u>Answer:</u>

The dielectric constant for Ge is 16. Assume the net bulk impurity concentration (N) is $1\times10^{10}cm^{-3}$**, this is a typical accepted value for HPGe.** Such a low impurity concentration corresponds to levels that are less than 1 part in 10^{12}, a virtually unprecedented degree of material purity! The charge density is hence eN.

$$V_d = \frac{\rho}{2\varepsilon}\left[r_1^2 \ln\left(\frac{r_2}{r_1}\right) - \frac{1}{2}(r_2^2 - r_1^2)\right]$$

$$V_d = \frac{1\times10^{16}\times1.6\times10^{-19}}{2\times16\times8.85\times10^{-12}}\left[0.0075^2\times\ln\left(\frac{0.04}{0.0075}\right) - \frac{1}{2}(0.04^2 - 0.0075^2)\right]$$

$$= 5654771.9\times(-6.78\times10^{-4})$$

$$V_d = -3.8kV$$

A photon interacts via the photoelectric effect at a radial position 5mm from the outside of the detector. Calculate the charge collection time for the electrons in a fully depleted n-type germanium detector, assuming that the electric field strength is 10^5V/m.

<u>Answer:</u>

Electrons drift towards the centre a distance of 2.75cm.
There are two possible routes here, they might utilise the electron mobility at 77K and calculate the drift velocity. (This assumes proportionality which in reality is not the case as the drift velocity is saturated at this field strength). Hence the charge collection time.

$$v_d = \mu_e E = (3.6\times10^4)cm^2/V\cdot s\times(1\times10^3)V/cm = 3.6\times10^7 cm/s$$

$$t = \frac{d}{v_d} = \frac{2.75}{3.6\times10^7} = 76.4ns$$

Or better still they should look at the plot on page 16 of lecture 4 which shows the relationship between E and V_d for germanium.

$$v_d =\sim 6\times10^6 cm/s$$

$$t = \frac{d}{v_e} = \frac{2.75}{6\times10^6} = 458ns$$