Detection of Light: Exercise 4

Set: Fri 4th Mar 2016,
Due: Fri 11th Mar 2016
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1 BIB Detectors [15 marks]

Consider the Blocked Impurity Band (BIB) photoconductor shown in Fig. 1, consisting of a highly-doped Si:As (n-type) infrared-active layer with a small but non-negligible fraction of p-type impurities, which is overlaid with a high-purity Si blocking layer to which a positive bias voltage V_b is applied. A depletion region of width w is formed in which photons may be absorbed and subsequently detected with high efficiency.

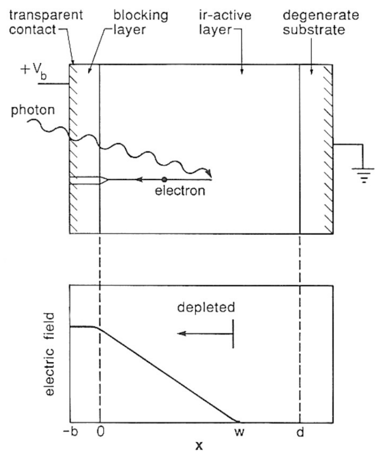

Figure 1: Diagram of a BIB depletion region.

For this question take the blocking and IR-active layer widths to be $t_B = 4.5\,\mu$m and $t_A = 15.0\mu$m respectively, and the densities of of n-type dopants and p-type impurities are $N_D = 5\times10^{17}\,\text{cm}^{-3}$, $N_A = 10^{13}\,\text{cm}^{-3}$. The dielectric constant $\kappa_0 = 11.8$ for Si at room temperature, and the permittivity of free space $\epsilon_0 = 8.854 \times 10^{-12}$ F m^{-1}.

a Sketch an energy-level diagram for this BIB detector, and with reference to this explain:

i) how this design helps overcome the conventional problem associated with over-doping in extrinsic semiconductors.

ii) what is meant by the depletion region, and why it has a finite extent within the IR-active layer.

[5 marks]

b i) By solving the one-dimensional Poisson equation

$$\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{\rho}{\epsilon_0 \kappa_0},$$

obtain an expression for the electric field E as a function of distance x from the inner edge of the blocking layer, depletion layer width w and acceptor density N_A.

ii) Hence show that the width of the depletion region as a function of the bias voltage V_b and thickness of the blocking layer t_B is given by:

$$w = \left(\frac{2\kappa_0\epsilon_0}{qN_A} |V_b| + t_B^2 \right)^{\frac{1}{2}} - t_B$$

[Hint: Use the boundary condition $V(x = -t_B) = |V_b|$ at the outer edge of the blocking layer.]

[6 marks]

c What is the value of the critical bias voltage in this detector for which the thickness of the depletion region is the same as the thickness of the IR-active layer, t_A?

[2 marks]

d Consider photo-electrons accelerated near the boundary of the blocking layer, where the mean-free path length is $\langle l \rangle \sim 0.3$ μm.

i) On average how much energy will these electrons gain in between collisions?

ii) Given that the ionisation energy of arsenic in Si:As is $E_i = 54$ meV, explain briefly how gains of $G > 1$ may be obtained in BIB detectors.

[2 marks]

2 Diffusion in photodiodes [5 marks]

In a photodiode, the diffusion length L$_n$ can be understood as the average distance a carrier can move (or diffuse) in the neutral p-type and n-type regions, before it recombines. This is defined as:

$$L_n = (D\tau)^{1/2}$$

where

$$D = \frac{kT\mu}{q}$$

is the diffusion coefficient and τ is the recombination time.

a In order to increase detectability of photogenerated carriers, what condition should be imposed on the thickness l of the neutral absorber layer overlying the depletion region, in terms of the impurity concentration N_I? Assume that the variation of the mobility μ with impurity concentration is negligible and that $\tau \propto N_I^{-1}$.

[1 mark]

b Test your condition by calculating the detector quantum efficiency η for three values of l about the limit determined in part a (eg. the limiting value itself and a factor of 2 either side), where

$$\eta = \frac{2b}{e^{l/L_n} + e^{-l/L_n}}$$

and b is the fraction of incident photons available for absorption to produce carriers. What do you conclude?

[3 marks]

c On the other hand, what is the requirement on the thickness l in terms of N_I in order to guarantee good photon absorption rates? Is it in general possible to meet these two conditions simultaneously in an extrinsic photoconductor?

[1 mark]