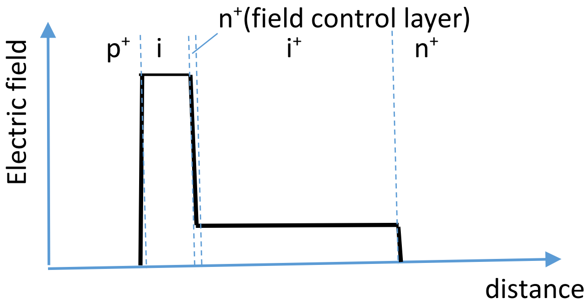
EEE337/348: Tutorial 5

1) An IMPATT diode consists of semiconductor layers with accurately controlled doping concentrations. A Silicon p^+-i-n^+-i-n^+ diode is designed such that impact ionisation is confined within the injection region of the IMPATT.
    a. Sketch and label the electric field profile of this p^+-i-n^+-i-n^+ diode.

Since p+ and n+ are highly doped, the electric changes rapidly as described by Poisson equation

$\frac{\partial E}{\partial x} = \frac{qN}{\varepsilon}$ where N is the doping concentration of the layer considered. Likewise the intrinsic layers or i-layers have very low doping concentrations and the electric field remains fairly uniform. The electric field profile therefore looks like



a. Suggest the operating voltage if the diode has the following parameters,
    i. the thickness of the injection region is 1 μm and its breakdown field is 300 kV/cm,
    ii. the drift region is 4 μm,
    iii. the n+ layer, sandwiched between the two i layers, (also referred to as the field control layer) has a doping concentration of 10^{18} cm^{-3} and thickness of 10 nm

We can see that the electric field profile is that of a lo-hi-lo structure. The breakdown voltage is

$$V_B(lo-hi-lo) = E_m x_a + \left(E_m - \frac{qQ_c}{\varepsilon_s}\right)(w - x_a)$$

We will need to calculate the charge density of the thin field control layer

$$Q_c = 10^{18} cm^{-3} \times 10 \times 10^{-7} cm = 10^{12} cm^{-2}$$

$$V_B(lo-hi-lo) = (300\times10^3 V/cm)(1\times10^{-4} cm) + \left(300\times10^3 - \frac{1.6\times10^{-19}\times10^{12}}{11.9\times8.85\times10^{-14}}\right)(4\times10^{-4}) = 89.2V$$

2) For the IMPATT diode in (1), calculate the electric field in the drift region. Is it sufficiently high to maintain velocity saturation of electrons?

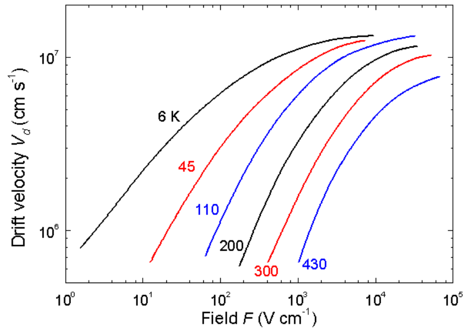
    The difference between the electric fields in the injection region and the drift region is given by $\frac{\partial E}{\partial x} = \frac{qN}{\varepsilon}$, where N is now the doping concentration in the n^+ field control layer.

    The electric field in the drift region is given by

$$E_{dirft} = E_{injection} - \frac{qQ_c}{\varepsilon_s}$$

$$E_{dirft} = 300 \times 10^3 - \frac{1.6 \times 10^{-19} \times 10^{12}}{11.9 \times 8.85 \times 10^{-14}} = 148 kV/cm$$

Clearly the electric is sufficiently high for the electrons to travel at the saturated velocity (see the plot below).



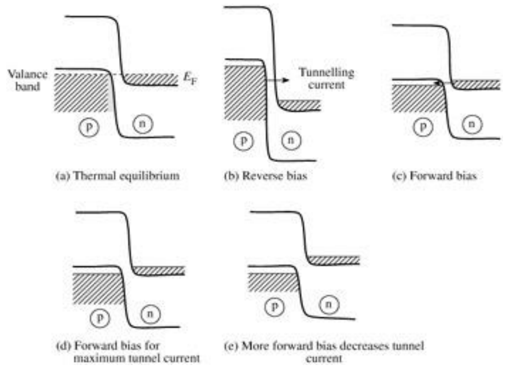
3) Assuming that the saturation velocity in Silicon is 10^5 ms^{-1}, calculate the operating frequency of the IMPATT diode in (1).

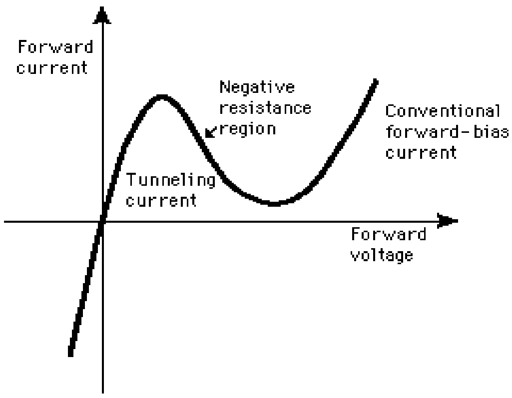
The operating frequency is $f_o = \frac{10^5 ms^{-1}}{2(4 \times 10^{-6})} = 12.5 GHz$.

4) Describe how a pn diode can be modified to work as a tunnel diode. Explain how the negative resistance is achieved in the tunnel diode.

In an intrinsic semiconductor, occupied states are in the valence band while the empty states are in the conduction band. Therefore tunnelling can only occur when electrons tunnel through, from the p to the n-side under a large reverse bias across the pn diode (see figure (b)). To achieve tunnelling effect in the forward bias, we need to modify the pn diode so that electrons can tunnel through, in the reverse direction from n to p-side (see figure (c)). By increasing the doping on n-side we can raise the Fermi level into the conduction and ensure that there are sufficiently large concentration electrons in the conduction. Likewise increasing the doping on the p-side leads to a Fermi level in the valence band and we have a sufficiently larger concentration of holes (unoccupied states).

The strength of the tunnelling effect depend on the “overlap” between the occupied and empty states. As the forward bias increases, tunnelling current increases with bias, then reaches a peak, drops to a minimum corresponding to the changes in the “overlap” as illustrated below. The drop in the current produces the negative resistance.





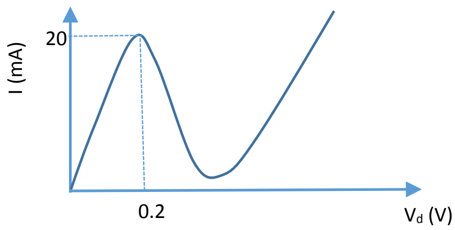
5) Consider a GaAs tunnel diode with the following parameters; a lead inductance of 0.1 nH, a series resistance of 4 Ω, a junction capacitance of 70 fF and a negative resistance of -20 Ω. Calculate the frequency when the real part of the impedance becomes zero.

$$Z_{in} = \left[R_s + \frac{-R}{1+(\omega RC_j)^2} \right] + j\left[\omega L_s + \frac{-\omega C_j R^2}{1+(\omega RC_j)^2} \right]$$

The real part becomes zero when

$$f_{r0} = \frac{1}{2\pi RC_j}\sqrt{\frac{R}{R_s}-1} = \frac{1}{2\pi\times 20\times 70\times 10^{-15}}\sqrt{\frac{20}{4}-1} = 2.27\times 10^{11} Hz$$

6) The typical I-V characteristics of a GaAs tunnel diode is shown below.



The device area is 10^{-7} cm^2, the doping concentration is 10^{20} cm^{-3} on p and n-sides, and the built-in potential is 600 mV. The speed index of a tunnel diode is defined by I_p/C_j, where I_p is the peak current and C_j is the diode capacitance. Calculate the speed index for this tunnel diode.

First we need to calculate the junction capacitance at 0.2V. The depletion width is

$$W = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)(V_{bi}-V_d)} = \sqrt{\frac{2\times 13.1\times 8.85\times 10^{-14}}{1.6\times 10^{-19}}\left(\frac{10^{20}+10^{20}}{10^{20}\times 10^{20}}\right)\times(0.6-0.2)} = 0.34\mu m$$

The capacitance is

$$C_j = \frac{\varepsilon_s A}{W} = \frac{13.1\times 8.85\times 10^{-14}\times 10^{-7}}{0.34\times 10^{-4}} = 3.41 fF$$

The speed index is 20mA/3.41fF = 5865 mA/pF.

7) Explain the key features in a semiconductor material that allows a Gunn diode to produce the negative resistance.

A semiconductor that exhibits a velocity-field profile with an overshoot and saturated velocities as shown below can be exploited as a Gunn diode. To achieve this profile, the effective mass should be small in the Γ valley so that electron can acquire high velocity as the field increases. When the electron transfer to a higher valley with larger effective mass, the velocity reduces. To ensure that electron can transfer to the higher valley, it is important that the semiconductor bandgap is much larger than the energy difference between the Γ valley and the next higher valley. Otherwise the electron will encounter impact ionisation, loses its energy and return to the bottom of Γ valley.