Series _ Electronic and optical semiconductor devices

Series 9 _ Analysis of figures.

Figure 1

This figure displays the evolution of the electron (e^-) concentration with increasing temperature for an n_type doped semiconductor (Si doped with $10^{15}\,cm^{-3}$ donors). Three main regions can be noticed that are governed by the evolution of the neutrality condition.

① At very low temperature, the ionization of impurities is incomplete and the concentration of free carriers is given by the relationship:

$$n + N_A^- = p + N_D^+.$$

Physically, a decrease of the free e^- and holes (h^+) is observed with decreasing temperature because they do not possess a thermal energy large enough to get free from the donor or acceptor atoms and thus take part to transport phenomena in the conduction or the valence band. The decrease of n and p with T(K) is thus due to the "condensation" of free carriers on impurity atoms. At T = 0 K, none of the donors are ionized (Fig. 1) ⇒ fully insulating behavior.

② At intermediate temperatures, donors and acceptors are fully ionized and one gets the relationship:

$$n \approx N_D - N_A \approx \text{constant} \quad \text{(n_doped case)}$$
$$p \approx N_A - N_D \approx \text{constant} \quad \text{(p_doped case)}$$

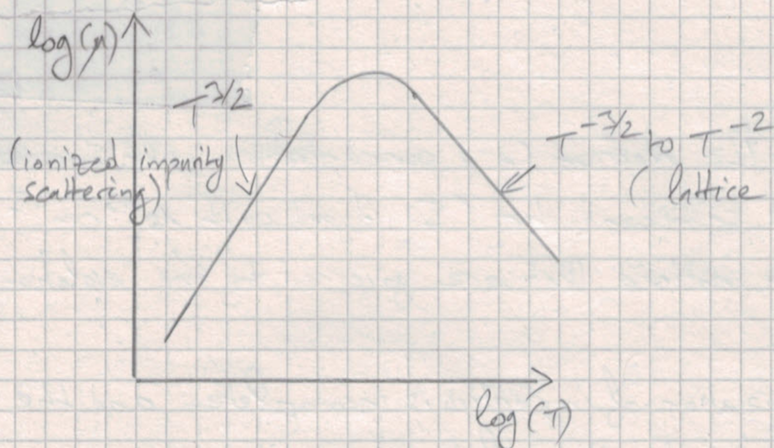
The temperature range over which n or p is almost constant is the extrinsic T_region.

③ At high temperatures, the intrinsic concentration n_i becomes very large compared with the net concentration of impurities (dopants) $N_D - N_A$ or $N_A - N_D$ so that the neutrality condition reduces to $n = p = n_i$ (intrinsic T_region).

Figure 2

The two subfigures depicts the evolution of the free carrier mobility (for e^- and h^+) at room temperature (RT) for three types of semiconductors (Si, Ge and GaAs) as a function of the doping level. It is seen that the mobility μ remains constant for impurity levels $\leq 10^{15}\,cm^{-3}$. The maximum value in each case is the so_called lattice mobility since its magnitude is an intrinsic property of the host crystalline lattice. It is seen that the lighter

the effective mass, the larger the mobility. On a log-log plot, the temperature dependence of the mobility exhibits the following shape:



Maximum occurring between ~ 10 and 80K depending on the semiconductor of interest and the doping level.

⇒ At 300 K the mobility is thus governed by the lattice. However, the higher the doping level the smaller the RT mobility

Matthiessen rule will apply as a first approximation:

$$1/\mu_{tot} = 1/\mu_{latt} + 1/\mu_{impurities} + \dots$$

Figure 3

Figure 3(a) displays the variation of the drift velocity of e^- and h^+ with increasing electric field for two semiconductors, Si and GaAs measured at RT.

For small E field values (region a), the drift velocity is small compared to the thermal velocity of carriers so that the e^--phonon scattering event rate is not strongly modified by this E field and e^- remain at thermal equilibrium with the lattice. ⇒ drift velocity ∝ E field

⇒ Ohm's law is satisfied $\vec{v_d} = \mu \vec{E}$

For moderate to high fields (region b), the velocity reached by e^- accelerated by the field cannot be neglected vs the thermal velocity. Along the mean free path λ, e^- acquire an energy equal to $qE\lambda$ which is partly transferred to the lattice through e^--phonon scattering. Accelerated e^- can reach a velocity exceeding the thermal velocity:

$$\langle v_d \rangle \geq \langle v_{th} \rangle = \left(\frac{3k_BT}{m^*}\right)^{1/2}$$

However, e^- cannot acquire a velocity larger than the saturation velocity (v_{sat}), which is determined by the energy of an optical phonon $\hbar\omega_{op}$ and the average time between two scattering events τ_{op}. Then one gets

$$qE_{sat}v_{sat} = \hbar\omega_{op}/\tau_{op}$$ and (i) $\lambda \simeq v_{sat}\tau_{op}$

(ii) $v_{sat} \approx \mu E_{sat} \approx \left(\frac{q\tau_{op}}{m^*}\right) E_{sat}$

$$\Rightarrow v_{sat} \approx \left(\frac{\hbar\omega_{op}}{m^*}\right)^{1/2}$$ value independent from E field / from the lattice temperature

(region c)

In some semiconductors like GaAs, e^- can acquire enough energy when they are subjected to an electric field to scatter in a secondary minimum of the conduction band. In such a region, the larger DOS and e^- effective mass will induce a decrease of the mean drift velocity (cf. Fig. 3(b)). From Fig. 3(a), it is seen that this transfer occurs for a critical field equal to ~ 3 kV/cm.

Figure 4

This figure shows the evolution of the I–V characteristics for a forward biased p–n junction (a) schematic behavior, (b) characteristics of a commercial diode measured at 300K.

The dashed lines in Fig. 4(a) indicate the slopes of different ideality factors n (η in the lectures). When the ideal diffusion current dominates, n equals 1, whereas when the recombination current dominates, n equals 2. When both currents are comparable, n has a value between 1 and 2 (crossover between the two regimes). In fact, the ideal diode equation ($J = J_s \left(\exp\left(\frac{qV}{k_BT}\right) - 1\right)$) can well account for the current-voltage characteristics of Ge p–n junctions at low current densities but not for Si or GaAs p–n junctions. For the latter, defects located in the bandgap will act as generation-recombination centers whose current in the depletion region (to be admitted) under reverse bias is given by:

$$J_{gen} = \frac{q n_i W}{\tau_g}$$, where the parameters have their usual meaning

and τ_g is the generation lifetime.

Under forward bias, the recombination current is given by (to be admitted)

$$J_{rec} = \frac{q W n_i}{2\tau_r} \exp\left(\frac{qV}{2k_BT}\right)$$ where τ_r is the effective recombination lifetime

The total forward current can be approximated, when $p_{n_0} \gg n_{p_0}$ (cf. series on p–n junction out of equilibrium + lectures) and $V \gg 3k_BT/q$, by:

$$J_F = q\sqrt{\frac{D_p}{\tau_p}}\,\frac{n_i^2}{N_D}\, e^{qV/k_BT} + \frac{qWn_i}{2\tau_r}\, e^{qV/2k_BT}$$

⚠ use of the mass action law: $p_{n_0} n_{p_0} = n_i^2$ + neutrality condition at RT

It is thus seen that the 2nd term on the right-hand side is a monomolecular one whereas the 1st one is a bimolecular one. In other words,

the first one will dominate for larger currents only.
The saturation observed for large voltages is due to both the impact of the series resistance effect (large IR drop which reduces the bias across the depletion region) and the strong increase of the minority carrier density that becomes comparable to the majority concentration.

Figure 5

When the two sides of a junction are doped such that the n and p-type doped regions are degenerate (i.e. the Fermi level is located into the bands (failure of the Boltzmann approximation), there is a forward bias regime where the current flow is governed by tunneling. Usually the quasi-Fermi levels penetrate into the bands by a few k_BT (V_n and $V_p \sim 50$ mV, cf. Fig. 5(a)) and the width of the depletion region is of the order of 5 to 10 nm, which is much smaller than in conventional p-n junctions. For such diodes, the reverse current increase monotonously with the applied voltage. This is the Zener mechanism which can be effective from zero voltage due to the reduced depletion width. Under forward bias, the current first increases up to a peak value and then decreases down to a minimum current (valley current) for an applied voltage V_v. Beyond V_v, the current exhibits an exponential increase with V as in conventional p-n junctions (Fig. 5(b)).
The fast rise of I up to I_p is due to e^- tunneling from the conduction band of the n-type region to the valence band of the p-type region where many states remain unoccupied because of the high doping level. Beyond voltage V_p, the overlap between filled states of the conduction band on the n-type side and empty states of the valence band on the p-type side decreases and the tunneling current disappears once the bands are fully decoupled (no overlap anymore).