Lecture 8

- Majority and Minority Carriers (more detail)
- Generation and Recombination of Carriers
    - Steady State
- Excess Minority Carriers
    - Minority Carrier Lifetime

Extrinsic Semiconductor

$$conductivity\ \sigma_{Drift} = ne\mu_e + pe\mu_h$$

Extrinsic Si

– p-doped with B to give
$p = 10^{21}\ m^{-3}$
$n \sim n_i = 10^{16}\ m^{-3}$ (approximately)

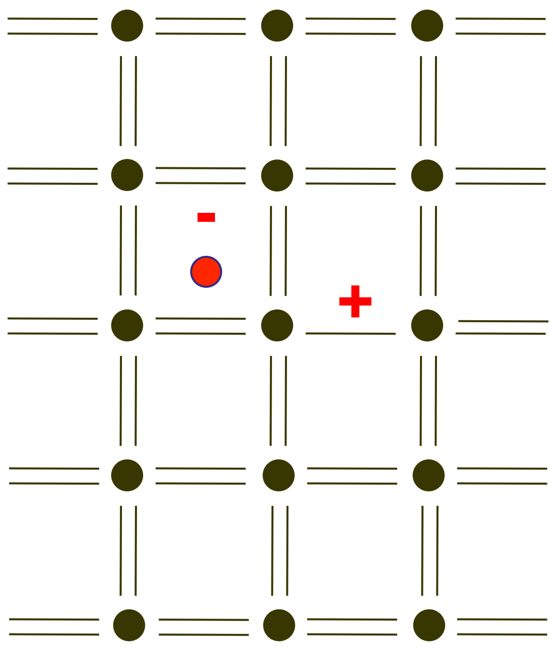
Holes = majority carriers
Electrons = minority carriers

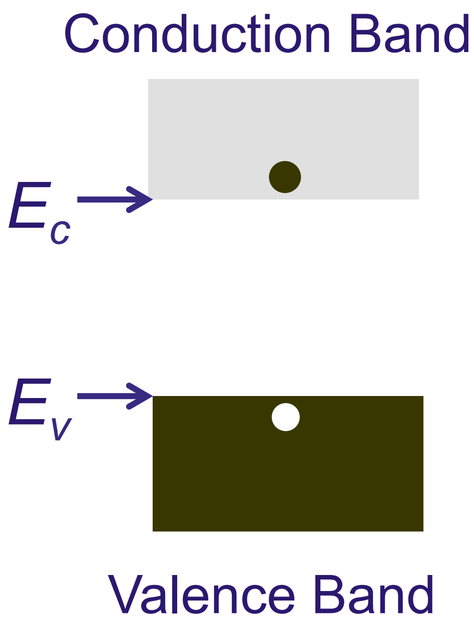
– n-doped with As to give
$n = 10^{21}\ m^{-3}$
$p \sim n_i = 10^{16}\ m^{-3}$ (approximately)

Electrons = majority carriers
Holes = minority carriers

Recombination:

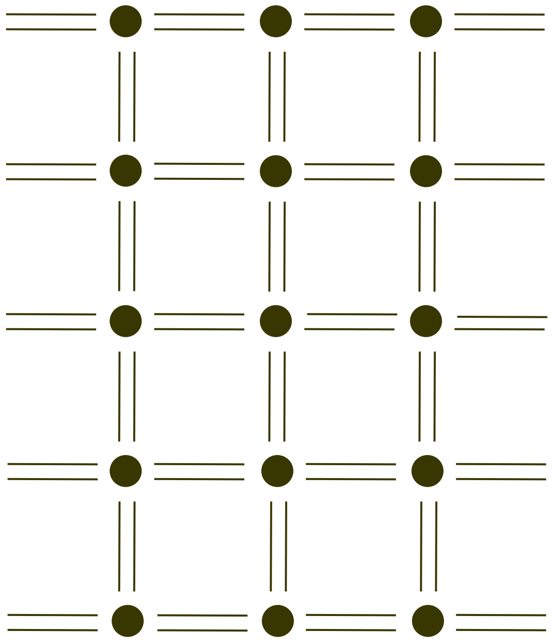
Consider electrons and hole generated by thermal excitation across the bandgap

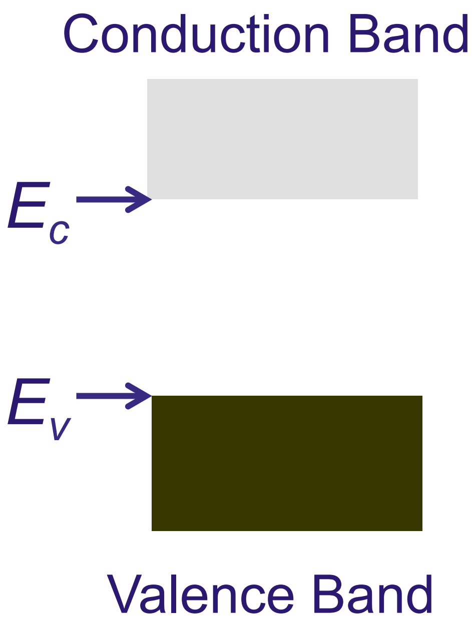




Recombination:

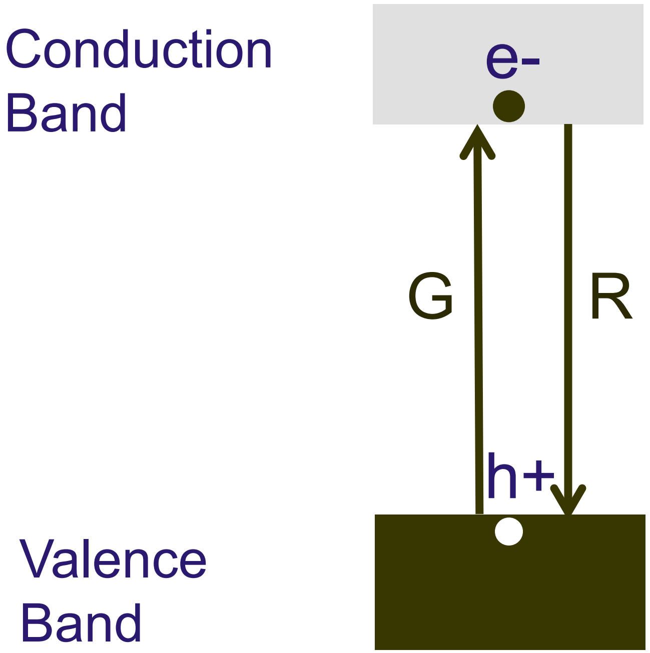
- The energy gained by the electron can be lost if it is 'recaptured' in a bonding process. This is called recombination.
- In the process, the electron returns to the valence band, the electron is no longer 'free' and the hole disappears.





Energy $= W_g = E_c - E_v$ is given up as light or phonons (heat).
We will follow this up in later lectures

Generation (G) & Recombination (R)



Within a semiconductor, there is a continuous cycle of electrons being promoted to the conduction band by thermal energy (leaving a hole in the valence band) together with the recombination of these electrons with holes.

In equilibrium or steady state the two processes exactly balance. That is, no net increase or decrease in electron or hole density.

Thermal Generation and Recombination

- Generation rate $G \propto T^{3/2} \exp\left(-\frac{W_g}{k_B T}\right)$ (for a particular semiconductor *G* depends only on temperature)

- Recombination rate depends on ‘encounters’ of electrons and holes. The more electrons there are and the more holes there are the more encounters are experienced hence get more recombination.
- Expressed mathematically, recombination can be written:

$$R \propto n\,p \Rightarrow R = B\,n\,p$$

Where *B* is the (Einstein) recombination constant
- Characteristic of different semiconductors
- Has the same value for all doping levels, *n, p*

Equilibrium

- In equilibrium $G = R$, otherwise the electron and hole population will continue to rise indefinitely (G>R) or decrease to zero (G<R)
- For an Intrinsic Semiconductor this means:

$$G = R = Bn_i p_i = B n_i^2 \text{ since } n_i = p_i$$

- For Extrinsic Semiconductor, in this case n-doped, $n >> n_i$

$$G = R = Bnp_n$$

p_n is hole concentration in the n-doped material (previously we assumed $p_n \sim p_i$ but in fact we will see that $p_n << p_i$)

Equilibrium

- From previous slide for intrinsic case

$$G = R = B\,n_i^2$$

- *G* is constant at a particular temperature and does not depend on doping hence:

$$G = R = Bnp_n \quad \text{and} \quad n_i^2 = np_n$$

- Same analysis for p-type gives

$$n_i^2 = pn_p$$

Where n_p is electron concentration in the p-doped material

Minority Carrier Density

- The minority carrier density in doped semiconductors for the usual doping levels is *much less* than in the intrinsic semiconductor case

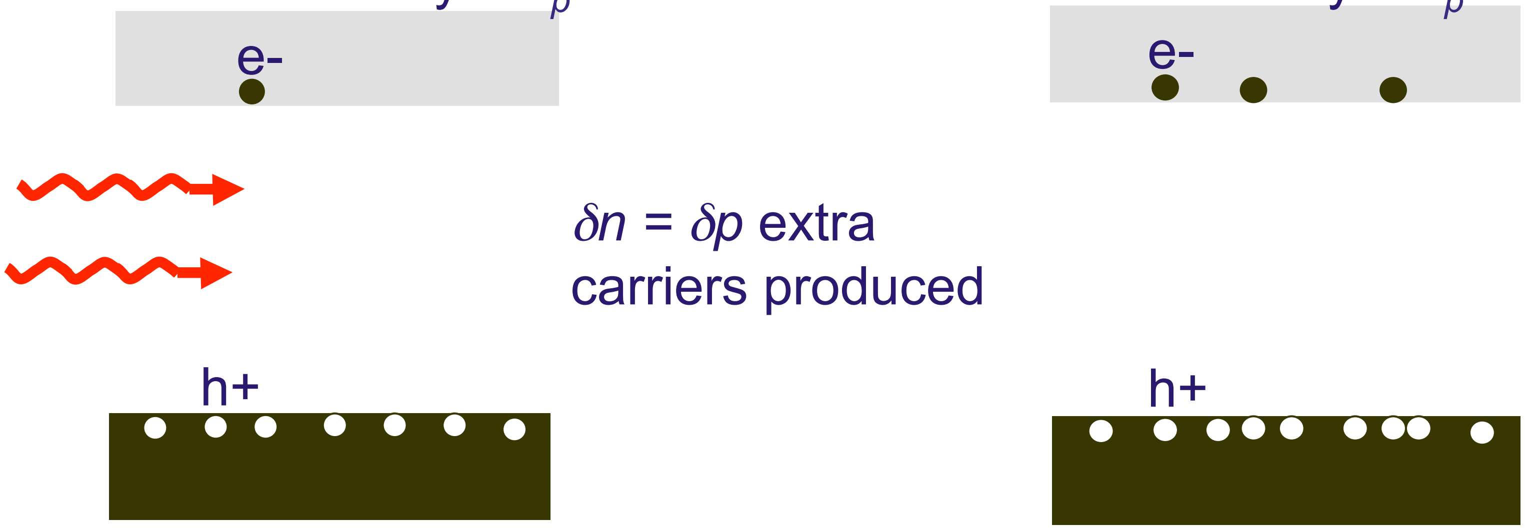
- Thermally generated minority carriers see many more majority carriers and hence experience greater recombination, reducing their number

Disturbing The Equilibrium

- For the moment consider uniformly exciting carriers in p-type material instantaneously with a light pulse

Before electron density = n_p

After electron density = $n_p + \delta n$



$\delta n = \delta p$ extra carriers produced

hole density = p

hole density = p

we assume $n_p << \delta p << p$ – *ignore* δp

What Happens Next?

- The thermal generation rate remains constant since temperature is the same
- Our recombination rate increases and is now (we assume $n_p << \delta p << p$ and *ignore* δp)

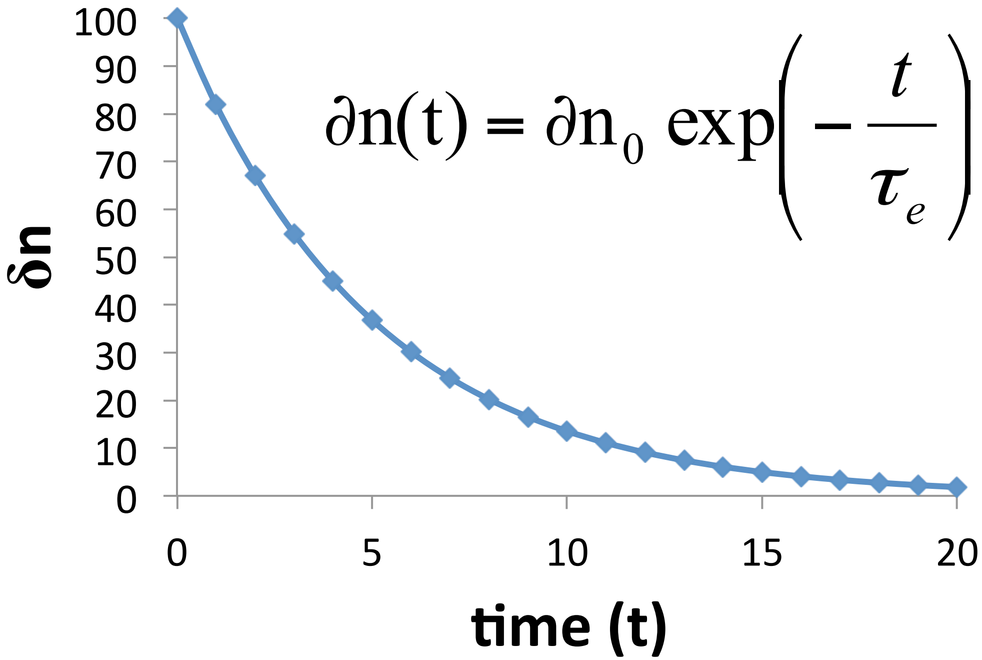
$$R = Bp(n_p + \partial n) > G = Bpn_p$$

$$\therefore \frac{dn}{dt} = G - R = G - \left[Bpn_p + Bp\partial n\right]$$

So $$\frac{dn}{dt} = -Bp\partial n$$ (first order differential equation)

This means extra light-induced electrons reduce with time to restore equilibrium

Solution of previous equation



$$\partial n(t) = \partial n_0 \exp\left(-\frac{t}{\tau_e}\right)$$

For this example, $\delta n_0 = 100$, $\tau_e = 5$)

τ_e = minority carrier lifetime

NOTE - don't confuse with carrier scattering time discussed previously – in this case electrons are minority

From the solution:

$$\tau_e = \left(\frac{1}{Bp}\right)$$

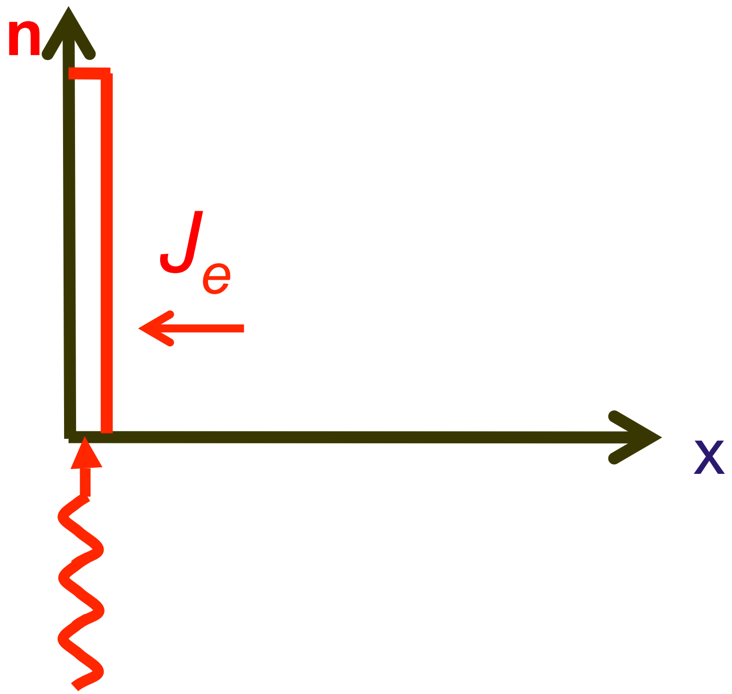
Minority Carrier Lifetime

- If excess electrons are introduced instantaneously their concentration decays exponentially until we return to equilibrium ($G = R$)

- τ_e is the time for excess electrons to reduce by 1/e (e is the exponent here) and can be taken as the time the extra electrons can exist in the material (useful concept for bipolar transistors later)

- τ_e decreases as p increases – more holes to recombine with

Minority Carrier Diffusion Length



- Introduce excess electrons to one side of a p-type block of semiconductor
- Carrier concentration gradient brings about carrier diffusion and diffusion current density J_e
- Assume that the supply of electrons is continuous at the edge (e.g. constant light) and look at the steady-state situation

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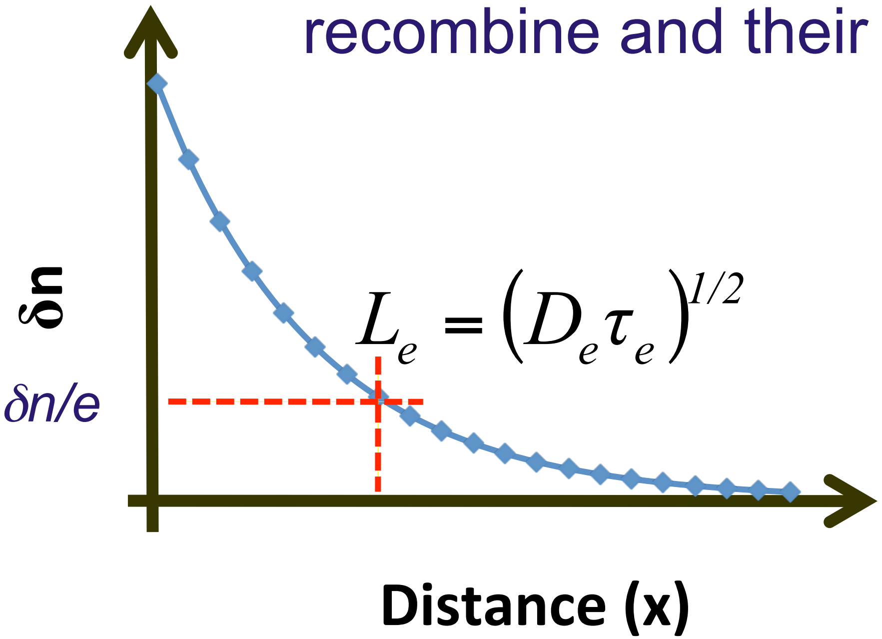
Minority Carrier Diffusion Length (2)

As the excess minority carriers diffuse they recombine and their density reduces with distance



$$L_e = \left(D_e \tau_e\right)^{1/2}$$

$$\partial n(x) = \partial n_0 \; exp\left(-\frac{x}{L_e}\right)$$

L_e is minority carrier diffusion length for electrons (replace subscript for holes) – involves diffusion coefficient and minority carrier lifetime

Summary

- In thermal equilibrium the rate of generation of free carriers is equal to the rate of recombination
- The rate of recombination of free carriers is proportional to the density of free electrons and holes
- The thermal generation is governed by the band-gap and temperature - it is the same in intrinsic and doped materials
- The density of minority carriers is suppressed in a heavily doped material compared to the intrinsic case

Summary (2)

- Modulating the carrier density temporally (time wise) shows that the excess majority carriers can be ignored and a minority carrier lifetime can be derived
- If the minority density is modulated spatially (space wise), the minority carriers diffuse over a characteristic length determined by the diffusion coefficient and the minority carrier lifetime