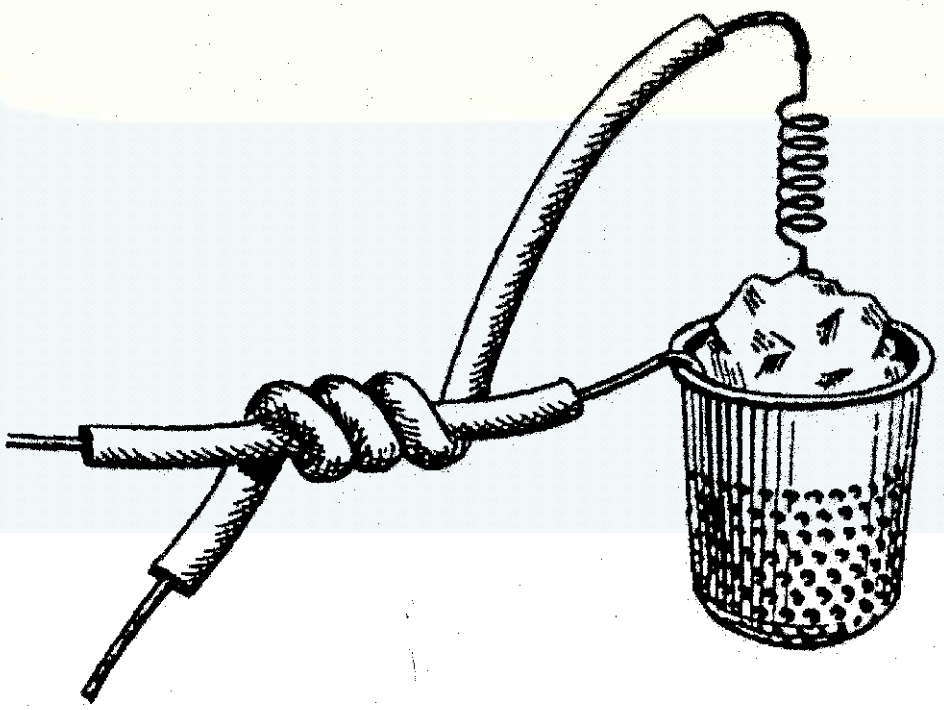
ELECTRONICS
Design Division

Introduction to semiconductor technology



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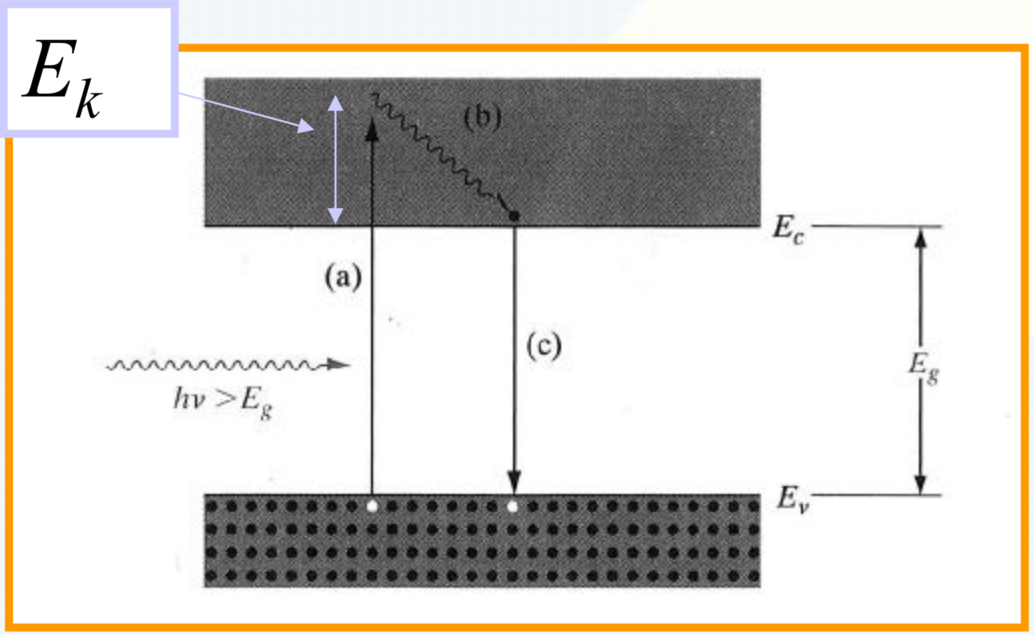
Outline

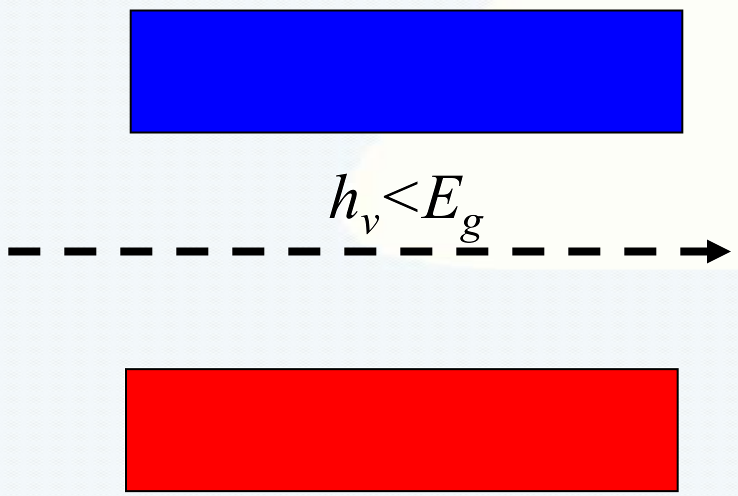
- **4 Excitation of semiconductors**
  - Optical absorption and excitation
  - Luminescence
  - Recombination
  - Diffusion of charge carriers

Optical absorption and excitation



$h\nu > Eg$ for the generation of an ehp, the energy in excess of Eg turns into kinetic energy. For photon energies of the order of the Eg, an ehp is generated. When the photon energy increases the electron gets kinetic energy which results in impact ionization which result in more than an ehp is generated/photon. When the electron is relaxed in the conduction it can recombine back into the valence band (c).

Optical absorption and excitation

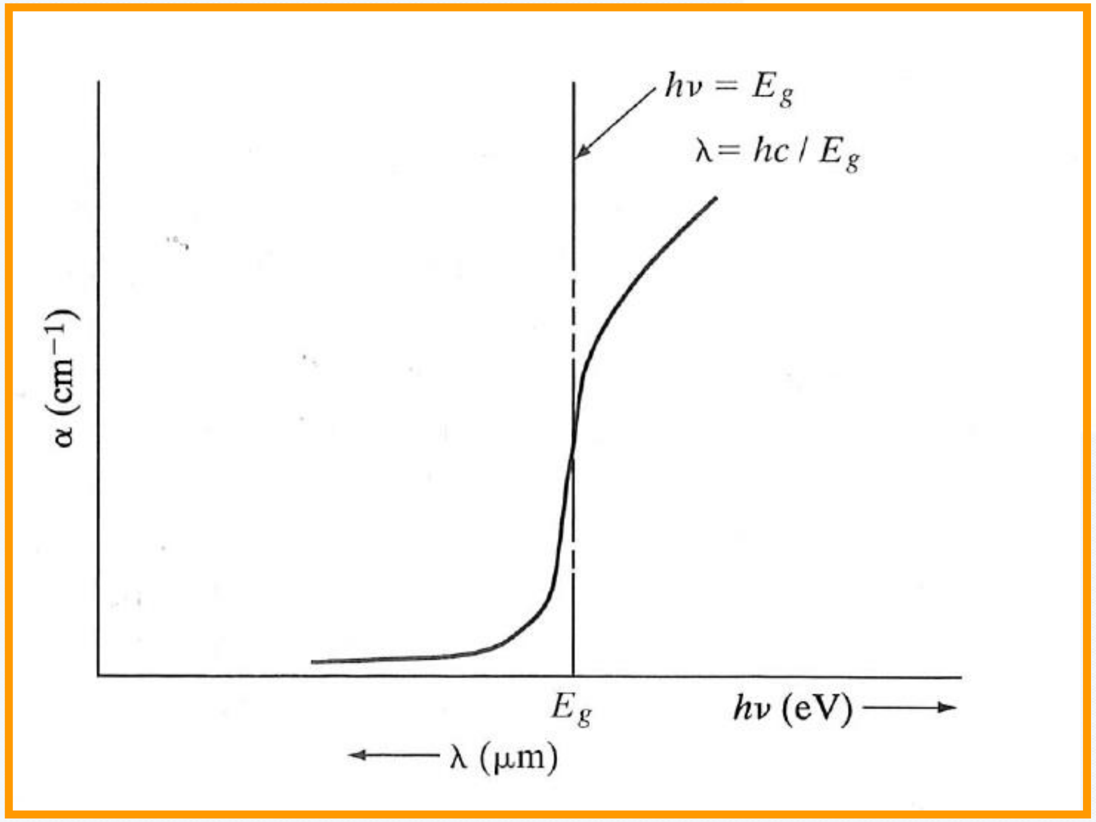


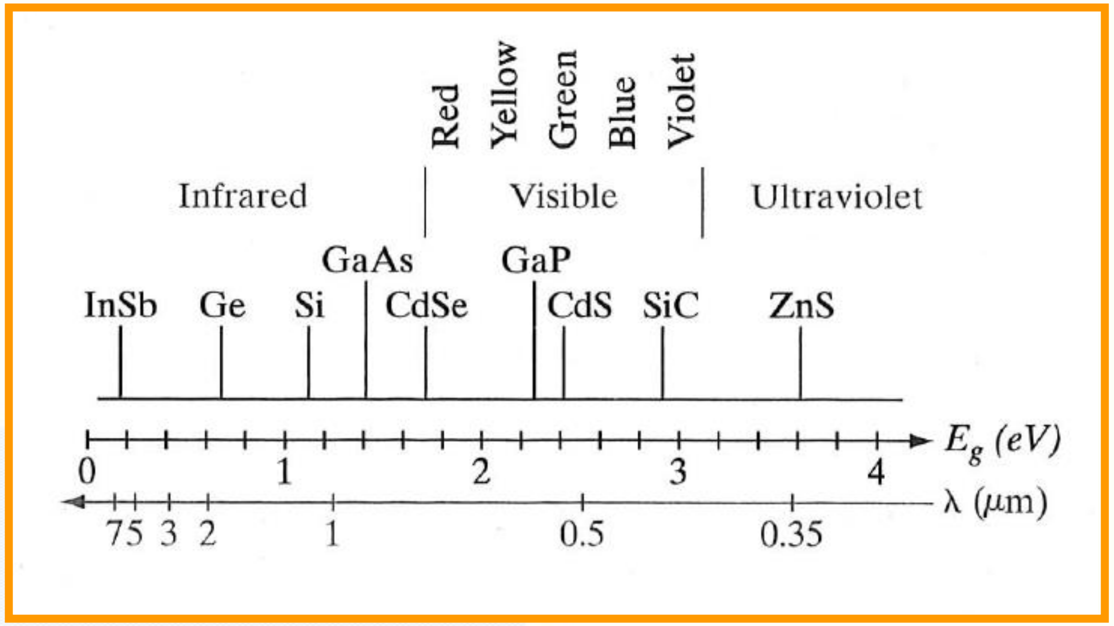
For photon energies below the band gap Semiconductor is transparent. Measurement of optical absorption is a way to determine the band gap.

$$\boxed{I_t = I_0 e^{-\alpha l}}$$

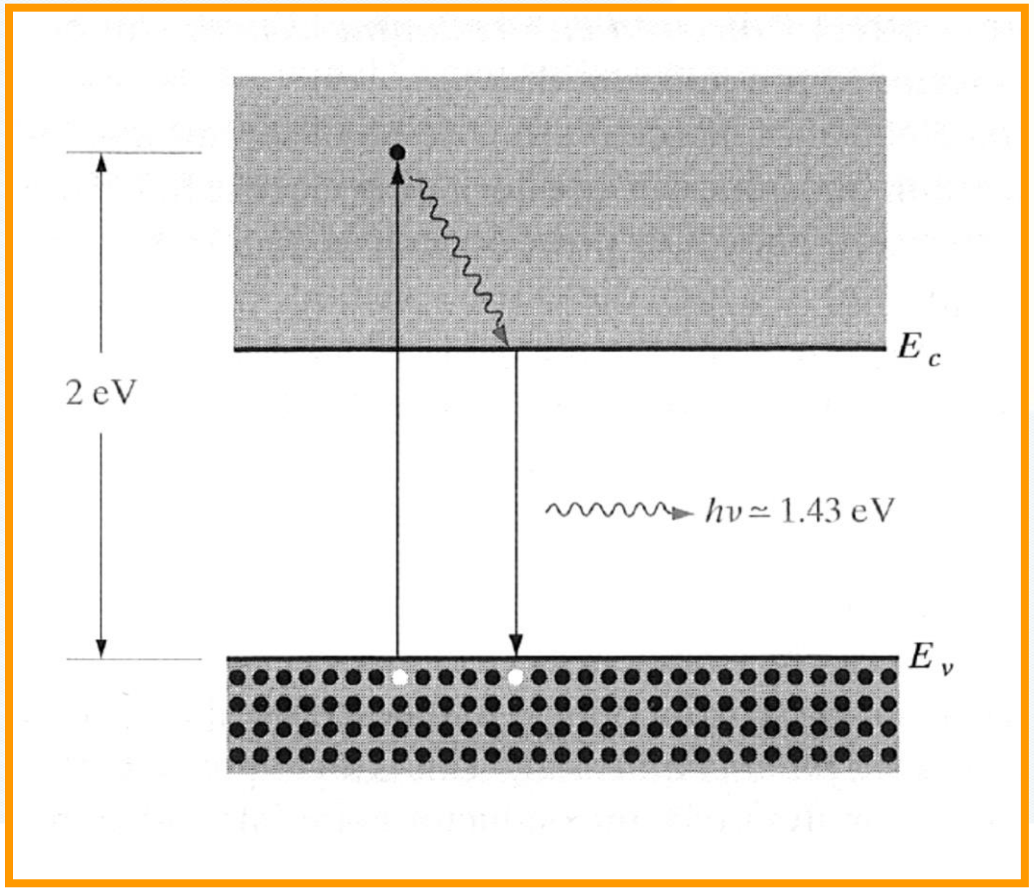
α is then the absorption coefficient

Optical absorption and excitation



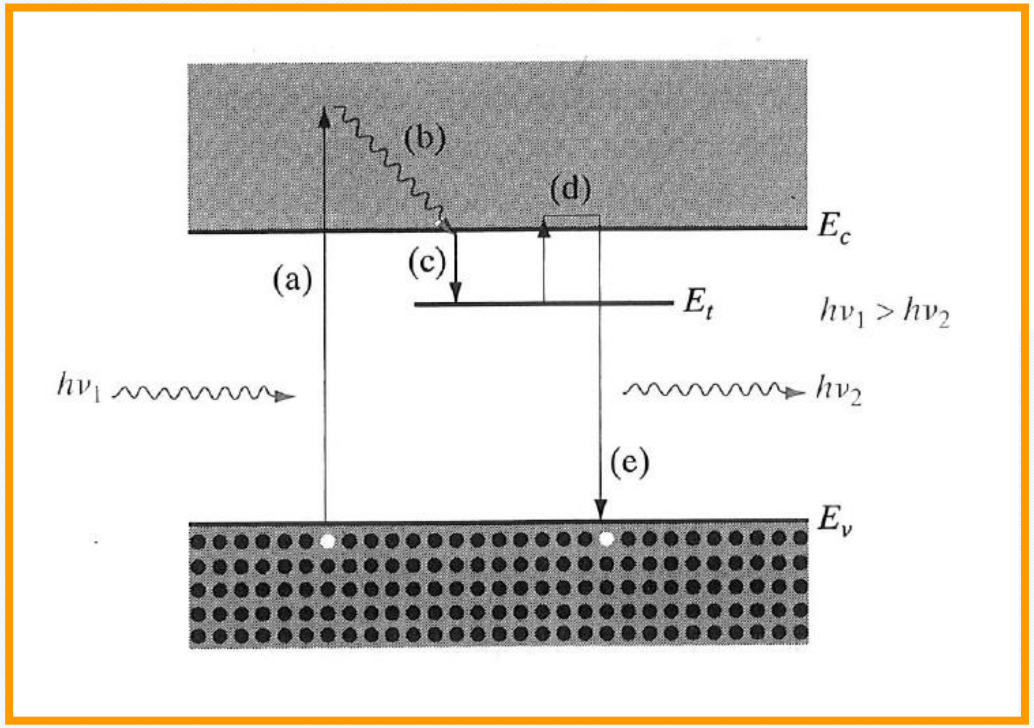


Luminescence



•Fotoluminiscens (fast emission)

Luminescence



- Phosphorus luminescence (delayed process via a trap in the band gap)
- Electro-luminscens injection of minority carriers, require a p-n junction, LED

Direct recombination (direct bandgap as GaAs)

$$\frac{dn(t)}{dt} = \alpha_r n_i^2 - \alpha_r n(t)p(t)$$

recombination

Thermal Generation

$$\frac{d\delta n(t)}{dt} = \alpha_r n_i^2 - \alpha_r[n_0 + \delta n(t)][p_0 + \delta p(t)]$$
$$= -\alpha_r[(n_0 + p_0)\delta n(t) + \delta n^2(t)]$$

Generation of ehp with a short light pulse

p_o and n_o are the concentrations at equilibrium

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Direct recombination (direct bandgap as GaAs)

P-type material has $p_0 >> n_0$ and the equation then becomes

$$\frac{d\delta n(t)}{dt} = -\alpha_r p_0 \delta n(t)$$

With the solution

$$\delta n(t) = \Delta n e^{-\alpha_r p_0 t} = \Delta n e^{-t/\tau_n}$$

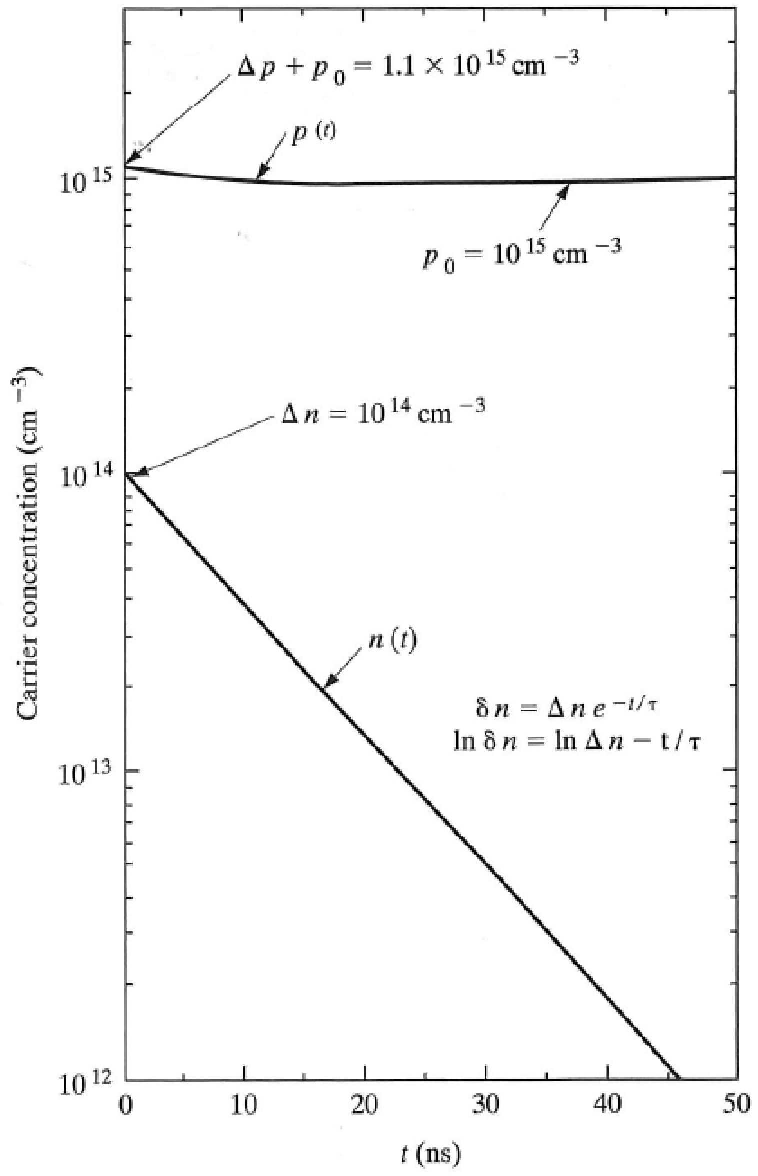
$$\tau_n = (\alpha_r p_0)^{-1}$$

Is called the minority carrier lifetime

$$\tau_p = (\alpha_r n_0)^{-1}$$

When n0 > > p0

Direct recombination (direct bandgap as GaAs)



P-type doping material with 10^{15} cm^{-3} GaAs with $n_i = 10^6$ cm^{-3} results in $n_0 = 10^{-3}$ cm^{-3}!!

Vid t=0 genereras 10^{14} ehp/cm^3

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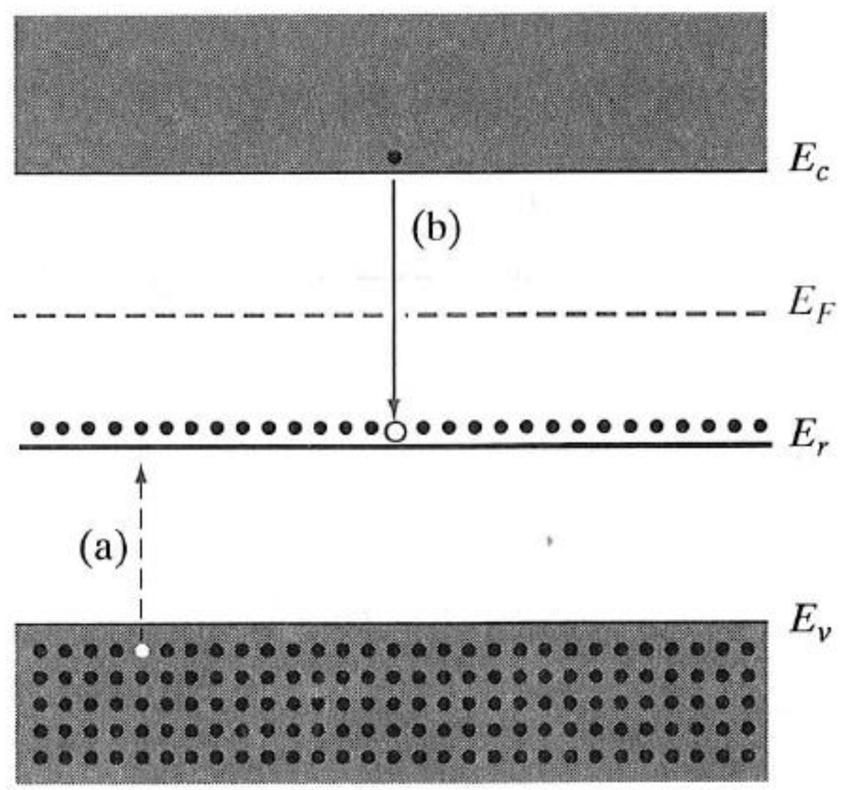
Indirect Recombination (indirect band gap)

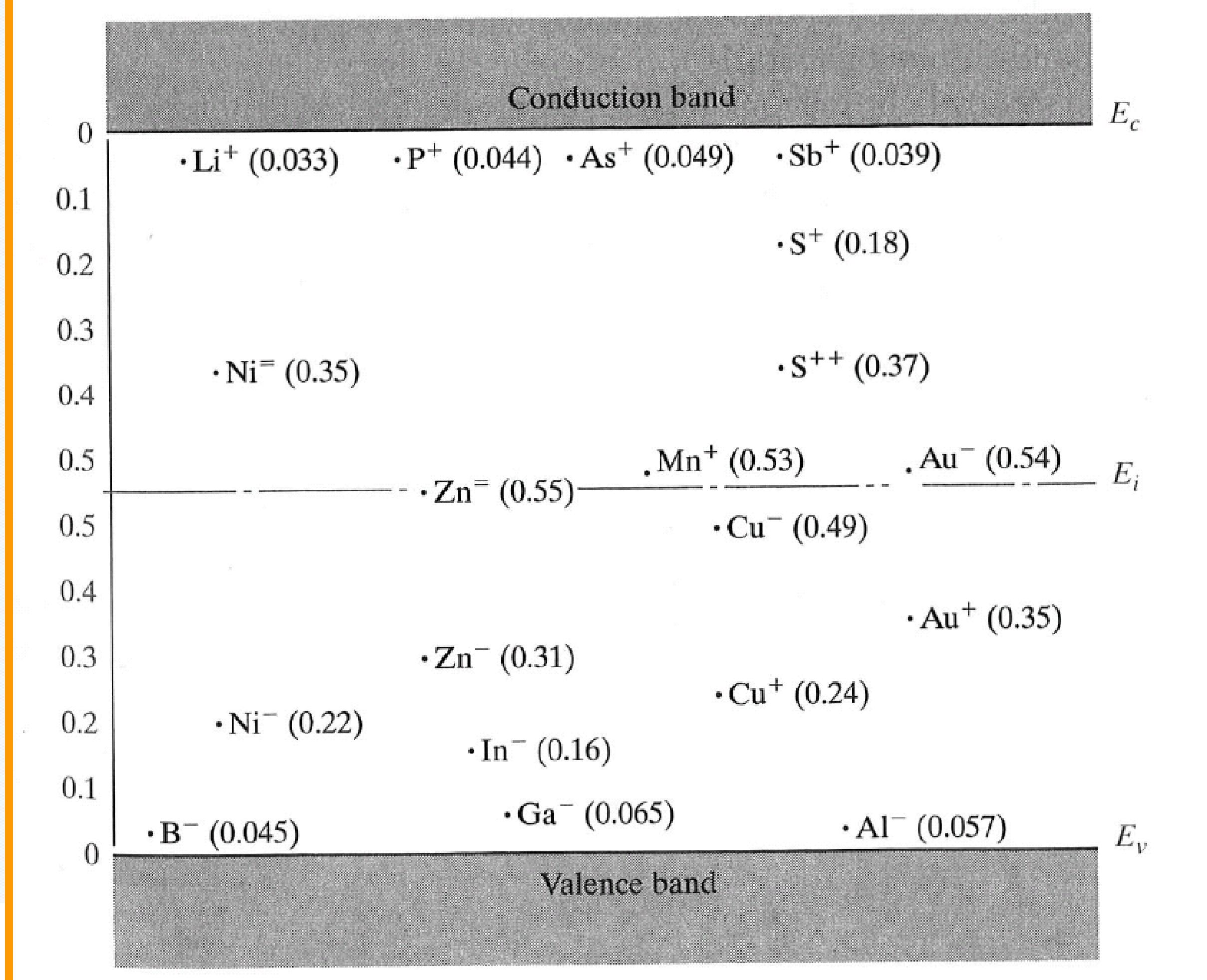


Direct recombination is unlikely process in indirect semiconductors such as Si and Ge.

Instead occurs recombination (holes and electrons annihilated) by recombination level (an impurity level) in the band gap.

An impurity level that takes up an electron temporarily and then emit electron again without recombination is called "trap" level

Indirect Recombination (indirect band gap)



Semiconductor excited with light pulse and the conductivity measured as fkn time for determination of the effective recombination

$$\sigma(t) = q[n(t)\mu_n + p(t)\mu_p]$$

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Generation in equilibrium and in constant excess of charge carriers

$g(T) = \alpha_r n_i^2 = \alpha_r n_0 p_0$ in equilibrium

$g(T) + g_{op} = \alpha_r np = \alpha_r (n_0 + \delta n)(p_0 + \delta p)$ with constant excess of charge carriers, as optical excitation (photo generation)

Quasi Fermi levels

Quasi Fermi levels are used as the semiconductor is not in equilibrium.

Quasi Fermi levels describes the electron and hole concentrations, such as photo generation and injection of minority carriers (PN junction)

$$n = n_i e^{(F_n - E_i)/kT}$$
$$p = n_i e^{(E_i - F_p)/kT}$$

0 is gone when concentration is not in equilibrium, mass action law is not valid

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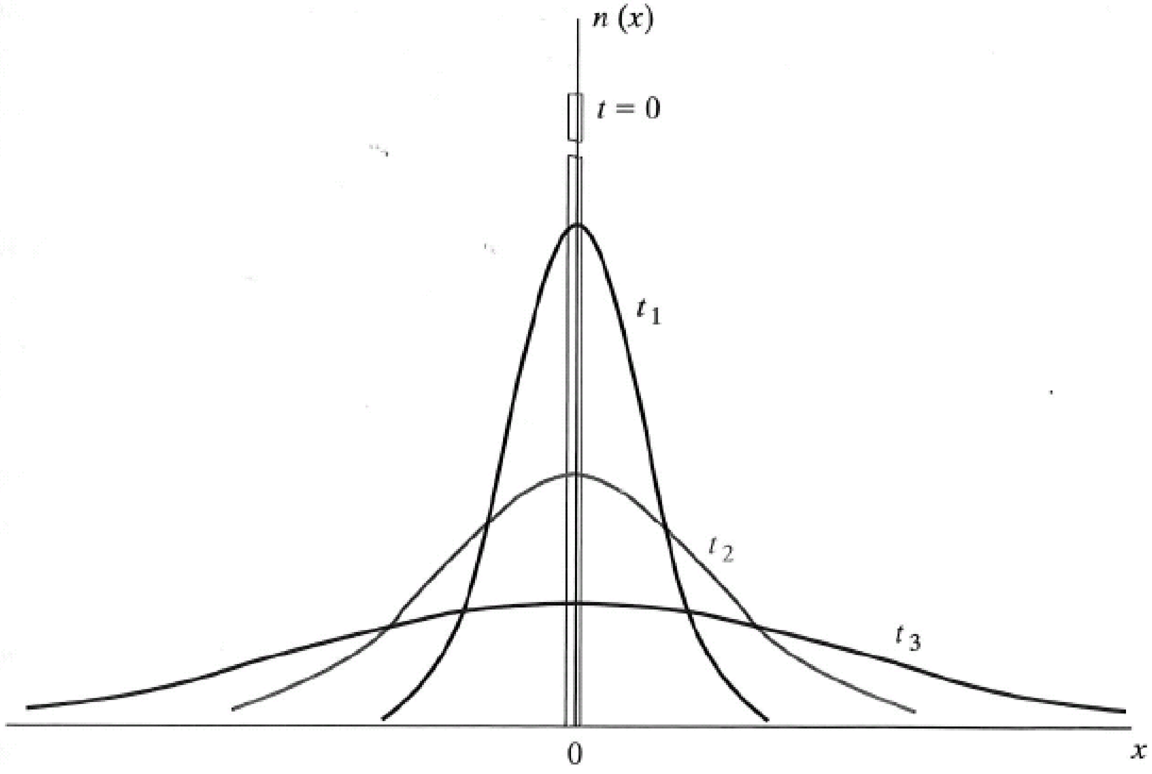
Diffusion of charge carriers



A light pulse creates a concentration gradient of ehp.

The driving force is that the charge carriers moving in the direction of lower concentration to even out the differences, which is called diffusion

Diffusion of charge carriers

The flow of electrons

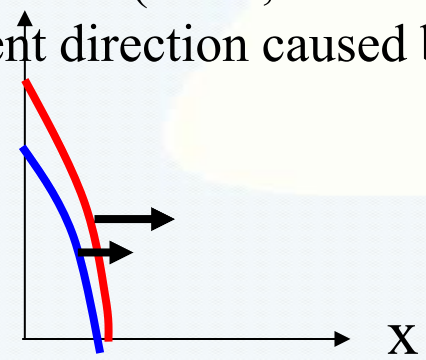
$$\phi_n(x) = -D_n \frac{dn(x)}{dx}$$

$$\phi_p(x) = -D_p \frac{dp(x)}{dx}$$

Diffusion coefficient

Concentration (holes, electrons)

Movement direction caused by the gradient



Diffusion current density

$$J_n(\text{diff.}) = -(-q)D_n \frac{dn(x)}{dx} = +qD_n \frac{dn(x)}{dx}$$

$$J_p(\text{diff.}) = -(+q)D_p \frac{dp(x)}{dx} = -qD_p \frac{dp(x)}{dx}$$

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Diffusion and drift of the charge carriers

Drift and diffusion components, for electron and hole current density

$$J_n(x) = q\mu_n n(x)\mathscr{E}(x) + qD_n \frac{dn(x)}{dx}$$

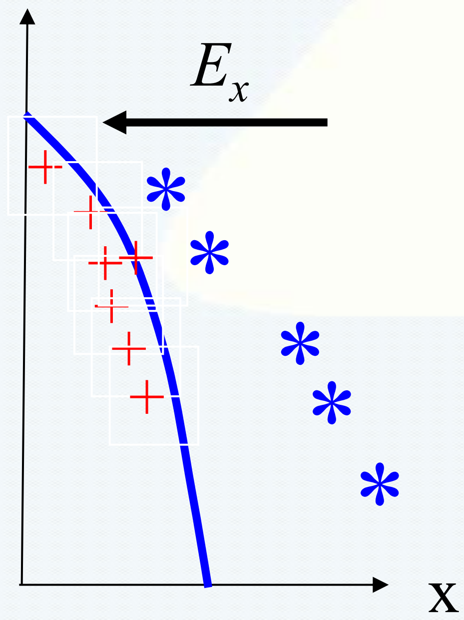
drift diffusion

$$J_p(x) = q\mu_p p(x)\mathscr{E}(x) - qD_p \frac{dp(x)}{dx}$$

Total current density

$$J(x) = J_n(x) + J_p(x)$$

Diffusion and drift of the charge carriers



$$J_n(x) = q\mu_n n(x)\mathscr{E}(x) + qD_n \frac{dn(x)}{dx} = 0$$

Doping profile with phosphorus, the net charge is 0

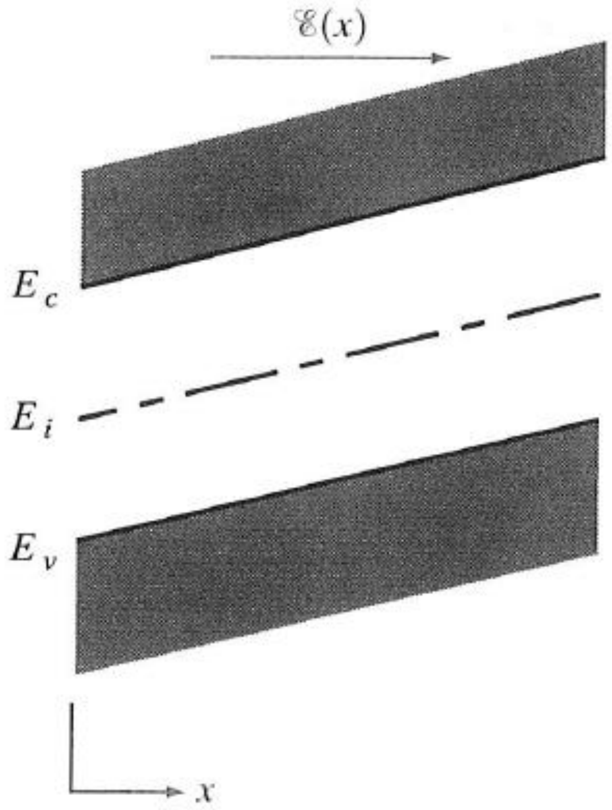
We have a doping gradient, the electrons would diffuse to even out the gradient

But the electrons leaves fixed positive ions in the lattice that results in an electric field, which balances the diffusion

$$\boxed{\overline{E}(x) = -\frac{D_n}{\mu_n n(x)}\frac{dn(x)}{dx}}$$

Diffusion and drift of the charge carriers

$$\mathscr{E}(x) = -\frac{d\mathscr{V}(x)}{dx} = -\frac{d}{dx}\left[\frac{E_i}{(-q)}\right] = \frac{1}{q}\frac{dE_i}{dx}$$



$$\mathscr{V}(x) = E(x)/(-q).$$

$V(x)$ Potential energy per unit charge

$$\vec{E}(x) = \frac{D_p}{\mu_p p(x)}\frac{dp(x)}{dx} \quad + \quad p_0 = n_i e^{(E_i - E_f)/kT}$$

At equilibrium applies

$$\vec{E}(x) = \frac{D_p}{\mu_p}\frac{1}{kT}\left(\frac{dE_i}{dx} - \frac{dE_F}{dx}\right)$$

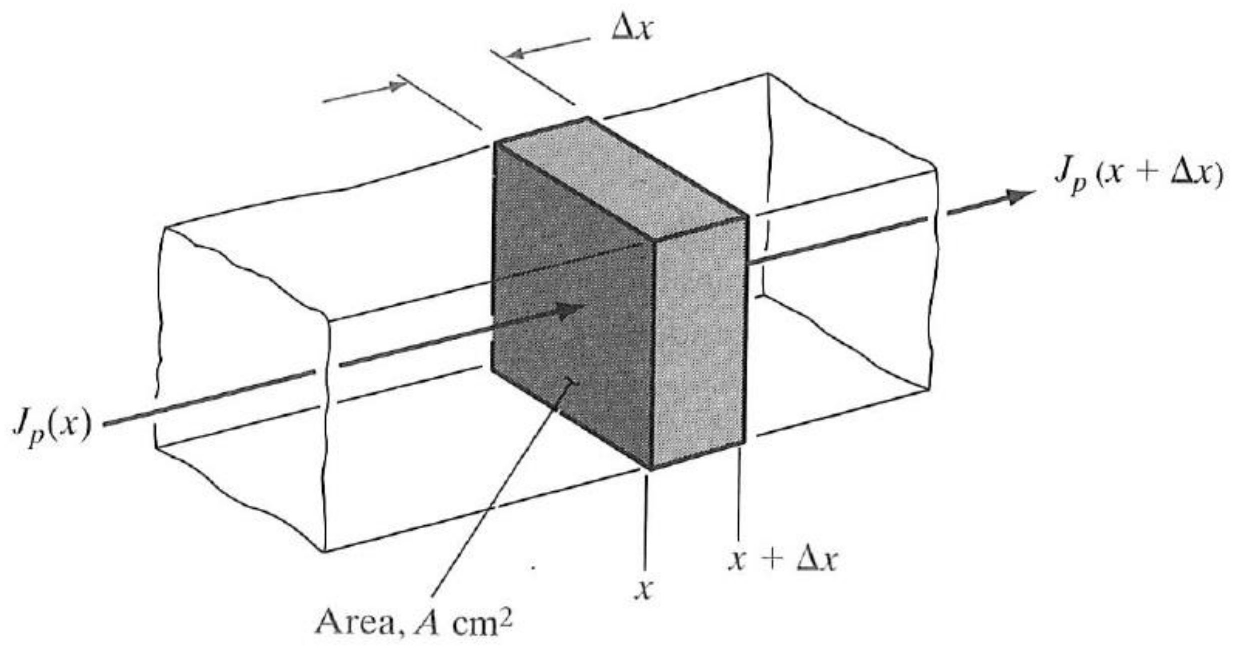
$$\frac{dE_F}{dx} = 0$$

$$\frac{dE_i}{dx} = \vec{E}\cdot q$$

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

Einstein's relation

Diffusion and Recombination, the continuity equation



$$\frac{\partial p(x,t)}{\partial t} = \frac{\partial \delta p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p}$$

$$\frac{\partial \delta n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_n}$$

$$\left.\frac{\partial p}{\partial t}\right|_{x \to x+\Delta x} = \frac{1}{q}\frac{J_p(x) - J_p(x+\Delta x)}{\Delta x} - \frac{\delta p}{\tau_p}$$

Rate of hole buildup = increase of hole concentration in $\delta x A$ per unit time − recombination rate

Partial differential equation

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Diffusion and Recombination, Diffusion equation

$$J_n(\text{diff.}) = qD_n \frac{\partial \delta n}{\partial x}$$

Without drift "negligible electric field"

$$\frac{\partial \delta n}{\partial t} = D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau_n}$$

$$\frac{\partial \delta p}{\partial t} = D_p \frac{\partial^2 \delta p}{\partial x^2} - \frac{\delta p}{\tau_n}$$

At steady state "the time derivative = 0"

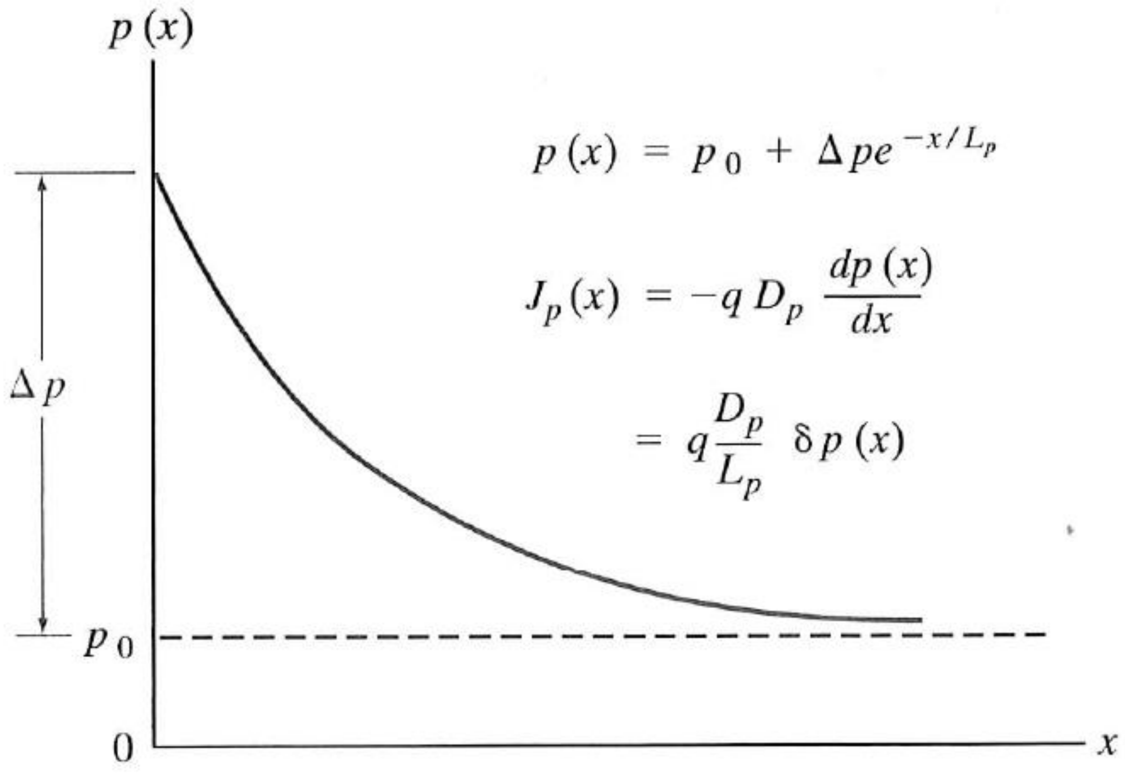
$$\frac{d^2 \delta n}{dx^2} = \frac{\delta n}{D_n \tau_n} \equiv \frac{\delta n}{L_n^2}$$

$$\frac{d^2 \delta p}{dx^2} = \frac{\delta p}{D_p \tau_p} \equiv \frac{\delta p}{L_p^2}$$

Diffusion length of electrons

$$L_n \equiv \sqrt{D_n \tau_n}$$

Diffusion and Recombination, Diffusion equation



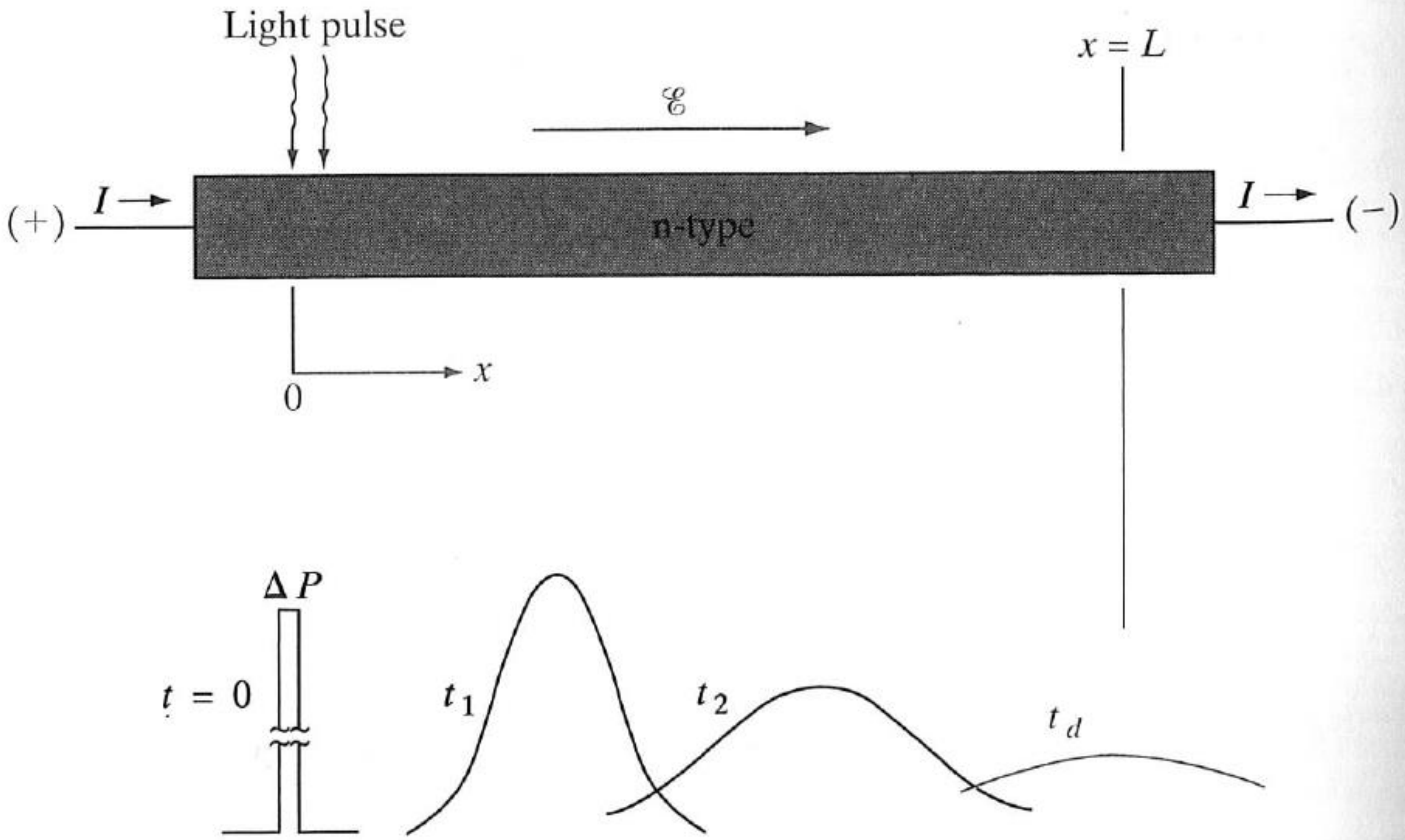
$$\langle x \rangle = \int_0^\infty x \frac{e^{-x/L_p}}{L_p} dx = L_p$$

$$\delta p(x) = \Delta p e^{-x/L_p}$$

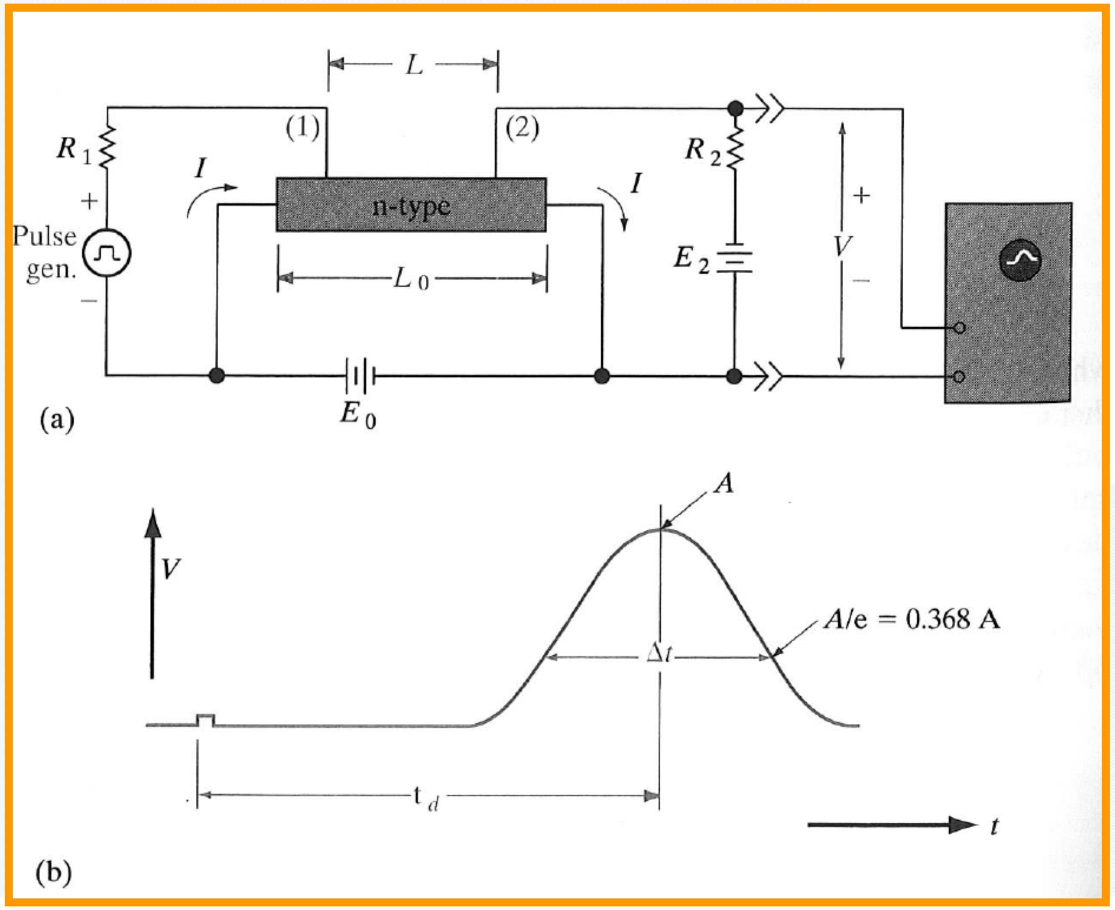
$$J_p(x) = -qD_p \frac{dp}{dx} = -qD_p \frac{d\delta p}{dx} = q \frac{D_p}{L_p} \Delta p e^{-x/L_p} = q \frac{D_p}{L_p} \delta p(x)$$

Haynes-Shockley Experiment

Allows measurement of minority carrier mobility and diffusion coefficient



Haynes-Shockley Experiment



$$v_d = \frac{L}{t_d}$$

$$\mu_p = \frac{v_d}{\mathscr{E}}$$

$$\frac{\partial \delta p(x,t)}{\partial t} = D_p \frac{\partial^2 \delta p(x,t)}{\partial x^2}$$

Partial differential equation with the solution

$$\delta p(x,t) = \left[\frac{\Delta P}{2\sqrt{\pi D_p t}}\right] e^{-x^2/4D_p t}$$

ΔP is the number of holes/area

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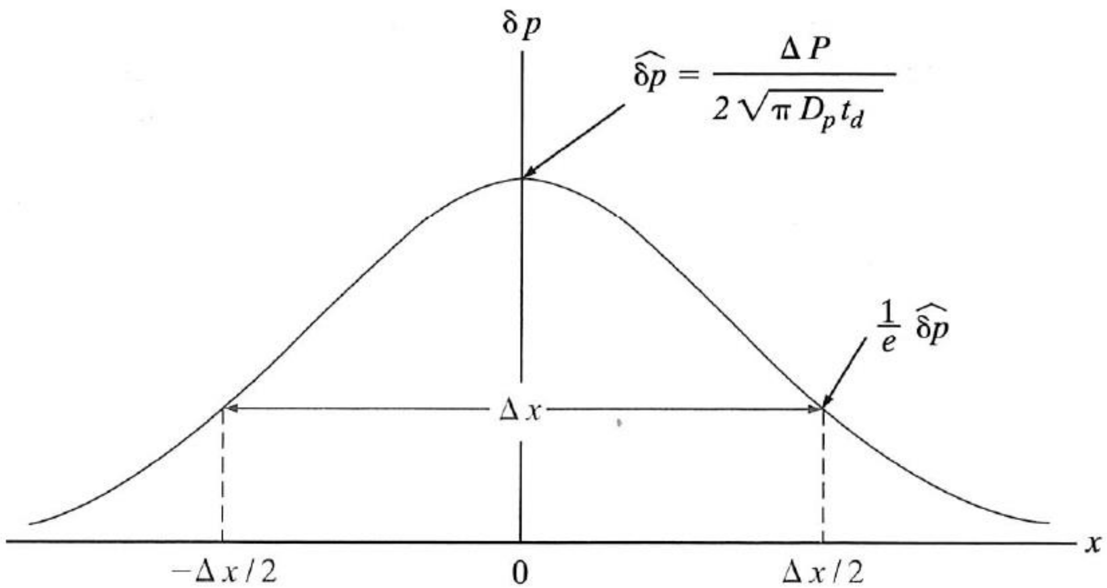
Haynes-Shockley Experiment

$$e^{-1}\delta\hat{p} = \delta\hat{p}e^{-(\Delta x/2)^2/4D_p t_d}$$

$$D_p = \frac{(\Delta x)^2}{16 t_d}$$

Δ *x/2* means that Gauss distribution has fallen to e^{-1}



$$\Delta x = \Delta t v_d = \Delta t \frac{L}{t_d}$$

Δ t, td and L is measured

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Haynes-Shockley Experiment

An n-type Ge sample is used in the Haynes–Shockley experiment shown in Fig. 4–20. The length of the sample is 1 cm, and the probes (1) and (2) are separated by 0.95 cm. The battery voltage E_0 is 2 V. A pulse arrives at point (2) 0.25 ms after injection at (1); the width of the pulse Δt is 117 μs. Calculate the hole mobility and diffusion coefficient, and check the results against the Einstein relation.

$$\mu_p = \frac{v_d}{\mathscr{E}} = \frac{0.95/(0.25 \times 10^{-3})}{2/1} = 1900 \text{ cm}^2/(\text{V-s})$$

$$D_p = \frac{(\Delta x)^2}{16 t_d} = \frac{(\Delta t L)^2}{16 t_d^3}$$

$$= \frac{(117 \times 0.95)^2 \times 10^{-12}}{16(0.25)^3 \times 10^{-9}} = 49.4 \text{ cm}^2/\text{s}$$

$$\frac{D_p}{\mu_p} = \frac{49.4}{1900} = 0.026 = \frac{kT}{q}$$

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