Primer on Semiconductors

Unit 4: Carrier Transport, Recombination, and Generation

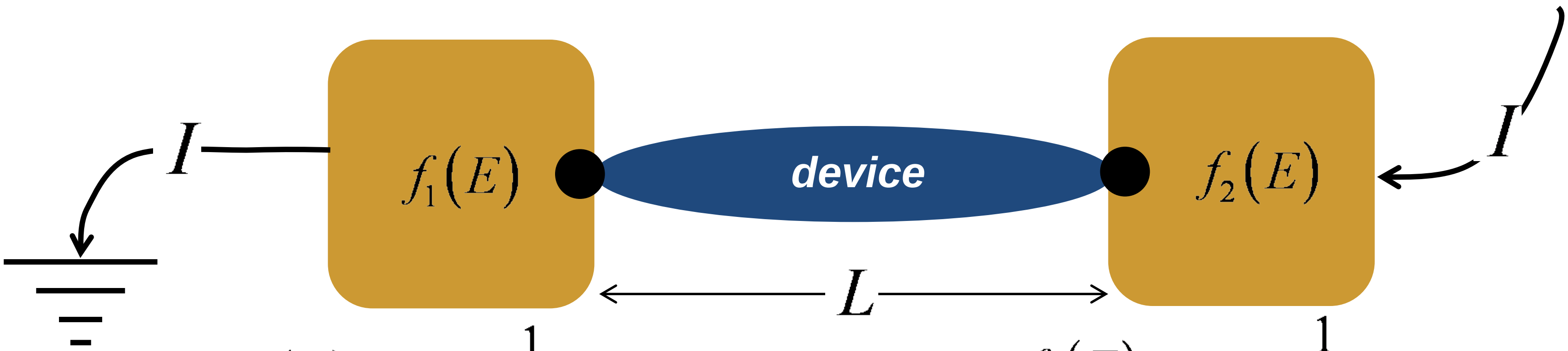
Lecture 4.6: Unit 4 Recap

Mark Lundstrom

lundstro@purdue.edu
Electrical and Computer Engineering
Purdue University
West Lafayette, Indiana USA

PURDUE UNIVERSITY

Landauer approach



$$f_1(E) = \frac{1}{1 + e^{(E - E_{F1})/k_B T}} \qquad f_2(E) = \frac{1}{1 + e^{(E - E_{F2})/k_B T}}$$

$$\boxed{I = \frac{2q}{h} \int \mathcal{T}(E) M(E) \left(f_1(E) - f_2(E) \right) dE}$$

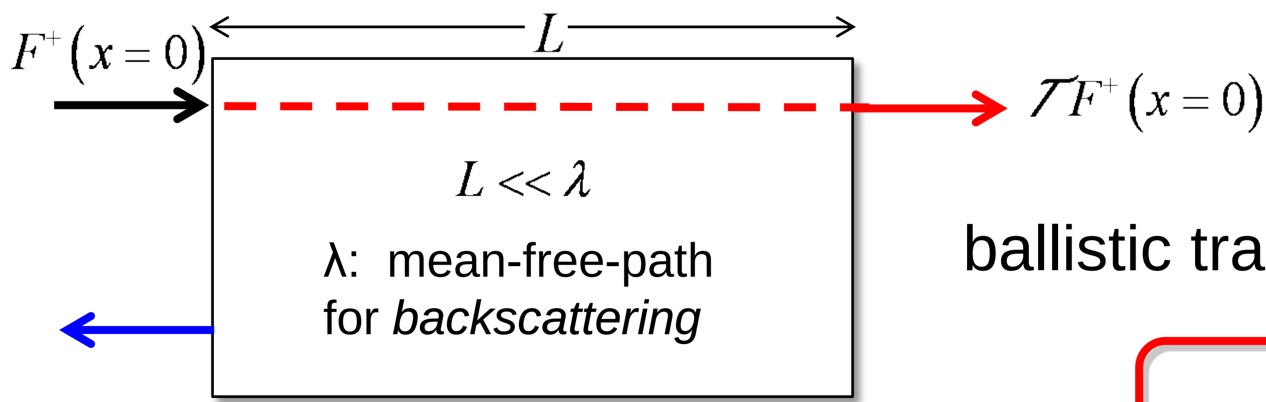
Fundamental constants

Transmission: $0 < \mathcal{T}(E) < 1$

No. of Channels

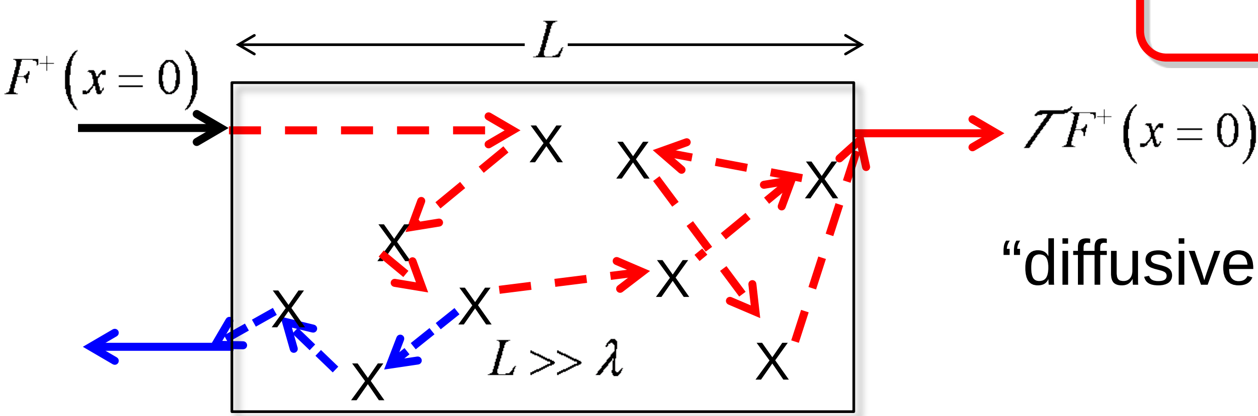
Ideal "Landauer" contacts

Transmission



ballistic transport: $\mathcal{T} = 1$

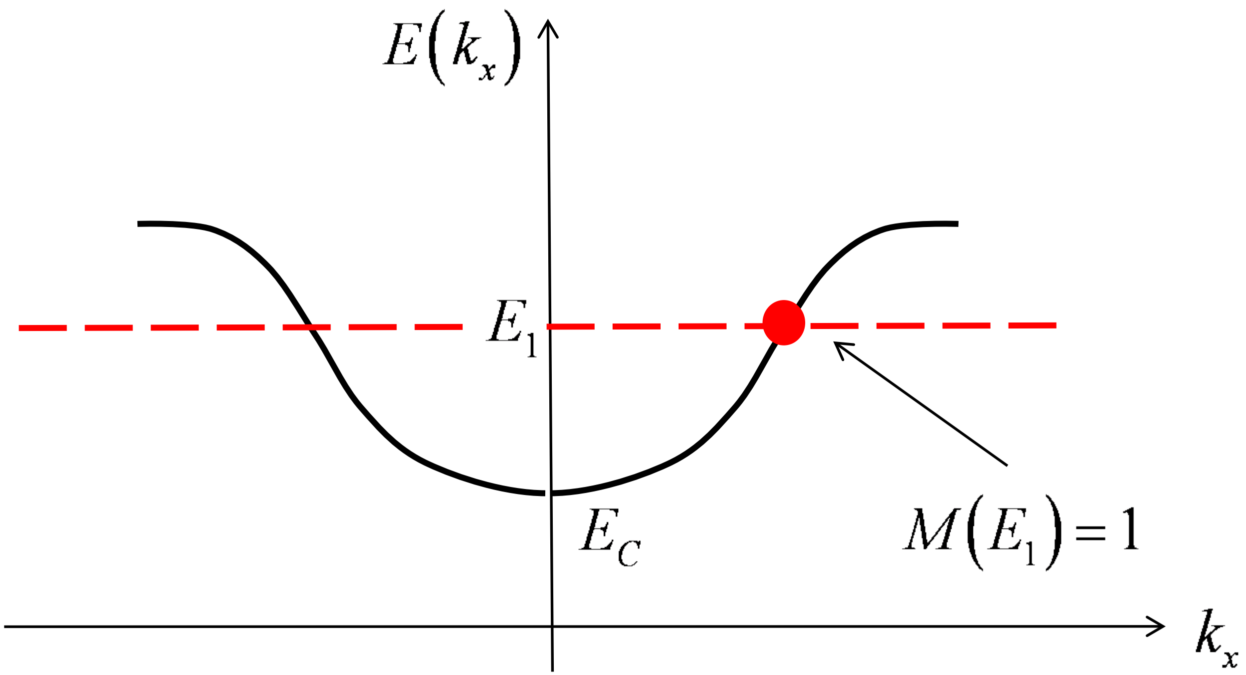
$$\boxed{\mathcal{T}(E) = \frac{\lambda(E)}{\lambda(E) + L}}$$



"diffusive transport" $\mathcal{T} \ll 1$

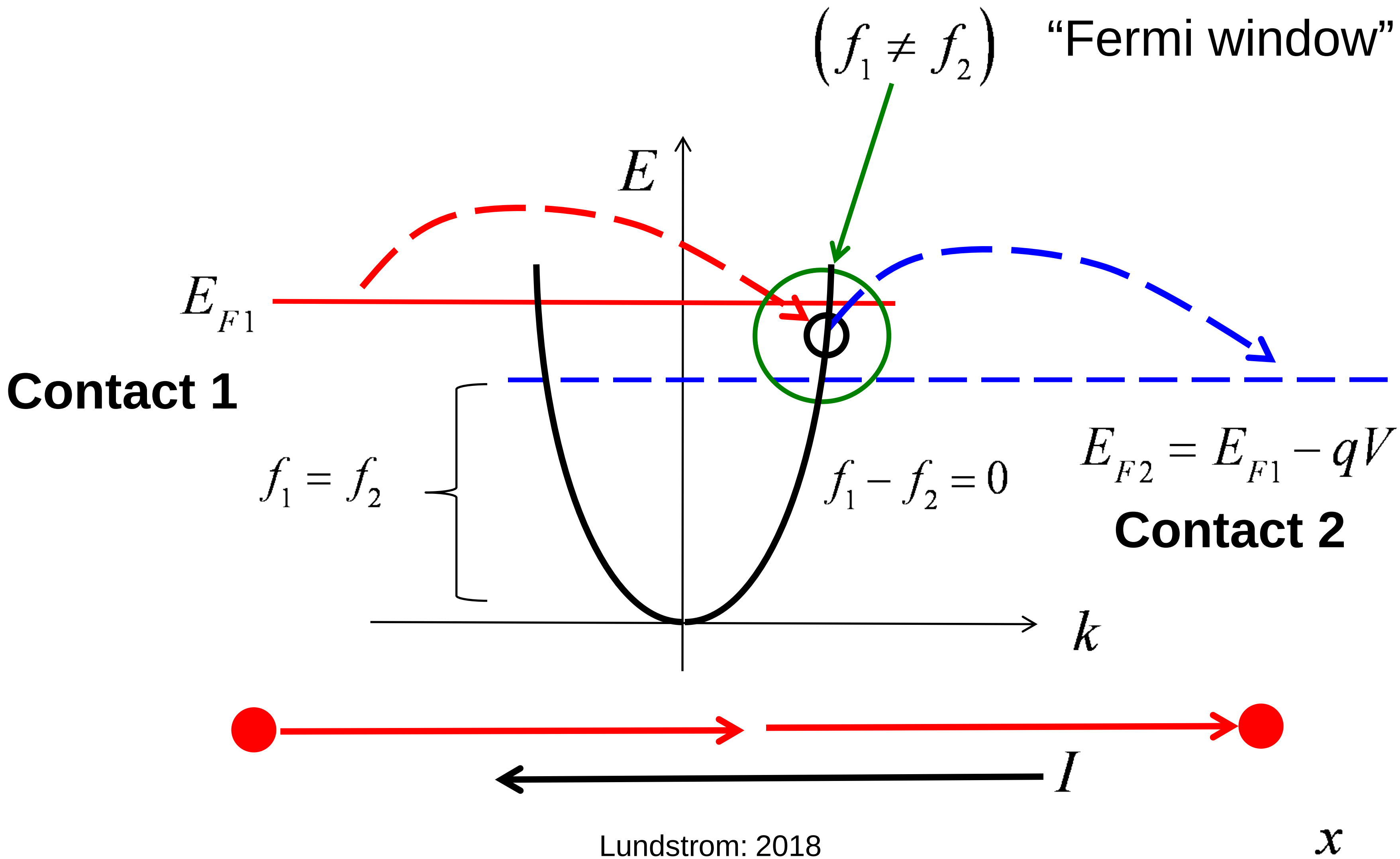
Channels

A channel is a state with a velocity.

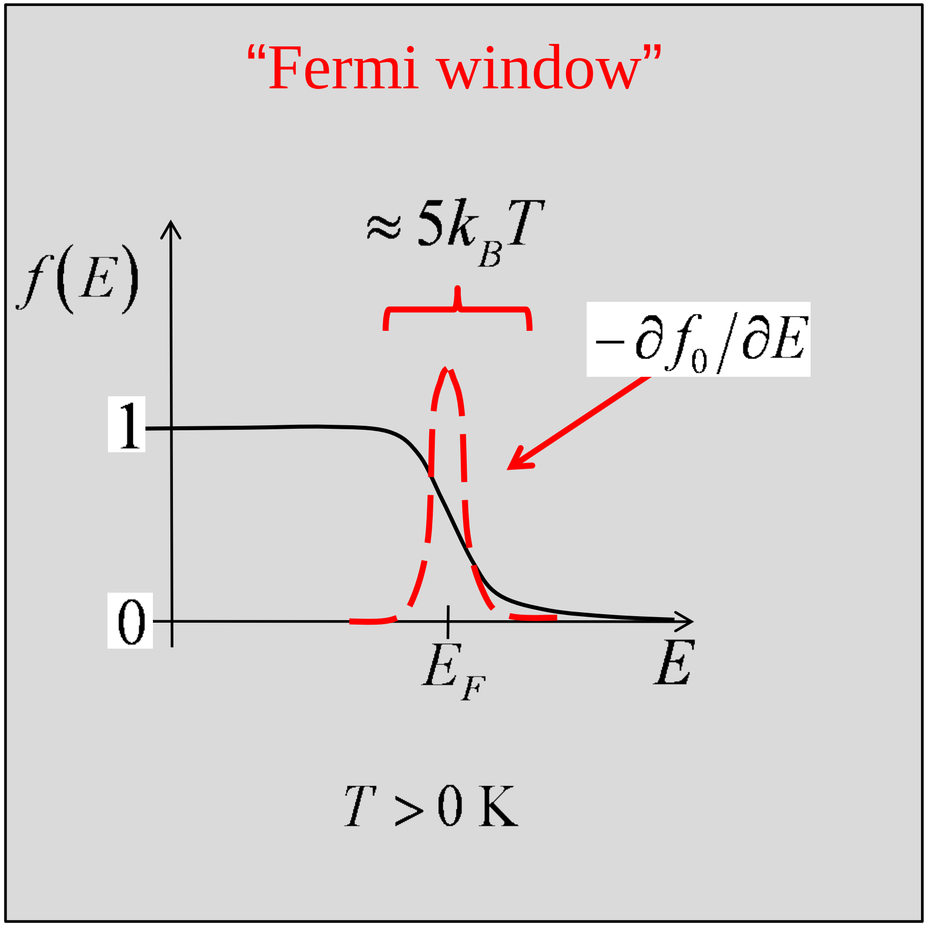


(Easily generalized to arbitrary band structures in 2D and 3D.)

How current flows



Fermi window under small bias



$$W_F(E) = \left(-\frac{\partial f_0}{\partial E}\right)$$

$$\int W_F(E)\,dE = 1$$

Small bias conductance

$$I = GV \qquad \text{A}$$

$$G = \frac{2q^2}{h}\int \mathcal{T}(E)M(E)\left(-\frac{\partial f_0}{\partial E}\right)dE \qquad \text{S}$$

$$G = \frac{2q^2}{h}\mathcal{T}(E_F)M(E_F)$$ (T = 0 K)

$$G = \frac{2q^2}{h}M(E_F)$$ (T = 0 K and ballistic)

Quantized conductance in nanostructures.

Small bias conductance

$$\mathcal{T}(E) = \frac{\lambda(E)}{\lambda(E)+L} \rightarrow \frac{\lambda(E)}{L} \rightarrow J_n = \sigma_n \frac{d(F_n/q)}{dx}$$

σ_n: Conductivity (S/m) $\rho_n = 1/\sigma_n$: Resistivity (Ohm-m)

$$\sigma_n \equiv nq\mu_n$$

n: electron density
q: magnitude of the electronic charge
μ_n: mobility m^2/V-s

$$\boxed{J_x = n\mu_n \frac{dF_n}{dx}}$$

Lundstrom: 2018

Drift-diffusion equation

$$\boxed{J_x = n\mu_n \frac{dF_n}{dx}}$$

$$n = N_C e^{(F_n - E_C)/k_B T}$$

$$\boxed{J_x = n\mu_n \mathcal{E} + qD_n \frac{dn}{dx}}$$

$$D_n / \mu_n = k_B T / q$$

Einstein Relation

Drift-diffusion equation

$$J_{px} = p\mu_p \vec{\nabla} F_p \qquad \vec{J}_p = \vec{J}_{p-drift} + \vec{J}_{p-diff} = pq\mu_p \vec{\mathcal{E}} - qD_p \vec{\nabla} p$$

current = drift current + diffusion current

$$J_{nx} = n\mu_n \vec{\nabla} F_n \qquad \vec{J}_n = \vec{J}_{n-drift} + \vec{J}_{n-diff} = nq\mu_n \vec{\mathcal{E}} + qD_n \vec{\nabla} n$$

total current = electron current + hole current

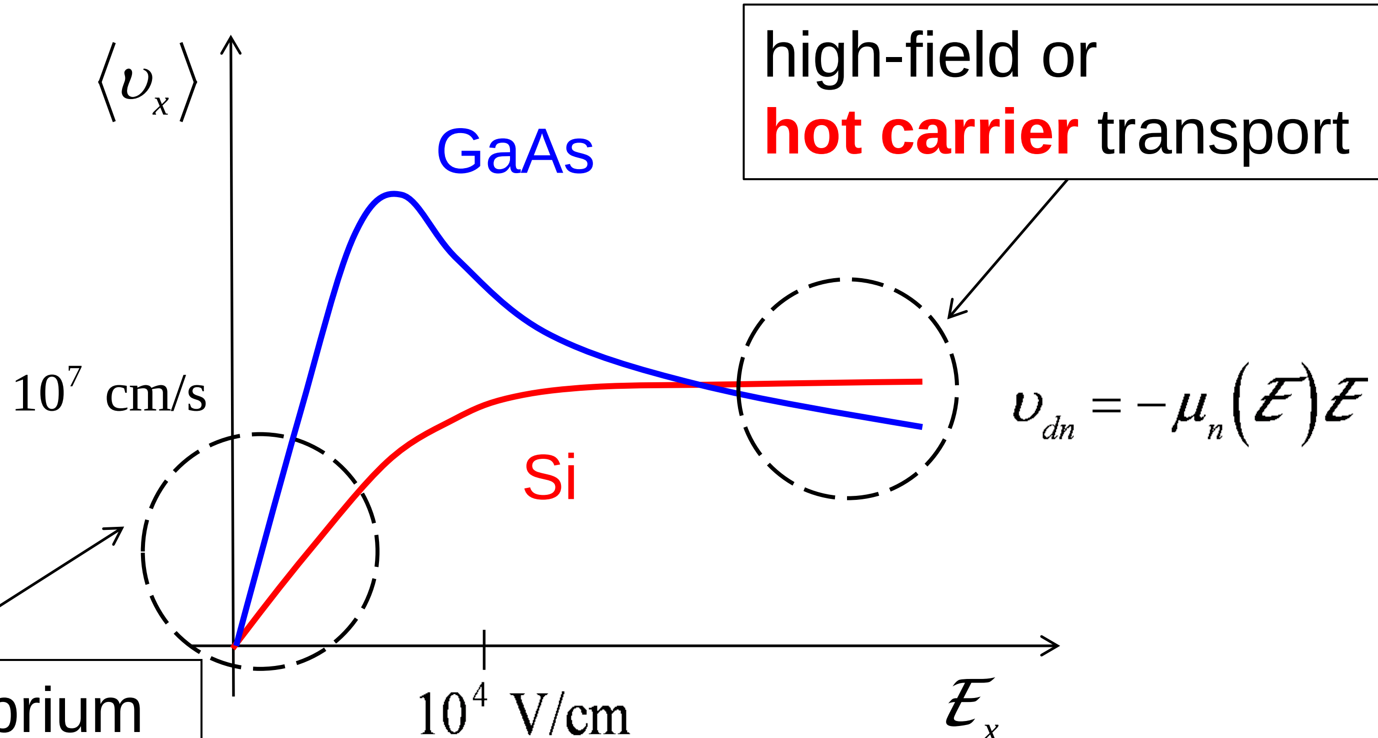
$$\vec{J} = \vec{J}_p + \vec{J}_n$$

$$\mu_p = \frac{\upsilon_T \lambda_0}{2\left(k_B T/q\right)} = \frac{q\tau}{m_p^*} \qquad D_p/\mu_p = D_n/\mu_n = k_B T/q$$

(Einstein, 1905)

Drift-diffusion equation

(***bulk*** semiconductors assumed)



Recombination

When excess carriers are introduced, a semiconductor responds by trying to restore equilibrium.

$$\Delta n(t) = \Delta n(t=0)\, e^{-t/\tau_n}$$

(low level injection)

The minority carrier lifetime is controlled by radiative, Auger, or defect-assisted process – or by some combination of these.

Recombination processes

1) Band-to-band radiative recombination

dominates in direct gap semiconductors
makes lasers and LEDs possible

2) Auger recombination

dominates when the carrier densities are very high
(heavily doped semiconductors or lasers)

3) SRH recombination

dominates in high quality, indirect gap semiconductors
and in low quality direct gap semiconductors

Generation processes

1) Optical generation

Inverse of radiative recombination

2) Thermal generation

Inverse of SRH recombination

3) Impact ionization

Inverse of Auger recombination

Unit 4 summary

1) Out of equilibrium, currents can flow:

$$J_{nx} = n\mu_n \vec{\nabla} F_n \qquad \vec{J}_n = nq\mu_n \vec{\mathcal{E}} + qD_n \vec{\nabla} n$$

2) Out of equilibrium, excess carriers recombine:

$$\Delta n(t) = \Delta n(t=0)\, e^{-t/\tau_n}$$

3) Out of equilibrium, carriers can be generated by processes such as optical absorption and impact ionization.

Vocabulary

Absorption coefficient
Auger recombination
Ballistic transport
Band-to-band recombination
Channels
Conductivity
Diffusive transport
Drift-diffusion equation
Drift velocity
Einstein relation
Electrochemical potential
Excess carriers
Impact ionization
Landauer approach

Mobility
Fermi window
Fick's Law
Low level injection
Minority carrier lifetime
Mean-free-path (MFP)
MFP for backscattering
Modes
Quantized conductance
Quasi-Fermi level
Radiative recombination
Resistivity
SRH recombination
Thermal velocity

Vocabulary (cont.)

Thermalization
Transmission
Velocity vs. field characteristic
Vertical transition