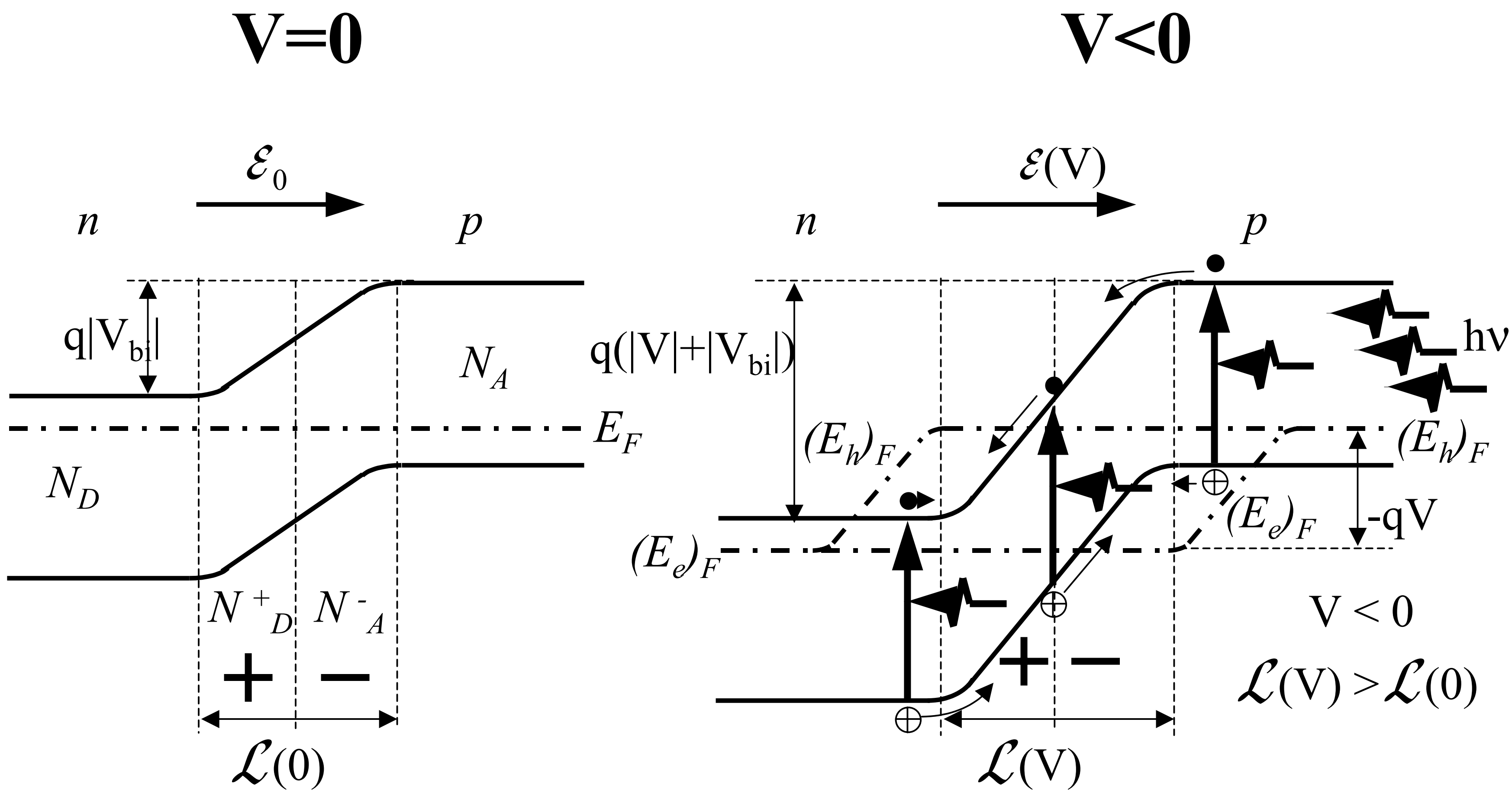
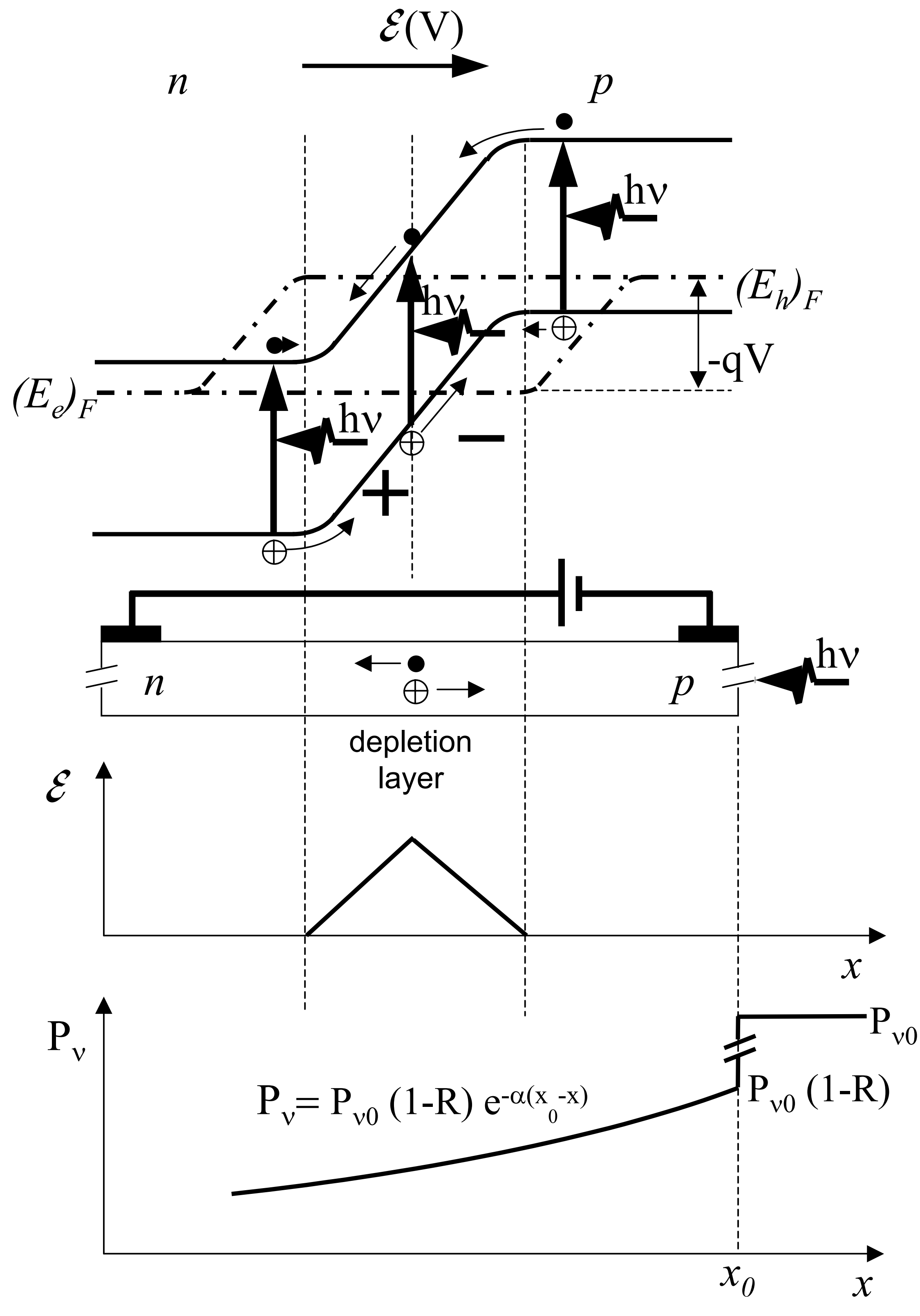
Junction photodiodes

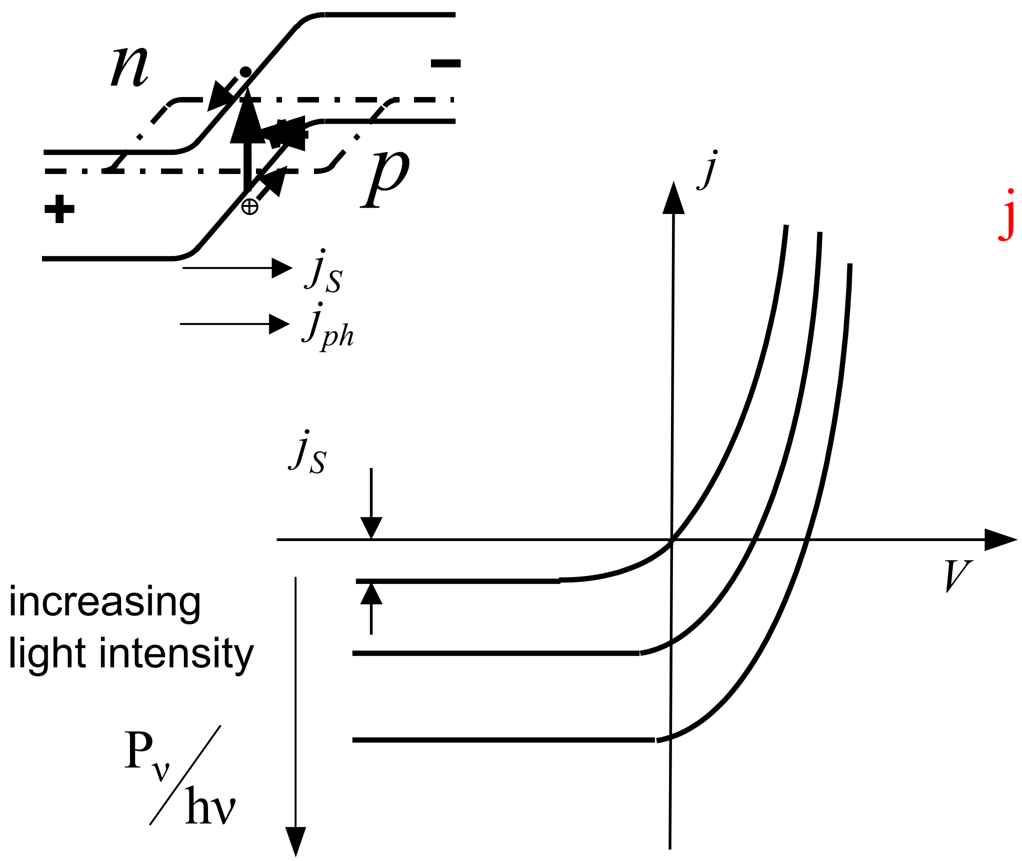


$$\mathcal{L}(V) = \left(\frac{\varepsilon \cdot q \cdot \left(|V_{bi}| + |V|\right)}{2\pi \cdot q^2} \cdot \frac{N_D + N_A}{N_D \cdot N_A} \right)^{1/2}, \quad V < 0$$

Junction photodiodes



Junction photodiodes
VI-characteristics



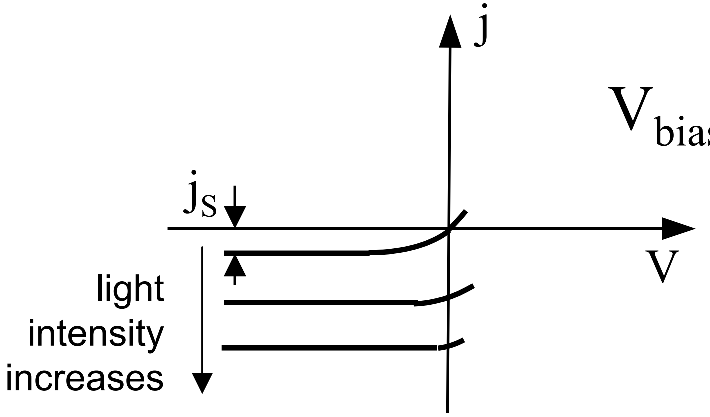
$$j = j_S \cdot \left(e^{\frac{qV}{k_B T}} - 1 \right) - q \cdot \eta \cdot \frac{P_\nu}{h\nu}$$

Coefficient η accounts for the carrier and photon losses

$$q \cdot \eta \cdot \frac{P_\nu}{h\nu} = j_{ph}$$

Junction photodiodes
IV-characteristics

Short circuit



$$V_{bias}<0$$

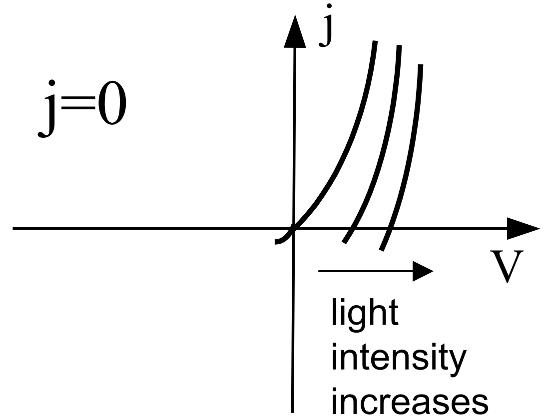
$$\left|-qV\right| >> k_B T$$

$$j_{S.C.} = -j_S - q \cdot \eta \cdot \frac{P_{\nu 0}}{h\nu} =$$

$$= -(j_S + j_{ph})$$

Open circuit

$$j=0$$

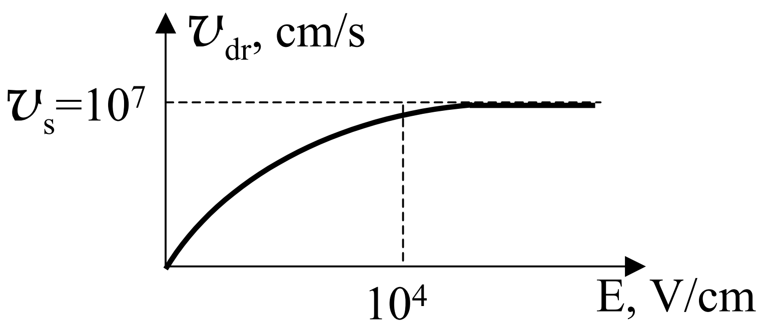


$$V_{O.C.} = \frac{k_B T}{q} \cdot \ln\left(\frac{j_{ph}}{j_S} + 1\right)$$

$$q \cdot \eta \cdot \frac{P_{\nu 0}}{h\nu} = j_{ph}$$

Junction photodiodes
Response time

1. Drift time through the depletion region



At $\mathcal{E} > 10^4$ V/cm carrier drift velocity saturates.

The response time is $t_{tr} = \dfrac{\mathcal{L}(V)}{\upsilon_S}$

$$\mathcal{L}(V) = \left(\frac{\varepsilon \cdot q \cdot (|V_{bi}| + |V|)}{2\pi \cdot q^2} \cdot \frac{N_D + N_A}{N_D \cdot N_A} \right)^{1/2},$$

$$\mathcal{L} \approx 1\text{mkm}, t_{tr} \approx 1 - 10\text{ps}$$

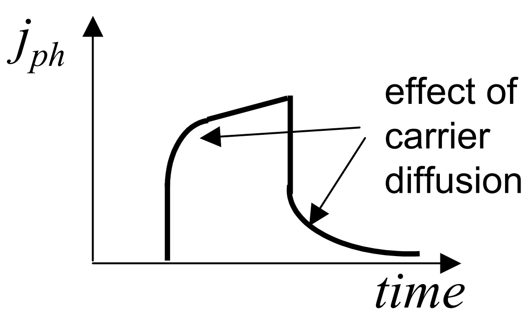
2. RC-time

$$t_{RC} = RC; \qquad C = \frac{\varepsilon}{4\pi} \cdot \frac{S}{\mathcal{L}(V)}$$

S - p-n junction cross-section

$\tau_{RC} \approx 30 - 40$ ps

3. Time of the carrier diffusion to the depletion region

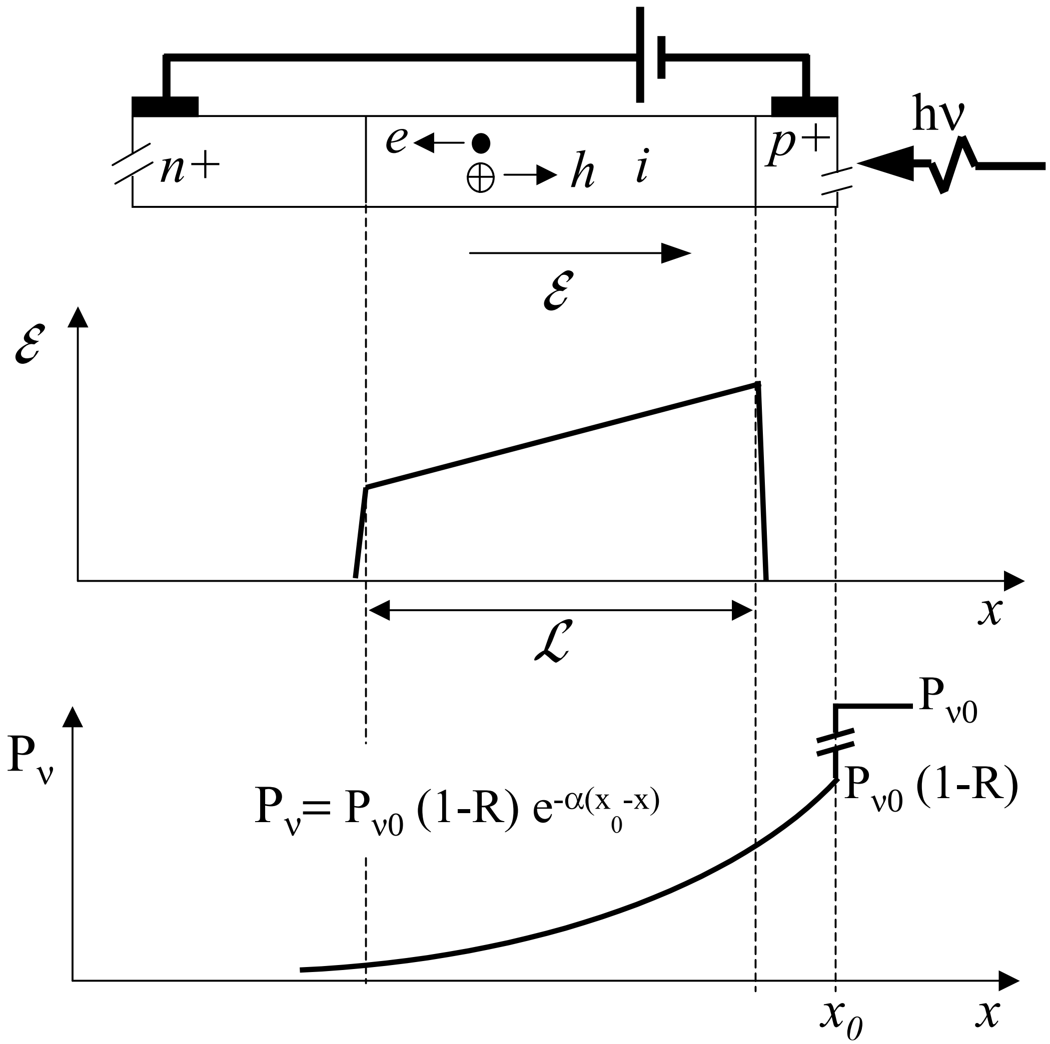


For carriers photogenerated outside of the depletion region

$$t_D = \frac{(\Delta x)^2}{D}; \qquad \left(\Delta x = \sqrt{D \cdot t_D}\right); \qquad t_D \approx 1\text{ns}$$

Δx is a distance from depletion region boundary

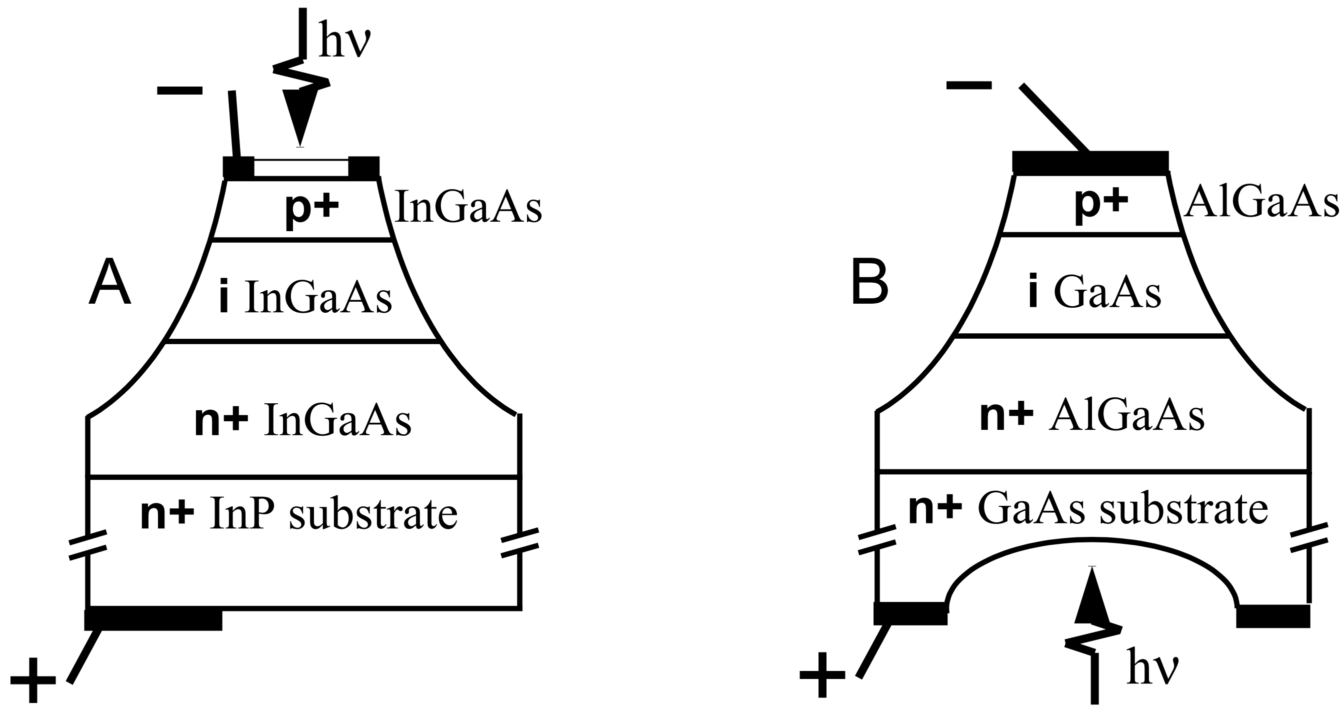
p-i-n (PIN) photodiodes



For PIN photodiodes the length of the region with strong electric field is increased. Thus the photocurrent is increased and response time is reduced because the contributions of the diffusion currents in n+ and p+ regions are small.

p-i-n (PIN) photodiodes
Design

Etched mesa PIN photodiodes for top (A) and back (B) illumination



Typical parameters
diameter: 0.5 - 1mm; response time: 20ps; dark current: pA-nA

p-i-n (PIN) photodiodes
Noise in PIN photodiode

1. Shot noise (generation – recombination noise)

$$\left\langle i_S^{\,2} \right\rangle = 2q \cdot B \cdot \left(I_{ph} + I_B + I_D\right)$$

$$I_{ph} = \frac{q \cdot \eta \cdot P_{\nu 0}}{h\nu}$$ - photocurrent:

I_D – dark current, I_B – background radiation current, B – device bandwidth

2. Johnson (resistance) noise

$$\left\langle i_J^{\,2} \right\rangle = \frac{4 \cdot k_B \cdot T \cdot \mathcal{B}}{R_{eq}}$$

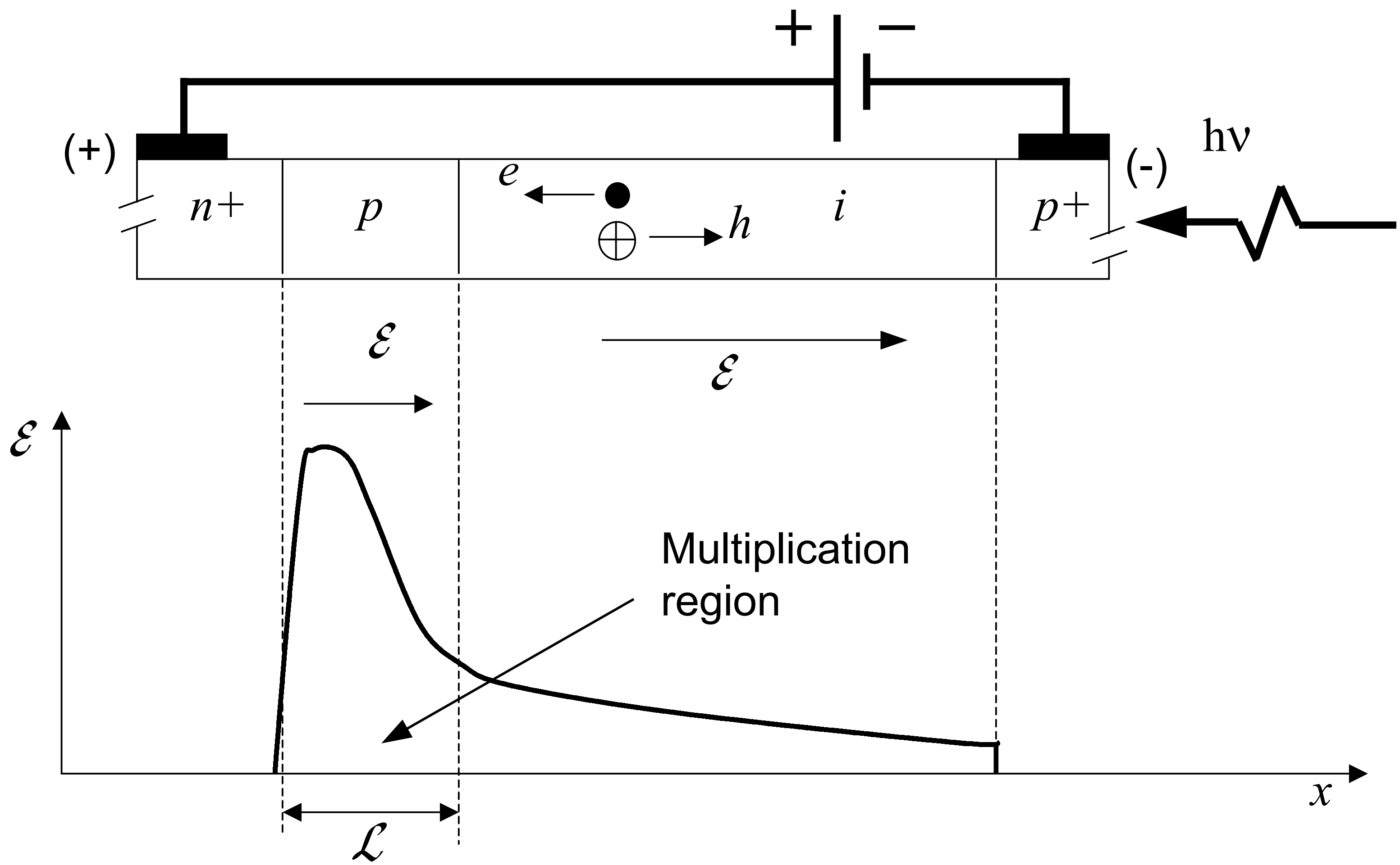
$$R_{eq}^{-1} = R_D^{-1} + R_L^{-1} + R_i^{-1}$$

where R_D^{-1}, R_L^{-1}, R_i^{-1} are diode shunt resistance (junction resistance ~ 100MΩ), external load resistance (usually 50Ω) and amplifier input resistance.
$\mathcal{B}$ – bandwidth.

Signal to Noise Ration (SNR)

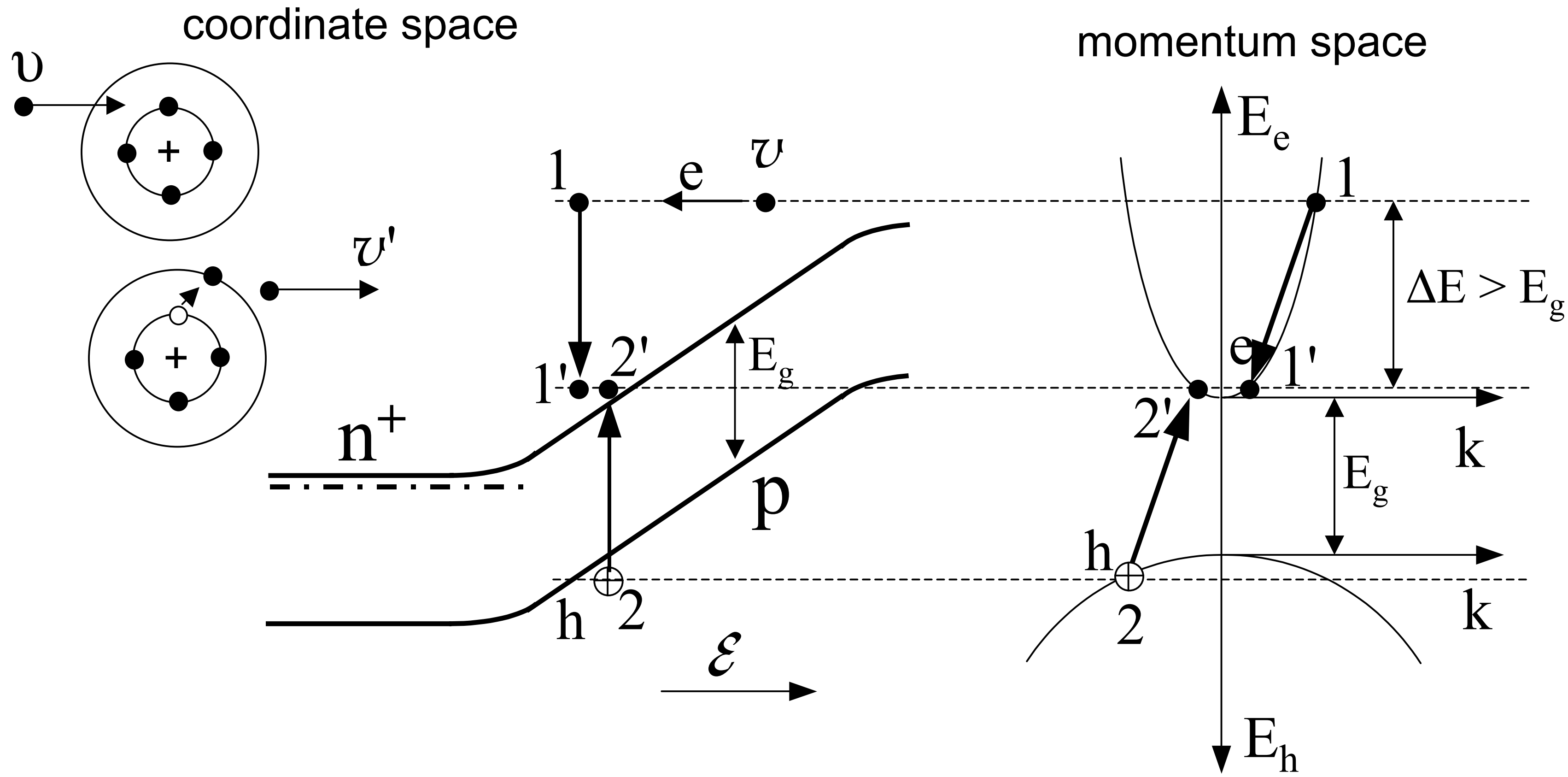
$$\left(\frac{S}{N}\right)_{power} = \frac{q \cdot \eta \cdot P_{\nu 0} / h\nu}{2q \cdot \left(I_{ph} + I_B + I_D\right) + 4k_B \cdot T \cdot \mathcal{B} / R_{eq}}$$

Avalanche photodiodes (APD)



Avalanche photodiodes (APD)

Impact ionization in strong electric field

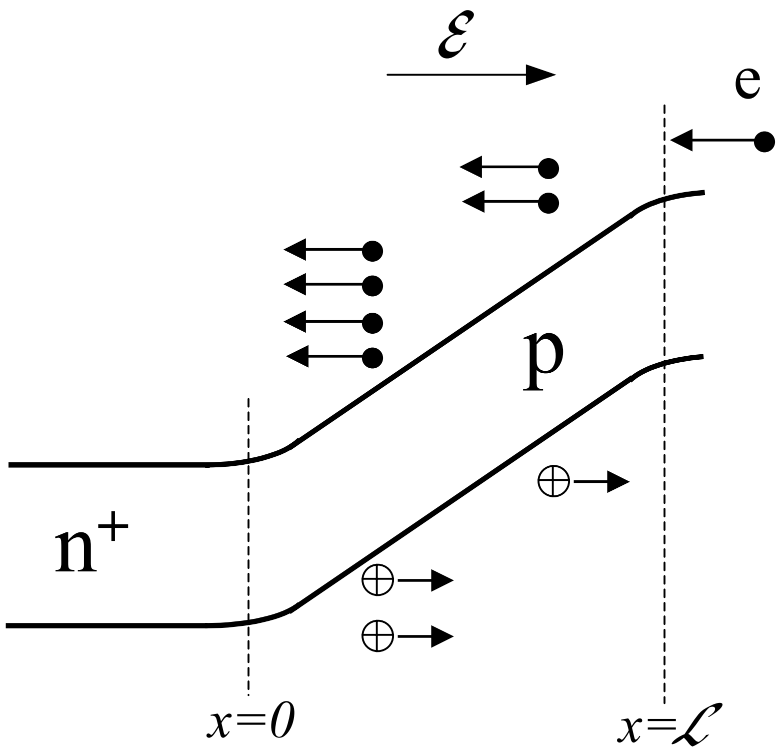


$$E_e(1) - E_e(1') = E_e(2') + E_h(2) + E_g$$

$$\vec{k}(1) - \vec{k}(1') = \vec{k}(2') - \vec{k}(2)$$

Avalanche photodiodes (APD)

Multiplication



Avalanche process sketch. The case when only electrons can ionize (α_h=0)

Multiplication factors for e or h: $M_{e,h}$

$$M_{e,h} = \frac{J_{e0,h\mathcal{L}}}{J_{e\mathcal{L},h0}} \qquad \frac{dJ_{e,h}(x)}{dx} = \alpha_{e,h} \cdot J_{e,h}(x)$$

$\alpha_{e,h}$ – ionization coefficients for electrons and holes: $\alpha_{e,h} = \alpha_{e,h}(\mathcal{E})$

When $\alpha_h = 0$: $M_e = e^{\alpha_e \mathcal{L}}$

When $\alpha_e = \alpha_h$: $M_e = \left(1 - \alpha \cdot \mathcal{L}\right)^{-1}$

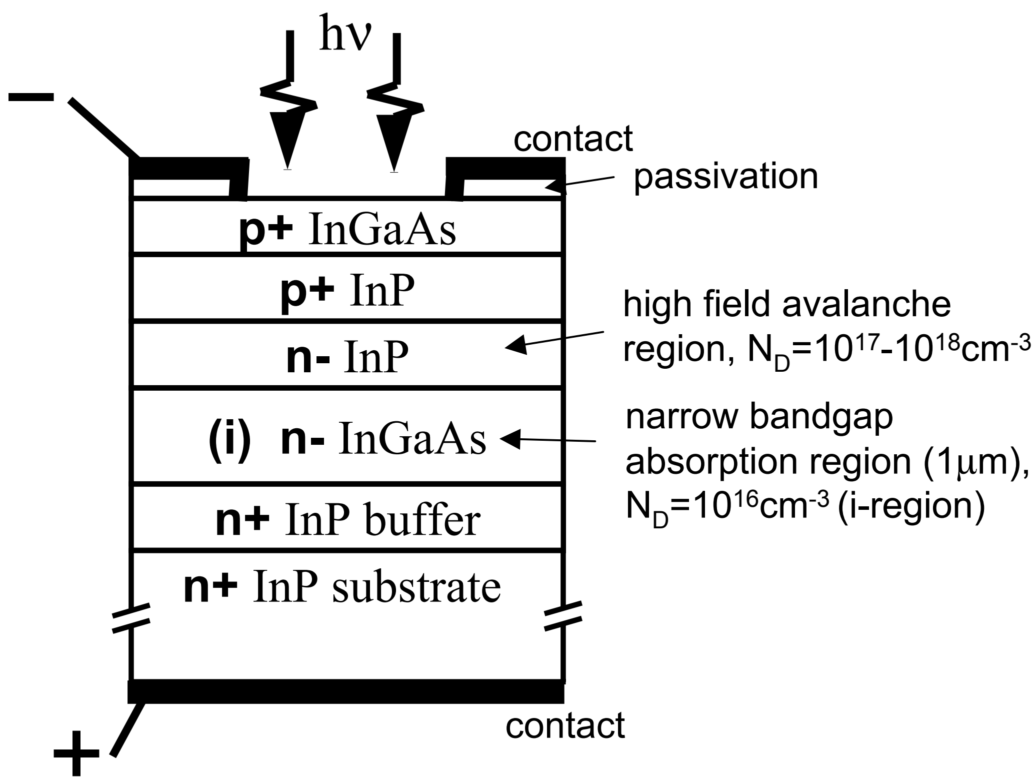
Avalanche breakdown occurs when $\alpha\mathcal{L} \sim 1$ and $M \to \infty$

GaAs: $\mathcal{E}$=3.10^5 V/cm, α_e=10^{4}cm^{-1}

$\mathcal{E}$=5.10^5 V/cm, α_e=10^{5}cm^{-1}

Avalanche photodiodes (APD)

Schematic of InP-based separate-absorption-multiplication (SAM) APD for optical communication systems (λ=1,3; 1.55μm)



Typical parameters

diameter: 10 -100mm;
dark current: pA-nA;
RC ~ 35ps; C ~ 0.5pF;
Gain M ~ 10-100;
Gain-Bandwidth product
$M\mathcal{B} \leq 100$GHz

Avalanche photodiodes (APD)

Noise in APD

Multiplication process adds new component to the device noise.

In APD, not only there are fluctuations in the carrier arrival times, but in the number of carriers as well. The variation in the number of carriers arises from random nature of the multiplication process; each initial photogenerated carrier gives rise to a random number of secondary e-h pairs.

Shot noise in APD

$$\left\langle {i_S}^2 \right\rangle = 2q \cdot B \cdot \left(I_{ph} + I_B + I_D\right) \cdot \left\langle M \right\rangle^2 \cdot F(M)$$

F(M) – excess noise factor. For *InGaAs F(M) ~ 5.*

$$\frac{S}{N} = \frac{{i_{ph}}^2}{\left\langle i_S \right\rangle^2 + \left\langle i_J \right\rangle^2} = \frac{\left(\dfrac{q\eta \cdot P_{\nu 0}}{h\nu}\right)^2}{2qB \cdot \left(I_{ph} + I_B + I_D\right) \cdot F(M) + \dfrac{4k_B T \cdot \mathcal{B}}{R_{eq} \left\langle M \right\rangle^2}}$$