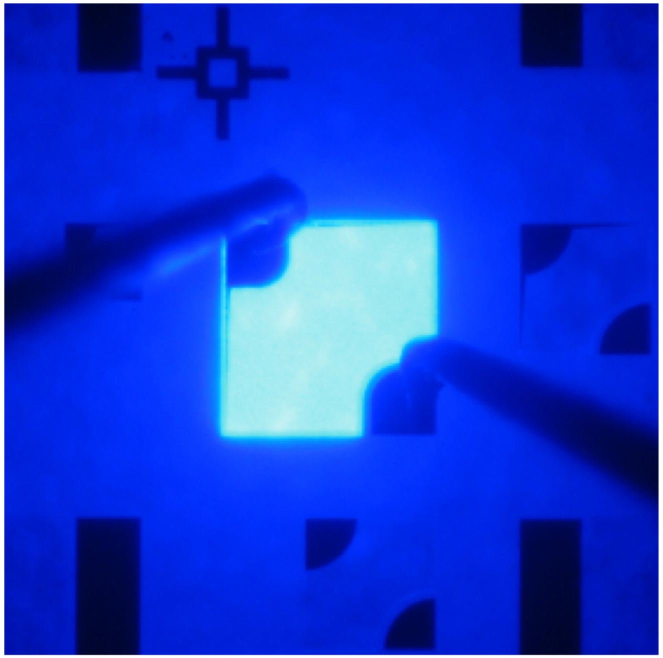
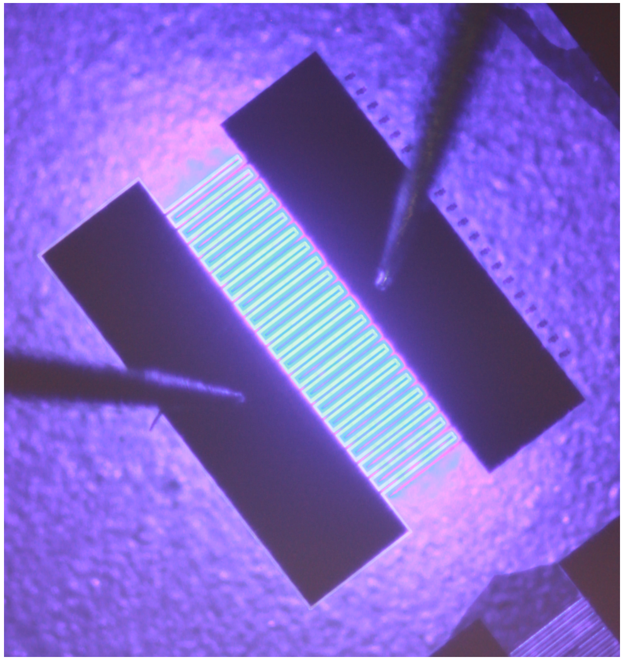
Optoelectronics
ELEC-E3210





Lecture 8

Outline

Introduction

Photoconductors

PIN photodetectors = Photodiodes

P. Bhattacharya: chapter 8
J. Singh: chapter 7

Outline

Introduction

Photoconductors

PIN photodetectors = Photodiodes

Photodetection process

1. Absorption of optical energy and generation of carriers

2. Transportation of photogenerated carriers across the absorption region, with or without gain

3. Carrier collection and generation of a **photocurrent**

Performance requirements:
- high sensitivity
- low noise
- wide bandwidth
- high reliability
- low cost
- high speed (in communications)
- high gain

Common applications:
-Optical communications
-Monitoring laser transmitters

Photodetector types

- **Goal**: converting the energy of absorbed photons into a measurable electrical voltage
- **3 main types**:

Photoelectric detectors

Thermal detectors

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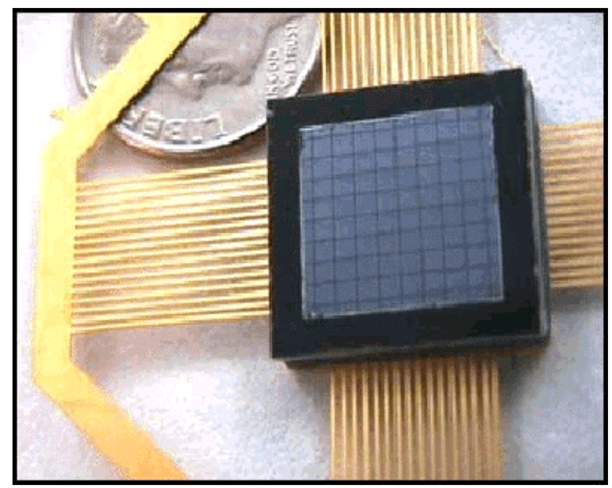
Semiconductor detectors



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Semiconductor photodetectors

- **Photoconductors:** based on conductivity variations
- **Photodiodes:** based on junction properties
  - PN-diodes (ex: solar cells)
  - PIN-diodes (no gain, but large bandwidth)
  - Avalanche photodiodes (APD)
  - Phototransistor
  - Schottky photodiode (metal-semiconductor)
- **Bandgap engineered photodetectors**
  - Quantum well infrared photodetector (QWIP)
  - Staircase avalanche photodiode

Photodetection mechanisms

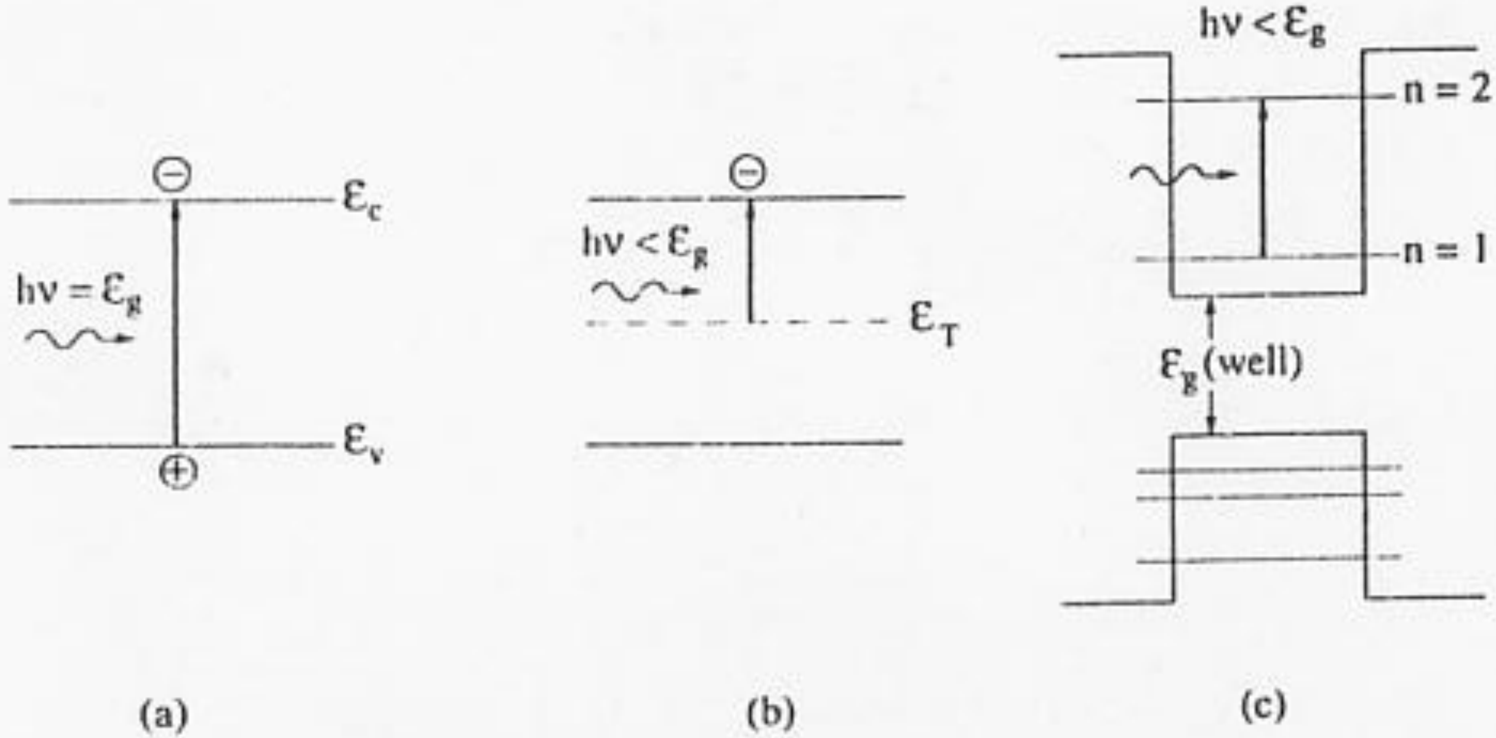


Figure 8.1 Different mechanisms of photodetection: (a) for intrinsic light ($h\nu \geq \mathcal{E}_g$); (b) for extrinsic light utilizing a deep level; and (c) for extrinsic light utilizing intersubband transitions in a quantum well.

Efficiency and responsivity

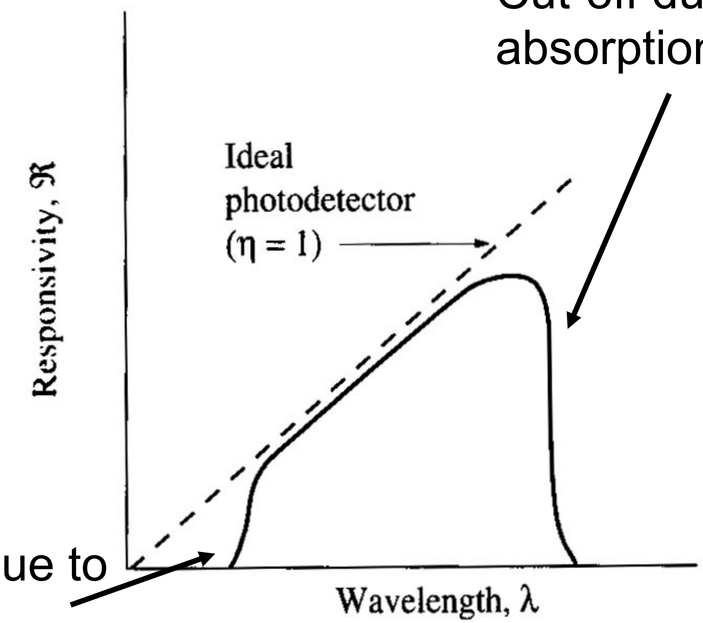
Quantum efficiency (external)

$$\eta = \frac{I_{ph} / q}{P_{inc} / h\nu} \qquad \eta \propto \left(1 - e^{-\alpha d}\right)$$

P_{inc} = incident optical power
I_{ph} = photocurrent
α = absorption coefficient
d = thickness of the active region

α depends on wavelength!

Cut-off due to absorption edge



Cut-off due to large α

Responsivity

$$R = \frac{I_{ph}}{P_{inc}} = \frac{\eta q}{h\nu} = \frac{\eta \lambda(\mu m)}{1.24} (A/W)$$

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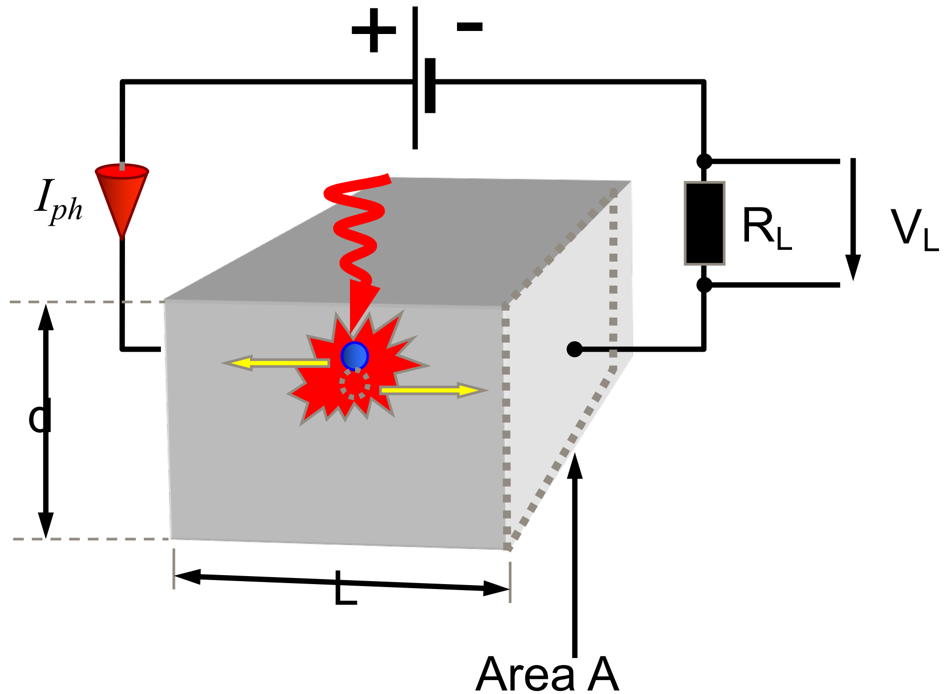
PIN photodetectors = Photodiodes

Photoconductor

Note: only photon energies above the bandgap will be efficiently absorbed!



- Optical electron-hole pair generation changes the conductivity of a semiconductor material
- Materials: Si, Ge, PbSe, PbS, CdSe, HgCdTe, PbSnTe, InGaAs (mostly IR)
- Cheap (from 5$)
- Applications: security alarm, street lights, IR-astronomy, IR-spectroscopy

Photoconductor efficiency

(External) quantum efficiency:

Electron-hole pair generation rate ($s^{-1}cm^{-3}$)

Device volume

$$\eta = \frac{GV_V}{P_{inc} / h\nu}$$

Number of incident photons/second

Power transmitted:

$$P_{trans} = P(d) = P_{inc} e^{-\alpha d}$$

Optical power absorbed in the detector:

$$P_{abs} = P_{inc} - P_{trans} = P_{inc}\left(1 - e^{-\alpha d}\right)$$

Internal quantum efficiency:

$$\eta_i = \frac{GV_V}{P_{abs} / h\nu} = \frac{\eta}{\left(1 - e^{-\alpha d}\right)}$$

Photoconductor current

Excess carrier concentration:

$$\Delta n = \Delta p = \tau G$$

Carrier recombination lifetime

Corresponding variation of conductivity:

$$\Delta \sigma = q \Delta n \left(\mu_e + \mu_h \right)$$

Photogenerated current:

Device cross-section

Electric field

$$I_{ph} = J_{ph} A = \Delta \sigma A E = q \Delta n \left(\mu_e + \mu_h \right) A E$$

$$= q \Delta n \left(\mu_e + \mu_h \right) A \frac{V}{L}$$

Bias voltage (do not mix with volume $\mathbf{v}_v$!)

Photoconductor gain

Photogenerated current:

$$I_{ph} = q\Delta n(\mu_e + \mu_h)AE$$

Electron velocity v_e and **electron transit time** t_{tr}^e

$$v_e = \mu_e E \Rightarrow t_{tr}^e = \frac{L}{\mu_e E} \Rightarrow E = \frac{L}{\mu_e t_{tr}^e}$$

$$I_{ph} = q\,\Delta n\,(\mu_e + \mu_h)A\,E$$

$$\Delta n = \tau G \qquad E = \frac{L}{\mu_e t_{tr}^e}$$

$$\Rightarrow I_{ph} = \left(\frac{\tau}{t_{tr}^e}\right)\left(1 + \frac{\mu_h}{\mu_e}\right) qGV_V$$

Photoconductor gain

Photogenerated current

$$I_{ph} = \left(\frac{\tau}{t_{tr}^{e}}\right)\left(1+\frac{\mu_h}{\mu_e}\right) qGV_V$$

Number of photogenerated charges per second (= current **directly** generated by photons)

$$I_g = qGV_V$$

Gain:

$$\Gamma_g = \frac{I_{ph}}{I_g} = \left(\frac{\tau}{t_{tr}^{e}}\right)\left(1+\frac{\mu_h}{\mu_e}\right) \approx \frac{\tau}{t_{tr}^{e}}$$

$$\Rightarrow \quad I_{ph} = qGV_V\Gamma_g = qP_{inc}\frac{\eta}{h\nu}\Gamma_g \quad \Rightarrow \quad \eta = \frac{GV_V}{P_{inc}/h\nu} = \frac{1}{\Gamma_g}\left(\frac{I_{ph}/q}{P_{inc}/h\nu}\right)$$

Photoconductor gain

$$t_{tr}^{e} = \frac{L}{\mu_e E} \Rightarrow$$ t_{tr}^{e} decreases with the electric field

- $t_{tr}^{e} >> \tau \quad t_{tr}^{h} >> \tau$ (small bias V)

Electrons (and holes) are slow and recombine before they drift through the detector

$$\Rightarrow \Gamma_g \approx \frac{\tau}{t_{tr}^{e}} << 1$$

- $t_{tr}^{e} < \tau \quad t_{tr}^{h} > \tau$ (moderate bias V)

Holes are slow and recombine before they drift through the detector, but electrons get re-injected

$$\Rightarrow \Gamma_g \approx \frac{\tau}{t_{tr}^{e}} > 1$$

- $t_{tr}^{e} < \tau \quad t_{tr}^{h} < \tau$ (very large bias V)

The current do not longer obey Ohm's law (**Space-charge limited currents**)

$$\Rightarrow \Gamma_g \approx 1$$

Photoconductor: responsivity

(Current) responsivity for a **photoconductor**:

$$\mathrm{R}_I = \frac{I_{ph}}{P_{inc}} = \frac{\Gamma_g \eta q}{h\nu} = \frac{\Gamma_g \eta \lambda}{1.24} \text{ (A/W)}$$

- Like quantum efficiency η, **responsivity** is a common figure of merit expressing the efficiency of a photoconductor.

- For photoconductors $0.5 < \mathrm{R}_I < 100$ at peak responsivity wavelength.

- **Voltage responsivity** is also commonly used:

$$\mathrm{R}_V = \frac{V_L}{P_{inc}} = R_L \mathrm{R}_I \qquad \text{(V/W)}$$

Frequency bandwidth

Let's assume that the incident light signal can be divided into two parts: a constant part and an amplitude-modulated part.

$$P_{inc} = P_0 + P_1 e^{j\omega t}$$
$$G = G_0 + G_1 e^{j\omega t}$$

For the light generated carrier density Δn holds the rate equation:

$$\frac{d(\Delta n)}{dt} = G - \frac{\Delta n}{\tau}$$

$$\frac{d(\Delta n)}{dt} = G_0 + G_1 e^{j\omega t} - \frac{\Delta n}{\tau}$$

$$\Delta n = G_0 \tau \left(1 - e^{-t/\tau}\right) + \frac{G_1 \tau}{1 + j\omega\tau}\left(e^{j\omega\tau} - e^{-t/\tau}\right)$$

Under steady-state $t \gg \tau$ $\Rightarrow$ $\Delta n = G_0 \tau + \dfrac{G_1 \tau}{1 + j\omega\tau} e^{j\omega\tau}$

Frequency bandwidth

Photocurrent: $i_{ph} = I_0 + i_1$

DC AC

$$\begin{cases} I_0 = qP_0 \dfrac{\eta}{h\nu} \dfrac{\tau}{t_{tr}^e} \\ i_1 = qP_1 \dfrac{\eta}{h\nu} \dfrac{\tau}{t_{tr}^e} \dfrac{e^{j\omega\tau}}{1 + j\omega\tau} \end{cases}$$

Cut-off frequency (bandwidth), f_c, is defined as the frequency at which $\omega\tau = 1$

$$f_c = \frac{1}{2\pi\tau}$$

Gain: $\Gamma_g = \dfrac{\tau}{t_{tr}^e}$

Gain-bandwidth product in photoconductor:

$$\Gamma_G f_c = \frac{1}{2\pi\tau} \frac{\tau}{t_{tr}^e} = \frac{1}{2\pi t_{tr}^e}$$

The gain-bandwith product can be increased by reducing elecron transit time i.e. the spacing between contact electrodes!

Photoconductor: parameter optimization

For maximum quantum efficiency:
- Antireflection coating
- **Thick** absorbing layer

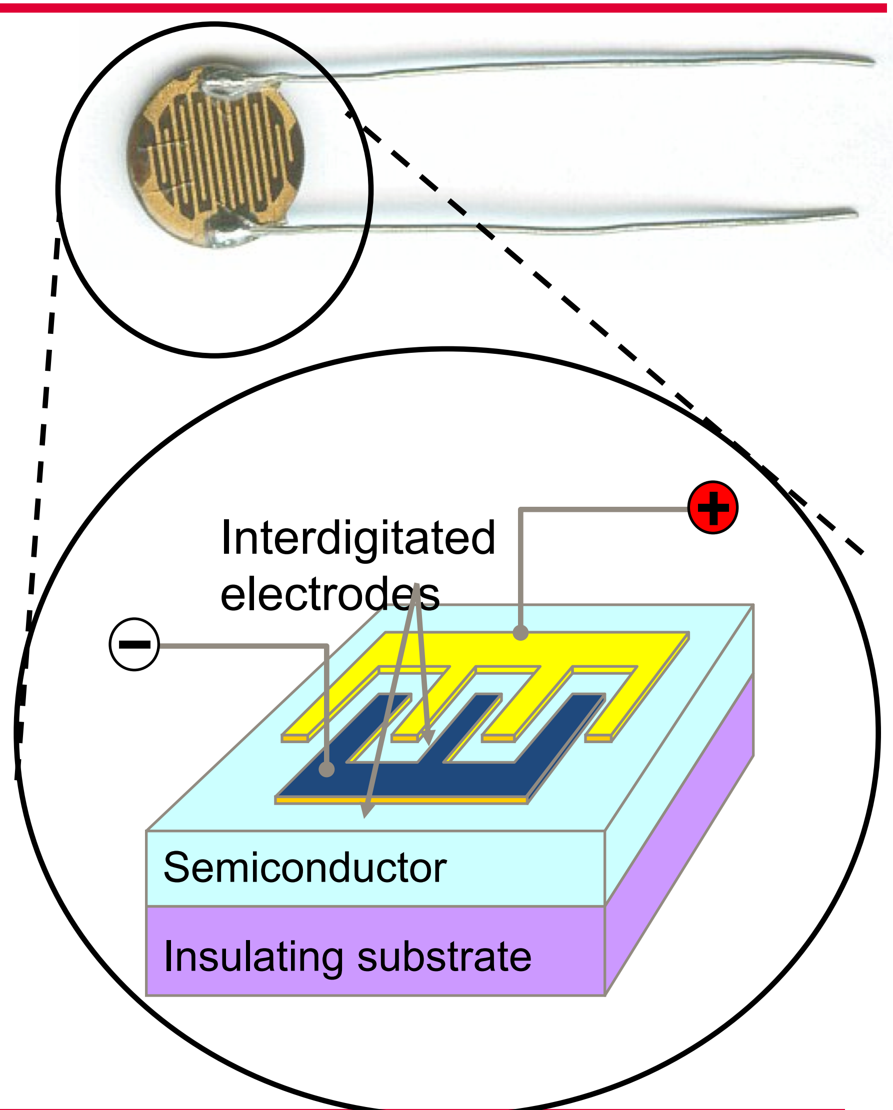
For large bandwidth:
- Small recombination time τ
- **Thin** absorbing layer

For maximum bandwidth-gain product:

$$\Gamma_g = \frac{\tau}{\tau_{tr}^e} \qquad B = \frac{1}{2\pi\tau}$$

$$B \times \Gamma_g = \frac{1}{2\pi\, t_{tr}^e}$$

Interdigitated electrodes are used in order to reduce t_{tr}^e



Photoconductor current

$$I(t) = I_{ph} + I_D + I_B + i_N(t)$$

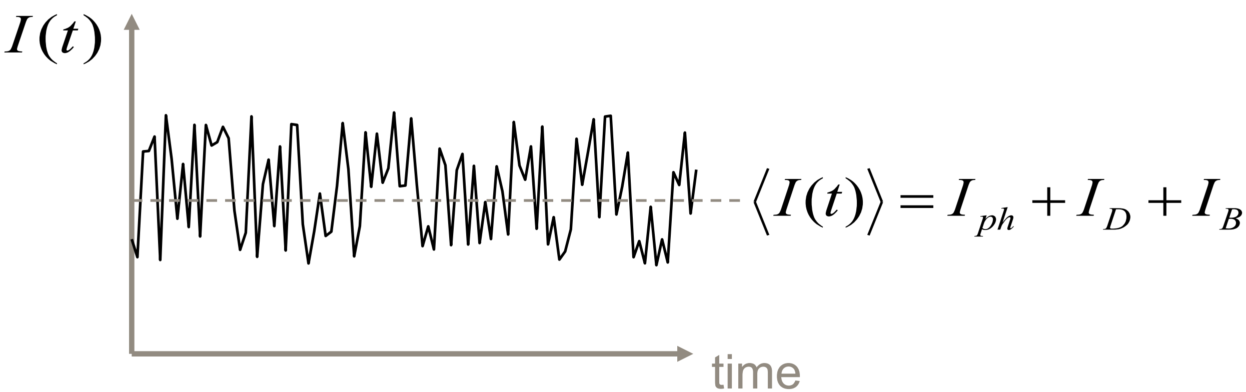
- The **dark current** I_D is the current through the device when $P_{inc}=0$

$$I_D = q\left(\mu_e n + \mu_h p\right) A \frac{V}{L}$$

I_D is relatively large for photoconductors

- I_B = **background current**. Can be reduced using optical filters

- The **photocurrent noise** $i_N(t)$ has different origins



Noise in photoconductors

$$I(t) = I_{ph} + I_D + I_B + \boxed{i_N(t)}$$

Thermal noise (=Johnson noise)

$$\overline{i_J}^2 = \frac{4k_B TB}{R_L}$$

Bandwidth

Load resistance

Shot noise (=generation-recombination noise)

$$\overline{i_{GR}}^2 = \frac{4q\Gamma_G I_0 B}{1+\omega^2\tau^2}$$

Steady-state light-induced output current

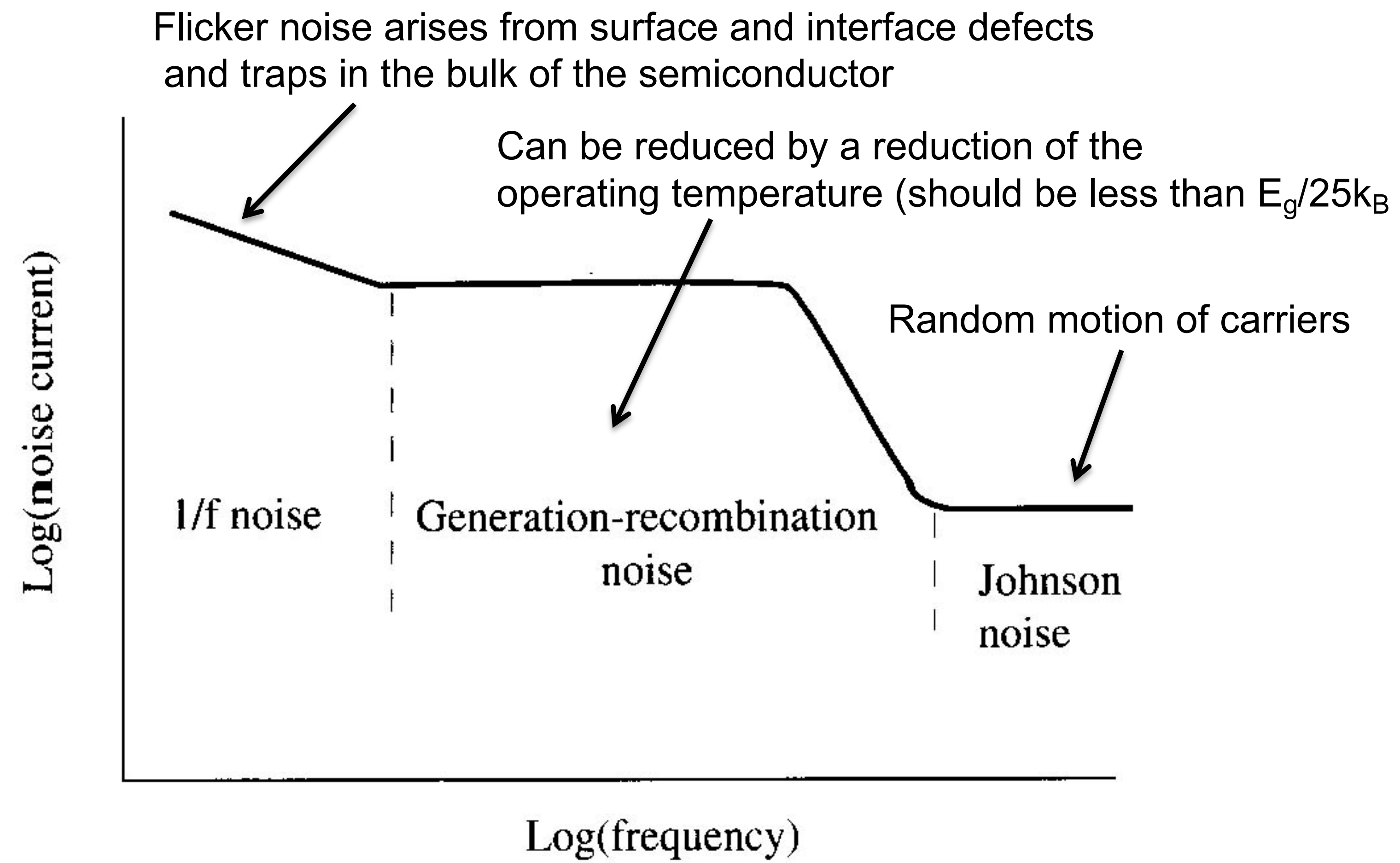
f << $1/2\pi\tau$: → i_{GR} is almost independent of f

f > $1/2\pi\tau$: → i_{GR} declines with increasing f with a $1/f^2$ dependence

⇨ Johnson noise dominates at high frequencies!

At frequencies less than 1kHz, flicker noise (1/f noise) becomes important.

Noise in photoconductors



Signal-to-noise ratio + NEP

- **Signal-to-noise ratio (SNR):**

$$\frac{S}{N} = \frac{i_{ph}^2}{\sum_m i_{N,m}^2} = \frac{i_{ph}^2}{i_J^2 + i_{GR}^2} = \frac{\eta P_1}{8Bh\nu}\left[1 + \frac{k_B T}{\Gamma_G q}\left(1+\omega^2\tau^2\right)\frac{G_C}{I_0}\right]^{-1}$$

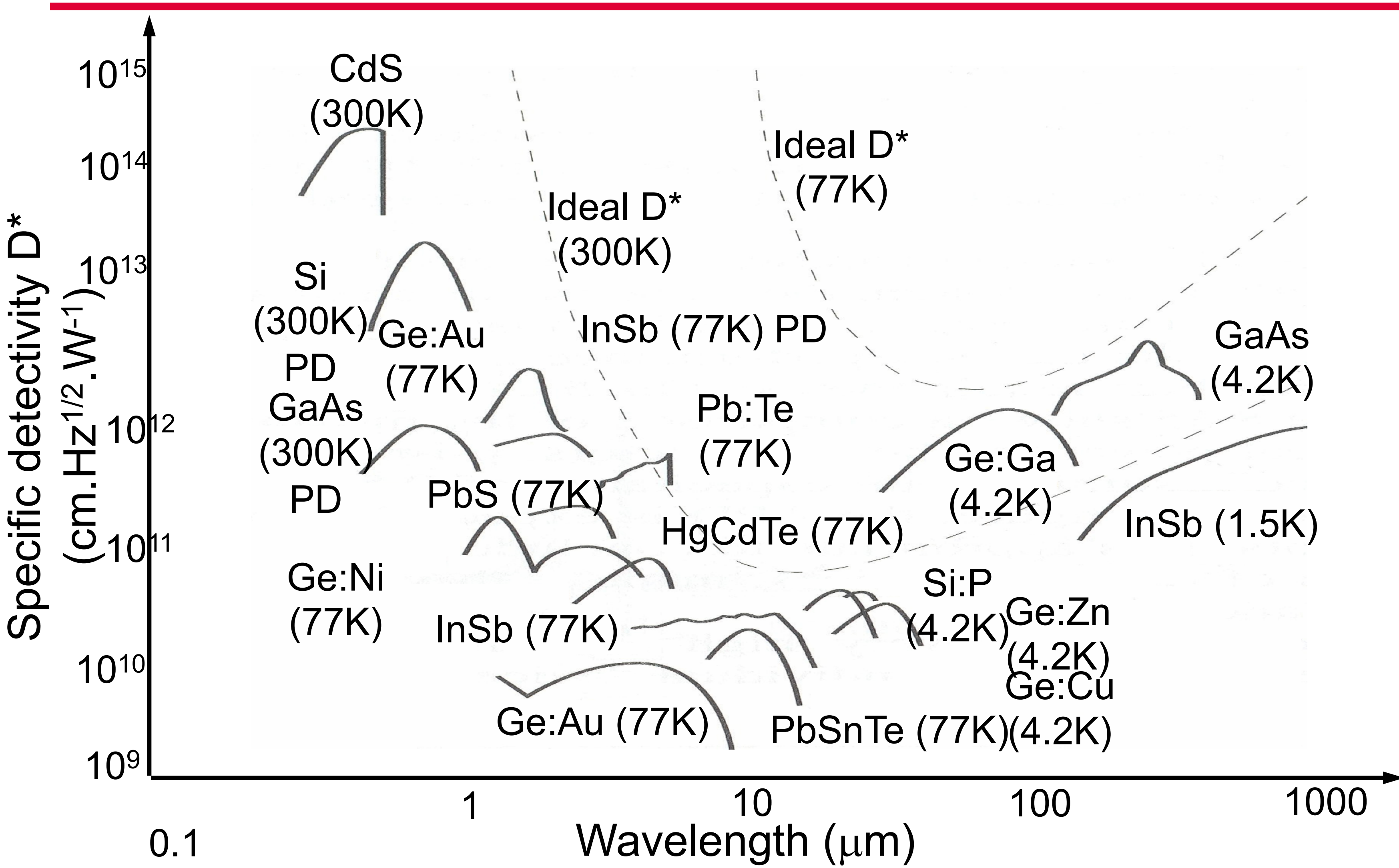
SNR is inversely proportional to the bandwidth!

- **Noise equivalent power (NEP):** incident rms optical power required to produce a SNR = 1 for a bandwidth of B=1Hz. NEP is a measure of the minimum detectable signal.

- The **detectivity D** is a measure of the detector sensitivity: $D = \frac{1}{NEP}$ (W^{-1})

Normalized or **specific detectivity D***: $D^* = \frac{\sqrt{AB}}{NEP}$ ($cm.Hz^{1/2}.W^{-1}$)

Specific detectivity



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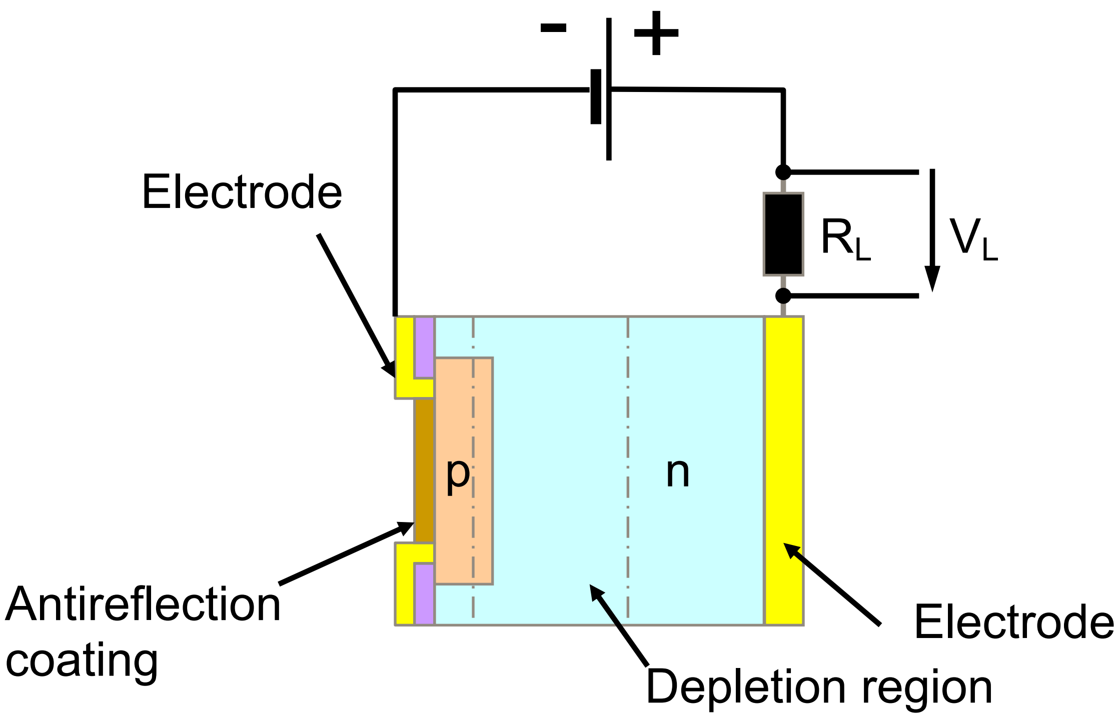
PIN photodetectors = Photodiodes

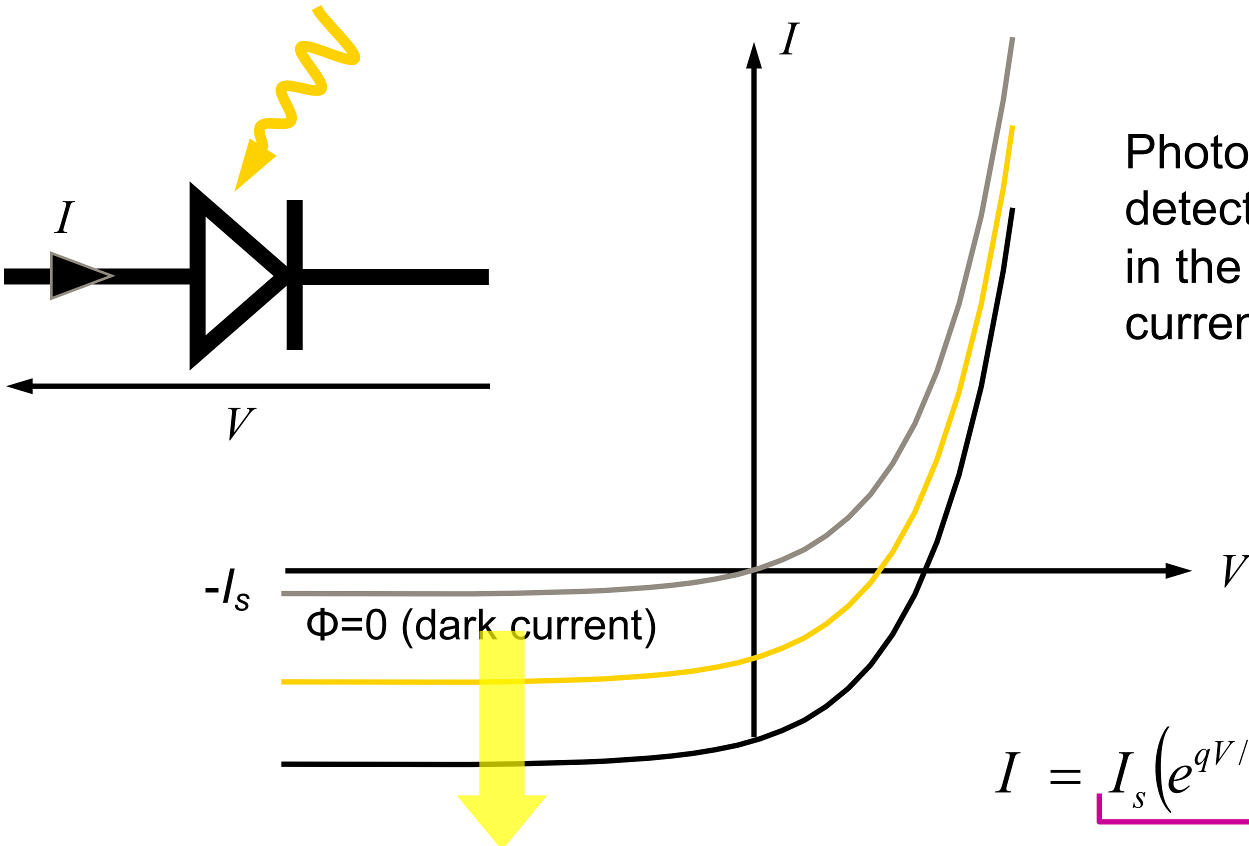
PN Photodetector



Operated under reverse-biased conditions!

The photogenerated carriers in the depletion region are accelerated in opposite directions by the reverse bias → photocurrent

PN Photodetector



Photoexcitation is detected as an increase in the reverse-biased current

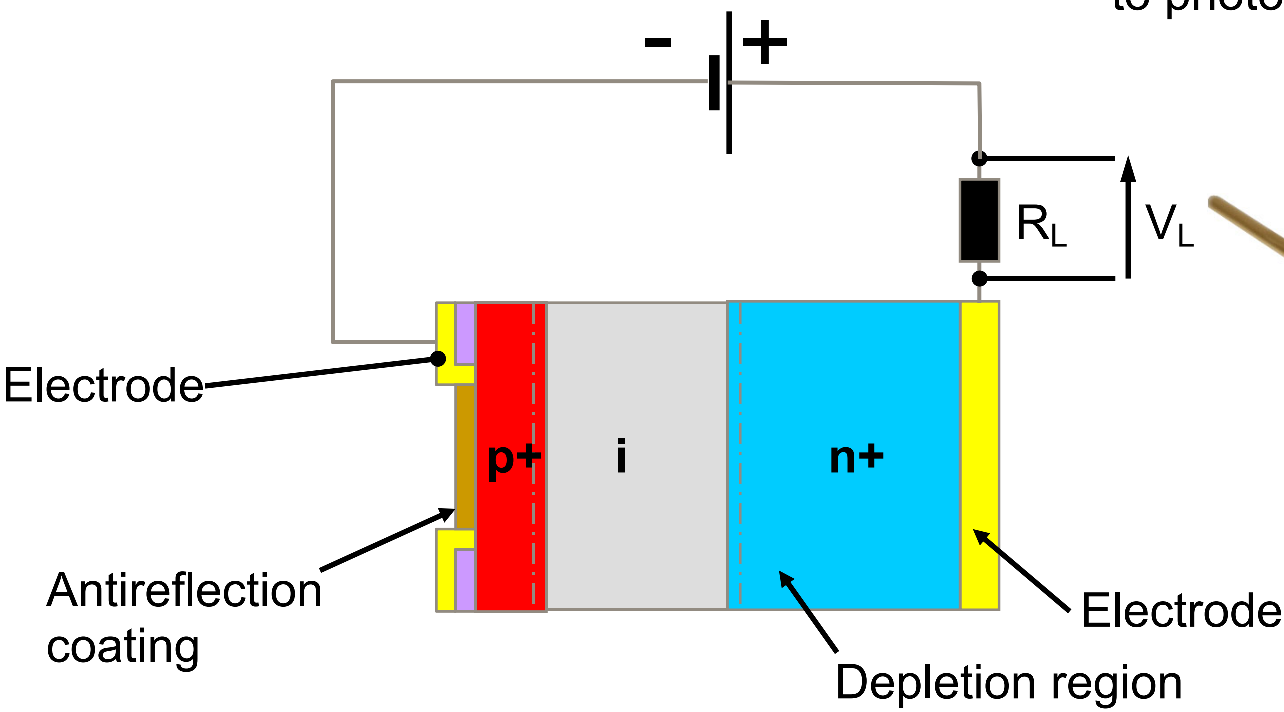
$$I = \underbrace{I_s\left(e^{qV/k_BT} - 1\right)}_{\text{Dark current}} - I_{ph}$$

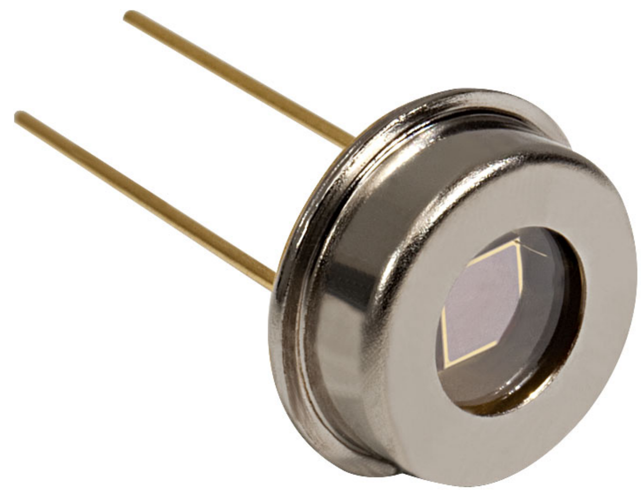
Small dark current compared to photoconductors ➡ **higher sensitivity**

PIN Photodetector

- Reverse bias operation!
- no internal gain

- dark current is very small
- shot noise is small compared to photoconductors





Possibility to control the depletion layer width!

Bandwidth and **quantum efficiency** can be optimized separately

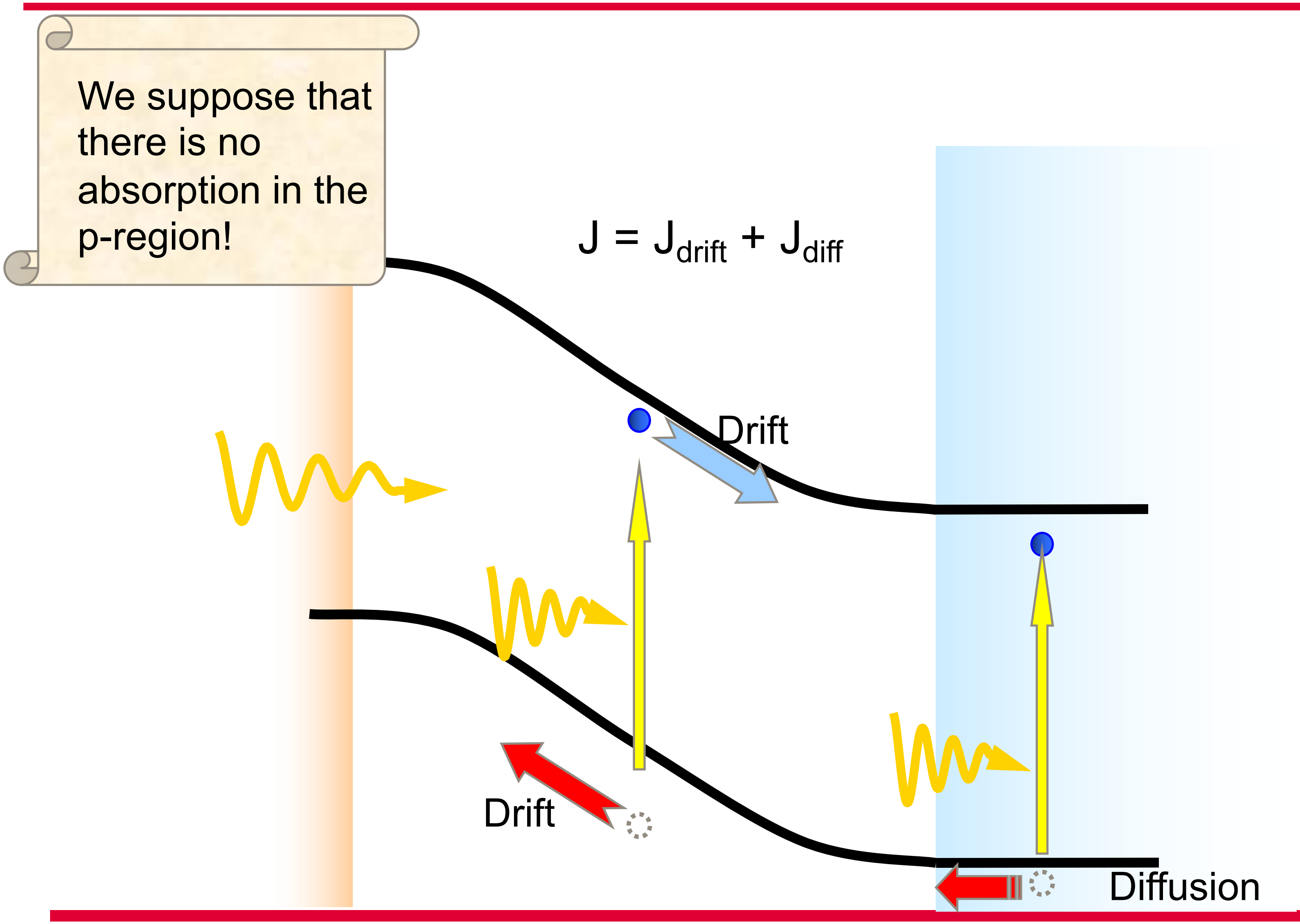
PIN Photodetector

Bandwidth and **quantum efficiency** can be optimized separately:

- For high response speed, make the depletion layer width small
- For high quantum efficiency or responsivity, make the width large

- Very large bandwidths can be attained
- The response speed and bandwidth are limited by either transit time effects or by circuit parameters. The transit time can be reduced by reducing the thickness of the i-layer.
- Lowering of the response speed due to diffusion of carriers created outside the i-region can be minimized by fabricating the junction close to the illuminated surface

PIN Photodetector



PIN detector: drift current

Photon flux:

$$\Phi_{ph}(x) = \phi_0 e^{-\alpha x} = \frac{P_{inc}\left(1-\Theta_R\right)}{Ah\nu} e^{-\alpha x}$$

Generated electron-hole pairs per volume per second *G(x)*:

$$G(x) = \eta_i \frac{d\Phi_{ph}}{dx} = \eta_i \frac{P_{inc}(1-\Theta_R)}{Ah\nu} \alpha e^{-\alpha x}$$

Drift current:

$$J_{drift} = -q\int_0^W G(x)dx = -q\eta_i\phi_0\left(1-e^{-\alpha W}\right)$$

W = width of the i-layer

Θ_R = reflectivity of the top surface

ϕ_0 = incident photon flux (photons/sec/cm^2)

PIN detector: diffusion current

Light absorption in the n-region generates a diffusion current density J_{diff} of minority holes oriented towards the depletion region.

Continuity equation on the n-side:

$$D_h \frac{\partial^2 p_N}{\partial x^2} - \frac{p_N - p_{NO}}{\tau_h} + G(x) = \frac{\partial p_N}{\partial t}$$

At quasi-equilibrium: $\frac{\partial p_N}{\partial t} = 0$

Boundary conditions:

$p_N = 0$ at $x = W$ (all holes at the very edge of the depletion region diffuse)

$p_N = p_{NO}$ at $x = +\infty$ (normal concentration far away from the depletion region)

PIN detector: diffusion current

Solution of the continuity equation at quasi-equilibrium:

$$p_N = p_{NO} - \left(p_{NO} + Ce^{-\alpha W}\right)e^{(W-x)/L_h} + Ce^{-\alpha x}$$

Diffusion length: $L_h = \sqrt{D_h \tau_h}$

From the boundary conditions:

$$C = \frac{\eta_i \phi_0 \alpha L_h^2}{D_h\left(1-\alpha^2 L_h^2\right)}$$

Diffusion current on the n-side:

$$J_{diff} = -qD_h\left(\frac{\partial p_N}{\partial x}\right)_{x=W} = -q\eta_i\phi_0 \frac{\alpha L_h}{1+\alpha L_h} e^{-\alpha W} - qp_{NO}\frac{D_h}{L_h}$$

PIN detector: total current

$$J = J_{drift} + J_{diff} = -q\eta_i\phi_0\left(1 - \frac{e^{-\alpha W}}{1+\alpha L_h}\right) - qp_{NO}\frac{D_h}{L_h}$$

External Quantum efficiency:

p_{NO} is typically very small

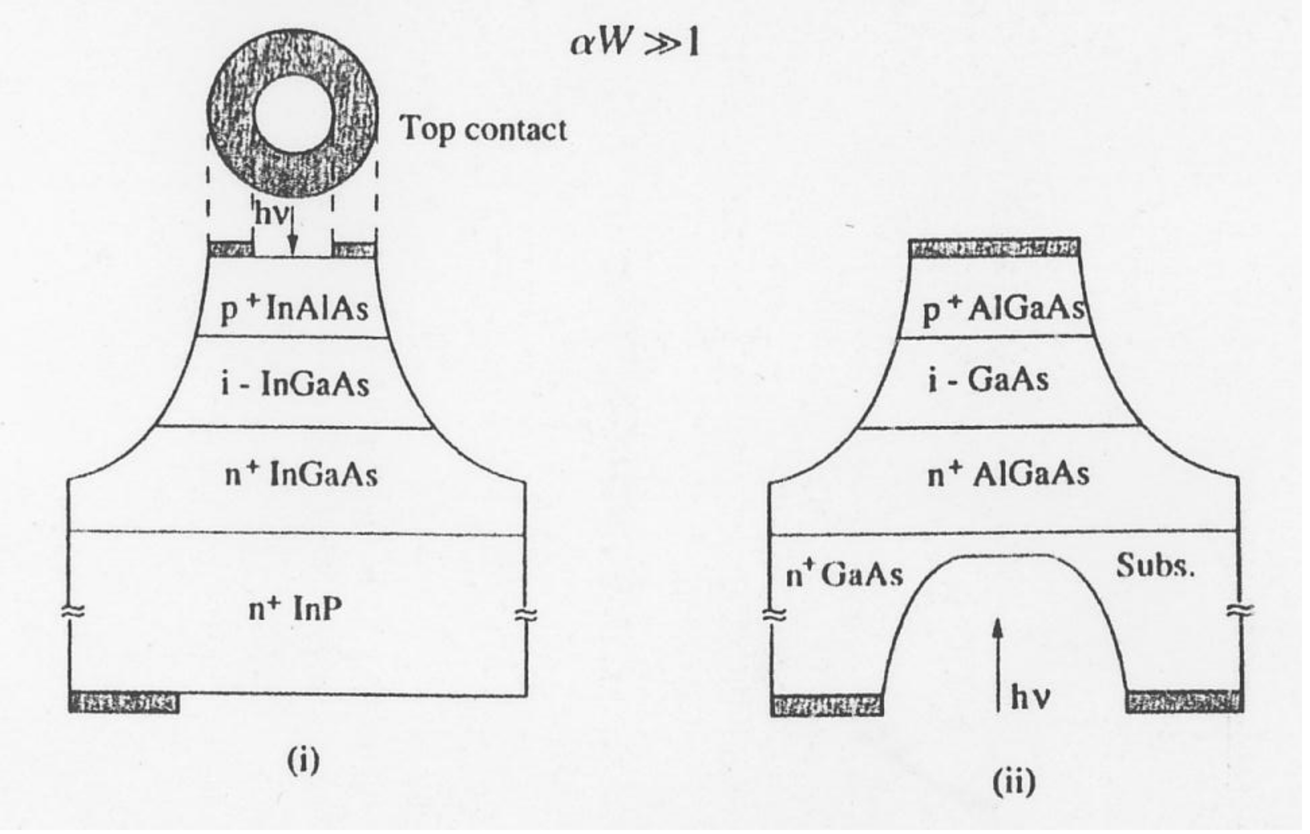
$$\eta_{ext} = \eta_i \frac{|J/q|}{P_{inc}/Ah\nu} = \eta_i\left(1-\Theta_R\right)\left(1 - \frac{e^{-\alpha W}}{1+\alpha L_h}\right)$$

Typically $\eta_i \cong 1$

In order to attain a high external quantum efficiency:

- $\Theta_R \cong 0$ (realized in practice by antireflection coatings)
- $\alpha W >> 1$ (If W is too large→ transit time becomes large and device speed is reduced. Also in most semiconductors α at the bandedge is determined by the bandstructure and cannot be changed)

Practical PIN photodiodes: structures

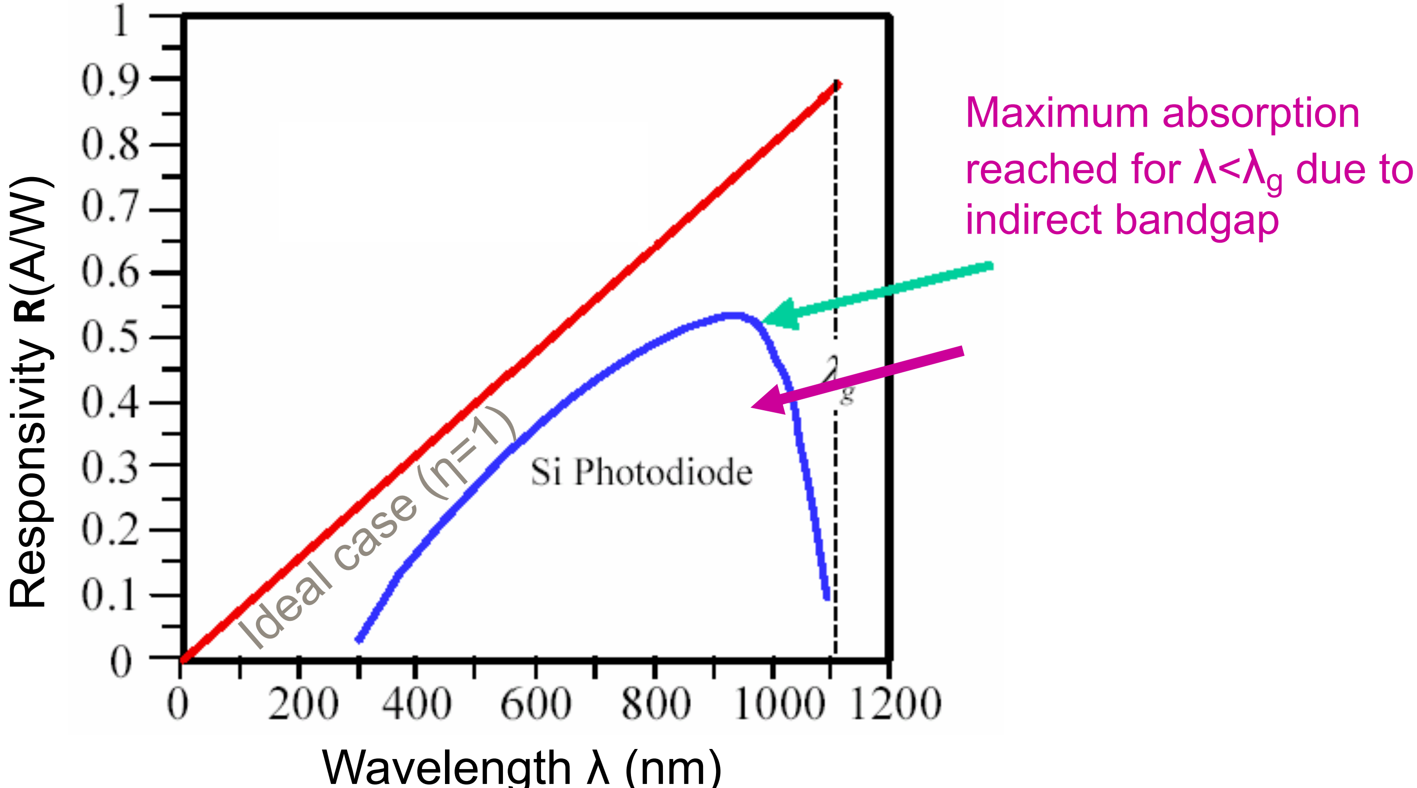


The bandedge absorption coefficient can be enhanced by using strained quantum well materials in the i-region. Excitation through an etched hole reduces the active area of the diode.

PIN photodetector: responsivity

$$R = \frac{I_{ph}}{P_{inc}} = \frac{\eta q}{h\nu} = \frac{\eta\lambda}{1.24} \quad \text{(A/W)}$$

Like the quantum efficiency η, the **responsivity** is a common figure of merit expressing the efficiency of a junction photodetector.



PIN photodetector: noise

Thermal noise (=Johnson noise)

$$\overline{i_J}^2 = \frac{4k_B TB}{R_{eq}}$$

Bandwidth

Resistance of the diode circuit

Shot noise (=generation-recombination noise)

$$\overline{i_S}^2 = 2q\left(I_{ph} + I_B + I_D\right)B$$

Signal-to-noise ratio:

$$SNR = \frac{i_{ph}^2}{\left\langle i_N^2(t)\right\rangle} = \frac{\frac{1}{2}\left(\frac{q\eta P_{inc}}{h\nu}\right)^2}{2q\left(I_{ph} + I_D + I_B\right)B + \frac{4k_B TB}{R_{eq}}}$$

PIN detector: noise and sensitivity

For most of PIN photodetectors the dark current is very small and the shot noise is small compared to that in photoconductors. The Johnson noise dominates:

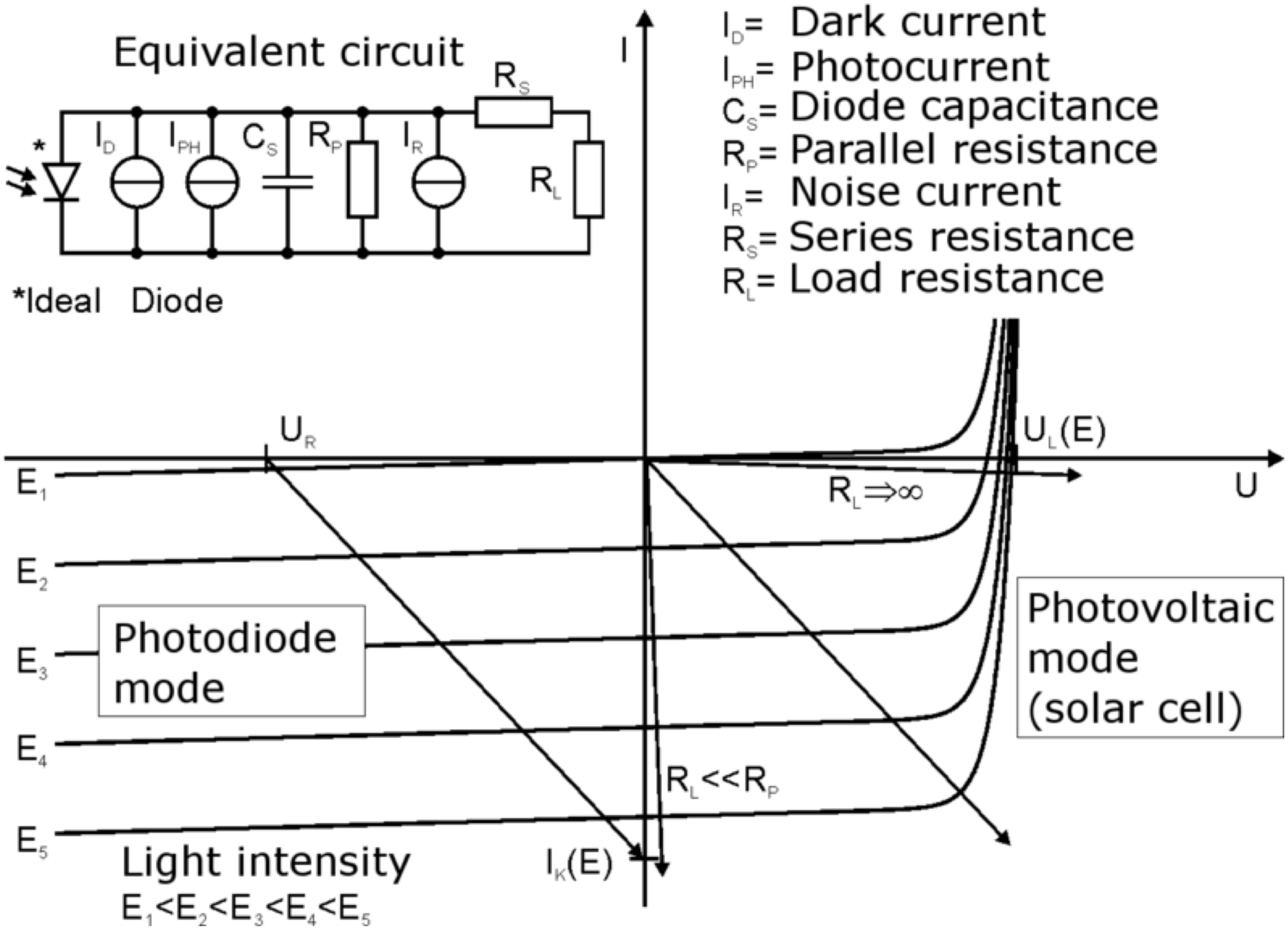
$$\overline{i_J}^2 >> \overline{i_S}^2$$

The minimum detectable power (NEP):

$$NEP = \frac{h\nu}{q\eta}\left[2q\left(I_{ph} + I_D + I_B\right) + \frac{4kT}{R_{eq}}\right]^{1/2} \qquad (\text{W.Hz}^{-1/2})$$

To improve the sensitivity of the PIN detector η and R_{eq} should be as large as possible, and the unwanted currents I_B and I_D as small as possible.

I-V characteristics and circuit model



I-V characteristics of a photodiode. The linear load lines represent the response of the external circuit: I=(Applied bias voltage-Diode voltage)/Total resistance. The points of intersection with the curves represent the actual current and voltage for a given bias, resistance and illumination.