Semiconductor photon detectors

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Dr. Francesco Quochi

Fundamentals of Photonics
B.A. Saleh, M.C. Teich
1991, John Wiley & Sons, Inc.

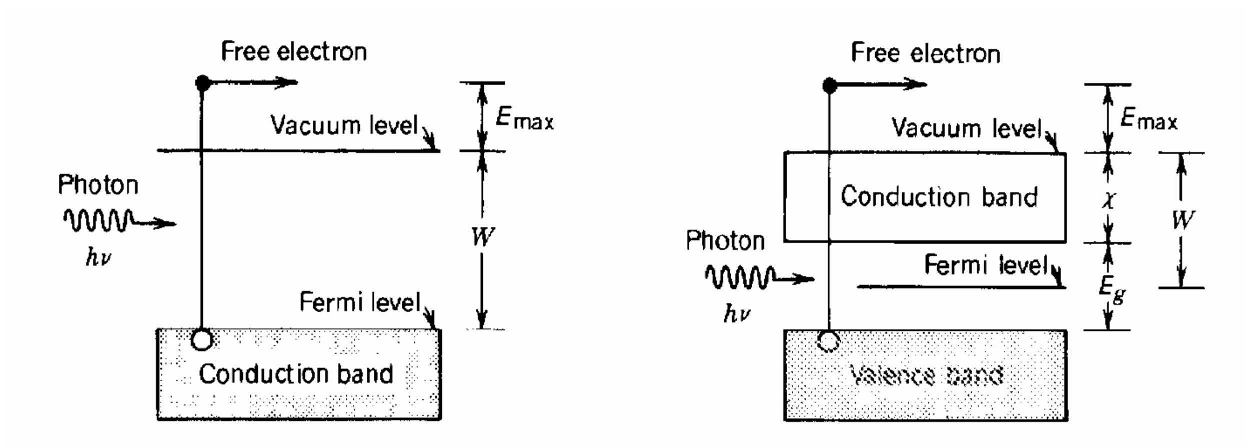
Classes of photodetectors

Thermal detectors: photon energy converted into heat

Photoelectric detectors: photon energy converted into mobile charge carries to yield electric current

External photoeffect: photoelectric emission

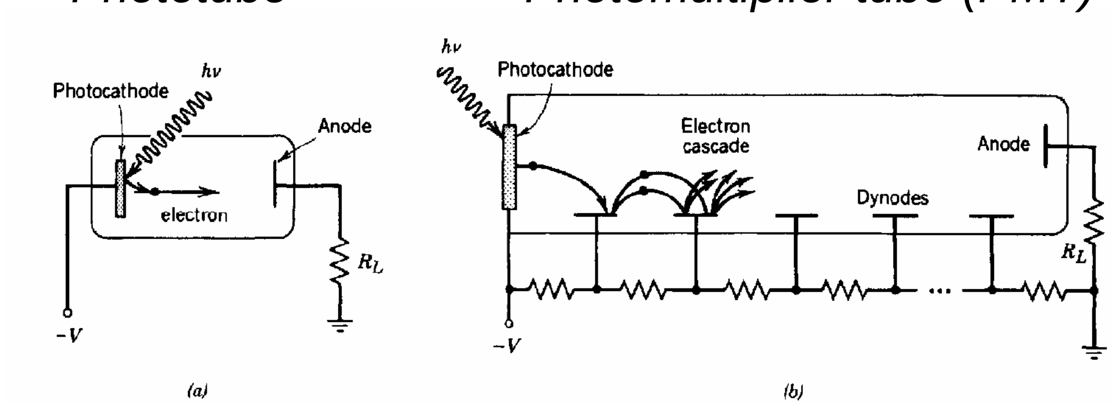
(a) (b)



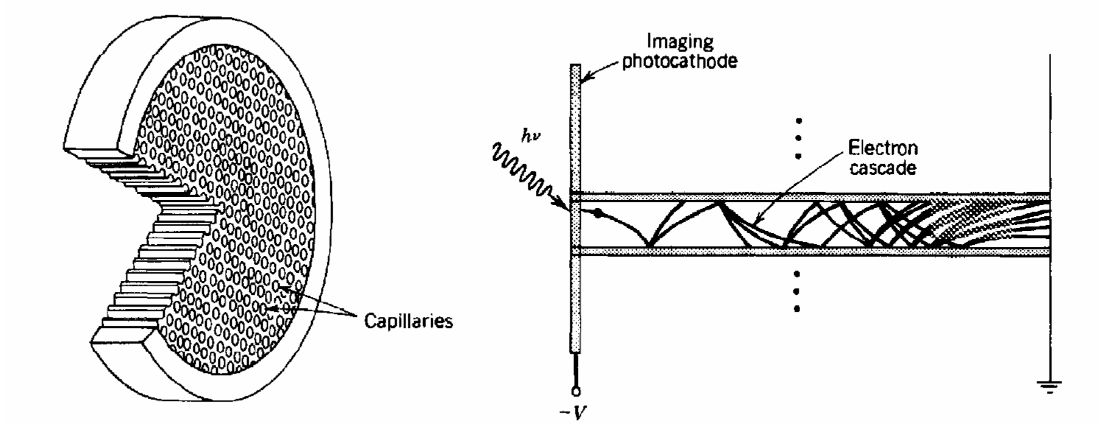
Photoelectric emission from (a) a metal and (b) a semiconductor

Photodetectors based on photoelectric emission

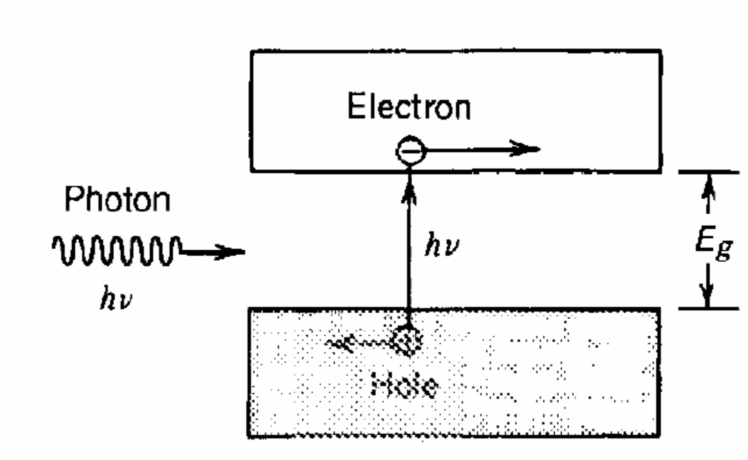
Phototube *Photomultiplier tube (PMT)*



Microchannel plate



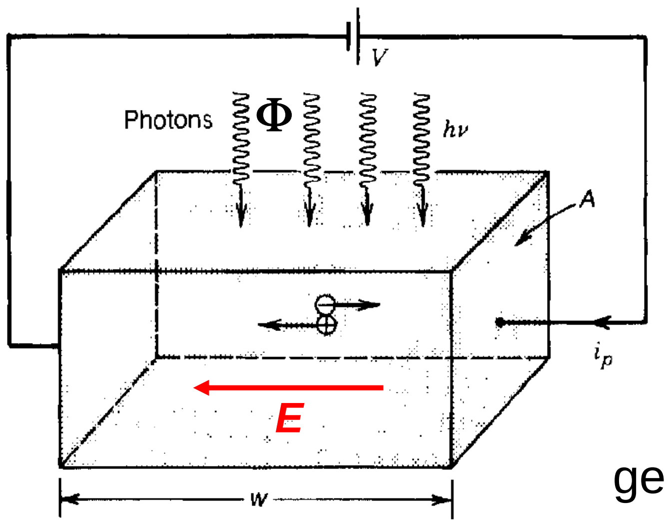
Internal photoeffect: photoconductivity



electron-hole photogeneration in a semiconductor

Photoconductor detectors

biased photoconductor detector



$V = A \cdot w$

Φ = photon flux (photons/s)

i_p = photocurrent (A)

$v_{e(h)} = \mu_{e(h)} E$ drift velocity

$\tau_{e(h)} = \frac{w}{v_{e(h)}}$ transit time

generation and recombination rate (per unit volume)

$$R_{gen} = \frac{Abs \cdot \Phi}{A \cdot w} \qquad R_{rec} = \frac{n_{e\text{-}h}}{\tau_{rec}}$$

$$R_{gen} = R_{rec} \implies i_p \approx \xi \cdot e \cdot Abs \cdot \Phi$$

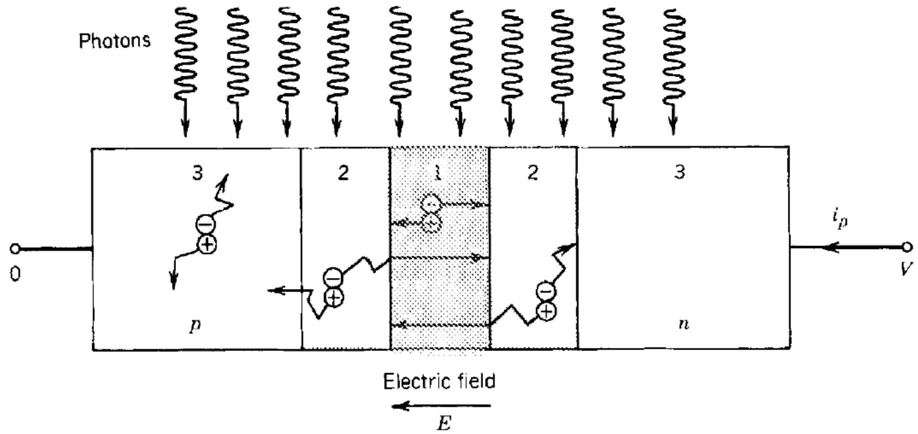
$(v_h \ll v_e)$

$$\xi = \frac{\tau_{rec}}{\tau_e}$$

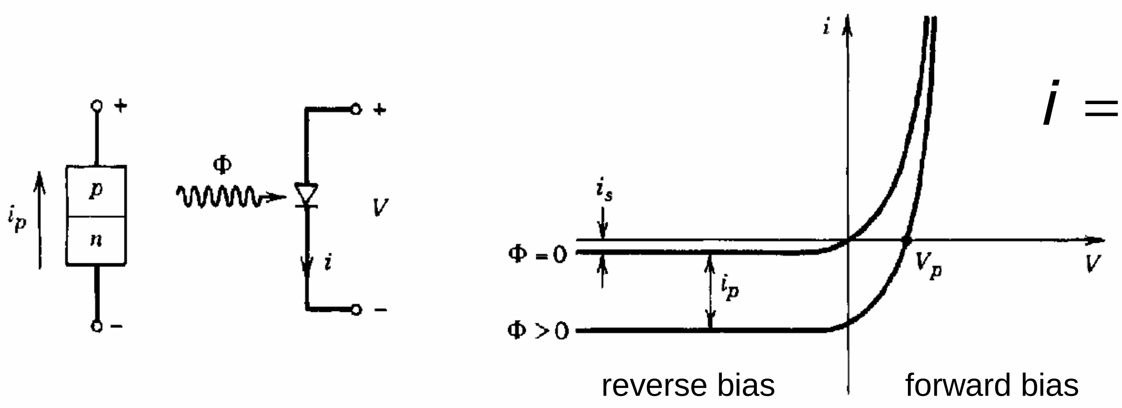
photoconductive gain

Photodiodes

Electron-hole pair generation in a p-n photodiode



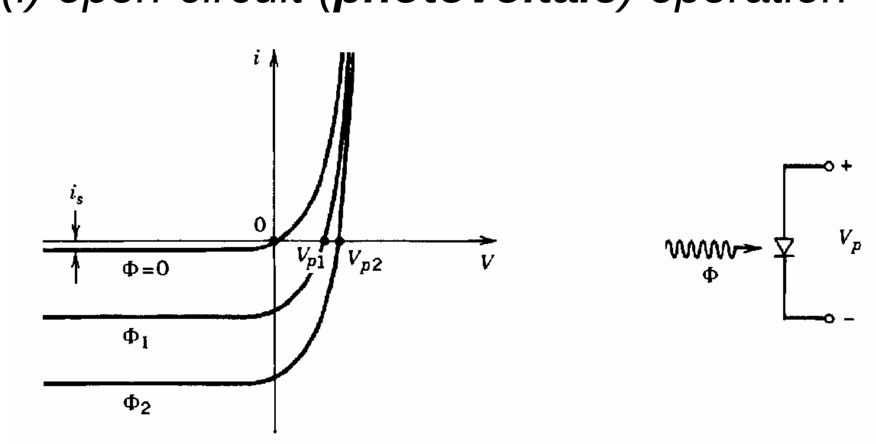
i-V characteristics



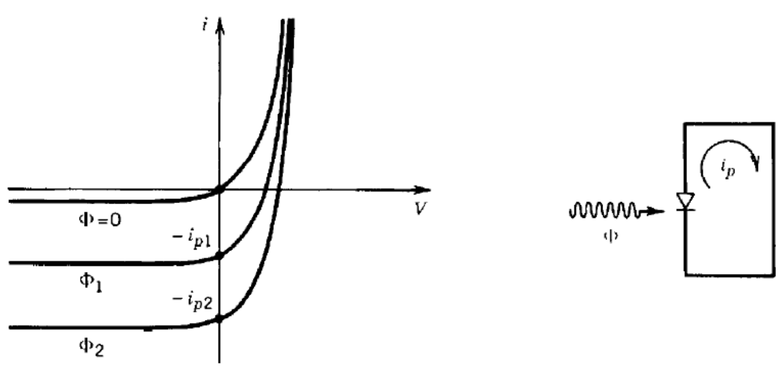
$$i = i_s \cdot \left[\exp\left(\frac{eV}{k_B T} \right) - 1 \right] - i_p$$

Operation of a *p-n* photodiode

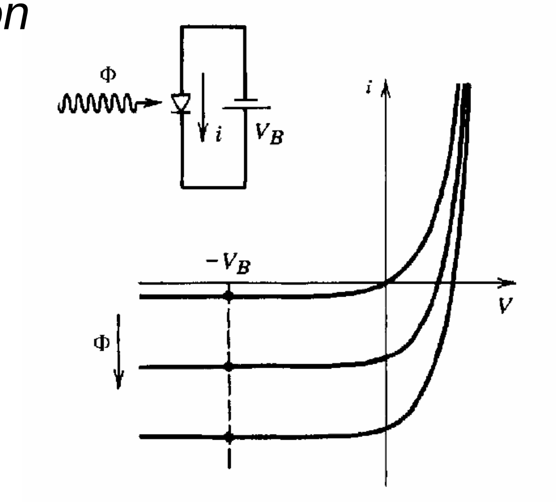
*(i) open-circuit (**photovoltaic**) operation*



(ii) short-circuit operation

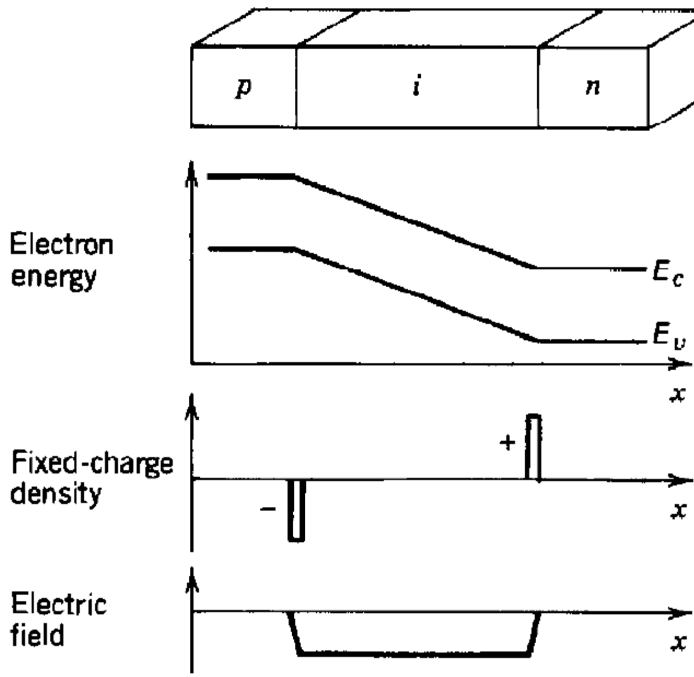


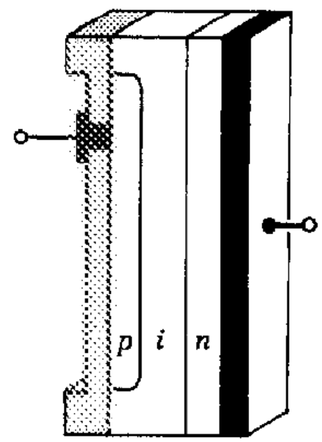
*(iii) reverse-bias (**photoconductive**) operation*



The *p-i-n* photodiode

Intrinsic (lightly doped) layer sandwitched between the *n* and *p* layers

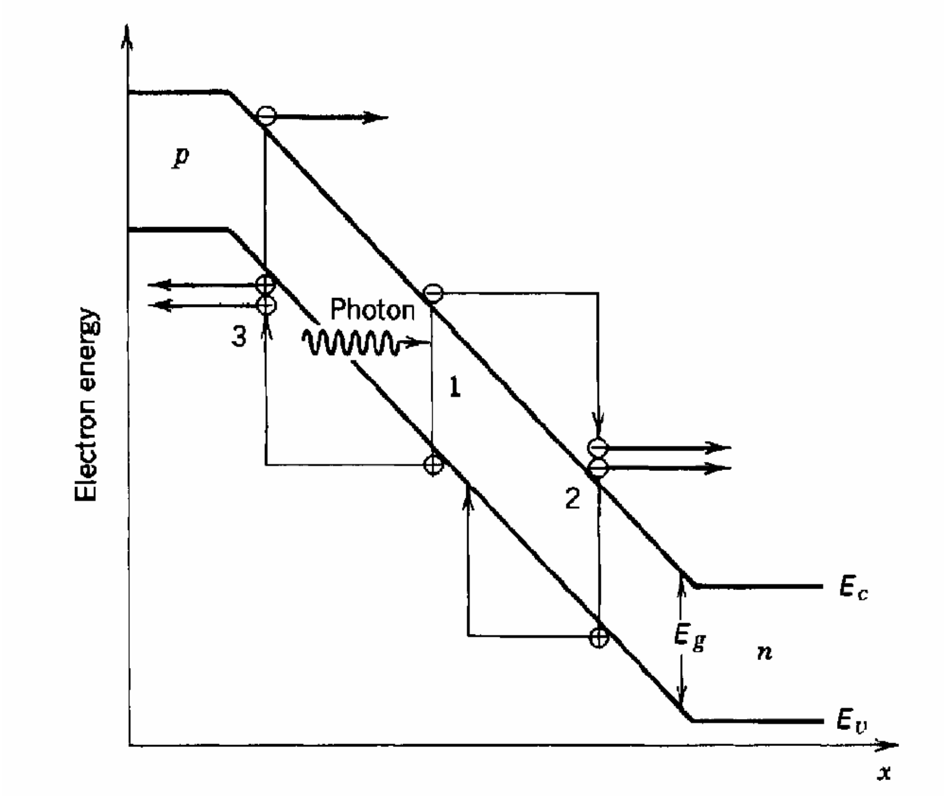




Heterostructure devices: AlGaAs/GaAs, InGaAs/InP, HgCdTe/CdTe …

The avalanche photodiode

An avalanche photodiode (APD) converts each detected photon into a cascade of moving carrier pairs by *impact ionization*



Properties of semiconductor photodetectors

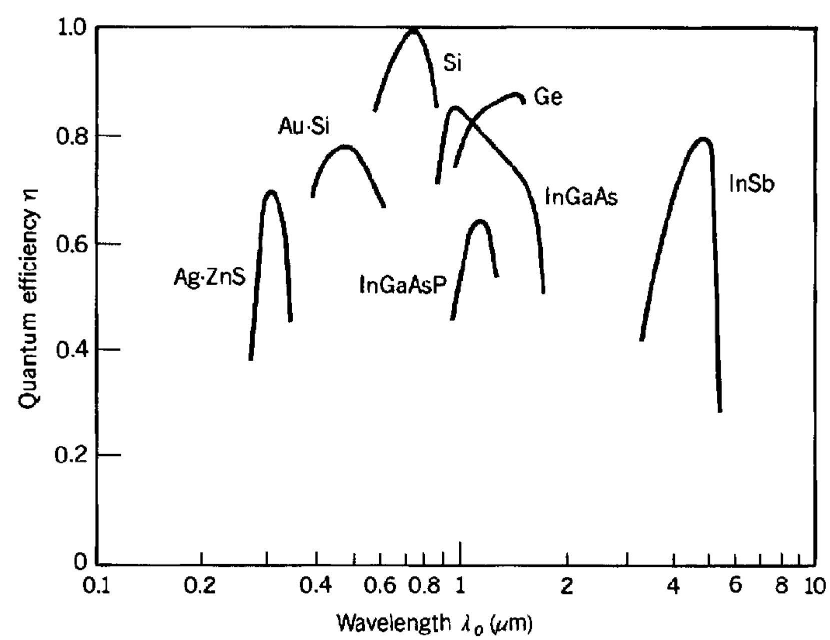
- Quantum efficiency
- Responsivity
- Gain
- Response time

Quantum efficiency

Probability that a single photon incident on the device generates a photocarrier pair that contribute to the detector current

$$\eta = \xi\left[1 - \exp(-\alpha d)\right](1 - R) = \xi \cdot Abs$$

quantum efficiency vs. wavelength
for photodiodes based on various materials



R = optical reflectance at the surface

α = absorption coefficient of the material

d = photodetector depth

ξ = e-h fraction contributing to the detector current

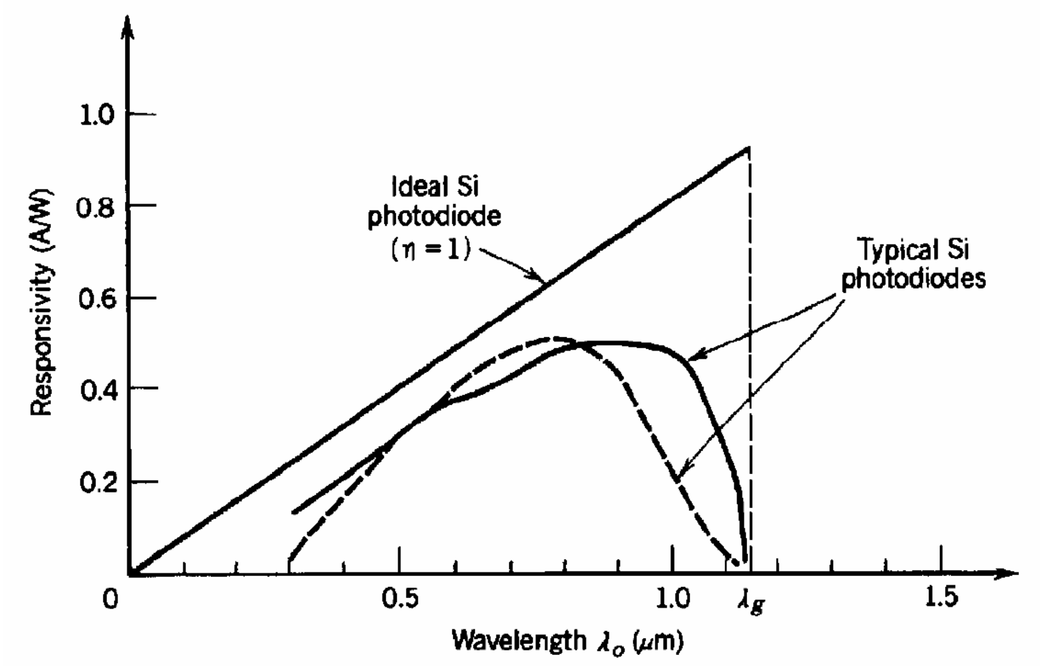
Responsivity

Relates the electric current (i_p) flowing in the device to the incident optical power (P)

$$i_p = \eta \frac{eP}{h\nu} = \Re P \quad \Longrightarrow \quad \Re = \eta \frac{e}{h\nu} = \eta \frac{e\lambda_0}{hc} \quad \left(\frac{\text{A}}{\text{W}}\right)$$

P = incident optical power

$h\nu$ = photon energy

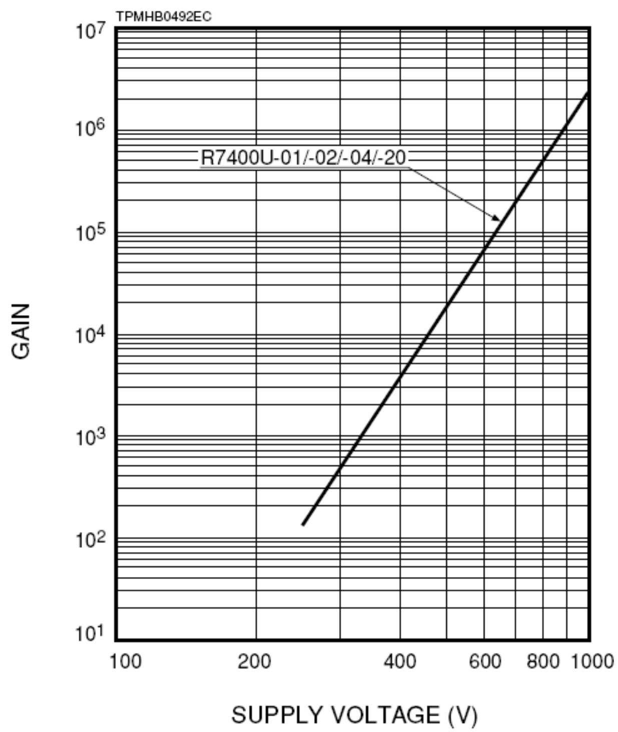


Device with gain

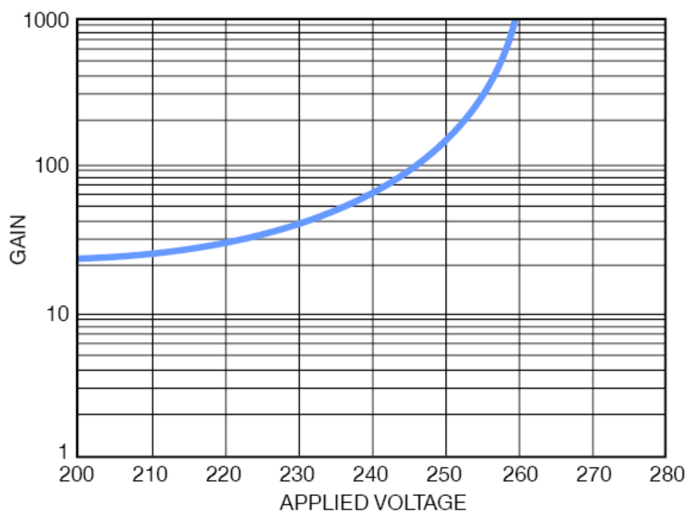
Each carrier pair produces in the external circuit a current pulse of charge *q >e:*

$$G = \frac{q}{e} \quad \Longrightarrow \quad \Re = G\eta \frac{e\lambda_0}{hc}$$

PMT   (G: $10^2 \div 10^8$)



APD   (G: 1÷1000)

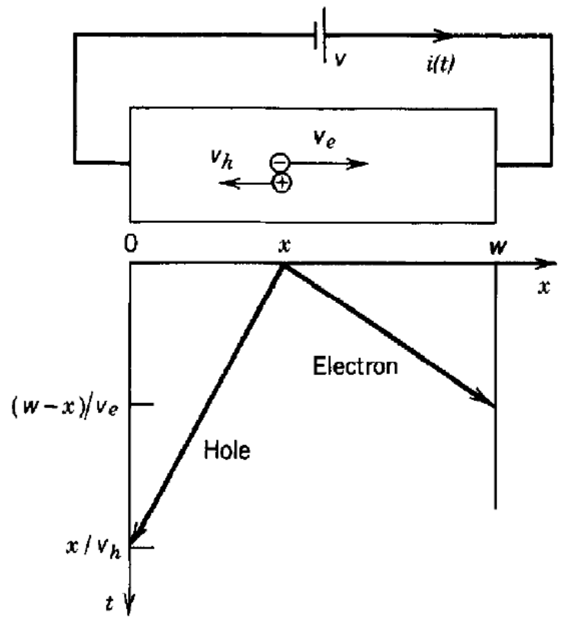


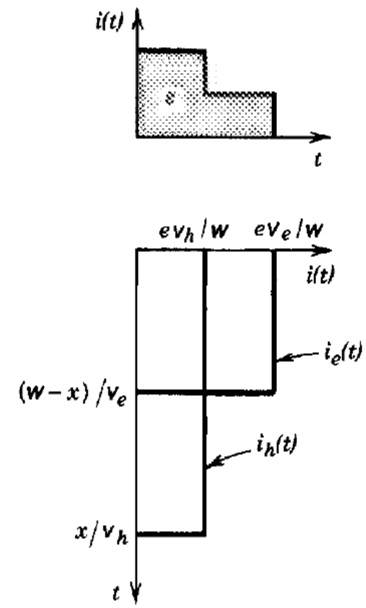
Response time

Charge delivered to the external circuit by carrier motion occupies an extended time

$$t_{e(h)} = \frac{w}{v_{e(h)}}$$

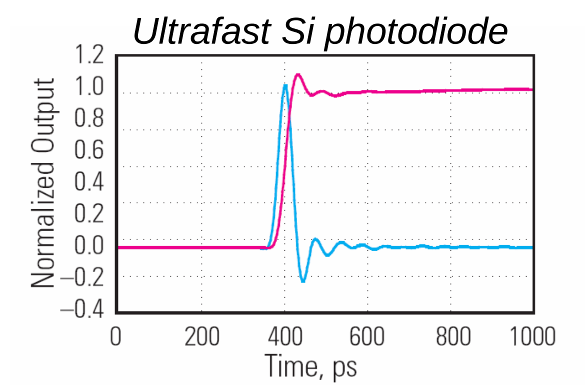
transit time





Impulse-response function determined by convolving $i(t)$ with time-constant spread function $f(t)$:

$$f(t) = \frac{1}{RC}\exp\left(-\frac{t}{RC}\right)$$



Noise in photodetectors

Photocurrent randomly fluctuates above and below its average:

$$i_{\mathrm{p}} = \Re P \qquad i_{\mathrm{p}} = \overline{i_{\mathrm{p}}} + \delta i_{\mathrm{p}} \qquad \sigma_{\mathrm{p}}^2 = \left\langle \delta i_{\mathrm{p}}^2 \right\rangle = \sum_k \sigma_k^2$$

Several noise sources:

- *Photocurrent noise.* Reflects photon-counting statistics
- *Gain noise.* Induced by randomness of the gain process
- *Receiver circuit noise.* Various components of the photodetector, such as resistors and transistors, give rise to fluctuations of the electric current

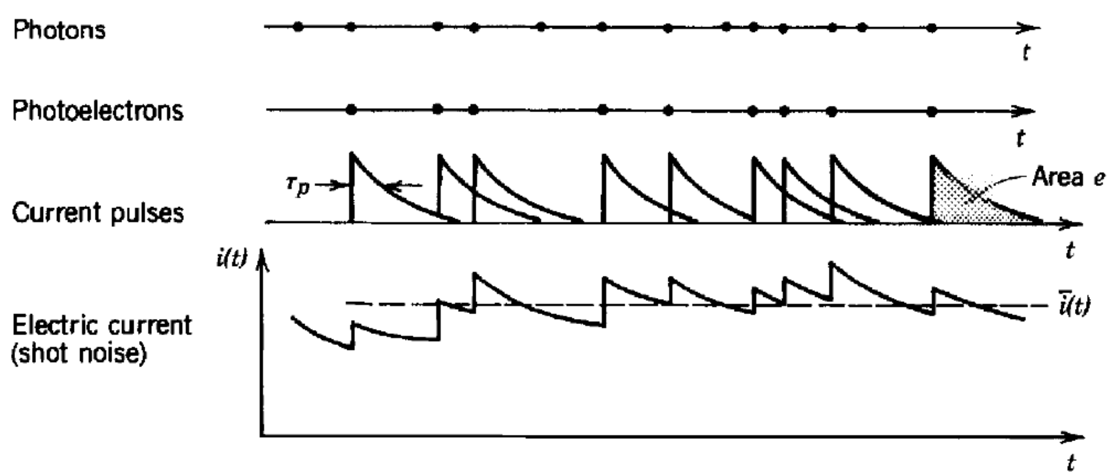
Photocurrent noise

Number of photoelectrons collected in time interval *T*

$$\bar{m} = \eta\Phi T = \frac{\eta\Phi}{2B} \qquad T = \frac{1}{2B}$$ (*B* = detection bandwidth)

Photoelectron noise (reflecting Poisson distribution for random counting)

$$\sigma_m^2 = \bar{m}$$



Photocurrent

$$\bar{i}_p = \frac{e}{T}\bar{m} = \eta e\Phi$$

Photocurrent noise

$$\sigma_p^2 = \frac{e^2}{T^2}\sigma_m^2 = 2e\bar{i}B$$

Dark current noise $\sigma_i^2 = 2e\,\bar{i}_d\,B$

Gain noise

Randomness of gain

$$G = \bar{G} + \delta G \qquad \sigma_G^2 = \left\langle \delta G^2 \right\rangle$$

Photocurrent mean and variance

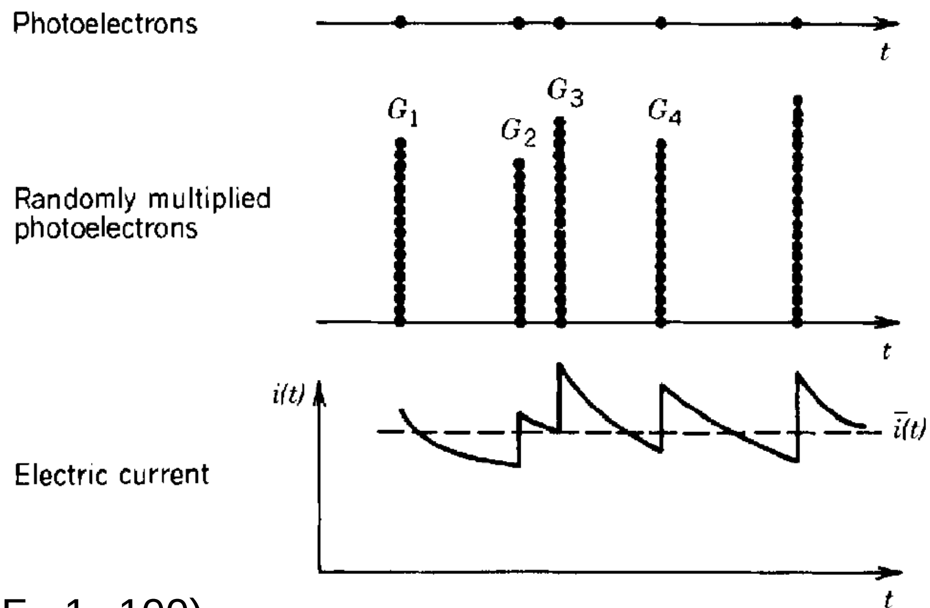
$$\overline{i_\mathrm{p}} = e\bar{G}\eta\Phi$$

$$\sigma_\mathrm{p}^2 = 2e\,\overline{Gi}\,BF$$

Excess noise factor

$$F = \frac{\left\langle G^2 \right\rangle}{\left\langle G \right\rangle^2} = 1 - \frac{\sigma_G^2}{\left\langle G \right\rangle^2}$$

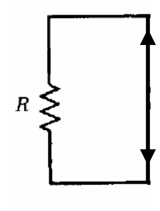
(APDs: F ~1–100)



Circuit noise: thermal noise

Thermal noise (or *Johnson noise*) arises from random motion of mobile carriers in resistive electrical materials at finite temperatures

Random electric current i(t) in the absence of an external power source



$$\langle i(t) \rangle = 0$$

Power spectral density of thermal noise

$$S_{\mathrm{th}}(f) = \frac{4}{R} \frac{hf}{\exp\left(\dfrac{hf}{k_{\mathrm{B}}T}\right) - 1}$$

$$S_{\mathrm{th}}(f) \approx \frac{4k_{\mathrm{B}}T}{R}$$

for $f \ll k_{\mathrm{B}}T / h = 6.25\,\mathrm{THz}$ (300K)

Noise variance

$$\sigma_i^2 = \int_0^B S_{\mathrm{th}}(f)df \approx \frac{4k_{\mathrm{B}}T}{R} B$$

Signal-to-noise ratio

Signal-to-noise ratio (SNR)

$$SNR = \frac{i_p^2}{\sigma_i^2} = \frac{i_p^2}{\sigma_p^2 + \sigma_r^2}$$

$$i_p = e\bar{G}\eta\Phi$$ *photocurrent mean*

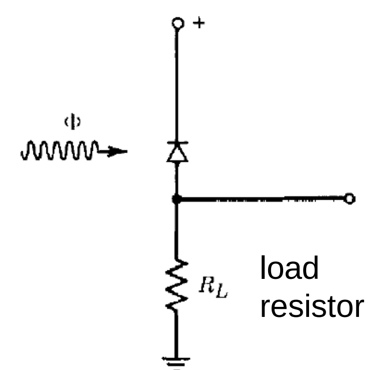
$$\sigma_p^2 = 2e\,\overline{Gi_p}\,FB$$ *photocurrent variance*

Receiver noise

$$\sigma_r^2 = \left[2e\,\overline{Gi_d}\,F + \frac{4k_B T}{R_L}\right]B + \int_0^B S_{add}(f)df$$

dark current noise + thermal noise + additional noise sources

Resistance-limited receiver



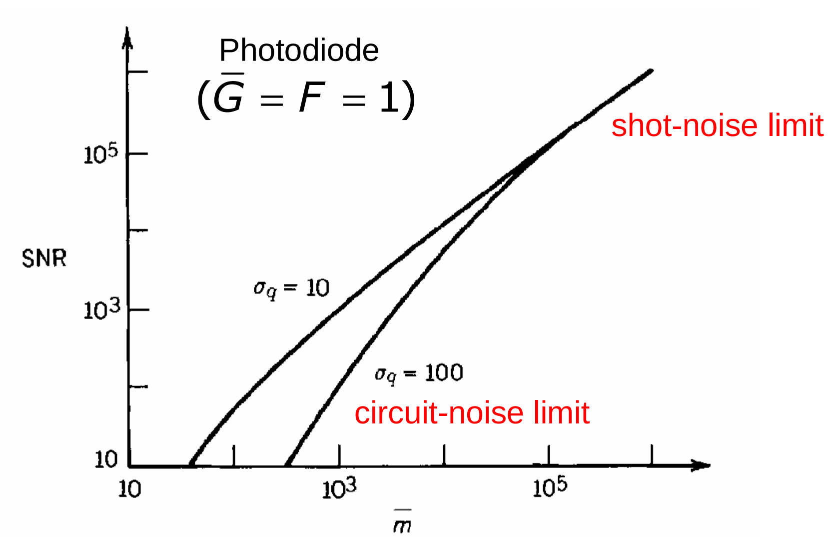
Signal-to-noise ratio

$$\bar{m} = \frac{\eta\Phi}{2B}$$

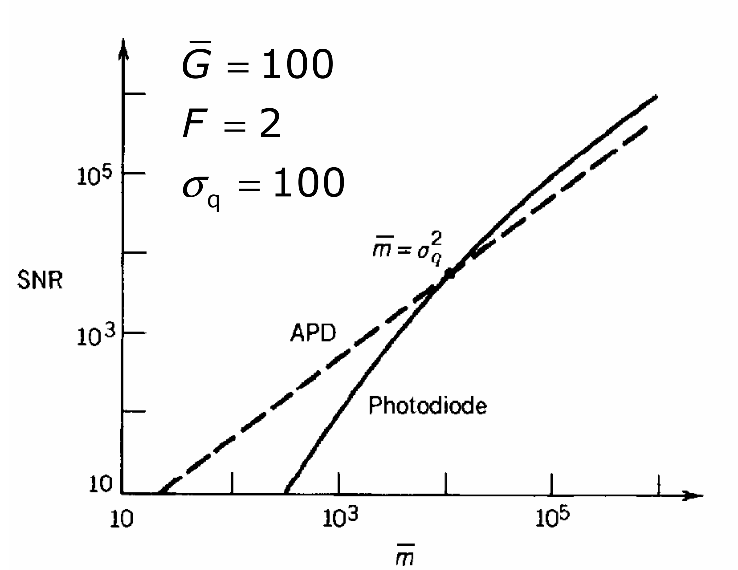
$$\sigma_q = \frac{\sigma_r}{2eB}$$

$$\Longrightarrow \quad SNR = \frac{\bar{G}^2 \bar{m}^2}{\bar{G}^2 F\,\bar{m} + \sigma_q^2}$$

SNR degradation with increasing receiver noise



Effect of gain on SNR



Noise-equivalent power NEP

Noise-equivalent power (NEP): incident optical power that produces a signal-to-noise of unity per square-root bandwidth at a given operating wavelength (λ_0) and modulation frequency (*f*)

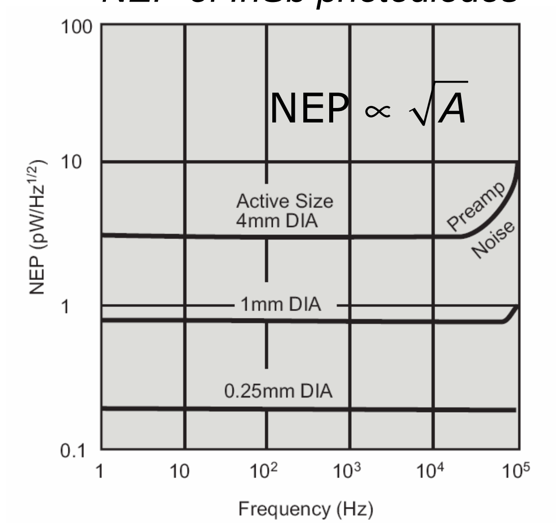
$$i_{\mathrm{p,rms}}(f) = \sigma_{\mathrm{r}}(f, B)$$

$$\Re(\lambda_0) \cdot P_{\mathrm{eq,rms}}(\lambda_0, f) = \sqrt{\int_{f-B/2}^{f+B/2} S(f')\,df'}$$

$$\mathrm{NEP}(\lambda_0, f) = \frac{P_{\mathrm{eq,rms}}(\lambda_0, f)}{\sqrt{B}} = \frac{\sqrt{\bar{S}(f)}}{\Re(\lambda_0)} \quad \left(\frac{\mathrm{W}}{\sqrt{\mathrm{Hz}}}\right)$$

resistance-limited receiver:

$$\bar{S}(f) = S = 2e\,\overline{Gi_{\mathrm{d}}}\,F + \frac{4k_{\mathrm{B}}T}{R_{\mathrm{L}}}$$



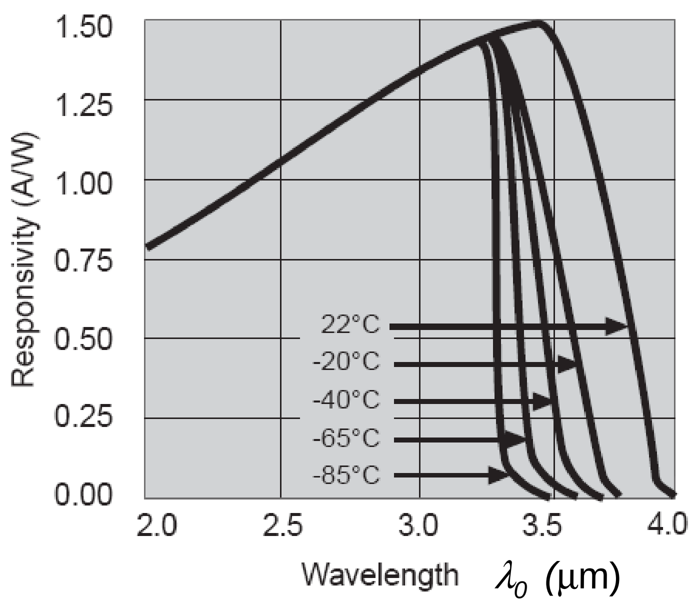
NEP of InSb photodiodes

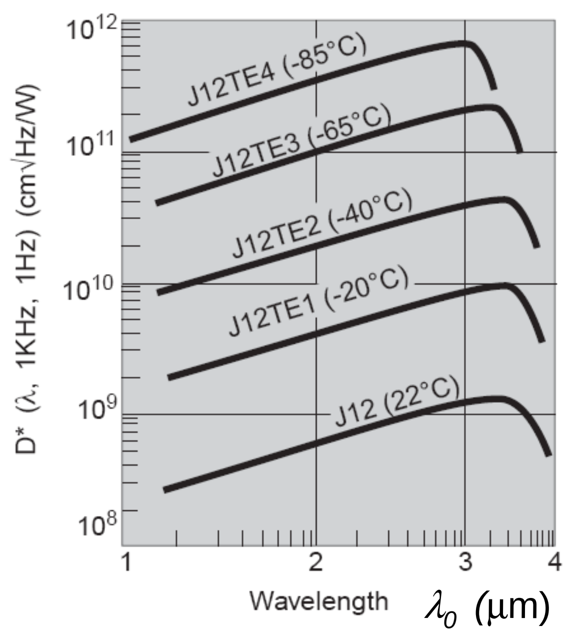
Detectivity D^*

Detectivity (D^*): reciprocal NEP per square-root area

$$D^* = \frac{\sqrt{A}}{NEP} = \Re(\lambda_0)\sqrt{\frac{A}{\bar{S}(f)}} \qquad \left(\frac{\mathrm{cm}\sqrt{\mathrm{Hz}}}{\mathrm{W}} = Jones\right)$$

Responsivity and detectivity of InAs photodiodes





Exercises

1. Consider three photodetectors in series with a 50-Ω load resistor that are to be used in detecting a 1-μm wavelength optical signal with a bandwidth B = 1 GHz bandwidth at 77K (liquid nitrogen temperature):

(i) a *p-i-n* photodiode with quantum efficiency $\eta = 0.9$;

(ii) an avalanche photodiode (APD) with quantum efficiency $\eta = 0.6$, mean gain $G = 100$ and excess noise factor $F = 2$;

(iii) a 10-stage photomultiplier tube (PMT) with quantum efficiency $\eta = 0.3$, overall mean gain $G = 4^{10}$ and overall variance $\sigma_G^2 = G^2/4$.

a) For each detector, find the photocurrent signal-to-noise ratio when the detector is illuminated by a photon flux $\Phi = 10^{10}\ s^{-1}$.

b) By which devices is the signal detectable?

2. Give an estimate for *NEP* and *D** of a InGaAs photomultipier detecting 1.55 μm radiation, with the following parameters:
   - Cathode quantum efficiency $\eta = 8\times10^{-3}$
   - Cathode area $A = 3\times8\ mm^2$
   - Gain $G = 1\times10^6$
   - Anode dark current I_d = 40 nA