3.46 PHOTONIC MATERIALS AND DEVICES

Lecture 16: Detectors—Part 1

Lecture

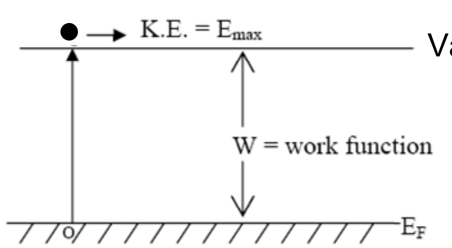
Semiconductor Photon Detectors

Photodetector ≡ transducer
P_{input}(optical) $\rightarrow$ I_{output}(current)

Attributes

- efficient
- low noise
- uniform spectral response
- high speed
- linear
- small, integrated, reliable, low cost

1) Photodetectors
   a) Human eye: 10^8 dynamic range
      Retina:
      edge: 1.2×10^9 rod shaped cells
      (low light levels)
      center: 6×10^6 cone shaped cells
      (high light levels, color)
      (3 sets: red, green, blue)
      Cell diameter $\approx 2.5\ \mu$m
   b) External photoemitters:
      A class of photodetectors called photoemissive in which electrons are emitted into a vacuum or gas.



$$E_{max} = h\nu - W(\text{metal})$$

$$E_{max} = h\nu - \left(E_g + \chi\right)\left(\text{semiconductor}\right)$$

$$\chi = \text{electron affinity}$$
$$= E_{vaccuum} - E_{CB}$$

Notes

Supplemental reading:
1. Fundamentals of photonics ch. 17
2. Burle – Electro-Optics Handbook §10 can be downloaded for free from: www.burle.com/cgi-bin/byteserver.pl/pdf/Electro_Optics.pdf

Lecture

Photoemissive "surfaces"

metals → visible $\eta_i \approx 10\%$

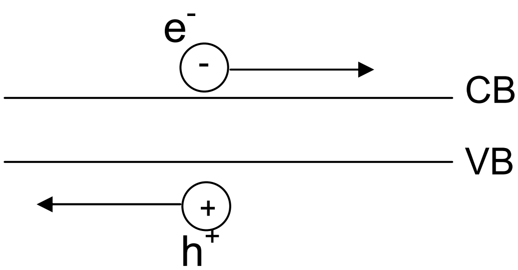
semiconductors → IR $\eta_i \approx 0.1\%$

Photomultipliers

- A series of dynodes yields secondary electrons ($M \approx 10^6$) by field acceleration of photoelectron

$$I = \frac{\Delta Q}{\Delta \tau} = \frac{\phi \cdot A \cdot t \cdot \eta_i \cdot gain \cdot e}{RC} = 10^{-8}\, A/\text{photon}$$

c) Internal photoemitters:



- generation
- transport
- multiplication ?

1) Quantum efficiency

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

Charge collection efficiency

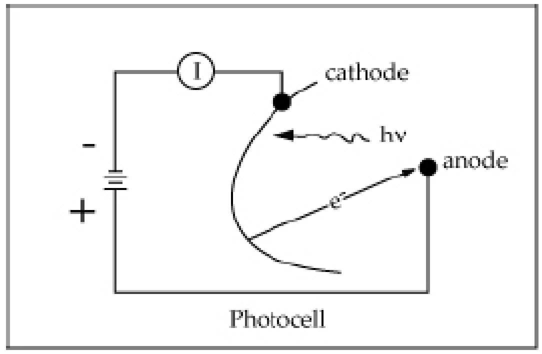
Fraction of photons absorbed in active region

2) Responsivity

$$R = \frac{\eta e}{h\nu} = \eta \cdot \frac{\lambda}{1.24} A/W$$

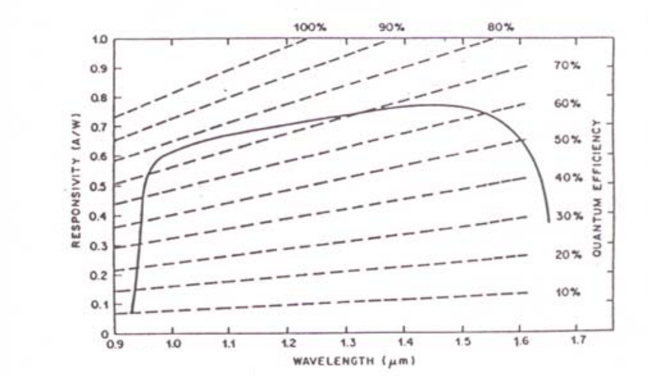
varies linearly with η, λ

Notes



Lecture

Notes



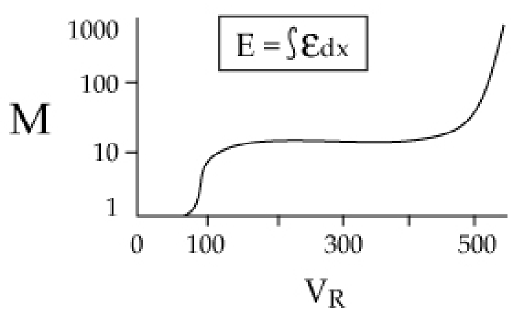
R cutoffs:

long λ: $\lambda_g = \frac{E_g}{hc}$

short λ: surface recombination

3) Gain

$$\text{gain} = \frac{\#\ \text{charges}}{\#\ \text{photoelectrons}} = \frac{Q}{e} = \frac{Q}{\phi}$$



4) Response Time

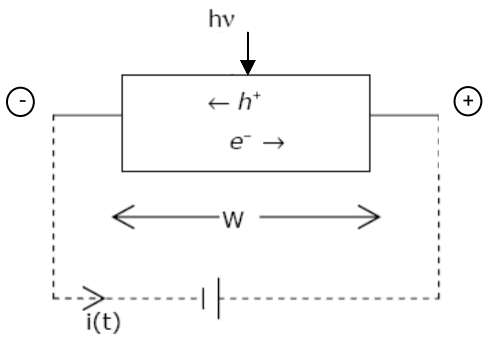
Transit time (τ_{tr}) $\equiv$ time for photocarriers to reach electrodes

Ramo's theorem:

$$i(t) = -\frac{Q}{W} v(t)$$

Lecture

Notes



drift velocity: $\vec{v}_d = \mu\vec{E}$

[↑ same justification ↓]

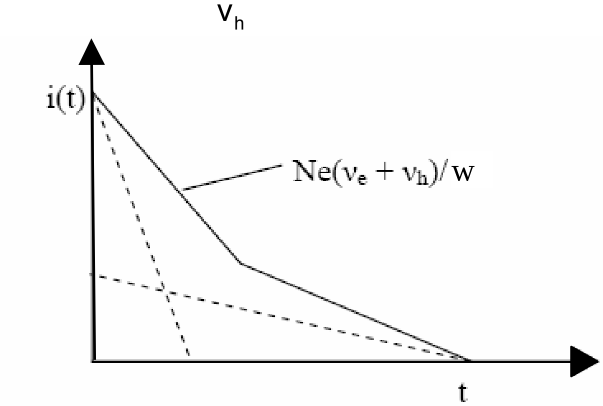
electric field: $\vec{E} = V/w$

⇒ since each carrier moves <w/2>, the effective charge moving in the external circuit is e not 2e.

a. usually $v_h < v_e$

- transit time spread
- τ_{tr} determined by slowest carrier

$$\Rightarrow \Delta t \approx \frac{w}{v_h}$$



b. $\tau_{RC} = R \cdot C$ of detector circuit

- heavy doping (R ↓, C ↑)
- small device area (C ↓)

c. w collection length

$w_{junction} << w_{photoconductor}$

Lecture

Notes

5) Photoconductor

$$\Delta\sigma = e\Delta n(\mu_e + \mu_h)$$
$$= e\eta\tau\frac{\Phi}{w \cdot A}(\mu_e + \mu_h)$$

$$i_p \approx e\eta\frac{\tau}{\tau_{tr}}\Phi \qquad \tau_{tr} \approx \frac{w}{v_e}$$

$$v_h \ll v_e$$

$\tau =$ recombination lifetime

$\frac{\tau}{\tau_{tr}} =$ fraction of e^- collected

$en\Phi =$ generation rate/unit volume

Typical values

w = 1 mm $\Leftarrow$ slow

$v_e = 10^7$ cm/s

$\tau_{tr} \geq 10^{-8}$ s

If $\tau \ll \tau_{tr}$, $\tau =$ response time

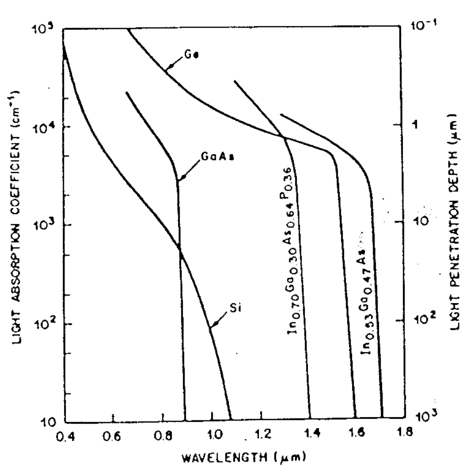
$\therefore$ fast $\equiv$ low R

6) Photodiodes

PIN: positive-intrinsic-negative

APD: avalanche photodiode

$\lambda = 1.3\ \mu$m or $\lambda = 1.5\ \mu$m



Lecture

Notes

InP substrate

InGaAsP $\lambda = 1.3\ \mu\text{m}$

InGaAs $\lambda = 1.55\ \mu\text{m}$

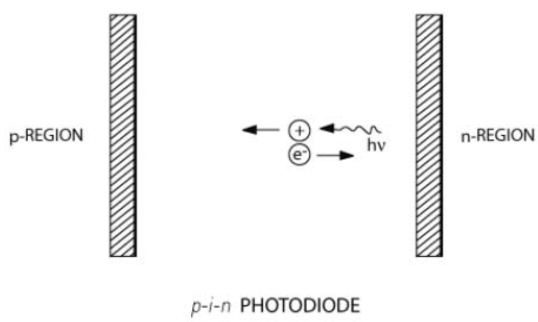
would like to have high α/β

α = ionization multiplication rate for e^-

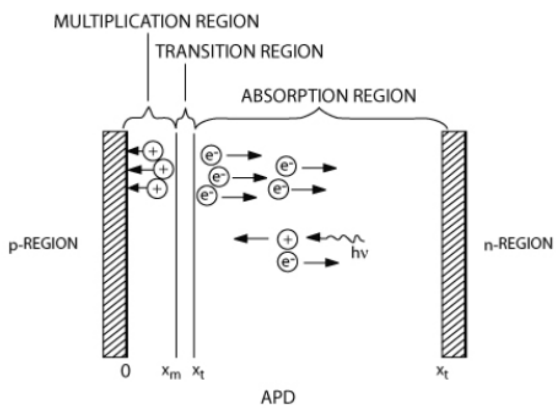
β = ionization multiplication rate for $\hbar^+$

Bulk GaAs $\Rightarrow \frac{\alpha}{\beta} = 2$

50 layer GaAs/AlGaAs $\Rightarrow \frac{\alpha}{\beta} = 8$



(a)



(b)

PIN

- easy to fabricate
- shot noise (thermal leakage)

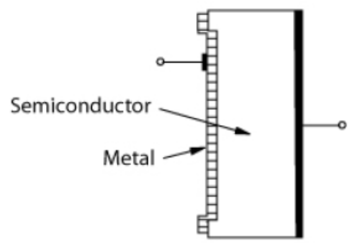
Lecture

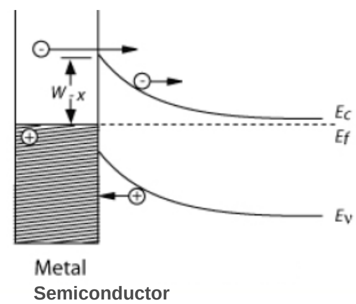
Notes

APD

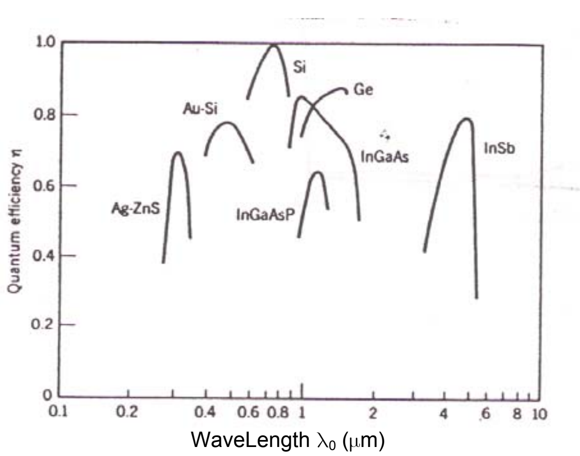
- high gain bandwidth product
- heavily doped n-InP for M
- gain noise (M statistics)

7) Schottky Barries Photodiode





8) Relative performance



3.46 PHOTONIC MATERIALS AND DEVICES

Lecture 16: Detectors—Part 1

Lecture

9) Materials for IR detectors

NIR	SWIR (Short Wave)	MIR (Mid IR)	FIR (Far or long wave IR)
0.6-1.1 μm	1.1-2.5 μm	3-5 μm	8-12 μm
Si, Ge	PbS, InGaAs (0.9-1.7 μm), Ge (0.7-1.85 μm)	InSb, HgCdT	Ge

*wavelength range is practical detector values from various manufacturers