Photodetector Basics

Photodetection: Absorption => Current Generation

Materials for photodetection: $E_g < h\nu$
Various methods for generating currents with photo-generated carriers:
photoconductors, photodiodes, avalanche photodiodes
Photodetector Basics

- Sharp decrease in $\alpha$ for $\lambda > E_g$
- Photodetection for indirect bandgap materials?
Photodetector Basics

- Photodetection for indirect bandgap materials?

(a) GaAs (Direct bandgap)

(b) Si (Indirect bandgap)
Photodetection efficiency

\[ R \text{ (Responsivity)} = \frac{I}{P} \]

\[ \eta \text{ (Quantum Efficiency)} = \frac{I}{q} \frac{P}{h\nu} \]

\[ R = \eta \cdot \frac{q}{h\nu} = \eta \cdot \frac{\lambda[\mu m]}{1.24} \]

Responsive (A/W)

![Graph showing responsivity as a function of wavelength for an ideal photodiode and a Si photodiode.](image)
**Photodetector Basics**

Without light,

Conductivity: \( \sigma = q\mu_e n + q\mu_h p \)

\((\mu_{e,h} : \text{electron, hole mobility})\)

\[ J = \sigma E \quad \text{and} \quad I = wd\sigma \frac{V}{L} \]

With light,

\[ n = n_0 + \Delta n, \quad p = p_0 + \Delta p \]

\[ \sigma + \Delta\sigma = q\mu_e (n + \Delta n) + q\mu_h (p_0 + \Delta p) \]

\[ \Delta I = wd \cdot \Delta\sigma \cdot \frac{V}{L} = wd \cdot (q\mu_e \Delta n + q\mu_h \Delta p) \cdot \frac{V}{L} \]
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With light,

\[ \Delta I = wd\Delta \sigma \frac{V}{L} = wd\left(q\mu_e\Delta n + q\mu_h\Delta p\right)\frac{V}{L} \]

Since \( \Delta n = \Delta p = \eta_{\text{int}} \cdot \frac{P}{h\nu} \cdot \frac{\tau}{wLd} \) and assuming \( \Delta n, \Delta p \) are uniform,

\[ \Delta I = wd\Delta \sigma \frac{V}{L} = wd \cdot q\left(\mu_e + \mu_h\right) \cdot \tau \cdot \frac{\eta_{\text{int}} \cdot \frac{P}{h\nu} \cdot \tau \cdot V}{L} \]

\[ \therefore R = \frac{\Delta I}{P} \text{ (assuming dark current is small)} = \frac{q}{h\nu} \left(\mu_e + \mu_h\right) \cdot \eta_{\text{int}} \cdot \frac{\tau}{L^2} \]

\[ \eta = \left(\mu_e + \mu_h\right) \cdot \frac{\eta_{\text{int}} \cdot \tau}{L^2} = G \cdot \eta_{\text{int}} \]
Gain: \( G = (\mu_e + \mu_h) \cdot \frac{\tau}{L^2} \cdot V \)

Assuming \( \mu_e \gg \mu_h \), \( G = \mu_e \cdot \frac{\tau}{L^2} \cdot V = \frac{\tau}{L^2/\mu_e \cdot V} = \frac{\tau}{\tau_e} \)

\( \tau_e = \frac{L}{\mu_e \cdot \frac{V}{E}} = \frac{L}{\mu_e \cdot \frac{V}{v}} \); time for travelling distance L

\( \tau \gg \tau_e \Rightarrow \) electrons circulate many time before recombination
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Photoconductors:
- Very easy to make
- Large gain
- But slow (speed limited by $\tau$)
  and significant dark currents
Photodetector Basics

photodiode

Faster, dark-current-free photodetectors?

PN junction in reverse bias

- No significant current flow => small dark currents
- Photo-generated carriers are removed by built-in field in depletion region (space charge region)
Photo-detector Basics

Photo-generated carriers drift into P (holes) and N (electrons) regions creating currents.

\[ I = \eta_{\text{int}} \frac{P}{h\nu} q \]

One photon creates electron and hole

Problem: depletion region is very thin (< 1 μm)

\[ \Rightarrow \eta_{\text{int}} \text{ is very small.} \]

\[ \Rightarrow \text{Use PIN structure} \]
Photodetector Basics

PIN Photodiode
Photodetector Basics

CMOS Image Sensor

Special Topics in Optical Comm.: Si Photonics (11/1)
Photodetector Basics

MSM (Metal–Semiconductor Metal) PD

Carrier collection by lateral E–field provided by Schottky contacts

⇒ Not very efficient but can be very fast
Avalanche Photodiode (APD): PIN PD + Gain
(avalanche: a large mass of snow, ice, earth, rock, or other material in swift motion down a mountainside)

Achieve gain by multiplying electrons and/or holes.

Impact Ionization: Under high E-field, electrons and holes can have sufficiently high kinetic energies breaking bonds and creating new e–h pairs.
Photodetector Basics

In real APD, care is taken so that only one type of carrier (either electron or hole) causes impact ionization.

APD has limited application for optical communication since high-performance EDFA is easily available.

→ APD is very useful for optical interconnect applications.