Optical Communications: Detection
- Holes and electrons generated in the depletion region
- Optical Beam induced current

Zero Bias

Reverse Bias
Photodiodes and wavelength

• Si photodiodes: 0.8–0.9 μm (up to 1.1 μm maximum)
• Ge photodiodes: 1.1-1.6 μm..........but large dark currents
• So........Ill-V alloys: tailor the bandgap to suit absorption wavelength eg. InGaAs lattice matched to InP, useful up to 1.7 μm
Absorption

• Absorption coefficient, $\alpha$, depends on $\lambda$

• $I_p = P_0 e^{(1-r)(1-\exp(-\alpha d))}/hf$

• $r$: Fresnel reflection coefficient at the air/semiconductor interface

• $d$: width of the absorption region
Responsivity, R

- $r_e = \eta \cdot r_p = \eta \frac{P_0}{(hf)}$

- $I_p = e \cdot r_e = \eta \frac{P_0 \cdot e}{(hf)}$

- $R = \frac{I_p}{P_0} = \eta \frac{e}{(hf)} = \eta \frac{e\lambda}{(hc)}$

- Note that $\eta$ depends on the wavelength and is zero below the band-edge
Long Wavelength Cut-off

For absorption \( hf = \frac{hc}{\lambda} \geq E_g \)

Threshold for detection: long wavelength cut-off point, \( \lambda_c = \frac{hc}{E_g} \)
Example

• A photodiode has a quantum efficiency of 65% when photons of energy \(1.5 \times 10^{-19}\) are incident on it.

• (a) At what wavelength is the photodiode operating?

• (b) Calculate the incident optical power required to obtain a photocurrent of 2.5 \(\mu\)A
Example

• (a) $E = \frac{hc}{\lambda}$ hence $\lambda = 1.32 \mu m$

• (b) $R = \frac{\eta e}{(hf)} = 0.694 \text{ A/W}$
• $R = \frac{I_p}{P_0}$
• $P_0 = \frac{2.5 \times 10^{-6}}{0.694} = 3.6 \mu W$
Figure 8.2 Optical absorption curves for some common semiconductor photodiode materials (silicon, germanium, gallium arsenide, indium gallium arsenide and indium gallium arsenide phosphide).
<table>
<thead>
<tr>
<th>Material</th>
<th>Indirect (eV)</th>
<th>Direct (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.14</td>
<td>4.10</td>
</tr>
<tr>
<td>Ge</td>
<td>0.67</td>
<td>0.81</td>
</tr>
<tr>
<td>GaAs</td>
<td></td>
<td>1.43</td>
</tr>
<tr>
<td>InAs</td>
<td></td>
<td>0.35</td>
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<tr>
<td>InP</td>
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<td>1.35</td>
</tr>
<tr>
<td>GaSb</td>
<td></td>
<td>0.73</td>
</tr>
<tr>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>In$<em>{0.5}$Ga$</em>{0.5}$As</td>
<td></td>
<td>1.15</td>
</tr>
<tr>
<td>GaAs$<em>{0.69}$Sb$</em>{0.12}$</td>
<td></td>
<td>1.15</td>
</tr>
</tbody>
</table>
Semiconductor Photodiode Without Internal Gain

Depletion Region

Diffusion Region
Semiconductor photodiode without internal gain

• In depletion region: Carrier pairs separate and drift under influence of E field.
• In diffusion region: Diffusion until carriers are collected.
• Diffusion slow compared to drift
• Limits speed of the device.
• So......try to assure photons are absorbed in the depletion region
To achieve longer wavelength operation when light penetrates the semiconductor more deeply, we want a wider depletion region. For a pin photodiode, get most absorption in the depletion region.

**PIN PHOTODIODE**
FRONT ILLUMINATED SILICON PIN PHOTODIODE

Standard operation at approx. 0.9 micron
Depletion width: 20-50 micron
Dark current: due to surface leakage currents and generation/recombination currents in the depletion region
Large absorption width (approx. 500 micron)
Very sensitive to wavelengths close to the bandgap limit (approx. 1.09 micron for Si) where absorption is small

**SIDE-ILLUMINATED PIN PHOTODIORDE**
Other detection materials...

• Ge photodiodes: high dark currents

• III-V: eg. InGaAs/InP
  – Detects up to 1.67 micron
  – Epitaxial growth on InP substrate
  – Light absorbed in InGaAs
Semiconductor photodiode with internal gain, Avalanche Photodiode

APD: more efficient structure than pin structure to create an extremely high electric field region ($3 \times 10^5$ V/cm)
APD

• In the high field region electrons and holes can acquire sufficient energy to excite new electron-hole pairs i.e. impact ionisation
• Need high reverse voltages ed. 15-25V
• Get carrier multiplication up to $10^4$ times using defect-free materials.
Response Time

- Need full depletion in the absorption region to avoid the slower process of diffusion.
- Response time:
  - (a) Transit time of carriers across the absorption region (depletion width)
  - (b) Time taken by carriers to perform the avalanche process.
  - (c) RC time constant due to the junction capacitance.
Benefits & Disadvantages of Avalanche Photodiodes

• +
  • + Useful to detect very low light levels used in optical communications
  • + Often give wider dynamic range
• –
  • More difficult to fabricate
  • Random nature of gain: added noise
  • High bias voltage
  • Need temperature stabilisation
Noise

• Overall sensitivity of a photodiode results from random fluctuations in I and V at device output terminals both with & without an optical signal.

• To reduce dark current:
  • Use high-quality, defect free materials
  • Careful fabrication: Reduces surface currents
Noise

• But....
• Still have a **Quantum Detection Process**
• - Statistical Nature
• - Average detector current exhibits a fluctuation about a mean value
• **Noise:** \((I_s^2)^{1/2} = (2eB\bar{I})^{1/2}\)
  
  \(I_s\): rms value of this shot noise current  
  \(B\): photodiode received bandwidth  
  \(\bar{I}\): average photocurrent
Shot Noise

\[ i_{\text{rms shot}} = (2eB|I|)^{1/2} \]
Johnson Noise

• Due to thermal agitation of charge carriers in a conducting medium
• Random nature => fluctuating voltage appears across the medium
• The rms value of this voltage across a resistor, R, at temp, T, having frequency components between f and f+Δf is:
  \[ \Delta V_f = (4kTRΔf)^{1/2} \]
• In practice Johnson noise is often smaller than Shot noise
To assess the noise performance

- Noise equivalent Power (NEP)
- NEP = incident optical power (at a particular wavelength) to produce a photodetector current equal to the r.m.s. noise within a unit bandwidth.
- $I_p = \text{photocurrent} = e r_e = \eta P_0 e/(hf)$
- $P_0 = I_p hf / (\eta e) = I_p hc / (\eta e \lambda)$
NEP

• [Put Ip = rms shot noise current]
• Ip = \((2eB_i)^{1/2}\)
• Where \(I_\text{=} = Ip + Id = \) photodiode average current
• If we put rms shot noise current equal to the photocurrent to get an expression for NEP
• \(I_e. \) Set Ip to approximately equal \((2eB \ I_p )^{1/2}\)
NEP

• $I_p^2 = 2eB I_p$
• $I_p = 2eB$
• Now NEP is the power, $P_0$, when $I_p = 2eB$ and when $B=1$Hz
• Since $P_0 = I_p \frac{hc}{(\eta e \lambda)}$ then
• $\text{NEP} = \frac{2hc}{(\eta \lambda)}$
• For an ideal detector, $\eta = 1$ and $\text{NEP} = \frac{2hc}{\lambda}$
• Above true when photocurrent dominates ie. $I_p$ much greater than $I_d$
If dark current dominates...

• ie. Ip much less than Id
• Then Ip = (2eB Id)^{1/2}
• So if dark current dominates, using B=1Hz
• NEP = P_0 = (2e Id)^{1/2}hc / (\eta e \lambda)
DETECTIVITY

- DETECTIVITY, $D = \frac{1}{NEP}$
Fundamental limitations on signal size

Consider a digitally coded optical signal:
For a low photon arrival rate... statistics are important
Say the average power transmitted corresponds to approximately 20 photons/pulse:
Pulses arrive at the detector with mostly 17 to 24 photons, but some pulses will contain zero or one photons......Poisson statistics
Poisson statistics

• The probability of detecting n photons/s when the mean arrival rate is $n_m$ is:
• $P(n,n_m) = (n_m)^n \exp(-n_m)/n!$
• What is the probability a pulse will contain zero photons when $n_m = 20$?
• $P(0,20) = (20)^0 \exp(-20)/0! = 2 \times 10^{-9}$
So if we have a signal with equal numbers of ones and zeros where:

- “one”: pulse with an average of 20 photons
- “zero”: pulse with zero photons

The probability of a “one” being mistaken for a ‘zero’ is: \( P(0, 20) = 2 \times 10^{-9} \)

ie. A signal containing an average of 10 photons has a BIT ERROR RATE (BER) = \( \text{approx } 10^{-9} \)
BER and frequency

• The average number of photons emitted in time $\tau$: $P \tau /hf$
• The av. number of detected photons in $\tau$: $\eta P \tau /hf = n_m$
• So .......... $n_m$ is proportional to $\tau$
• So .......... $n_m$ is proportional to $1/f$
• As $f$ increases, $n_m$ decreases, $\exp (-n_m)$increases and BER increases
Receiver sensitivity comparison

Receiver Sensitivity Comparison of pin PD and APD devices at

\[ \text{BER} = (0.9) \]

Bit error rate (using Si detectors at 0.82 μm)

\[ M = \frac{I}{I_p} \]

M: total output current where we get carrier multiplication

Ip: initial or primary photocurrent before carrier multiplication
Minimum power for analog transmission

• For digital transmission $BER =_{\text{approx}} 10^{-9}$
• The corresponding quantity in analog transmission is: $S/N = 50\text{dB}$
• The limiting factor on $S/N$ will be Shot noise
• $(S/N)_{\text{max}} = \frac{i_{\text{sig}}^2}{i_{\text{shot}}^2} = \frac{i_{\text{sig}}^2}{(2ei_{\text{sig}}\Delta f)} = i_{\text{sig}}/(2e\Delta f)$
• $i_{\text{sig}} = \eta Pe / hf = \eta Pe\lambda / hc$
Minimum power for analog transmission

- \( (S/N) = \frac{i_{\text{sig}}}{2e\Delta df} = \eta \frac{P\lambda}{2hc\Delta f} \) equivalent to 50dB
- or... \( 10\log_{10}(S/N) = 50 \)
- \( \log_{10}(S/N) = 5 \)
- \( S/N = 10^5 \)
- \( \eta \frac{P\lambda}{2hc\Delta f} = 10^5 \)
- \( P = 2 \times 10^5 \frac{hc\Delta f}{\eta \lambda} \)
- If \( \lambda = 0.85\mu m, \eta = 1, \Delta f = 6.25\text{MHz}, P_{\text{min}} = 0.3\mu W \)
- (Digital systems better for low-noise, long-distance communications)
Optical transmission systems

• Losses:
  • Laser – fibre coupling loss : 10dB
  • 10 slices (0.5dB x 10) : 5dB
  • Fibre detection coupling loss : 5dB
  • Fibre attenuation (0.3dB/km) : 0.3L
  • Total attenuation: 20+0.3L
Optical transmission systems

• Say receiver sensitivity is -50dBm
• 1 mW corresponds to 0dBm
• So we must keep 20+0.3L less than 50
• ie. 0.3L less than 30
• Keep L below 100km
Power margin

• Say the total attenuation is 41dB
• Then the excess power margin for the last example is 9dB = 50dB-41dB
• An “excess power margin” of 9dB is sufficient for optical link operation