Semiconductor Detectors - Photodetectors

- Principle of the pn junction photodiode
- Absorption coefficient and photodiode materials
- Properties of semiconductor detectors
- The pin photodiodes
- Avalanche photodiodes
- Schottky junction photodetector
Electrons and holes must be separated without energy input !!
pn Junction Photodiode

Short Circuit

Reverse Bias

$I_{ph} = \text{Photocurrent}$
External Quantum Efficiency

\[ R = \frac{\text{Photocurrent (A)}}{\text{Incident Optical Power (W)}} = \frac{I_{\text{ph}}}{P_o} \]

\[ R = \eta_e \frac{e}{h \nu} = \eta_e \frac{e \lambda}{hc} \]
- Larger absorption region (intrinsic region)
- Smaller capacitance lead to faster RC time (50-100 ps)
- Response time is limited by electron travel time in intrinsic region
pin Photodiode Capacitance

\[ E = E_o + \frac{V_r}{W} \approx \frac{V_r}{W} \]

\[ C_{dep} = \frac{\varepsilon_o \varepsilon_r A}{W} \]

\[ t_{drift} = \frac{W}{V_d} \]
Drift velocity vs. electric field for holes and electrons in Si.

**pin Photodiode Response Time**

Drift velocity (m s\(^{-1}\))

\[ V_d = \mu_e/h E \]

Width of \(i\)-region (Depletion region)

Transit time (Drift time)

Drift velocity

\[ t_{\text{drift}} = \frac{W}{V_d} \]
Avalanche Photodiode

Converts incident light to large electric current by impact ionization processes.

- Photons generate electron hole pairs (EHP) in π-region.
- Electrons are drifted to avalanche region.
- Electrons impact ionize Si covalent bonds (secondary carriers).
- Current is amplified with internal gain mechanisms.
- Annular electrode for light to enter.
- Holes could cause excess noise (inefficient impact ionization processes).
Impact of an energetic conduction electron with crystal vibrations transfers the electron's kinetic energy to a valence electron and thereby excites it to the conduction band.

Impact ionization processes causes EHP generation.

EHP are separated resulting avalanche multiplication.
Avalanche Multiplication Factor

\[ M = \frac{\text{Multiplied photocurrent}}{\text{Primary unmultiplied photocurrent}} = \frac{I_{ph}}{I_{pho}} \]

\[ M = \frac{1}{1 - \left(\frac{V_r}{V_{br}}\right)^m} \]

Si APD

-20 °C

60 °C

20 °C
Avalanche Photodiode

Antireflection coating
Guard ring
Avalanche breakdown

Substrate
Electrode

$\pi$

$n^+$
$p$

$p^+$

$\text{SiO}_2$

Electrode
Avalanche Multiplication Factor

\[ dN = N \alpha_e \, dx \]

Ionization coefficient ratio
\[ \alpha_e = A \exp(-B/E) \]

Chyoweth's law

Electrons only
\[ M = \exp(\alpha_e w) \]

Electrons and holes
\[ M = \frac{1 - k}{\exp[-(1 - k)\alpha_e w] - k} \]

Ionization coefficient for holes
\[ k = \frac{\alpha_h}{\alpha_e} \]
- Energy band diagrams for a SAM detector with a step junction between InP and InGaAs. There is a valence band step $\Delta E_v$ from InGaAs to InP that slows hole entry into the InP layer.

- An interposing grading layer (InGaAsP) with an intermediate bandgap breaks $\Delta E_v$ and makes it easier for the hole to pass to the InP layer for a detector with a graded junction between InP and InGaAs. This is the SAGM structure.
Superlattice APD MQW Detectors

Superlattice APD

$E_c$

$E_v$

$E_{g1}$

$E_{g2}$

$\Delta E_c$

$\Delta E_v$

$p^+$

$n^+$

Impact ionization

$E$

$h^+$

$e^-$

$hv$
Typical current and gain ($M$) vs. reverse bias voltage for a commercial InGaAs reach-through APD. $I_d$ and $I_{ph}$ are the dark current and photocurrent respectively. The input optical power is ~100 nW. The gain $M$ is 1 when the diode has attained reach-through and then increases with the applied voltage. (The data extracted selectively from Voxtel Catalog, Voxtel, Beaverton, OR 97006)
EXAMPLE: Silicon APD

A Si APD has a QE of 70 % at 830 nm in the absence of multiplication, that is $M = 1$. The APD is biased to operate with a multiplication of 100. If the incident optical power is 10 nW what is the photocurrent?
EXAMPLE: Silicon APD

A Si APD has a QE of 70 % at 830 nm in the absence of multiplication, that is $M = 1$. The APD is biased to operate with a multiplication of 100. If the incident optical power is 10 nW what is the photocurrent?

Solution

The unmultiplied responsivity is given by,

$$ R = \eta_e \frac{e \lambda}{hc} = (0.70) \frac{(1.6 \times 10^{-19} \text{ C})(830 \times 10^{-9} \text{ m})}{(6.626 \times 10^{-34} \text{ J s})(3 \times 10^8 \text{ m s}^{-1})} = 0.47 \text{ A W}^{-1} $$

The unmultiplied primary photocurrent from the definition of $R$ is

$$ I_{pho} = RP_o = (0.47 \text{ A W}^{-1})(10 \times 10^{-9} \text{ W}) = 4.7 \text{ nA} $$

The multiplied photocurrent is

$$ I_{ph} = MI_{pho} = (100)(4.67 \text{ nA}) = 470 \text{ nA or } 0.47 \text{ \mu A} $$
Schottky Junction

$I-V$ characteristics
pn Junction Diode (FORWARD)

pn junction diode

Shockley equation

$I$ vs. $V$

$V$ vs. $I$
Reverse biased Schottky junction and the dark current due to the injection of electrons from the metal into the semiconductor over the barrier $F_B$. 

$I-V$ characteristics
Schottky Junction

LEFT: Photogeneration in the depletion region and the resulting photocurrent.

RIGHT: The Schottky junction photodetector
Schottky junction based photodetectors and some of their features. $\tau_R$ and $\tau_F$ are the rise and fall times of the output of the photodetector for an optical pulse input. The rise and fall times represent the times required for the output to rise from 10% to 90% of its final steady state value and to fall from 90% to 10% of its value before the optical pulse is turned off.

<table>
<thead>
<tr>
<th>Schottky junction</th>
<th>$\lambda$ range nm</th>
<th>$R_{\text{peak}}$ (at peak) (A/W)</th>
<th>$J_{\text{dark}}$ per mm$^2$</th>
<th>Features with typical values</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAsP</td>
<td>190–680</td>
<td>0.18 (610 nm)</td>
<td>5 pA</td>
<td>UV to red, $\tau_R = 3.5$ µs. (G1126 series$^a$)</td>
</tr>
<tr>
<td>GaP</td>
<td>190–550</td>
<td>0.12 (440 nm)</td>
<td>5 pA</td>
<td>UV to green, $\tau_R = 5$ µs. (G1961$^a$)</td>
</tr>
<tr>
<td>AlGaN</td>
<td>220–375</td>
<td>0.13 (350 nm)</td>
<td>1 pA</td>
<td>Measurement of UV; blind to visible light. (AG38S$^b$)</td>
</tr>
<tr>
<td>GaAs</td>
<td>320–900</td>
<td>0.2 (830 nm)</td>
<td>$\sim$ 1 nA</td>
<td>Wide bandwidth $&gt; 10$ GHz, $\tau_R &lt; 30$ ps. (UPD-30-VSG-P$^c$)</td>
</tr>
<tr>
<td>InGaAs MSM</td>
<td>850–1650</td>
<td>0.4 (1300 nm)</td>
<td>5 µA</td>
<td>Optical high speed measurements, $\tau_R = 80$ ps, $\tau_F = 160$ ps. (G7096$^a$)</td>
</tr>
<tr>
<td>GaAs MSM</td>
<td>450–870</td>
<td>0.3 (850 nm)</td>
<td>0.1 nA</td>
<td>Optical high speed measurements, $\tau_R = 30$ ps, $\tau_F = 30$ ps. (G4176$^a$)</td>
</tr>
</tbody>
</table>
Schottky Junction Photodiodes

LEFT: The metal electrodes are on the surface of the semiconductor crystal (which is grown on a suitable substrate).

RIGHT: The electrodes are configured to be interdigital and on the surface of the crystal.
Schottky Junction Photodiodes