**pn Junction Photodetectors**

Most detectors used in communications are based on the *pn* or *pin* junction is a semiconductor.

A *pn* junction is formed by doping adjacent regions of a semiconductor with excess donor and acceptor atoms, respectively.
**pn Junction Detectors – Quantum Efficiency**

In a reverse-biased photodiode it is desired that the light be absorbed in the depletion region so that carriers can be collected before they recombine.

Power absorbed elsewhere does not contribute to the overall photocurrent.

The quantum efficiency is determined by the amount of power absorbed in the depletion region relative to the total incident power on the detector.
Reflection from the surface reduces the incident power by $R$, leaving $(1 - R)P_o$

The transmitted light must pass through the $p$-region, whose absorption coefficient $\alpha_p$ is essentially identical to the bulk attenuation coefficient for the semiconductor material.

The amount of power reaching the depletion edge is:

$$P\left(w_p\right) = P_o\left(1 - R\right)e^{-\alpha_p w_p}$$

The depletion region will absorb light depleting the power by $\exp[-\alpha_w]$

The fraction of light deposited in the depletion region is $1 - \exp[-\alpha_w]$

The overall quantum efficiency is

$$\eta = \left(1 - R\right)e^{-\alpha_p w_p}\left(1 - e^{-\alpha_w}\right)$$
It is clearly desirable to reduce reflections and absorption in the bulk region.

This can be done by making $w_p$ as thin as possible, making $W$ as wide as possible, and adding an anti-reflection coating (AR coating) to the detector substrate.

Recombination of photo-generated carriers will also reduce the quantum efficiency.

Recombination is increased by defects and impurities which act as recombination centers in the lattice, so these must be minimized.
*pn* Junction Detectors – Quantum Efficiency – Example

Determine the quantum efficiency of a Si photodiode operating at 700 nm with the following parameters:

\[
\alpha_{Si} = 10^4 \text{ cm}^{-1}
\]
\[
n_{Si} = 3.5
\]
\[
\kappa = 11.7
\]
\[
N_d = 10^{18} \text{ atoms cm}^{-3}
\]
\[
N_a = 10^{17} \text{ atoms cm}^{-3}
\]
\[
n_i^2 = 1.96 \times 10^{20} \text{ cm}^{-6} \text{ at } T = 300^\circ K
\]
**pn Junction Detectors – Quantum Efficiency – Example**

Total depletion width:

\[
W = a + b = \sqrt{\frac{2k\varepsilon_o}{q}} (\Phi - V_a) \left[ \sqrt{\frac{N_d}{N_a(N_a + N_d)}} + \sqrt{\frac{N_a}{N_d(N_d + N_a)}} \right]
\]

\[
W = 0.112 \, \mu m
\]

\[
N_a a = N_d b \Rightarrow b = \frac{N_a}{N_d} a \Rightarrow W = a + b = \left( 1 + \frac{N_a}{N_d} \right) a \Rightarrow a = \frac{W}{1 + \frac{N_a}{N_d}}
\]

\[
a = \frac{W}{1 + \frac{10^{17}}{1.1}} = \frac{W}{0.909W} = 0.1018 \, \mu m
\]
pn Junction Detectors – Quantum Efficiency – Example

Power loss due to Fresnel reflection:

\[ R = \left( \frac{n - 1}{n + 1} \right)^2 = \left( \frac{2.5}{4.5} \right)^2 = 0.31 \]

The transmitted light must propagate through \( w_p = 1 - 0.1 = 0.9 \) µm of silicon before reaching the depletion region.

This will have an attenuation of \( \exp[-10^4 \times 0.9 \times 10^{-4}] = 0.4 \)

40% of the light transmitted through the front surface makes it to the depletion region.

Only a fraction of the light is absorbed in the depletion region:
\[ 1 - \exp[-10^4 \times 0.112 \times 10^{-4}] = 0.106; \text{ only 10\% of the light that reaches the depletion region is actually absorbed there.} \]
**pn Junction Detectors – Quantum Efficiency – Example**

The quantum efficient is:

\[
\eta = (1 - R) e^{-\alpha \beta_{\text{p}}} \left(1 - e^{-\alpha w}\right)
\]

\[
= 0.69 \cdot 0.4 \cdot 0.1
\]

\[
= 0.0276
\]

The quantum efficiency for this example is less that 3%

This illustrates a major problem with *pn*-junction photodetectors.

A large reverse bias can widen the depletion region width, but breakover becomes an issue.

The preferred solution is to use a *pin* diode.
**pin Detectors**

The *pin* diode (*p*-intrinsic-*n*) is the most widely used detector in optoelectronic systems.

It is difficult to increase the depletion region of a typical *pn* junction beyond 1 or 2 µm which is what limits the quantum efficiency and the capacitance.

The width of the depletion region can be artificially increased by adding an intrinsic semiconductor between the doped region.
**pin Detectors**

Diagram of a pin detector showing the layers of metal, $p^+$, $n^+$, and SiO$_2$. Arrows indicate the incident light and the intrinsic electric field. © 2012 Henry Zmuda
pin Detectors

http://ecee.colorado.edu/~bart/book/book/chapter4/ch4_7.htm#4_7_1_1
**pin Detectors**

An $n$-doped semiconductor has a layer of intrinsic material grown on the surface followed by a thin epilayer or diffusion of $p$-doped material.

The undoped intrinsic layer is made thick enough to absorb most of the incident radiation, so that most free carriers are generated in this region.

Contact is made to the $p$-region through an annular contact at the surface, and to the $n$-doped substrate through a ground plane.

A thin (1000 Angstrom) layer of SiO$_2$ is sometimes deposited on the surface of the detector to reduce reflections.

Under reverse bias, a strong static field is established across the intrinsic region to rapidly sweep out any photo generated carriers.
Anti-Reflection Coatings – A Single Layer Coating

Incident Light

$n_0$

$n_{film}$

$d_{film}$

$n_{substrate}$

Optical Component

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AR Coatings
Anti-Reflection Coatings – A Single Layer Coating

\[ n_{film} = \sqrt{n_0 n_s} \]

\[ d_{film} = \frac{1}{n_1} \frac{\lambda_o}{4} \]

Incident Light

No reflected wave at \( \lambda_o \)
Anti-Reflection Coatings – A Single Layer Coating

\[ \Gamma(\lambda) = \frac{\left(1 - \frac{n_s}{n_0}\right) \cos\left(\frac{\pi \lambda_o}{2 \lambda}\right) - j \left(\frac{n_1 - n_s}{n_0 n_1}\right) \sin\left(\frac{\pi \lambda_o}{2 \lambda}\right)}{\left(1 + \frac{n_s}{n_0}\right) \cos\left(\frac{\pi \lambda_o}{2 \lambda}\right) + j \left(\frac{n_1 + n_s}{n_0 n_1}\right) \sin\left(\frac{\pi \lambda_o}{2 \lambda}\right)} \]

\[ \left(\left|r_1(\lambda)\right|\right)^2 = 8 \times 10^{-3} \]

- \[ r_1(\lambda = \lambda_o) = 0 \Rightarrow \text{if } n_0 n_s = n_1^2, \quad r_1 = 0 \]
1. If normal incidence in not assumed, the reflection with angle varies as:

\[ r = \frac{\lambda_1 \sqrt{n_0 n_r}}{4 \sqrt{n_0 n_r}} \left( 0, \frac{\pi}{180} \right) \]

\[ r = \frac{\lambda_1 \sqrt{n_0 n_r}}{4 \sqrt{n_0 n_r}} \left( 10, \frac{\pi}{180} \right) \]

\[ r = \frac{\lambda_1 \sqrt{n_0 n_r}}{4 \sqrt{n_0 n_r}} \left( 15, \frac{\pi}{180} \right) \]

\[ r = \frac{\lambda_1 \sqrt{n_0 n_r}}{4 \sqrt{n_0 n_r}} \left( 20, \frac{\pi}{180} \right) \]

2. Note that for non-normal incidence that the reflection minimum does not go to zero or even occur at the central wavelength.
Common Coating Materials

<table>
<thead>
<tr>
<th>Multi-Layer Coating Materials</th>
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<tbody>
<tr>
<td>$n_H$ Materials</td>
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<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Zirconium Dioxide:</td>
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<tr>
<td>Titanium Dioxide:</td>
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<tr>
<td>Zinc Sulfide:</td>
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* Very durable, hence frequently used.
Anti-Reflection Coatings

Generally $d$ is chosen so that the electrical length is a quarter-wave in the yellow-green portion of the spectrum where the eye is most sensitive.

At wavelengths on either side of the central yellow-green region, the reflectivity increases and the coated optical component will appear blue-red in reflected light.

Of the materials just cited, none satisfy the condition for zero reflection for an air-glass interface, but they do substantially reduce reflections (see next slide). The durability of $\text{M}_9\text{F}_2$ makes it a popular material to use.
Anti-Reflection Coatings

Glass-air interface:

\[
\frac{n_s - n_o}{n_s + n_o}
\]

\[
\sqrt{n_o n_s} = 1.225
\]

\[
n_{MgF_2} = 1.38
\]
Anti-Reflection Coatings

Glass-air interface:

THE VISIBLE SPECTRUM • Wavelength in Nanometers

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Anti-Reflection Coatings

Glass-air interface:

\[ n_{\text{air}} = 1.225 \]

\[ n_{\text{MgF}_2} = 1.38 \]

\[ n_{\text{air}} - n_{\text{MgF}_2} = \frac{n_{\text{air}} - n_{\text{MgF}_2}}{n_{\text{air}} + n_{\text{MgF}_2}} \]

\[ \sqrt{n_{\text{air}}n_{\text{MgF}_2}} = 1.225 \]