Diode Sensors

Dr. Lynn Fuller
Dr. Fuller’s Webpage: http://people.rit.edu/lfcee
Microelectronic Engineering
Rochester Institute of Technology
82 Lomb Memorial Drive
Rochester, NY 14623-5604

Email: Lynn.Fuller@rit.edu
Program Webpage: http://www.microe.rit.edu
OUTLINE

Uniform Doped pn Junction
Real pn Junctions
Photodiodes
Light Sources
Diode Temperature Sensors
Solar Cells
Applications:
  Temperature
  Turbidity
  Spectral Radiometer
Diode Sensors

UNIFORMLY DOPED PN JUNCTION

- Phosphorous donor atom and electron
- Ionized Immobile Phosphorous donor atom
- Ionized Immobile Boron acceptor atom
- Boron acceptor atom and hole

\[ p = N_A \rightarrow n = N_D \]

\[ qN_A W_1 = qN_D W_2 \]

Charge density, \( \rho \)

Potential, \( \Psi \)

Electric Field, \( \varepsilon \)

Potential, \( \Psi_0 + V_R \)
From Physical Fundamentals:

Potential Barrier - Carrier Concentration: \( \Psi_0 = \frac{KT}{q} \ln \left( \frac{N_A N_D}{n_i^2} \right) \)

From Electric and Magnetic Fields:

Gauss’s Law, Maxwell’s 1st eqn: \( \rho = \nabla \cdot \mathbf{D} \)

Relationship between electric flux \( \mathbf{D} \) and electric field \( \mathbf{E} \): \( \mathbf{D} = \varepsilon \mathbf{E} \)

Poisson’s Equation: \( \nabla^2 \Psi_0 = -\frac{\rho}{\varepsilon} \)

Definition of Electric Field: \( \mathbf{E} = -\nabla \mathbf{v} \)
[from Physics (Fermi Statistics)]

\[ q(V_{bi}) = (E_i - E_f)p\text{-side} + (E_f - E_i)n\text{-side} \]

\[ p = n_i e^{(E_i - E_f)/kT/q} \quad n = n_i e^{(E_f - E_i)/kT/q} \]

\[ \ln(p/n_i) = \ln e^{(E_i - E_f)/kT/q} \quad \ln(n/n_i) = \ln e^{(E_f - E_i)/kT/q} \]

\[ kT/q \ln(p/n_i) = (E_i - E_f)p\text{-side} \quad kT/q \ln(n/n_i) = (E_f - E_i)n\text{-side} \]

\[ \Psi_0 = kT/q \ln \left( N_A N_D / n_i^2 \right) \]

\[ n_i = 1.45E10 \text{ cm}^{-3} \text{ for silicon} \]

Where \( N_A = \sim p \) in p-type silicon and \( N_D = \sim n \) in n-type silicon
Diode Sensors

**UNIFORMLY DOPED PN JUNCTION**

Built in Voltage:  
\[ \Psi_0 = \frac{KT}{q} \ln \left( \frac{N_A N_D}{n_i^2} \right) \]

\[ n_i = 1.45 \times 10^{10} \text{ cm}^{-3} \]

Width of Space Charge Layer, \( W \): with reverse bias of \( V_R \) volts

\[ W = (W_1 + W_2) = \left[ \frac{2\varepsilon}{q} (\Psi_0 + V_R) \left( \frac{1}{N_A} + \frac{1}{N_D} \right) \right]^{1/2} \]

- \( W_1 \) width on p-side
- \( W_2 \) width on n-side

\[ W_1 = W \left[ \frac{N_D}{(N_A + N_D)} \right] \]

\[ W_2 = W \left[ \frac{N_A}{(N_A + N_D)} \right] \]

Maximum Electric Field:

\[ E_0 = - \left[ \frac{2q}{\varepsilon} (\Psi_0 + V_R) \left( \frac{N_A N_D}{(N_A + N_D)} \right) \right]^{1/2} \]

Junction Capacitance per unit area:

\[ C_j' = \varepsilon_0 \varepsilon_r / W = \varepsilon_0 \varepsilon_r / \left[ \frac{2\varepsilon}{q} (\Psi_0 + V_R) \left( \frac{1}{N_A} + \frac{1}{N_D} \right) \right]^{1/2} \]

\[ \varepsilon = \varepsilon_0 \varepsilon_r = 8.85 \times 10^{-12} \text{ (11.7) F/m} \]

\[ = 8.85 \times 10^{-14} \text{ (11.7) F/cm} \]
**Example**: If the doping concentrations are Na=1E15 and Nd=3E15 cm\(^{-3}\) and the reverse bias voltage is 0, then find the built in voltage, width of the space charge layer, width on the n-side, width on the p-side, electric field maximum and junction capacitance. Repeat for reverse bias of 10, 40, and 100 volts.

\[
\Psi_0 = V_{bi} = \frac{KT}{q} \ln \left( \frac{N_A N_D}{n_i^2} \right) = \\
W = (W_1 + W_2) = \left[ \left( \frac{2\varepsilon}{q} \right) (\Psi_0 + V_R) \left( \frac{1}{N_A} + \frac{1}{N_D} \right) \right]^{1/2} = \\
W_1 = \\
W_2 = \\
E_{max} = \\
C_j =
\]
### Example Calculations

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>ROCHESTER INSTITUTE OF TECHNOLOGY</td>
<td>MICROELECTRONIC ENGINEERING</td>
<td>3/4/2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>CALCULATIONS FOR PN JUNCTION (ELECTROSTATICS)</td>
<td>DR. LYNN FULLER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>26</td>
<td>27</td>
<td>28</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>CONSTANTS</td>
<td>VARIABLES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>1.38E-23</td>
<td>JK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>q</td>
<td>1.60E-19</td>
<td>Coul</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eg</td>
<td>1.12</td>
<td>eV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>so</td>
<td>8.85E-14</td>
<td>Fl/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sr</td>
<td>11.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ni</td>
<td>1.45E+10</td>
<td>cm^-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp</td>
<td>300</td>
<td>K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nd</td>
<td>1.00E+19</td>
<td>cm^-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td>5.00E+14</td>
<td>cm^-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vr</td>
<td>0</td>
<td>Volts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reverse Bias Voltage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Calculations:

\[ V_{bi} = \left( \frac{K}{T} \right) q \ln \left( \frac{NaNd}{ni} \right) \]

\[ W = \left[ \frac{2}{3} \right] q \left( V_{bi} + V_r \right) \left[ \frac{1}{3} \left( \frac{Na}{Na+Nd} \right) \right]^{0.5} \]

\[ W_1 = W \left[ \frac{Nd}{Na+Nd} \right] \]

\[ W_2 = W \left[ \frac{Na}{Na+Nd} \right] \]

\[ E_0 = \left( \frac{2}{3} q \epsilon_o \epsilon_r \right) \left( V_{bi} + V_a \right) \left[ \frac{1}{3} \left( \frac{NaNd}{Na+Nd} \right) \right]^{0.5} \]

\[ C_f = \epsilon_o \epsilon_r W \]

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025887</td>
<td>Volts</td>
</tr>
<tr>
<td>0.80</td>
<td>Volts</td>
</tr>
<tr>
<td>1.44 μm</td>
<td>μm</td>
</tr>
<tr>
<td>1.44 μm</td>
<td>μm</td>
</tr>
<tr>
<td>0.00 μm</td>
<td>μm</td>
</tr>
<tr>
<td>-1.11E+04 Fl/cm</td>
<td>Fl/cm</td>
</tr>
<tr>
<td>7.21E-09 Fl/cm²</td>
<td>Fl/cm²</td>
</tr>
</tbody>
</table>
Real pn junctions: The uniformly doped abrupt junction is rarely obtained in integrated circuit devices. (epi layer growth is close).

Diffused pn junction:

\[ N_{BC} = N_D(x) \]
Given, $X_j$, $N_A(X)$, $N_D(X)$

Pick an $X_1$ to the left of $X_j$. Calculate the total charge per unit area in the region between $X_1$ and $X_j$. This charge is $Q_1$.

Pick an $X_2$ to the right of $X_j$. Calculate the total charge per unit area in the region between $X_2$ and $X_j$. This charge is $Q_2$.

Calculate potential $V_1$ from physical fundamentals:
$$V_1 = \frac{KT}{q} \ln \left( \frac{N_A N_D}{n_i^2} \right) + V_R$$

Calculate potential $V_2$ from E & M fields fundamentals:
$$\nabla^2 \Psi_o = -\frac{\rho}{\varepsilon}$$

If $V_1 = V_2$ then $\nabla^2 \Psi_o = -\frac{\rho}{\varepsilon}$.

If $Q_1 = Q_2$ then $\nabla^2 \Psi_o = -\frac{\rho}{\varepsilon}$.

$L = W_1 + W_2$, $C_j$, other

$V_1 = V_2$

$Q_1 = Q_2$

$\nabla^2 \Psi_o = -\frac{\rho}{\varepsilon}$

Yes

No

$V_1 = V_2$

$Q_1 = Q_2$

$\nabla^2 \Psi_o = -\frac{\rho}{\varepsilon}$

Yes

No
CURRENTS IN PN JUNCTIONS

V_{RB} = reverse breakdown voltage

V_{bi} = turn on voltage
\sim 0.7 \text{ volts for Si}

\begin{align*}
Id &= I_s \left[ \exp \left( \frac{q V_D}{KT} \right) - 1 \right] \\
\text{Ideal diode equation}
\end{align*}
INTEGRATED DIODES

p+ means heavily doped p-type
n+ means heavily doped n-type
n-well is an n-region at slightly higher doping than the p-wafer

Note: there are actually two pn junctions, the well-wafer pn junction should always be reverse biased
REAL DIODES

Series Resistance = 1/4.82m = 207
Junction Capacitance ~ 2 pF
Is = 3.02E-9 amps
BV = > 100 volts
Size 80µ x 160µ
## DIODE SPICE MODEL

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Default Value</th>
<th>Extracted Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is reverse saturation current</td>
<td>1e-14 A</td>
<td>3.02E-9 A</td>
</tr>
<tr>
<td>N emission coefficient</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RS series resistance</td>
<td>0</td>
<td>207 ohms</td>
</tr>
<tr>
<td>VJ built-in voltage</td>
<td>1 V</td>
<td>0.6</td>
</tr>
<tr>
<td>CJ0 zero bias junction capacitance</td>
<td>0</td>
<td>2pF</td>
</tr>
<tr>
<td>M grading coefficient</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>BV Breakdown voltage</td>
<td>infinite</td>
<td>400</td>
</tr>
<tr>
<td>IBV Reverse current at breakdown</td>
<td>1E-10 A</td>
<td>-</td>
</tr>
</tbody>
</table>

DXXX N(anode) N(cathode) Modelname
.model Modelname D Is=1e-14 Cjo=.1pF Rs=.1
.model RITMEMS D IS=3.02E-9 N=1 RS=207
+VJ=0.6 CJ0=2e-12 M-0.5 BV=400
Diode Sensors

**DIODE TEMPERATURE DEPENDENCE**

\[ I_d = I_s \left[ \exp \left( \frac{q V_d}{K T} \right) - 1 \right] \]

Neglect the \(-1\) in forward bias, Solve for \(V_d\)

\[ V_d = \frac{K T}{q} \ln \left( \frac{I_d}{I_s} \right) = \frac{K T}{q} \left( \ln(I_d) - \ln(I_s) \right) \quad \text{eq 1} \]

Take \(dV_d/dT\): note \(I_d\) is not a function of \(T\) but \(I_s\) is

\[ \frac{dV_d}{dT} = \frac{K T}{q} \left( \frac{d \ln(I_d)}{dT} - \frac{d \ln(I_s)}{dT} \right) + \frac{K}{q} \left( \ln(I_d) - \ln(I_s) \right) \]

Rewritten

\[ \frac{dV_d}{dT} = V_d/T - \frac{(K T/q)}{(1/I_s) \frac{dI_s}{dT}} \quad \text{eq 2} \]

Now evaluate the second term, recall

\[ I_s = q A \left( \frac{D_p}{(L_p N_d)} + \frac{D_n}{(L_n N_a)} \right) n \ni^2 \]

Note: \(D_n\) and \(D_p\) are proportional to \(1/T\)
and \[ n_i^2(T) = A T^3 e^{-qE_g/KT} \]

This gives the temperature dependence of \( I_s \)

\[ I_s = C T^2 e^{-qE_g/KT} \quad \text{eq 3} \]

Now take the natural log

\[ \ln I_s = \ln (C T^2 e^{-qE_g/KT}) \]

Take derivative with respect to \( T \)

\[
\frac{1}{I_s} \frac{d}{dT} (I_s) = \frac{d}{dT} \ln (C T^2 e^{-qE_g/KT}) = \frac{d}{dT} [\ln (C) + \ln (T^2) + \ln (e^{-qE_g/KT})]
\]

\[
= \frac{1}{I_s} \left[ C T^2 e^{-qE_g/KT} \left( qE_g/KT^2 \right) + (C e^{-qE_g/KT}) 2T \right]
\]

Back to eq 2

\[
\frac{dV_D}{dT} = \frac{V_D}{T} - \left( \frac{KT}{q} \right) \left[ (qE_g/KT^2) + \left( \frac{2}{T} \right) \right]
\]

\[
\frac{dV_D}{dT} = \frac{V_D}{T} - \frac{E_g}{T} - \frac{2K}{q}
\]
EXAMPLE: DIODE TEMPERATURE DEPENDENCE

\[ \frac{dV_D}{dT} = \frac{V_D}{T} - \frac{E_g}{T} - \frac{2K}{q} \]

Silicon with \( E_g \approx 1.2 \text{ eV} \), \( V_D = 0.6 \text{ volts} \), \( T = 300 \text{ °K} \)

\[
\frac{dV_D}{dT} = \frac{0.6}{300} - \frac{1.2}{300} - \left( \frac{2(1.38E-23)}{1.6E-19} \right)
= -2.2 \text{ mV/°}
\]

\( T_1 < T_2 \)
DIODE AS A TEMPERATURE SENSOR

Poly Heater, Buried pn Diode, N+ Poly to Aluminum Thermocouple

Compare with theoretical -2.2mV/°C
SIGNAL CONDITIONING FOR TEMPERATURE SENSOR

\[ 0.2 < V_{out} < 0.7V \]

Diagram:
- 3.3V
- Diode
- R1 20K
- Ground
- Positive terminal
- Negative terminal
- Diagram of diode sensor circuit with 3.3Vdc and 20k resistor

Rochester Institute of Technology
Microelectronic Engineering

© April 10, 2011 Dr. Lynn Fuller, Motorola Professor
Diode Sensors

**SIGNAL CONDITIONING CIRCUIT**

Diode Voltage Buffer

Gain and Inversion

Level Shifting and Buffer

**Signal Conditioning Circuit**

Improves the sensitivity to changes in temperature
TEMPERATURE TEST RESULTS OF WATER

**Dr. WatSen Temperature Sensor**

Measurement of Amplified and Shifted Diode Voltage in Different Temperature Water Baths

The output changes by -19 mV/°C
PHOTODIODE

space charge layer

Phosphorous donor atom and electron
Ionized Immobile Phosphorous donor atom
Ionized Immobile Boron acceptor atom
Boron acceptor atom and hole

electron and hole pair

© April 10, 2011 Dr. Lynn Fuller, Motorola Professor
\[ E = h\nu = hc / \lambda \]

\[ h = 6.625 \times 10^{-34} \, \text{j/s} \]
\[ = (6.625 \times 10^{-34} / 1.6\times10^{-19}) \, \text{eV/s} \]

- \( E = 1.55 \, \text{eV} \) (red)
- \( E = 2.50 \, \text{eV} \) (green)
- \( E = 4.14 \, \text{eV} \) (blue)
ADSORPTION VERSUS DISTANCE

\[ \phi(x) = \phi(0) \exp^{-\alpha x} \]

Find % adsorbed for Green light at \( x=5 \mu m \) and Red light at 5 \( \mu m \)
**PN JUNCTION DESIGN FOR PHOTO DIODE**

Diagram showing the space charge layer with data points for 0µm, 1µm, 2µm, 3µm, and 4µm, along with percentages at 850nm and 550nm wavelengths.
LARGE 5mm X 5mm PHOTODIODE

5mm x 3.33mm

Isc = 0.15mA (short circuit current) or 9.09 A/m²
SINGLE AND DUAL PHOTO CELL

Isc = 1.088 uA or 6 A/m²

Isc = 0.585 uA or 3.25 A/m²
16000um x 16000um

Ellen Sedlack 2011

Rochester Institute of Technology
Microelectronic Engineering
I-V CHARACTERISTICS OF PHOTO CELL

Ellen’s Photo Diode

Conditions:
Swp: SMU1
Start: -2.00000 V
Stop: 2.00000 V
Step: 8.00000m V
Pts: 501
Con: SMU2
Val: 0.00000 V

Von = 0.6 volts
Rseries = 1/slope = 1/0.129
= 7.75ohms
Is = 1.48uA (in room light)
PHOTOCELL – QUANTUM EFFICIENCY

93% between 550nm and 650nm

Ellen Sedlack 2011
SOME TERMS AND DEFINITIONS:

Air Mass – amount of air between sun and solar cell. In space AM=0 at the equator at noon AM=1, if the sun is arriving at an angle $\theta$, AM=1/cos $\theta$. AM1.5 is the standard for most solar cell work in USA and gives a sum total of 1000w/m2 over the entire spectrum of wavelengths from 0.2um to 2.0um.

Efficiency is the ratio of the power out of a solar cell to the power falling on the solar cell (normally 1000w/m2 with the AM1.5 spectrum). Since Si solar cells cannot absorb much of the infrared spectrum from the sun, and other factors, typical efficiencies are limited to 26-29% for basic silicon solar cells.

Quantum Efficiency – normalized ratio of electrons and holes collected to photons incident on the cell at a single wavelength, given in %.

FF – Fill Factor, a figure of merit, the “squareness” of the diode I-V characteristic in 4th quadrant with light falling on the cell.
**SOLAR CELL TUTORIAL**

\[
\begin{align*}
\text{Voc} & \quad \text{open circuit voltage} \\
\text{Isc} & \quad \text{short circuit voltage} \\
\text{Vmp} & \quad \text{Voltage at maximum power} \\
\text{Imp} & \quad \text{Current at maximum power} \\
\text{FF} & \quad FF = \frac{\text{Vmp}\text{Imp}}{\text{Voc}\text{Isc}}
\end{align*}
\]

- **I** vs **V**
  - **Power** = **I** \(\times\) **V**

**Diode Symbols**:
- **No Light**
- **Most Light**
- **Max Power**
- **Isc**
- **Vmp**
- **Voc**
Figure 1.3. Spectral distribution of sunlight. Shown are the cases of AM0 and AM1.5 radiation together with the radiation distribution expected from the sun if it were a black body at 6000K.
PHOTOCELL – POWER EFFICIENCY

AM 1.5 Light Source

Zachary Bittner

Ivan Puchades
Diode Sensors

POWER, EFFICIENCY, Isc, Voc

<table>
<thead>
<tr>
<th>Setting</th>
<th>Spot size</th>
<th>Cell size (cm²)</th>
<th>Current</th>
<th>J (A/cm²)</th>
<th>Irradiance (mW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.25x @maj</td>
<td>1.267</td>
<td>0.25</td>
<td>2.77E-04</td>
<td>1.11E-03</td>
<td>3.39</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column1</th>
<th>P 4_G5</th>
<th>P 4_G4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pmax</td>
<td>-5.06E-04</td>
<td>-4.65E-04</td>
</tr>
<tr>
<td>Jmax</td>
<td>-1.21E-03</td>
<td>-1.160E-03</td>
</tr>
<tr>
<td>Vmax</td>
<td>0.42</td>
<td>0.380</td>
</tr>
<tr>
<td>Jsc</td>
<td>-1.30E-03</td>
<td>-1.30E-03</td>
</tr>
<tr>
<td>Voc</td>
<td>5.60E-01</td>
<td>0.540</td>
</tr>
<tr>
<td>FF</td>
<td>69.8%</td>
<td>62.8%</td>
</tr>
<tr>
<td>efficiency</td>
<td>-15%</td>
<td>-14%</td>
</tr>
</tbody>
</table>

E = hν = hc / λ

What wavelengths will not generate e-h pairs in silicon. Thus silicon is transparent or light of this wavelength or longer is not adsorbed?

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Bandgap (eV) 300 K</th>
<th>Bandgap (eV) 0 K</th>
<th>λ_{max} (μm) 300 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN</td>
<td>7.500</td>
<td>-</td>
<td>0.165</td>
</tr>
<tr>
<td>C</td>
<td>5.470</td>
<td>5.480</td>
<td>0.227</td>
</tr>
<tr>
<td>ZnS</td>
<td>3.680</td>
<td>3.840</td>
<td>0.337</td>
</tr>
<tr>
<td>GaN</td>
<td>3.360</td>
<td>3.500</td>
<td>0.369</td>
</tr>
<tr>
<td>ZnO</td>
<td>3.350</td>
<td>3.420</td>
<td>0.370</td>
</tr>
<tr>
<td>Alpha-SiC</td>
<td>2.996</td>
<td>3.030</td>
<td>0.414</td>
</tr>
<tr>
<td>CdS</td>
<td>2.420</td>
<td>2.560</td>
<td>0.512</td>
</tr>
<tr>
<td>GaP</td>
<td>2.260</td>
<td>2.340</td>
<td>0.549</td>
</tr>
<tr>
<td>BP</td>
<td>2.000</td>
<td>-</td>
<td>0.620</td>
</tr>
<tr>
<td>CdSe</td>
<td>1.700</td>
<td>1.850</td>
<td>0.729</td>
</tr>
<tr>
<td>AlSb</td>
<td>1.580</td>
<td>1.680</td>
<td>0.785</td>
</tr>
<tr>
<td>CdTe</td>
<td>1.560</td>
<td>-</td>
<td>0.795</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.420</td>
<td>1.520</td>
<td>0.873</td>
</tr>
<tr>
<td>InP</td>
<td>1.350</td>
<td>1.420</td>
<td>0.919</td>
</tr>
<tr>
<td>Si</td>
<td>1.120</td>
<td>1.170</td>
<td>1.107</td>
</tr>
<tr>
<td>GaSb</td>
<td>0.720</td>
<td>0.810</td>
<td>1.722</td>
</tr>
<tr>
<td>Ge</td>
<td>0.660</td>
<td>0.740</td>
<td>1.879</td>
</tr>
<tr>
<td>PbS</td>
<td>0.410</td>
<td>0.286</td>
<td>3.024</td>
</tr>
<tr>
<td>InAs</td>
<td>0.360</td>
<td>0.420</td>
<td>3.444</td>
</tr>
<tr>
<td>PbTe</td>
<td>0.310</td>
<td>0.190</td>
<td>4.000</td>
</tr>
<tr>
<td>InSb</td>
<td>0.170</td>
<td>0.230</td>
<td>7.294</td>
</tr>
<tr>
<td>Sn</td>
<td>-</td>
<td>0.082</td>
<td>15.122 @ 0 K</td>
</tr>
</tbody>
</table>

*Table of various semiconductors in order of increasing λ_{max}. From Sze (1981).*
## TYPES OF PHOTODETECTORS

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Gain</th>
<th>Response Time (s)</th>
<th>Typical Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photomultiplier</td>
<td>&gt; $10^6$</td>
<td>$10^{-7}$ to $10^{-9}$</td>
<td>300 (sometimes cooled)</td>
</tr>
<tr>
<td>Photoconductor</td>
<td>1 to $10^6$</td>
<td>$10^{-3}$ to $10^{-8}$</td>
<td>4.2 to 300</td>
</tr>
<tr>
<td>Metal-Semiconductor-Metal Photodetector</td>
<td>1 or less</td>
<td>$10^{-10}$ to $10^{-12}$</td>
<td>300</td>
</tr>
<tr>
<td>p-n Photodiode</td>
<td>1 or less</td>
<td>$10^{-6}$ to $10^{-11}$</td>
<td>300 (sometimes cooled to 77 K)</td>
</tr>
<tr>
<td>p-i-n Photodiode</td>
<td>1 or less</td>
<td>$10^{-6}$ to $10^{-9}$</td>
<td>300</td>
</tr>
<tr>
<td>Metal-Semiconductor Diode</td>
<td>1 or less</td>
<td>$10^{-9}$ to $10^{-12}$</td>
<td>300</td>
</tr>
<tr>
<td>Avalanche Diode</td>
<td>$10^2$ to $10^4$</td>
<td>$10^{-10}$</td>
<td>300</td>
</tr>
<tr>
<td>Bipolar Phototransistor</td>
<td>$10^2$</td>
<td>$10^{-6}$ to $10^{-8}$</td>
<td>300</td>
</tr>
<tr>
<td>Bipolar Photo-Darlington</td>
<td>$10^4$</td>
<td>$10^{-5}$ to $10^{-6}$</td>
<td>300</td>
</tr>
<tr>
<td>Field-Effect Phototransistor</td>
<td>10</td>
<td>$10^{-7}$</td>
<td>300</td>
</tr>
<tr>
<td>CCD Cell (Metal-Insulator-Semiconductor Capacitor)</td>
<td>1 or less</td>
<td>$10^{-5}$ to $10^{-8}$</td>
<td>300 (sometimes cooled)</td>
</tr>
</tbody>
</table>

Gains and response times of some typical photodetectors (some are optimistic!). After Sze (1981). Note that the CCD cell, and some extrinsic photoconductors, are integrating detectors, and thus the response time figures can be somewhat misleading.
In the forward biased diode current flows and as holes recombine on the n-side or electrons recombine on the p-side, energy is given off as light, with wavelength appropriate for the energy gap for that material. $\lambda = \frac{h \cdot c}{E}$

$h = \text{Plank’s constant}$
$c = \text{speed of light}$
## LEDs

### SEP8736

**AIGaAs Infrared Emitting Diode**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SYMBOL</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNITS</th>
<th>TEST CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance ((1))</td>
<td>H</td>
<td>0.8</td>
<td>1.2</td>
<td>3.0</td>
<td>mW/cm²</td>
<td>(I=20) mA</td>
</tr>
<tr>
<td>SEP8736-001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEP8736-002</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEP8736-003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward Voltage</td>
<td>(V_f)</td>
<td>1.7</td>
<td></td>
<td></td>
<td>V</td>
<td>(I=20) mA</td>
</tr>
<tr>
<td>Reverse Breakdown Voltage</td>
<td>(V_{BR})</td>
<td>3.0</td>
<td></td>
<td></td>
<td>V</td>
<td>(I=16) (\mu)A</td>
</tr>
<tr>
<td>Peak Output Wavelength</td>
<td>(\lambda_p)</td>
<td>880</td>
<td></td>
<td></td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Spectral Bandwidth</td>
<td>(\Delta\lambda)</td>
<td>80</td>
<td></td>
<td></td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Spectral Shift With Temperature</td>
<td>(\Delta\lambda/\lambda)</td>
<td>0.2</td>
<td></td>
<td></td>
<td>nm/°C</td>
<td></td>
</tr>
<tr>
<td>Beam Angle</td>
<td>(\phi)</td>
<td>10</td>
<td></td>
<td></td>
<td>deg</td>
<td>(I=\text{Constant})</td>
</tr>
<tr>
<td>Radiation Rise And Fall Time</td>
<td>(t_r, t_f)</td>
<td>0.7</td>
<td></td>
<td></td>
<td>(\mu)s</td>
<td></td>
</tr>
</tbody>
</table>

**Notes**

1. Measured in mW/cm² into a 0.104 (0.04) diameter aperture placed 0.500 (12.7) from the lens tip.
2. Beam angle is defined as the total included angle between the half intensity points.
PHOTODIODE I TO V LINEAR AMPLIFIER

- IR LED
- NJU703
- Gnd
- Vout 0 to 1V
- R1 10K
- R2 20K
- R3 10K
- R4 100K
- 3.3V

Rochester Institute of Technology
Microelectronic Engineering

© April 10, 2011 Dr. Lynn Fuller, Motorola Professor
PHOTO DIODE I TO V LOG AMPLIFIER

Linear amplifier uses 100K ohm in place of the 1N4448

Vout vs. Diode Current

Photodiode
Integrator and amplifier allow for measurement at low light levels
UV LED AND PHOTO DIODE SENSOR

Material Characterization by UV Light Absorption

Diode Sensors

Rochester Institute of Technology
Microelectronic Engineering

© April 10, 2011 Dr. Lynn Fuller, Motorola Professor
TURBIDITY

Turbidity = loss of transparency due to the presence of suspended solids, water < 1-5 NTU (Nephelometric Turbidity Units), measured by a nephelometer or turbidimeter, which measures the intensity of light scattered at 90 degrees as a beam of light passes through a water sample.

\[ V_{out} = IR \]
Light Emitting Diode -LED

Flat
n - V_a + p
TURBIDITY

Infrared LED

Photocell

Packaged Sensor Chip and LED

Sensor Chip
Digital Cameras can see the light from an infrared LED that the human eye can not see
TURBIDITY – SIGNAL CONDITIONING CIRCUIT

Gain and Level Shifting

Photo-Current to Voltage

Diode Sensors
TURBIDITY TEST RESULTS

Plot of output voltage for different standard turbidity samples

Turbidity Standards
**Micro Spectro Radiometer**

- Plasma Etch Endpoint Detection
- Nanospec Like Film Thickness
- Light Source Characterization

**Acknowledgments:**
Marion Jess, Visiting Scholar from Germany
Wessel Valster, Student of Hogeschool Enschede, The Netherlands
Zoran Uskokovic, RIT, graduate student in MicroE
Light is diffracted into a series of intensity spots called diffraction orders.
CALCULATIONS

Grating of 2 um lines and 2 um space gives \( S = 4 \) um

\( k \) is the diffraction order

\( \lambda \) is wavelength

The angle \( \xi \)

\[
\sin \xi = \frac{k \lambda}{n S}
\]

and

\[
\tan \xi = \frac{r}{d}
\]

for \( d = 1000 \) um, and \( n = 1.5 \) for glass

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>( \xi_1 )</th>
<th>( \xi_2 )</th>
<th>( r_1 )</th>
<th>( r_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>3.34</td>
<td>6.71</td>
<td>58um</td>
<td>117um</td>
</tr>
<tr>
<td>550</td>
<td>5.24</td>
<td>10.6</td>
<td>92um</td>
<td>187um</td>
</tr>
<tr>
<td>750</td>
<td>7.17</td>
<td>14.5</td>
<td>126um</td>
<td>259um</td>
</tr>
</tbody>
</table>
Diode Sensors

MICRO-SPECTRO-RADIOMETER

- Diffraction Grating
- 1mm Glass
- 128 Ion Implanted p+ diode Photo Detectors
- n-type silicon
- Analog Switches
  - Multiplexer
  - Shift Registers
- I/O Pads

Rochester Institute of Technology
Microelectronic Engineering

© April 10, 2011 Dr. Lynn Fuller, Motorola Professor
FIRST TEST CHIP

Marion Jess
1996

Photo diodes

Shielded area

Pads to 128 diodes
RESULTS OF FIRST TEST CHIP

Measurements from 128 diodes illuminated through different color filters

Photodiode Current vs Voltage

Some Light

More Light

Rochester Institute of Technology
Microelectronic Engineering

© April 10, 2011 Dr. Lynn Fuller, Motorola Professor
Micro-spectro-photometer on chip electronics for electronic readout
Diode Sensors

POLY GATE PMOS + DEPLETION MODE IMPLANT MULTIPLEXER

7 Bit Counter

Rf

Ri

Internal 100 pF

Reset

Vout
SECOND TEST CHIP

T Type FF Binary Counter

Multiplexer

Photodiodes
REFERENCES

4. Solar Cells, Martin A. Green, Prentice-Hall
1. Calculate the temperature change if a diode's forward voltage increases from 0.65 volts to 0.69 volts. Repeat for a change from 0.65 volts to 0.55 volts.

2. For the diode sensor and circuit shown on page 43 calculate the output voltage when the diode is illuminated.