ECEN 5645
Introduction to Optoelectronics
Class Meeting 25

Non- PIN Solid State Detectors
Today’s Topics

• Avalanche Photodiodes
• Problem 5.6
• APD Numerics and Examples
• Heterojunction Detectors
• Problem 5.10
• Quantum Well Detectors
• Schottkey Diodes
• Phototransistors
• Photoconductive Detectors
Avalanche Photodiode

(a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain. (b) The net space charge density across the photodiode. (c) The field across the diode and the identification of absorption and multiplication regions.
(a) A pictorial view of impact ionization processes releasing EHPs and the resulting avalanche multiplication. (b) 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.
Avalanche Photodiode Gain or Multiplication $M$

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

$$M = \frac{1}{1 - \left(\frac{V_r}{V_{br}}\right)^m}$$
Typical multiplication (gain) $M$ vs. reverse bias characteristics for a typical commercial Si APD, and the effect of temperature. ($M$ measured for a photocurrent generated at 650 nm of illumination)
Avalanche Photodiode

(a) A Si APD structure without a guard ring. (b) A schematic illustration of the structure of a more practical Si APD. Note: SiO$_2$ is silicon dioxide and serves as an insulating passivation layer.
# Photodiode Comparison

<table>
<thead>
<tr>
<th>Photodiode</th>
<th>$\lambda_{\text{range}}$</th>
<th>$\lambda_{\text{peak}}$</th>
<th>$R_{\text{at } \lambda_{\text{peak}}}$</th>
<th>Gain</th>
<th>$I_d$ For 1 mm$^2$</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaP pin</td>
<td>150–550</td>
<td>450</td>
<td>0.1</td>
<td>&lt;1</td>
<td>1 nm</td>
<td>UV detection$^a$</td>
</tr>
<tr>
<td>GaAsP pn</td>
<td>150–750</td>
<td>500–720</td>
<td>0.2–0.4</td>
<td>&lt;1</td>
<td>0.005–0.1 nA</td>
<td>UV to visible, covering the human eye, low $I_d$.</td>
</tr>
<tr>
<td>GaAs pin</td>
<td>570–870</td>
<td>850</td>
<td>0.5–0.5</td>
<td>&lt;1</td>
<td>0.1–1 nA</td>
<td>High speed and low $I_d$</td>
</tr>
<tr>
<td>Si pn</td>
<td>200–1100</td>
<td>600–900</td>
<td>0.5–0.6</td>
<td>&lt;1</td>
<td>0.005–0.1 nA</td>
<td>Inexpensive, general purpose, low $I_d$</td>
</tr>
<tr>
<td>Si pin</td>
<td>300–1100</td>
<td>800–1000</td>
<td>0.5–0.6</td>
<td>&lt;1</td>
<td>0.1–1 nA</td>
<td>Faster than pn</td>
</tr>
<tr>
<td>Si APD</td>
<td>400–1100</td>
<td>800–900</td>
<td>0.4–0.6$^b$</td>
<td>$10^{10}$</td>
<td>1–10 nA$^c$</td>
<td>High gains and fast</td>
</tr>
<tr>
<td>Ge pin</td>
<td>700–1800</td>
<td>1500–1580</td>
<td>0.4–0.7</td>
<td>&lt;1</td>
<td>0.1–1 $\mu$A</td>
<td>IR detection, fast</td>
</tr>
<tr>
<td>Ge APD</td>
<td>700–1700</td>
<td>1500–1580</td>
<td>0.4–0.8$^b$</td>
<td>$10^{20}$</td>
<td>1–10 $\mu$A$^c$</td>
<td>IR detection, fast</td>
</tr>
<tr>
<td>InGaAs pin</td>
<td>800–1700</td>
<td>1500–1600</td>
<td>0.7–1</td>
<td>&lt;1</td>
<td>1–50 nA</td>
<td>Telecom, high speed, low $I_d$</td>
</tr>
<tr>
<td>InGaAs APD</td>
<td>800–1700</td>
<td>1500–1600</td>
<td>0.7–0.95$^b$</td>
<td>$10^{20}$</td>
<td>0.05–10 $\mu$A$^c$</td>
<td>Telecom, high speed and gain.</td>
</tr>
<tr>
<td>InAs pn</td>
<td>2–3.6 $\mu$m</td>
<td>3.0–3.5 $\mu$m</td>
<td>1–1.5</td>
<td>&lt;1</td>
<td>&gt;100 $\mu$A</td>
<td>Photovoltaic mode. Normally cooled</td>
</tr>
<tr>
<td>InSb pn</td>
<td>4–5.5 $\mu$m</td>
<td>5 $\mu$m</td>
<td>3</td>
<td>&lt;1</td>
<td>Large</td>
<td>Photovoltaic mode. Normally cooled</td>
</tr>
</tbody>
</table>

NOTE: $^a$FGAP71 (Thorlabs); $^b$At $M = 1$; $^c$At operating multiplication.
Problem 5.6

• Solution by Imbert Wang
Responsivity at given wavelengths

<table>
<thead>
<tr>
<th>A</th>
<th>Responsivity (A/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450nm</td>
<td>0.2</td>
</tr>
<tr>
<td>700nm</td>
<td>0.45</td>
</tr>
<tr>
<td>1000nm</td>
<td>0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B</th>
<th>Responsivity (A/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450nm</td>
<td>0.1</td>
</tr>
<tr>
<td>700nm</td>
<td>0.45</td>
</tr>
<tr>
<td>1000nm</td>
<td>0.425</td>
</tr>
</tbody>
</table>
Avalanche Photodiode Gain or Multiplication $M$

Ionization coefficient ratio is the ratio of hole to electron ionization

$$k = \frac{\alpha_h}{\alpha_e}$$

$$\alpha_e = A \exp(-B/E)$$

Chyoweth's law
Avalanche Photodiode Gain or Multiplication $M$

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

**Electrons only**

$M = \exp(\alpha_e w)$

**Ionization coefficient**

**Electrons and holes**

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

$k = \alpha_h / \alpha_e$
APD Characteristics

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 \( \sim 100 \) 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: InGaAs APD Responsivity
An InGaAs APD has a quantum efficiency (QE, $\eta_e$) of 60 % at 1.55 µm in the absence of multiplication ($M = 1$). It is biased to operate with a multiplication of 12. Calculate the photocurrent if the incident optical power is 20 nW. What is the responsivity when the multiplication is 12?
EXAMPLE: InGaAs APD Responsivity
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Solution
The responsivity at $M = 1$ in terms of the quantum efficiency is $R = 0.75$ A W$^{-1}$

$$R = \eta_e \frac{e \lambda}{hc} = (0.6) \frac{(1.6 \times 10^{-19} \text{ C})(1550 \times 10^{-9} \text{ m})}{(6.626 \times 10^{-34} \text{ J s})(3 \times 10^{8} \text{ m s}^{-1})}$$

If $I_{pho}$ is the primary photocurrent (unmultiplied) and $P_o$ is the incident optical power then by definition, $R = I_{pho}/P_o$ so that

$$I_{pho} = RP_o$$

$$= (0.75 \text{ A W}^{-1})(20 \times 10^{-9} \text{ W})$$

$$= 1.5 \times 10^{-8} \text{ A or 15 nA.}$$

The photocurrent $I_{ph}$ in the APD will be $I_{pho}$ multiplied by $M$,

$$I_{ph} = MI_{pho}$$

$$= (12)(1.5 \times 10^{-8} \text{ A})$$

$$= 1.80 \times 10^{-7} \text{ A or 180 nA.}$$

The responsivity at $M = 12$ is

$$R' = I_{ph}/P_o = MR = (12) / (0.75) = 9.0 \text{ A W}^{-1}$$
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 \(= 0.47 \text{ A W}^{-1}\)

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

The unmultiplied primary photocurrent from the definition of \(R\) is

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

The multiplied photocurrent is

\[
I_{ph} = M I_{ph_o} = (100)(4.67 \text{ nA}) = 470 \text{ nA or 0.47 \mu A}
\]
EXAMPLE: Avalanche multiplication in Si APDs

The electron and hole ionization coefficients $\alpha_e$ and $\alpha_h$ in silicon are approximately given by Eq. (5.6.4) with $A \approx 0.740 \times 10^6 \text{ cm}^{-1}$, $B \approx 1.16 \times 10^6 \text{ V cm}^{-1}$ for electrons ($\alpha_e$) and $A \approx 0.725 \times 10^6 \text{ cm}^{-1}$ and $B \approx 2.2 \times 10^6 \text{ V cm}^{-1}$ for holes ($\alpha_h$). Suppose that the width $w$ of the avalanche region is $0.5 \mu\text{m}$. Find the multiplication gain $M$ when the applied field in this region reaches $4.00 \times 10^5 \text{ V cm}^{-1}$, $4.30 \times 10^5 \text{ V cm}^{-1}$ and $4.38 \times 10^5 \text{ V cm}^{-1}$. What is your conclusion?

What is the point of this Exercise?
EXAMPLE: Avalanche multiplication in Si APDs

The electron and hole ionization coefficients $\alpha_e$ and $\alpha_h$ in silicon are approximately given by Eq. (5.6.4) with $A \approx 0.740 \times 10^6$ cm$^{-1}$, $B \approx 1.16 \times 10^6$ V cm$^{-1}$ for electrons ($\alpha_e$) and $A \approx 0.725 \times 10^6$ cm$^{-1}$ and $B \approx 2.2 \times 10^6$ V cm$^{-1}$ for holes ($\alpha_h$). Suppose that the width $w$ of the avalanche region is 0.5 $\mu$m. Find the multiplication gain $M$ when the applied field in this region reaches $4.00 \times 10^5$ V cm$^{-1}$, $4.30 \times 10^5$ V cm$^{-1}$ and $4.38 \times 10^5$ V cm$^{-1}$. What is your conclusion?

What is the point of this Exercise?

Breakdown

$$\alpha_e w = \frac{-\log(k)}{1 - k}$$

Stability improves when $k$ is small
EXAMPLE: Avalanche multiplication in Si APDs

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Solution

At the field of $E = 4.00 \times 10^5$ V cm$^{-1}$, from Eq. (5.6.4)

$$\alpha_e = A \exp(-B/E) = (0.74 \times 10^6 \text{ cm}^{-1}) \exp[-(1.16 \times 10^6 \text{ V cm}^{-1})/(4.00 \times 10^5 \text{ V cm}^{-1})] = 4.07 \times 10^4 \text{ cm}^{-1}.$$ 

Similarly using Eq. (5.6.4) for holes, $\alpha_h = 2.96 \times 10^3$ cm$^{-1}$. Thus $k = \alpha_h / \alpha_e = 0.073$. Using this $k$ and $\alpha_e$ above in Eq. (5.6.6) with $w = 0.5 \times 10^{-4}$ cm,

$$M = \frac{1 - 0.073}{\exp[-(1 - 0.073)(4.07 \times 10^4 \text{ cm})(0.5 \times 10^{-4} \text{ cm}^{-1})] - 0.073} = 11.8$$

Note that if we had only electron avalanche without holes ionizing, then the multiplication would be

$$M_e = \exp(\alpha_e w) = \exp[(4.07 \times 10^4 \text{ cm}^{-1})(0.5 \times 10^{-4} \text{ cm})] = 7.65$$
EXAMPLE: Avalanche multiplication in Si APDs
Solution (continued)

We can now repeat the calculations for $E = 4.30 \times 10^5$ V cm$^{-1}$ and again for $E = 4.38 \times 10^5$ V cm$^{-1}$. The results are summarized in Table 5.3 for both $M$ and $M_e$. Notice how quickly $M$ builds up with the field and how a very small change at high fields causes an enormous change in $M$ that eventually leads to a breakdown. ($M$ running away to infinity as $V_r$ increases.) Notice also that in the presence of only electron-initiated ionization, $M_e$ simply increases without a sharp run-away to breakdown.

<table>
<thead>
<tr>
<th>$E$ (V cm$^{-1}$)</th>
<th>$a_e$ (cm$^{-1}$)</th>
<th>$a_h$ (cm$^{-1}$)</th>
<th>$k$</th>
<th>$M$</th>
<th>$M_e$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.00$\times$10$^5$</td>
<td>4.07$\times$10$^4$</td>
<td>2.96$\times$10$^3$</td>
<td>0.073</td>
<td>11.8</td>
<td>7.65</td>
<td>$M$ and $M_e$ not too different at low $E$</td>
</tr>
<tr>
<td>4.30$\times$10$^5$</td>
<td>4.98$\times$10$^4$</td>
<td>4.35$\times$10$^3$</td>
<td>0.087</td>
<td>57.2</td>
<td>12.1</td>
<td>7.5% increase in $E$, large difference between $M$ and $M_e$</td>
</tr>
<tr>
<td>4.38$\times$10$^5$</td>
<td>5.24$\times$10$^4$</td>
<td>4.77$\times$10$^3$</td>
<td>0.091</td>
<td>647</td>
<td>13.7</td>
<td>1.9% increase in $E$</td>
</tr>
</tbody>
</table>
Simplified schematic diagram of a separate absorption and multiplication (SAM) APD using a heterostructure based on InGaAs-InP. \( P \) and \( N \) refer to \( p \) and \( n \)-type wider-bandgap semiconductor.
Heterojunction Photodiodes: SAM

(a) 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.

(b) 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.
Heterojunction Photodiodes: SAM

Simplified schematic diagram of a more practical mesa-etched SAGM layered APD
Problem 5.10

• Solution by Ian Barry
5.10 **Shockley–Ramo theorem** Consider a *pin* photodiode with an *i*-layer width *W*. A very short pulse of light is absorbed just inside the depletion region on the *p*⁺-side (Figure 5.9). The photogenerated electrons drift through the *i*-layer with a velocity given in Figure 5.10. What is the current generated by this drift? How long does it last? Suppose that *W* is 30 μm, and assume that the quantum efficiency is 0.80. A voltage of 20 V is applied to reverse bias the *pin* detector. The light pulse from a femtosecond laser operating at 515 nm is used for photoexcitation, and the light pulse energy is 37.5 fJ. Assume all of this energy is absorbed very close to the depletion region and *p*⁺-layer boundary, *i.e.* electrons drift across *W* and constitute the photocurrent. Calculate the transient photocurrent. How long does it last?

\[
P_0 = \text{Pulse Energy} / \text{Pulse Length}
\]

\[
E \approx V_r / W = 6.667 \times 10^5 \text{ V/m}
\]

\[
\nu_d = 8 \times 10^4 \text{ m/s}
\]

\[
I_{ph} = e\lambda P_0 \eta_e / hc = 12.46 \text{ A}
\]

\[
t_{\text{drift}} = W / \nu_d = 0.375 \text{ ns}
\]
A Different Solution

\[ \mathbf{J} = e n_e \mathbf{v}_d \]

\[ I = \int \mathbf{J} \cdot d\mathbf{A} = e \frac{N_e}{W} \mathbf{v}_d \cdot \hat{e}_z \]

\[ N_e = \eta N_{ph} = \eta \frac{\varepsilon_{pulse}}{\varepsilon_{photon}} \]

The current is constant for 0.375 ns. This is the substance of the Shockley-Ramo theorem. (The genie is out of the bottle theorem). Find the magnitude and length of the current pulse.
(a) Energy band diagram of a MQW superlattice APD.
(b) Energy band diagram with an applied field and impact ionization.
Schottky Junction Photodiodes

GaAsP Schottky junction photodiode for 190-680 nm detection, from UV to red (Courtesy of Hamamatsu)

GaP Schottky junction photodiode for 190 nm to 550 nm detection. (Courtesy of Hamamatsu)

AlGaN Schottky junction photodiode for UV detection (Courtesy of sglux, Germany)
(a) Metal and an $n$-type semiconductor before contact. The metal work function $\Phi_m$ is greater than that of the $n$-type semiconductor (b) A Schottky junction forms between the metal and the semiconductor. There is a depletion region in the semiconductor next to the metal and a built-in field $E_0$ (c) Typical $I$ vs. $V$ characteristics of a Schottky contact device.
Reverse biased Schottky junction and the dark current due to the injection of electrons from the metal into the semiconductor over the barrier $\Phi_B$. 
Schottky Junction

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

**RIGHT:** The Schottky junction photodetector

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

**RIGHT:** The Schottky junction photodetector
## Schottky Junction Photodiodes

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>

$^a$Hamamatsu (Japan); $^b$sglux (Germany); $^c$Alphalas
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

LEFT: Two neighboring Schottky junctions are connected end-to-end, but in opposite directions as shown for A and B. The energy band diagram without any bias is symmetrical. The grey areas represent the SCL\textsubscript{1} and SCL\textsubscript{2} at A and B. RIGHT: Under a sufficiently large bias, the SCL\textsubscript{1} from A extends and meets that from B so that the whole semiconductor between the electrodes is depleted. There is a large field in this region, and the photogenerated EHPs become separated and then drifted, which results in a photocurrent.
Phototransistor

Transistor action

\[ I_E \propto \exp(eV_{BE}/k_B T) \]

Gain

\[ I_{ph} \approx \beta I_{pho} \]
Photoconductive Detectors

PbS (lead sulfide) photoconductive detectors for the detection of IR radiation up to 2.9 µm. They are typically used in such applications as radiation thermometers, flame monitors, water content and food ingredient analyzers, spectrophotometers etc.. (P9217 series) (Courtesy of Hamamatsu.)
Photoconductive Detectors

A semiconductor slab of length $\ell$, width $w$ and depth $d$ is illuminated with light of wavelength $\lambda$.

$n = n_o + \Delta n$

$p = p_o + \Delta p$

A semiconductor slab of length $\ell$, width $w$ and depth $d$ is illuminated with light of wavelength $\lambda$. 

$V$ 

$I_{ph}$ 

Photocurrent
A photoconductor with ohmic contacts (contacts not limiting carrier entry) can exhibit gain. As the slow hole drifts through the photoconductors, many fast electrons enter and drift through the photoconductor because, at any instant, the photoconductor must be neutral. Electrons drift faster which means as one leaves, another must enter.
Photoconductivity $\Delta \sigma$ and Photocurrent Density $J_{\text{ph}}$

**Photon flux** \( \Phi_{\text{ph}} \)

**Photoconductivity**

\[
\Delta \sigma = e \eta_i l \tau (\mu_e + \mu_h)
\]

\[
J_{\text{ph}} = \Delta \sigma \frac{V}{\ell} = \Delta \sigma E
\]

**Steady state illumination**

\[
\frac{d\Delta n}{dt} = g_{\text{ph}} - \frac{\Delta n}{\tau} = 0
\]

**Photogeneration rate**

\[
g_{\text{ph}} = \eta_i A \Phi_{\text{ph}} = \eta_i \left( \frac{l}{h v} \right) = \frac{\eta_i l \lambda}{h c d}
\]

\( \eta_i = \text{Internal quantum efficiency} \)
Photoconductive Gain

Photon flux = $\Phi_{ph}$

Rate of electron flow = $\frac{I_{ph}}{e} = \frac{wdJ_{ph}}{e} = \frac{\eta_1 w \lambda \tau (\mu_e + \mu_h) E}{hc}$

Rate of electron generation = (Volume)$g_{ph} = (wd\ell)g_{ph} = w\ell \frac{\eta_1 \lambda}{hc}$

Photoconductive gain $G$

$G = \frac{\text{Rate of electron flow in external circuit}}{\text{Rate of electron generation by light absorption}} = \frac{\tau(\mu_e + \mu_h)E}{\ell}$
Photoconductive Gain

Photon flux = $\Phi_{ph}$

$G = \frac{\text{Rate of electron flow in external circuit}}{\text{Rate of electron generation by light absorption}} = \frac{\tau (\mu_e + \mu_h)E}{\ell}$

Electron and hole transit times (time to cross the semiconductor) are

$\tau_e = \frac{\ell}{(\mu_e E)}$  

$\tau_h = \frac{\ell}{(\mu_h E)}$

Photoconductive gain $G$

$G = \frac{\tau}{\tau_e} + \frac{\tau}{\tau_h} = \frac{\tau}{\tau_e} \left(1 + \frac{\mu_h}{\mu_e}\right)$