ECE 536
Integrated Optics and Optoelectronics
TuTh 11:00-12:20, 3020 ECEB
Professor John Dallesasse
2114 Micro and Nanotechnology Laboratory
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E-mail: jdallesa@illinois.edu
Office Hours: Tuesday 1:00-2:00 pm
Upcoming Dates

- Revised Homework Schedule Posted
- Final Project Report Due 5/2
- Final Project Presentation Schedule (5/6):

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Comments on Abstracts

- Pay attention to who you attribute things to in your background section!
- Make sure you are operating at a graduate-school level in your analysis. Ask yourself “Would I submit this to a journal for publication as a mini-review?”
- Pay attention to formatting
- Pay attention to grammar
- As much as possible, make your figures “journal quality”
Additional Comments

• Pay attention to “Required Elements” stated in assignment – have a section in the paper for each of these

• Make sure you describe some of the theory of operation or theory aspects

• Make sure you provide a critical analysis – what are the strengths and weaknesses of the technology? Do you think it will become important, or is it merely interesting?

• Make sure your paper “reads” like a journal article
Exam II Comments

• Inclusive exam (entire semester), but emphasis on material covered since last exam

• 2 formula sheets allowed (your sheet from Exam I, plus a new sheet for Exam II), 8.5x11, front and back

• Bring calculator
## Tentative Schedule [3]

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**Subject to Change**
Today’s Discussion

• Finish Photoconductors
• Junction Diodes
• APDs
• Intersubband Detectors
• Solar Cells
• Assignments
• Topics for Next Lecture
Photoconductors

§ 15.1 and § 2.4
Uniform Optical Injection (§ 2.4.1)

\[
\frac{\partial n}{\partial t} = G_n - R_n + \frac{1}{q} \frac{\partial}{\partial x} J_n(x)
\]
\[
\frac{\partial p}{\partial t} = G_p - R_p - \frac{1}{q} \frac{\partial}{\partial x} J_p(x)
\]

If there is no external perturbation (i.e. electrical or optical injection), then, at thermal equilibrium, the net recombination rate is zero: \( G_n = R_n \) and \( G_p = R_p \).

Assuming the material is p-type with acceptor concentration \( N_A \): \( p_0 = N_A \) and \( n_0 \approx \frac{n_i^2}{N_A} \).

With optical injection, the new carrier densities are: \( p = p_0 + \delta p \) and \( n = n_0 + \delta n \) where \( \delta p = \delta n \).

We take the recombination rate as \( R_n = \frac{\delta n}{\tau_n} \). If the generation is uniform and constant, \( G_n(x,t) = G_0 \).

Thus, the steady-state solution is: \( 0 = \frac{\partial (\delta n)}{\partial t} = G_0 - \frac{\delta n}{\tau_n} + \frac{1}{q} \frac{\partial}{\partial x} J_n(x) \implies \delta n = G_0 \tau_n \).
Photoconductivity (§ 2.4.1)

With an applied electric field, the conduction current is:

\[ J = J_n + J_p = q(\mu_n n + \mu_p p)E = \sigma E = \frac{\sigma V}{l}. \]

Without illumination, the "dark" conductivity is: \( \sigma = q(\mu_n n_0 + \mu_p p_0) \)

With illumination, the photoconductivity is: \( \Delta \sigma = q(\mu_n \delta n + \mu_p \delta p) = q(\mu_n + \mu_p)G_0 \tau_n. \)

The photocurrent is: \( \Delta I = \Delta \sigma \frac{A}{l} V = q(\mu_n + \mu_p)G_0 \tau_n \frac{A}{l} V. \)

Since \( \mu_n \gg \mu_p \), \( \Delta I \approx q\mu_n G_0 \tau_n \frac{V}{l} = qG_0 A\tau_n v_d = qG_0 A\tau_n \frac{l}{\tau_t} = qG_0 Al \frac{\tau_n}{\tau_t}, \)

where \( v_d \) is drift velocity and \( \tau_t \) is transit time. Some notes:

1. \( G_0 Al \) is the number of electron-hole pairs generated in the volume

2. \( \frac{\tau_n}{\tau_t} \) is the photoconductive gain

3. If we include both electron and hole contributions, \( \frac{1}{\tau_t} = \frac{1}{\tau_{tn}} + \frac{1}{\tau_{tp}} = \left(\mu_n + \mu_p\right)\frac{E}{l} \)

\[ \mu \frac{V}{l} \] is a velocity (mobility \( \times \) field)
Photoconductivity (§ 15.1)

If $\tau_n \ll \tau_i$, the photocurrent is small because generated electrons recombine before they can be collected by the electrodes.

If $\tau_i \ll \tau_n$, there is photoconductive gain because generated electrons can reach the left electrode, travel through the external circuitry that measures current and then re-appear on the right electrode. Note, as soon as an electron leaves through the left electrode, a new electron enters the semiconductor from the right electrode to preserve charge neutrality (note difference from book).

If $\frac{\tau_n}{\tau_i} = 10$, electrons on average make 10 passes through the length "l" before they recombine in the photoconductor.
Photoconductivity ( § 15.1)

\[ G_0 = \eta \frac{P_{opt}}{lwd} = \eta \frac{P_{opt}}{lwd}, \]

where \( P_{opt} \) is incident power,

\( \eta \) is quantum efficiency (fraction of photons creating electron-hole pairs)

\[ \eta = \eta_i (1 - R)(1 - e^{-\alpha d}), \]

where \( R \) is the air-semiconductor reflectivity.

Note: \( I_{ph} = \eta q \frac{P_{opt}}{\hbar \omega} \) and \( \Delta I = \frac{\tau_n}{\tau_t} I_{ph} \) and the gain is \( \frac{\Delta I}{I_{ph}} = \frac{\tau_n}{\tau_t} \) and the responsivity is \( R_\lambda (A/W) = \frac{\Delta I}{P_{opt}} = \eta q \frac{\tau_n}{\hbar \omega \tau_t} = \eta q \frac{\tau_n}{\hbar \omega \tau_t}. \)
n-i-p-i Superlattice Photoconductor

We can have large photoconductive gain if we can prevent the carriers from recombining in the semiconductor.

By using modulation doping, the n-i-p-i superlattice creates separate channels for electrons and holes. After a pair is created, they drift or diffuse into their respective potential valleys.

By spatially separating the charge, the recombination lifetime can be made many orders of magnitude larger than the bulk carrier lifetime.

Where should the electrodes be placed?
Transient Response (§ 15.1)

Step response: Given $G(t) = G_0 H(-t) = \begin{cases} G_0, & t \leq 0 \\ 0, & t > 0 \end{cases}$,
the equation for $t > 0$ is: $\frac{\partial}{\partial t} \delta n = -\frac{\delta n}{\tau_n}$ with $\delta n(0) = G_0 \tau_n$.
The solution is: $\delta n(t) = \delta n(0)e^{-t/\tau_n} = G_0 \tau_n e^{-t/\tau_n}$.

Impulse response: Given $G(t) = g_0 \delta(t)$,
the equation for all $t$ is: $\frac{\partial}{\partial t} \delta n = g_0 \delta(t) - \frac{\delta n}{\tau_n}$.
Integrating from $t = 0^-$ to $t = 0^+$, we get: $\delta n(0^+) - \delta n(0^-) = g_0$.
Since the semiconductor was in equilibrium before the impulse, $\delta n(t < 0) = 0$. Thus, $\delta n(0^+) = g_0$.
For $t > 0$, we have $\frac{\partial}{\partial t} \delta n = -\frac{\delta n}{\tau_n}$.
So as before, $\delta n(t > 0) = \delta n(0)e^{-t/\tau_n} = g_0 e^{-t/\tau_n}$.
Overall, we can write $\delta n(t) = H(t) g_0 e^{-t/\tau_n}$ for all $t$.

Quick trick: since $\delta(t) = \frac{d}{dt} H(t)$,
where $H$ is the Heaviside function,
and above we did $G(t) = G_0 H(-t)$,
the impulse response could have been obtained by taking the negative derivative of the step response.
**Sinusoidal Response (§ 15.1)**

**Sinusoidal response:** Given \( G(t) = G_0 \cos(\omega t) = \text{Re} \left[ G_0 e^{-i\omega t} \right] \),

\[
\delta n(t) = \text{Re} \left[ \delta n(\omega) e^{-i\omega t} \right], \text{ so: }
\]

\[
\frac{\partial}{\partial t} \delta n = G_0 \cos(\omega t) - \frac{\delta n}{\tau_n} \quad \text{becomes} \quad -i\omega \delta n = G_0 - \frac{\delta n}{\tau_n} \quad \text{and we get:}
\]

\[
\delta n(\omega) = \frac{G_0}{1 - i\omega} = \frac{G_0 \tau_n}{1 - i\omega \tau_n}.
\]

Thus, \( \delta n(t) = \frac{G_0 \tau_n}{\sqrt{1 + \omega^2 \tau_n^2}} \cos(\omega t - \phi) \), where \( \phi = \tan^{-1} \left( \omega \tau_n \right) \) is the phase delay.

**Alternate derivation:** Given \( G(t) = G_0 \cos(\omega t) \), we can find the response using the impulse response.

Recall for any linear operator \( L \) that if \( Lu = \delta \), then \( v = u \otimes f \) solves \( Lv = f \).

\[
\delta n(t) = H(t)e^{-t/\tau_n} \otimes G_0 \cos(\omega t)
\]

\[
\delta n(t) = \frac{G_0 \tau_n}{1 + \omega^2 \tau_n^2} \left[ \cos(\omega t) + \omega \tau_n \sin(\omega t) \right] \quad \text{(using Mathematica)}.
\]

You can also use Mathematica to show that this is equal to the above expression.
Gain-Bandwidth Tradeoff

Sinusoidal response:

\[ \delta n(\omega) = \frac{G_0 \tau_n}{1 - i\omega\tau_n} \]

For constant injection, we had:

\[ R_\lambda = \frac{\Delta I}{P_{\text{opt}}} = \frac{\eta q}{\hbar \omega} \frac{\tau_n}{\tau_t} \]

For sinusoidal injection, this is modified as:

\[ R_\lambda(\omega) = \frac{\eta q}{\hbar \omega} \frac{\tau_n}{\tau_t} \frac{1}{1 - i\omega\tau_n} \]

- Quantum efficiency
- Photoconductive gain
- Normalized frequency response

For a fixed size device, \( \tau_t \) is fixed. So, if you want high photoconductive gain, \( \tau_n \) needs to be large, but that reduces the 3dB bandwidth.
AC + DC response: Given \( P(t) = P_{opt}(1 + m \cos(\omega t)) \) so \( G(t) = G_0(1 + m \cos(\omega t)) \),

Use simple superposition: 
\[
I(t) = I_p \left[ 1 + m \frac{1}{\sqrt{1 + \omega^2 \tau_n^2}} \cos(\omega t - \phi) \right],
\]

where 
\[
I_p = q\eta \frac{P_{opt}}{\hbar \omega} \frac{\tau_n}{\tau_t}.
\]

To talk in terms of rms (root-mean-square) optical power, replace \( mP_{opt} = \sqrt{2} P_{rms} \).

The photocurrent is then: 
\[
I(t) = I_{DC}(t) + I_{AC}(t) = I_p \left[ 1 + \frac{\sqrt{2} P_{rms}}{P_{opt}} \frac{P_{rms}}{P_{opt}} \frac{1}{\sqrt{1 + \omega^2 \tau_n^2}} \cos(\omega t - \phi) \right]
\]

and the rms of the AC portion of the photocurrent signal is:
\[
i_p = \sqrt{ \left( I_p \left[ \frac{2 P_{rms}^2}{P_{opt}^2} \frac{2}{1 + \omega^2 \tau_n^2} \cos^2(\omega t - \phi) \right] \right)^2 } = I_p \frac{P_{rms}}{P_{opt}} \frac{1}{\sqrt{1 + \omega^2 \tau_n^2}} = q\eta \frac{P_{rms}}{\hbar \omega} \frac{\tau_n}{\tau_t} \frac{1}{\sqrt{1 + \omega^2 \tau_n^2}}.
\]
Noise in Photoconductors (definitions)

Given photocurrent in the time domain \( i(t) \), we can discuss its Fourier transform \( i(f) \) in the frequency domain:

\[
i(t) = \int_{-\infty}^{\infty} i(f)e^{-2\pi ift} df
\]

\[
i(f) = \int_{-\infty}^{\infty} i(t)e^{2\pi ift} dt
\]

The time averaged power is:

\[
P = \frac{1}{T} \int_{-T/2}^{T/2} i^2(t) dt = \frac{1}{T} \int_{-\infty}^{\infty} |i(f)|^2 df \quad \text{using Parseval's theorem in the limit } T \to \infty.
\]

\[
P = \frac{2}{T} \int_{0}^{\infty} |i(f)|^2 df = \int_{0}^{\infty} S(f) df \quad \text{where } S(f) = \frac{2}{T} |i(f)|^2 \quad \text{is the power spectral density.}
\]
Noise

Since electric charge is discrete, the total number of carriers collected in a given time $T$ is a random variable. This gives photocurrent noise. The noise from such a process is usually Poisson distributed.

Consider a sequence of carrier collection events that occur at random times $t_i$. For each event, the current is increased by some quantity $h(t - t_i)$ where $h(t < 0) = 0$:

$$i(t) = \sum_{i=1}^{N_t} h(t - t_i) \text{ where } N_t \text{ is the # of events within time } T.$$

We can Fourier transform this as: $i(f) = \sum_{i=1}^{N_t} \mathcal{F}(h(t)|t_i)$. The ensemble average of $|i(f)|^2$ is:

$$\langle |i(f)|^2 \rangle = \left| \mathcal{F}(h(f)) \right|^2 \left( \sum_{i,j=1}^{N_t} 1 + \sum_{i\neq j}^{N_t} \sum_{j=1}^{N_t} \exp[2\pi if(t_i - t_j)] \right) = |h(f)|^2 \langle N_t \rangle = |h(f)|^2 \langle N \rangle T$$

where $\langle N \rangle = \frac{\langle N_T \rangle}{T}$ is the average number of events per second.

Thus, the noise spectral density is: $S(f) = \frac{2}{T} \langle |i(f)|^2 \rangle = 2 \langle N \rangle |h(f)|^2$
Shot Noise

Shot noise is due to the randomness in the number of charges collected in a given time interval. The origin of shot noise is the quantum nature of photons and charge carriers.

For low enough frequencies ($f \tau \ll 1$), we get the simple result that $h$ is constant: $h(f) = q$. The average current $\langle I \rangle = q \langle N \rangle$, where $\langle N \rangle$ is the average # of electrons injected per second. Thus, $S(f) = 2q \langle I \rangle$ is the noise spectral density for shot noise.

If we put a filter and measure the noise between $f$ and $f + \Delta f$, we would measure the shot noise to be: $\langle i_s^2(f) \rangle = S(f) \Delta f = 2q \langle I \rangle \Delta f$. 

In a photoconductor, each photogenerated carrier has a finite lifetime $\tau$, during which it can be make several round-trips through the circuit and generate gain. We assume this lifetime is itself a Poisson random variable with mean $\tau_n$ (i.e. on average, $\tau$ is the minority carrier lifetime). After some math, $\langle |h(f)|^2 \rangle = \frac{2q^2(\tau_n/\tau)^2}{1+(2\pi f \tau_n)^2}$.

Due to photoconductive gain, the average current is $I_p = \langle I \rangle = q \langle N \rangle \frac{\tau_n}{\tau_t}$.

Thus, $S(f) = \frac{4qI_p(\tau_n/\tau_t)}{1+(2\pi f \tau_n)^2}$ is the noise spectral density for generation-recombination noise.

The generation-recombination noise is: $\langle i_{GR}^2(f) \rangle = S(f) \Delta f = \frac{4qI_p(\tau_n/\tau_t)}{1+(2\pi f \tau_n)^2} \Delta f$.

Generation-recombination noise is due both to the randomness in the number of charges collected in a given time interval and to the randomness in the amount of photoconductive gain each charge experiences.
Thermal Noise (aka Johnson/Nyquist Noise)

In a photodetector, the random thermal motion of carriers contribute to a thermal noise current. Given a resistor $R$ and temperature $T$, the noise spectral density is:

$$S(f) = \frac{4}{R} \frac{hf}{e^{hf/k_BT} - 1} \approx \frac{4k_B T}{R} \text{ at low frequency } (hf \ll k_BT).$$

The thermal noise is:

$$\langle i_T^2(f) \rangle = S(f) \Delta f \approx \frac{4k_B T}{R} \Delta f.$$
Signal-to-Noise Ratio for Photoconductors

If a photoconductor is driven with an optical signal \( P(t) = P_{\text{opt}}(1 + m \cos(\omega t)) \),

we saw the AC rms signal was \( i_p = q\eta \frac{P_{\text{rms}} \tau_n}{h\omega} \frac{1}{\tau_t} \sqrt{1 + \omega^2 \tau_n^2} = q\eta \frac{m P_{\text{opt}} / \sqrt{2}}{h\nu} \frac{\tau_n}{\tau_t} \frac{1}{\sqrt{1 + \omega^2 \tau_n^2}} \).

The DC photocurrent was \( I_p = q\eta \frac{P_{\text{opt}} \tau_n}{h\nu} \).

Thus, the power signal-to-noise ratio for the photoconductor is:

\[
SNR = \frac{i_p^2}{\langle i_T^2 \rangle + \langle i_{GR}^2 \rangle} = \left( q\eta \frac{m P_{\text{opt}} / \sqrt{2} \tau_n}{h\nu} \frac{1}{\tau_t} \sqrt{1 + \omega^2 \tau_n^2} \right)^2 = \frac{1}{2} \left( q\eta \frac{P_{\text{opt}} \tau_n}{h\nu} \right)^2 \frac{m^2}{1 + \omega^2 \tau_n^2} \frac{4k_B T}{4qI_p (\tau_n / \tau_t)^2 \Delta f} + \frac{4qI_p (\tau_n / \tau_t)^2 \Delta f}{1 + (2\pi f \tau_n^2)^2} \Delta f.
\]

\[
SNR = \frac{1}{2} \left( q\eta \frac{P_{\text{opt}} \tau_n}{h\nu} \right)^2 \frac{m^2}{1 + \omega^2 \tau_n^2} \frac{4k_B T}{4qI_p (\tau_n / \tau_t)^2 \Delta f} + \frac{4qI_p (\tau_n / \tau_t)^2 \Delta f}{1 + (2\pi f \tau_n^2)^2} \Delta f.
\]
Signal-to-Noise Ratio for Photoconductors

We have:

\[
SNR = \frac{1}{4\Delta f} \frac{1}{k_B T + \frac{\tau_n}{R} \frac{q I_p}{\tau_t} 1 + \left(2\pi f \tau_n\right)^2}
\]

\[
SNR = \frac{1}{8\Delta f} \frac{\tau_t}{\tau_n q I_p R} \frac{k_B T}{1 + \left(2\pi f \tau_n\right)^2}
\]

\[
SNR = \frac{1}{8\Delta f} \frac{\eta \frac{m^2}{P_{opt}}}{\frac{1}{h \nu} \frac{1}{1 + \omega^2 \tau_n^2}}
\]

\[
\therefore \quad SNR = \frac{\eta m^2 \left(\frac{P_{opt}}{h \nu}\right)}{8\Delta f \left[1 + \frac{\tau_t}{\tau_n q I_p R} \left(1 + \omega^2 \tau_n^2\right)\right]}
\]
The noise equivalent power (NEP) is defined as the amount of optical power that yields a signal-to-noise ratio of one when the detector bandwidth is 1 Hz. Note $p_{rms} = mP_{opt} / \sqrt{2}$.

The specific detectivity, or $D^*$, for a photodetector is a figure of merit used to characterize performance taking into account how the detector's noise increases in proportion to the square root of detector area and detector bandwidth:

$$D^* = \frac{\sqrt{A\Delta f}}{NEP} \text{ cm (Hz)}^{1/2} / W$$

The specific detectivity allows one to compare the intrinsic properties of two detectors since it does not depend on area or bandwidth. Higher values of detectivity indicate higher sensitivity, making the detector more suitable for detecting low light signals.
Find the \( \text{NEP} \):

\[
\text{Answer: } \text{NEP} = \frac{\sqrt{A\Delta f}}{D^*} = \frac{2 \text{mm} \sqrt{\Delta f}}{2.5 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}}.
\]

\[
\Delta f \approx \frac{0.35}{t_r} = 35 \text{kHz} = 35000 \text{Hz} \quad \text{so}
\]

\[
\text{NEP} \approx \frac{0.2 \text{cm} \sqrt{35000} \cdot \text{Hz}^{1/2}}{2.5 \times 10^9 \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}} = 15 \text{nW}
\]
Sample Spec Sheet (NEP and D*)

PbS Photoconductor: 1.0 - 2.9 μm

- Good Performance for 1.0 - 2.9 μm Range
- For Detection of CW Light We Recommend an Optical Chopper
- Also Comes as a Packaged, Amplified Detector, the PDA306

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<th>Peak Sensitivity</th>
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<td>9 mm²</td>
<td>TO-5</td>
<td>200 μs</td>
<td>2.2 μm (Typ.)</td>
<td>2 x 10^6 V/W (Min)</td>
<td>5.0 x 10^7 V/W (Typ.)</td>
<td>1 x 10^{11} cmHz^{1/2}/W</td>
<td>0.25 - 2.5 MΩ</td>
<td>STUP ST02P</td>
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Note: D* is better

Find the NEP:

Answer: \[ \text{NEP} = \frac{\sqrt{A \Delta f}}{D^*} = \frac{3 \text{mm} \sqrt{\Delta f}}{10^{11} \text{cm} \cdot \text{Hz}^{1/2} / W} \]

\[ \Delta f \approx \frac{0.35}{t_r} = 1.75 \text{kHz} = 1750 \text{Hz} \] so

\[ \text{NEP} \approx \frac{0.3 \text{cm} \sqrt{1750} \cdot \text{Hz}^{1/2}}{10^{11} \text{cm} \cdot \text{Hz}^{1/2} / W} = 125 \text{pW} \]

Junction Diodes

p-n (§ 15.2) and p-i-n (§ 15.3)
Continuity Equation on the n-side for minority carriers ($p_n$):

$$\frac{\partial p_n}{\partial t} = G(x,t) - \frac{\delta p_n}{\tau_p} - \frac{1}{q} \frac{\partial}{\partial x} J_p(x)$$

Note that: $p_n = p_{n0} + \delta p_n$

In the quasi-neutral region, $E \approx 0$, so diffusion current is dominant:

$$J_p(x) \approx -qD_p \frac{\partial p_n}{\partial x}$$

Under steady-state conditions, assuming uniform illumination:

$$D_p \frac{\partial^2}{\partial x^2} \delta p_n - \frac{\delta p_n}{\tau_p} = -G_0$$

The solution to this equation is given by:

$$\delta p_n(x) = c_1 e^{-(x-x_n)/L_p} + c_2 e^{(x-x_n)/L_p} + G_0 \tau_p$$

where $L_p = \sqrt{D_p \tau_p}$

For a given voltage $V$, minority carriers are injected on either side of the depletion region:

$$p_n(x = x_n) = p_{n0} e^{qV/k_BT} \quad \text{and} \quad \delta p_n(x_n) = p_{n0} \left(e^{qV/k_BT} - 1\right)$$

so:

$$\delta p_n(x) = \left[p_{n0} \left(e^{qV/k_BT} - 1\right) - G_0 \tau_p\right] e^{-(x-x_n)/L_p} + G_0 \tau_p \quad \text{(note } c_2 = 0)$$
I-V Characteristic

The hole current density can be determined from $\delta p_n(x)$:

$$J_p(x) = -qD_p \frac{\partial}{\partial x} \delta p_n(x) = q \frac{D_p}{L_p} \left[ p_{n0} \left( e^{qV/k_B T} - 1 \right) - G_0 \tau_p \right] e^{-(x-x_n)/L_p}$$

at the edge of the depletion region:

$$J_p(x_n) = q \frac{D_p}{L_p} p_{n0} \left( e^{qV/k_B T} - 1 \right) - qG_0L_p$$

similarly, for electrons:

$$J_n(-x_p) = q \frac{D_n}{L_n} n_{p0} \left( e^{qV/k_B T} - 1 \right) - qG_0L_n$$

The total current is given by (assuming no recombination in depletion region):

$$I = A \left[ J_p(x) + J_n(-x_p) \right] = I_0 \left( e^{qV/k_B T} - 1 \right) - I_{ph}$$

$$I_0 = qA \left[ \frac{D_p}{L_p} p_{n0} + q \frac{D_n}{L_n} n_{p0} \right] \quad \text{and} \quad I_{ph} = qAG_0 \left( L_p + L_n \right)$$

Note also:

$$C_j = A \left[ \frac{q\epsilon}{2(V_0 - V)} \frac{N_D N_A}{N_D + N_A} \right]^{1/2}$$

Problems with p-n structures:

- Small optical absorption
  - Needs to be within ~1 diffusion length
- Slow diffusion process
- High junction capacitance
Current Responsivity:

The current delivered for an incident optical power at a specified wavelength is given by:

The RMS photon flux density for a given wavelength is given by: \( \Phi(\lambda) = \frac{P_\lambda}{h \nu A} \)

The RMS photocurrent is given by: \( i_p = q \eta \Phi(\lambda) A = q \eta \frac{P_\lambda}{h \nu} \)

The current responsivity is thus: \( R_\lambda = \frac{i_p}{P_\lambda} = \eta \frac{q}{h \nu} \).

where \( \eta \) includes the intrinsic quantum efficiency, the reflection, and absorption depth:

\[ \eta = \eta_i (1 - R)(1 - e^{-\alpha d}) \]

Clearly, we want to maximize \( R_\lambda \) by maximizing \( \eta \).
p-n Junction Figures of Merit

**$R_0A$ Product:**

In many direct detection applications, the photodiode is operated at zero bias. Thus, a useful figure of merit is the differential resistance at zero bias multiplied by junction area $R_0A$.


DOI: [http://dx.doi.org/10.1063/1.120551](http://dx.doi.org/10.1063/1.120551)

It is desirable to have large $R_0A$ because at a given temperature $T$, the Johnson-noise-limited specific detectivity $D^*$ of a photodiode is given by the current responsivity $R_\lambda$ and the dynamic impedance $R_0A$ at zero voltage: $D^* = R_\lambda \sqrt{R_0A / 4k_B T}$

Note that: $(R_0A)^{-1} = \frac{1}{A} \frac{dI}{dV} \bigg|_{V=0} = \frac{dJ}{dV} \bigg|_{V=0}$. Using the expression for current density:

$$(R_0A)^{-1} = \frac{q^2}{k_B T} \left( \frac{D_p}{L_p} p_{n0} + \frac{D_n}{L_n} n_{p0} \right) = \frac{q^2}{k_B T n_i^2} \left( \frac{D_p N_D}{L_p} + \frac{D_n N_A}{L_n} \right) = \frac{q}{n_i^2} \sqrt{\frac{q}{k_B T}} \left( N_D \sqrt{\frac{\mu_p}{\tau_p}} + N_A \sqrt{\frac{\mu_n}{\tau_n}} \right)$$
p-n Junction Figures of Merit

Signal to Noise Ratio:
\[
\frac{S}{N} = \frac{i_p}{\sqrt{\langle i_n^2 \rangle}} = \frac{R_\lambda P_\lambda}{\sqrt{\langle i_n^2 \rangle}}
\]

Noise Equivalent Power (NEP):
\[
NEP\text{(Watts)} = \frac{\sqrt{\langle i_n^2 \rangle}}{R_\lambda} \quad \text{(just set SNR = 1)}
\]

Specific Detectivity \(D^*_\lambda\):
\[
D^*_\lambda = \sqrt{\frac{A\Delta f}{\text{NEP}}} = \frac{R_\lambda \sqrt{A\Delta f}}{\sqrt{\langle i_n^2 \rangle}} \text{cm(}Hz\text{)}^{1/2} / W
\]

Using simplifications for RMS current noise:

At zero bias: \(D^*_\lambda = \frac{q\eta}{h\nu} \frac{1}{\sqrt{\left[\frac{4k_B T}{R_0 A} + 2q^2 \eta \Phi_B\right]}}\)

When thermal noise is dominant,
\[
(D^*_\lambda)_T = \frac{q\eta}{h\nu} \sqrt{\frac{R_0 A}{4k_B T}} = R_\lambda \sqrt{\frac{R_0 A}{4k_B T}} \quad \text{as stated before.}
\]

When the thermal noise is negligible, the photocurrent is background radiation limited:
\[
(D^*_\lambda)_{BLIP} = \frac{1}{h\nu} \sqrt{\frac{\eta}{2\Phi_B}}
\]

BLIP=background limited infrared photodetector

33
To solve the pn photodiode issues, an intrinsic region used for absorption is inserted to make a p-i-n photodiode. Assuming light is incident on the left $p^+$ side, \( G(x) = \eta_i (1 - R) \Phi(\lambda) \alpha e^{-\alpha x} \)

where \( \Phi(\lambda) = \frac{P_{opt}}{A} \). Assume \( \alpha W \gg 1 \).

The total injected # of photoelectrons per area per second is: \( S_0 = \int_{0}^{\infty} G(x)dx = \eta_i (1 - R) \Phi(\lambda) \).

After some math, it can be shown that:

\[
J_{pin} = J_{drift} + J_{diff} = -qS_0 = -q\eta_i (1 - R) \Phi(\lambda)
\]

Compare to pn photodetector:

\[
J_{pn} = -qG_0(L_p + L_n) \approx -qS_0 \alpha (L_p + L_n).
\]

the intrinsic layer allows absorption anywhere in the i-layer to produce current, resulting in higher external efficiency and lower noise.
Spec Sheet for p-i-n Photodiode

Biased InGaAs Detectors: 500 - 2600 nm

Find $D^*$ for DET10C:

Answer: $D^* = \frac{\sqrt{A \Delta f}}{NEP} = \frac{0.9 \text{mm} \sqrt{\Delta f}}{2.5 \times 10^{-14} W}$.

$\Delta f \approx \frac{0.35}{t_r} = 35 \text{MHz} = 3.5 \times 10^7 \text{Hz}$ so

$NEP \approx \frac{0.09 \text{cm} \sqrt{3.5 \times 10^7 \text{Hz}}}{2.5 \times 10^{-14} W} = 2.13 \times 10^{16} \text{cm} \cdot \text{Hz}^{1/2} / W$

Note $D^*$ is significantly better than the p-n photodiode.
APDs

§ 15.4
Applications for APDs

• Telecommunications (long haul)
• Scientific & Medical Instrumentation
• Photon Counting
• Distance Measurement / Range Finding
Basic Principles and Definitions

• The absorption of photons within the multiplication region creates electron-hole pairs
• Within this region, the electrons and holes are accelerated by the electric field and produce more electron-hole pairs through impact ionization
• To minimize noise, it’s best if only one type of carrier ionizes pairs
• Definitions:
  – $\alpha_n$: electron ionization coefficient, number of e-h pairs created per unit distance per incident electron ($\text{cm}^{-1}$)
  – $\alpha_h$: hole ionization coefficient, number of e-h pairs created per unit distance per incident hole ($\text{cm}^{-1}$)

Ionization Coefficient Dependence on Electric Field:

$$\alpha_n (E) = \alpha_0 e^{-C_n/E}$$

$$\beta_p (E) = \beta_0 e^{-C_p/E}$$
Simplified Analysis: Single Carrier Ionization

**Electron Multiplication:**

Consider the current density at two planes in the avalanche region that are a distance "\(\Delta x\)" apart:

Plane 1: Current density is \(J_n(x)\)

Generated e-h pairs in \(\Delta x\) is \(\alpha_n \Delta x J_n(x)\)

Plane 2: Current density is \(J_n(x + \Delta x) = J_n(x) + \alpha_n \Delta x J_n(x)\)

Rewriting

\[
\frac{J_n(x + \Delta x) - J_n(x)}{\Delta x} = \frac{d}{dx} J_n(x) = \alpha_n J_n(x)
\]

In the most general case, \(\alpha_n = \alpha_n(x)\) so:

\[
J_n(x) = J_n(0) e^\int_0^x \alpha_n(x') dx'
\]

The multiplication factor "M" is defined as:

\[
M_n = \frac{J_n(W)}{J_n(0)} = e^\int_0^W \alpha_n(x') dx'
\]

For uniform \(\alpha\):

\[
J_n(x) = J_n(0) e^{\alpha_n x} \quad \text{and} \quad M_n = e^{\alpha_n W}
\]

The current multiplication factor increases exponentially with the width of the multiplication region.
Hole Multiplication:

For holes propagating in the -x direction:

\[- \frac{d}{dx} J_p(x) = \beta_p J_p(x) \]

\[ J_p(x) = J_p(W) e^x \]

The hole multiplication factor "M_p" is defined as:

\[ M_p = \frac{J_p(0)}{J_p(W)} = e^{\int_0^W \alpha_n(x') dx'} \]

For uniform \( \beta \): \( J_p(x) = J_p(W) e^{\beta_p(W-x)} \) and \( M_p = e^{\beta_p W} \)
Coupled Electron - Hole Ionization Equations:

\[
\frac{d}{dx} J_n(x) = \alpha_n(x) J_n(x) + \beta_p(x) J_p(x) + qG(x)
\]

\[
-\frac{d}{dx} J_p(x) = \alpha_n(x) J_n(x) + \beta_p(x) J_p(x) + qG(x)
\]

Subtracting these equations leads to:

\[
\frac{d}{dx} (J_n(x) + J_p(x)) = 0
\]

The implication of this is that \( J = J_n(x) + J_p(x) = \text{constant} \)

Adding the top two equations and eliminating \( J_p = J - J_n \):

\[
\frac{d}{dx} J_n(x) - \frac{d}{dx} J_p(x) = 2 \left( \alpha_n(x) J_n(x) + \beta_p(x) J_p(x) + qG(x) \right)
\]

\[
2 \frac{d}{dx} J_n(x) = 2 \left( \alpha_n(x) J_n(x) + \beta_p(x) J - \beta_p(x) J_n(x) + qG(x) \right)
\]

\[
\frac{d}{dx} J_n(x) - \alpha_n(x) J_n(x) + \beta_p(x) J_n(x) = \beta_p(x) J + qG(x)
\]
Coupled Electron - Hole Ionization Equations (continued):

\[
\frac{d}{dx} J_n(x) - \alpha_n(x) J_n(x) + \beta_p(x) J_n(x) = \beta_p(x) J + qG(x)
\]

or

\[
\frac{d}{dx} J_n(x) - \left[ \alpha_n(x) - \beta_p(x) \right] J_n(x) = \beta_p(x) J + qG(x)
\]

This equation has the form

\[
\frac{d}{dx} y(x) + p(x) y(x) = Q(x)
\]

which has the solution:

\[
y(x) = \frac{\int_{x_0}^{x} dx' Q(x') e^{\int_{x_0}^{x'} p(x')dx'}}{e^{\int_{x_0}^{x} p(x')dx'}} + y(x_0)
\]
Solving for Current Densities

Using initial conditions and boundary conditions, it can be shown:

\[
J_n(x) = e^{\phi(x)} \left[ J \int_0^x \beta_p(x') e^{-\phi(x')} dx' + q \int_0^x G(x') e^{-\phi(x')} dx' + J_n(0) \right]
\]

and

\[
J = \left( \frac{1}{1-B} \right) \left[ J_p(W) + J_n(0) e^{\phi(W)} + q \int_0^W G(x') e^{\int_x^W [\alpha_n(x') - \beta_p(x')] dx'} \right]
\]

Where:

\[
\phi(x) = \int_0^x [\alpha_n(x') - \beta_p(x')] dx' \quad \text{and} \quad B = \int_0^W dx' \beta_p(x') e^{\int_x^W [\alpha_n(x') - \beta_p(x')] dx'}
\]

A similar method can be used to solve for \( J_p \) and \( J \):

\[
J_p(x) = e^{-\int_x^W [\alpha_n(x') - \beta_p(x')] dx'} \int_x^W dx' \left[ \alpha_n(x') J + qG(x') \right] e^{\int_x^W [\alpha_n(x') - \beta_p(x')] dx'}
\]

\[
J = \left( \frac{1}{1-A} \right) \left[ J_n(0) + J_p(W) e^{-\phi(W)} + q \int_0^W G(x') e^{-\int_0^x [\alpha_n(x') - \beta_p(x')] dx'} \right]
\]

Where:

\[
A = \int_0^W dx' \alpha_n(x') e^{-\int_0^x [\alpha_n(x') - \beta_p(x')] dx'}
\]
Special Case: No Generation and Constant/Equal Ionization Coefficients

For the case where there is no optical generation of carriers in the active region \((G = 0)\) and where \(\alpha = \beta\) are constants:

\[
\frac{d}{dx} J_n(x) - \alpha_n J_n(x) + \beta_p J_n(x) = \beta_p J + qG(x)
\]

\[
\frac{d}{dx} J_n(x) = \beta_p J
\]

\[\therefore J_n(x) = J_n(0) + \beta_p Jx\]

Evaluated at \(x = W\): \(J_n(W) = J_n(0) + \beta_p JW\)

Evaluating \(J = J_n(x) + J_p(x)\) at \(x = W\) gives: \(J_n(W) = J - J_p(W)\)

Thus, \(J = \frac{J_n(0) + J_p(W)}{1 - \beta_p W}\)
Noise in APDs

- Field accelerates carriers (kinetic energy > $E_g$)
- Transfers energy to generate electron hole pair $\rightarrow$ Gain!
- Stochastic nature of impact ionization $\rightarrow$ Noise!
  - Limited by $k$-ratio:
    $$\langle i^2 \rangle \propto \langle M \rangle k = \langle M \rangle \frac{\beta}{\alpha}$$

Slide courtesy of S. Bank (UT Austin)
Noise and Bandwidth

InAs!

\[ k = \frac{\beta}{\alpha} << 1 \]

Most III-V’s

\[ k = \frac{\alpha}{\beta} \approx 1 \]

\[ k = \frac{\beta}{\alpha} >> 1 \]

(Quiet)

(Noisy)

(Noisy)

(Very fast)

(Slow!)

(Fast)

Slide courtesy of S. Bank (UT Austin)
APD Excess Noise

- Multiplication is a random process
- Any random process introduces noise
- Secondary random processes further increase noise
- Increasing the magnitude of secondary random processes relative to primary random processes increases noise even further

Excess Noise:

\[ F(M) = \frac{\langle M^2 \rangle}{\langle M \rangle^2} \]

\[ F_n = \frac{\beta_p}{\alpha_n} \langle M_n \rangle + \left( 1 - \frac{\beta_p}{\alpha_n} \right) \left( 2 - \frac{1}{\langle M_n \rangle} \right) \]

\[ F_p = \frac{\alpha_n}{\beta_p} \langle M_p \rangle + \left( 1 - \frac{\alpha_n}{\beta_p} \right) \left( 2 - \frac{1}{\langle M_p \rangle} \right) \]

Other Noise Sources in APDs:

Multiplication (Gain) Noise: \[ \langle i_M^2 \rangle = 2q \langle M \rangle I_p F(M) \langle M \rangle I_p \]

Shot Noise: \[ \langle i_S^2 \rangle = 2q \left( I_p + I_B + I_D \right) \langle M \rangle^2 F(M) \langle M \rangle B \]

Thermal Noise: \[ \langle i_S^2 \rangle = \frac{4k_B T}{R_{eq}} B \]
A separate absorption-multiplication APD is used to reduce dark current at high reverse bias. Specifically, the dark current from carriers tunneling across the bandgap.
APD Excess Noise

Green: APDs that Epitaxx is selling for 10 GB/s receivers
Blue: (S. Bank) Thin AlInAs multiplication regions
Red: Si APD – the standard for low noise
Black: (S. Bank) Impact ionization engineered APD

If you can precisely control how many impact ionization events occur, you can reduce the excess noise below the k=0 limit.

Figure: Joe Campbell UVA.

Slide courtesy of S. Bank (UT Austin)
Intersubband quantum-well photodetectors

§ 15.5
Quantum Well Infrared Photodetectors (QWIPs)

• Lattice matched GaAs/Al$_x$Ga$_{1-x}$As
  – Much better crystal quality than HgCdTe.
• Can control: wavelength, dark current, responsivity
  – Well width and barrier height
• Spectrum response are much narrower and sharper than HgCdTe detectors. Highest QE demonstrated is 32%.
• Need electrons in well $\rightarrow$ n-doped $\rightarrow$ dark current
• Thermionic escape $\rightarrow$ Low T

Slide courtesy of S. Bank (UT Austin)
Many transitions to play with

Fig. 38  Energy-band diagrams of QWIPs under bias showing (a) bound-to-bound intersubband transition, (b) bound-to-continuum transition, and (c) bound-to-miniband transition in superlattice.

Slide courtesy of S. Bank (UT Austin)
Need special geometries

- We saw previously that the selection rule for intersubband transitions require the polarization to have a z-component (TM)
  - For p-doped QWIPs, valence band mixing allows absorption for TE
- Two solutions above; grating is favorable for 2-D arrays (imaging)
Solar Cells

§ 15.6
Integrated intensity is 1350 W/m²
That’s a lot of power if we can efficiently harvest it
Ideal IV for solar cell

\[ I = I_0 (e^{qV/\gamma k_B T} - 1) - I_{ph} \]

\[ I_{sc} = I_{ph}; \quad V_{oc} = \frac{\gamma k_B T}{q} \ln \left( \frac{I_{ph}}{I_0} + 1 \right) \]

Find the maximum power point by maximizing:

\[ P = IV = \left[ I_0 (e^{qV/\gamma k_B T} - 1) - I_{ph} \right] V \]

with respect to \( V \)

\[ FF = \frac{I_m V_m}{I_{sc} V_{oc}} \]

\[ \eta = \frac{I_m V_m}{P_{opt}} \quad \text{(recall} \ I_{ph} \ \text{depends on} \ P_{opt}) \]
Applications of the pn junction

\[ I = I_0 \left( e^{qV/\gamma k_B T} - 1 \right) - I_{ph} \]

- **Quad 1: LED / LASER**
  - Drives a load
  - \( P = 0 \text{nW} \)

- **Quad 2: Photodiode**
  - Converts photocurrent to a voltage
  - \( P = 5 \text{nW} \)

- **Quad 3: Photodiode**
  - \( P = 10 \text{nW} \)

- **Quad 4: Solar Cell**
  - \( P = 1 \text{nW} \)

\[ V = \frac{q}{k_B T} \ln \left( \frac{I}{I_0} \right) \]
Assignments
Assignments

• Reading
  – Physics of Photonic Devices (S.L. Chuang)
    • Tues 3/26: §’s 8.2 C&C
    • Thurs 3/28: §’s 8.1, 8.2
    • Tues 4/2: N/A
    • Thurs 4/6: §’s 14.2, 14.3
    • Tues 4/9: §’s 14.4, 14.5, 14.6
    • Thurs 4/11: §’s 15.1, 2.4
    • Tues 4/16: §’s 15.2, 15.3
    • Thurs 4/18: §’s 15.4, 15.5
  – Diode Lasers and Photonic Integrated Circuits (Coldren & Corzine)
    • § 8.2.5
    • §’s 3.6-3.7, 8.2.3-8.2.4
    • §’s 6.6-6.8
    • Appendix 1, 2, 3, 9 (Supplemental)
Topics for Next Lecture
Agenda for Thursday, 4/11

- Continue VCSELs
- Laser Modulation
- Coupled Waveguides
Thank You for Listening!
Course Purpose & Objectives
Course Purpose

• Cover the theory and design of semiconductor devices used in optical communication systems and electronic-photonic integrated circuits
Course Objectives

• Discuss, at a graduate level, key topics in semiconductor physics
• Discuss, at a graduate level, key topics in electromagnetics as applied to photonic devices
• Provide an understanding of active photonic devices used in optical communication systems and photonic integrated circuits
• Provide an understanding of passive photonic devices used in optical communication systems and photonic integrated circuits
Overlap With ECE/PHYS Courses

- Quantum Mechanics (PHYS 486/487)
- Semiconductor Physics (ECE 488)
- E&M (ECE 452/520)

ECE 536
Course Schedule
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**Subject to Change**
Grading, Expectations, and Policies
Determination of Grade

• Homework: 20%
• Exam I: 25%
• Exam II: 25%
• Class Participation & Term Project Presentation: 15%
• Term Project Report: 15%
Homework

• Assigned per posted class schedule on Thursdays, due 1 week later

• TA is Fu-Chen Hsiao, 3211 MNTL
  – Office hours Wednesday from 10-11am, 4034 ECEB
  – TA: good first contact for questions on homework

• Do not copy solutions from others in class or from other sources
Term Project

- Collaborative presentation: teams of 2
- Individual paper
- Details and a list of topics will be provided in early February
Expectations

• Diligence
  – Attend class & participate

• Honesty
  – No cheating on exams or homework
  – Original work on term project
  – Accurate/legitimate representation of any issues affecting homework/exams/project

• Mutual Respect

• Maturity
  – Graduate-level class
Policies

• Where applicable, general university policies on academic affairs will be used
• Any issues involving homework, exams, semester project, etc. should be disclosed and discussed as soon as the issue is known
Text Errata
Text Errata

• Text errata provided by Professor Chuang will be posted on the class website
  – I will include additional errata in the lecture slides

• Handout: inside book cover

• Additional errata:
  – Equation 3.2.18 “=“ should be “>”
    • $|z| > L/2$
  – Equation 3.2.23 “=“ should be “<“
    • $|z| < L/2$
  – Equation 3.2.23: “L/2” not “L2” in exponent
1) Equation 1.3.1 should be:
\[ a(A_x B_{1-x} C) = xa(AC) + (1 - x)a(BC) \]
where \( a(AC) \) is the lattice constant of the binary compound AC and...

2) Equation 1.3.2 should be:
\[ E_g(A_x B_{1-x} C) = xE_g(AC) + (1 - x)E_g(BC) - bx(1 - x) \]

3) Other printing errors in book - see errata posted on website

Errors in some copies of Second Edition
Errata

• Equation 3.6.15 should be:

\[ a_m^{(0)}(t = 0) = 0 \quad \text{not} \quad a_m^{(0)}(t) = 0 \]
Correction: Typo in Book

- Pg. 41, top of page, between equations 2.3.3 and 2.3.4
- Current Text is: \(0 = Bn_o p_o = e_r\)
- Should Be: \(0 = Bn_o p_o - e_r\)

The consequence of this is that \(Bn_o p_o = e_r\) in equilibrium where there is no optical generation or electrical injection of carriers.
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