Photodetectors and Solar Cells

1. Photodetector noise
2. Performance parameters
3. Photoconductors
4. Junction photodiodes
5. Solar cells

Reading: Liu, Chapter 14: Photodetectors; Bhattacharya, Chapter 10: Solar Cells
Ref: Bhattacharya, Sec. 8.2-8.3
Photodetector Noise

Shot noise: 
\[
\bar{i}_{n,sh}^2 = 2eB(i_s + i_b + i_d)
\]
\[
\bar{i}_{n,sh}^2 = 2eBGF(i_s + i_b + i_d)
\]  for photodetectors with internal gain \( G \)

\( i_s \) : signal current
\( i_b \) : background radiation current
\( i_d \) : dark current

\( F = G^2 / G' \) : Excess noise factor

Thermal noise: 
\[
P_{n,th} = 4k_BTR = \bar{i}_{n,th}^2R = \bar{v}_{n,th}^2 / R
\]

Exercise: A photodetector without internal gain has a load resistance of \( R = 50 \ \Omega \) and a bandwidth of \( B = 100 \ \text{MHz} \). Input optical power is adjusted to generate photocurrent ranging from 1 \( \mu \text{A} \) to 10 mA. Discuss the behavior of its SNR vs photocurrent. At what photocurrent is the shot noise equal to thermal noise?
Noise Characteristics of Photodetectors

<table>
<thead>
<tr>
<th>Photodiode</th>
<th>GaP</th>
<th>Si</th>
<th>Ge</th>
<th>InGaAs</th>
<th>PbS (PC)</th>
<th>PbSe (PC)</th>
<th>InSb (PC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schottky</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−10°C</td>
<td>−10 °C</td>
<td>−10°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>λ_{peak} (μm)</th>
<th>0.44</th>
<th>0.96</th>
<th>1.5</th>
<th>1.55</th>
<th>2.4</th>
<th>4.1</th>
<th>5.5</th>
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</thead>
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<thead>
<tr>
<th>I_d or R_d</th>
<th>10 pA</th>
<th>0.4 nA</th>
<th>3 μA</th>
<th>5 nA</th>
<th>0.1–1 MΩ</th>
<th>0.1–1 MΩ</th>
<th>1–10 kΩ</th>
</tr>
</thead>
</table>

<table>
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<tr>
<th>NEP W Hz^{1/2}</th>
<th>5.4×10^{-15}</th>
<th>1.6×10^{-14}</th>
<th>1×10^{-12}</th>
<th>4×10^{-14}</th>
<th>-</th>
<th>-</th>
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</thead>
</table>

<table>
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<tr>
<th>D* cm Hz^{1/2}/W</th>
<th>1×10^{13}</th>
<th>1×10^{12}</th>
<th>1×10^{11}</th>
<th>5×10^{12}</th>
<th>1×10^{9}</th>
<th>5×10^{9}</th>
<th>1×10^{9}</th>
</tr>
</thead>
</table>

Graph showing NEP (W/Hz^{1/2}) vs. dark current (nA) with data points for Si pin (25 °C), GaAsP Schottky (25 °C), InGaAs pin (25 °C), InGaAs pin (−10 °C), and InGaAs pin (−20 °C). The slope of the line is 1/2.
Discussion: Noise Characterization for a QD Photoconductor

This figure is from the paper “Ultrasensitive solution-cast quantum dot photodetectors” published in Nature in 2006. The device structure is shown in Slide 7. The noise characterization was done using a lock-in amplifier, which reported a noise current in $A/Hz^{1/2}$. From the experimental results presented in Figure (b), determine the NEP and root-mean-square noise current at various modulation frequencies.

$$NEP = \frac{\text{rms}(i_n)}{R} = \frac{(2ei_b^2 + 2ei_d^2 + 4k_BT/R)^{1/2}}{R} B^{1/2} \, (W)$$

$$D^* = \frac{(AB)^{1/2}}{(NEP)} \, (cm \cdot Hz^{1/2} \cdot W^{-1}) \text{ Normalized detectivity}$$
Dynamic Range (DR) \[ = 10 \log \frac{P_s^{sat}}{NEP} \]
Considering the rectangular time interval used to define the electrical bandwidth $B$ when discussing noise,

$$f_{3dB} = \frac{0.35}{t_r}$$

$$f_{3dB} = \frac{0.443}{T} = 0.886B$$
Photoconductor Structure and Principle

Photogenerated carriers drift across the photoconductor multiple times during their lifetime. → Gain
Exercise: Photoconductor Gain

An n-type GaAs intrinsic photoconductor for $\lambda = 850\text{nm}$ has the following parameters: $l = w = 100\ \mu\text{m}$, $d = 1\ \mu\text{m}$, $\alpha = 1 \times 10^4\ \text{cm}^{-1}$ at 850 nm, $\eta_{\text{coll}} = 1$, and $\eta_t = 1$ with antireflection coating on the incident surface. It’s lightly doped with $n_0 = 1 \times 10^{12}\ \text{cm}^{-3}$. GaAs has the following characteristic parameters at 300 K: $\varepsilon = 13.2\varepsilon_0$ at DC or low frequencies, $\mu_e = 8500\ \text{cm}^2\text{V}^{-1}\text{s}^{-1}$, $\mu_h = 400\ \text{cm}^2\text{V}^{-1}\text{s}^{-1}$, $n_i = 2.33 \times 10^6\ \text{cm}^{-3}$. The bimolecular recombination coefficient $B = 8 \times 10^{-11}\ \text{cm}^3\text{s}^{-1}$.

(a) Find the external quantum efficiency for this device.
(b) Under an incident optical power of $P_s = 1\ \mu\text{W}$ on the detection area, what is the carrier lifetime assuming bimolecular recombination dominates?
(c) Find the dark conductivity. The device is biased at $V = 2\ \text{V}$. Is the device limited by a space-charge effect at any level of input optical signal?
(d) What are the gain and the responsivity of this device?
(e) What is the space charge-limited gain?
Exercise: Photoconductor Noise

The photoconductor considered in the previous exercise is loaded with a sufficiently large resistance such that the resistive thermal noise is negligible compared to the shot noise from its dark current at the operating temperature of 300 K. The background radiation noise is also negligible. The incident wavelength $\lambda = 850 \text{nm}$.

(a) Find the dark resistance of the device. Then, find its dark current at 2V bias.

(b) Find the NEP of the device for a bandwidth of 1 Hz, $\text{NEP}/B^{1/2}$ (W Hz$^{-1/2}$).

(c) Find the specific detectivity $D^*$ for the device.

(d) Discuss how gain affects the NEP for a photoconductor.
p-n Junction Photodiode

(a) Schematic of a p-n junction photodiode with an antireflection coating.

(b) Energy band diagram showing the depletion region, positive donors, and negative acceptors.

(c) Electric field profile within the depletion region.

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Photogeneration:

- Small $\alpha$: Long $\lambda$
- Medium $\alpha$: Medium $\lambda$
- Large $\alpha$: Short $\lambda$

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Drift and Diffusion:

- Long $\lambda$:
  - Drift dominates
- Medium $\lambda$:
  - Drift and diffusion balance
- Short $\lambda$:
  - Diffusion dominates

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$I_{ph}$: Photogenerated current

$V_{out}$: Output voltage

$R$: Resistance

$E$: Electric field

$W$: Width of the depletion region

$\rho_{net}$: Net charge density

$eN_d$: Number of positive donors

$-eN_a$: Number of negative acceptors

$E(x)$: Electric field as a function of position $x$
**p-i-n Photodiode**

Drawbacks of p-n junction photodiode:
1. High junction capacitance $\rightarrow$ long RC time.
2. Thin depletion layer $\rightarrow$ low quantum efficiency.
3. Depletion width changes as bias changes.
4. Non-uniform e-field in the depletion region.

Transit time across the depletion layer $\tau_{tr} = \frac{W}{v_d}$

$\rightarrow$ Desirable to operate at saturation velocity $(v_d = v_{sat})$

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

![Diagram showing drift velocity vs. electric field for holes and electrons in Si.](image)

$$i_{ph} = \frac{eP_s (1 - R)}{h\nu} \left[1 - \exp(-\alpha W)\right]$$
Photodetection Modes
Exercise: Si p-i-n Photodiode

Discuss the responsivity of a Si p-i-n photodiode at $\lambda = 900$ nm, given $P_s = 100$ nW and the reflection coefficient of the top surface = 32%. What would be the photocurrent and responsivity if the depletion layer thickness is 20 $\mu$m?

What would be the maximum responsivity given an ideal device structure? Discuss the possible drawbacks of such a structure.

For 20 $\mu$m-thick depletion layer, what’s the 3-dB cutoff frequency assuming saturation velocities are achieved for both electrons and holes, and the photodiode bandwidth is limited by its transit time?
Solar Radiation Spectrum

Solar cell aircraft Helios
(Source: NASA Dryden Research Center)

AM0: Solar spectrum in outer space
AM1: Solar spectrum at sea level under normal light incidence
AM2: Solar spectrum at an incident angle resulting in twice the path length through the atmosphere
Example: Solar Cell Driving a Load

Solar cell area: 1cm x 1cm
Illumination light intensity: 900 W m\(^{-2}\)
Load resistance: 16 Ohm

What are the current and voltage in the circuit?
What is the power delivered to the load?
What is the efficiency of the solar cell?
Assume it is operating close to the maximum efficiency point, what is the fill factor?
Absorption isn’t the Whole Story

Anti-reflection surface is necessary

Light-trapping structures are desirable

Atwater and Polman, “Plasmonics for improved PV devices,” Nature Materials 2010
Utilizing the Full Solar Spectrum

Multi-junction or tandem structure

Tandem colloidal QD solar cell

Sargent group, Nature Photonics (2011)