EE 443/CS 543 Optical Fiber Communications
Dr. Donald Estreich
Fall Semester

Lecture 13

Avalanche Photodiodes & Solar Cells

http://www.wiretechworld.com/the-future-of-optical-fibres/
Highlights from Lecture 12 (October 1, 2019)

1. Photodiodes can be illuminated from the front side or back side
2. The PIN photodiode has an intrinsic (or low doped) region between the n-type and the p-type regions and increases the depletion region volume (by widening the depletion region of width W)
3. All photodiodes are operated in the reverse bias mode
4. There are three factors that affect the photodiode’s response time – (a) drift time of the carriers within the depletion region, (b) diffusion time of carriers generated outside the depletion region, but within several diffusion lengths, and (c) junction capacitance resulting in an RC time constant with external resistances in a receiver
5. Carriers move in semiconductors under the influence of an electric field because these carriers are electrically charged – (a) at low electric fields by mobility \( \mu \), and (b) at high electric fields at their saturated velocity \( v_{\text{sat}} \)
6. Most often photodiodes are bandwidth limited via their response time by drift time in the depletion region (i.e., maximum bandwidth is

\[ BW_{\text{max}} = \frac{v_{\text{drift}}}{2\pi W} \]

This is essentially a “gain-bandwidth product” figure of merit.

7. The best pulse response from a photodiode is when \( W > > 1/\alpha \) (\( \alpha \) is the absorption coefficient of the semiconductor) and the capacitance is small.

8. Photodiodes are always designed to avoid being \( RC \) time constant limited in response time.
Avalanche Multiplication in Semiconductors

Avalanche of impact ionization processes

(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.

© 1999 S.O. Kasap Optoelectronics (Prentice Hall)

https://www.slideshare.net/chinkitkit/chapter-6a
Avalanche Multiplication in Reverse-Biased pn-Junctions

Avalanche Cartoon:

\[
M = \frac{\text{Multiplied photocurrent}}{\text{Primary unmultiplied photocurrent}} = \frac{I}{I_p}
\]

\[
M = \frac{1}{1 - \left(\frac{V_r}{V_{brkdn}}\right)^m}
\]

Exponent \( m \) is an empirical number from \( 2 < m < 6 \)

See Section 8.9.6 (p. 482) in Senior, 3\textsuperscript{rd} ed.

https://slideplayer.com/slide/7456453/
Avalanche Multiplication in Reverse-Biased pn-Junctions

100 µm diameter shallow junction APD
Temp = 17°C

Avalanche Photodiode Region

https://www.researchgate.net/figure/Different-operation-modes-for-solid-state-Silicon-detectors-showing-Photodiode-linear_fig1_237447114
Gain in a Photodiode Using Avalanche Multiplication

![Graph showing 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)](https://slideplayer.com/slide/7456453/)

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 Photodiodes

Always reverse biased in operation

https://et.wikipedia.org/wiki/Laviinfotodiood
An Avalanche Photodiode’s Doping Profile and Electric Field

Ionization Coefficients for Si, InP, GaN, GaP & Others

https://link.springer.com/chapter/10.1007/978-3-319-48933-9_2
The origin of **avalanche noise** from the discreteness of electronic charge.

Controlling High Electric Fields at Junction Edges

https://dbnst.nii.ac.jp/english/detail/966
A Modern Al$_x$In$_{(1-x)}$As$_y$Sb$_{(1-y)}$ Avalanche Photodiode

Advantages and Disadvantages of Avalanche Photodiodes

Avalanche photodiodes have an advantage over photodiodes without internal gain for the detection of very low-level light signals. Typically the improvement is from 5 dB to 15 dB over PIN photodiodes in practical applications.

From: Section 8.9.5, Figure 8.26(b), p. 480, in Senior, 3rd ed.
Advantages and Disadvantages of Avalanche Photodiodes

PIN photodiodes are
1. Not as sensitive as APDs because they have no internal gain
2. Have slower response times that APDs

Avalanche photodiodes are
1. More difficult to fabricate
2. Have higher noise because avalanche mechanism is noisier
3. Require higher operating voltages
4. Typically have lower reliability
5. APD output is nonlinear
6. Gain varies with temperature
Traveling-Wave Photodiode Operation

Anode and cathode connections

Optical input

Depletion layer of diode

https://www.researchgate.net/figure/Travelling-wave-photodetector-structure_fig1_264858168
Traveling-Wave Photodiode (From Senior, Fig. 8.12)

Basic Structure

Transmission Line Representation

Periodic Traveling-Wave Photodiode Structure

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Fully Distributed, Parallel-Plate, PIN, Traveling-Wave Photodiode


Requirement: Need to match the velocity of light propagation down the depletion layer to the velocity of current down the waveguide structure.
Traveling-Wave Photodiode Observations

• Absorption and carrier drift regions are positioned orthogonally to each other by design.
• The distributed capacitance along transmission line is terminated into matching impedance → bandwidth is independent of capacitance.
• Electrical and optical wave velocities are matched by controlling electrode geometry.
• Best experimental performance achieved to date approximately 200 GHz.
Question: In what way are solar cells like photodiodes?

https://textbook-photovoltaics.org/figures_1.html
The Solar Cell (Another pn-Junction)

A solar cell, or photovoltaic cell, is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon.

The overwhelming majority of solar cells are fabricated from silicon—with increasing efficiency and lower cost materials ranging from amorphous (non-crystalline) to polycrystalline to crystalline (single crystal) silicon forms.

https://sunlinkpv.com/products/pvcell.html
Solar Spectrum Compared to Absorption in a Silicon Solar Cell

Physical Structure of a Solar Cell

Want to maximize surface area

https://www.britannica.com/technology/solar-cell
I-V Characteristic of an Ideal Diode Solar Cell

Reverse Voltage

Forward Voltage

I-V Characteristic of Photodiode (with Load Lines)

https://en.wikipedia.org/wiki/Photodiode#/media/File:Photodiode_operation.png
Typical I-V and Power-Voltage Curves

https://www.powerelectronicstips.com/solar-cells-power-part-2-power-extraction/
Solar Spectrum Compared to Absorption in a Silicon Solar Cell

Single Junction vs. Triple Junction Solar Cells

https://www.photonics.com/Articles/LED-Based_Sun-Simulator_Design_Technical_and/a57253
Novel Quadruple-Junction Solar Cell

Grown by Molecular Beam Epitaxy

## Comparing Solar Cell To a Photodiode

<table>
<thead>
<tr>
<th>Solar Cell</th>
<th>Photodiode</th>
</tr>
</thead>
<tbody>
<tr>
<td>No applied bias voltage</td>
<td>Applied reverse bias voltage (can be a high voltage)</td>
</tr>
<tr>
<td>No avalanche current present</td>
<td>Can structure diode for avalanche current to be generated</td>
</tr>
<tr>
<td>Output: electrical power</td>
<td>Output: current</td>
</tr>
<tr>
<td>Dark current not an issue</td>
<td>Dark current is important in receiver design</td>
</tr>
<tr>
<td>Power dissipation depends upon I-V operating point and solar cell efficiency</td>
<td>Power dissipation is product of output current and bias voltage</td>
</tr>
</tbody>
</table>
Photodiode Packaging

Coupled differential feedthrough

Pre- & post-amplifier IC

Offset parabolic mirror

Photodiode

Ca

Heade

Optical fiber

Ball lens
PIN Photodiode Followed by Transimpedance Amplifier

https://www.semanticscholar.org/paper/Optoelectronic-Analogue-Signal-Transfer-for-LHC-Arbet-Engels-Cervelli/68e514db0cda12b9b2fc5f245aa966ea943a0bec
Photodiode Followed by Transimpedance Amplifier

But what is the major limitation of using an operational amplifier?

https://www.allaboutcircuits.com/technical-articles/negative-feedback-part-8-analyzing-transimpedance-amplifier-stability/
40 Gb/s PIN Photodiode Detector Assembly

- Mesh bond (CC to CPW)
- Long ground current path
- T/F Circuit
- F/C Diode
40 Gb/s Flip-Chip PIN Photodiode

Photodiode: InGaAs/InP PIN
12 μm diameter
0.7 μm I-layer

FC-10 Photo Diode
(30 μm diameter solder bumps)

TF-IV Thin-Film Circuit

FC-10 Photo Diode

F/C Underfill

Thin-film:
Sapphire substrate
1.95 mm x 1.98 mm
A photoreceiver using an InGaAs APD and peripheral electronics (ICs) to achieve high gain and high sensitivity. There is also a thermoelectric cooler (TEC) and a temperature sensor. Courtesy of Voxtel, Inc.
Thermo-electric Cooler and Peltier Effect

https://www.researchgate.net/figure/Schematic-of-thermoelectric-refrigeration-left-power-generation-and-power-generation_fig2_268330588
Thermo-electric Cooler

Thermo-electric Cooler Construction

http://kryothermtec.com/thermoelectric-cooler-technology.html
Phototransistors

The phototransistor is a semiconductor device able to sense light levels to alter the current flowing between emitter and collector proportional to the light intensity.

Phototransistor is equivalent to photodiode plus transistor

Packaging

Two common biasing and load resistor connections (both BJT and FET)

http://hades.mech.northwestern.edu/index.php/File:Phototransistor_amplifiers.png
Why Use Phototransistors?

- More sensitive than photodiodes of comparably sized area
- Available with gains form 100 to over 1500
- Moderately fast response times
- Available in a wide range of packages
- Usable with almost any visible or near infrared light source such as IREDs, lasers, sunlight, and etc
- Same general electrical characteristics as familiar signal transistors

https://www.slideserve.com/jeanne/diodes-triodes-thermistors-opto-isolators-phototransistors
Phototransistors Have Gain (Photodiodes Do Not)

Phototransistor Cross-Section Showing Base Collection Region

https://learnabout-electronics.org/Semiconductors/opto_50.php
Phototransistor Advantages & Disadvantages

Phototransistor Advantages

• Generates much higher currents than photodiodes because of the gain from the transistor
• Low price, small chip size and easily assembled into electronic assemblies (modules)
• Less noisy than avalanche photodiodes
• It generates a voltage output (with resistor included), whereas a photodiode does not

Phototransistor Disadvantages

• The phototransistor has large capacitances to charge & discharge
• This device has charge storage effects that limit its response times leading to slow tails on the falling edge
• Higher dark currents
Phototransistor Applications

Light sensitive switches (relay drivers)
Light measurement transducers
Opto-Coupler assemblies
Object detection sensors
Camera shutter controls
Night vision systems (IR)
Smoke detectors
Punch-card readers
... and many more
https://www.skipprichard.com/ask-questions-to-improve-your-leadership/
Supplementary Backup Slides