ELEN E3106/4106 Lecture 12

Optoelectronics Part I: Solar Cells & Photodiodes

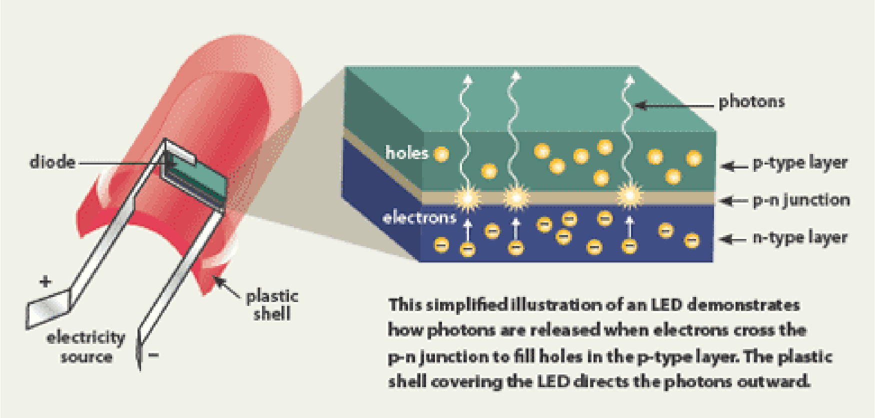
Outline

- *I*-*V* in illuminated junctions
- Solar Cells
- Photodetectors
- Gain, Bandwidth, and SNR

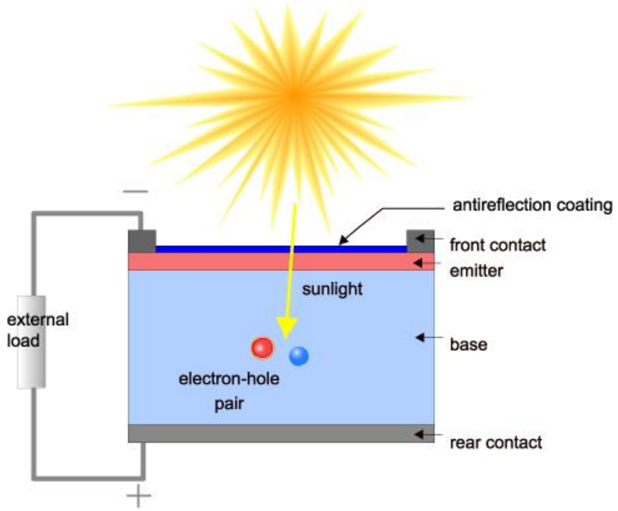
Assignments:
Reading: Streetman and Banerjee §8.1
Homework 5 due Friday Oct. 17th by 5pm

p-n Diode: Applications in Optoelectronics

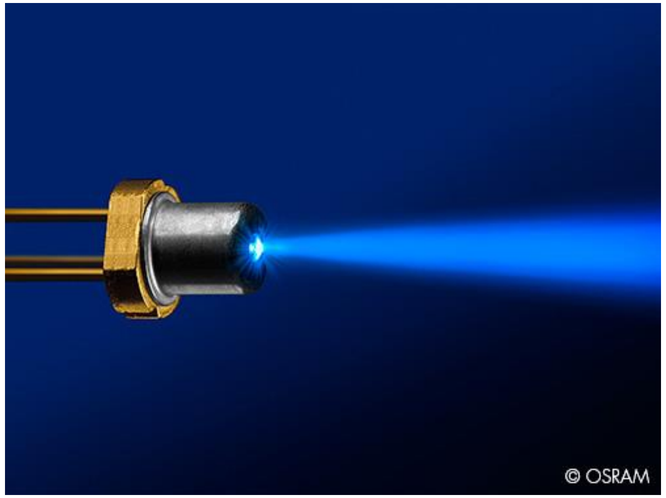
LEDs

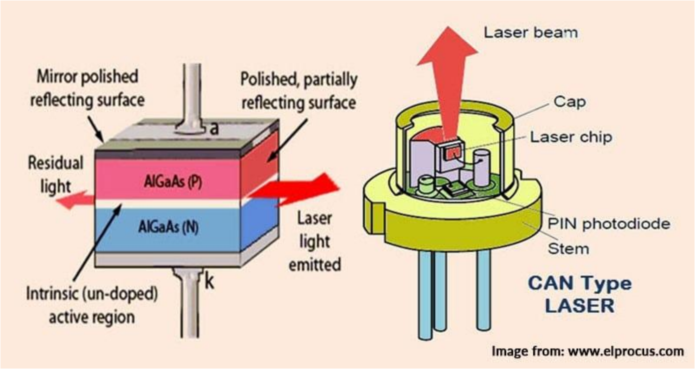


Solar cells



Laser Diodes





Sources: UPS Battery Center, Wikipedia, Electronics Hub, Electron Test Equipment, Laser Components, PV Education

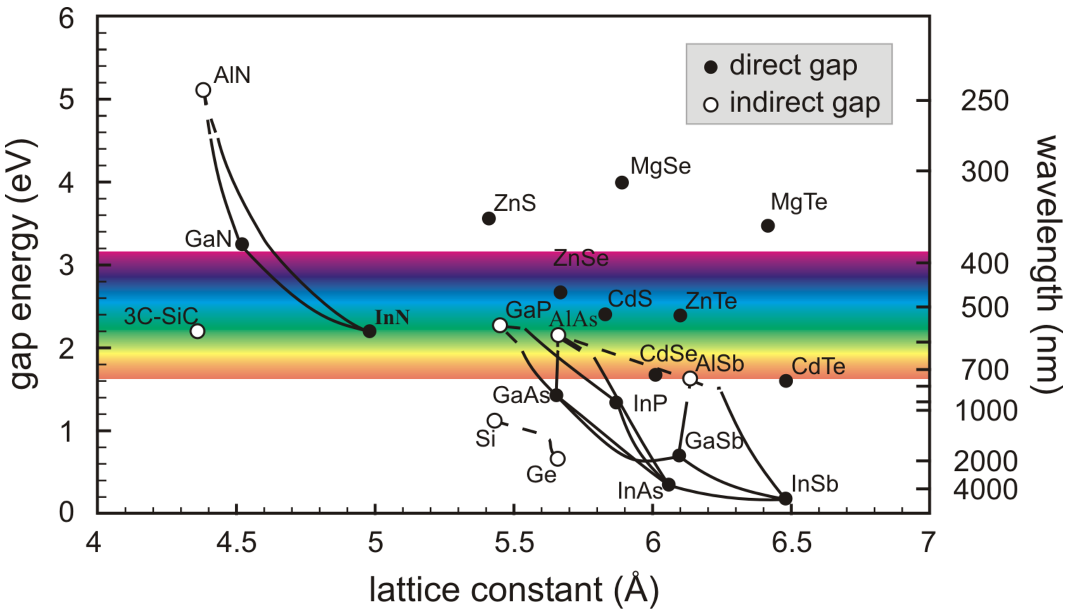
Optoelectronic Materials

- Recall, conventional Si has a lot going for it
  - Easily purified and grown as a single crystal
  - Cheap
  - Abundant in nature
  - Easily passivated by SiO_2 (a great insulator w/ high etch selectivity to Si)
- Overall, good solution for ________________ digital & analog circuits

- **But** we also need ________________ optical components like receivers and emitters
- Many other semis have superior properties
  - Higher mobility
  - Better light emission/absorption

TABLE 2–1 • Electron and hole mobilities at room temperature of selected lightly doped semiconductors.

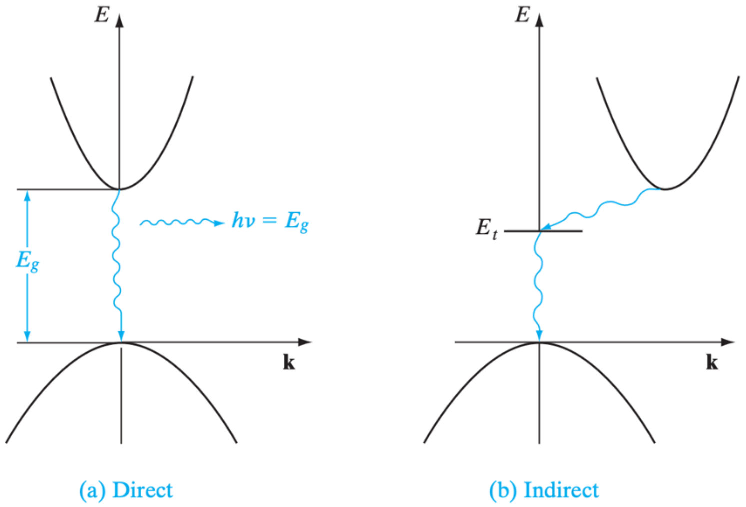
	Si	Ge	GaAs	InAs
μ_n (cm²/V·s)	1400	3900	8500	30, 000
μ_p (cm²/V·s)	470	1900	400	500

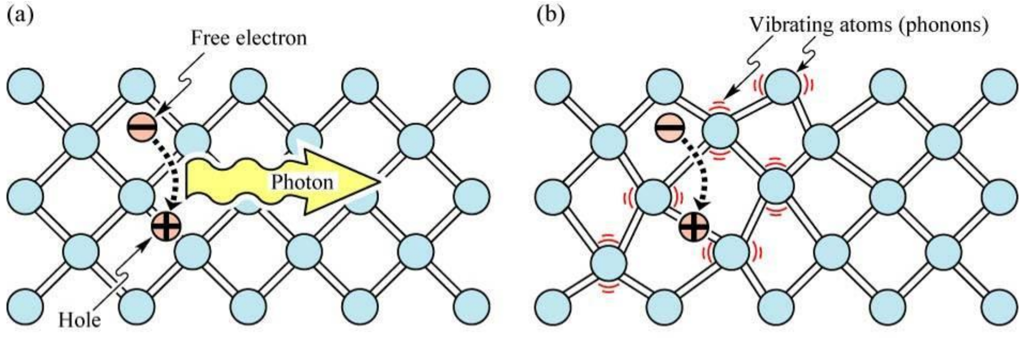


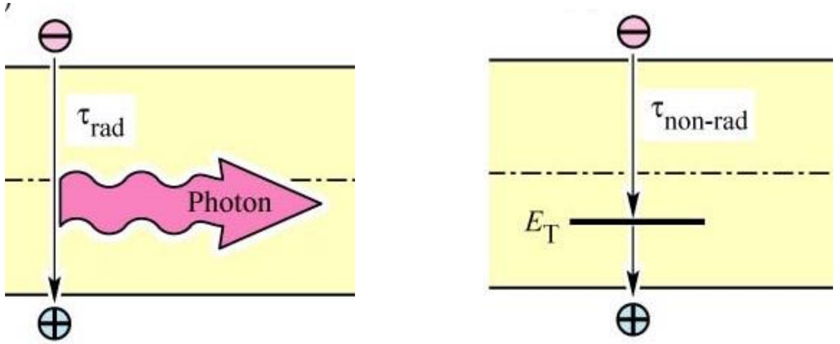
Sources: E. Pop ECE 340 Slides, C. Hu *Modern Semiconductor Devices for Integrated Circuits*, http://web.tiscali.it/decartes/phd_html/node4.html

Recall: Direct and Indirect Bandgap

- Direct: recombination results in photon emission (_______)
- Indirect: $E_{c,min}$ and $E_{v,max}$ do not occur at same __ ->
  - Recombination requires a change of __________ for the e$^-$
  - Non-radiative!
  - Released energy converted to thermal lattice vibrations (________)



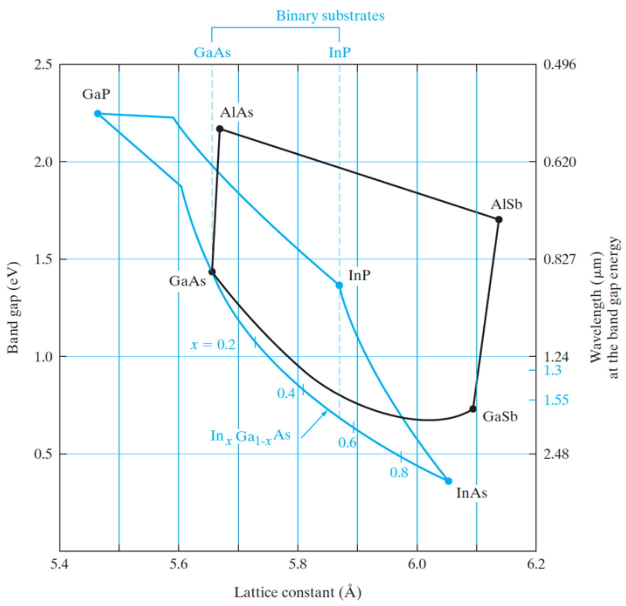


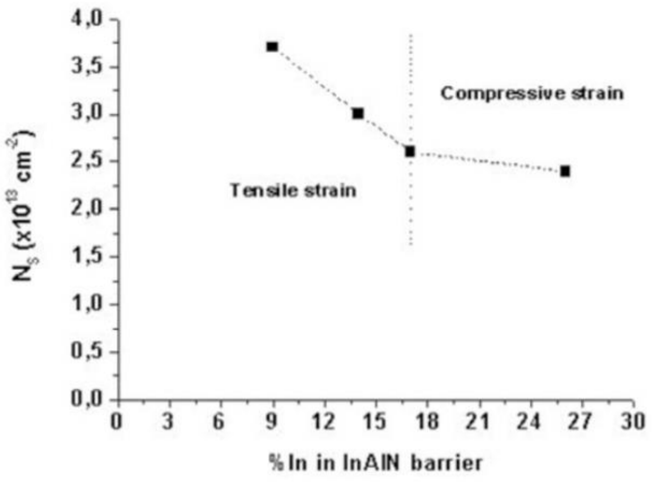


Sources: E. Pop ECE 340 Slides, Textbook,https://sites.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap02/chap02.htm

Direct Band Gaps and Lattice Matcing for Optoelectronics

- Generally, we focus on ________ bandgaps for optoelectronics
  - GaAs
  - InP
  - GaN
- Recall: we can tailor the lattice constant ____ through ___________________ (generally it varies linearly)
- **Important: _________________**
  - When all the semiconductors in the structure have the same lattice constant
  - Otherwise, the lattice mismatch can produce defects
- Why do we need to grow some semiconductors on substrates of a different material? Called *heteroepitaxy*



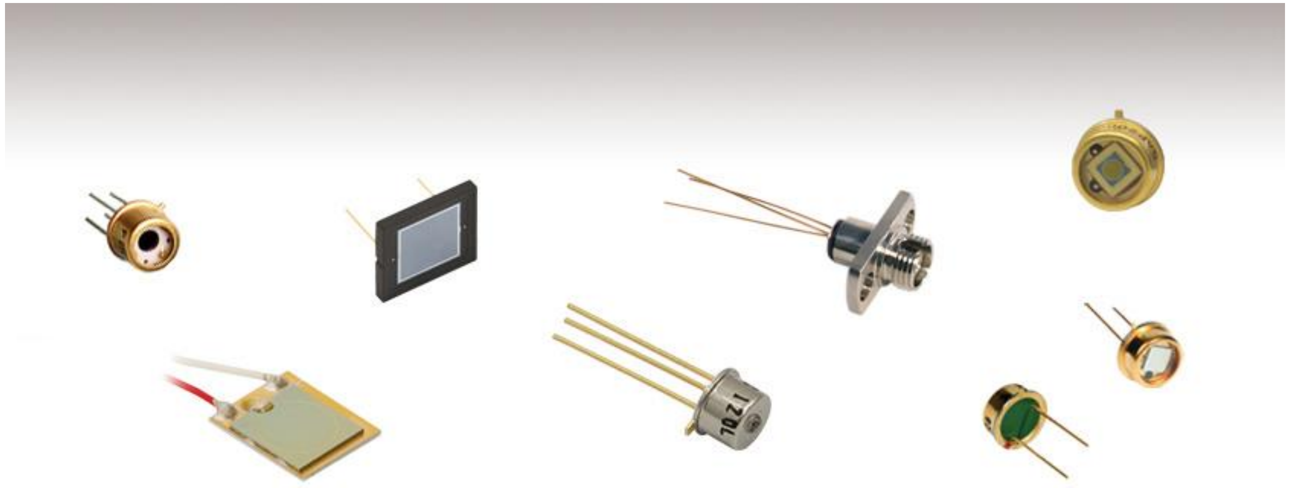


17-18% InN in InAlN → Lattice matched to underlying GaN → No strain

Sources: E. Pop ECE 340 Slides, Textbook, F. Medjdoub et al., *The Open Electrical and Electronic Engineering Journal* (2008)

Photodiode Basics

- 2 terminal devices designed to respond to ___________ absorption
- Principle of operation based on ____________!
- Recall from Ch. 4, semiconductors can absorb light with photon $h\nu >$ ____
- Why do we use a junction instead of a a slab of semiconductor?
  - Junctions can improve _______________ and ____________



Sources: Thorlabs

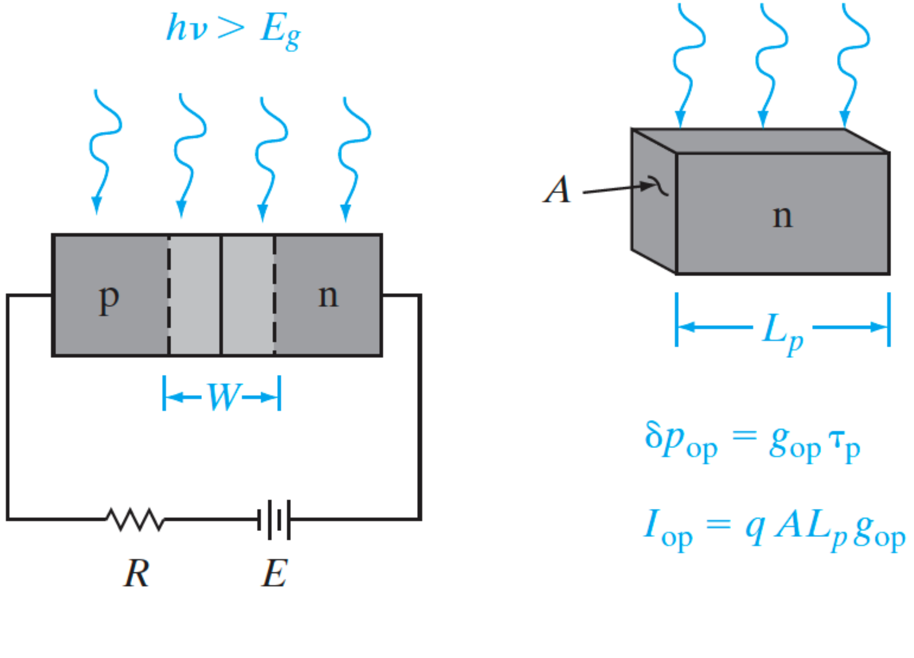
Current and Voltage in an Illuminated Junction

- Assumptions: quantum efficiency (Q.E.) = 1 EHP created for every 1 incoming photon
- If we shine a light with $g_{op} = 10^{17} \frac{EHP}{cm^3 - s}$ on a p-n junction, we generate additional current (proportional to _________ and _________):

$$I_{op} = q \times g_{op} \times (\text{generation volume})$$

$$I_{op} = q g_{op} A(\qquad\qquad\qquad\qquad)$$

- Recall: low-level injection, minority carrier concentration changes a lot!
- Which way is current directed?
  - From ____ to _____



(a) (b)

Sources: E. Pop ECE 340 Slides, Textbook

Current and Voltage in an Illuminated Junction

- How does the photogenerated current add (or subtract) to the current already induced by the diode voltage?
  - Recall, ideal diode equation (in the dark):

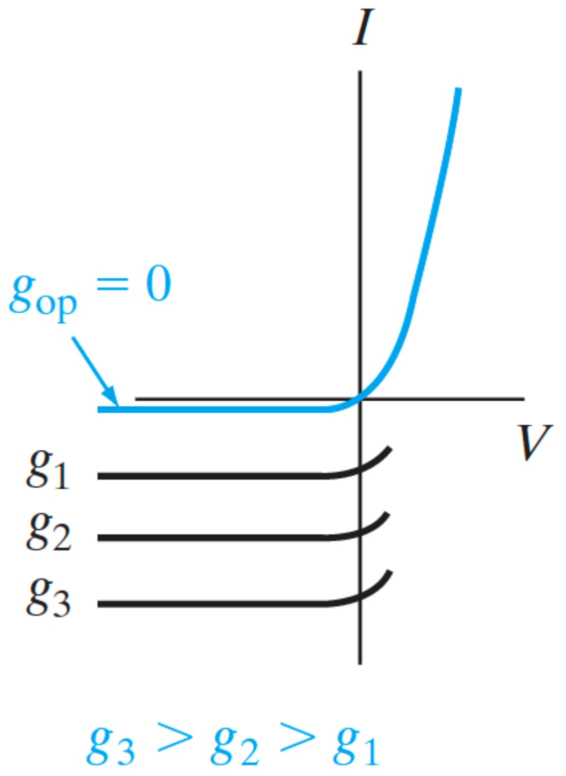
$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$$

  - Let $I_{gen} = I_0 =$ ____,
- Our total current in the illuminated junction is now

$$I = I_{\text{th}}(e^{qV/kT} - 1) - I_{\text{op}}$$

$$I = qA\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)(e^{qV/kT} - 1) - qAg_{\text{op}}(L_p + L_n + W)$$

- Meaning the I-V curve is _____ proportional to g_{op}



Sources: E. Pop ECE 340 Slides, Textbook

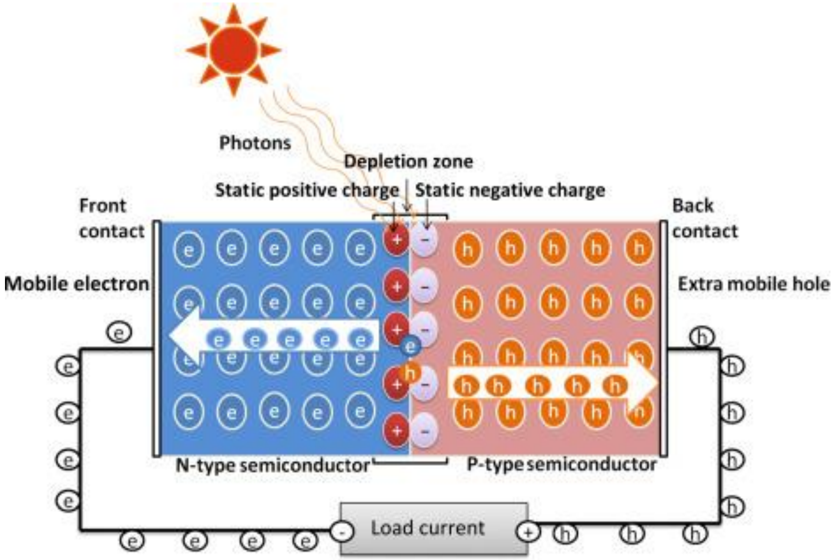
Photovoltaic Effect

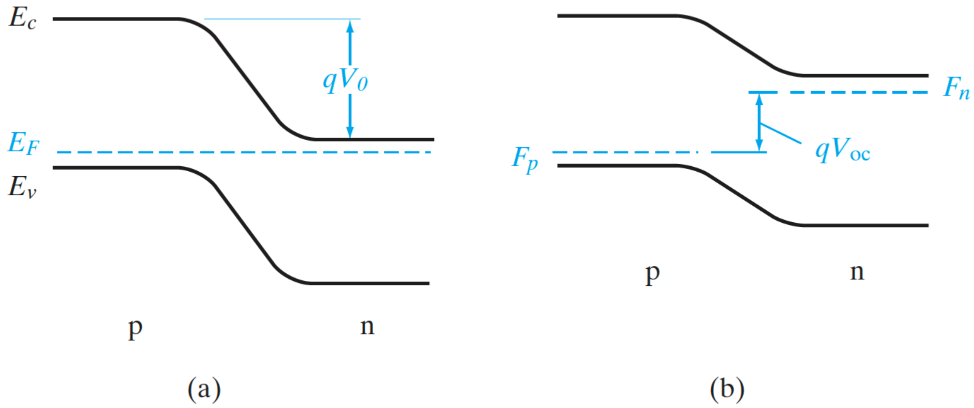
- Short-circuit (external V = 0), $I_{sc} = $ ____
- Open-circuit voltage (external I = 0),

$$V_{oc} = \frac{kT}{q}\ln[I_{op}/I_{th} + 1]$$
$$= \frac{kT}{q}\ln\left[\frac{L_p + L_n + W}{(L_p/\tau_p)p_n + (L_n/\tau_n)n_p}g_{op} + 1\right]$$

- This appearance of a forward open-circuit voltage across an illuminated junction is called the *photovoltaic effect*

- Note there is a limit: $V_{oc} \leq V_0$

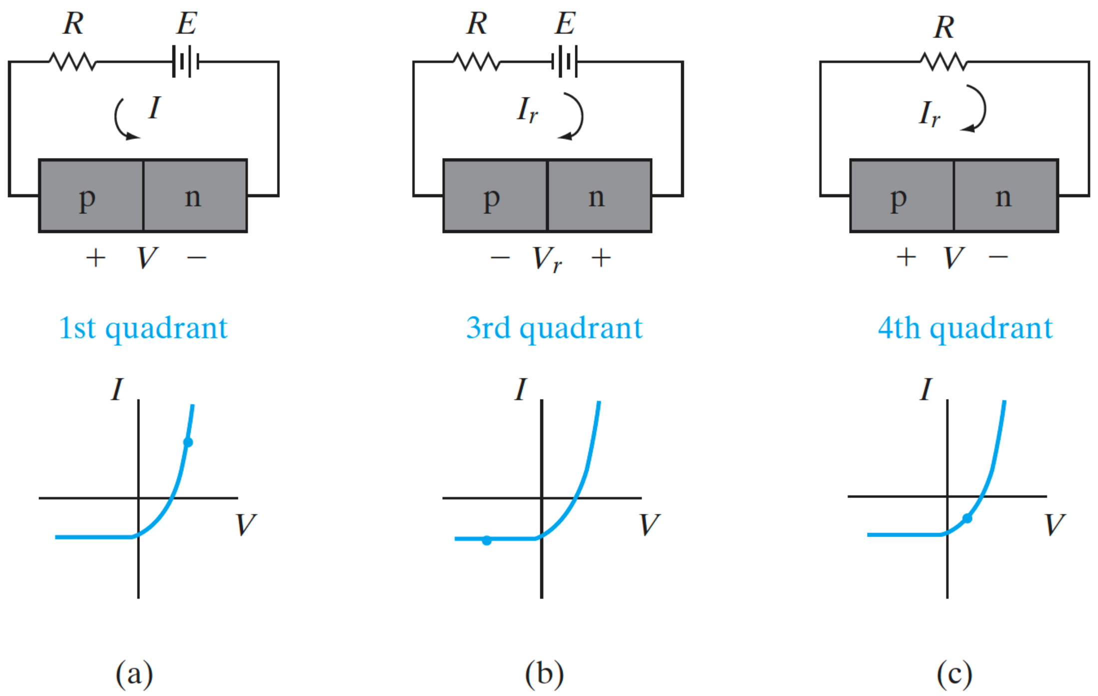




Sources: E. Pop ECE 340 Slides, Textbook, ScienccDirect

Power Delivery

- $P = |I \times V|$
- +P: power __________ to the device
- -P: power is ____________ by the device



Operating in which quadrant(s) requires power from external circuit?

Operating in which quadrant(s) generates power?

- We choose which quadrant to operate in depending on application.

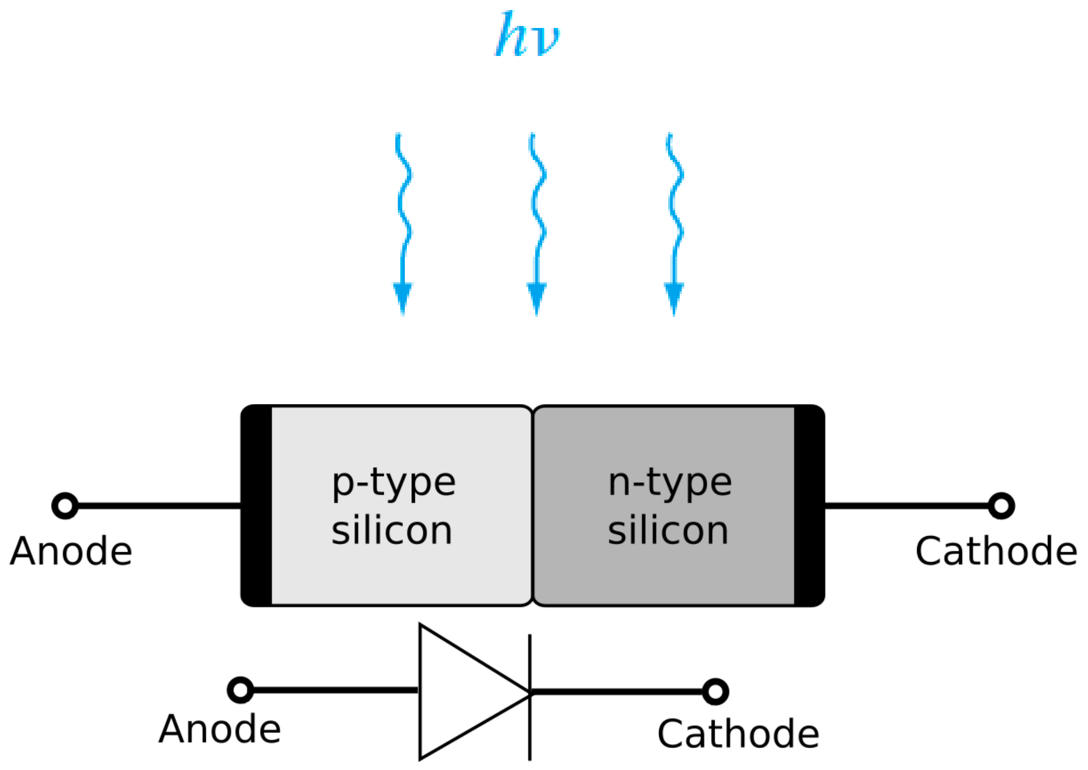
Sources: Textbook

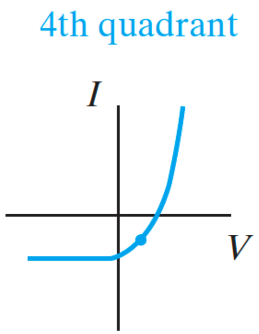
Solar Cell Basics

- A type of photodiode

- Also called ___________ cells
- Convert ___________ into electricity
  - ____ quadrant

- Energy efficiencies usually 15-30%
- Structure: identical to p-n diode, with transparent anti-reflective coating on top
- How much power can a single 1 cm^2 device deliver?
  - $V_{oc} <$ ____
  - $I_{op} \approx 10 - 100\ mA$





Sources: Wikipedia, Textbook

Solar Cell Design

- How do we generate more power?

- Connect cells in ________ to obtain desired voltage, then connect in parallel

- Desired:
  - Large junction area located ______________
  - Small series resistance in the device (maximize output power)

- Compromises:
  - Increasing V_0 through doping inadvertently reduces lifetime

(a)

Sources: UPS Battery Center, Wikipedia, Electronics Hub, Electron Test Equipment, Laser Components, PV Education

Solar Cell Contact Design

- Contacts are designed as narrow fingers across the surface. Why?
  - Decrease ____________________
- Region is heavily doped, so resistance is small
- BUT if we put contacts only on the ________, current must flow across entire long surface
  - __________ would become large
- Fingers reduce distance current travels, without interfering with incoming light

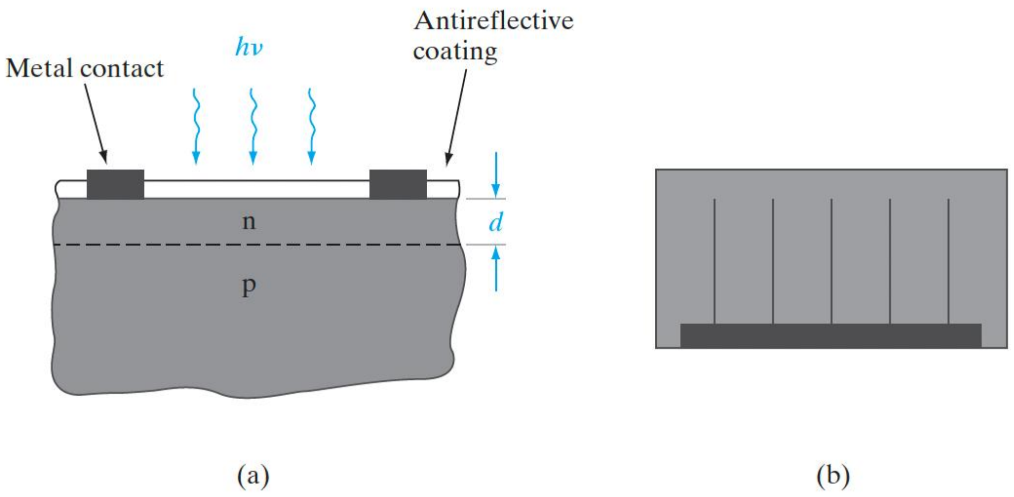


Figure 8–5 Configuration of a solar cell: (a) enlarged view of the planar junction; (b) top view, showing metal contact "fingers."

Sources: UPS Battery Center, Wikipedia, Electronics Hub, Electron Test Equipment, Laser Components, PV Education

Solar Cell Fill Factor and Efficiencies

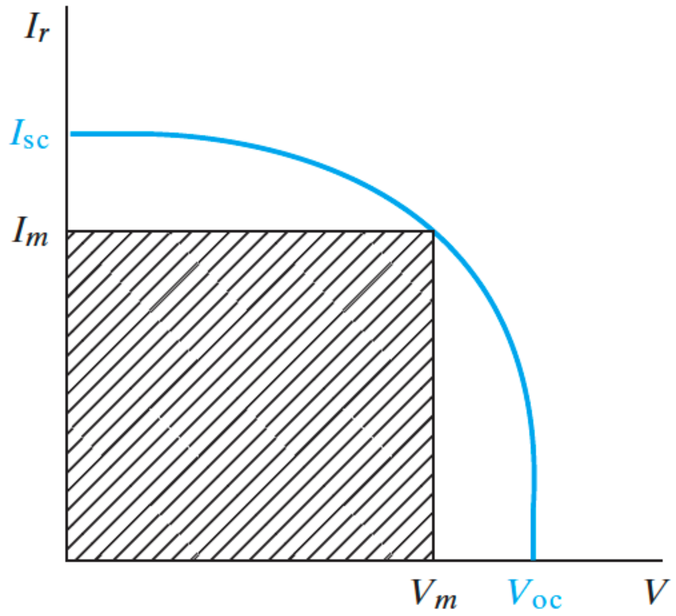
- Fill factor is an important metric of solar cell quality
- The ratio of the actual maximum obtainable power to the product of $I_{sc}V_{oc}$

$$I_m V_m / I_{sc} V_{oc}$$

- We want to ___________ f.f.

- Which means we need to manage resistance

- Which means we must optimize:
  - The size and shape of the cell
  - Thickness of device layers
  - Choice of layers
  - Doping



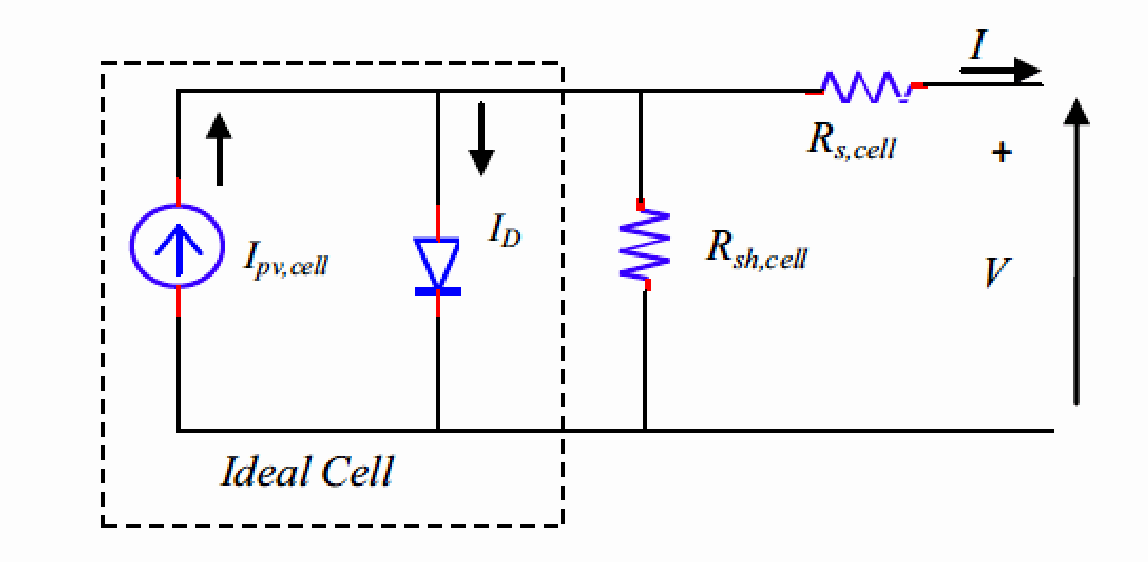
$$P_{max} = (f.f.)\, I_{sc} V_{oc}$$

Sources: Textbook

Equivalent Circuit Model of Solar Cells

- I_{pv}: Photocurrent generated due to illumination (photovoltaic effect)
- I_D: Diode characteristics in the dark. Some current passing through the diode doesn't reach the load due to ________________
- R_s: series resistance due to device (p, n layer and __________)
- R_{sh}: shunt resistance due to parallel conductive ________________

- We want to manage resistance to increase power:
  - Decrease series (internal)
  - Increase shunt (external)
- $I = I_{pv} - I_D - I_{R_{sh}}$



•Sources:DOI: 10.1109/ICoSC.2017.7958647

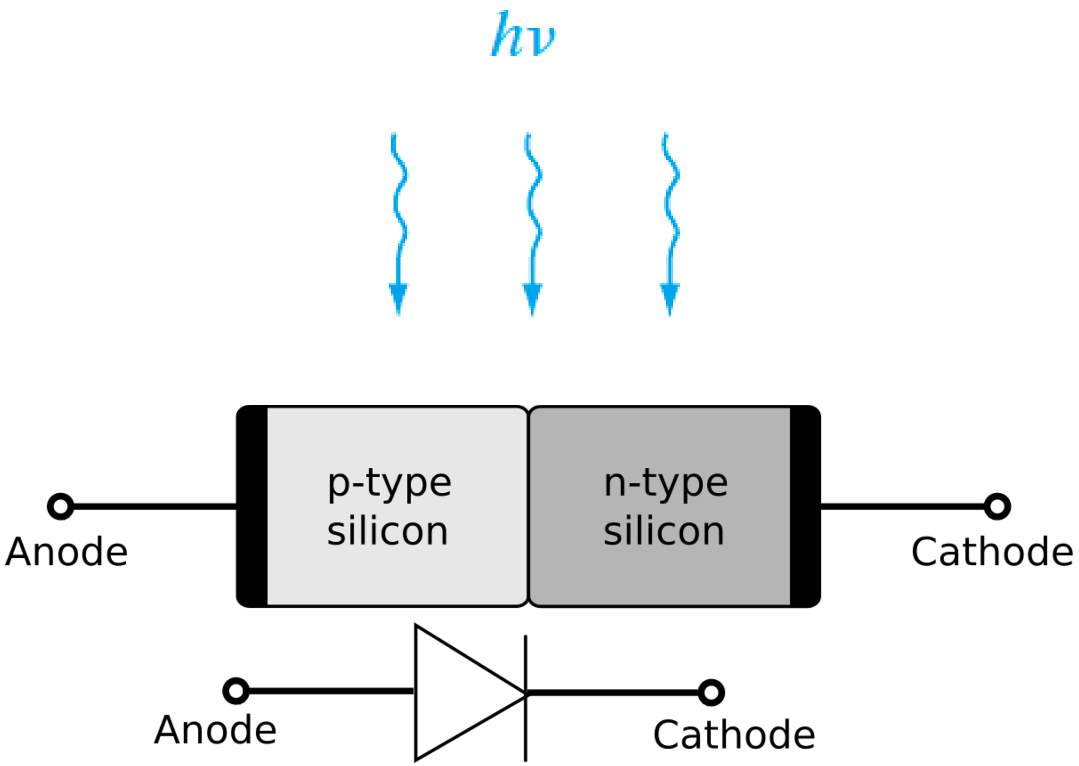
Photodetector Basics

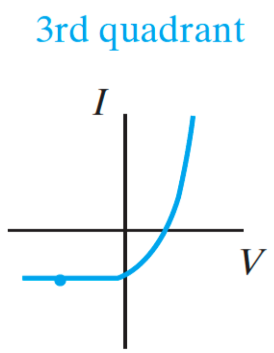
- A type of photodiode

- Converts time-varying ____________ signals into __________ signals
  - ______ quadrant

- Current is essentially independent of voltage, and proportional to ______

- Imagine we need to detect a series of light pulses 1 ns apart
- The photogenerated minority carriers must _________ to the junction and be swept across in time $\ll 1\, ns$
- Important metric: ______________________________





Sources: Wikipedia, Textbook

Photodetector Design and Speed

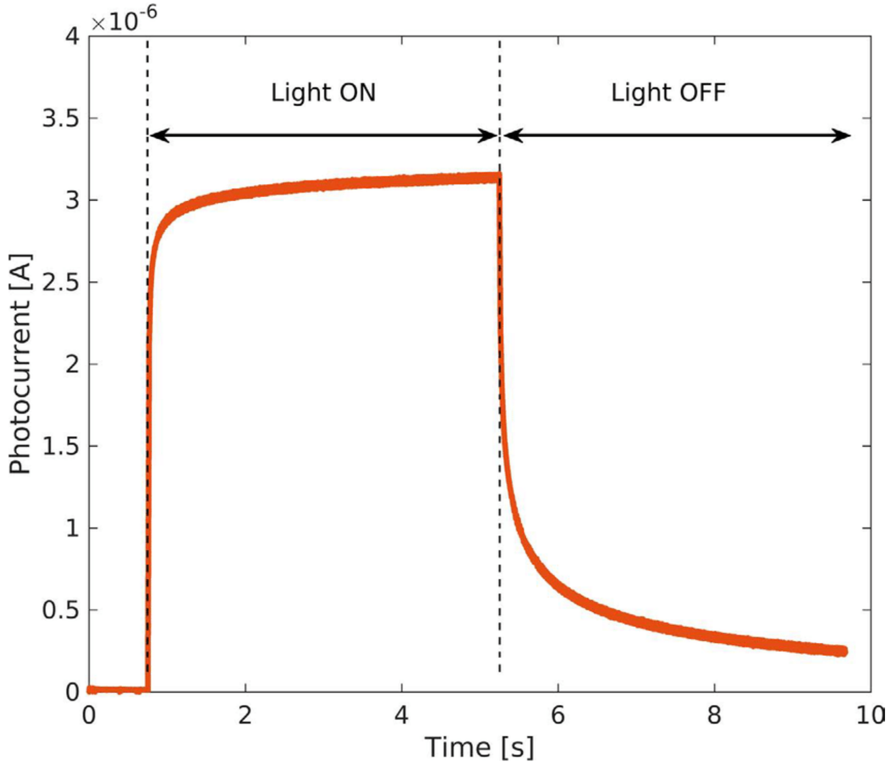
- To improve response time (Bandwidth), increase _____ so most devices are absorbed in the SCR

- EHPs generated in W will be swept to other side very quickly

- Called a _____________ photodiode

- How can we increase W?

- Compromise:
  - Larger W, most photos absorbed in W and sensitivity is ____
  - Larger W, C_j is small and RC of circuit is low, increasing ________
  - Larger W, time for carriers to drift across goes up and lowers _____.....



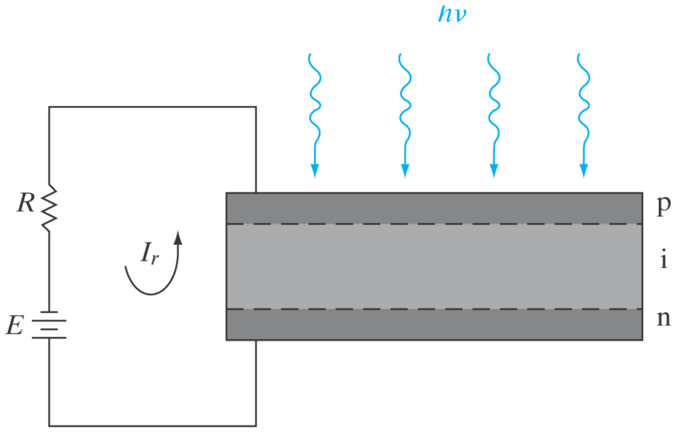
$$f_{max} \approx \frac{1}{transit\ time} \approx \frac{1}{\frac{W}{v_{sat}}} \approx \frac{v_{sat}}{W}$$

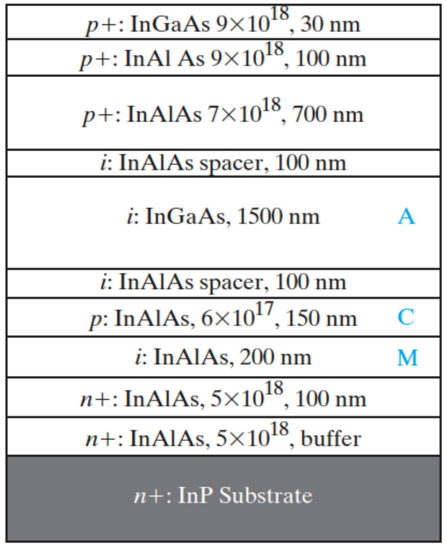
•Sources: E. Pop ECE 340 Slides, DOI: 10.1038/srep37913

Approaches to Improve Photodetector Performance

- Use __________ as photodetector to enlarge depletion region W, improving response time (left)
- Use lattice-matched layers of compound semis with wider bandgap material _________. Lower energy photons can easily be transmitted through to junction with _________________ material, reducing surface recombination effects (right)
- Operate detector in avalanche region (called an ______). Each photogenerated carrier significantly increases current due to avalanche multiplication (external Q.E. ___ > 100%)

$$\eta_Q = (J_{op}/q)/(P_{op}/h\nu)$$

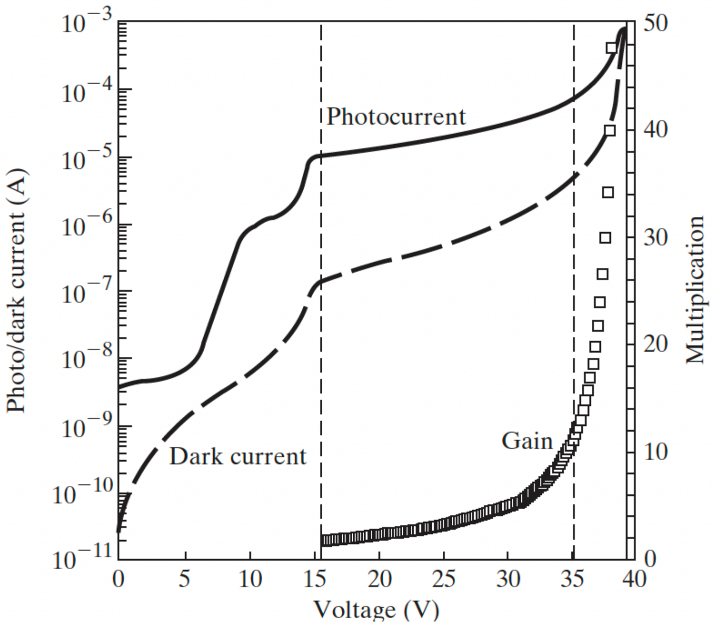


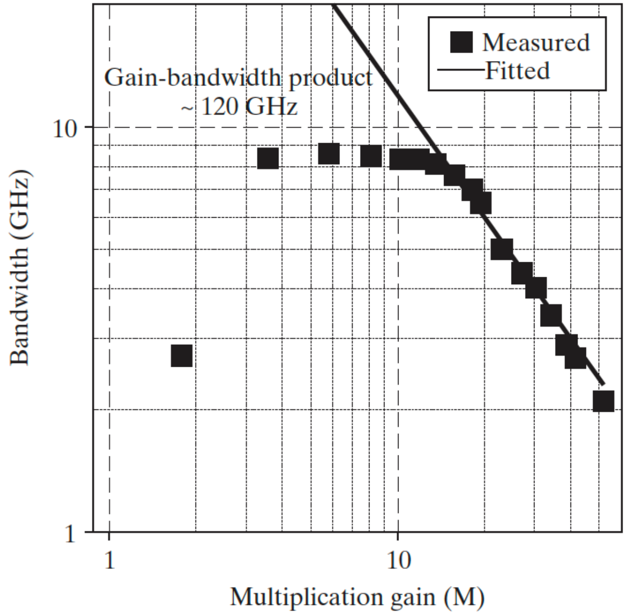


Sources: E. Pop ECE 240 Slides, Textbook

Photodetector Figures of Merit

- Quantum efficiency: # of EHPs generated per photon.
- Responsivity: output current divided by total light power falling upon the photodetector.
- Signal-to-noise ratio (SNR): ratio of desired signal to level of background noise
- Noise-equivalent power (NEP): amount of light power needed to generate a signal comparable in size to the noise of the device (major source: random thermal motion of carriers)
- Detectivity (D): Inversely proportional to the noise equivalent power. $D = 1/\mathrm{NEP}$
- Gain: Output current of a photodetector divided by the current directly produced by the photons incident on the detectors, i.e., the built-in current gain.
- Dark current: The current flowing through a photodetector even in the absence of light.
- Response time: The time needed for a photodetector to go from 10% to 90% of final output.





•Sources: Textbook