Columbia Engineering
The Fu Foundation School of Engineering and Applied Science

ELEN E3106/4106 Lecture 12

Optoelectronics Part I: Solar Cells & Photodiodes

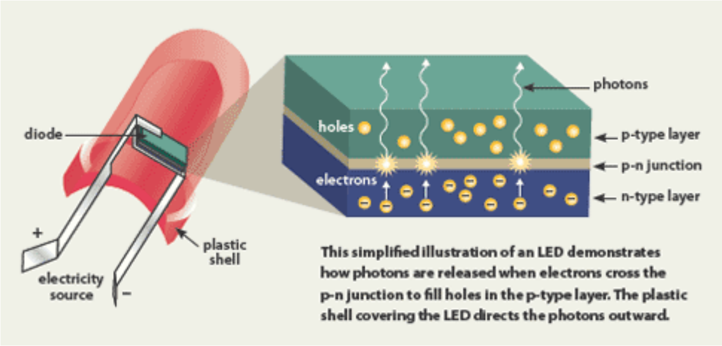
Outline

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

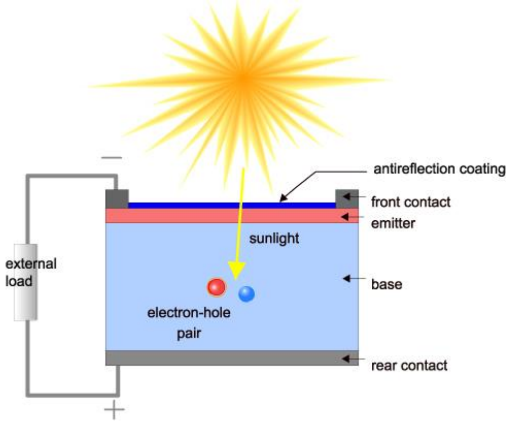
Assignments:
Reading: Streetman and Banerjee §8.1
Homework 5 due Friday Oct. 17th by 5pm

p-n Diode: Applications in Optoelectronics

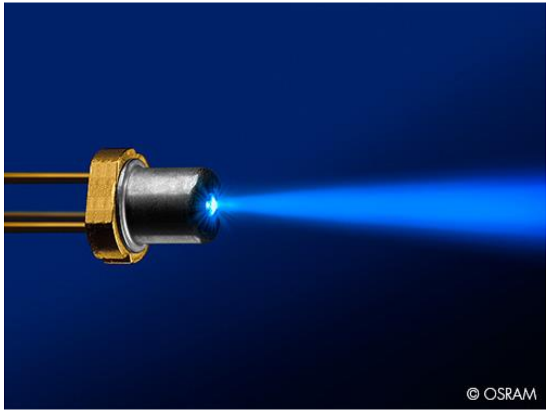
LEDs

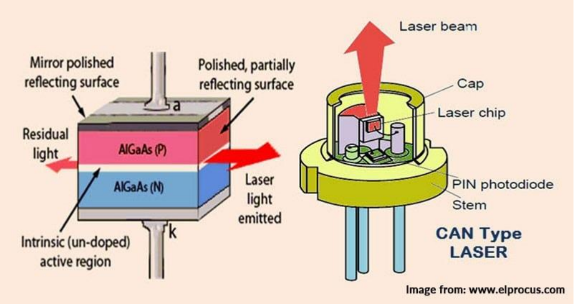


Solar cells



Laser Diodes





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

Optoelectronic Materials

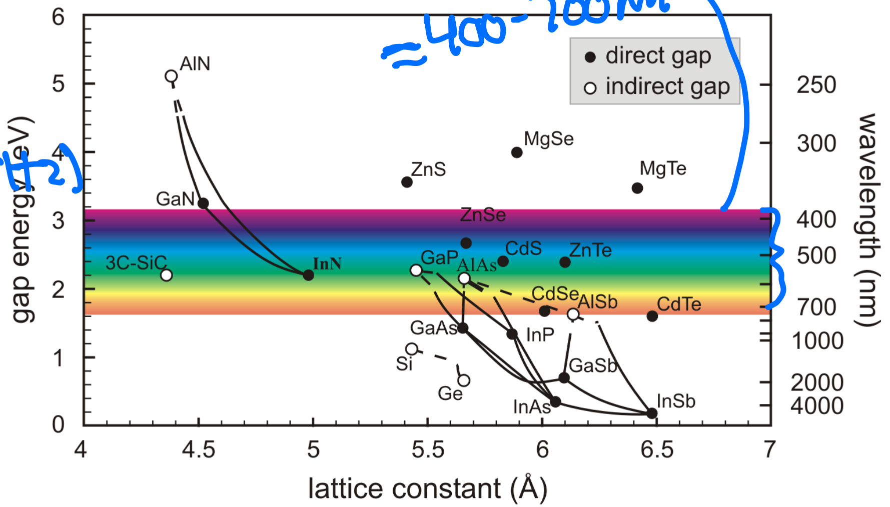
- Recall, conventional Si has a lot going for it
  - Easily purified and grown as a single crystal
  - Cheap
  - Abundant in nature
  - Easily passivated by SiO_2 (a great insulator w/ high etch selectivity to Si)
- Overall, good solution for complex & cheap digital & analog circuits
- **But** we also need high speed (10GHz-1THz) optical components like receivers and emitters
- Many other semis have superior properties
  - Higher mobility → higher frequencies
  - Better light emission/absorption

Theoretical

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

visible light ≈400-700nm

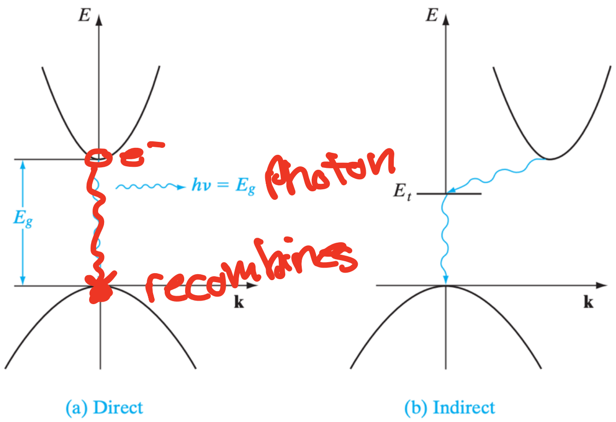


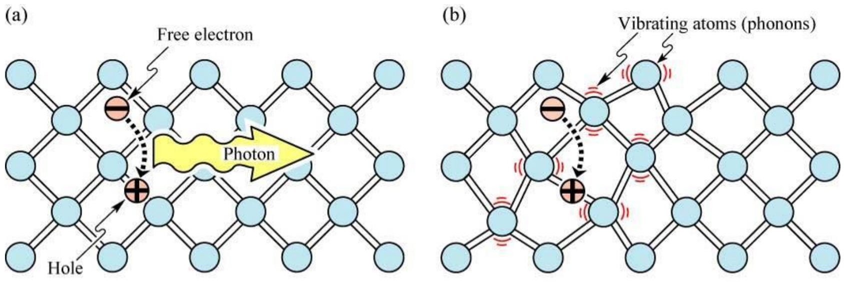
Sources: E. Pop ECE 340 Slides, C. Hu *Modern Semiconductor Devices for Integrated Circuits*, http://web.tiscali.it/decartes/phd_html/node4.html

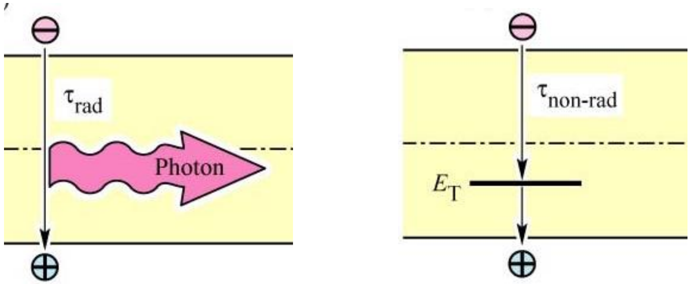
Recall: Direct and Indirect Bandgap

- Direct: recombination results in photon emission (radiative)

- Indirect: $E_{c,min}$ and $E_{v,max}$ do not occur at same k ->
  - Recombination requires a change of momentum for the e$^-$
  - Non-radiative!
  - Released energy converted to thermal lattice vibrations (phonons)







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

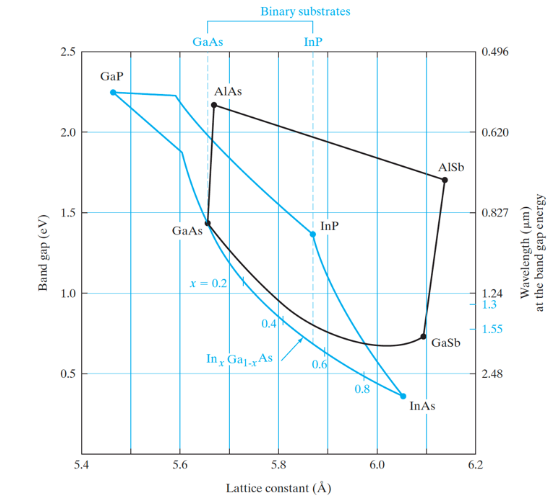
- Generally, we focus on direct bandgaps for optoelectronics
  - GaAs
  - InP
  - GaN

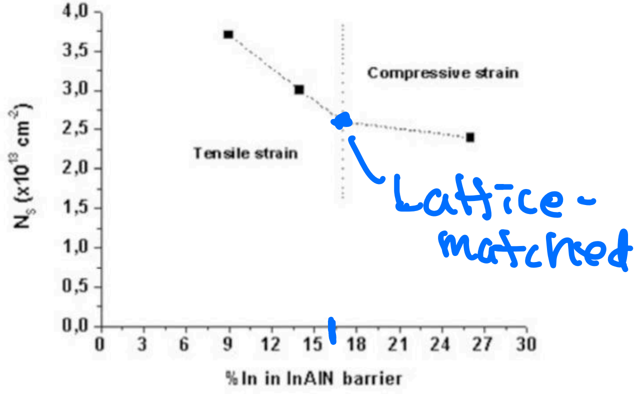
- Recall: we can tailor the lattice constant a through alloy composition (generally it varies linearly)

- **Important:** Lattice-matching
  - 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*

Difficult & expensive to produce some semiconductors in bulk; ability to grow thin layer





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 photon absorption
- Principle of operation based on p-n junction!
- Recall from Ch. 4, semiconductors can absorb light with photon $h\nu \geq E_g$
- Why do we use a junction instead of a a slab of semiconductor?
  - Junctions can improve response speed (time) and sensitivity

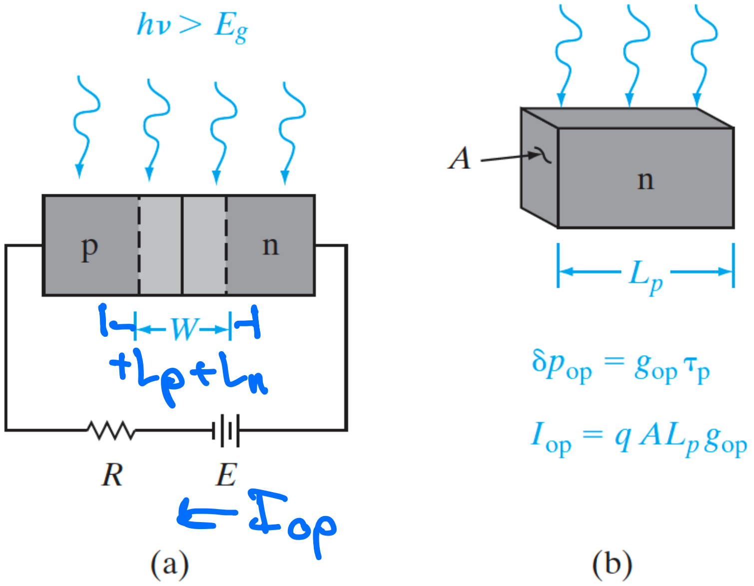
Sources: Thorlabs

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 light intensity and cell area):

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

$$I_{op} = qg_{op}A(L_p + L_n + W)$$



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

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):

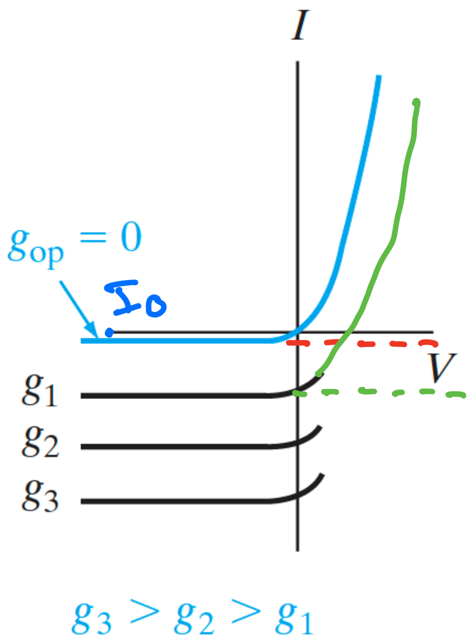
$$I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$$

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

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

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

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



Sources: E. Pop ECE 340 Slides, Textbook

Photovoltaic Effect

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

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

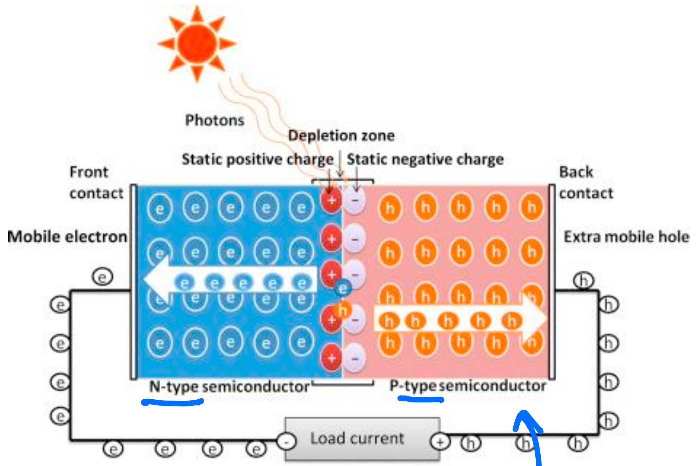
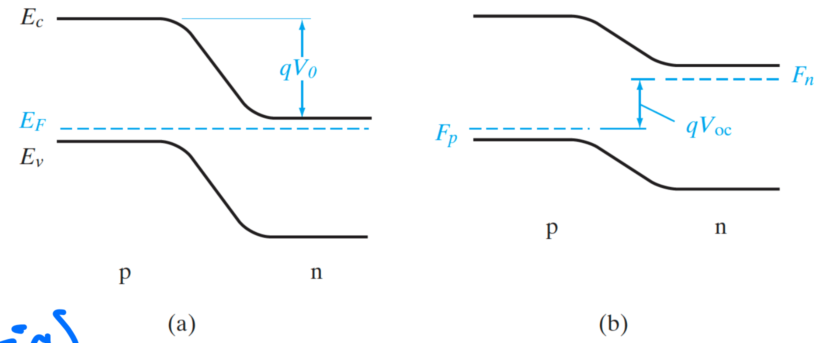


diagram is backwards

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



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

contact potential / built-in potential

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

Power Delivery

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

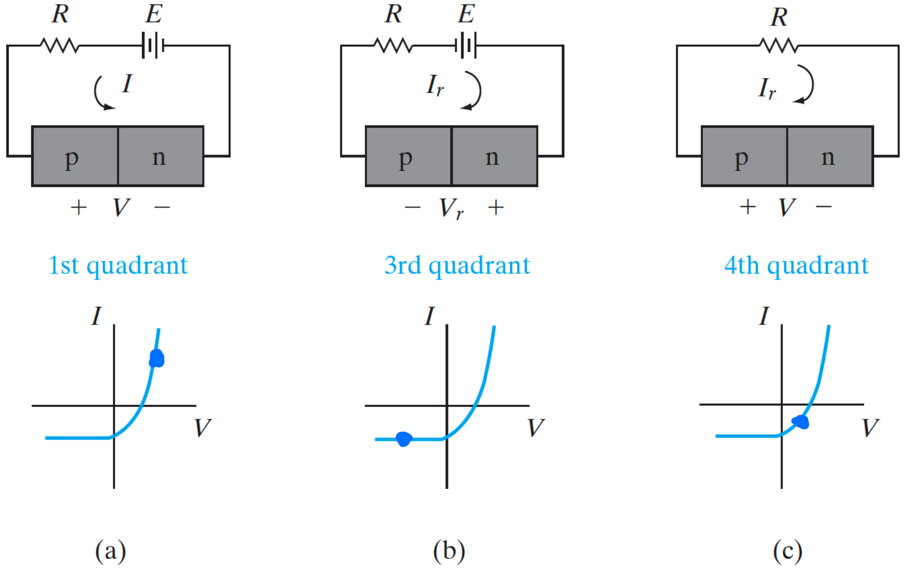
Operating in which quadrant(s) requires power from external circuit?

1st and 3rd

Operating in which quadrant(s) generates power?

4th (product I x V is negative)

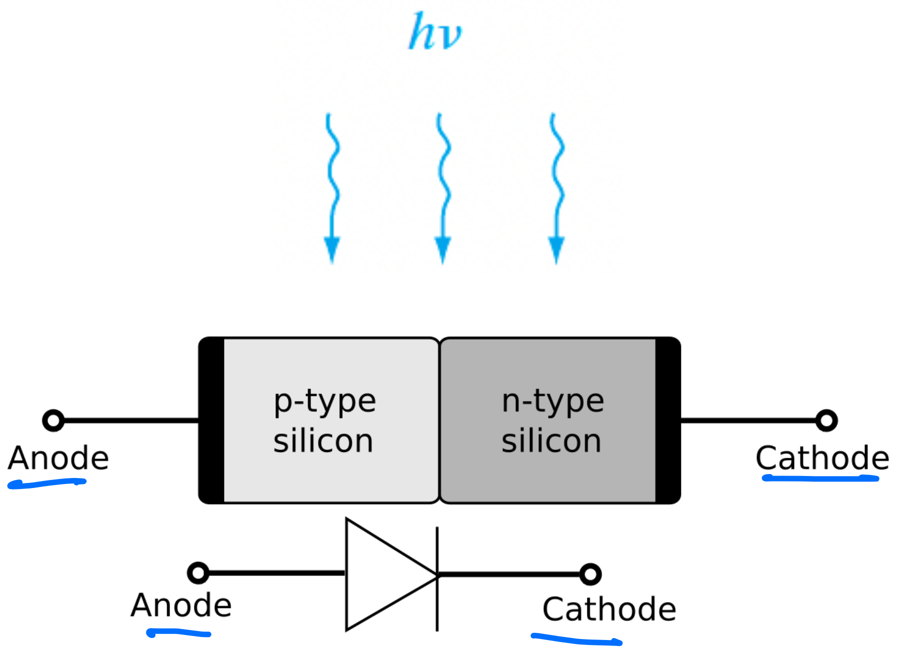
- We choose which quadrant to operate in depending on application.

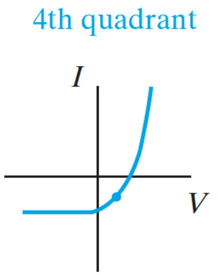


Sources: Textbook

Solar Cell Basics

- A type of photodiode
- Also called photovoltaic cells
- Convert optical power (sunlight) into electricity
  - 4th 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? Not a lot! Why solar cells are arrayed
  - $V_{oc} <$ 0.5 - 1 V
  - $I_{op} \approx 10 - 100\ mA$





Sources: Wikipedia, Textbook

Solar Cell Design

- How do we generate more power?

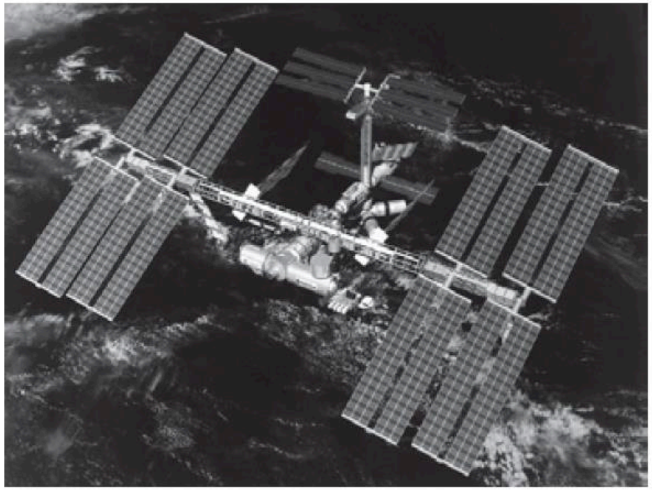
  Operate an array (panel)

- Connect cells in <u>series</u> to obtain desired voltage, then connect in parallel

  series: share a current
  parallel: share a voltage

- Desired:
  - Large junction area located <u>near the surface</u>
  - Small series resistance in the device (maximize output power)

- Compromises:
  - Increasing V_0 (limit for V_{oc}) through doping inadvertently reduces lifetime

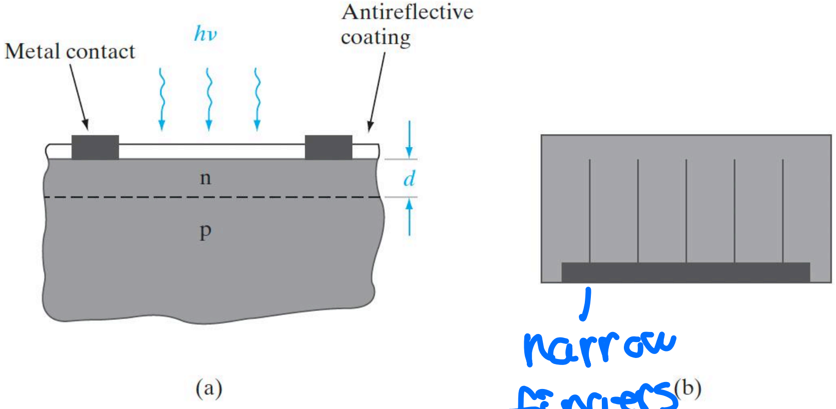


(a)

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 series resistance
  - More exposed surface
- Region is heavily doped, so resistance is small good ohmic contacts! (tunneling)
- BUT if we put contacts only on the edges, current must flow across entire long surface
  - Series resistance would become large
- Fingers reduce distance current travels, without interfering with incoming light!



narrow fingers

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

* sometimes transparent electrodes are used!

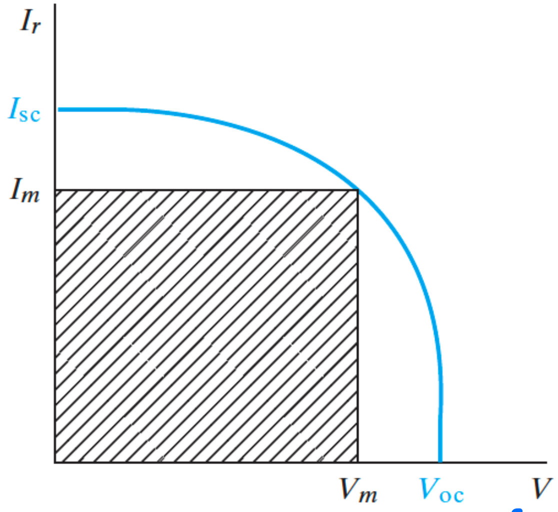
Sources: UPS Battery Center, Wikipedia, Electronics Hub, Electron Test Equipment, Laser Components, PV Education

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 $I_{sc}V_{oc}$ = P predicted

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

- We want to maximize 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



Typically 0.7 (70%)

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

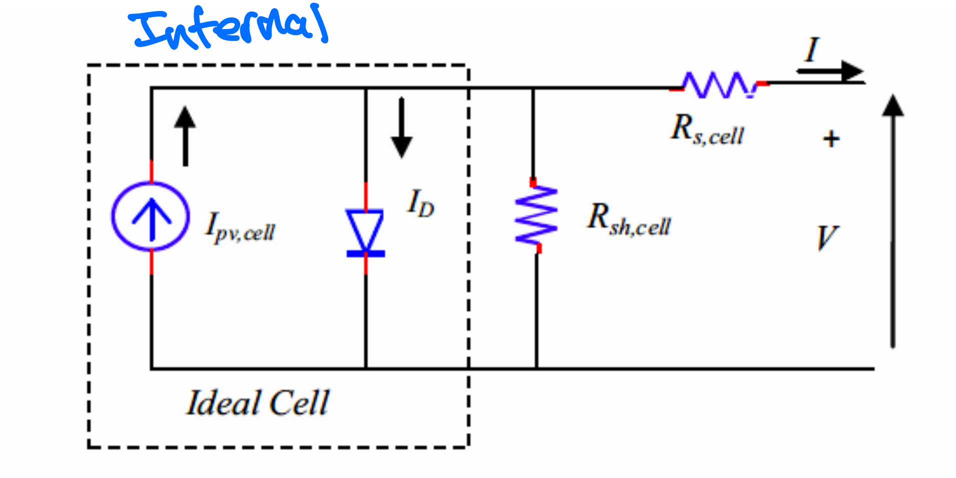
P predicted

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 recombination
- R_s: series resistance due to device (p, n layer and metal contacts)
- R_{sh}: shunt resistance due to parallel conductive leakage pathways

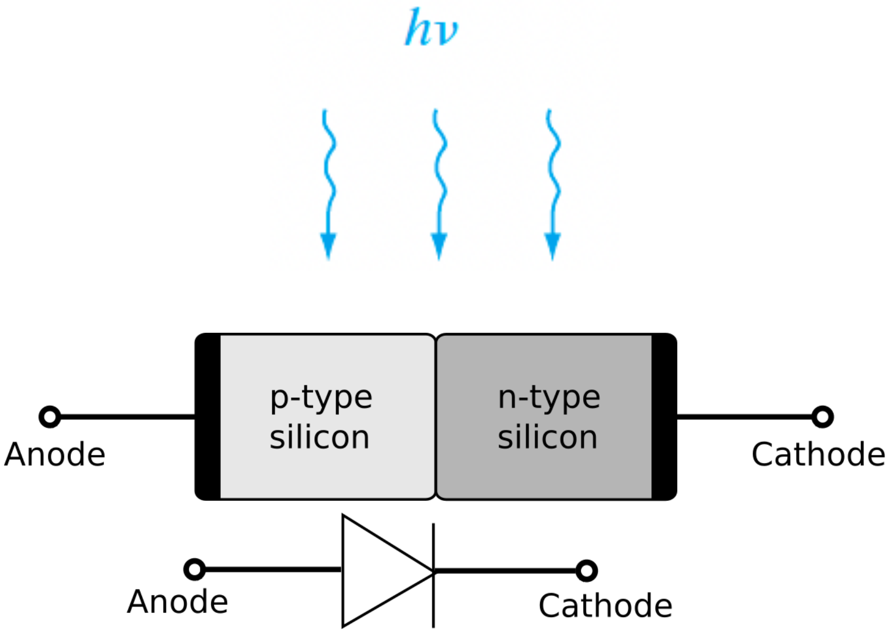
- We want to manage resistance to increase power:
  - Decrease series (internal)
  - Increase shunt (external)
- $I = I_{pv} - I_D - I_{R_{sh}}$

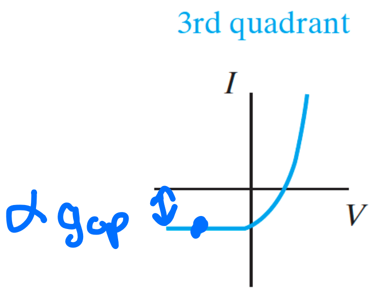


•Sources:DOI: 10.1109/ICoSC.2017.7958647

Photodetector Basics

- A type of photodiode
- Converts time-varying optical/light signals into electrical signals
  - 3rd quadrant consume power to operate
- Current is essentially independent of voltage, and proportional to gop
- Imagine we need to detect a series of light pulses 1 ns apart
- The photogenerated minority carriers must diffuse to the junction and be swept across in time $\ll 1\,ns$
- Important metric: response speed (frequency)





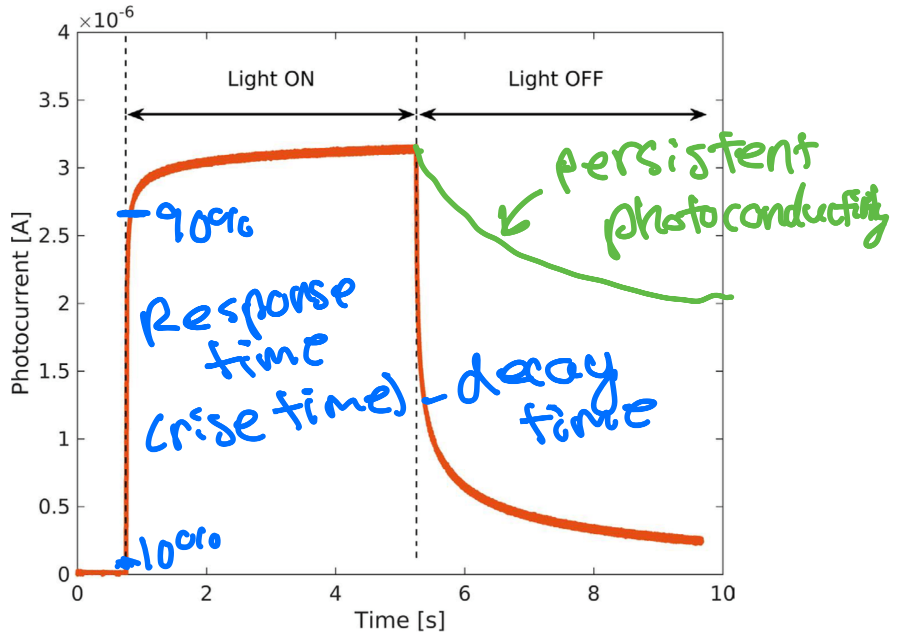
Sources: Wikipedia, Textbook

Photodetector Design and Speed

- To improve response time (Bandwidth), increase W so most ~~devices~~ photons are absorbed in the SCR
- EHPs generated in W will be swept to other side very quickly
- Called a depletion-layer photodiode
- How can we increase W?

Dope 1 side heavily (p^+n or n^+p)

- Compromise:
  - Larger W, most photons absorbed in W and sensitivity is high (pro)
  - Larger W, C_j is small and RC of circuit is low, increasing speed (pro)
  - Larger W, time for carriers to drift across goes up and lowers speed ..... (cons)



[Hz = s^{-1}]

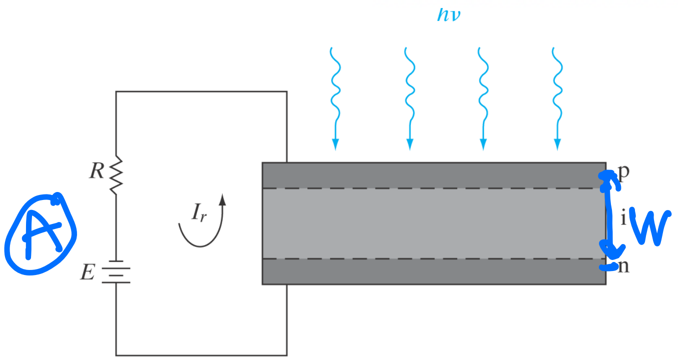
$$f_{max} \approx \frac{1}{transit\ time} \approx \frac{1}{\frac{W}{v_{sat}}} \approx \frac{v_{sat}}{W}$$

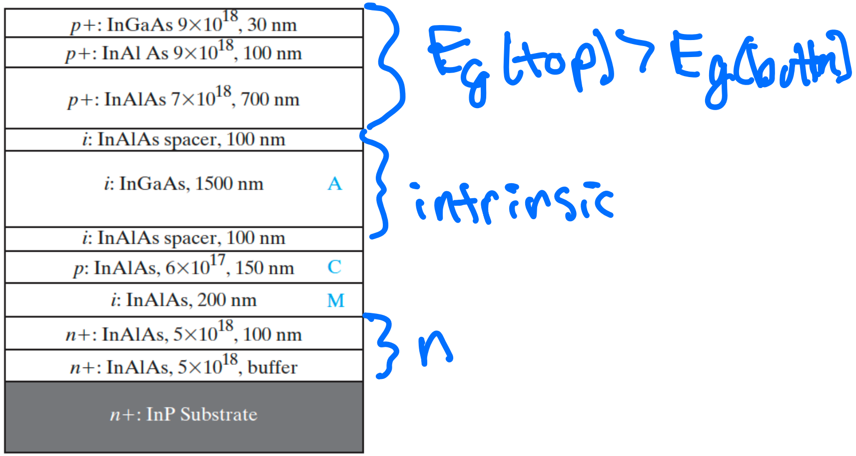
•Sources: E. Pop ECE 340 Slides, DOI: 10.1038/srep37913

Approaches to Improve Photodetector Performance

- Use p-i-n ________ as photodetector to enlarge depletion region W, improving response time (left) ↑intrinsic
- Use lattice-matched layers of compound semis with wider bandgap material on top ________. Lower energy photons can easily be transmitted through to junction with narrower bandgap ________ 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%)

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

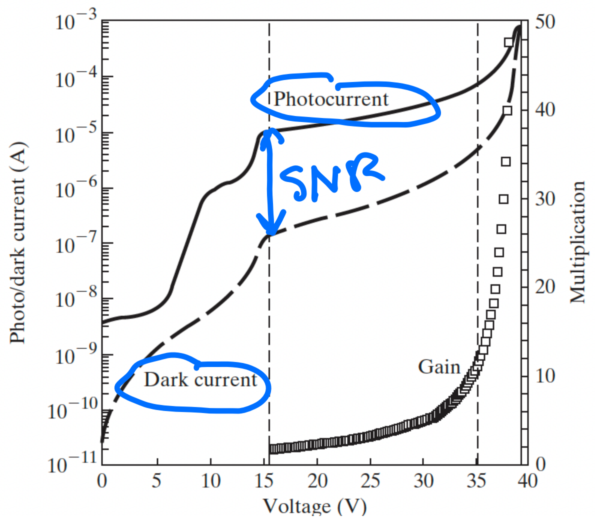


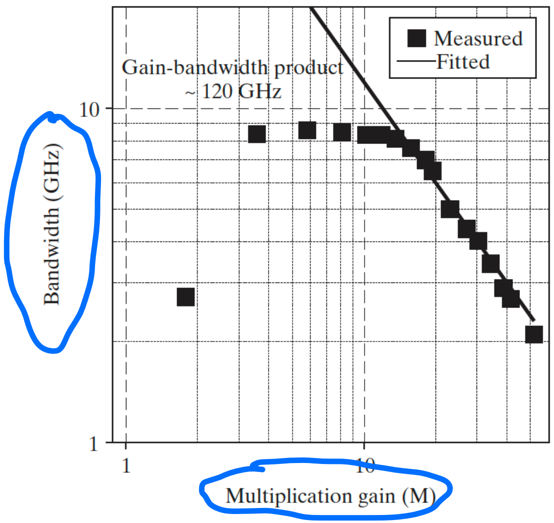


Sources: E. Pop ECE 240 Slides, Textbook

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