EE 116 Lectures 28-29

P-N optoelectronics; photodetectors, solar cells, LEDs

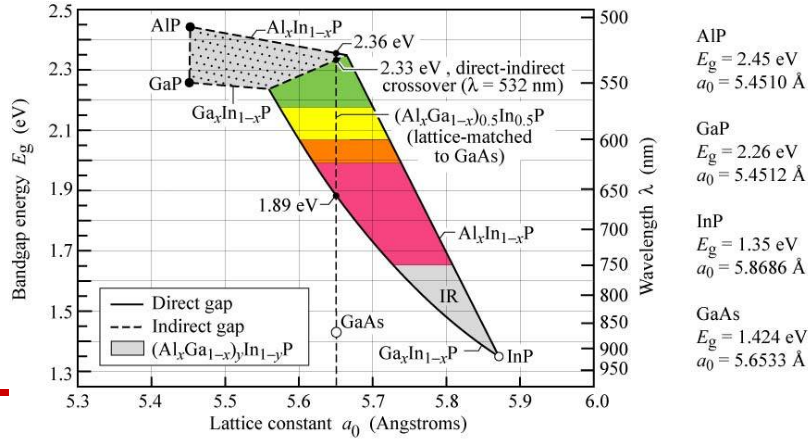
Read: Chapter 4.6 in BVZ book and/or Chapter 4.12 in CCH book

Recall: Si is great (cheap, good SiO_2 insulator) for high complexity digital & cheap analog circuits

What if we want: High-speed (10s GHz – 1 THz) analog amplifiers; Optical receivers, emitters (LEDs, lasers)

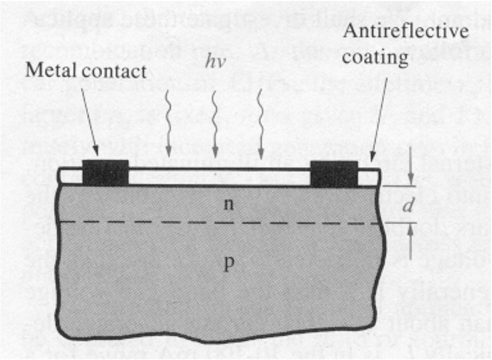
	Si	Ge	GaAs	InAs
μ_n (cm^2/V·s)	1400	3900	8500	30000
μ_p (cm^2/V·s)	470	1900	400	500

Look at other semiconductors with BETTER mobility and light emission / absorption properties ("custom" E_G).



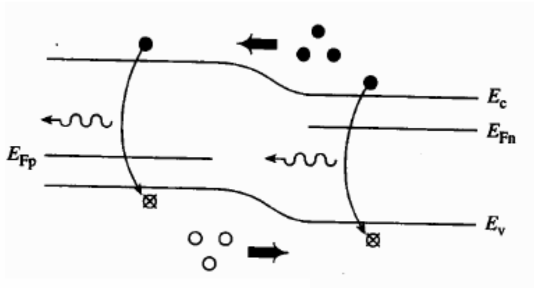
Two diode applications in optoelectronics:

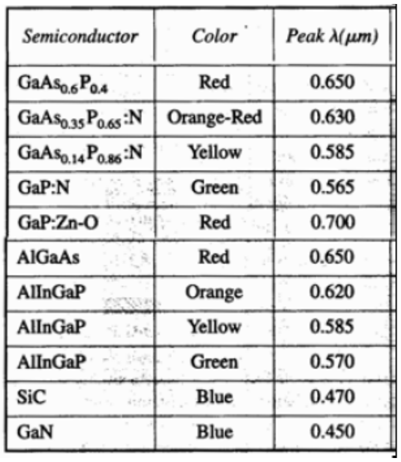
1) Photodiode or solar cell



→ must tailor $E_G < E_{phot}$ for good absorption

2) Light-emitting diode (LED) → must tailor E_G to emit desired color

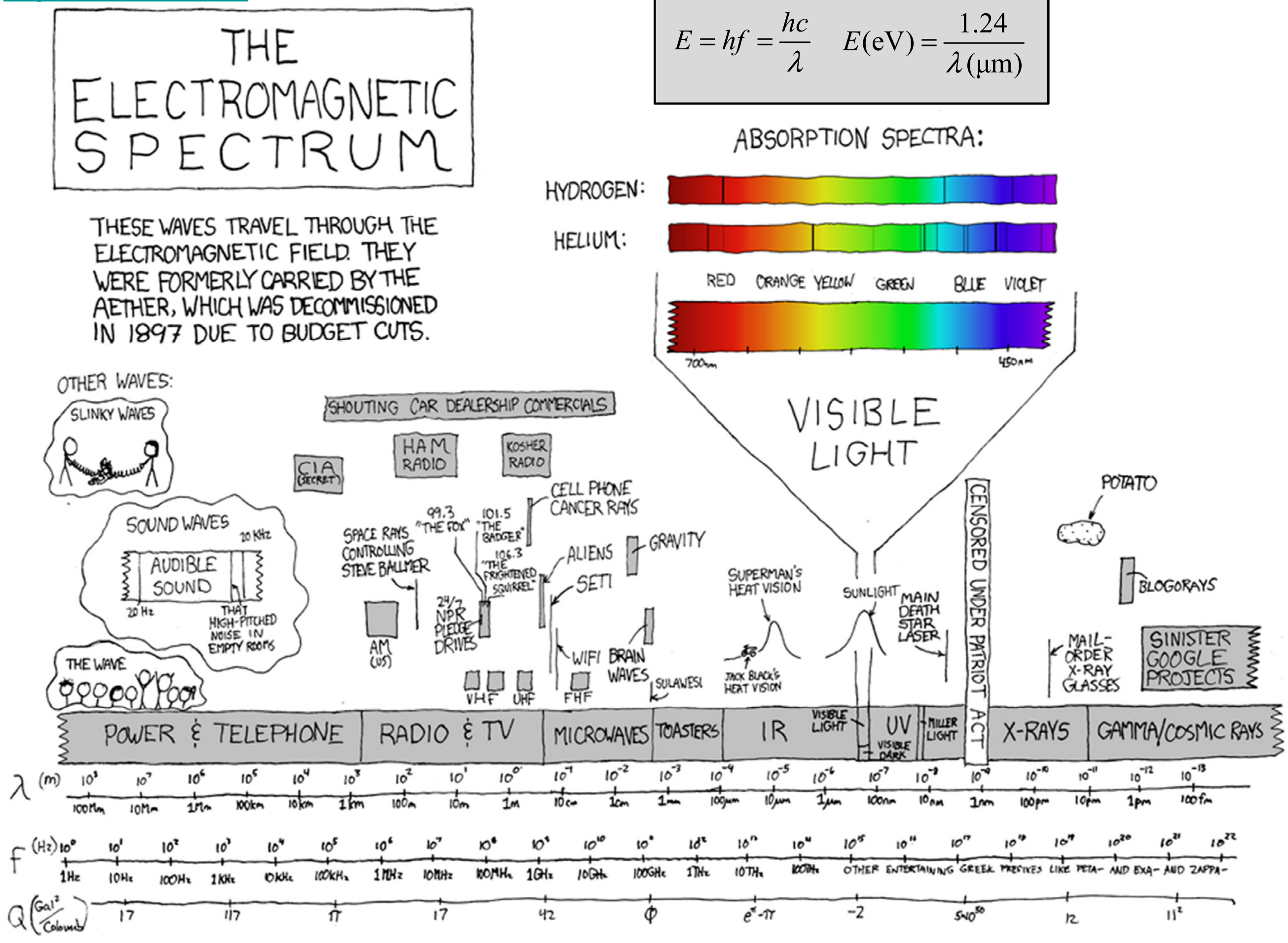




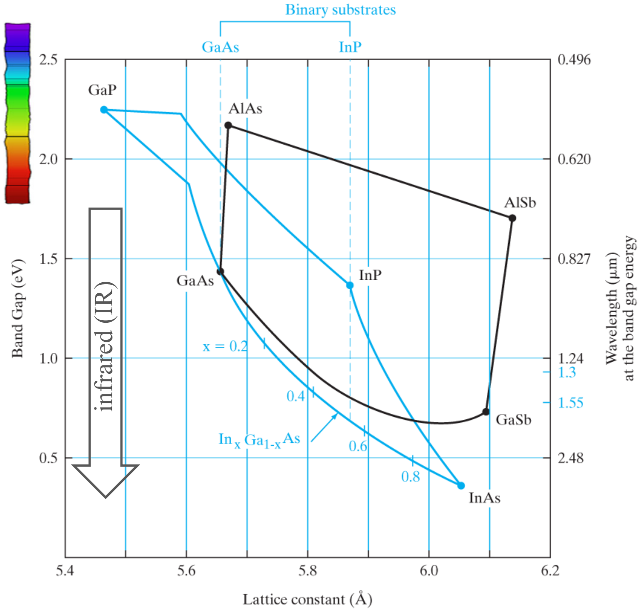
Semiconductor	Color	Peak λ(μm)
$GaAs_{0.6}P_{0.4}$	Red	0.650
$GaAs_{0.35}P_{0.65}$:N	Orange-Red	0.630
$GaAs_{0.14}P_{0.86}$:N	Yellow	0.585
GaP:N	Green	0.565
GaP:Zn-O	Red	0.700
AlGaAs	Red	0.650
AlInGaP	Orange	0.620
AlInGaP	Yellow	0.585
AlInGaP	Green	0.570
SiC	Blue	0.470
GaN	Blue	0.450

http://xkcd.com/273/

$$E = hf = \frac{hc}{\lambda} \qquad E(\text{eV}) = \frac{1.24}{\lambda\,(\mu\text{m})}$$

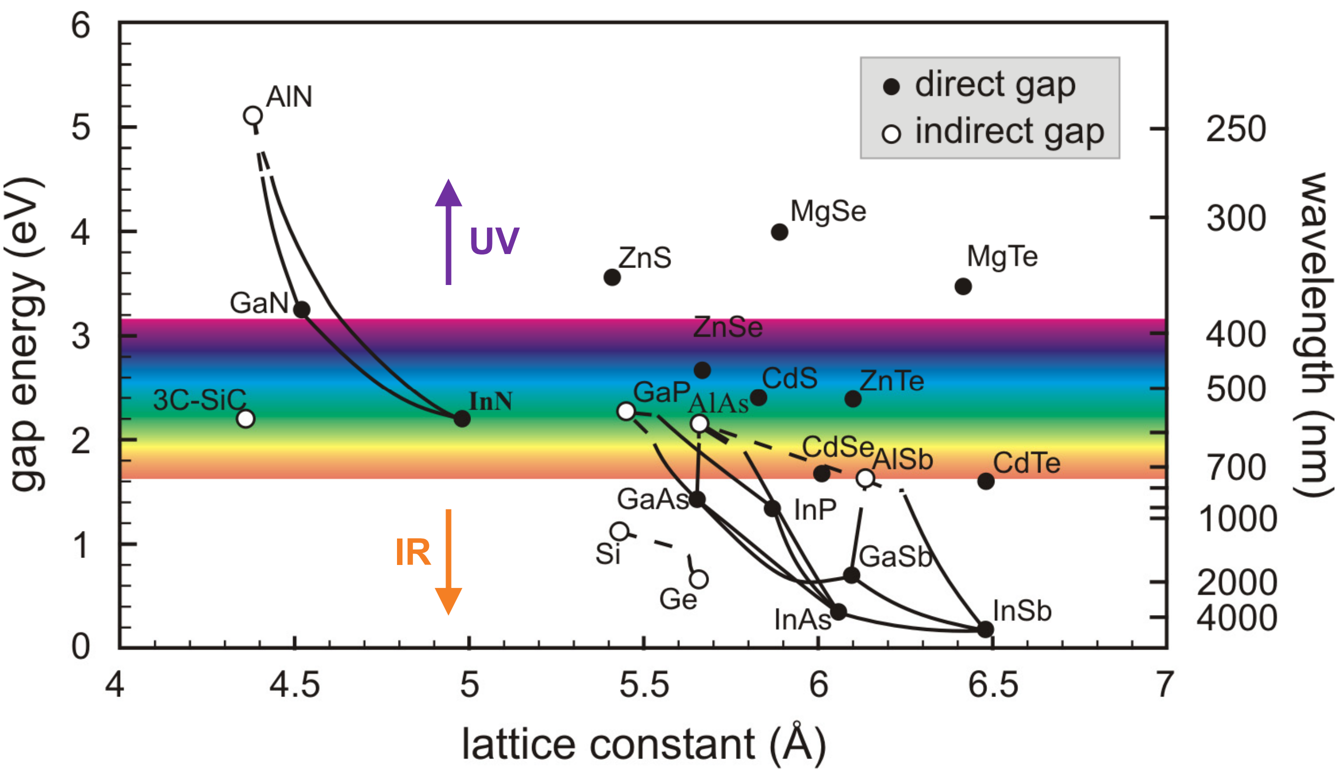


- Q: How do we tailor the band gap E_G?
- A: Choose different materials (e.g. Si, Ge) or alloy some materials (e.g. $In_xGa_{1-x}As$)



- Generally, we can assume lattice constant (a) and E_G vary linearly with alloy fraction (x)
- Note: prefer same lattice constant as the substrate (e.g. GaAs or InP) to minimize lattice defects in a device
- Defects are bad, they serve as recombination centers (traps)!

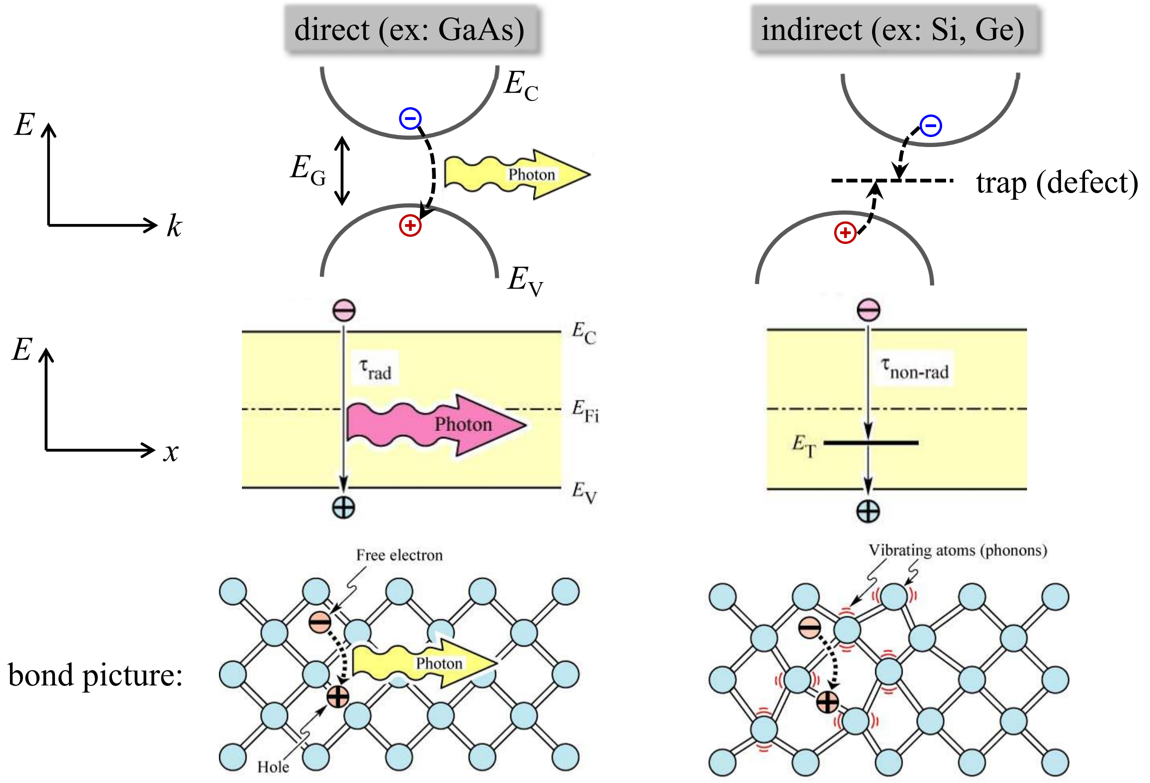
Taking a broader look:



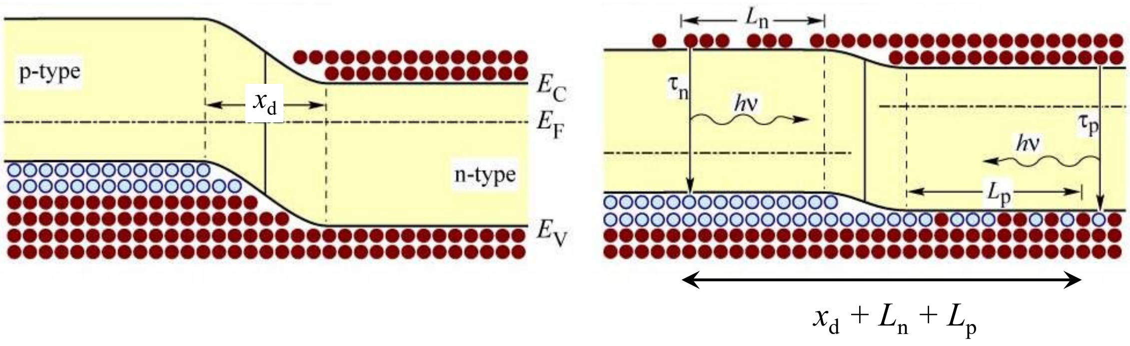
http://gorgia.no-ip.com/phd/html/thesis/phd_html/node4.html

- Q: Do we want direct or indirect band gap E_G?
- A: Direct E_G whenever possible. Indirect is OK for light absorbers (solar cells) but not emitters (LEDs)

→ *Make a Si LED, get a Nobel prize!*



- We know p-n junction can be used to:
    - Emit light (EHP recombination at forward bias, with direct E_G)
    - Absorb light (EHP generation at reverse bias)



- Minority & majority carriers recombine and/or emit light
    - In the depletion region (x_d)
    - Within a recombination length (L_n, L_p) in n- and p-sides

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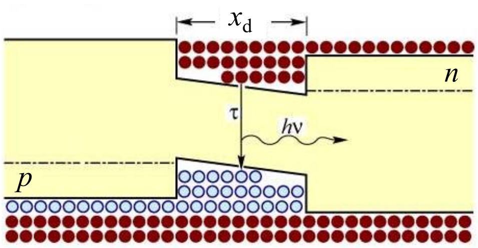
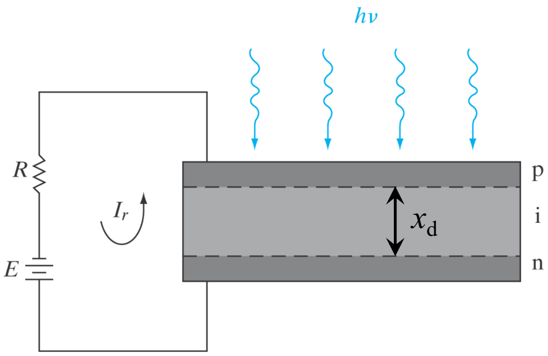
Can we control & improve p-n light emission / absorption?

1) Use p-n *heterojunction*, i.e. force depletion region to occur in a material with smaller E_G



Herbert Kroemer
Nobel Prize 2000

2) Use p-i-n diode by inserting an intrinsic ("i") region to enlarge x_d, increasing absorption volume

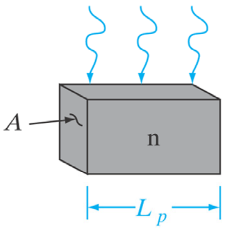


- What are the current & voltage in a solar cell?
  1) Note: need illumination photon energy hf > E_G
  2) Assume quantum efficiency Q.E. = 1 = one EHP created for every incoming photon

- For example, if EHP generation is $g_{op} = 10^{17}$ EHPs/cm^3/s
- What is the optically generated current?

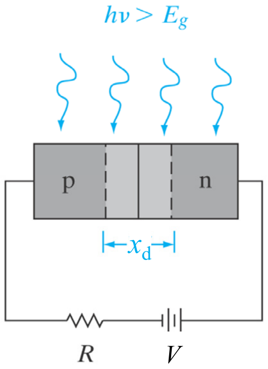
$$I_{op} = q \times g_{op} \times (\text{generation volume})$$

- What is the generation volume for a PN diode?



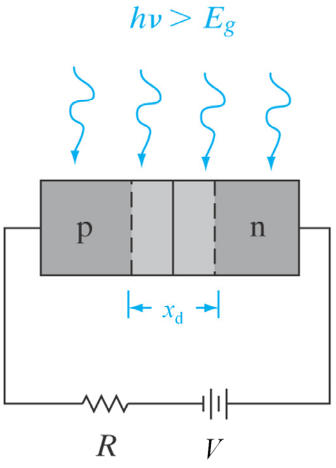
$\delta p_{op} = g_{op} \tau_p$

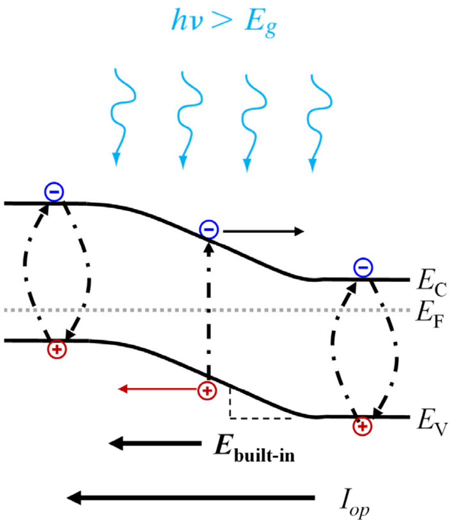
$I_{op} = q A L_p g_{op}$



- How do photogenerated carriers flow out as current?
- Built-in electric field causes short circuit current “for free”

Short circuit, $V = 0$

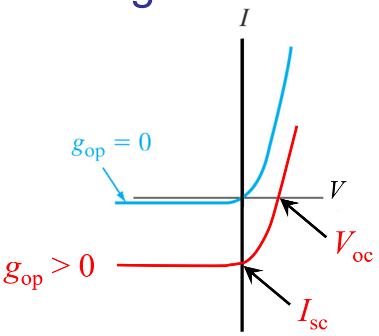




$$I_{op} = q g_{op} A \left(x_d + L_n + L_p \right)$$

- How does the photogenerated current add (or subtract) to the current already induced by the diode voltage?

$$I = qn_{\mathrm{i}}^2 A\left[\frac{D_n}{L_n N_{\mathrm{A}}} + \frac{D_p}{L_p N_{\mathrm{D}}}\right](e^{qV/kT} - 1) - I_{op}$$



- Short-circuit current: external $V = 0$ → $I_{sc} = -I_{op}$
- Open-circuit voltage: external $I = 0$ → $V_{oc} = \frac{kT}{q}\ln\left(\frac{I_{op}}{I_0} + 1\right)$
- This is a *photovoltaic* effect.

- How fast is the photodiode speed (response frequency)?

$f_{max} \approx v_{sat}/x_d$

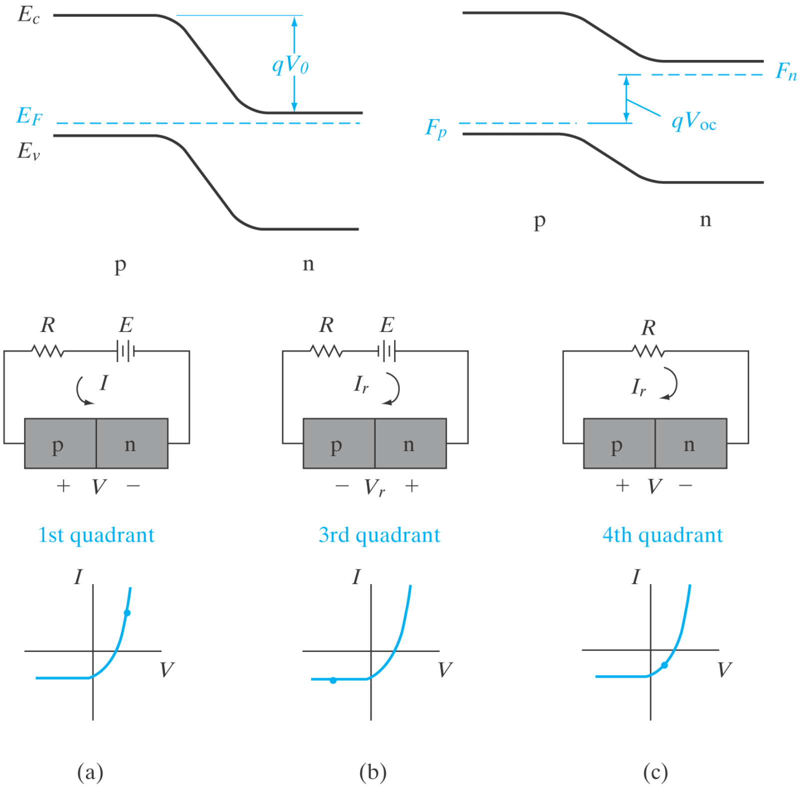


Figure 8.3

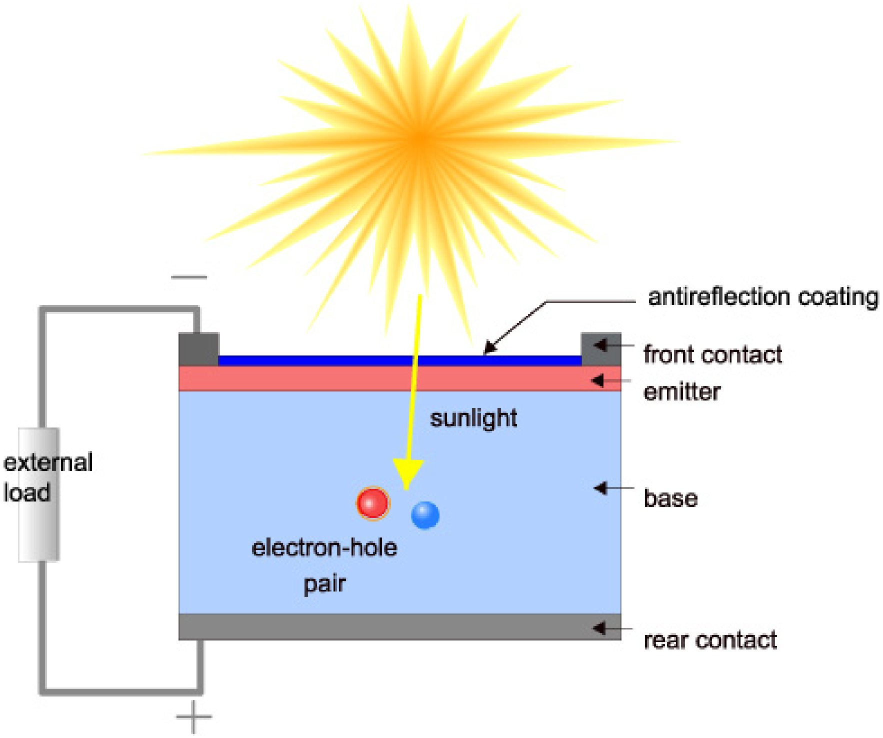
Operation of an illuminated junction in the various quadrants of its I–V characteristic; in (a) and (b), power is delivered to the device by the external circuit; in (c) the device delivers power to the load.

Ex: **Photodiode Design.** Consider a p-i-n photodiode with "i" region made of $In_xGa_{1-x}As$. Design stoichiometry "x" and thickness of the "i" region (W_i) to enable response at 1.3 μm wavelength, up to 20 GHz signals. Assume fields are sufficiently high to reach $v_{sat} \approx 10^7$ cm/s in the "i" region. Name at least one design constraint on the "p" and "n" regions of this photodiode. You may assume the lattice constant and band gap of $In_xGa_{1-x}As$ vary linearly with composition "x".

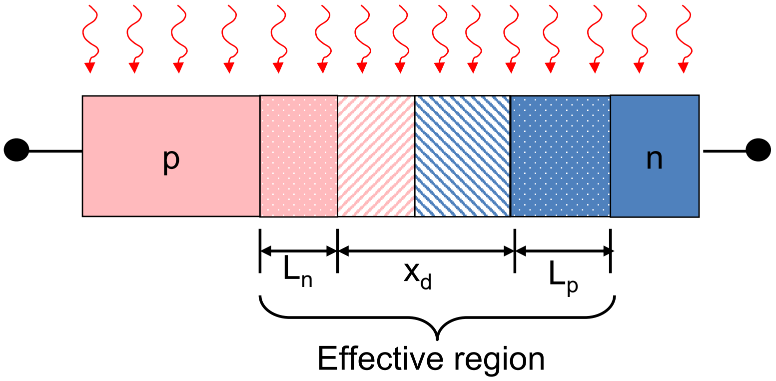
Deeper look at the solar cell

Read: BVZ Ch. 4.8

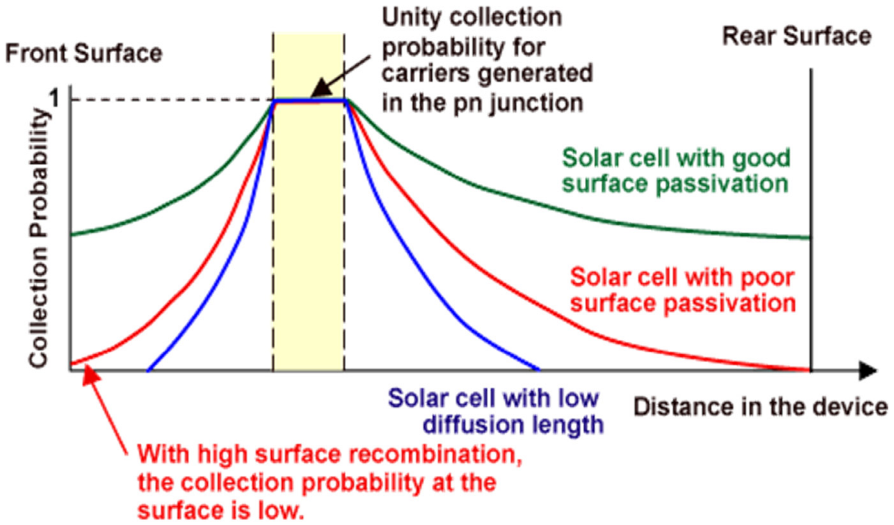
Goal: collect as many photon-generated carriers as possible



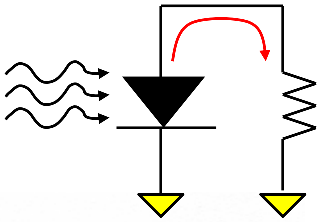
pveducation.org



Importance of large x_d, L_n, L_p (long τ's) and good surfaces (low surface recombination)



- Solar Cell I-V (flip 4th quadrant of pn diode I-V)
  - Note short-circuit current
  - Note open-circuit voltage



- At what operating voltage can we extract maximum power?*

→ maximize $P = I_m V_m$ "rectangle"

$$\left.\frac{dP}{dV}\right|_{V_m} = 0$$

→ in practice V_m is typically < E_G/q

Note: Fill factor = $FF = \frac{I_m V_m}{I_{sc} V_{oc}}$

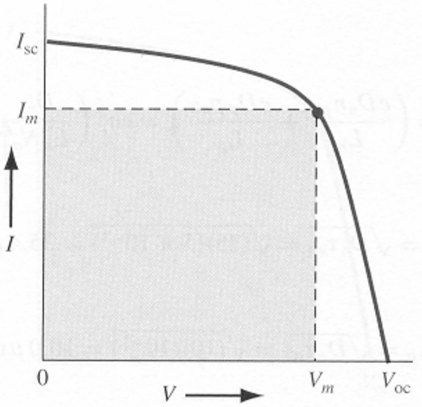
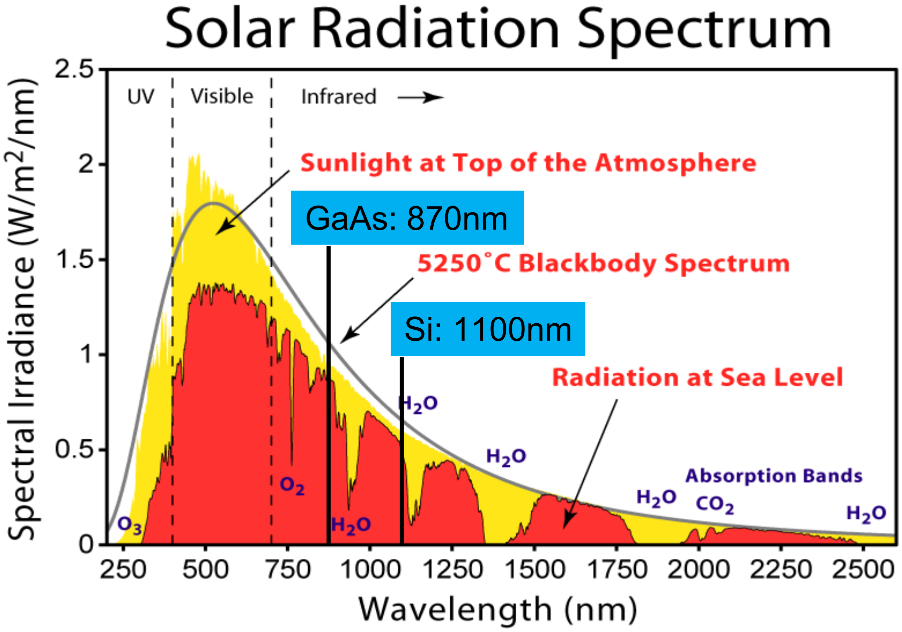


Figure 14.8 | Maximum power rectangle of the solar cell I–V characteristics.

*also see BVZ section 4.8.2

- Solar radiation (note “gaps” in the spectrum)
- About 1 kW/m^2 reaches us (note: 1 HP ≈ 0.75 kW)



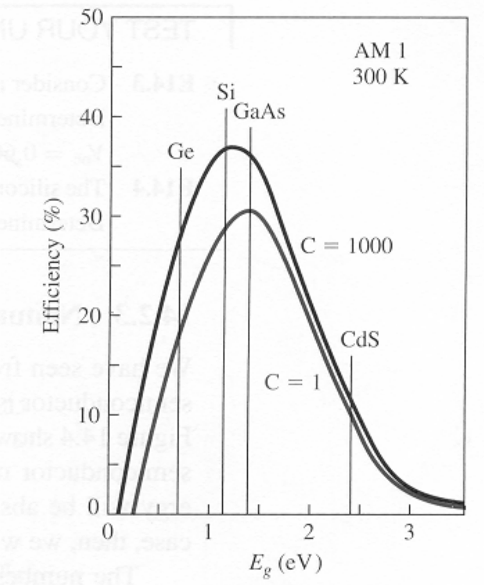


Figure 14.10 | Ideal solar cell efficiency at $T = 300$ K for C = 1 sun and for a C = 1000 sun concentration as a function of bandgap energy. *(From Sze [16].)*

- Solar cell efficiency

$$\eta = \frac{P_m}{P_{in}} \times 100\% = \frac{I_m V_m}{P_{in}} \times 100\%$$

- **Shockley-Queisser limit***
- Max efficiency ~30% at E_G=1.1 eV

- Factors limiting efficiency:
  - Spectral width of solar radiation
  - If $E_{phot} < E_G$ not absorbed
  - If $E_{phot} > E_G$ then $E_{phot} - E_G$ portion is wasted as heat

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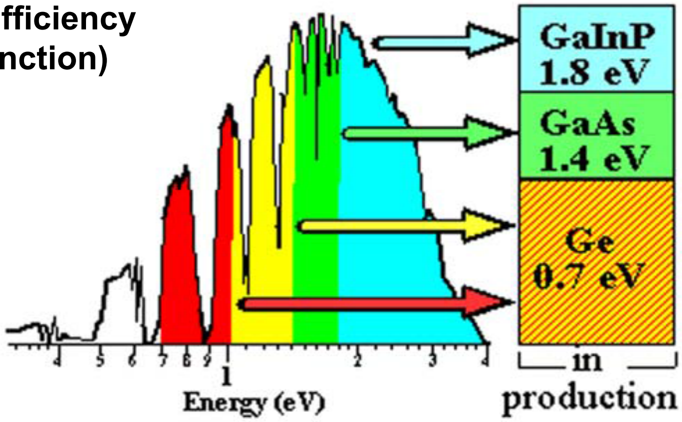
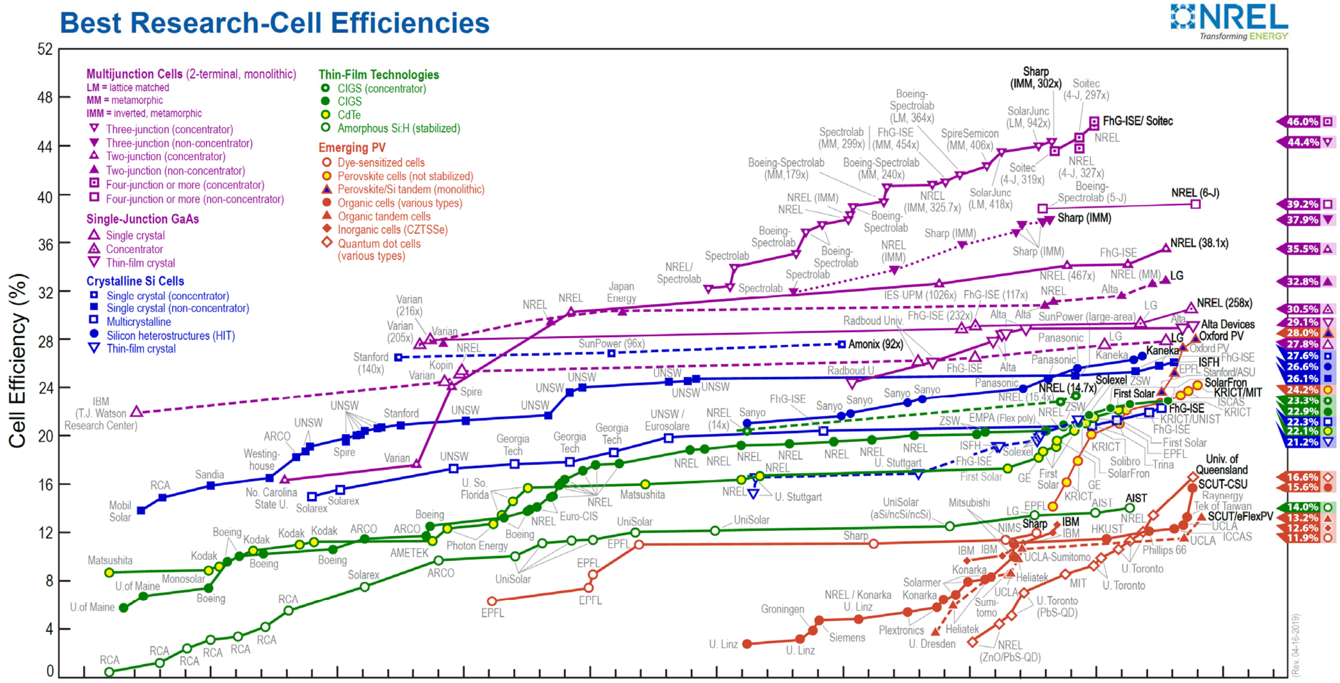
*W. Shockley and H.J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", *J. Appl. Phys.* **32**, pp. 510-519 (1961)

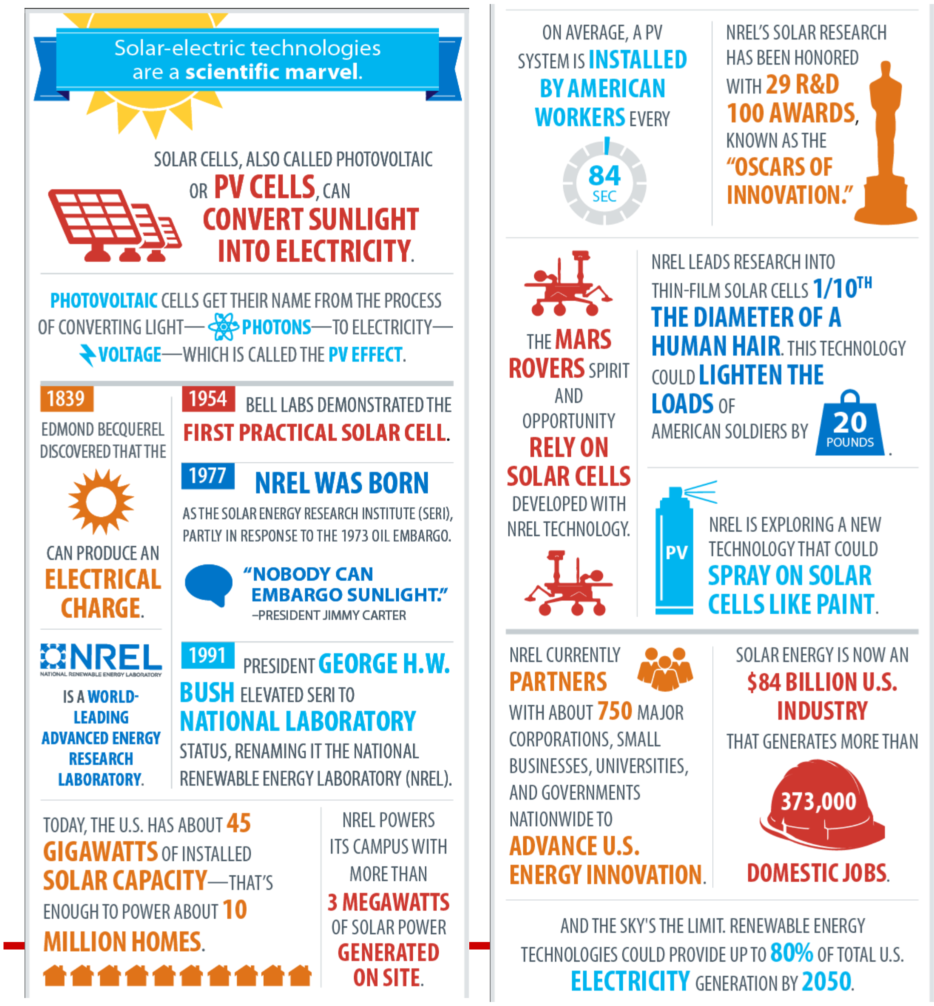
- How can we increase solar cell efficiency?
- Use multi-junction cells (multiple band gap materials, prefer direct band gaps) instead of single-junction

World Record Efficiency 43.5% (Solar Junction)





source: https://www.nrel.gov/pv/cell-efficiency.html



Solar-electric technologies are a **scientific marvel**.

SOLAR CELLS, ALSO CALLED PHOTOVOLTAIC OR **PV CELLS**, CAN **CONVERT SUNLIGHT INTO ELECTRICITY**.

PHOTOVOLTAIC CELLS GET THEIR NAME FROM THE PROCESS OF CONVERTING LIGHT—**PHOTONS**—TO ELECTRICITY—**VOLTAGE**—WHICH IS CALLED THE **PV EFFECT**.

1839 EDMOND BECQUEREL DISCOVERED THAT THE ☀ CAN PRODUCE AN **ELECTRICAL CHARGE**.

1954 BELL LABS DEMONSTRATED THE **FIRST PRACTICAL SOLAR CELL**.

1977 **NREL WAS BORN** AS THE SOLAR ENERGY RESEARCH INSTITUTE (SERI), PARTLY IN RESPONSE TO THE 1973 OIL EMBARGO.

"NOBODY CAN EMBARGO SUNLIGHT."
–PRESIDENT JIMMY CARTER

NREL NATIONAL RENEWABLE ENERGY LABORATORY IS A **WORLD-LEADING ADVANCED ENERGY RESEARCH LABORATORY**.

1991 PRESIDENT **GEORGE H.W. BUSH** ELEVATED SERI TO **NATIONAL LABORATORY** STATUS, RENAMING IT THE NATIONAL RENEWABLE ENERGY LABORATORY (NREL).

TODAY, THE U.S. HAS ABOUT **45 GIGAWATTS** OF INSTALLED **SOLAR CAPACITY**—THAT'S ENOUGH TO POWER ABOUT **10 MILLION HOMES**.

NREL POWERS ITS CAMPUS WITH MORE THAN **3 MEGAWATTS** OF SOLAR POWER **GENERATED ON SITE**.

ON AVERAGE, A PV SYSTEM IS **INSTALLED BY AMERICAN WORKERS** EVERY **84** SEC

NREL'S SOLAR RESEARCH HAS BEEN HONORED WITH **29 R&D 100 AWARDS**, KNOWN AS THE **"OSCARS OF INNOVATION."**

THE **MARS ROVERS** SPIRIT AND OPPORTUNITY **RELY ON SOLAR CELLS** DEVELOPED WITH NREL TECHNOLOGY.

NREL LEADS RESEARCH INTO THIN-FILM SOLAR CELLS **1/10TH THE DIAMETER OF A HUMAN HAIR**. THIS TECHNOLOGY COULD **LIGHTEN THE LOADS** OF AMERICAN SOLDIERS BY **20** POUNDS.

PV

NREL IS EXPLORING A NEW TECHNOLOGY THAT COULD **SPRAY ON SOLAR CELLS LIKE PAINT**.

NREL CURRENTLY **PARTNERS** WITH ABOUT **750** MAJOR CORPORATIONS, SMALL BUSINESSES, UNIVERSITIES, AND GOVERNMENTS NATIONWIDE TO **ADVANCE U.S. ENERGY INNOVATION**.

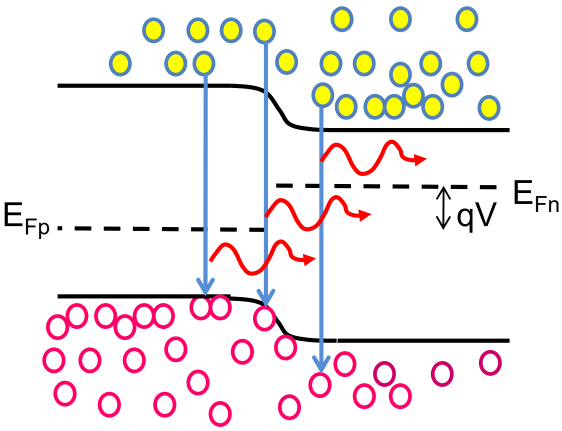
SOLAR ENERGY IS NOW AN **$84 BILLION U.S. INDUSTRY** THAT GENERATES MORE THAN **373,000 DOMESTIC JOBS**.

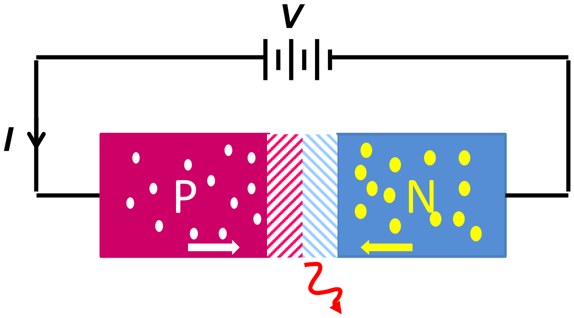
AND THE SKY'S THE LIMIT. RENEWABLE ENERGY TECHNOLOGIES COULD PROVIDE UP TO **80%** OF TOTAL U.S. **ELECTRICITY** GENERATION BY **2050**.

NREL NATIONAL RENEWABLE ENERGY LABORATORY | 40 1977 - 2017

July 2017 nrel.gov/solar/infographic.html

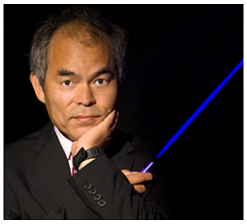
- Few more (final) words on LEDs

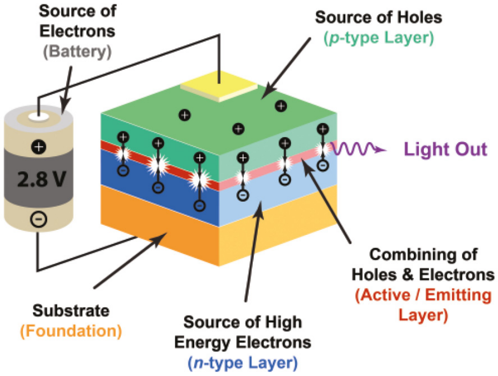




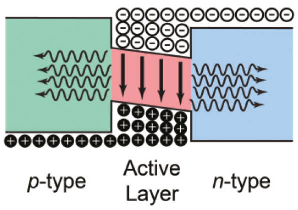
Forward biased pn junction

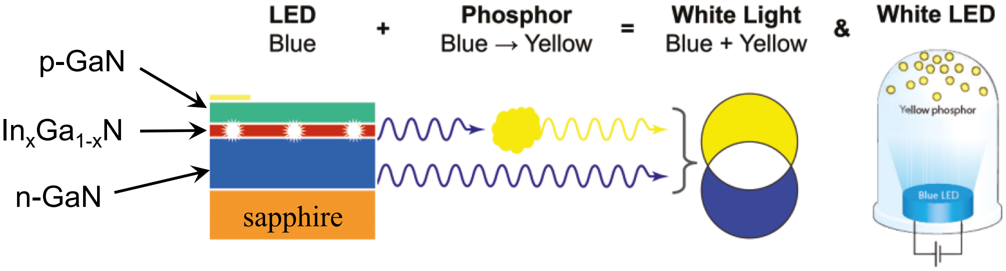
- Blue LED and revolution in lighting
- Nakamura, Akasaki, Amano (1990s) → Nobel prize 2014



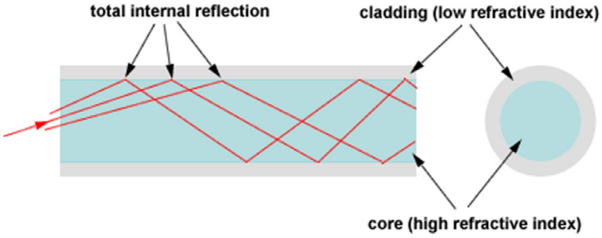


Double Heterostructure LED





- Optical fiber communications → why use wavelengths of 1.3 or 1.55 μm?
  - Minimum attenuation
  - Minimum dispersion



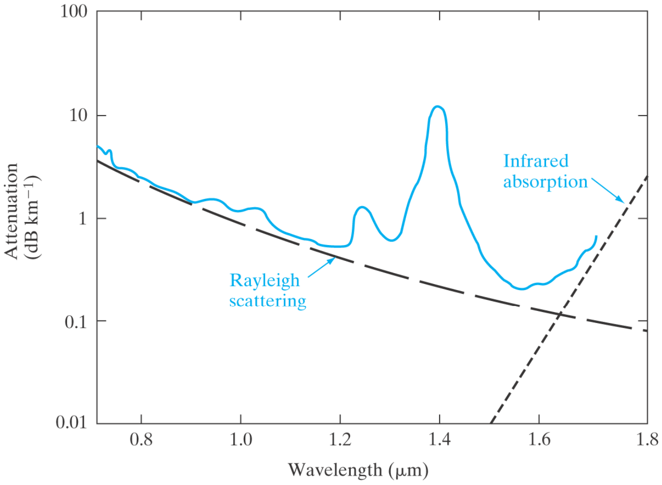
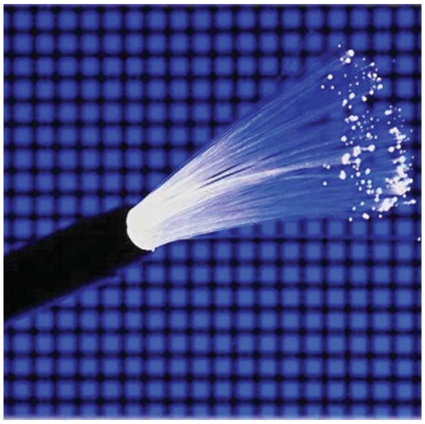


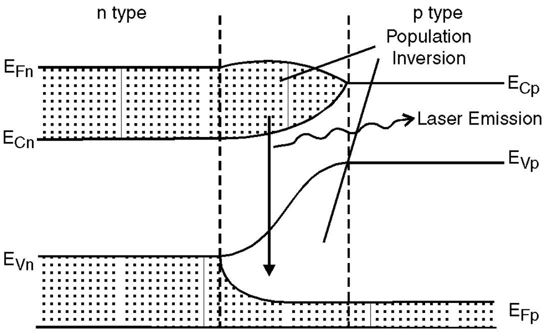
Figure 8.13

Typical plot of attenuation coefficient **α** vs. wavelength λ for a fused silica optical fiber. Peaks are due primarily to OH^- impurities.



Semiconductor lasers vs. LEDs:

- Strong fwd. bias, population inversion
- Recombination region + resonant cavity (length L, between semi-reflective mirrors)
- Stimulated emission at λ = 2L/m



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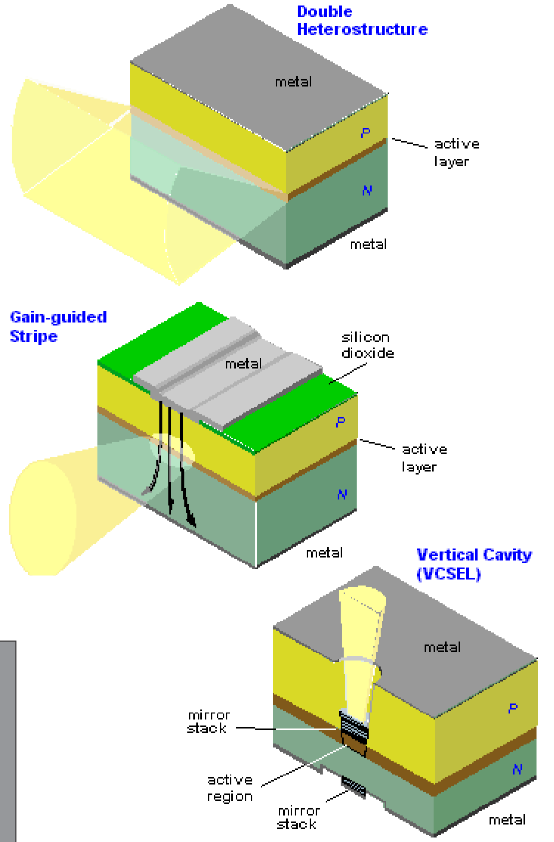
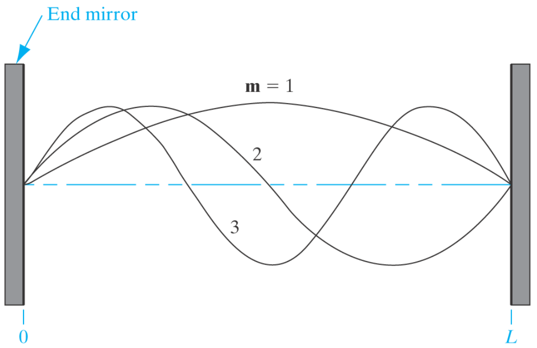
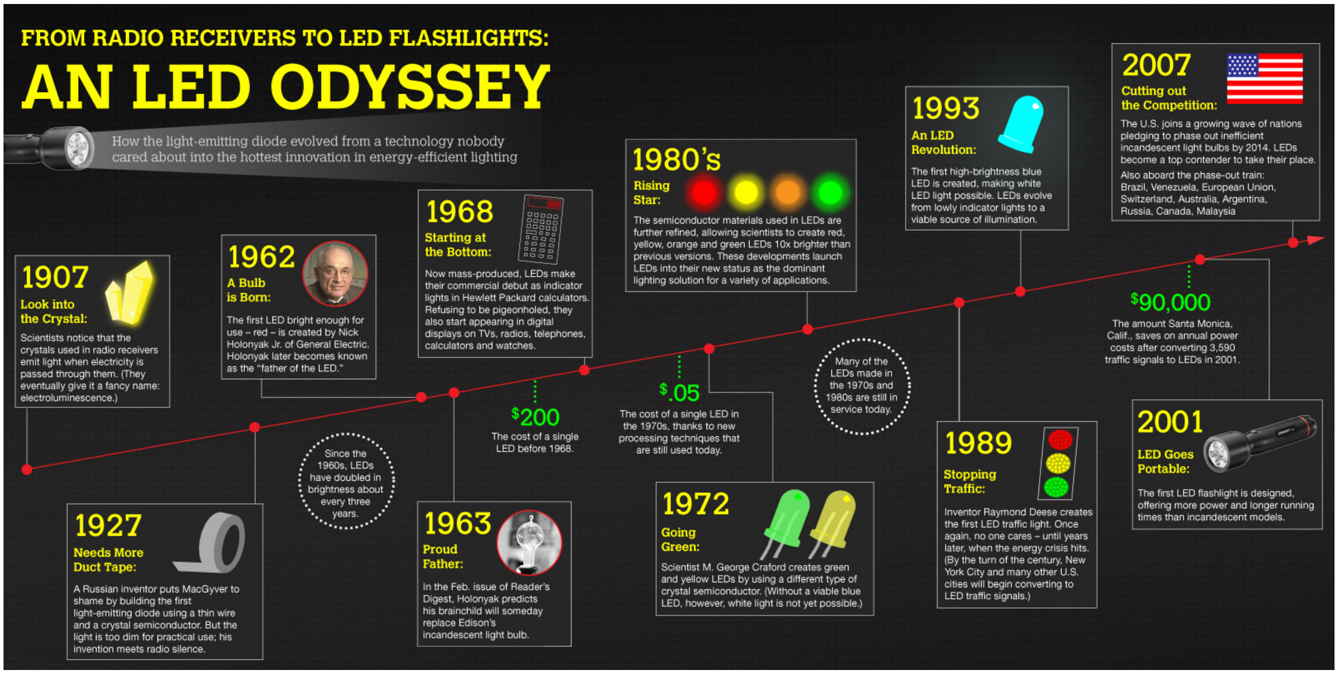


resonant modes **between mirrors** in laser cavity





FROM RADIO RECEIVERS TO LED FLASHLIGHTS:

AN LED ODYSSEY

How the light-emitting diode evolved from a technology nobody cared about into the hottest innovation in energy-efficient lighting

1907 Look into the Crystal: Scientists notice that the crystals used in radio receivers emit light when electricity is passed through them. (They eventually give it a fancy name: electroluminescence.)

1927 Needs More Duct Tape: A Russian inventor puts MacGyver to shame by building the first light-emitting diode using a thin wire and a crystal semiconductor. But the light is too dim for practical use; his invention meets radio silence.

1962 A Bulb is Born: The first LED bright enough for use – red – is created by Nick Holonyak Jr. of General Electric. Holonyak later becomes known as the "father of the LED."

Since the 1960s, LEDs have doubled in brightness about every three years.

1963 Proud Father: In the Feb. issue of Reader's Digest, Holonyak predicts his brainchild will someday replace Edison's incandescent light bulb.

1968 Starting at the Bottom: Now mass-produced, LEDs make their commercial debut as indicator lights in Hewlett Packard calculators. Refusing to be pigeonholed, they also start appearing in digital displays on TVs, radios, telephones, calculators and watches.

$200 The cost of a single LED before 1968.

$.05 The cost of a single LED in the 1970s, thanks to new processing techniques that are still used today.

1972 Going Green: Scientist M. George Craford creates green and yellow LEDs by using a different type of crystal semiconductor. (Without a viable blue LED, however, white light is not yet possible.)

1980's Rising Star: The semiconductor materials used in LEDs are further refined, allowing scientists to create red, yellow, orange and green LEDs 10x brighter than previous versions. These developments launch LEDs into their new status as the dominant lighting solution for a variety of applications.

Many of the LEDs made in the 1970s and 1980s are still in service today.

1989 Stopping Traffic: Inventor Raymond Deese creates the first LED traffic light. Once again, no one cares – until years later, when the energy crisis hits. (By the turn of the century, New York City and many other U.S. cities will begin converting to LED traffic signals.)

1993 An LED Revolution: The first high-brightness blue LED is created, making white LED light possible. LEDs evolve from lowly indicator lights to a viable source of illumination.

2001 LED Goes Portable: The first LED flashlight is designed, offering more power and longer running times than incandescent models.

$90,000 The amount Santa Monica, Calif., saves on annual power costs after converting 3,590 traffic signals to LEDs in 2001.

2007 Cutting out the Competition: The U.S. joins a growing wave of nations pledging to phase out inefficient incandescent light bulbs by 2014. LEDs become a top contender to take their place. Also aboard the phase-out train: Brazil, Venezuela, European Union, Switzerland, Australia, Argentina, Russia, Canada, Malaysia

http://www.infographicsshowcase.com/from-radio-receivers-to-led-flashlights-an-led-odyssey/coast-led-timeline/