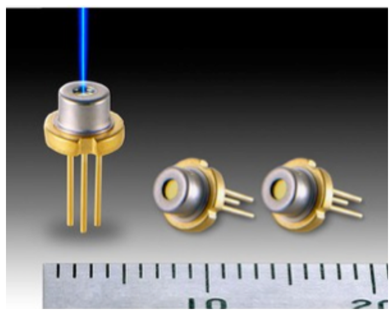
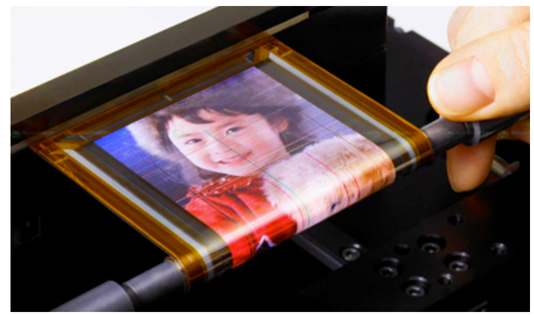
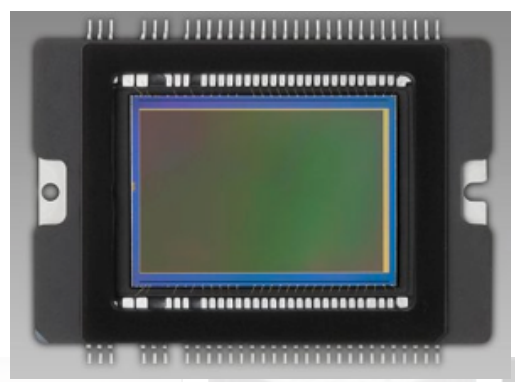
8.1 - Light Emission / Absorption in Semiconductors / Compound Semiconductors

- Most of these are just diode structures!

- LEDs
- Lasers
- Solar Cells
- Photodetectors
- Digital Cameras
- etc…

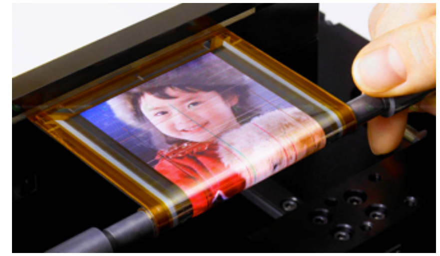



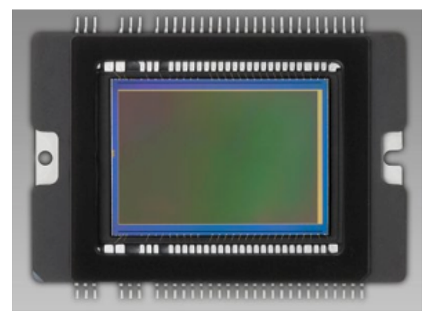
- Sure, you are eager to talk about the devices at right… but we need to first cover some fundamentals…

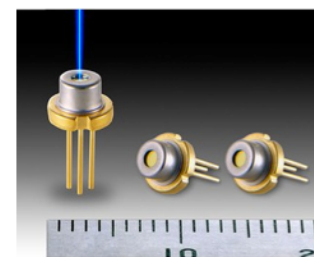
- Today we will talk about photon absorption first, and then photon emission…

  - *all semiconductors absorb light, but not all emit light*

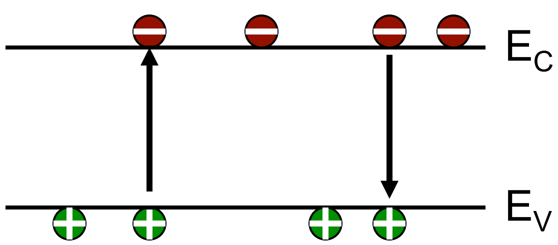
  - *and efficient absorption or emission <u>always</u> requires careful material and device design*

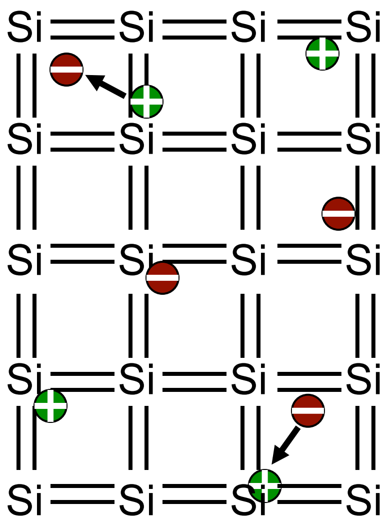






- Lets start with the undoped case.



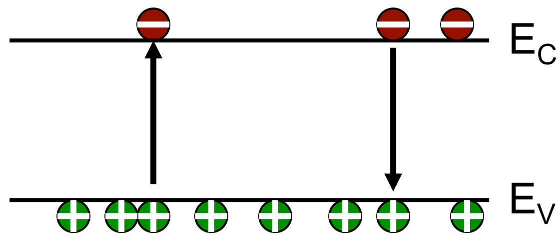


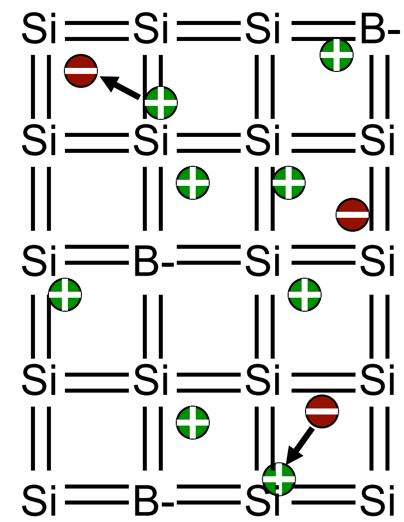
$$g_i = r_i = \alpha_r n_i^2 = 1/cc-s \quad (eq.\ valid\ for\ undoped\ only) \quad units\ for\ \alpha_r = cc/s$$

- Generation (g_i) and recombination (r_i)!
- Note units.
- Note recombination factor α_r depends on what mechanism dominates (more on that later).

- Now add doping… does doping effect recombination?

- *yes, more carriers, electrons and holes find each other faster!*
- *but… is not dopants recapturing their carriers!*
- *therefore lifetimes for electrons and holes must be equal, even with with doping!*





- The generation and recombination are *rates (1/s)* so there must be a lifetime (*s*) for carriers. Remember, *doping goes up, these average lifetimes go down!*

$$g_i = r_i = 1/cc-s$$

$$\tau_n = \tau_p = \frac{1}{\alpha_r(n_0 + p_0)}$$

$$(eq.\ valid\ for\ doped\ and\ undoped\ cases)$$

Remember: the e and h lifetimes MUST be equal!

(1) the doped amount of the carriers don't go back to the dopant atoms (therefore have infinite lifetime), so the only amount that can recombine and which we keep track of are the generated ones!

(2) So… if 10^{14}/cc holes disappear, than that requires a change of 10^{14}/cc electrons, right?! So the lifetimes for the generated amounts of carriers must be equal.

- Example (4-2), assume GaAs is doped p-type to $p_0=10^{15}$/cc, $n_i=10^6$/cc, therefore $n_0=n_i^2/p_0=10^{-3}$/cc. Assume 10^{14} EHPs are created at t=0…

(Q1) Will the electron and hole lifetimes be equal?

Yes! Remember, the doped holes are always there (ionized acceptors, so don't worry about them).

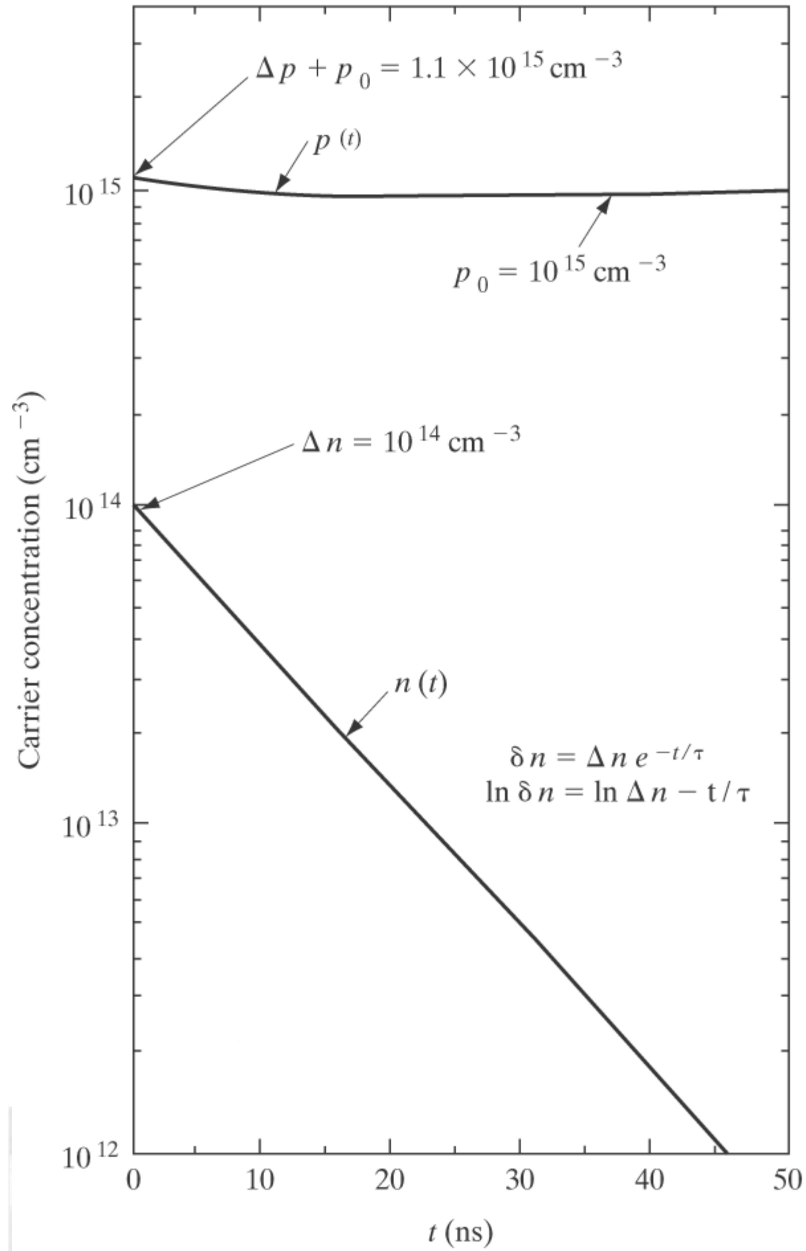
For example, from data tables:

$$\tau_n = \tau_p = \frac{1}{\alpha_r (n_0 + p_0)} = 10^{-8} s$$

(Q2) Should the generated EHPs effect the carrier populations? Yes, but practically only one… ☆

$$\delta n = \Delta n \, e^{-t/\tau_n} = 10^{14} \, e^{-t/10^{-8}} \, / cc$$

- note that p(t) is changing, just can't see it on the log plot because N_A is 10^{15}/cc!



- For the semiconductor shown at right. When it comes to recombination and generation, is it more important to track the electron or hole concentration? *Hint, only one will change much…*

- Why are e and h lifetimes equal even if the number of carriers are as much as orders of magnitude different (e.g p+n)? *Hint, do the dopants recapture their carriers (e.g can ionized B- capture a hole to become neutrally charged B)?*

- A semiconductor with $n_i=10^8$/cc is doped p-type to $Na=10^{15}$/cc, and I optically generate 10^{16} electron-hole pairs. If the electron and hole mobility is the same, for a given voltage applied to the semiconductor how much will my drift current increase due to the optical generation?

(a) no change
(b) 10X
(c) 11X
(d) 20X

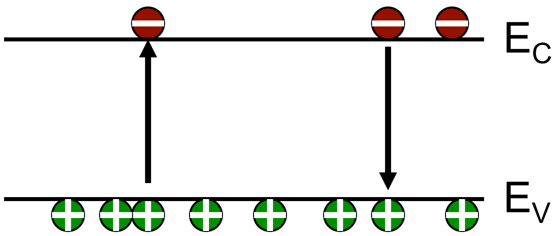
… hint, think of where you were before for both e and h, and where you are now, in terms of total # of carriers for drift current.

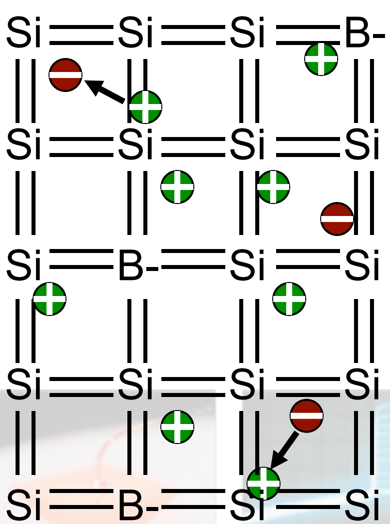
$$\tau_n = \tau_p = \frac{1}{\alpha_r(n_0 + p_0)}$$

$$r_i = \alpha_r n_0 p_0$$

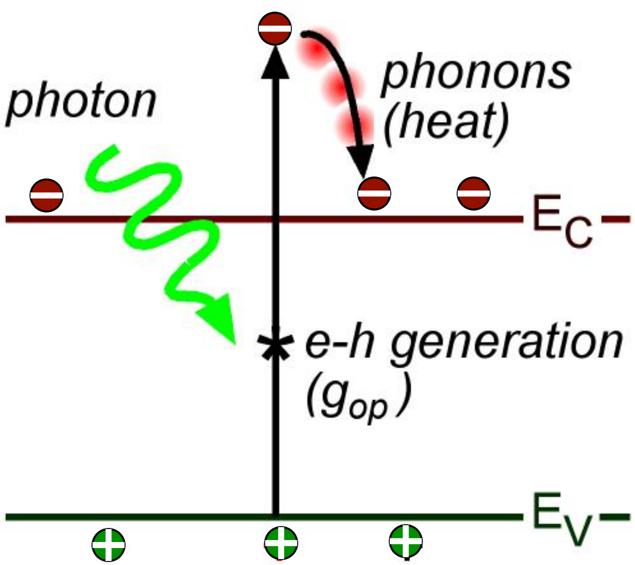
$$g_i = r_i = 1/cc - s$$

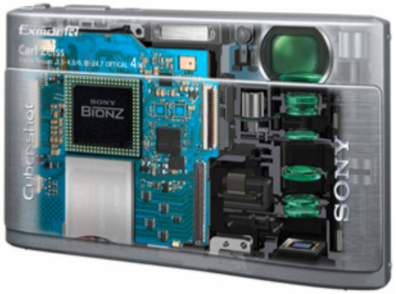
Diagrams for p-type semiconductor:

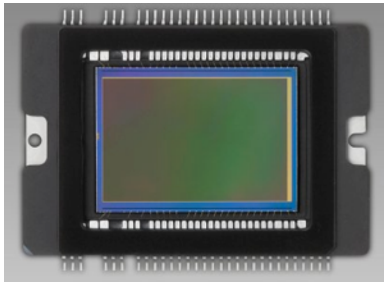


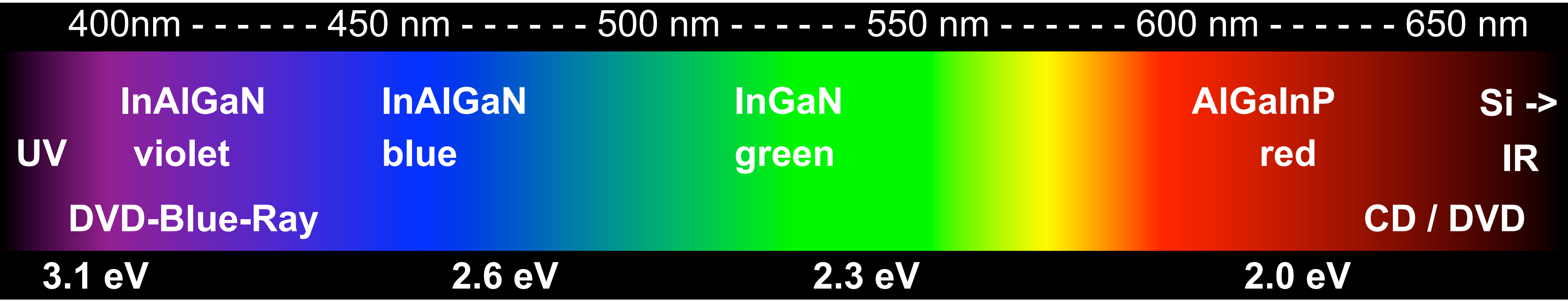


- So, besides temperature and doping? are there other ways to increase carriers?
  - you could electrically inject them (PN junctions)
  - you could also bring in photons of light with energy greater than the band-gap! ☆





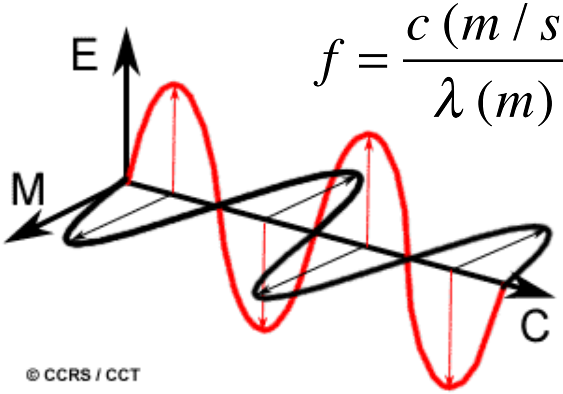




- Light, EM Radiation, Photon, etc…
  - *elementary particle with near zero mass!*

$$E(eV) = hc/\lambda \approx 1240/\lambda(nm)$$ ☆

$$f = \frac{c\,(m/s)}{\lambda\,(m)}$$

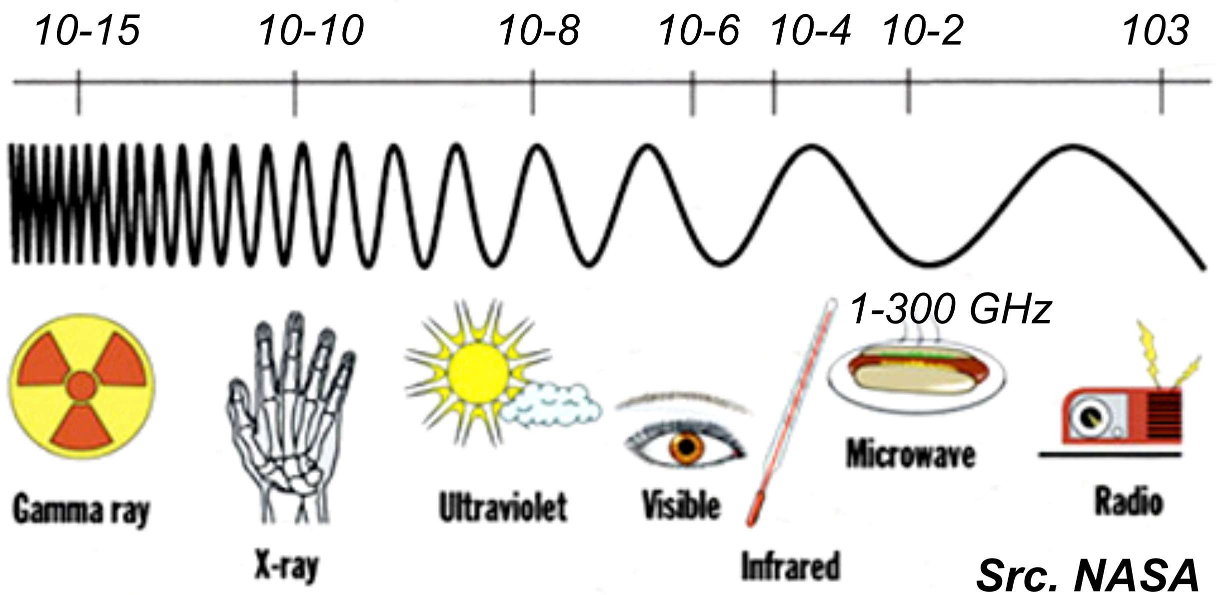


$$E = E_{\max}\sin(wt - kx)$$

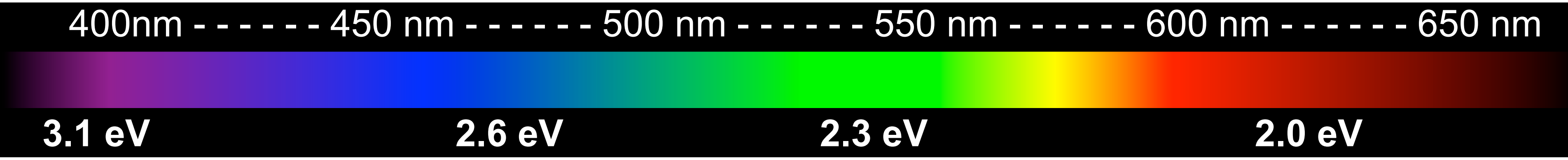
$$B = B_{\max}\sin(wt - kx)$$

$$w = (2\pi f, radians/s)$$

$$k = (2\pi/\lambda, radians/m)$$



Why are Gamma, X-ray, and UV harmful? But we are allowed to stick a cell-phone (Microwave) right next to our head?



- If it were not for e-h generation, Si would look like glass…

$$E(eV) = hc/\lambda$$
$$\approx 1240/\lambda(nm)$$

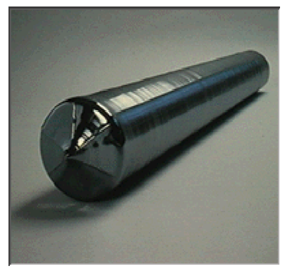
- What λ's will Si absorb?

  $E_{photon} > 1.12$ eV
  $\lambda_{photon} < 1.1$ µm

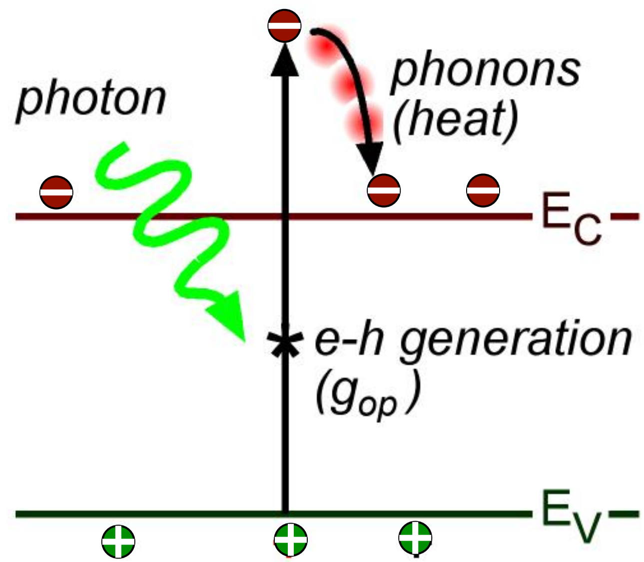
  … take a guess for sapphire too…

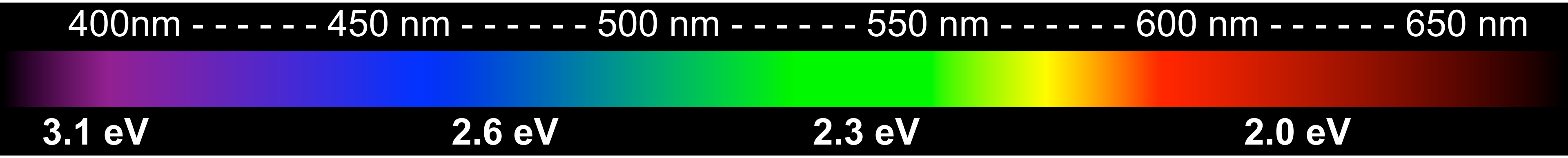
- Question, for Si, if $\lambda_{photon} < 0.55$ µm and $E_{photon} > 2.2$ eV, would we get two EHPs in Si for each photon? What does this tell you about Si solar cells?

Si



Sapphire (Al_2O_3)





- Example, hit Si with 10^{10} photons of green light (2.2 eV) every 1 μs or 10^{16}/s How much power is that? A lot? A little? ☆

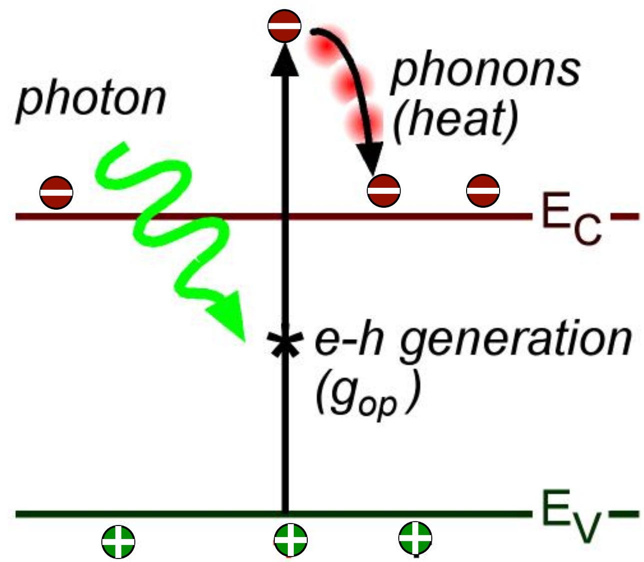
$$J(energy, eV) = Volt \times Coulomb$$

$$2.2\,eV = 2.2 \times 1.6 \times 10^{-19}\,J$$

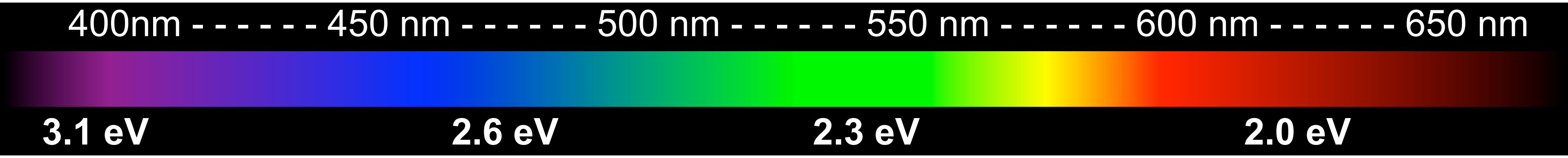
$$W = J/s = 2.2 \times 1.6 \times 10^{-19} \times \frac{10^{10}}{10^{-6}} = 3.5\,mW$$

$$\sim 1.7\,mW \text{ becomes heat}$$

$$\sim 1.7\,mW \text{ becomes } e-h \text{ pairs} \rightarrow \text{which becomes?}$$

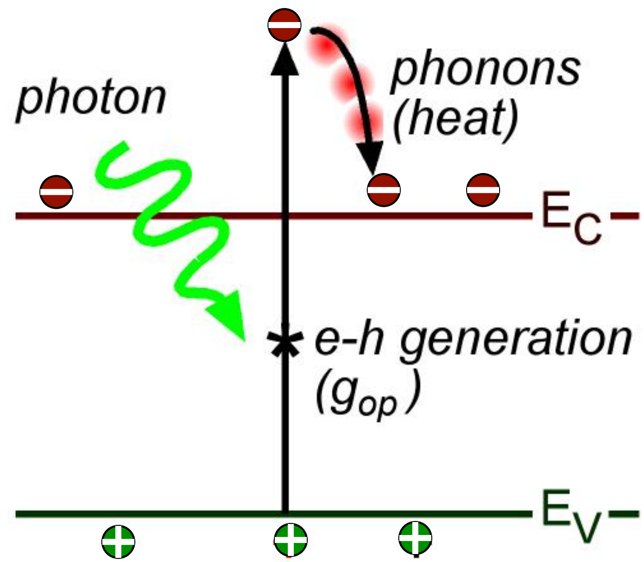


- So a simple slab of Si is not useful as a solar cell to collect energy, but it is useful as a simple photodetector based on I=V/R… how? ☆



- If we wanted to calculate the optically generated excess carrier concentration (for low level injection condition) then use this formula. Units for g_{op}?

$$\delta_n = \delta_p = g_{op}\tau_n = g_{op}\tau_p$$



- Example, hit 1 cc of Si with 10^{13} photons of light every 1 μs. λ_{photon}<1.1 μm (E_{photon}> 1.12 eV). Minority carrier lifetime is $\tau_n \sim \tau_p = 5$ μs.

$$g_{op} = 10^{13} / cc - \mu s$$

$$\delta n = g_{op}\tau_n \qquad \delta p = \delta n = 5 \times 10^{13} / cc$$

Generation vs. recombination!

- So what does the absorption look like?

Are all the photons absorbed instantly at the surface??

Do they penetrate a bit of distance before being absorbed???

- *Some disciplines/ books use log base 10 (not ln base 2.303). Remember, you can go back and forth*

e x log(X) = ln(X)

- *Remember, if someone reports attenuation in dB it is 10 log (I/Io)… you only use "20 log" in cases such as circuits where you measure current and voltage because power is I^2R or V^2/R*

$$I(z) - I(z + dz) = \alpha\, I(z)\, dz$$

$$\alpha = amount\ absorbed\ over\ dz$$

$$\frac{dI(z)}{dz} = -\alpha I(z)$$

simple first order linear diff. eq. , the derivative is proportional to α so you can maybe guess the solution?

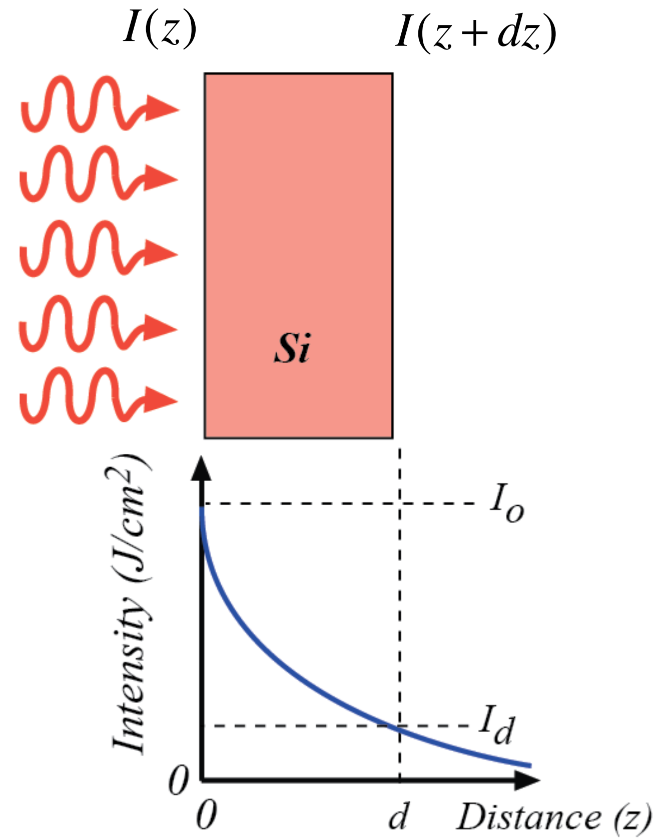
$$\frac{d\,I(z)}{dz} + \alpha\, I(z) = f(z) = 0$$

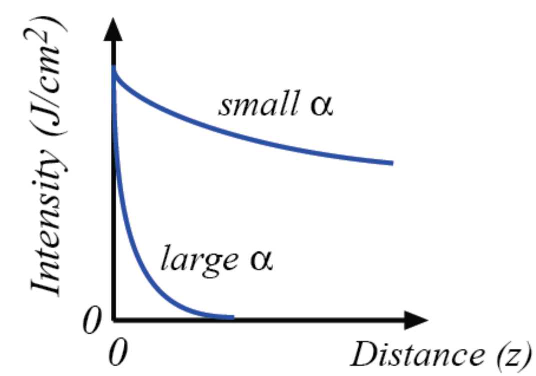
$$gen.\ sol. = e^{-h}\left[\int e^{-h} f(z)\,dz + c\right]$$

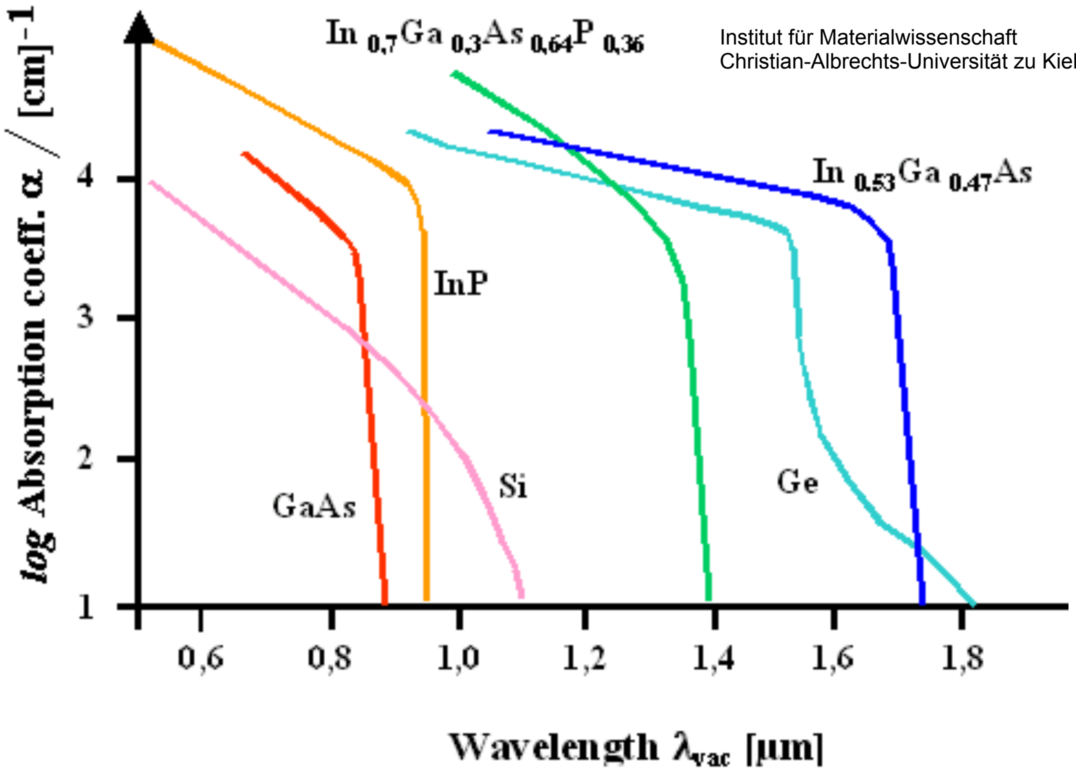
$$where\ h = \int \alpha\, dz = \alpha z$$

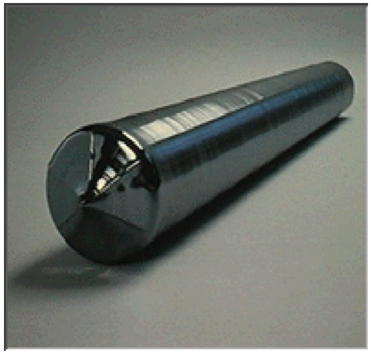
$$\therefore I(z) = I(0)e^{-\alpha Z}$$

$$\alpha = absorbtion\ coef. = (1/cm)$$









- Example, how thick does a Si wafer need to be to absorb 90% of 1.0 µm light? Assume α~100 cm^{-1} (is a bit less)

$$I(z) = I(0)e^{-\alpha Z}$$

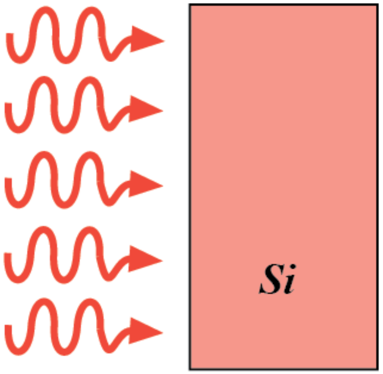
$$\frac{I(z)}{I(0)} = 0.1 = e^{-100 \times Z} \quad \therefore z = \frac{\ln(0.1)}{-100} cm = 230\,\mu m$$

- Same 90% calculation for green light (peak of sunlight spectrum), and z only ~2 µm!

- If I viewed a Si wafer with night vision (infrared) goggles where the light has <1.0 eV energy, would it look dark like it normally does or will it be transparent like glass? Why?

- If the light is absorbed in a semiconductor, what mathematical profile will the decrease in intensity follow?

- If I keep shining light on a semiconductor and the photons have energy greater than the bandgap, the carrier populations will:



(a) not change
(b) keep increasing indefinitely (until I turn the light off)
(c) increase, but then balance out to a higher level as recombination counteracts optical generation
(d) decrease.

- Lets briefly review all types of light emission (so you can appreciate the unique advantages that semiconductors provide).

- First type, blackbody radiation. When you heat up a solid material you create more phonons (lattice vibration). Eventually many phonons locally can add up to a photon energy.

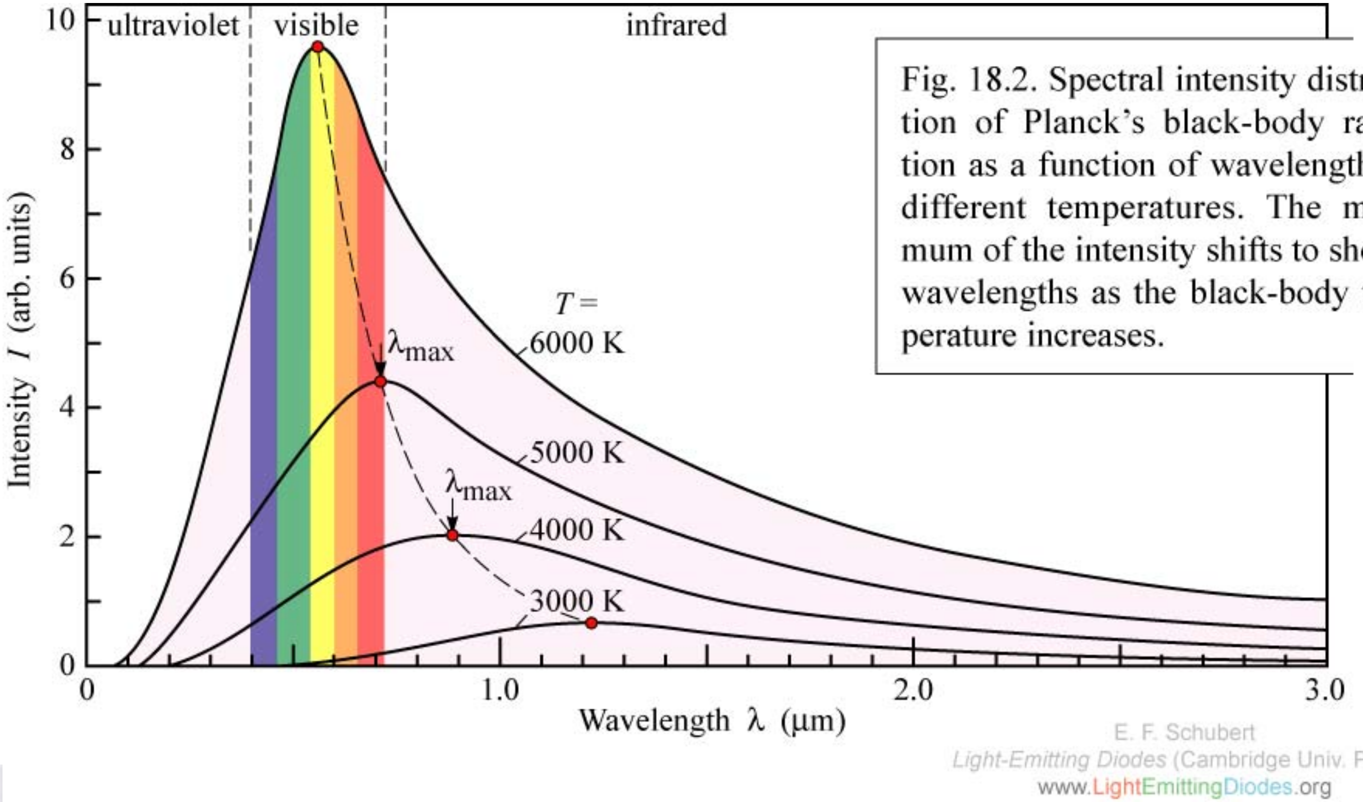


Fig. 18.2. Spectral intensity distribution of Planck's black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.

- Plasma: ionize gas with electric field and gas atoms emit light). Typically plasma emits UV light which then causes a phosphor to emit visible light.

- Cathodoluminescence: like old cathode-ray-tube televisions, or green VFD displays in cars, hit a semiconductor or a phosphor with a high energy electron beam

- Electroluminescent (not a diode!): high voltage across a phosphor accelerates electrons which bang into the phosphor and cause light emission…

- So why do we have LEDs? Why are many of these other technologies going to be replaced more and more by LEDs?

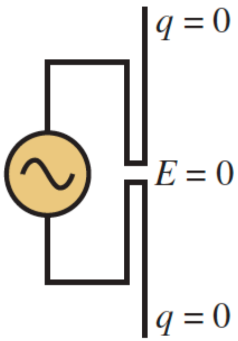
- Blackbody (incandescence) light emission is very inefficient.

- Cold cathode fluorescent bulbs are efficient, but LEDs can be more efficient, brighter, smaller and eventually lower cost.

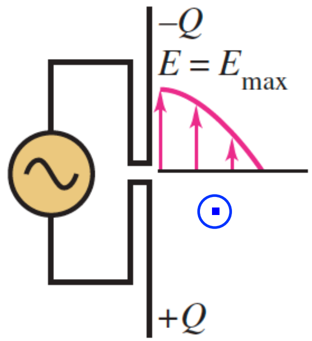
- Cathodoluminescence (old TVs etc.) is inefficient and is bulky.

- Electroluminescence is inexpensive but very, very, inefficient (only use in dark lighting typically).

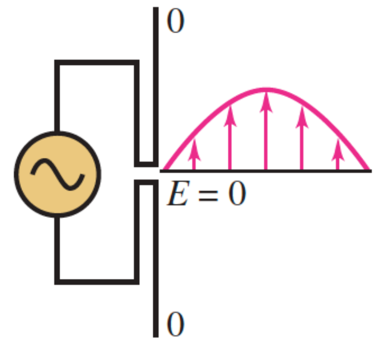
Credit: Young - Physics



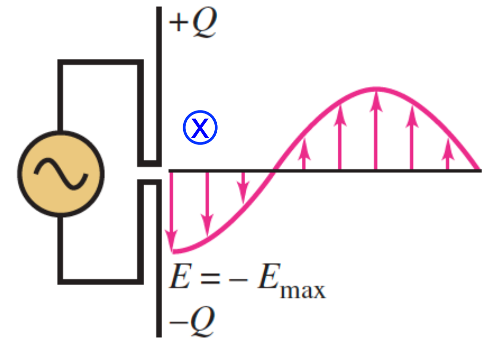
(b) $t = 0$



(c) $t = T/4$

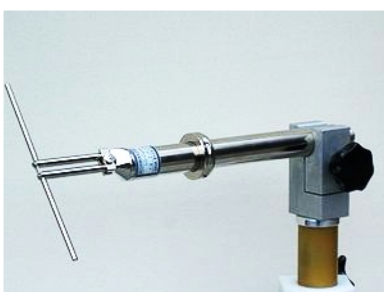


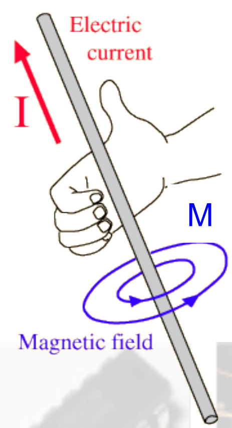
(d) $t = T/2$

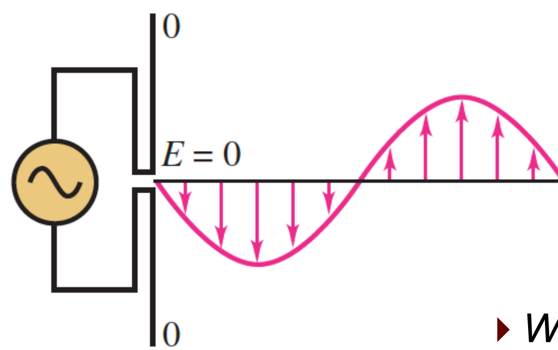


(e) $t = 3T/4$

- Consider a simple dipole antenna with two wires each about λ/4 long attached to a 10 GHz sinusoidal voltage(microwave)…
- The voltage hits its 1st positive maximum in ¼ the period, notice the E-field from + to – direction. As current flows 'down' to create the +/-Q, 'M' field is out of the plane.
- In ½ the period V and E = 0 again.
- The voltage hits its first negative max in ¾ the period, E-field from + to – direction. As current flows 'up' to create the +/-Q, 'M' field is into the plane.





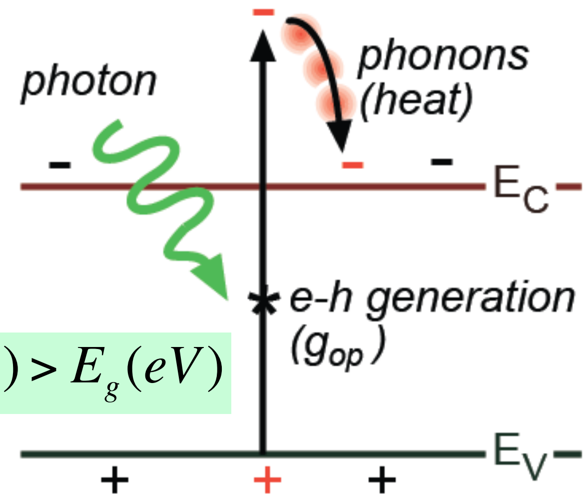


(f) $t = T$

- Cycle complete! These time varying E and M fields sustain each other through freespace!
- *Why were the first mass-broadcasts 'AM radio' @ f~200 kHz?*

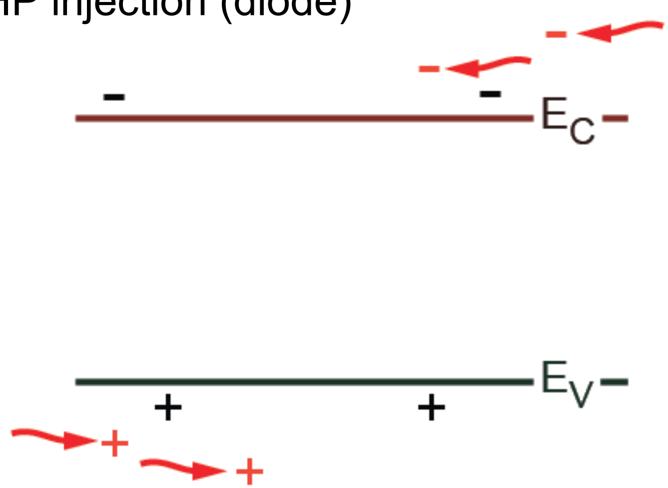
- Like the previous slide, during recombination in a semiconductor we also have transitioning charge which can generate E&M field! Which can also radiate a photon!

- Ways to create more carriers



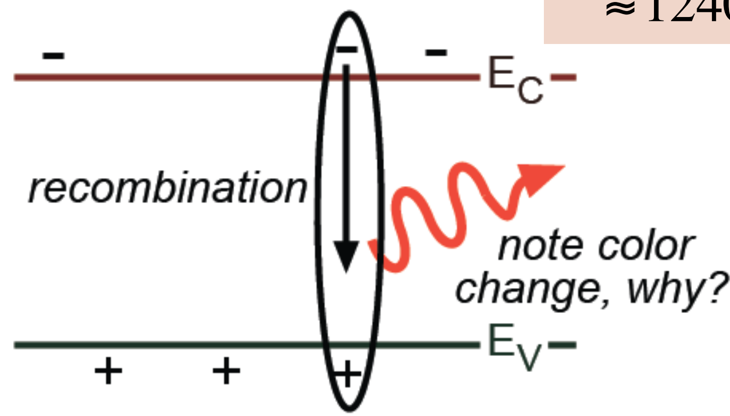
$$E_{photon}(eV) > E_g(eV)$$

EHP injection (diode)

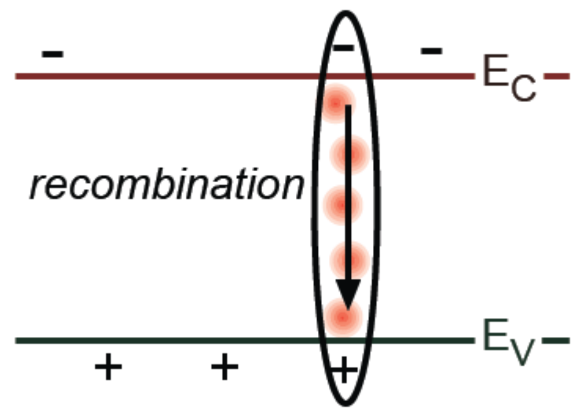


- Ways to decrease carriers

$$E_g(eV) = hc/\lambda_{emit}$$
$$\approx 1240/\lambda(nm)$$



(phonons = ?)



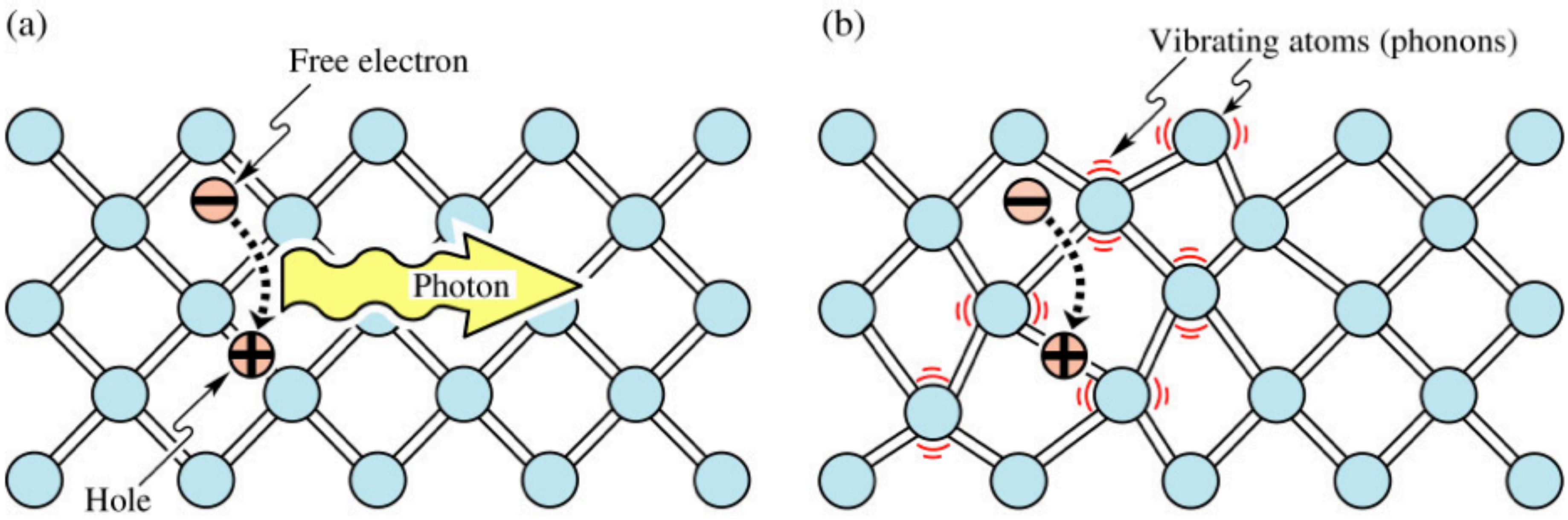


Fig. 2.5. (a) Radiative recombination of an electron-hole pair accompanied by the emission of a photon with energy $h\nu \approx E_g$. (b) In non-radiative recombination events, the energy released during the electron-hole recombination is converted to phonons (adopted from Shockley, 1950).

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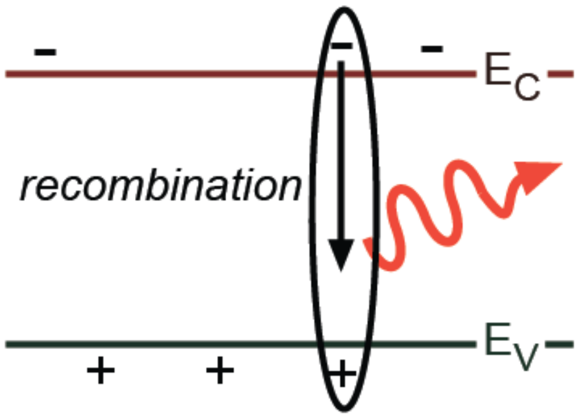
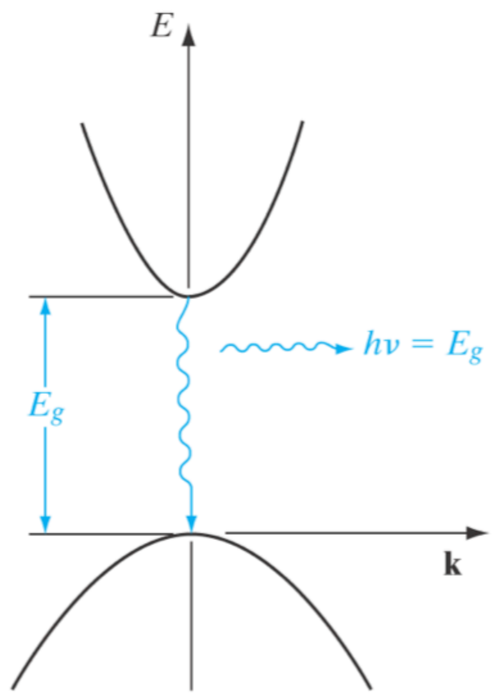
- Now, not all semiconductors emit light (photons). What types do?

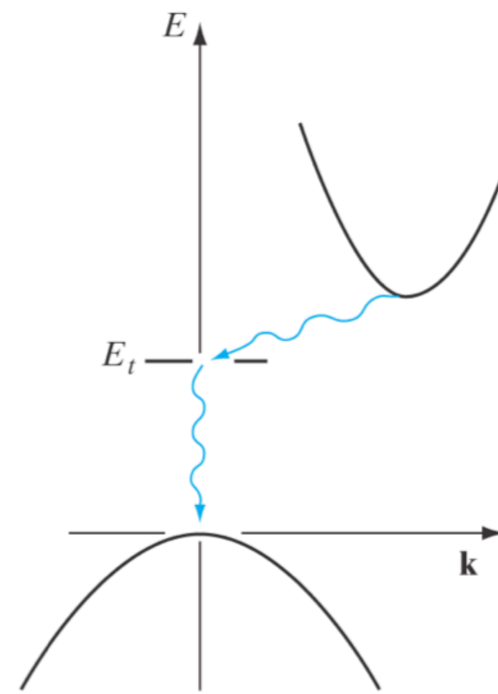


- Only if direct bandgap! Energy diagrams can be plotted vs. carrier propagation constant (k) which is related to carrier momentum.

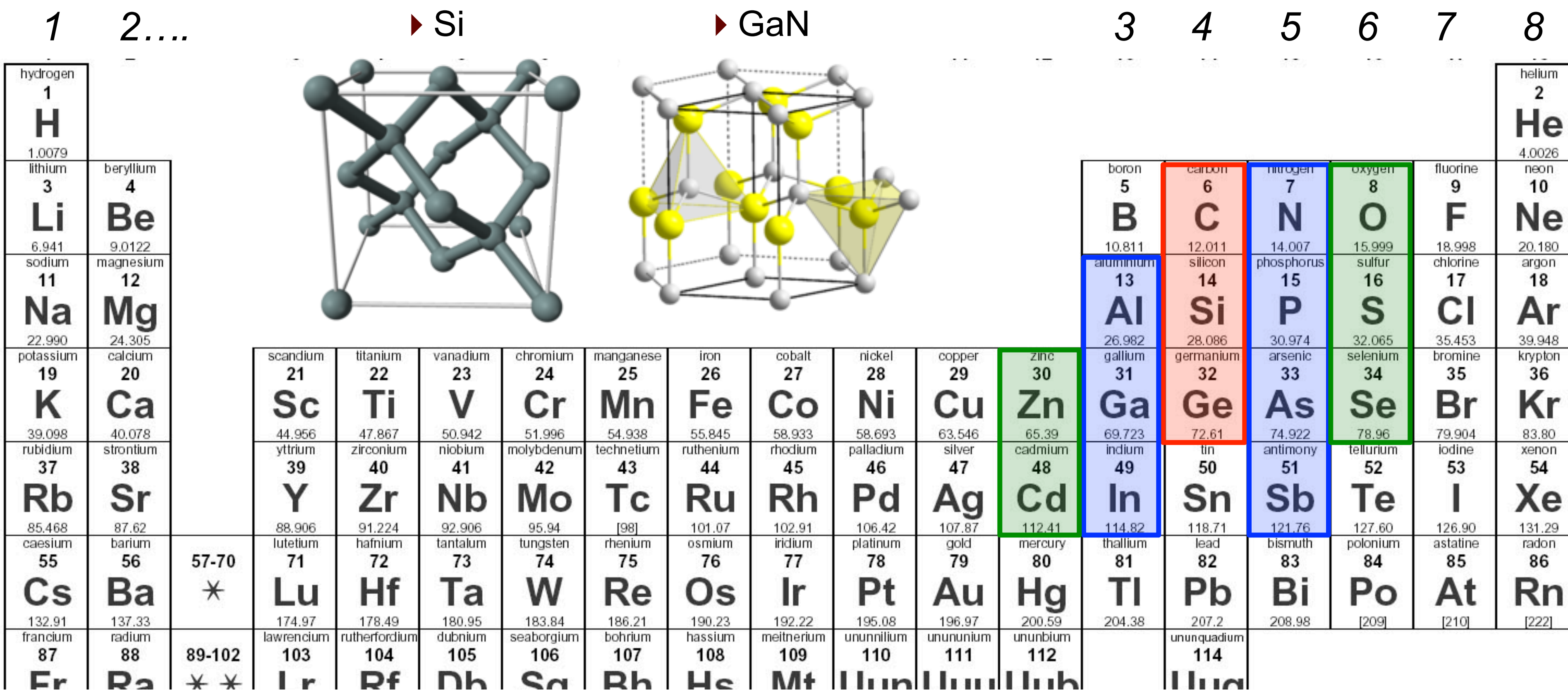
- For light emission to occur in indirect band material, you also need phonons, where the phonon momentums equal the difference between the electron and hole momentum 'direction'. This makes light emission improbable. Its all about probability!



Direct: GaAs, GaN, InP, etc..



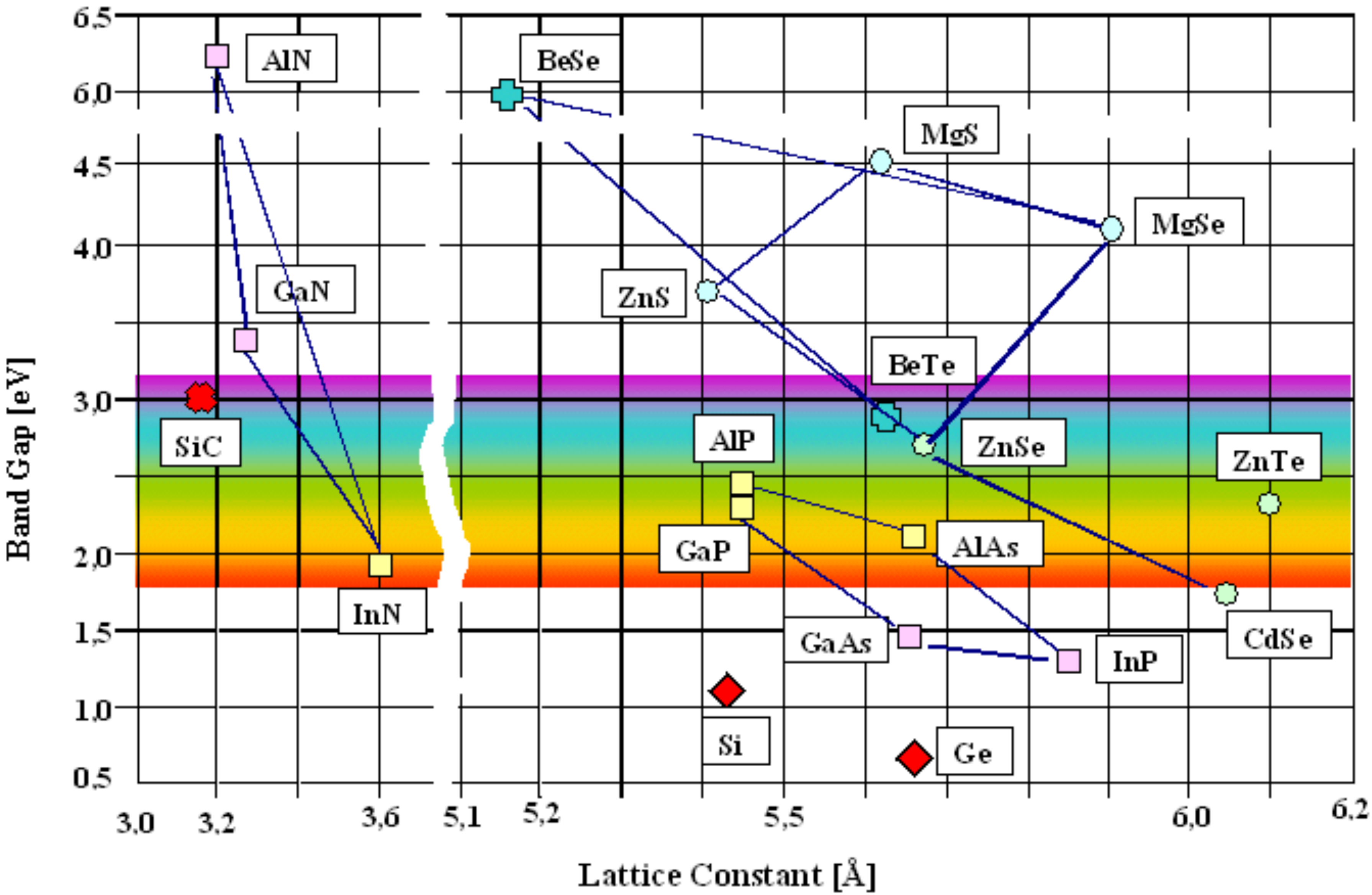
Indirect: Si, Ge, SiC



- IV (4) semicon., indirect, narrow (Ge) to wide bandgap (SiC), low cost/common.
- II-VI (2-6) semicon., many direct, (CdSe) to wide bandgap (ZnO), emerging for transistors!
- III-V (3-5) semicon., many direct, really narrow (InSb) to really wide bandgap (AlN), nitrides are super durable but hard to make.
- Nearly all LEDs are based on III-V materials, why not II-VI? Which is more stable, a highly ionic bond like NaCl, or a highly covalent bond like Diamond (C-C)? ☆

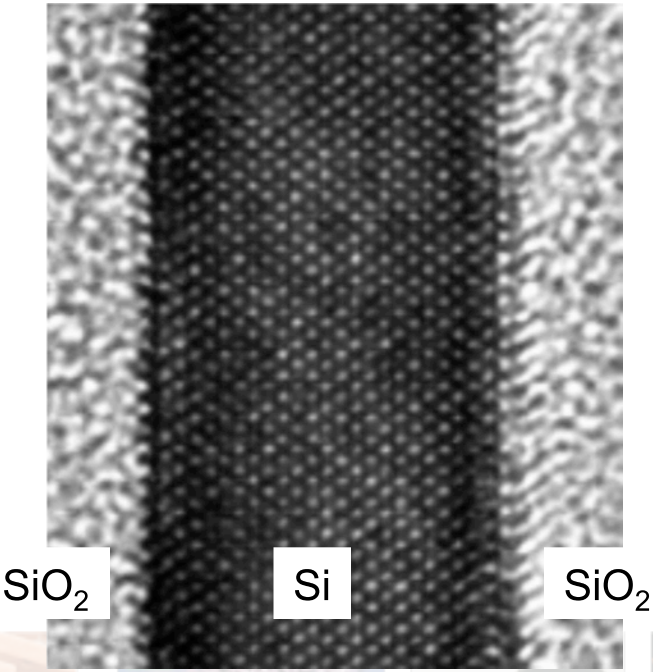
- Why can't we make GaN lasers etc. on Si substrates? ☆

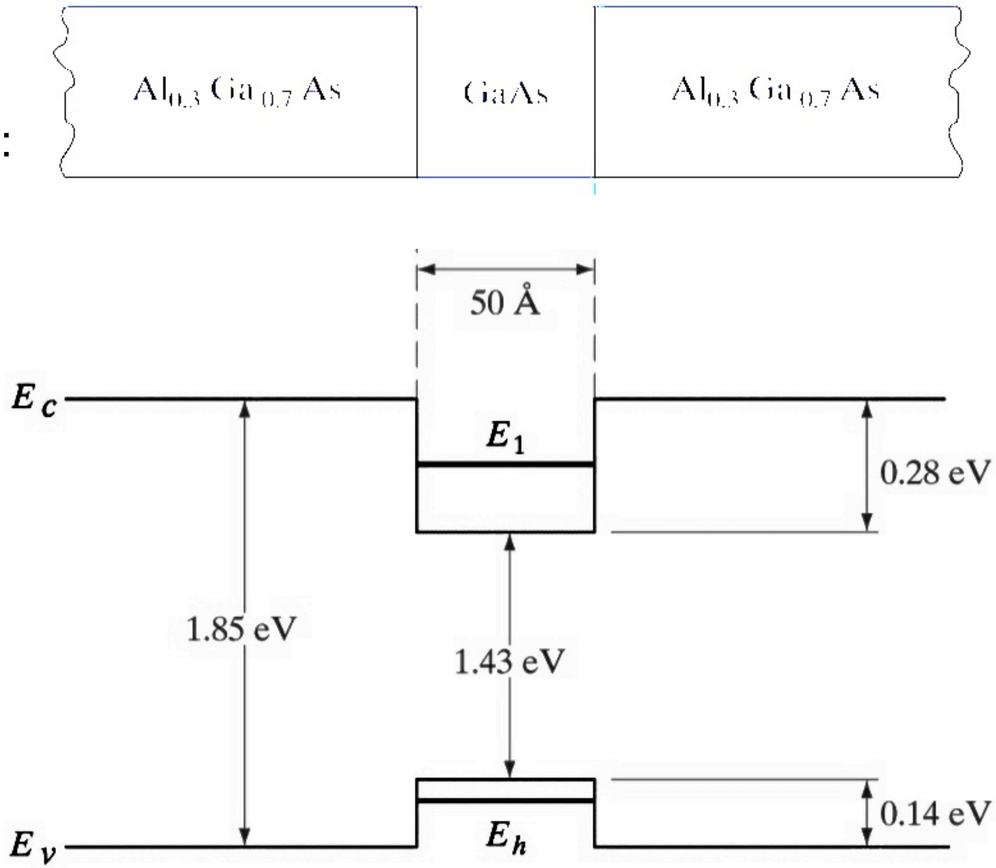
http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_5/backbone/r5_1_4.html



- We can also tune emission wavelengths through quantum confinement!
- Energy levels for an infinite quantum well:

$$E_n = \frac{h^2}{2m^*}\left(\frac{n}{2L}\right)^2 \quad n = 1, 2 \ldots$$





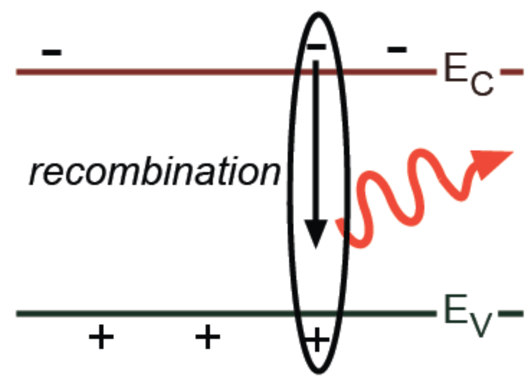
- Light emission by EHP recombination, does it occur for all semiconductors?

- Why don't we have LED TVs? (real ones, that is…) *Hint, could you make crystalline GaN on top of amorophous glass?*

- Tell me TWO ways how we can tune the emission wavelength due to recombination.

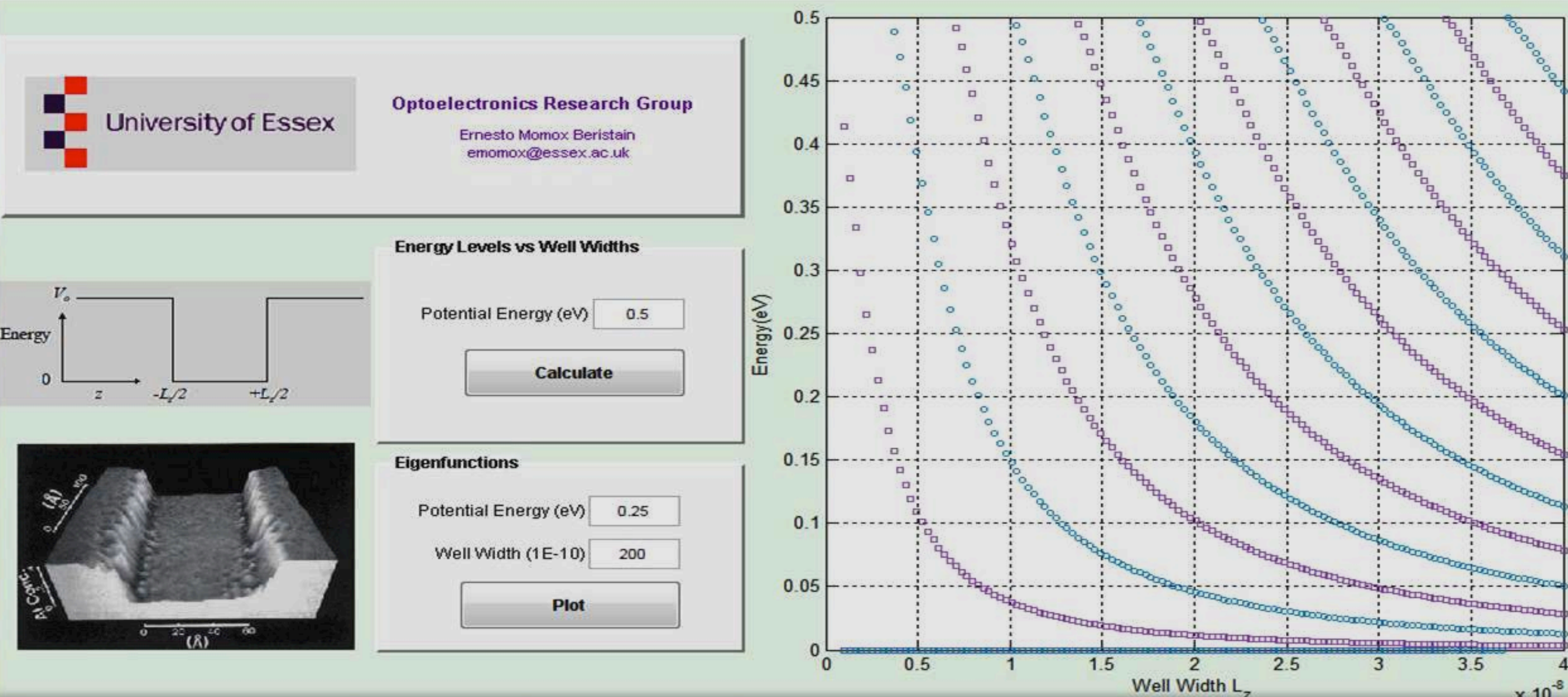
- Modern semiconductor LASERS and LEDs are dominantly make using <u>durable</u> semiconductors with direct bandgap and strong covalent bonding, *these semiconductors are made from what columns?*

	boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999
	aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065
zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96
cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60
mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]



This m-file (GaAs_QW) calculates the energy levels in a GaAs single quantum well with constant effective mass vs. different well widths. It also plots the corresponding eigenfunctions given the potential energy and well width.

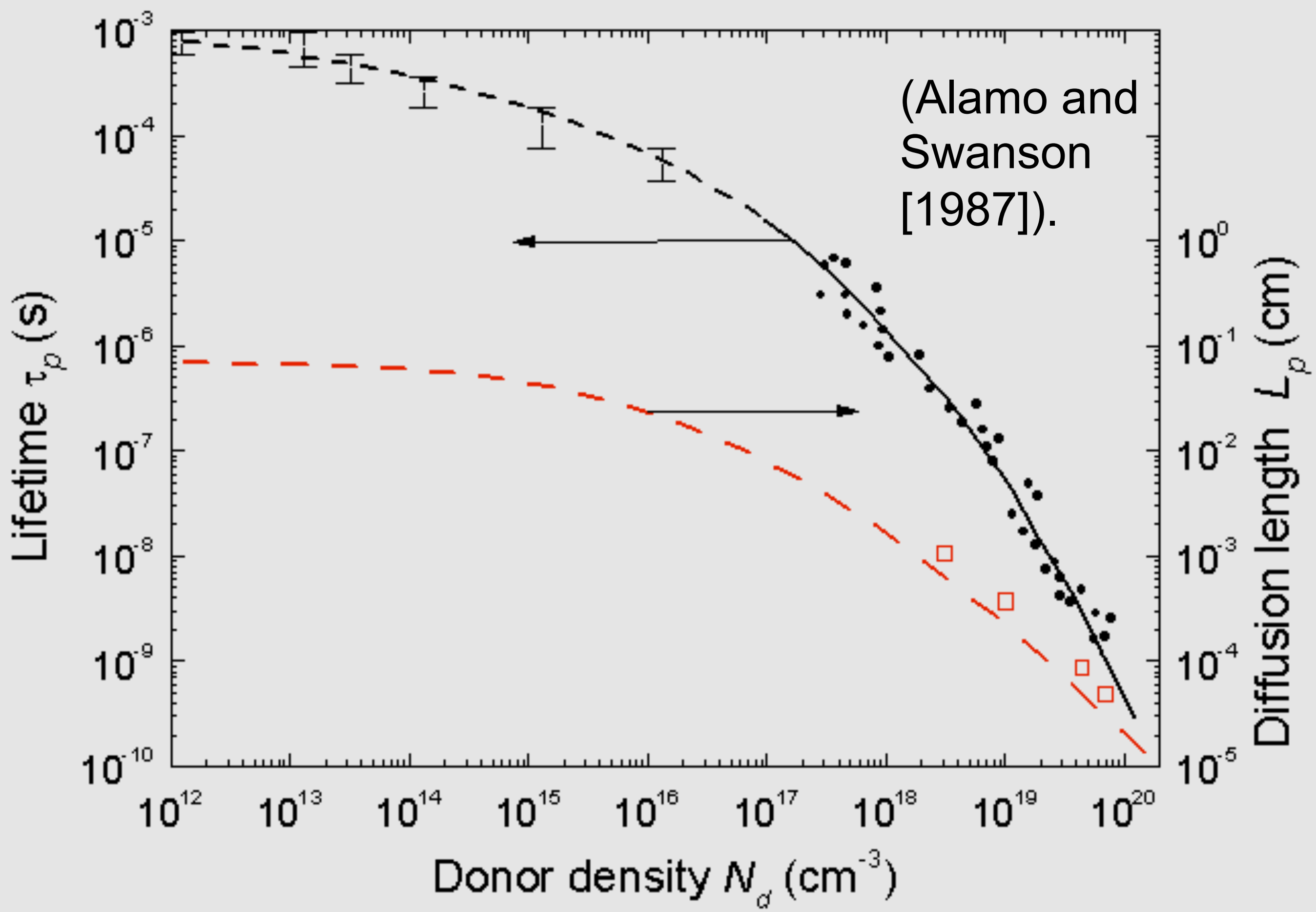
David. A. B. Miller, Quantum Mechanics for Scientist and Engineers. Cambridge. PhD Student. Ernesto Momox Beristain. http://www.mathworks.com/matlabcentral/fileexchange/23193-gaas-single-quantum-well



- Again, there are tables to get the lifetime data…

- The table below is for n-type Si, so when calculating hole lifetime only need N_d, why?

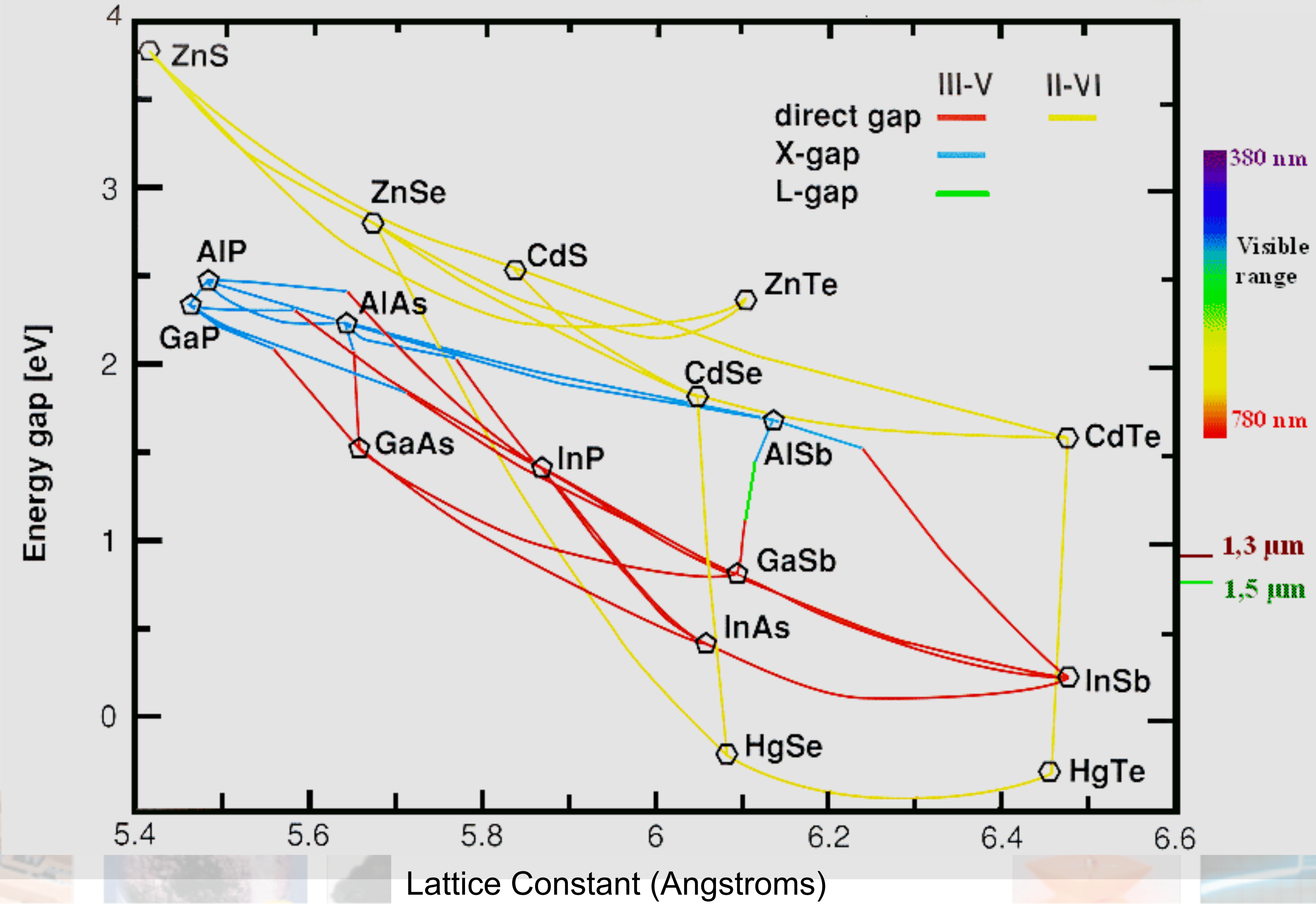
$$\tau_n = \tau_p = \frac{1}{\alpha_r(n_0 + p_0)}$$



- Obviously diffusion length (L_p) follows the same trend as lifetime…

- So what semiconductor options do we have?

http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_5/backbone/r5_1_4.html



- Can also dope semiconductors with atoms that will instead emit the light (like Rare Earths, was the topic of my PhD research… (just an FYI, you will not be tested on this).