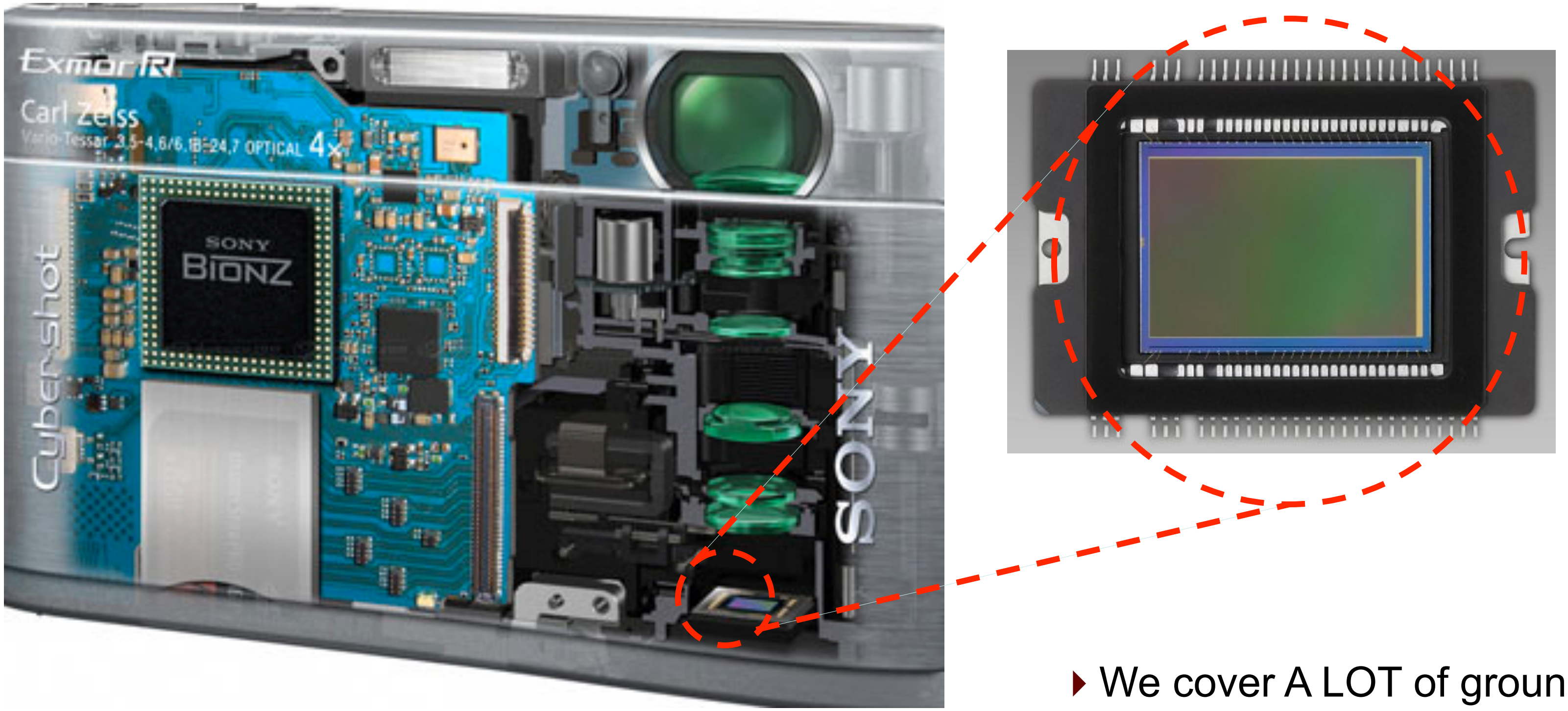
Charged Carrier Dynamics: Generation! Recombination! Diffusion! and Drift!



- We cover A LOT of ground in this lecture, so ask questions if <u>anything</u> is unclear! These concepts are critical!

- *Effective Density of States:*

$$N_{c,v} = 2\left(\frac{2\pi\ m^*_{n,p} kT}{h^2}\right)^{3/2}$$

- *Fermi Distribution:*

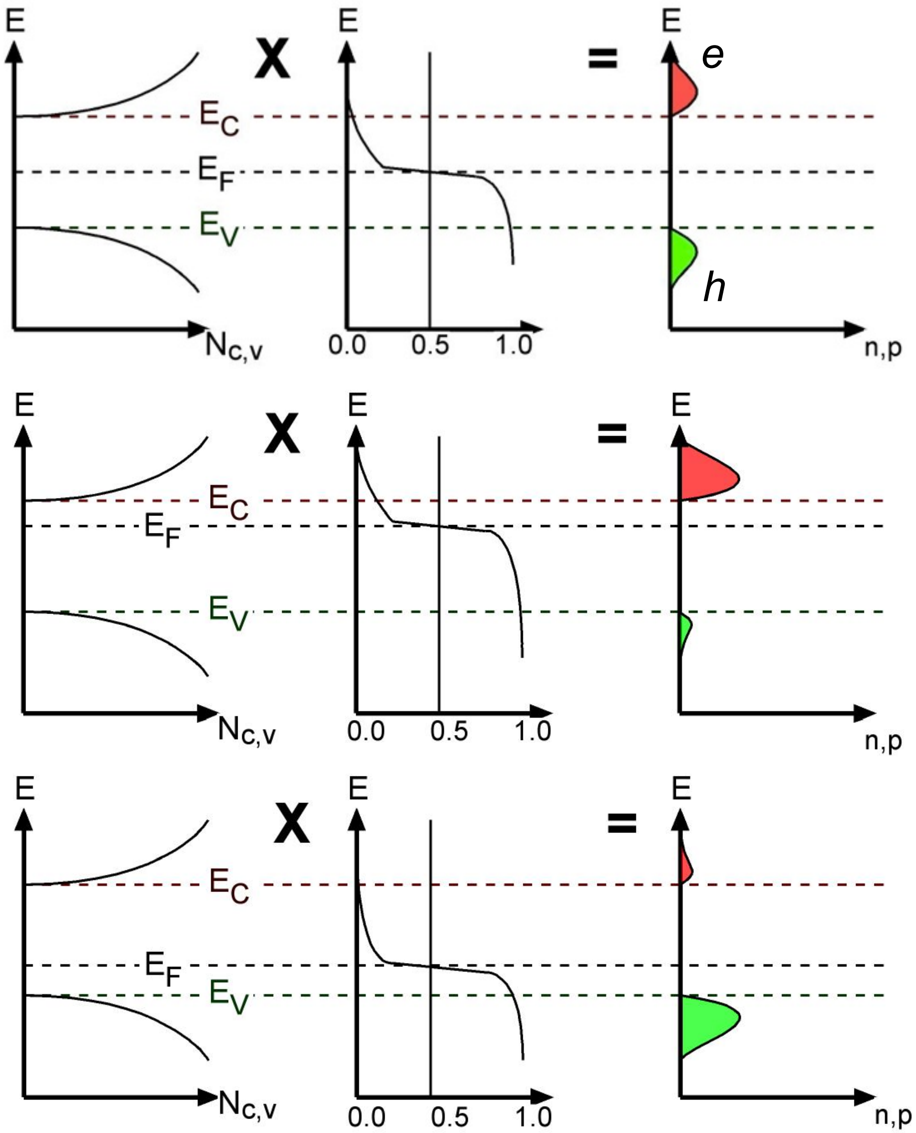
$$f(E) = 1/(1 + e^{(E-E_F)/kT})$$

- *Carrier Concentration:*

  n_0, p_0, n_{0n}, p_{0n}, n_{0p}, p_{0p}

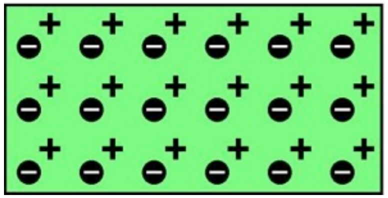
  '0' = thermal equilib.

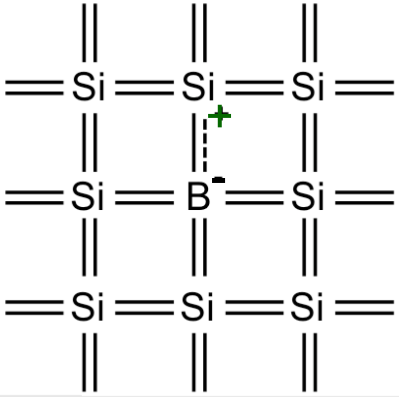
Density of States X Fermi Dist. = Carrier Conc.

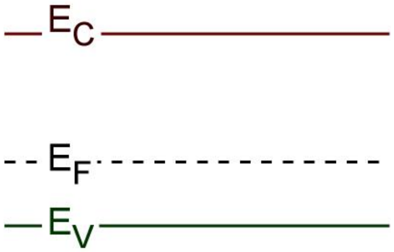


- p-type semiconductor

$$\boxed{\begin{aligned} p_0 &= N_A \\ n_0 p_0 &= n_i^2 \end{aligned}}$$





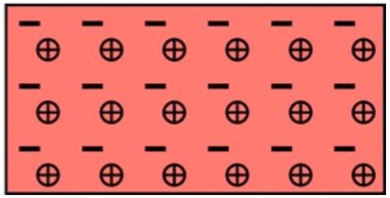


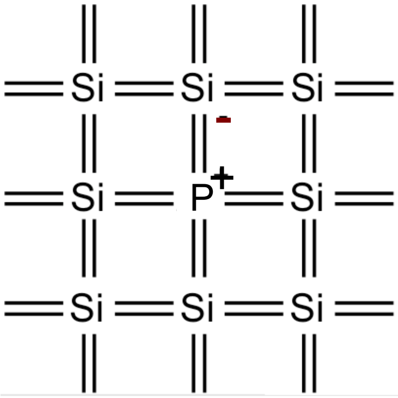
$$p_0 = N_v e^{-(E_F - E_v)/kT} = N_A$$

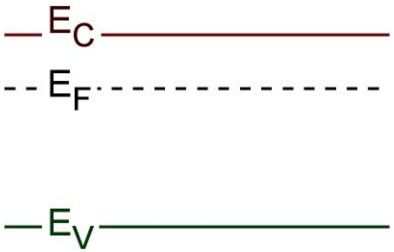
$$n_{0p} = N_c e^{-(E_c - E_F)/kT} = \boxed{\frac{n_i^2}{N_A}}$$

- n-type semiconductor

$$\boxed{\begin{aligned} n_0 &= N_D \\ n_0 p_0 &= n_i^2 \end{aligned}}$$







$$n_0 = N_c e^{-(E_C - E_F)/kT} = N_D$$

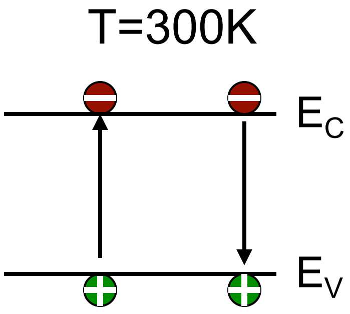
$$p_{0n} = N_v e^{-(E_F - E_v)/kT} = \boxed{\frac{n_i^2}{N_D}}$$

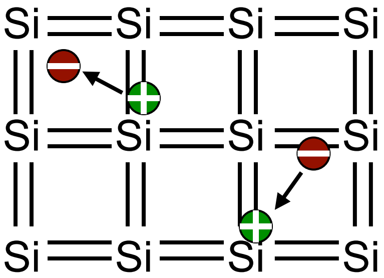
Thermal Generation

- Undoped Si (intrinsic carriers):

(1) at 300K, some electrons bound to Si atoms (valence band) get enough energy to reach the conduction band, this creates both and electron (-) and a hole (+) which are mobile

(2) Because they have energy at 300K, the electrons and holes freely diffuse around until they match up again (not necessarily the same two, any two) and recombine, which releases energy back into heat of the Si.



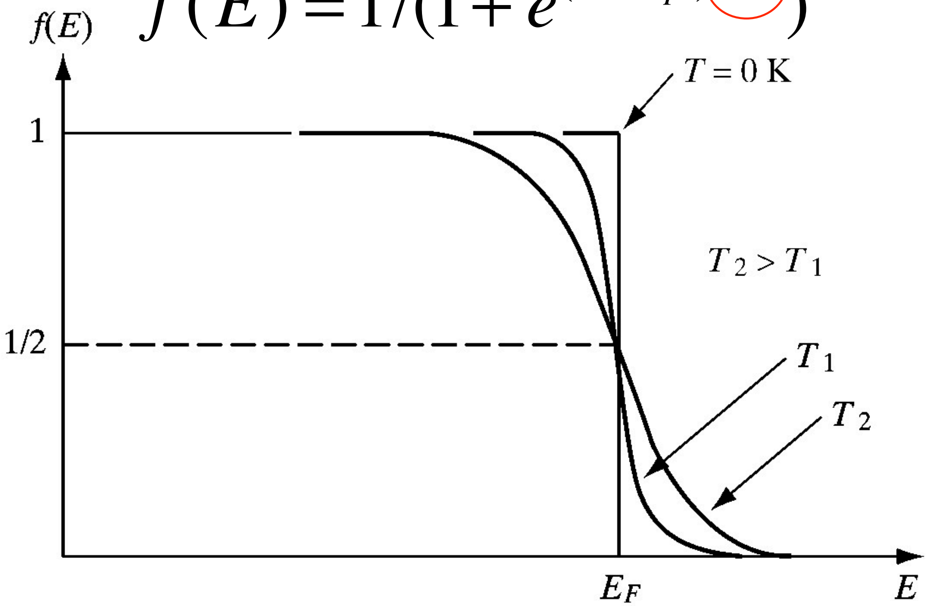


- Two competing processes – generation and recombination balance out (the balance results in n_0 and p_0)

- *the more carriers we generate thermally, they will find each other faster and recombine faster…*
- *also, higher temperature to generate more, also causes them to move and find each other faster...*

… but the <u>net effect is still an increase i</u>n the number of intrinsic carriers (n_0, p_0).

$$f(E) = 1/(1 + e^{(E-E_F)/kT})$$



Thermal Generation

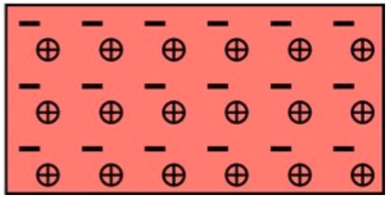
- But what about doping?

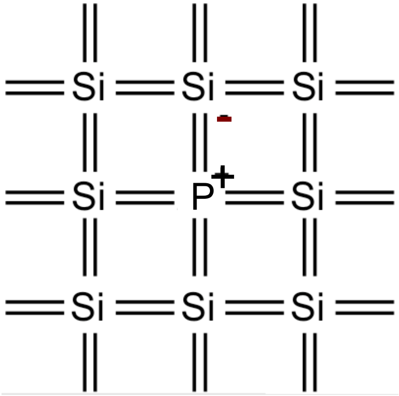
(1) We typically only choose dopants like B, P, As, that completely ionize at 300K (only at real low temp. do they take back their carrier…)

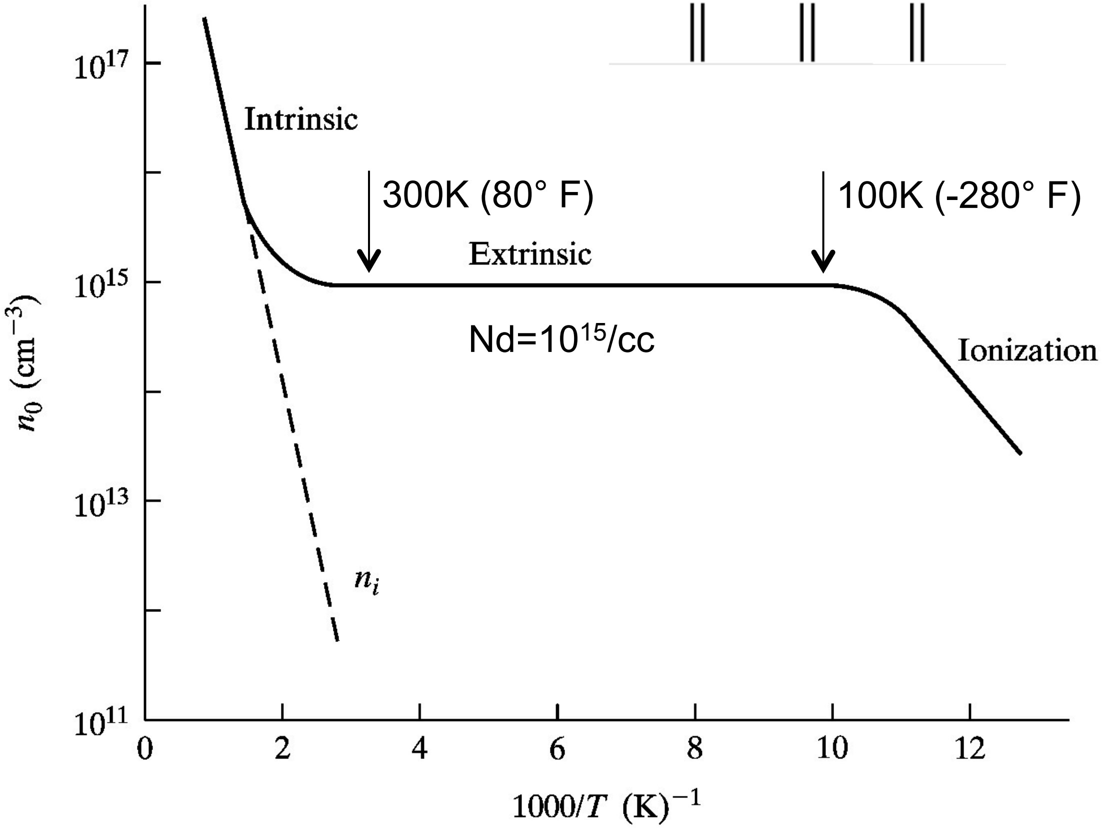
(2) Doped levels are typically orders of magnitude more than intrinsic levels, so only until the semiconductor gets really hot (lots of energy) does thermal generation start to matter again…

$$n_0 = N_c e^{-(E_C-E_F)/kT}$$

- *Make a simple I-V temperature sensor, use doped Si, undoped Si, or a metal?*

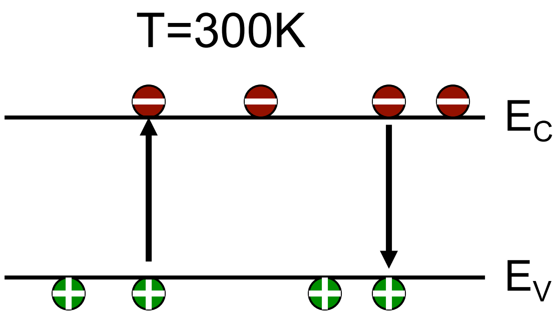


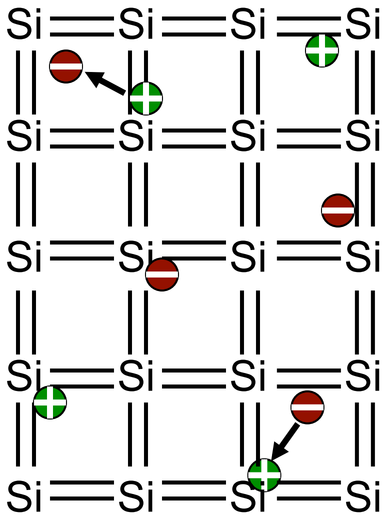




- Does doping effect recombination?

- yes, but it only has to do with electrons and holes finding each other (not dopants recapturing their carriers!).





- For g_i and r_i see the units. Note, the factor α_r is just a based on what mechanism drives the recombination (more on that later)…

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

$$r_i = \alpha_r n_0 p_0 = \alpha_r n_i^2 \quad (eq.\ valid\ for\ undoped\ only) \qquad units\ for\ \alpha_r = cc/s$$

- The generation and recombination are *rates* so there must be a lifetime for carriers. Obviously they all don't disappear at the exact same time (e & h have to find each other), so this lifetime is a statistical average.

Doping goes up, lifetimes go down!

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

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

Lifetimes MUST be equal, even if doped p or n-type and # of electrons does not equal # of holes! If 10^{14}/cc holes disappear, than that requires a change of 10^{14}/cc electrons, right?! (The doped electrons or holes cannot recombine, so the lifetime is with respect to only the thermally generated carriers).

Recombination

- 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 instantly created at t=0…

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

Yes! Remember, the doped holes don't recombine, only the thermally generated ones (the thermally generated e's = the number of thermally generated h's).

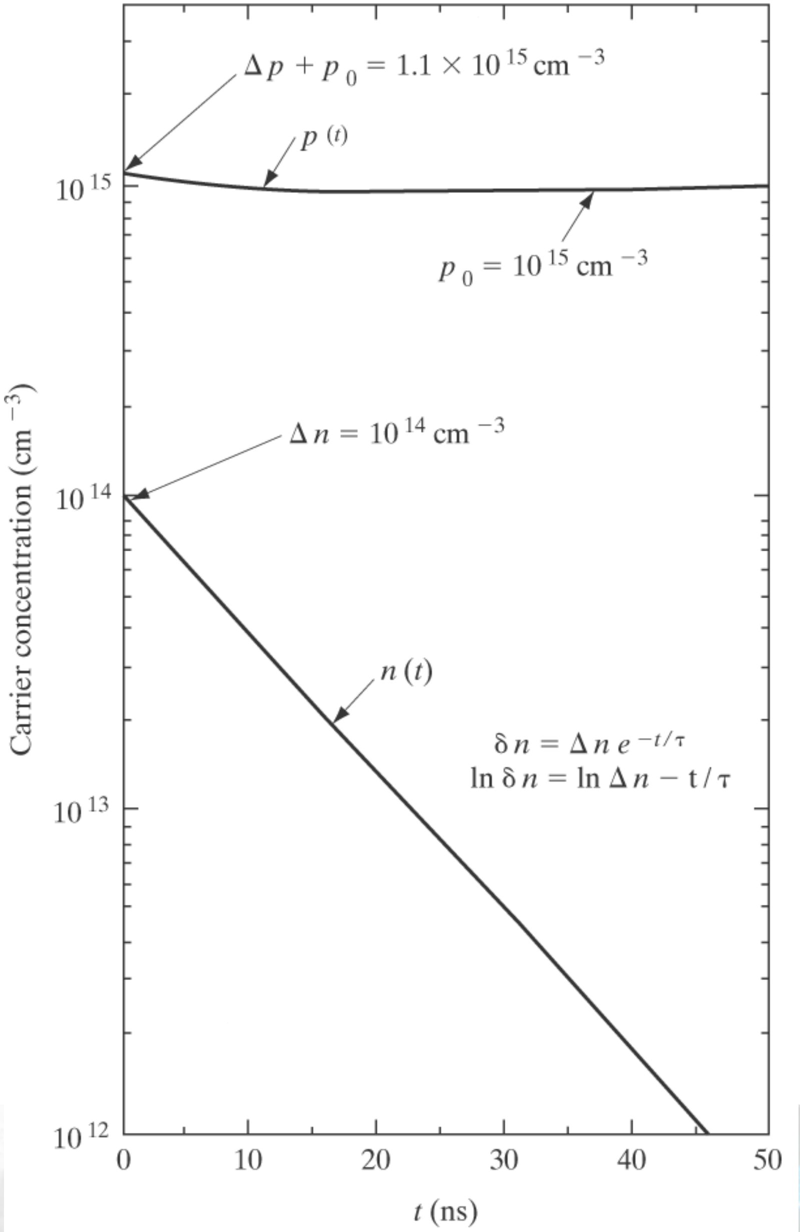
From data tables:

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

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

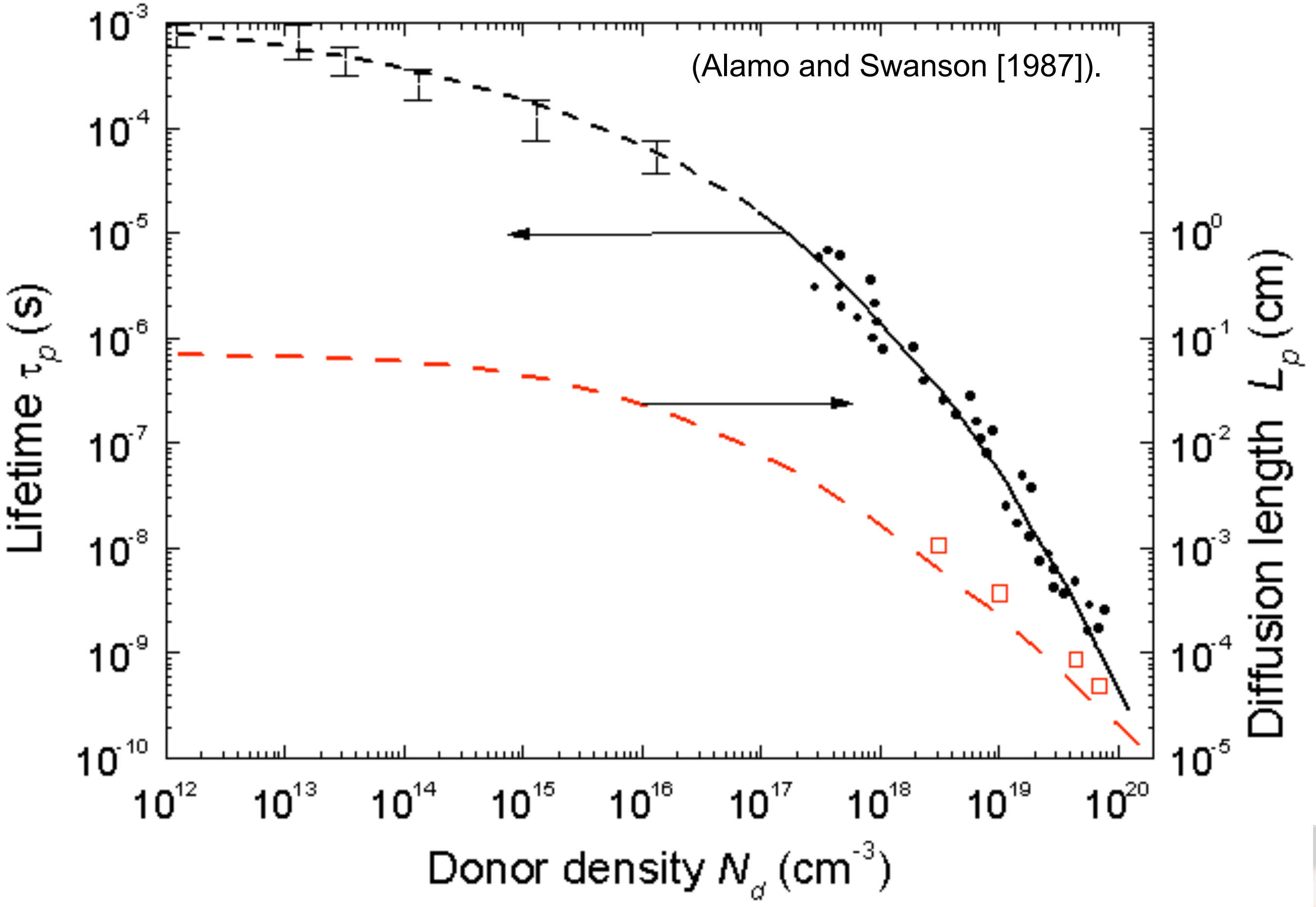
$$\delta n = \Delta n\, e^{-t/\tau_n} = 10^{14}\, e^{-t/10^{-8}}\ /cc$$

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



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

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

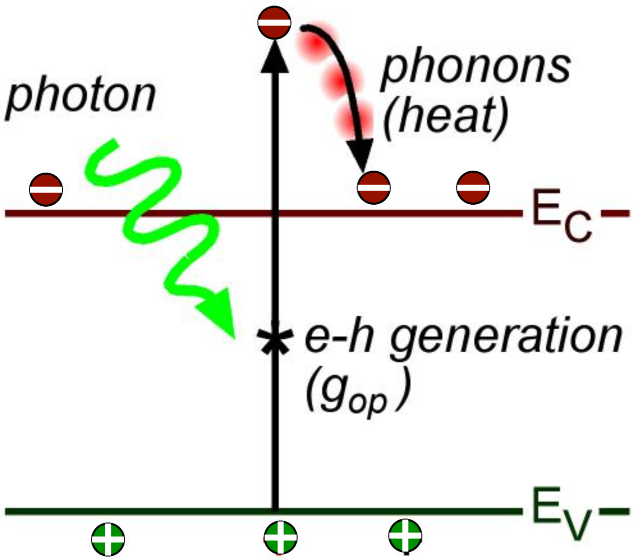


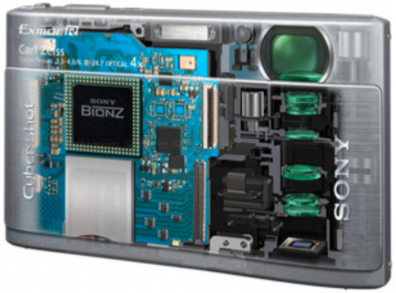
- See this new term called diffusion length (L_p)… what do you think it is? Why does it follows the same trend as lifetime?

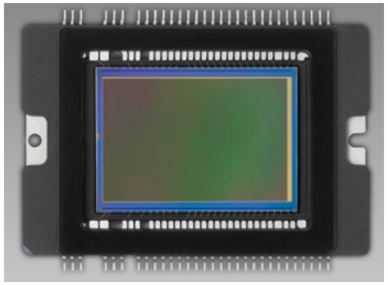
More on diffusion length later…

- So, besides temperature and doping? are there other ways to increase carriers?

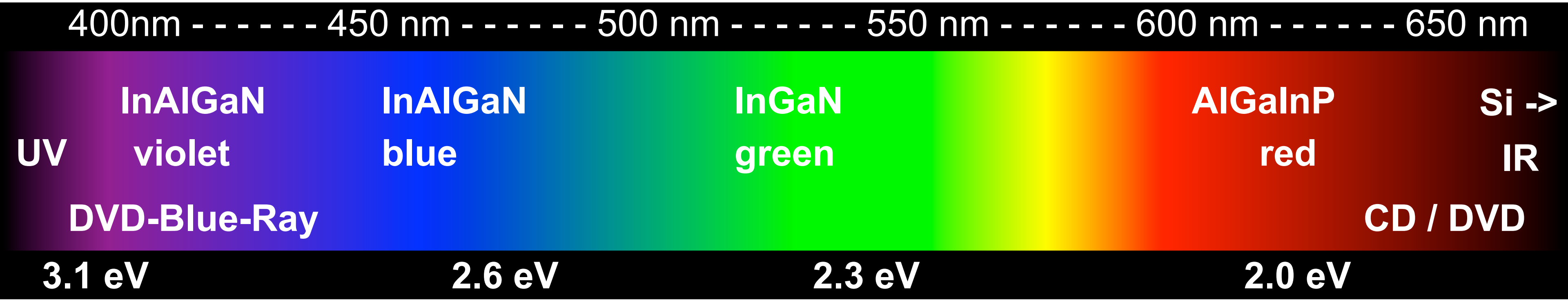
- you could electrically inject them (more on that next week with PN junctions…)
- you could also bring in photons of light with energy greater than the band-gap! You may have not finished E&M yet… so lets describe what a photon is…



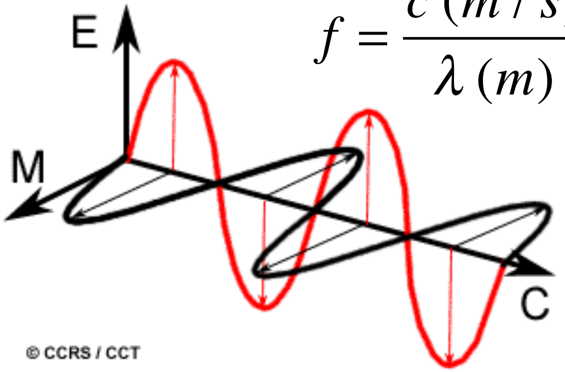




Optical Generation



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



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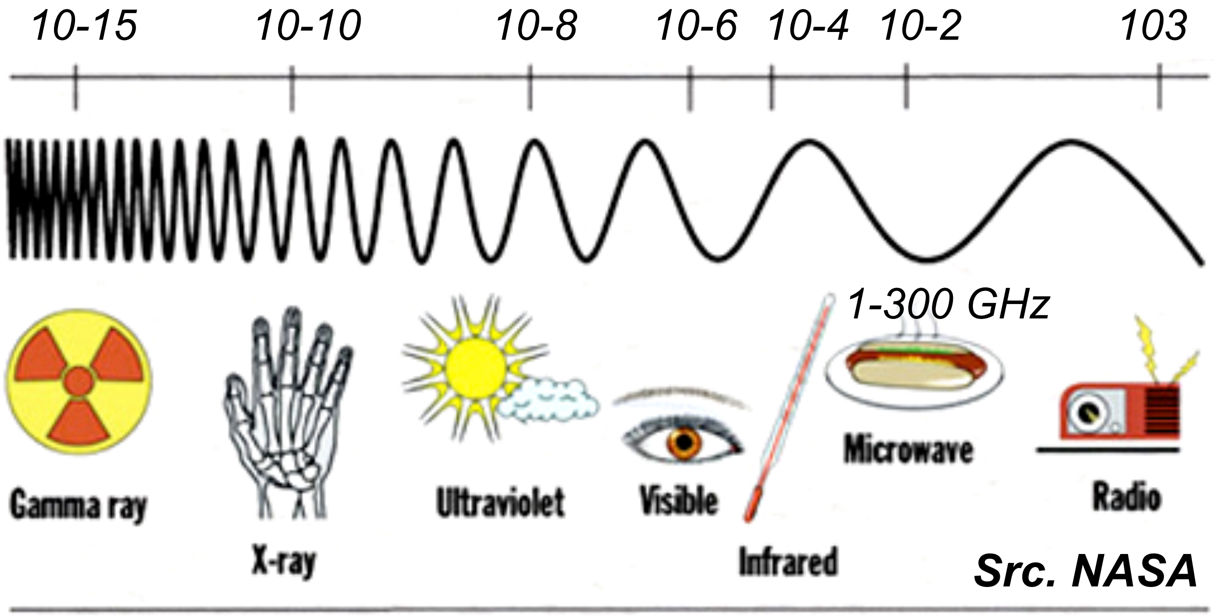
$$f = \frac{c\,(m/s)}{\lambda\,(m)}$$

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



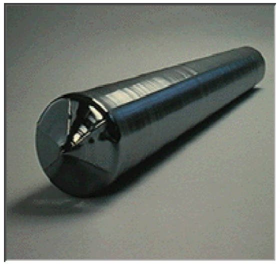
Src. NASA

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…

Sapphire (Al_2O_3)

Si



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

- What λ's will Si absorb?

E_{photon}> 1.12 eV (the bandgap of Si) … therefore λ_{photon}<1.1 µm

- *what if* $E_{photon}>2E_g$ *?*
  Still only 1 e-h pair!

- Example, hit Si with 10^{13} photons of green light (2.2 eV) every 1 µs or 10^{19}/s How much power is that? A lot? A little?

$$J(energy, eV) = Coulomb \times Volt$$
$$2.2\,eV = 1.6\times10^{-19}\times 2.2\ J$$
$$W = J/s = 2.2\times1.6\times10^{-19}\times\frac{10^{13}}{10^{-6}} = 3.5\ pW$$
$$\sim 1.7\ pW\ becomes\ heat$$
$$\sim 1.7\ pW\ becomes\ e-h\ pairs \rightarrow which\ becomes?$$

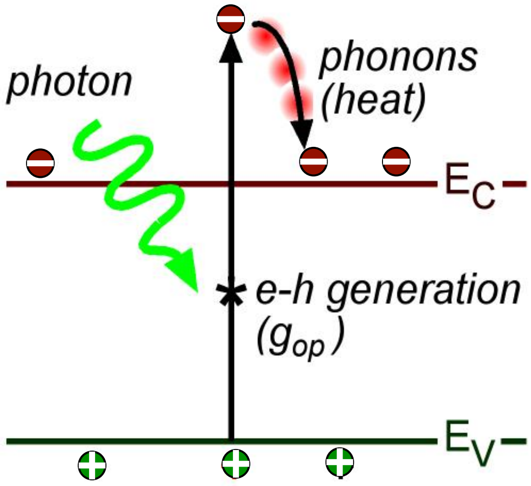
- If we wanted to calculate the excess carrier concentration (for low level injection condition) then use this formula:

$$\delta_n(1/cc) = \delta_p = g_{op}\tau_n = g_{op}\tau_p$$

g_{op} = optical generation rate = 1/cc-s

Optical Recombination

- Now, semiconductors can absorb photons greater than or equal to the band-gap energy…

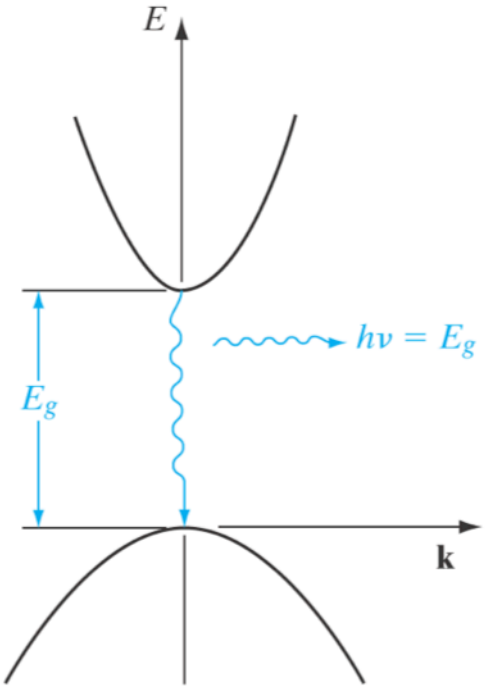


- Can they recombine and create a photon (reverse the process)?

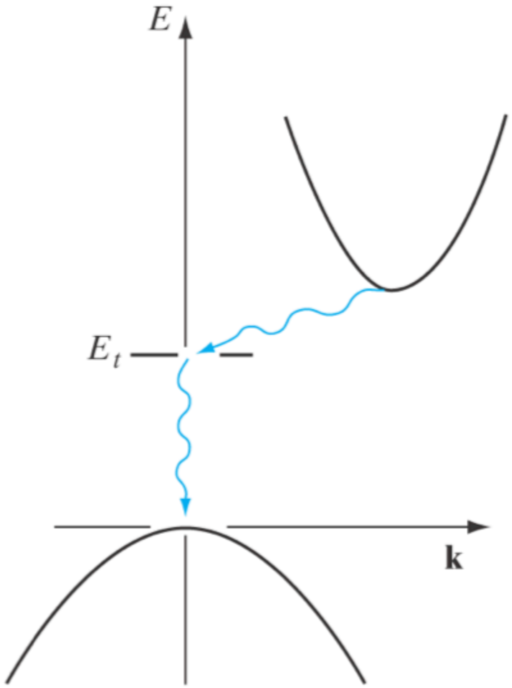
- Direct bandgap recombination is the heart of semiconductor LEDs and LASERs!

- 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!

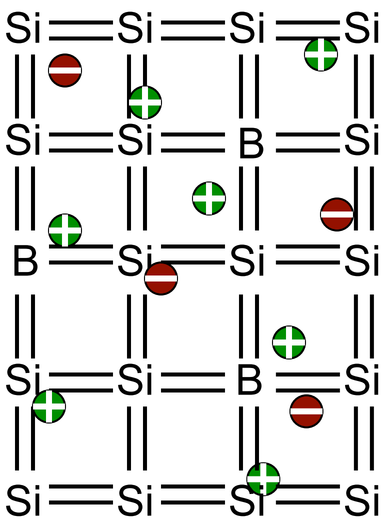


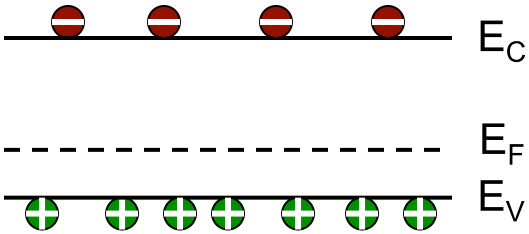
Direct: GaAs, GaN, InP, etc..



Indirect: Si, Ge, SiC

Bring it all together…





(1) At 300K, happening ALL the time is generation and recombination... if you raise the temperature further, generation increases, but obviously recombination will increase too, why? There are two reasons:

- hint 1 (think of increased concentrations)
- hint 2 (think of ability to move around faster and what ‘drives’ their movement after they are created)

(2) What term do we use for how far carriers go before they recombine?

(2) How does doping effect recombination in terms of:

- lifetime for holes, or electrons
- diffusion length for holes, or electrons

(3) What happens if we shine light on the sample uniformly?

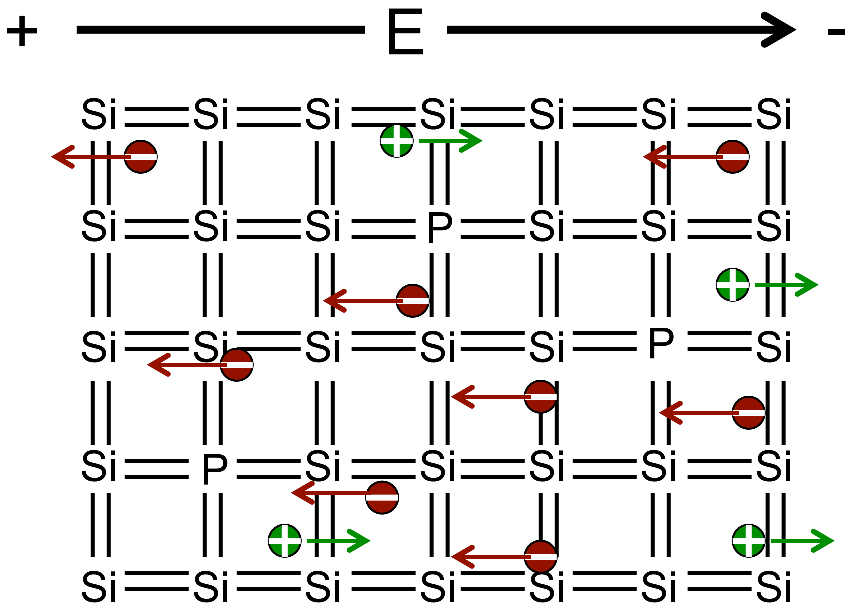
(4) There are two things that can result for recombining carriers, what are they?

Whew!

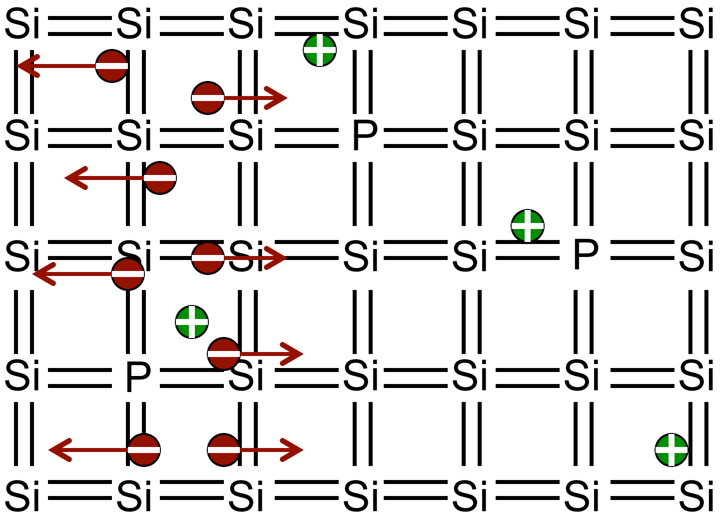
- Whew! So we have covered how electron and hole concentrations change with thermal generation, doping, recombination, optical generation, and light emitting (radiative) recombination….

- One more major topic before we can <u>start learning devices</u>…. CURRENT FLOW!

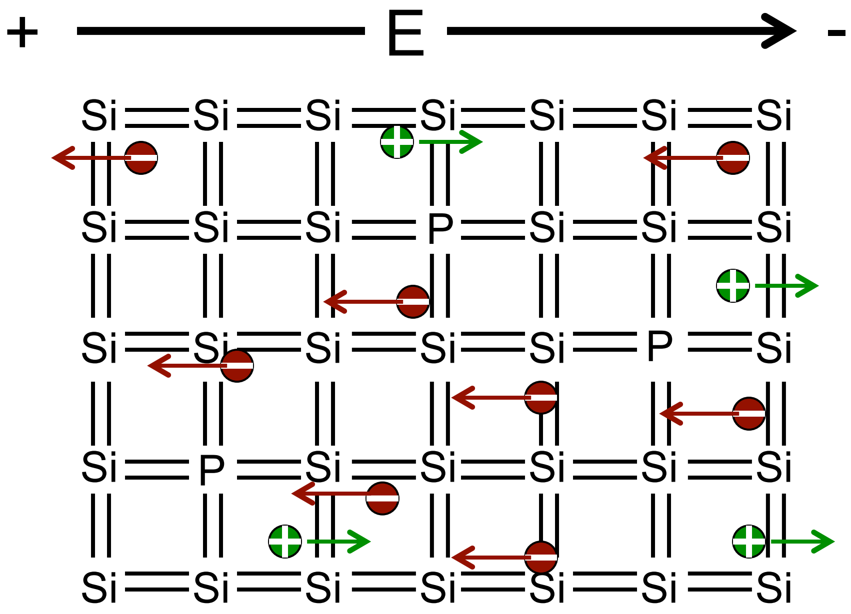
- Drift Current (E-field driven).

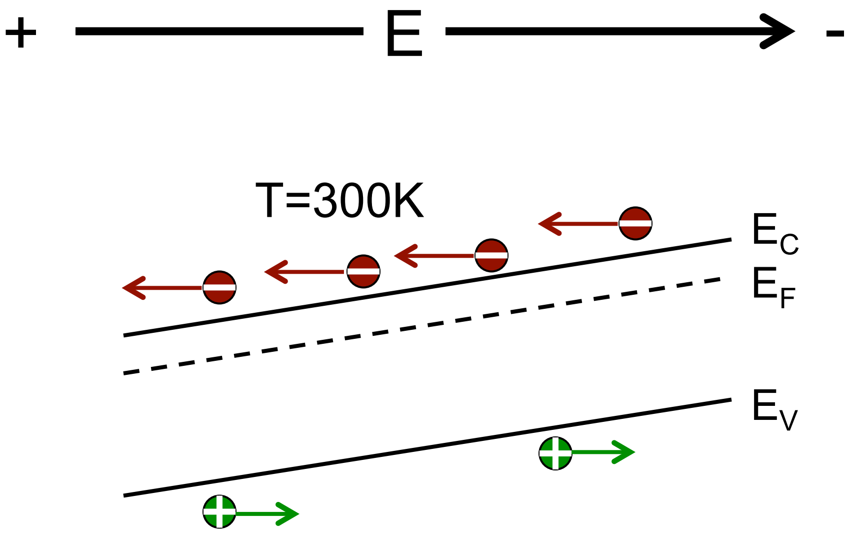


- Diffusion Current (entropy driven).



Drift Current (due to E-field)





$$J_n(drift) = q\mu_n n(x)\ E(x) = A/cm^2$$

$$= q\frac{(cm/s)}{(V/cm)}(1/cm^3)(V/cm)$$

- μ is mobility – units are ‘how fast’ / ‘how much E-field’.

- Mobility is reduced by scattering from ionized dopants, and as temperature increases due to lattice vibration. The carriers can also cause each other to scatter.

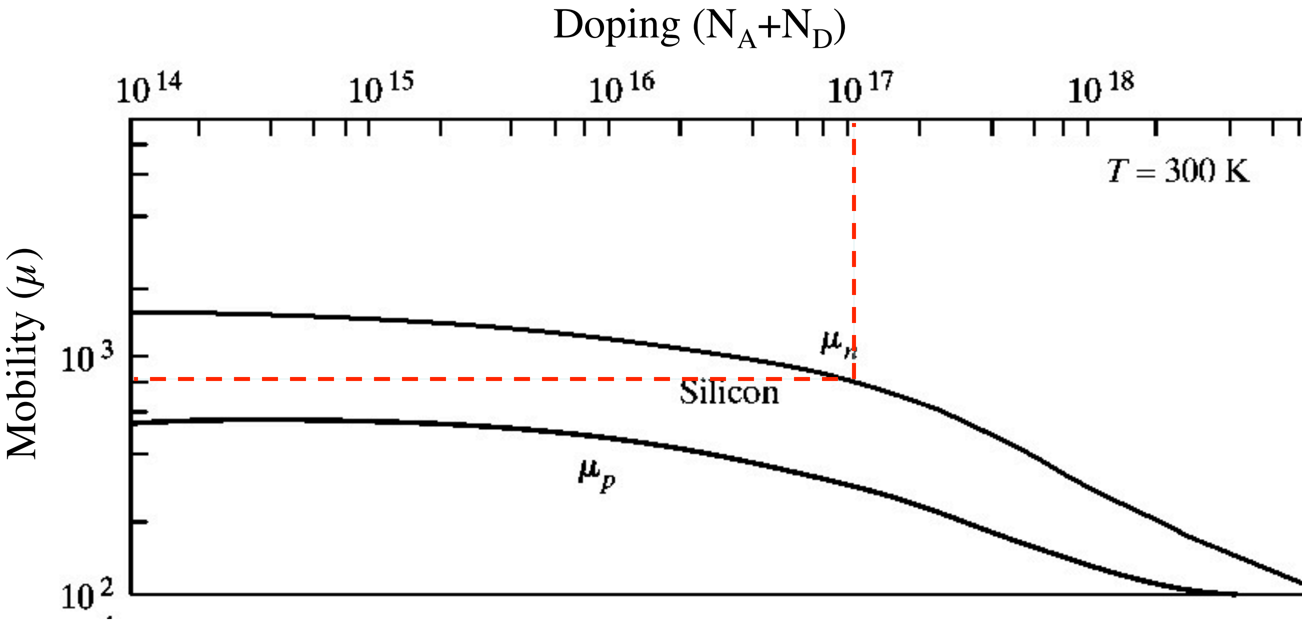
- To keep your sanity: soda pop analogy… e’s are water (flow down), h’s are absence of e’s or bubbles in water (float up).

- Positive voltage pushes the bands down! Negative voltage pushes the bands up!

- Remember E=qV !!!

Drift Current (Example)

- (Ex 3-7) A Si bar 0.1 cm long and 100 μm^2 in cross-sectional area is doped with 10^{17} phosphorus. What is the current with 10V applied?



$$I_n = q\mu_n n_0 \, E \, A$$

$$= 1.6\times10^{-19}\,C \times 700\,\frac{cm/s}{V/cm} \times 10^{17}/cc \times \frac{10\,V}{0.1\,cm} \times 10^{-6}\,cm^2$$

$$= 1.1\,mA$$

- Could also do it this way…

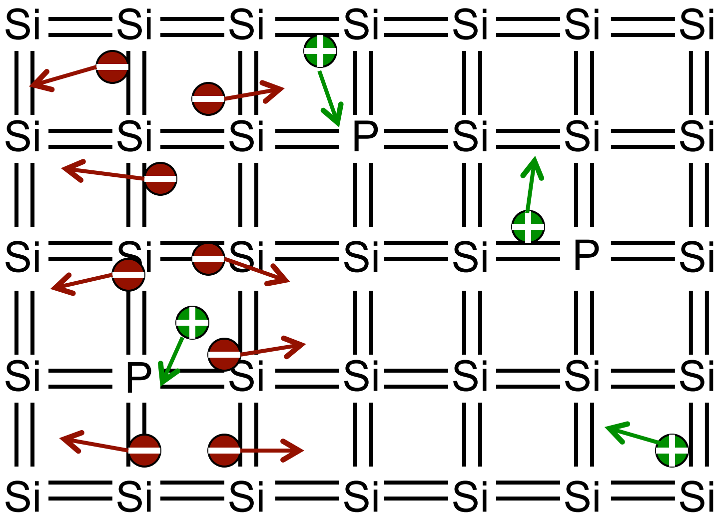
$$\sigma = q\mu_n n_0 = \rho^{-1}$$

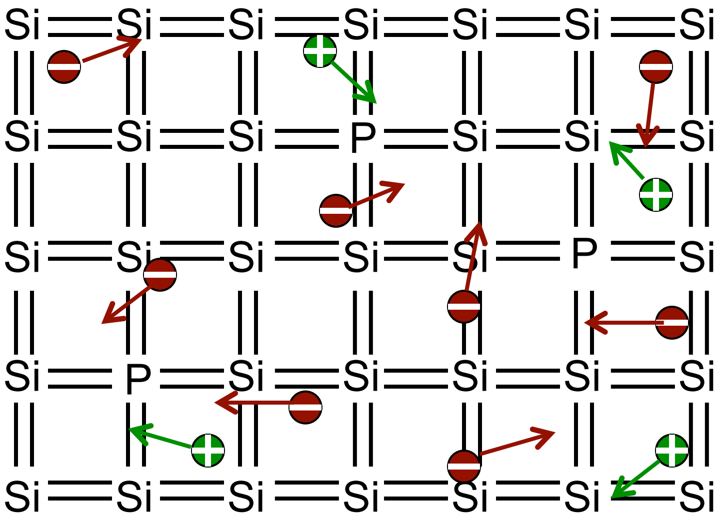
$$R = \rho L / A$$

$$I = V / R$$

Diffusion Current

- Diffusion relies on random motion (need temperature!) and drives any particle from high concentration to a random (evenly spread) distribution.
- Remember, even later, at 300K, Si lattice is vibrating (heat=phonons) and carriers are still *diffusing* randomly.





- The diffusion current equation tells you what makes this happen!

$$J_n(diffusion) = qD_n \frac{dn(x)}{dx} = q\ (cm^2/s)(1/cm^4) = A/cm^2$$

$$D_n = \mu_n kT/q$$

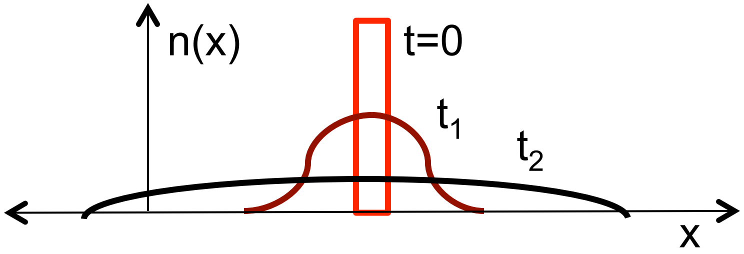
$$\mu_n = \frac{cm/s}{V/cm} \qquad k = eV/K$$

You need: charge, ease of movement, some energy (heat), and a concentration gradient! kT/q= thermal voltage (it turns mobility μ_n into diff. coef. D_n)

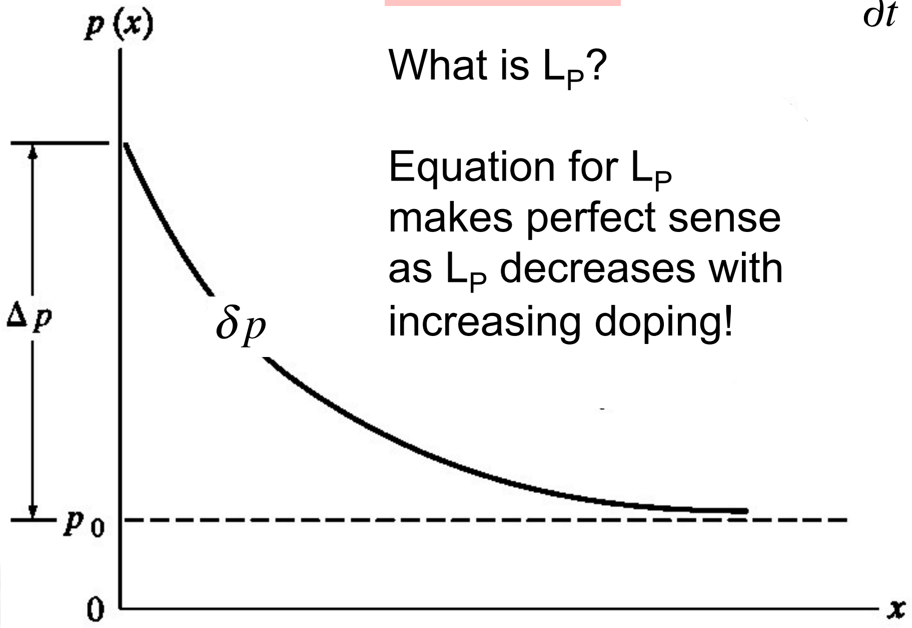
Note: in some cases, diffusion is more important than drift! When you apply forward bias voltage to a diode, the current is due to diffusion, not E-field! More next week…

Diffusion Current

- Example, spreading of a pulse of electrons by diffusion (Fig. 4.12). At what time do the electrons move the fastest? And why?



- Fig. 4-17, continuously inject Δp holes at x=0. Current flow? Why decrease with x?



$$L_P = \sqrt{D_P \tau_P}$$

What is L_P?

Equation for L_P makes perfect sense as L_P decreases with increasing doping!

How get this equation?, 1st start with the general diffusion equation (is continuous, section 4.43).

$$\frac{\partial \delta p}{\partial t} = D_p \frac{\partial^2 \delta p}{\partial x^2} - \frac{\delta p}{\tau_p}$$

δp is just the change in conc., not the total conc. For diffusion we just need the change!

$$\frac{\partial^2 \delta p}{\partial x^2} = \frac{\delta p}{D_p \tau_p}$$

(1) in steady state (no change with time)

(2) general solution $\rightarrow \delta p(x) = C_1 e^{x/L_P} + C_2 e^{-x/L_P}$

(3) C_1 must equal zero, why?

(4) Next, at x=0, what is p(x) and therefore C_2?

$$\rightarrow p(x) = \Delta p \; e^{-x/L_P} + p_0$$

$$\rightarrow p(x) = \delta p + p_0$$

Bring it all together…

- If apply positive voltage on left side of the diagrams shown at right what will happen? That is, how would you redraw each:
  - right after voltage was applied (t0+).
  - hold on voltage and system reaches equilibrium (t>>0).

- The carriers moved when we applied voltage, what type of current was this?

- You remove the voltage, the carriers should spread back out again based on the internal voltage you built up (notice in your drawing for t>>0 that there is an E-field and voltage created by the separated carriers). This respreading due to voltage is DRIFT. However, The carriers should also respread due not to voltage, but also what other type of current?

- The units for mobility are what, and practically, they describe X/Y (please state this using words for X and for Y).

- Diffusion is not driven by E-field, but by temperature and entropy (things want to spread out over time to a maximally disordered state). However, when calculating diffusion current we can use mobility and a driving force just like voltage (but which is driven by temperature). What is this 'voltage-like' driving force called?

- Diffusion length helps us statistically predict how far an electron or hole moves until it _______________. (fill in the blank)