ECE 4813

Semiconductor Device and Material Characterization

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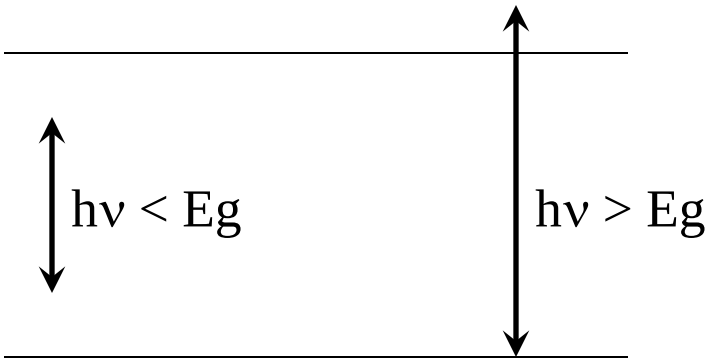
As with all of these lecture slides, I am indebted to Dr. Dieter Schroder from Arizona State University for his generous contributions and freely given resources. Most of (>80%) the figures/slides in this lecture came from Dieter. Some of these figures are copyrighted and can be found within the class text, *Semiconductor Device and Materials Characterization*. ***Every serious microelectronics student should have a copy of this book!***

Recombination/Generation

Recombination Mechanisms
Photoconductance Decay
Iron in Silicon
Surface Photovoltage
Generation

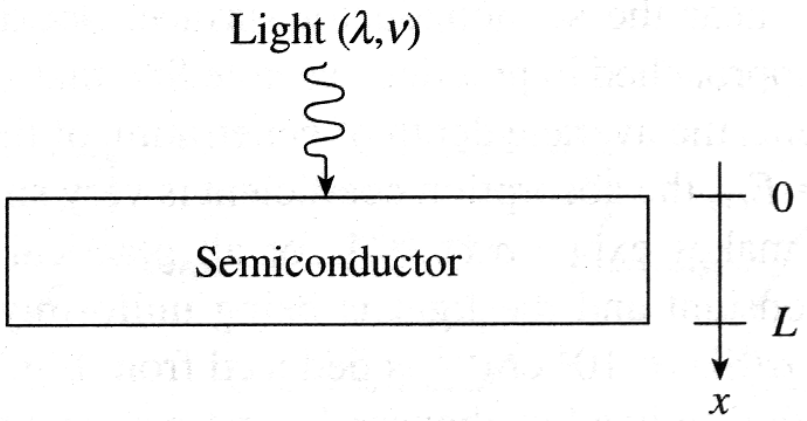
Photogeneration

Light with photon energy, hν < Eg is not easily absorbed. A convenient expression for the energy of light is E=1.24/λ where λ is the wavelength of the light in um.

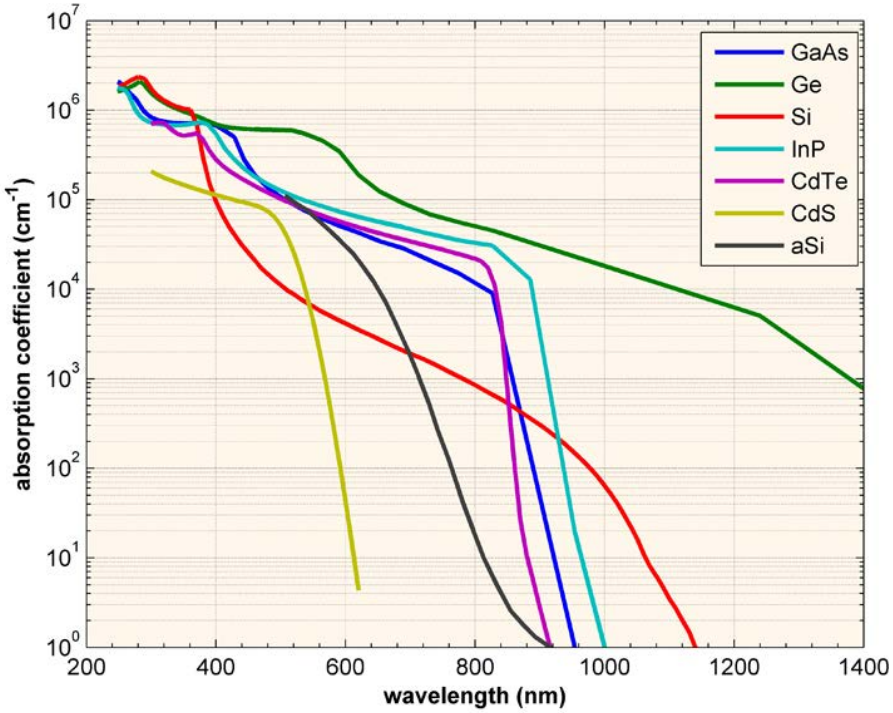


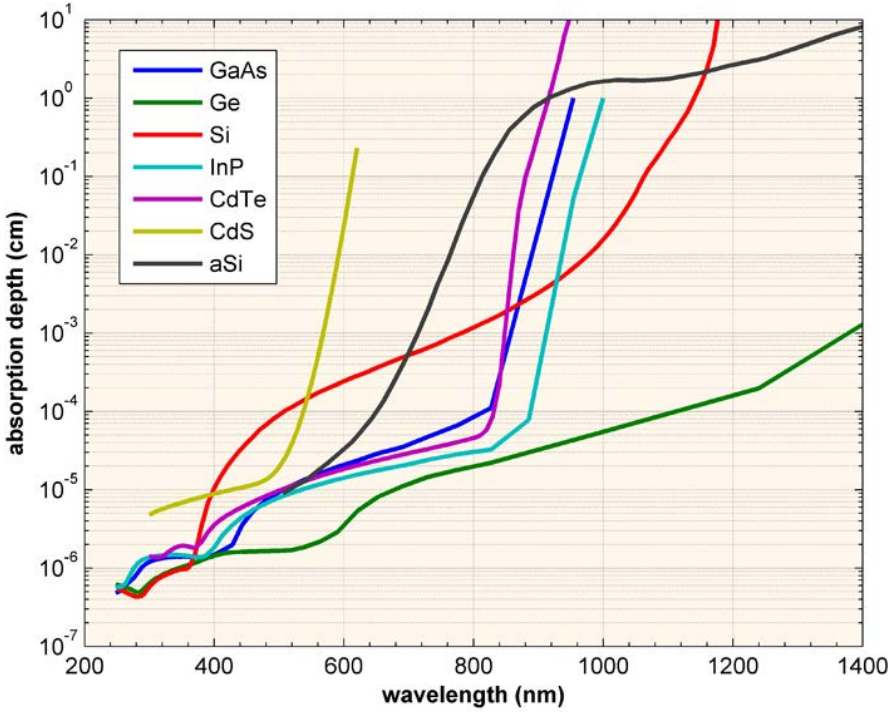
Light with energy, hν > Eg is absorbed with the "unabsorbed" light intensity as a function of depth into the semiconductor is $I(x) = I_o e^{-\alpha x}$

where Io is the initial light intensity, x is distance and α is the absorption coefficient [1/cm].



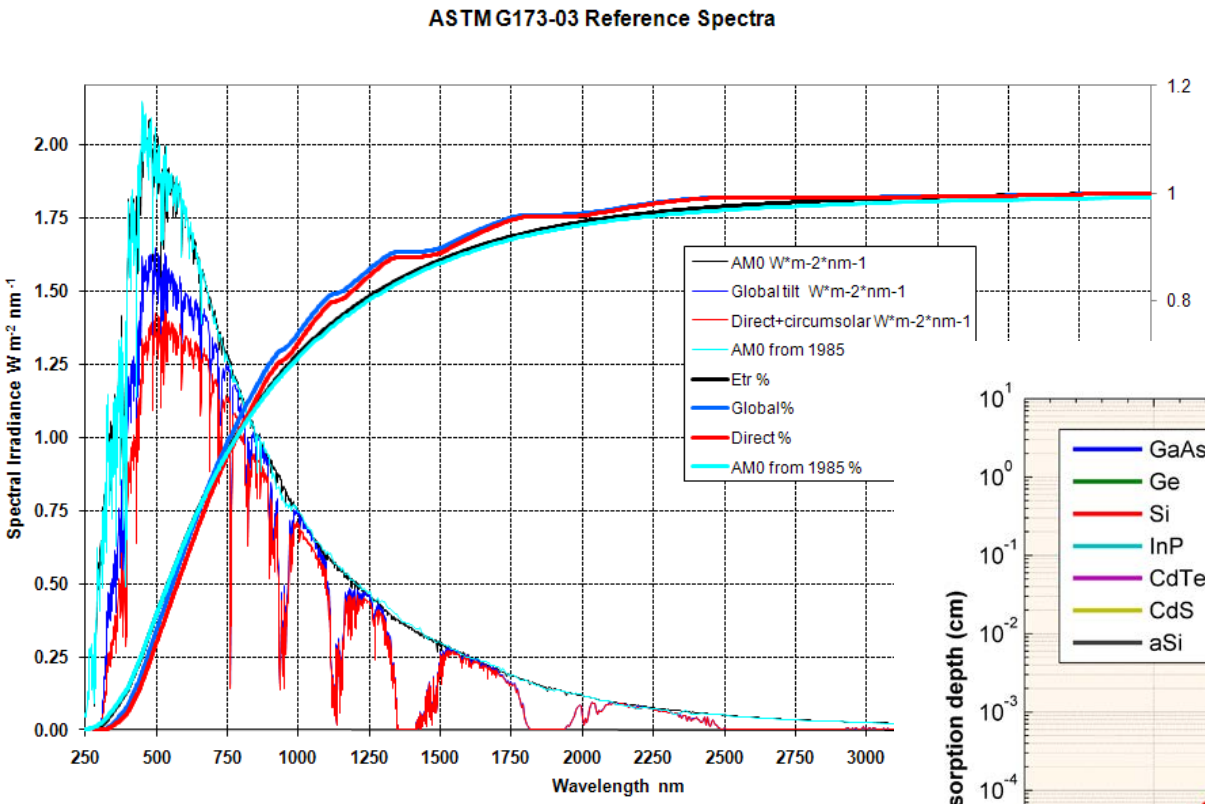
Absorption

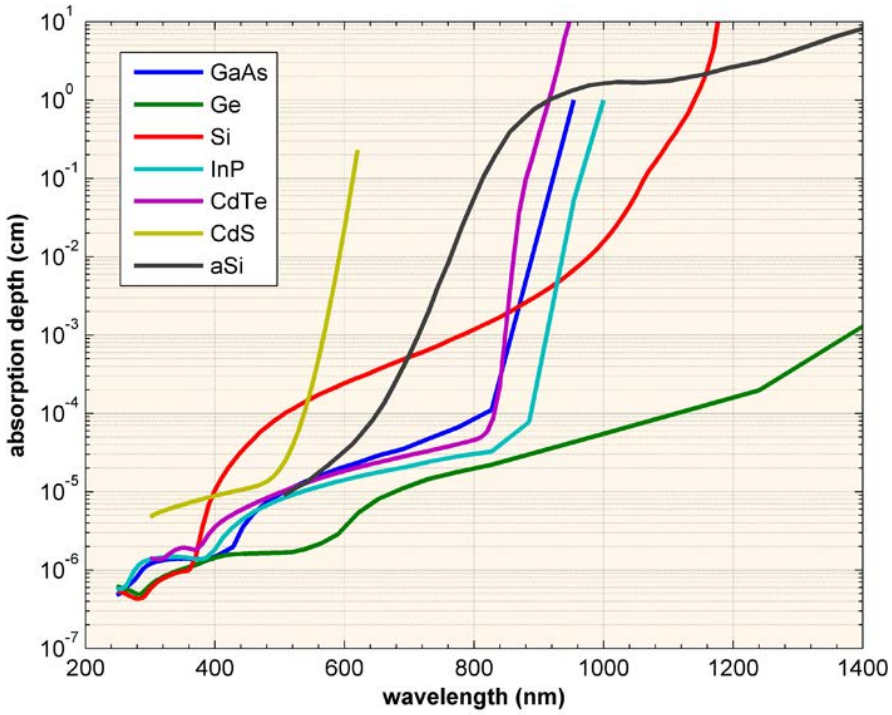




The absorption depth is given by the inverse of the absorption coefficient, or α^{-1}. The absorption depth gives the distance into the material at which the light at that wavelength drops to about 36% of its original intensity (by a factor of 1/e).

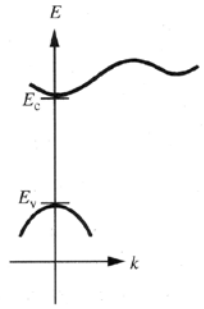
Absorption


ASTM G173-03 Reference Spectra
Spectral Irradiance W m-2 nm-1
Wavelength nm
AM0 W*m-2*nm-1
Global tilt W*m-2*nm-1
Direct+circumsolar W*m-2*nm-1
AM0 from 1985
Etr %
Global%
Direct %
AM0 from 1985 %

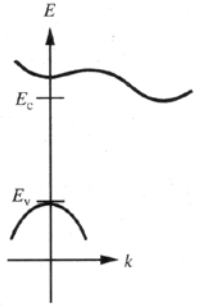

absorption depth (cm)
wavelength (nm)
GaAs
Ge
Si
InP
CdTe
CdS
aSi

Real Energy band Diagrams:

Direct verses Indirect Bandgaps

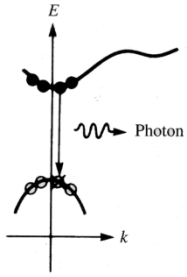


(a) Direct semiconductor

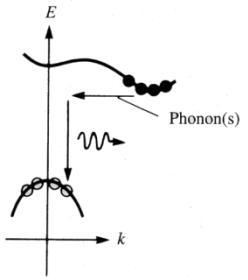


(b) Indirect semiconductor

Figure 3.17 General forms of E–**k** plots for direct and indirect semiconductors.



(a) Direct semiconductor



(b) Indirect semiconductor

Figure 3.18 E–**k** plot visualizations of recombination in direct and indirect semiconductors.

The energy required to liberate an electron from the atom (the energy bandgap) is the same in all “escape directions” (directions that an electron can leave the atom).

Example: Electrons directed toward a neighboring atom would have a high escape energy, while electrons directed toward a channel in the crystal (a hole through the crystal) would have a lower escape energy.

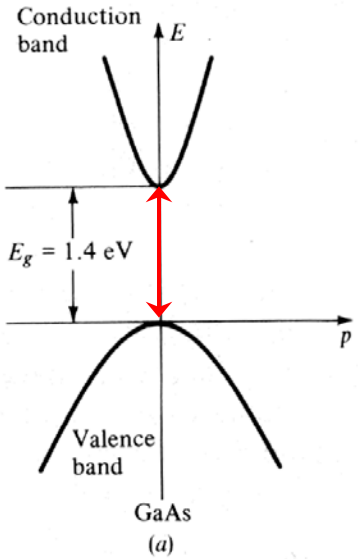
Thus, the energy band diagram is actually a function of momentum. Additionally, both energy and momentum (directed mass motion) must be conserved during any transition.

Real Energy band Diagrams:

Direct verses Indirect Bandgaps

Probability of a "direct transition" from valence band to conduction band is high!

Direct Bandgap



Indirect Bandgap

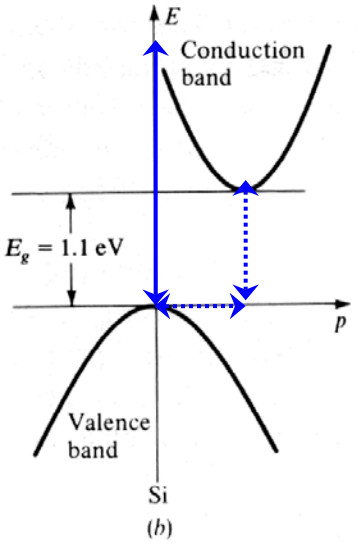


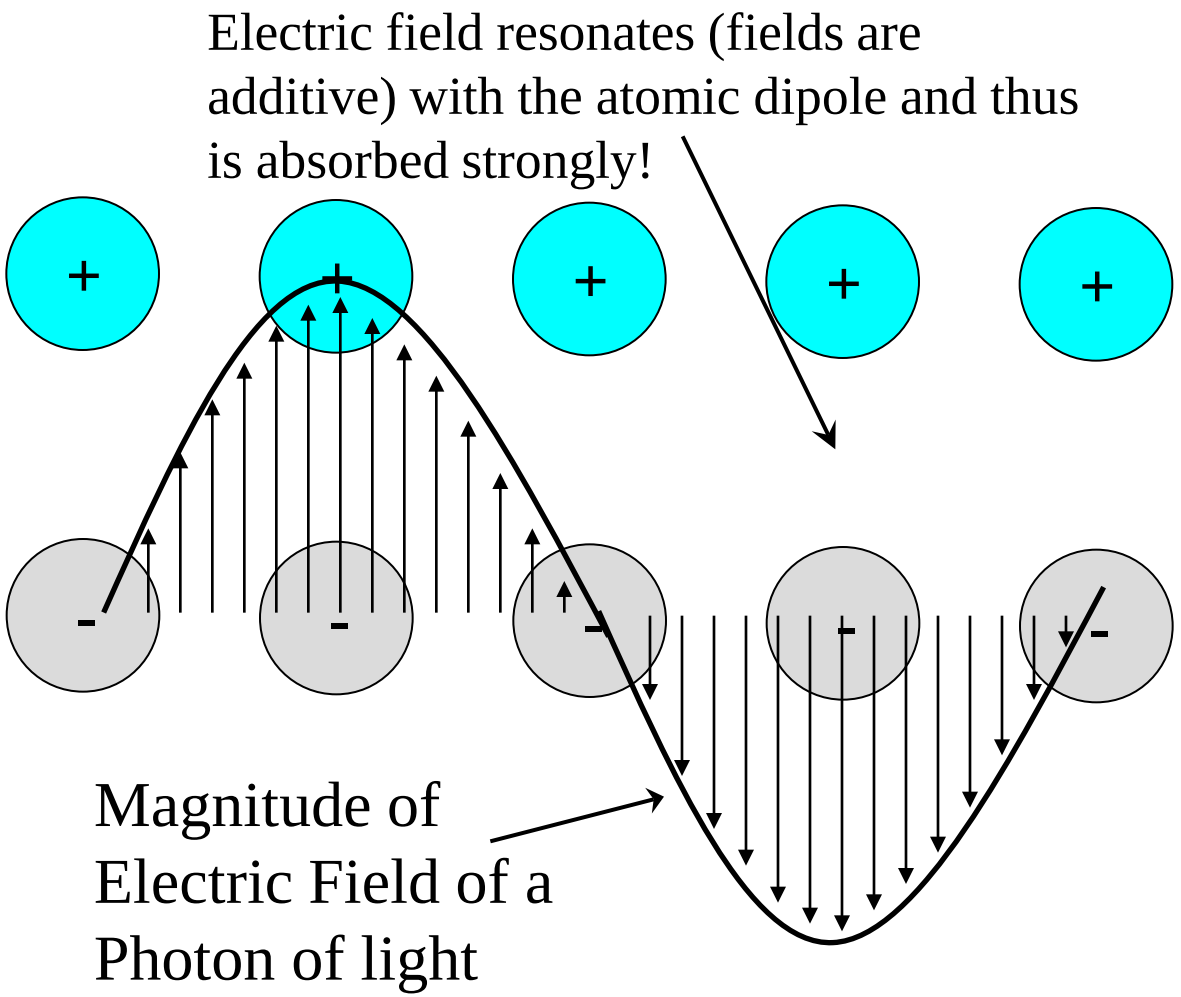
FIGURE 1-12
Energy-band diagram with energy vs. momentum for (*a*) GaAs (direct) and (*b*) Si (indirect).

Probability of a "direct transition" from valence band to conduction band is low but if the valence electron is on an atom vibrating in a direction (I.e. has momentum) that lowers the energy required, the probability increases!

Real Energy band Diagrams:

Direct verses Indirect Bandgap variations in Light Absorption

Polar materials like GaAs, InP, GaN etc… tend to be better at absorbing light. No lattice vibration is needed to absorb the light=direct gap.

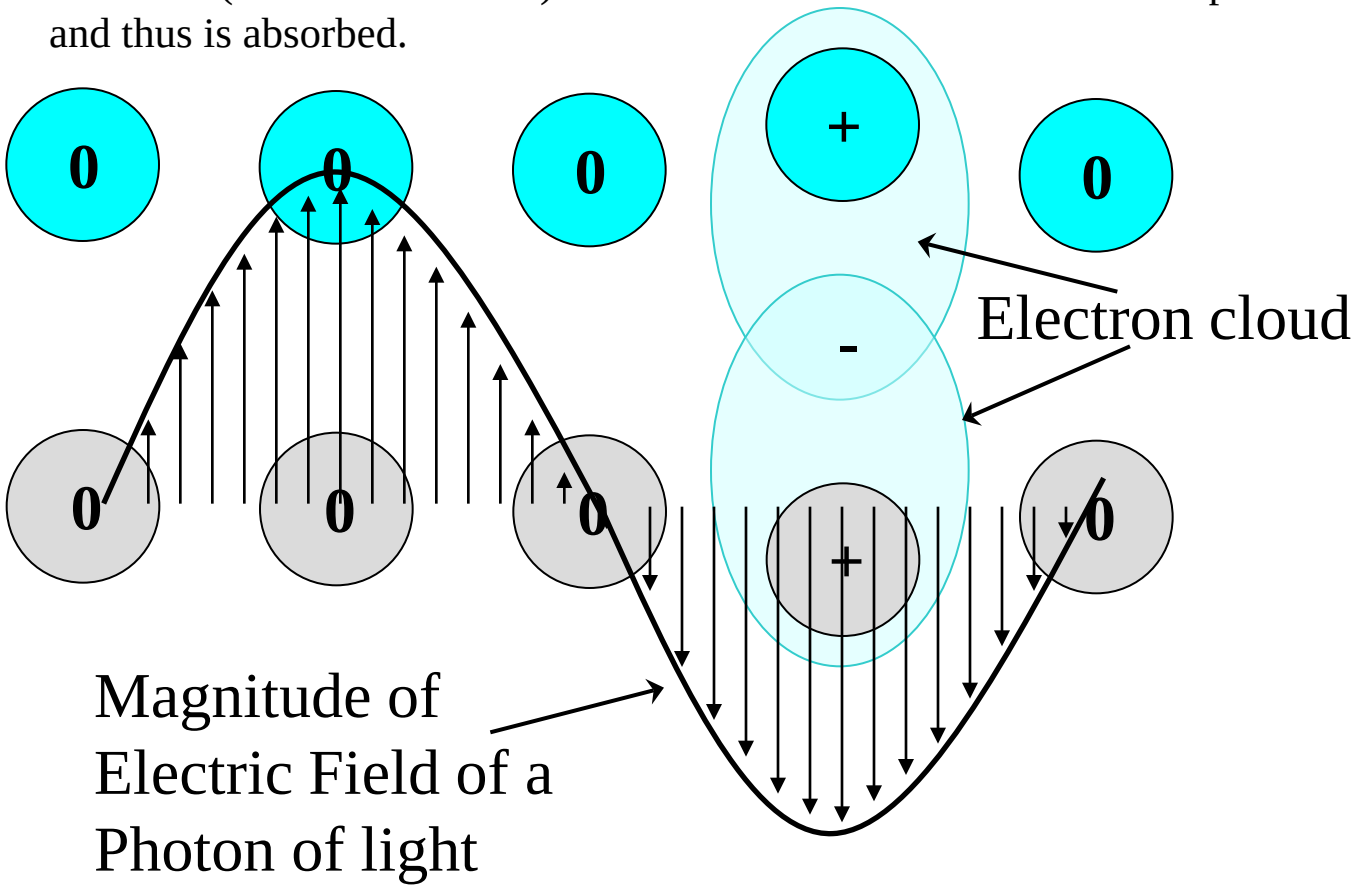


Real Energy band Diagrams:

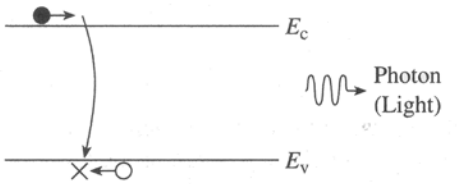
Direct verses Indirect Bandgap variations in Light Absorption

Covalent materials like Si, Ge etc… tend to be poor light absorbers. A lattice vibration is needed to induce a dipole in the crystal before the light can be absorbed=indirect gap.

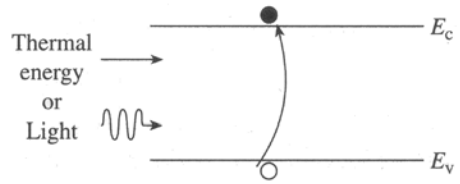
After the atoms move apart from their equilibrium positions, the core is displaced from the electron cloud. The photon's electric field then resonates (fields are additive) with the atom core - electron cloud dipole and thus is absorbed.



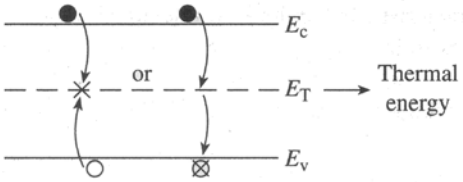
3 Recombination and 3 Generation Mechanisms…



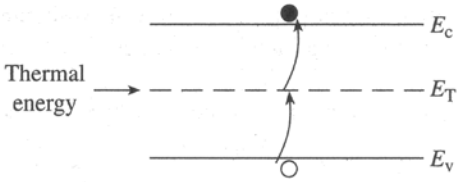
(a) Band-to-band recombination



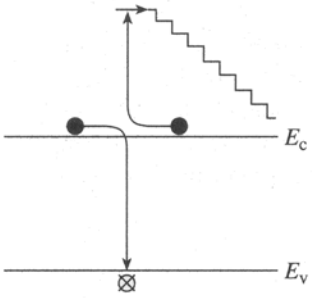
(d) Band-to-band generation



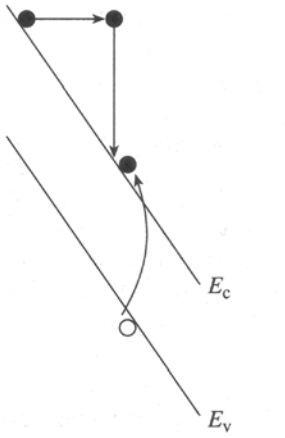
(b) R–G center recombination



(e) R–G center generation



(c) Auger recombination



(f) Carrier generation via impact ionization

Recombination and Generation Mechanisms

"Deep State" Impurities

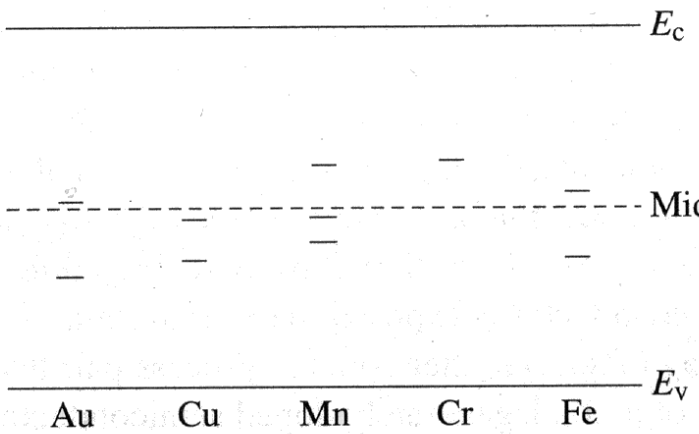
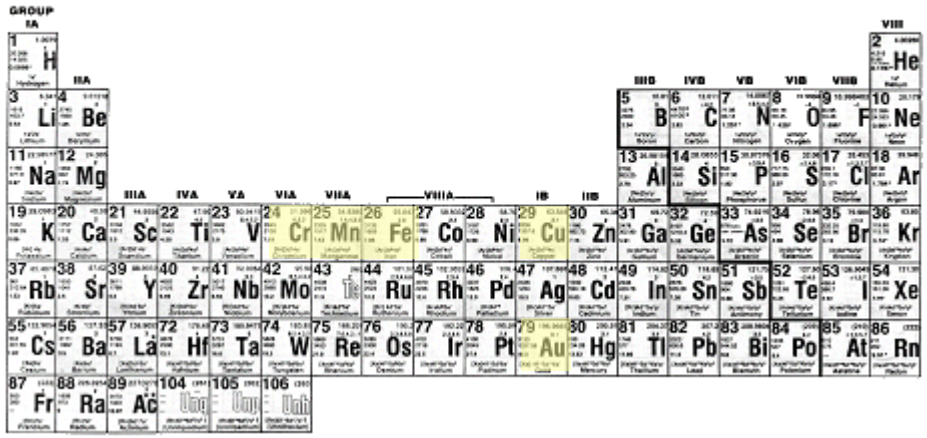
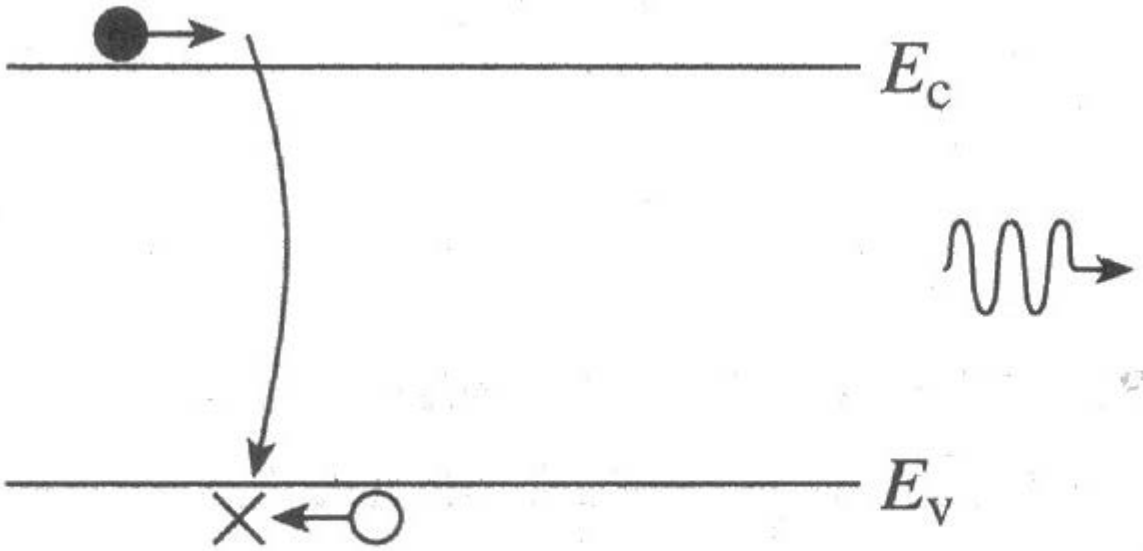


Figure 3.16 Near-midgap energy levels introduced by some common impurities in Si. When an impurity introduces multiple levels, one of the levels tends to dominate in a given semiconductor sample.

PERIODIC TABLE OF THE ELEMENTS



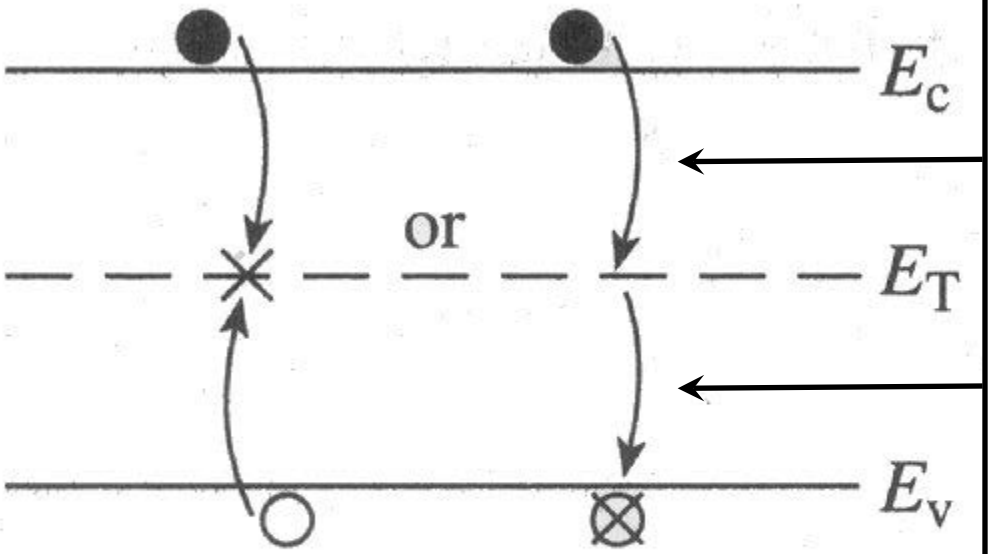
Recombination Mechanisms



Photon (single particle of light) or multiple phonons (single quantum of lattice vibration - equivalent to saying thermal energy)

- Band to Band or "direct" (directly across the band) recombination
- Does not have to be a "direct bandgap" material, but is typically very slow in "indirect bandgap" materials.
- Basis for light emission devices such as semiconductor LASERs, LEDs, etc…

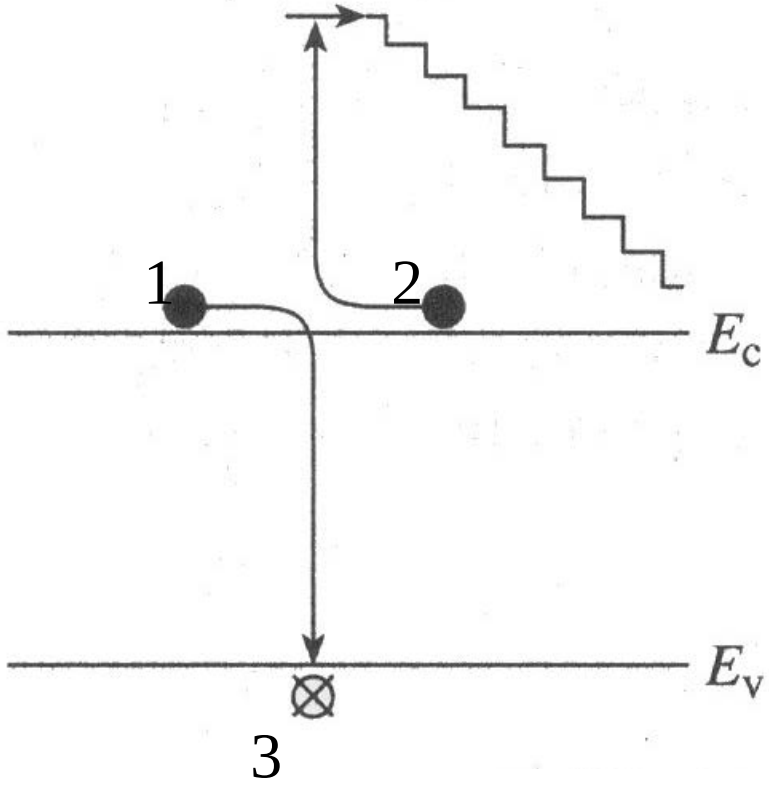
Recombination Mechanisms



Energy loss can result in a Photon (single particle of light) but is more often multiple phonons (single quantum of lattice vibration - equivalent to saying thermal energy)

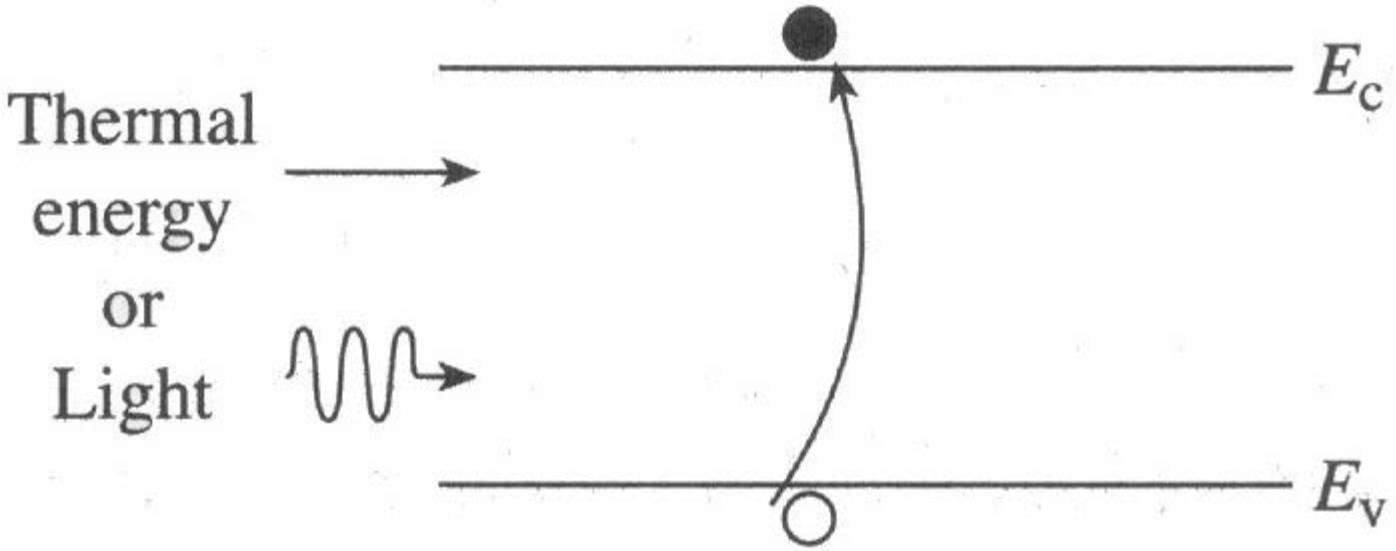
- Recombination-Generation (R-G) Center recombination.
- Also known as Shockley-Read-Hall (SRH) recombination.
- Two steps: 1.) 1st carrier is "trapped" (localized) at an unintentional (or intentional) defect/impurity. 2.) 2nd carrier (opposite type) is attracted to the R-G center and annihilates the 1st carrier.
- Useful for creating "fast switching" devices by quickly "killing off" ehp's.

Recombination Mechanisms



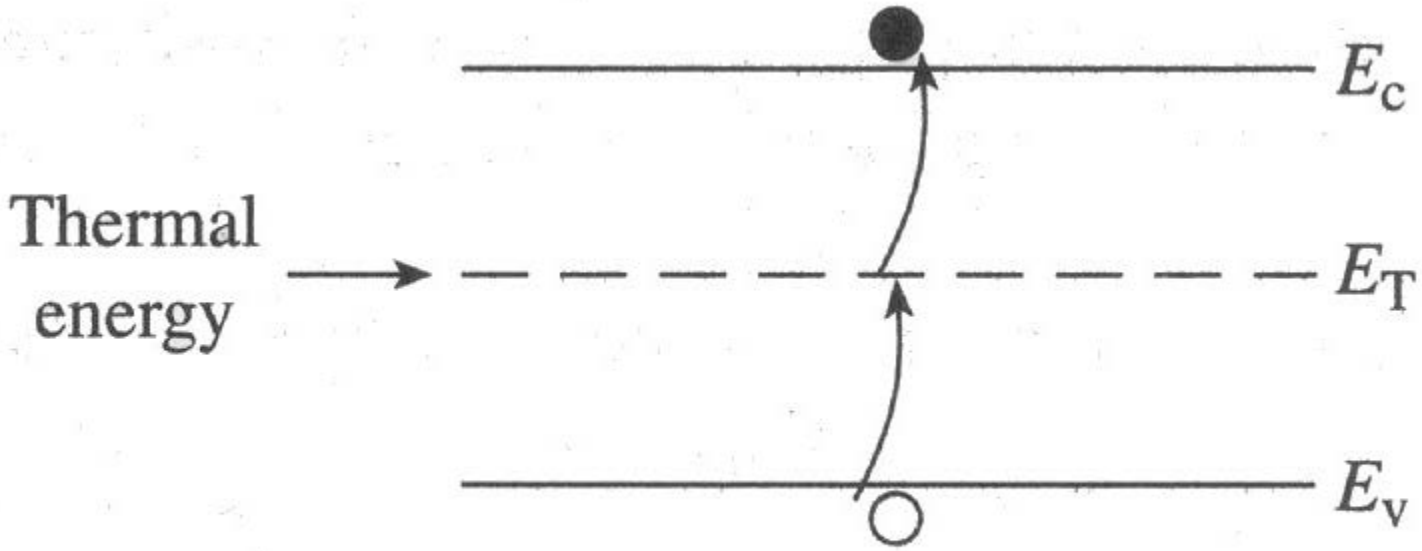
- Auger – "pronounced O-jay" recombination.
- Requires 3 particles.
- Two steps: 1.) 1st carrier and 2nd carrier of same type collide instantly annihilating the electron hole pair (1st and 3rd carrier). The energy lost in the annihilation process is given to the 2nd carrier. 2.) 2nd carrier gives off a series of phonons until it's energy returns to equilibrium energy ($E \sim = E_c$) This process is known as thermalization.

Generation Mechanisms



- Band to Band or "direct" (directly across the band) generation
- Does not have to be a "direct bandgap" material.
- Mechanism that results in n_i
- Basis for light absorption devices such as semiconductor photodetectors, solar cells, etc…

Generation Mechanisms

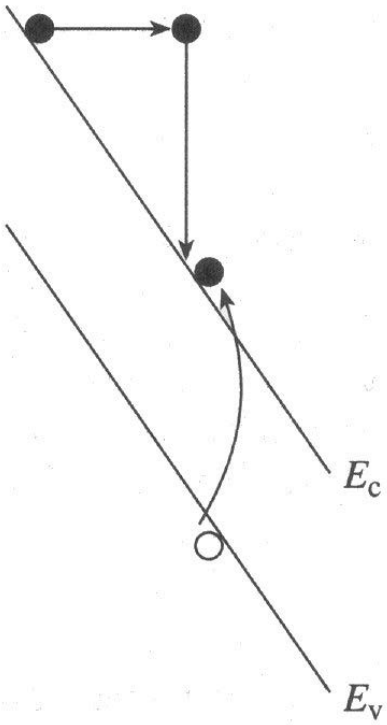


•Recombination-Generation (R-G) Center generation.

•Two steps: 1.) A bonding electron is “trapped” (localized) at an unintentional defect/impurity generating a hole in the valence band. 2.) This trapped electron is then promoted to the conduction band resulting in a new ehp.

•Almost always detrimental to electronic devices. AVOID IF POSSIBLE!

Generation Mechanisms



•Impact Ionization generation.

•Requires 3 particles and, typically, high electric fields (steeply bent bands).

•1st carrier is accelerated by high electric fields (or may very rarely gain enough kinetic energy on it's own) and collides with a lattice atom, knocking out a bonding electron creating an ehp.

•If the origin is a high electric field, this process can lead to rapid carrier multiplication known as "avalanching". Can be very useful for very sensitive (but noisy) photodiodes.

•Sets an upper limit on practical electric fields that can be tolerated in many transistors.

Photogeneration

Each Photon with energy greater than Eg can result in one electron hole pair. Thus, we can say,

$$\left.\frac{\partial n}{\partial t}\right|_{Light} = \left.\frac{\partial p}{\partial t}\right|_{Light} = G_L(x,\lambda) \quad where\ G_L(x,\lambda) = G_{LO}e^{-\alpha x} \quad \#/\left(cm^3 - Sec\right)$$

If α is small (near bandgap light), the generation profile can be approximately constant.

If α is large (light with energy>> bandgap), the generation profile can be approximated as at the surface.

Important Nomenclature

n_0, p_0	. . .	carrier concentrations in the material under analysis when equilibrium conditions prevail.
n, p	. . .	carrier concentrations in the material under arbitrary conditions.
$\Delta n \equiv n - n_0$ $\Delta p \equiv p - p_0$	. . .	deviations in the carrier concentrations from their equilibrium values. Δn and Δp can be both positive and negative, where a positive deviation corresponds to a carrier excess and a negative deviation corresponds to a carrier deficit.
N_T	. . .	number of R–G centers/cm^3.

$$n = \Delta n + n_o \text{ and } p = \Delta p + p_o$$

In Non-equilibrium, np does not equal n_i^2

Low Level Injection

$\Delta p = \Delta n << n_o$ and $n \sim n_o$ in n-type material

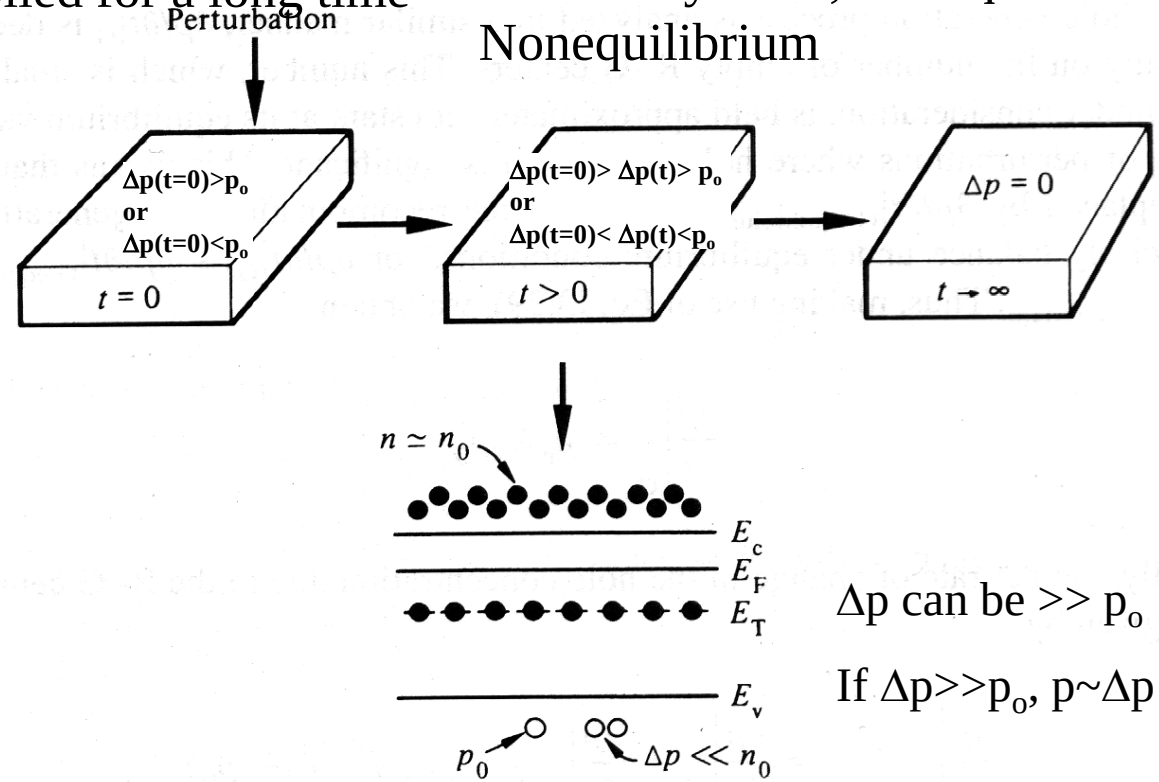
$\Delta p = \Delta n << p_o$ and $p \sim p_o$ in p-type material

Carrier Concentrations after a "Perturbation"

Steady State if perturbation has been applied for a long time

Non-Steady State, Nonequilibrium

Equilibrium



Δp can be >> p_o

If $\Delta p >> p_o$, $p \sim \Delta p$

After the carrier concentrations are perturbed by some stimulus (leftmost case) and the stimulus is removed (center case) the material relaxes back toward it's equilibrium carrier concentrations.

Material Response to "Non-Equilibrium": Relaxation Concept

Consider a case when the hole concentration in an n-type sample is not in equilibrium, i.e., pn does NOT equal n_i^2

$$\left.\frac{\partial p}{\partial t}\right|_{thermal \quad R-G} = -\frac{\Delta p}{\tau_p} \qquad where \quad \tau_p = \frac{1}{c_p N_T}$$

$$where\ \tau_p is\ the\ \text{min}ority\ carrier\ lifetime$$

$$c_p\ is\ a\ proportionality\ cons\tan t$$

$$N_T\ is\ the\ "trap"\ concentration$$

•The minority carrier lifetime is the average time a minority carrier can survive in a large ensemble of majority carriers.

•If Δp is negative➔Generation or an increase in carriers with time.

•If Δp is positive➔Recombination or a decrease in carriers with time.

•Either way the system "tries to reach equilibrium"

•The rate of relaxation depends on how far away from equilibrium we are.

Material Response to "Non-Equilibrium": Relaxation Concept

Likewise when the electron concentration in an p-type sample is not in equilibrium, i.e., pn does NOT equal n_i^2

$$\left.\frac{\partial n}{\partial t}\right|_{thermal \quad R-G} = -\frac{\Delta n}{\tau_n} \qquad where \quad \tau_n = \frac{1}{c_n N_T}$$

where τ_n *is the* minority *carrier lifetime*

c_n *is a different proportionality* constant

N_T *is the "trap" concentration*

More generally for any doping or injection case:

$$\left.\frac{\partial n}{\partial t}\right|_{thermal \quad R-G} = \left.\frac{\partial p}{\partial t}\right|_{thermal \quad R-G} = \frac{n_i^2 - np}{\tau_p(n+n_1)+\tau_n(p+p_1)}$$

Same unit as above

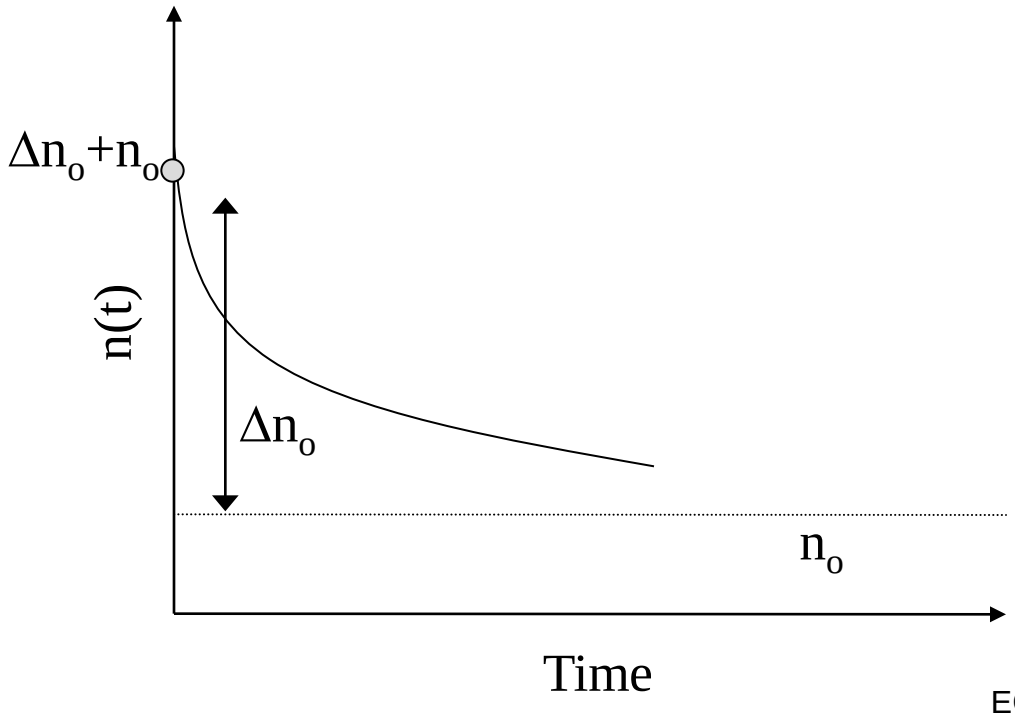
where...

$$n_1 \equiv n_i e^{(E_T - E_i)/kT} \quad and \quad p_1 \equiv n_i e^{(E_i - E_T)/kT}$$

Example: After a long time on, a light is switched off

$$\frac{\partial n}{\partial t} = -\frac{\Delta n}{\tau_n} \qquad \textit{has a solution}$$

$$n(t) = n_o + \underbrace{\Delta n_o e^{-\left(t/\tau_n\right)}}_{\Delta n(t)} \qquad \textit{where } \Delta n_o = \textit{initial excess electron concentration}$$



Material Response to "Non-Equilibrium": Relaxation Concept

Carrier Relaxation can also be achieved through Direct recombination

Given: $\Delta n = \Delta p$, $n = n_o + \Delta n$, $p = p_o + \Delta p$

Low Level Injection ==> $\Delta n << N_a$ and High Level Injection ==> $\Delta n >> N_a$

•Recombination Rate, $R = Bnp$ [#/cm^3 sec.] (depends on number of electrons and holes present)

• In Thermal Equilibrium,

$np = n_i^2$ where n_i^2 is the n-p product due to thermal generation (intrinsic generation)

Recombination rate, $R = B\, n_i^2 = G$, Generation Rate where B is a constant

Under Illumination (Non-thermal equilibrium), $np > n_i^2$

Net Recombination Rate, $-dn/dt = R - G = B(np - n_i^2)$

but, $\Delta n = \Delta p$

$$-dn/dt = B(np - n_i^2)$$
$$= B((n_o + \Delta n)(p_o +. \Delta p) - n_i^2)$$
$$= B(n_o p_o - n_i^2 + \Delta p n_o + \Delta n p_o + \Delta n \Delta p)$$
$$= B\Delta n(0 + n_o + p_o + \Delta n)$$
$$= B\Delta n(n_o + p_o + \Delta n)$$

Thus, using our lifetime definition,

$$-dn/dt = -\Delta n/ \tau_{direct}$$
$$\tau_{direct} = 1/(B(n_o + p_o + \Delta n))$$

Material Response to "Non-Equilibrium": Relaxation Concept

Carrier Relaxation can also be achieved through Direct recombination

Special cases:

Low Level Injection: $\Delta n << $ majority carrier density

$$\tau_{direct}=1/(B(n_o + p_o))$$

and if the material is n-type:

$$\tau_{direct}=1/(Bn_o)$$

or p-type:

$$\tau_{direct}=1/(Bp_o)$$

High level injection: $\Delta n >>$ majority carrier density

$$\tau_{direct}=1/(B\Delta n)$$

Material Response to "Non-Equilibrium": Relaxation Concept

Carrier Relaxation can also be achieved through "Auger" recombination

Derive the equation for the lifetime, τ_{Auger}, due to Auger recombination as was done for Band-to-Band.

Auger (pronounced "O-jay") recombination involves 3 particles: either (2 electrons and 1 hole) or (2 holes and 1 electron). As such, the net recombination rate is described by:

$$R - G = -\frac{dn}{dt} = C_n n\left(np - n_i^2\right) + C_p p\left(np - n_i^2\right)$$

where C_n and C_p are the Auger coefficients for electrons and holes respectively with units cm^6/Second.

In general, all these terms are important (especially in low bandgap materials where p~n) but let us examine each component separately by assuming an n-type material where n>p and assuming that $C_p \sim C_n$ (a very good assumption).

$$R - G = -\frac{dn}{dt} = C_n n\left(np - n_i^2\right)$$

$$R - G = -\frac{dn}{dt} = C_n (n_o + \Delta n)\left((n_o + \Delta n)(p_o + \Delta p) - n_i^2\right)$$

$$R - G = -\frac{dn}{dt} = C_n (n_o + \Delta n)\left(n_o p_o - n_i^2 + \Delta p n_o + \Delta n p_o + \Delta n \Delta p\right)$$

$$R - G = -\frac{dn}{dt} = C_n (n_o + \Delta n)(\Delta p n_o + \Delta n p_o + \Delta n \Delta p)$$

But since $\Delta n = \Delta p$,

$$R - G = -\frac{dn}{dt} = C_n (n_o + \Delta n)(n_o + p_o + \Delta n)\Delta n$$

$$R - G = -\frac{dn}{dt} = C_n [(n_o n_o + n_o p_o + n_o \Delta n) + (\Delta n n_o + \Delta n p_o + \Delta n \Delta n)]\Delta n$$

Material Response to "Non-Equilibrium": Relaxation Concept

Carrier Relaxation can also be achieved through "Auger" recombination

At this point, we could add the other equivalent expression for 2holes/1electrons to get a generalized case:

$$R - G = -\frac{dn}{dt} = C_n[(n_o n_o + n_o p_o + n_o \Delta n) + (\Delta n n_o + \Delta n p_o + \Delta n \Delta n)]\Delta n + C_p[(p_o p_o + n_o p_o + p_o \Delta n) + (\Delta n p_o + \Delta n n_o + \Delta n \Delta n)]\Delta n$$

Thus, by definition:

$$-\frac{dn}{dt} = \frac{\Delta n}{\tau_{Auger}}$$

$$\tau_{Auger}^{-1} = C_n[(n_o n_o + n_o p_o + n_o \Delta n) + (\Delta n n_o + \Delta n p_o + \Delta n \Delta n)] + C_p[(p_o p_o + n_o p_o + p_o \Delta n) + (\Delta n p_o + \Delta n n_o + \Delta n \Delta n)]$$

But for our assumed n-type material:

$$\tau_{Auger}^{-1} = C_n[(n_o n_o + n_o p_o + n_o \Delta n) + (\Delta n n_o + \Delta n p_o + \Delta n \Delta n)]$$

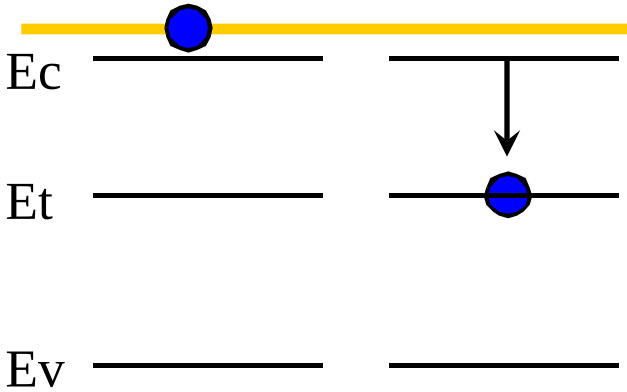
Note that this third order process (3 particles) follows the concentration squared (hence the unit of C as cm^6/second) whereas the second order process (2 particles) for band-to-band followed a the concentration linearly.
For our n-type case, we can further simplify this equation since $n_o >> p_o$,

$$\tau_{Auger}^{-1} = C_n[(n_o n_o + n_o \Delta n) + (\Delta n n_o + \Delta n \Delta n)]$$

$$\tau_{Auger}^{-1} = C_n(n_o + \Delta n)^2$$

$$\tau_{Auger}^{-1} = C_n n^2$$

SRH Electron Capture and Emission



Electron Capture

How many electrons are available for capture

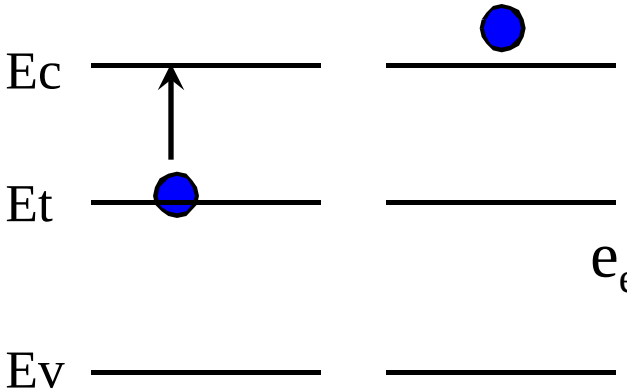
Number of empty defect sites

$$c_e = v_{th,e}\ \sigma_n\ n\ N_t\ (1-f(E))$$

Electron Capture Rate

Thermal velocity:How fast the electrons are moving

Capture cross section: Effective size of the defect. Units of area



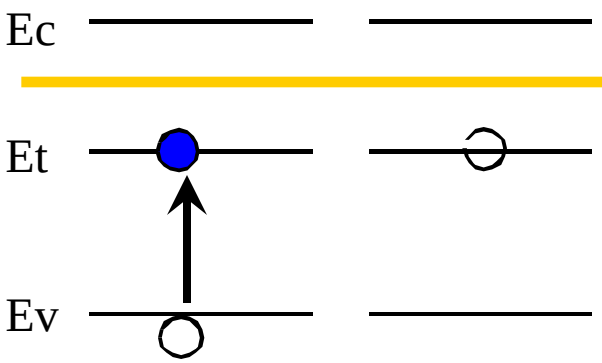
Electron Emission

Number of filled defect sites

$$e_e = e_n\ N_t\ f(E) \quad \text{where } e_n = v_{th,e}\ \sigma_n\ N_c\ e^{-(Ec-Et)/KT}$$

Electron Emission Rate

SRH Electron Capture and Emission



Hole Capture

How many holes are available for capture

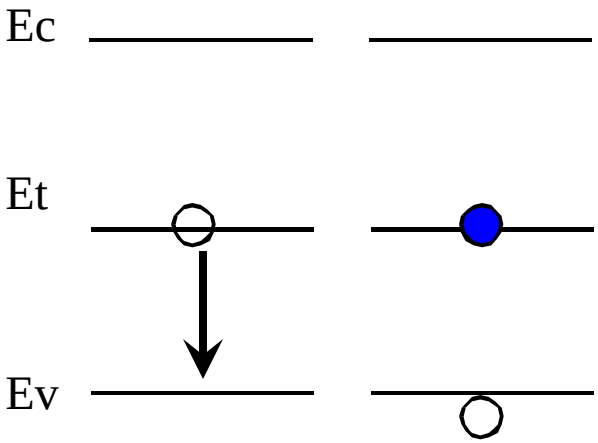
Number of filled defect sites

$$c_p = v_{th,p}\ \sigma_p\ p\ N_t\ f(E)$$

Hole Capture Rate

Thermal velocity:How fast the holes are moving

Capture cross section: Effective size of the defect. Units of area



Hole Emission

Number of empty defect sites

$$e_p = e_h\ N_t\ (1 - f(E))$$

where $e_h = v_{th,p}\ \sigma_p\ N_v\ e^{-(Et-Ev)/KT}$

Hole Emission Rate

SRH Electron Capture and Emission

Recombination:

electron capture / hole capture

hole capture / electron capture

Generation:

hole emission / electron emission

electron emission / hole emission

Recycling of carriers into bands:

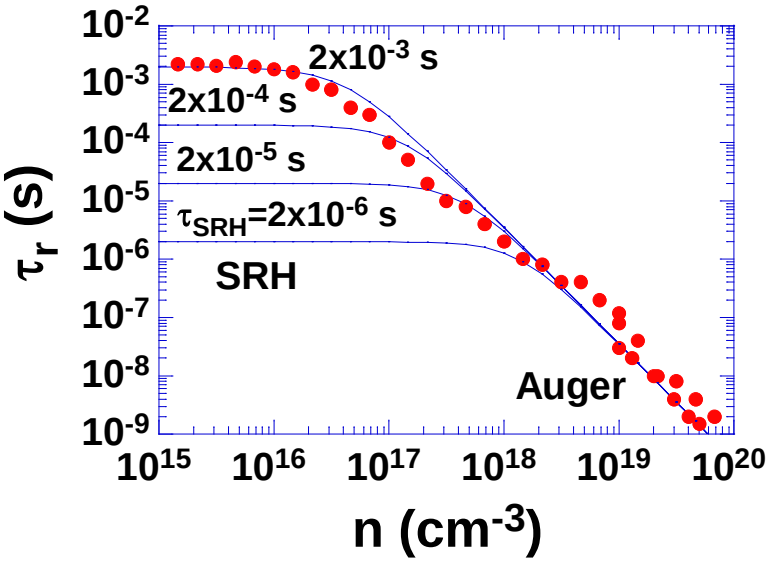
hole capture / hole emission

electron capture / electron emission

Recombination Lifetime

- The recombination lifetime is a combination of all three recombination processes

$$\tau_r = \frac{1}{\tau_{SRH}^{-1} + \tau_{rad}^{-1} + \tau_{Auger}^{-1}}$$



Electron and Hole Recombination at Surfaces

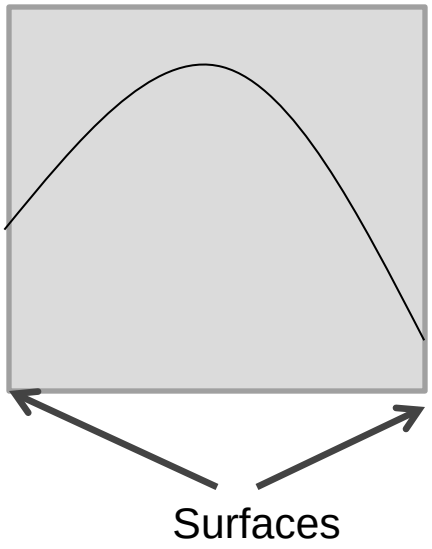
Surfaces (or interfaces) are considered “massive planar defects” due to the enormous numbers of broken bonds and thus large numbers of trap states.

Surfaces are characterized by a “Surface recombination velocity” which is the rate at which carriers are flowing toward that surface to recombine. Metals have large/infinite surface recombination velocities (s_e or s_h >1 million cm/Sec) where as well “passivated” surfaces may have s_e or s_h <100 cm/Sec.

Effect of Surfaces can be averaged with the effect of minority carrier lifetime by:

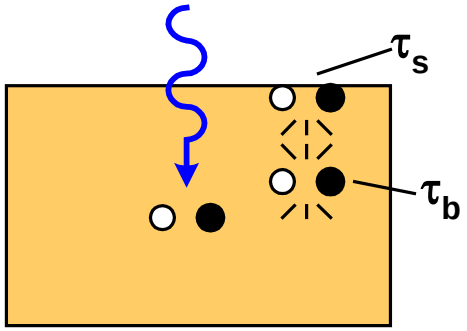
$$\frac{1}{\tau_{effective}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{Direct}} + \frac{1}{\tau_{Auger}} + \frac{2s}{d}$$

Minority Carrier profile under illumination due to high surface recombination velocities



Surface Recombination

- In addition to bulk recombination, there is also surface recombination which has a similar form as SRH for the bulk, *



$$R_s = \frac{\sigma_{ns}\sigma_{ps}v_{th}N_{it}\left(p_s n_s - n_i^2\right)}{\sigma_{ns}\left(n_s + n_{1s}\right) + \sigma_{ps}\left(p_s + p_{1s}\right)}$$

$$= \frac{s_n s_p\left(p_s n_s - n_i^2\right)}{s_n\left(n_s + n_{1s}\right) + s_p\left(p_s + p_{1s}\right)}$$

- The surface recombination rate, R_s, can be expressed as a surface recombination velocity,

$$s_r = \frac{R_s}{\Delta n_s} \qquad s_r = \frac{s_n s_p\left(p_{0s} + n_{0s} + \Delta n_s\right)}{s_n\left(n_{0s} + n_{1s} + \Delta n_s\right) + s_p\left(p_{0s} + p_{1s} + \Delta p_s\right)}$$

$$s_n = \sigma_{ns}v_{th}N_{it}; \quad s_p = \sigma_{ps}v_{th}N_{it}$$

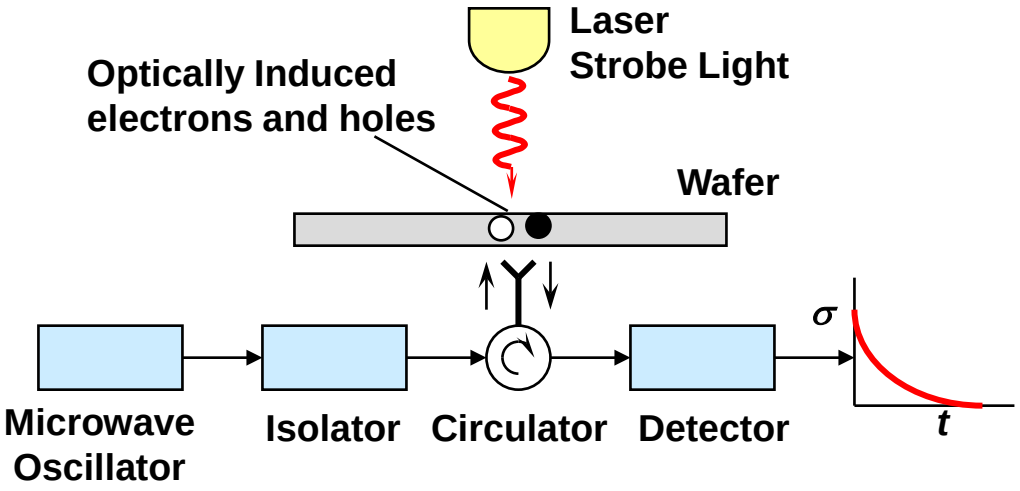
*See section 7.2 of text for derivation. Subscript “s” denotes quantity at the surface

Photoconductance Decay (PCD)

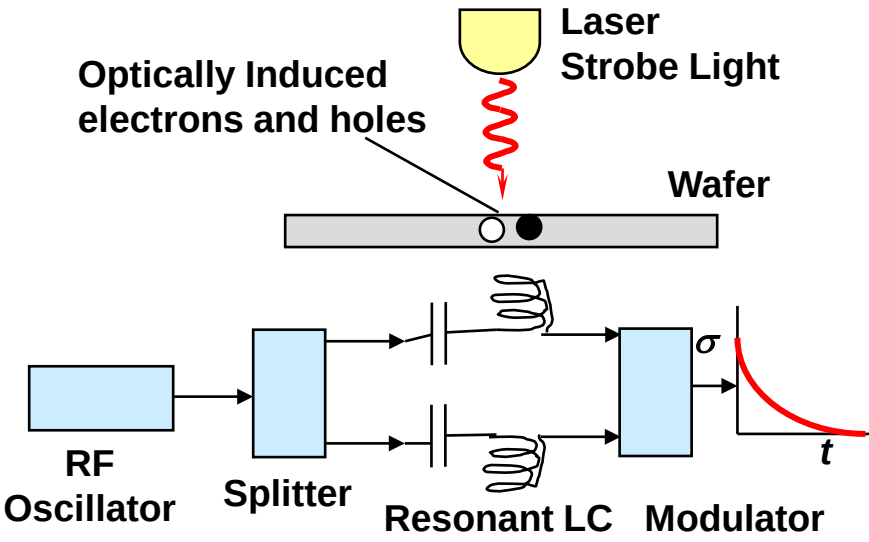
- Photoconductance decay is a common transient recombination lifetime measurement techniques
  - Laser pulses create electron-hole pairs (ehp)
  - The ehp change the conductivity
  - The time-varying conductivity is detected with microwaves (or RF)

$$\sigma = q(\mu_n n + \mu_p p)$$

Microwave Implementation

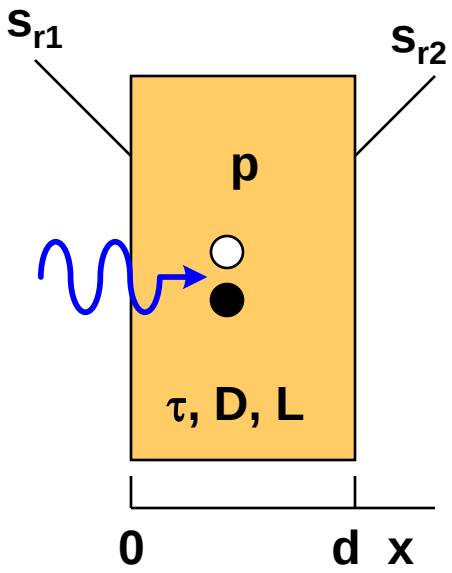


RF Bridge Implementation



Photoconductance Decay

- The analysis involves solutions of the minority carrier diffusion equation subject to boundary conditions on the two surfaces



$$\frac{\partial \Delta n(x,t)}{\partial t} = D\frac{\partial^2 \Delta n(x,t)}{\partial x^2} - \frac{\Delta n(x,t)}{\tau_B} + G(x,t)$$

$$\left.\frac{\partial \Delta n(x,t)}{\partial x}\right|_{x=0} = s_{r1}\frac{\Delta n(0,t)}{D}$$

$$\left.\frac{\partial \Delta n(x,t)}{\partial x}\right|_{x=d} = -s_{r2}\frac{\Delta n(d,t)}{D}$$

$$\Delta n(t) = \Delta n(0)\exp\left(\frac{-t}{\tau_{eff}}\right)$$

Photoconductance Decay

- **The effective lifetime is determined by bulk and surface recombination**

$$\Delta n(t) = \Delta n(0)\exp\left(\frac{-t}{\tau_{eff}}\right)$$

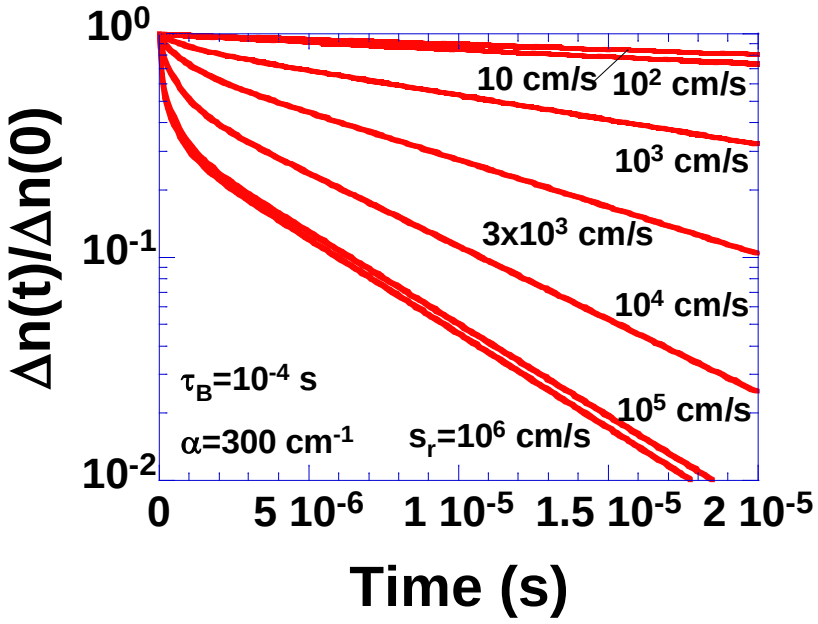
$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_B} + D\beta_1^2 \qquad \text{where } \tan\left(\frac{\beta_1 d}{2}\right) = \frac{2s_r}{\beta_1 D}$$

For low s_r:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_B} + \frac{2s_r}{d}$$

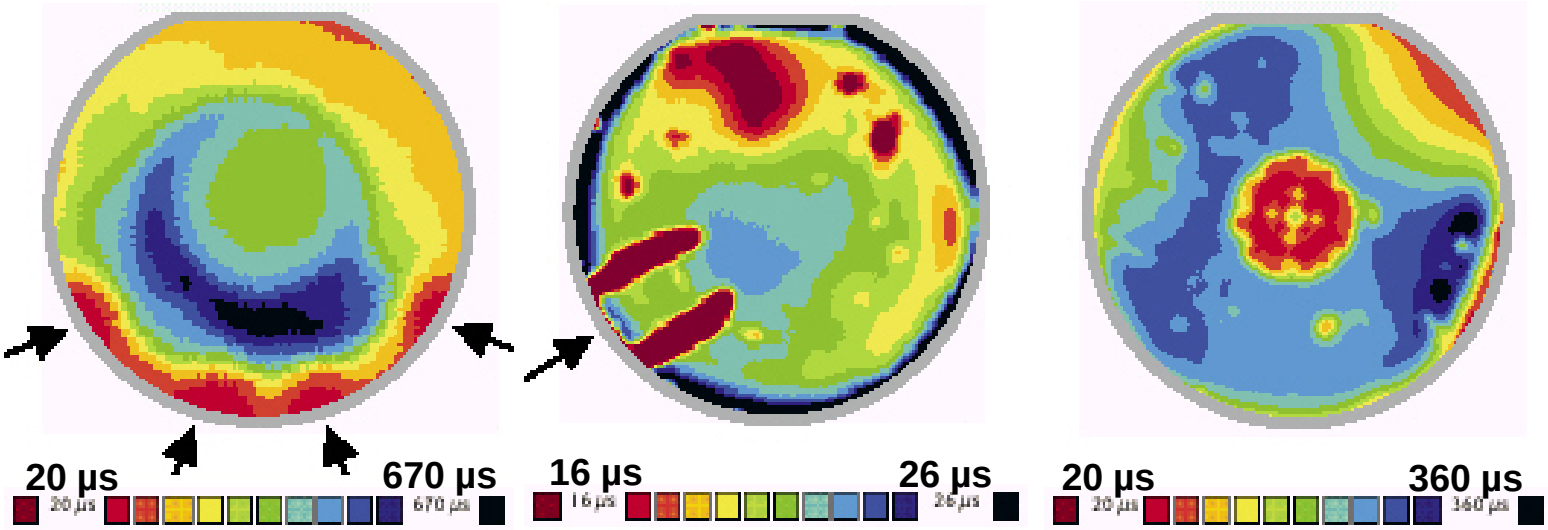
For high s_r:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_B} + \frac{\pi^2 D}{d^2}$$



Note: D is the MINORITY carrier diffusion constant for low level injection and the ambipolar diffusion constant for high level injection

Photoconductance Decay



Quartz Boat Touch ***Tweezers*** ***Vacuum Chuck***

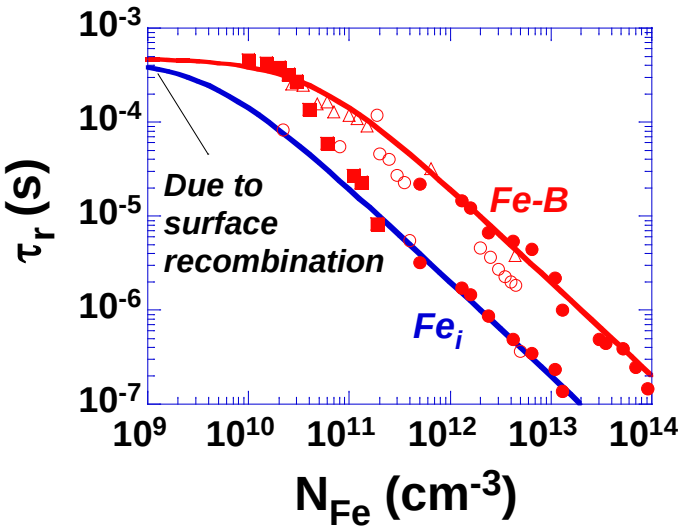
Images courtesy of Semilab

Iron in Silicon

- Iron in boron-doped p-type Si forms *iron-boron pairs*, Fe-B
- When heated to 200°C/ 5 min or illuminated with bright light, Fe-B $\Rightarrow$ interstitial iron, Fe_i, and substitutional boron, B_s
- $Fe_i \Rightarrow$ Fe-B at room temperature after ~ 24 hours
- The recombination properties of Fe-B differ from those of Fe_i
- Measuring the recombination lifetime before and after dissociation yields the iron density

$$N_{Fe}(cm^{-3}) = 2.8x10^{12}\left(\frac{1}{\tau_{r,after}} - \frac{1}{\tau_{r,before}}\right)$$

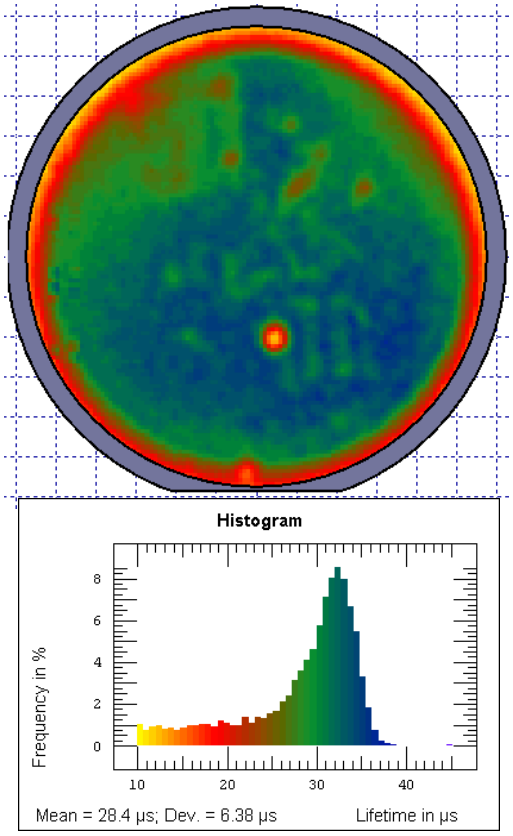
(τ in μs)



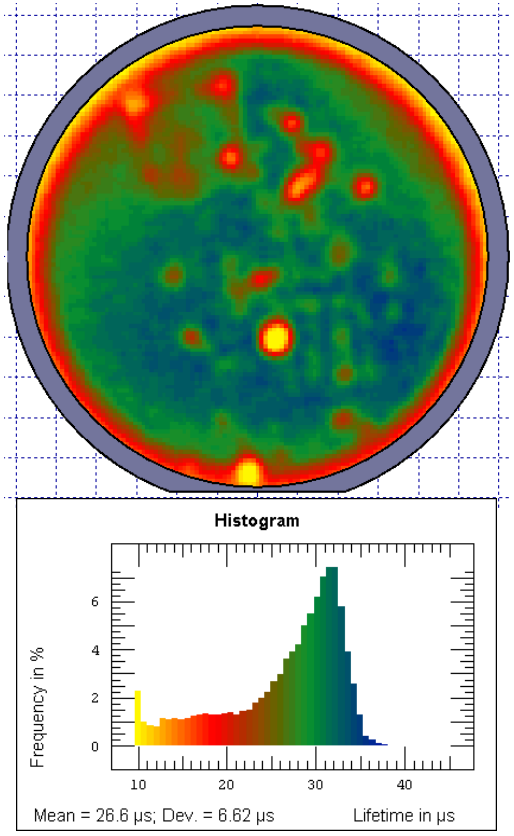
Iron in Silicon

Lifetime Maps

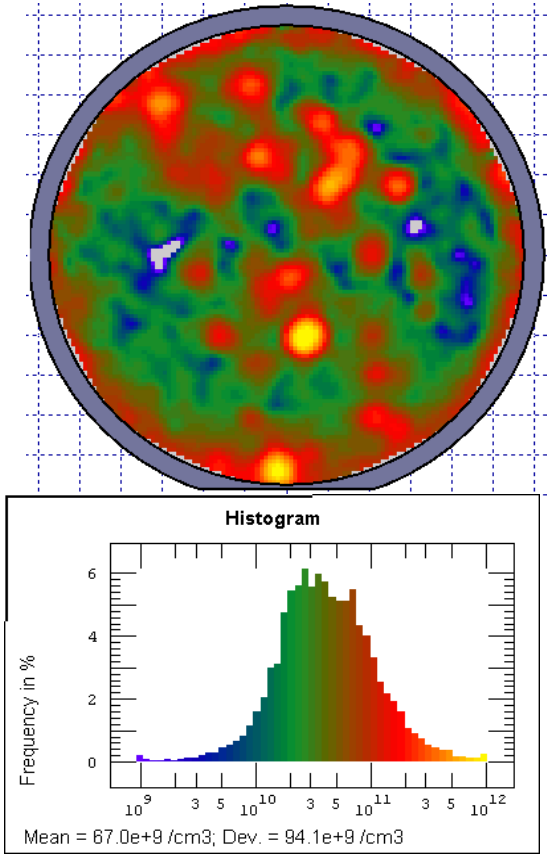
Before dissociation



After dissociation



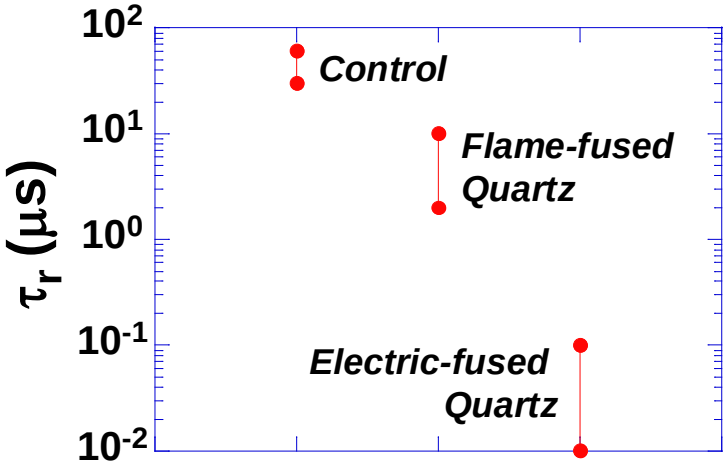
Fe Density



Images courtesy of U. Kumpf, AMECON GmbH

Quartz Tube Purity

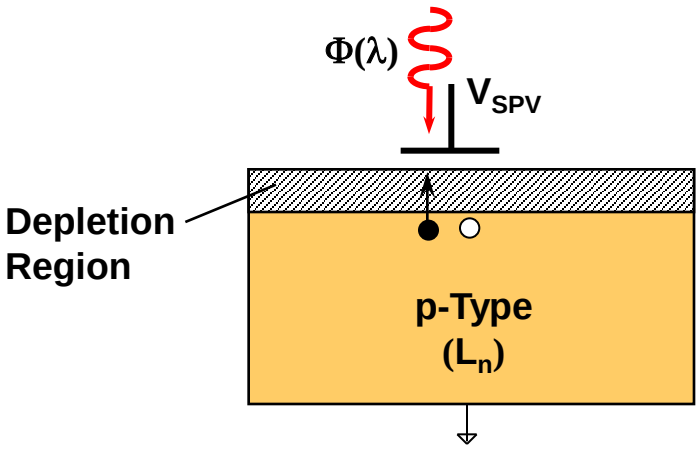
- Flame-fusion quartz, from crystalline quartz in hydrogen-oxygen flame
- Electric-fusion quartz, from electrically heated crucible melt

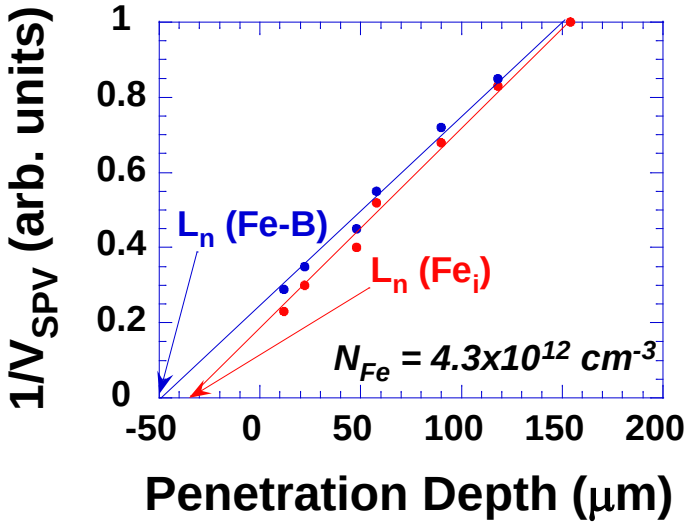


M. Hill, D. Hellmann and M. Rother, "Quartzglass Components and Heavy Metal Contamination," *Solid State Technol*. **37**, 49-52, March 1994.

Surface Photovoltage

- The sample is treated with a chemical to induce surface charge creating a depletion region at the surface.
- The sample is illuminated with light of wavelength λ and penetration depth $1/\alpha$
- λ is varied and hence $1/\alpha$ also changes
- Plot $1/V_{SPV}$ versus $1/\alpha$ at constant light Φ
- Diffusion length L_n is the intercept; $L_n = (D_n \tau_r)^{1/2}$
- Use intense light to change *Fe-B* into Fe_i and B_s



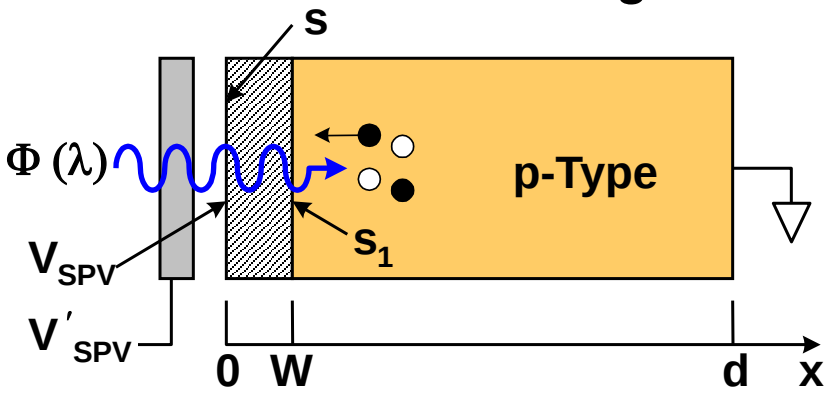


$$N_{Fe} = 1.05x10^{16}\left(\frac{1}{L^2_{n,final}} - \frac{1}{L^2_{n,initial}}\right) cm^{-3}$$

(L_n in microns)

Surface Photovoltage (SPV)

- **Surface photovoltage is a common steady-state minority carrier diffusion length measurement technique**



Light Intensity

Reflectance

Absorption coefficient

$$\Delta n(W) \approx \frac{(1-R)\Phi}{(s_1 + D_n/L_n)} \frac{\alpha L_n}{(1+\alpha L_n)}$$

Depletion edge surface recombination velocity

Diffusion Length

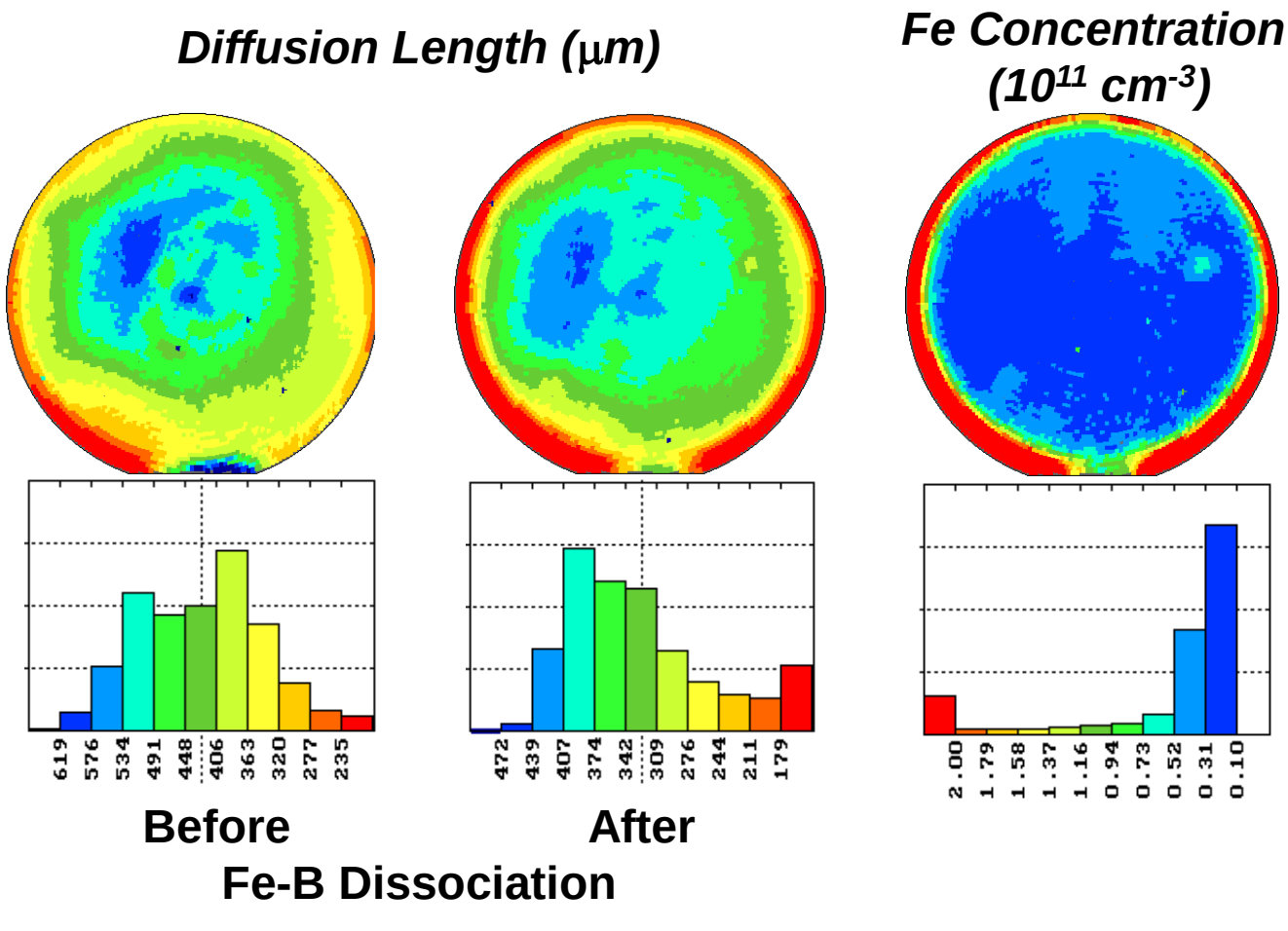
Law of the junction

$$\Delta n(W) = n_{p0}\left(\exp\left(\frac{qV_{SPV}}{kT}\right) - 1\right) \approx \frac{n_{p0} q V_{SPV}}{kT} \quad \text{for } V_{SPV} << \frac{kT}{q}$$

$$V_{SPV} = \frac{(kT/q)(1-R)\Phi L_n}{n_{p0}(s_1 + D_n/L_n)(L_n + 1/\alpha)}$$

$$\frac{1}{V_{SPV}} = \frac{n_{p0}(s_1 + D_n/L_n)(L_n + 1/\alpha)}{(kT/q)(1-R)\Phi L_n} = C_2\left(L_n + \frac{1}{\alpha}\right)$$

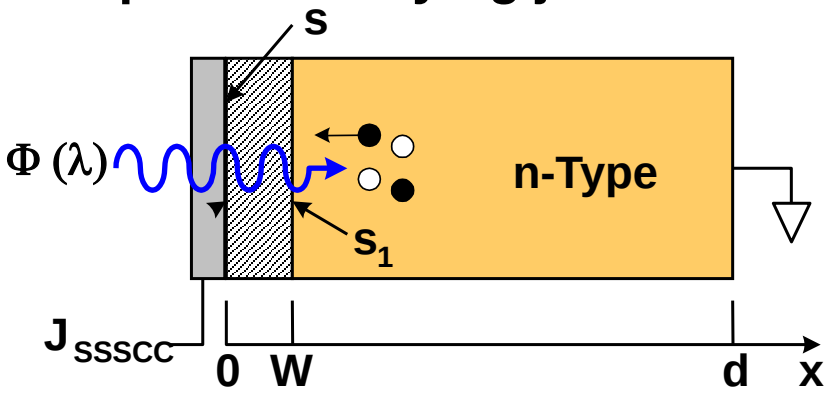
Iron in Silicon - SPV



Courtesy of P. Edelman and J. Lagowski, Semiconductor Diagnostics, Inc.

Steady State Short-Circuit Current (SSSCC)

- Requires either a p-n, Schottky, electrolyte or mercury probe rectifying junction



Light Intensity

Reflectance

$$J_{SSSCC} \approx q(1-R)\Phi\left(\frac{L_n}{L_n + 1/\alpha} + \frac{L_p}{L_p + 1/\alpha}\right)$$

Absorption coefficient

Diffusion Length in p-side (2nd can be neglected if heavily doped or if not existent).

- L_n can be extracted from plots similar to that for SPV provided one varies the intensity to maintain a constant J_{ssscc}
- Current is easier to measure but requires a junction

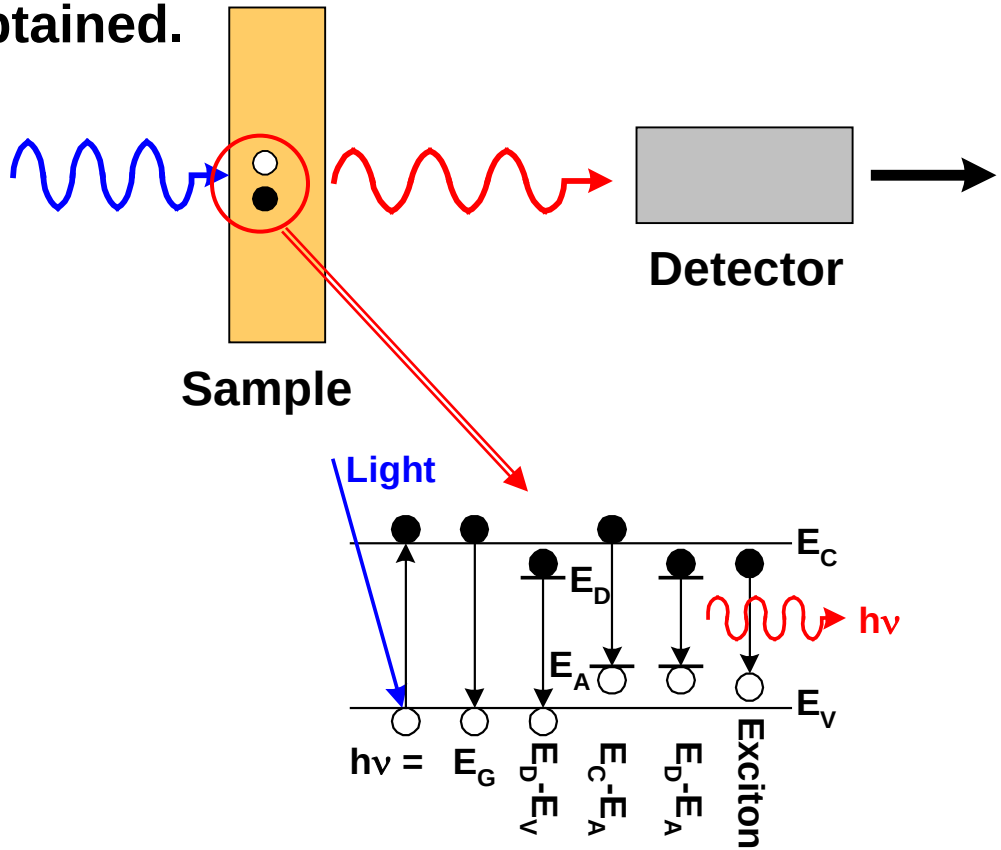
Luminescence

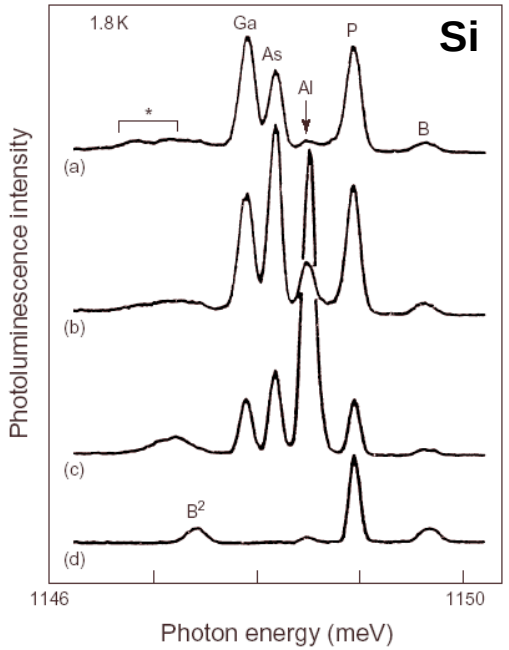
Luminescence is the emission of light due to:

- **Incandescence: energy supplied by heat**
- **Photoluminescence: energy supplied by light**
- **Fluorescence: energy supplied by ultraviolet light**
- **Chemiluminescence: energy supplied by chemical reactions**
- **Bioluminescence: energy supplied by chemical reactions in living beings**
- **Electroluminescence: energy supplied by electric current/voltage**
- **Cathodoluminescence: energy supplied by electron beams.**
- **Radioluminescence: energy supplied by nuclear radiation**
- **Phosphorescence: delayed luminescence or "afterglow"**
- **Triboluminescence: energy supplied by mechanical action**
- **Thermoluminescence: energy supplied by heat**

Photoluminescence

- Incident laser creates electron-hole pairs (ehp)
- When the ehp recombine, they emit light
- Quantification is difficult (due to light intensity, reflection and absorption differences) unless an intrinsic spectral line can be obtained.

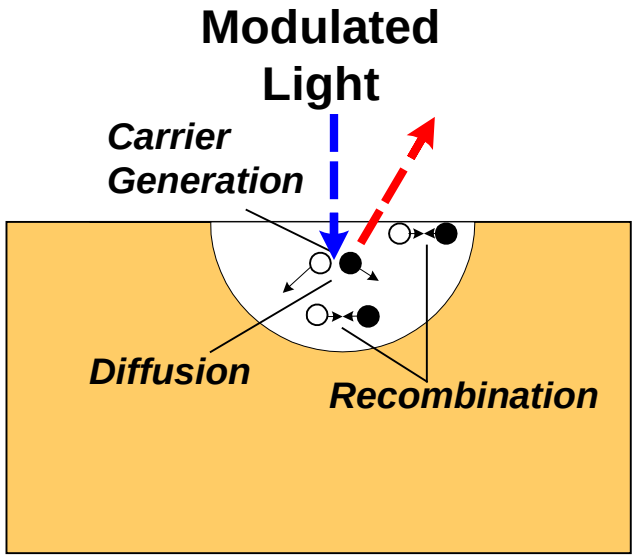




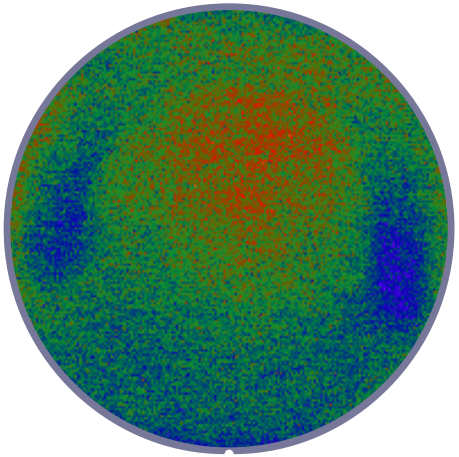
How Does PL Work And How Can It Be Used?

- Carrier generation depth
  - Wavelength ⇒ depth information
- Recombination
  - Shockley-Read-Hall (impurities) ⇒ impurity information
  - Auger (high carrier densities) ⇒ doping density information
  - Surface (surface states, impurities) ⇒ surface information
  - Radiative (light emission) ⇒ detection mechanism

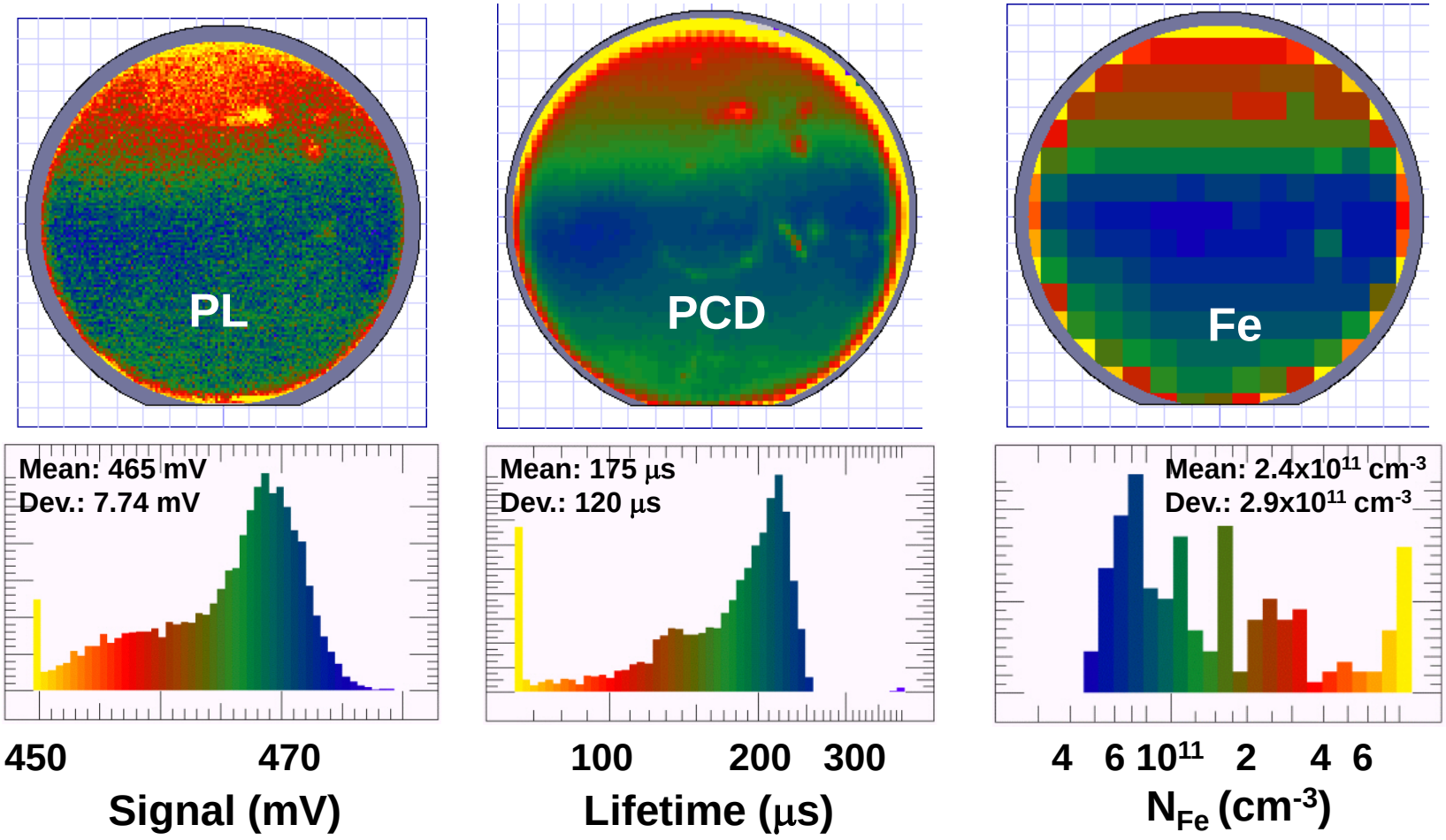
This is what we want!



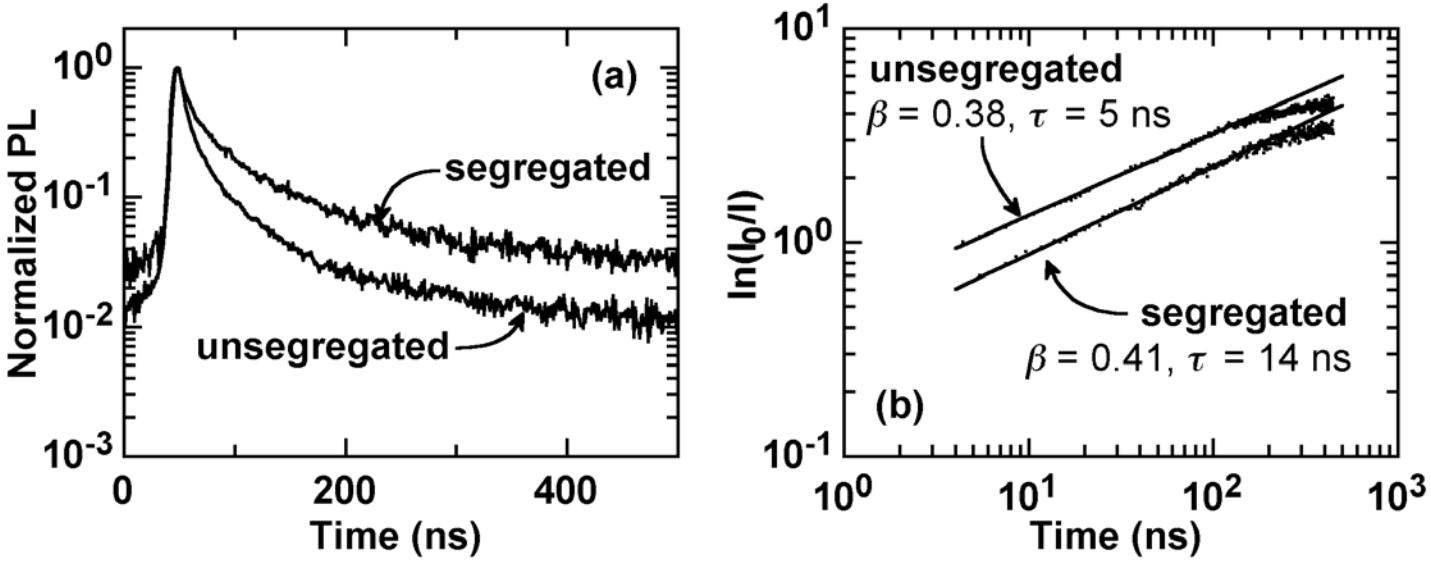
Depth Dependent PL Signals



Iron In Si by PL And PCD



Time Resolved PL



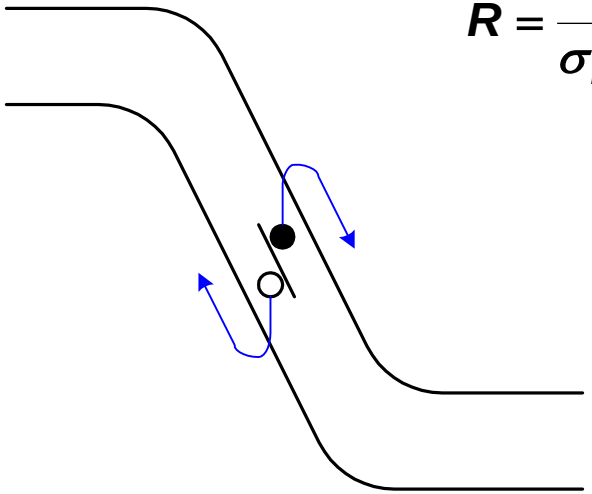
- **Signal at a constant wavelength is monitored as a function of time after an excitation light pulse is applied**
- **Wavelength (depth) and time information can both be obtained**

M.C. Cheung, G. Namkoong, F. Chen, M. Furis, H. E. Pudavar, A. N. Cartwright, and W. A. Doolittle, "Photoluminescence Study of MBE Grown InGaN with Intentional Indium Segregation," Phys. Stat. Sol. (c) Vol. 2, No. 7 , pp. 2779-2782, 2005.

Generation

- **Under reverse bias, generation dominates over recombination**

Bulk



$$R = \frac{\sigma_n \sigma_p v_{th} N_T \left(pn - n_i^2\right)}{\sigma_n \left(n + n_1\right) + \sigma_p \left(p + p_1\right)} = \frac{\left(pn - n_i^2\right)}{\tau_p \left(n + n_1\right) + \tau_n \left(p + p_1\right)}$$

$$G = -R = \frac{n_i^2}{\tau_p n_1 + \tau_n p_1} = \frac{n_i}{\tau_g}$$

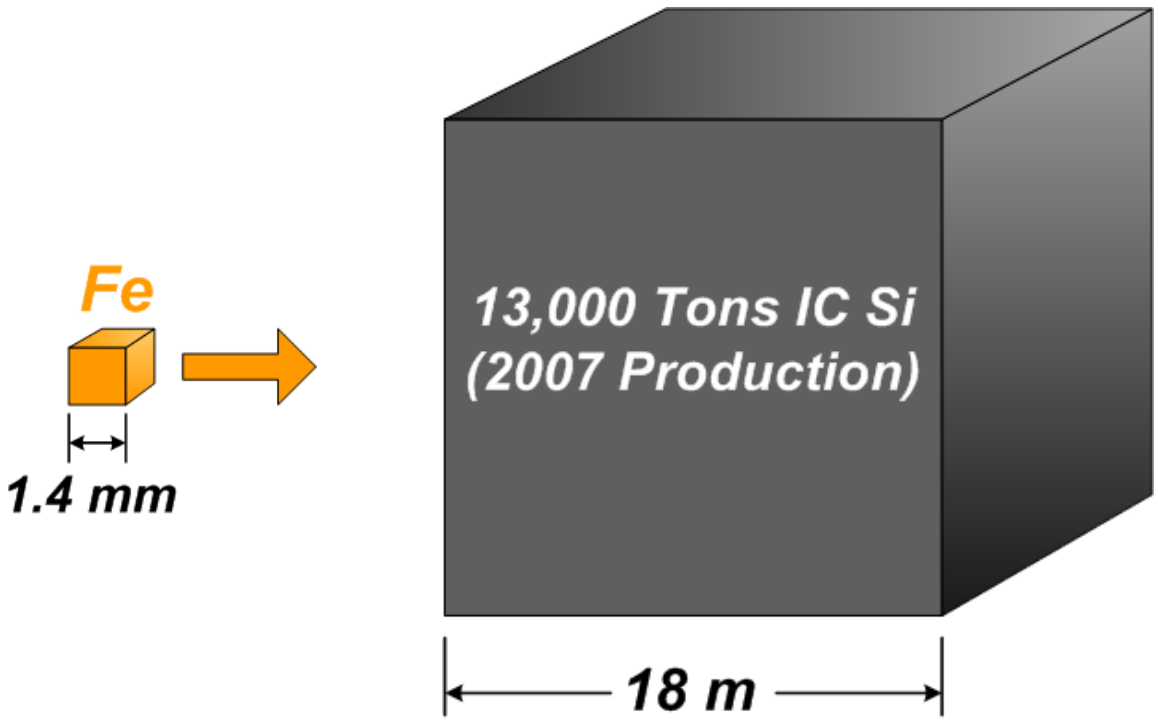
$$\tau_g = \tau_p \exp\left(\frac{\left(E_T - E_i\right)}{kT}\right) + \tau_n \exp\left(\frac{-\left(E_T - E_i\right)}{kT}\right)$$

Surface

$$G_S = -R_S = \frac{s_n s_p n_i^2}{s_p n_{1s} + s_n p_{1s}} = s_g n_i$$

Silicon Purity

- How much iron is required to contaminate the world's Si supply to $5x10^{10}$ cm^{-3}



Review Questions

- Name and explain the three bulk and one surface recombination mechanisms
- What is the difference between *recombination* and *generation* lifetimes?
- How does *photoconductance decay* work?
- How does *surface photovoltage* work?
- What is special about iron in p-Si?
- How does *surface recombination* affect the effective recombination lifetime?
- What can be obtained from a Photolumenescence measurement?