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
Light with photon energy, $h\nu < E_g$ is not easily absorbed. A convenient expression for the energy of light is $E = 1.24/\lambda$ where $\lambda$ is the wavelength of the light in um.

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

where $I_o$ is the initial light intensity, $x$ is distance and $\alpha$ is the absorption coefficient [1/cm].
The absorption depth is given by the inverse of the absorption coefficient, or $\alpha^{-1}$. 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/m² nm⁻¹

Wavelength nm

Absorption depth (cm)

absorption wavelength (nm)

GaAs
Ge
Si
InP
CdTe
CdS
aSi

ECE 4813 Dr. Alan Doolittle
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.
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!
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.

Electric field resonates (fields are additive) with the atomic dipole and thus is absorbed strongly!

Magnitude of Electric Field of a Photon of light
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.

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.

Magnitude of Electric Field of a Photon of light
3 Recombination and 3 Generation Mechanisms...

(a) Band-to-band recombination

(b) R–G center recombination

(c) Auger recombination

(d) Band-to-band generation

(e) R–G center generation

(f) Carrier generation via impact ionization
Recombination and Generation Mechanisms

“Deep State” Impurities

$E_c$

$E_v$

Au Cu Mn Cr Fe

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.
Recombination Mechanisms

- 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…

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

- 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.

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).
• Auger – “pronounced O-jay” recombination.
• Requires 3 particles.
• Two steps: 1.) 1\textsuperscript{st} carrier and 2\textsuperscript{nd} carrier of same type collide instantly annihilating the electron hole pair (1\textsuperscript{st} and 3\textsuperscript{rd} carrier). The energy lost in the annihilation process is given to the 2\textsuperscript{nd} carrier. 2.) 2\textsuperscript{nd} 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.
• 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…
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!
• 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 its 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 $E_g$ can result in one electron hole pair. Thus, we can say,

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

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

If $\alpha$ is large (light with energy $>>$ bandgap), the generation profile can be approximated as at the surface.
Important Nomenclature

\[ n_0, p_0 \quad \text{... \ carrier concentrations in the material under analysis when equilibrium conditions prevail.} \]

\[ n, p \quad \text{... \ carrier concentrations in the material under arbitrary conditions.} \]

\[ \Delta n \equiv n - n_0 \quad \text{... \ deviations in the carrier concentrations from their equilibrium values.} \]
\[ \Delta p \equiv p - p_0 \quad \text{... \ \Delta n \ and \ \Delta p \ can \ be \ both \ positive \ and \ negative, \ where \ a \ positive \ deviation \ corresponds \ to \ a \ carrier \ excess \ and \ a \ negative \ deviation \ corresponds \ to \ a \ carrier \ deficit.} \]

\[ N_T \quad \text{... \ number of R-G centers/cm}^3. \]

\[ n = \Delta n + n_0 \text{ and } p = \Delta p + p_0 \]

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

Low Level Injection

\[ \Delta p = \Delta n \ll n_0 \text{ and } n \sim n_0 \text{ in n-type material} \]
\[ \Delta p = \Delta n \ll p_0 \text{ and } p \sim p_0 \text{ in p-type material} \]
Carrier Concentrations after a “Perturbation”

Steady State if perturbation has been applied for a long time

Non-Steady State, Nonequilibrium

Equilibrium

$\Delta p(t=0) > p_o$ or $\Delta p(t=0) < p_o$

$t = 0$

$\Delta p(t) > p_o$

$t > 0$

$\Delta p = 0$

$t \rightarrow \infty$

$n \approx n_0$

$E_c$

$E_F$

$E_T$

$E_v$

$\Delta p$ 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., \( p_n \) does NOT equal \( n_i^2 \)

\[
\frac{\partial p}{\partial t} \bigg|_{\text{thermal}} \quad R - G = -\frac{\Delta p}{\tau_p}
\]

where \( \tau_p \) is the minority carrier lifetime

\( c_p \) is a proportionality constant

\( N_T \) 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 \( \Delta p \) is negative \( \rightarrow \) Generation or an increase in carriers with time.

• If \( \Delta p \) is positive \( \rightarrow \) 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.
Likewise when the electron concentration in an p-type sample is not in equilibrium, i.e., $p_n$ does NOT equal $n_i^2$

$$\frac{\partial n}{\partial t} \bigg|_{thermal}^{R-G} = -\frac{\Delta n}{\tau_n}$$

where $\tau_n = \frac{1}{c_n N_T}$

where $\tau_n$ 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:

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

where...

$$n_1 \equiv n_i e^{(E_T - E_i)/kT} \quad \text{and} \quad p_1 \equiv n_i e^{(E_i - E_T)/kT}$$
Example: After a long time on, a light is switched off

\[ \frac{\partial n}{\partial t} = -\frac{\Delta n}{\tau_n} \]

has a solution

\[ n(t) = n_o + \Delta n_o e^{-\left(\frac{t}{\tau_n}\right)} \]

where \( \Delta n_o = \text{initial excess electron concentration} \)
Carrier Relaxation can also be achieved through Direct recombination

Given: \( \Delta n = \Delta p, \quad n = n_0 + \Delta n, \quad p = p_0 + \Delta p \)

Low Level Injection \( \Rightarrow \) \( \Delta n \ll N_a \) and High Level Injection \( \Rightarrow \) \( \Delta n \gg N_a \)

- 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, \( -\frac{dn}{dt} = R - G = B(np - n_i^2) \)

but,

\[ \Delta n = \Delta p \]

\[ -\frac{dn}{dt} = B(np - n_i^2) \]

\[ = B((n_0 + \Delta n)(p_0 + \Delta p) - n_i^2) \]

\[ = B(n_0p_0 - n_i^2 + \Delta np_0 + \Delta n p_0 + \Delta n \Delta p) \]

\[ = B\Delta n(0 + n_0 + p_0 + \Delta n) \]

\[ = B\Delta n(n_0 + p_0 + \Delta n) \]

Thus, using our lifetime definition,

\[ -\frac{dn}{dt} = -\frac{\Delta n}{\tau_{\text{direct}}} \]

\[ \tau_{\text{direct}} = \frac{1}{B(n_0 + p_0 + \Delta n)} \]
Material Response to “Non-Equilibrium”: Relaxation Concept

Carrier Relaxation can also be achieved through Direct recombination

Special cases:

Low Level Injection: $\Delta n \ll$ majority carrier density
$$\tau_{\text{direct}} = \frac{1}{B(n_o + p_o)}$$
and if the material is n-type:
$$\tau_{\text{direct}} = \frac{1}{Bn_o}$$
or p-type:
$$\tau_{\text{direct}} = \frac{1}{Bp_o}$$

High level injection: $\Delta n \gg$ majority carrier density
$$\tau_{\text{direct}} = \frac{1}{B\Delta n}$$
Carrier Relaxation can also be achieved through “Auger” recombination

Derive the equation for the lifetime, $\tau_{\text{Auger}}$, 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:

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

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 $p \sim n$) 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).

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

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

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

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

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

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

Thus, by definition:

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

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

But for our assumed n-type material:

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

Note that this third order process (3 particles) follows the concentration squared (hence the unit of \( C \) as \( \text{cm}^6/\text{second} \)) 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 \( n_o \gg p_o \).

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

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

\[ \tau_{Auger}^{-1} = C_n n^2 \]
SRH Electron Capture and Emission

Electron Capture Rate

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

- \( c_e \): Capture rate
- \( v_{th,e} \): Thermal velocity
- \( \sigma_n \): Capture cross section
- \( n \): Number of electrons available for capture
- \( N_t \): Number of empty defect sites
- \( f(E) \): Fraction of the Fermi level

Electron Emission Rate

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

- \( e_e \): Emission rate
- \( e_n \): Number of filled defect sites
- \( N_c \): Number of empty defect sites
- \( N_t \): Number of filled defect sites
- \( f(E) \): Fraction of the Fermi level
- \( Ec \): Capture energy level
- \( Et \): Emission energy level
- \( Ev \): Fermi energy level
SRH Electron Capture and Emission

Hole Capture Rate

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

- **Capture cross section**: Effective size of the defect. Units of area.
- **Thermal velocity**: How fast the holes are moving.
- **Number of filled defect sites**
- **How many holes are available for capture**

Hole Emission Rate

\[ e_p = e_h N_t (1 - f(E)) \]

- **Number of empty defect sites**

**Equation**:

Where \( e_h = v_{th,p} \sigma_p N_v e^{-(E_t - E_v)/K_T} \)

**Diagram Notes**:
- **Ec**, **Et**, and **Ev** represent energy levels.
- **Hole Capture** and **Hole Emission** processes are illustrated.
- The diagram visually explains the concepts of capture and emission rates.
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

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

![Graph showing recombination lifetime versus carrier density with values for different recombination processes]
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:

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

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

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

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

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

\[
s_r = \frac{R_s}{\Delta n_s}
\]

\[
s_r = \frac{s_n s_p (p_{0s} + n_{0s} + \Delta n_s)}{s_n(n_{0s} + n_{1s} + \Delta n_s) + s_p(p_{0s} + p_{1s} + \Delta p_s)}
\]

\[
\sigma_{ns}v_{th}N_{it} ; \quad s_p = \sigma_{ps}v_{th}N_{it}
\]

*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 technique.
  - 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**

- Optically Induced electrons and holes
- Laser Strobe Light
- Wafer
- Microwave Oscillator
- Isolator
- Circulator
- Detector
- \( \sigma \)
- \( t \)

**RF Bridge Implementation**

- Optically Induced electrons and holes
- Laser Strobe Light
- Wafer
- RF Oscillator
- Splitter
- Resonant LC Modulator
- \( \sigma \)
- \( t \)
Photoconductance Decay

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

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

\[
\frac{\partial \Delta n(x,t)}{\partial x} \bigg|_{x=0} = s_{r1} \frac{\Delta n(0,t)}{D}
\]

\[
\frac{\partial \Delta n(x,t)}{\partial x} \bigg|_{x=d} = -s_{r2} \frac{\Delta n(d,t)}{D}
\]

\[
\Delta n(t) = \Delta n(0) \exp \left( -\frac{t}{\tau_{\text{eff}}} \right)
\]
Photoconductance Decay

- The effective lifetime is determined by bulk and surface recombination

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

\[
\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_B} + D\beta_1^2 \]

where \( \tan \left( \frac{\beta_1 d}{2} \right) = \frac{2s_r}{\beta_1 D} \)

**For low** \( s_r \):

\[
\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_B} + \frac{2s_r}{d} \]

**For high** \( s_r \):

\[
\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_B} + \frac{\pi^2 D}{d^2} \]

Note: \( D \) is the MINORITY carrier diffusion constant for low level injection and the ambipolar diffusion constant for high level injection.
Photoconductance Decay

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 → interstitial iron, Fe_i, and substitutional boron, B_s
- Fe_i → 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

\[
N_{Fe} (cm^{-3}) = 2.8 \times 10^{12} \left( \frac{1}{\tau_{r,after}} - \frac{1}{\tau_{r,before}} \right)
\]

(\(\tau\) in \(\mu s\))

\(\tau_r (s)\)

\(N_{Fe} (cm^{-3})\)

Due to surface recombination

Fe-B

Fe_i
Iron in Silicon

Lifetime Maps

Before dissociation

After dissociation

Fe Density

Histogram

Images courtesy of U. Kumpf, AMECO GmbH
Quartz Tube Purity

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

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 $\lambda$ and penetration depth $1/\alpha$.

$\lambda$ is varied and hence $1/\alpha$ also changes.

Plot $1/V_{SPV}$ versus $1/\alpha$ at constant light $\Phi$.

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 $B_s$.

$$N_{Fe} = 1.05 \times 10^{16} \left( \frac{1}{L_{n,final}^2} - \frac{1}{L_{n,initial}^2} \right) \text{cm}^{-3}$$

($L_n$ in microns)
Surface Photovoltage (SPV)

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

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

Law of the junction

\[ \Delta n(W) = n_p \left( \exp\left( \frac{qV_{SPV}}{kT} \right) - 1 \right) \approx \frac{n_p q V_{SPV}}{kT} \quad \text{for} \quad V_{SPV} \ll \frac{kT}{q} \]

\[ V_{SPV} = \frac{(kT/q)(1 - R)\Phi L_n}{n_p (s_1 + D_n/L_n)(L_n + 1/\alpha)} \]

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

Law of the junction

Reflectance

Absorption coefficient

Depletion edge surface recombination velocity

Diffusion Length

Light Intensity
Iron in Silicon - SPV

Diffusion Length (µm)

Fe Concentration
($10^{11}$ cm$^{-3}$)

Before
Fe-B Dissociation

After

Courtesy of P. Edelman and J. Lagowski, Semiconductor Diagnostics, Inc.
Steady State Short-Circuit Current (SSSxCC)

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

\[ J_{SSSxCC} \approx q(1-R)\Phi \left( \frac{L_n}{L_n + \frac{1}{\alpha}} + \frac{L_p}{L_p + \frac{1}{\alpha}} \right) \]

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

\[ h\nu = E_D - E_A \]

\[ h\nu = E_C - E_A \]

\[ h\nu = E_C - E_V \]

\[ h\nu = E_G \]
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

**PL**
- Mean: 465 mV
- Dev.: 7.74 mV

**PCD**
- Mean: 175 µs
- Dev.: 120 µs

**Fe**
- Mean: $2.4 \times 10^{11}$ cm$^{-3}$
- Dev.: $2.9 \times 10^{11}$ cm$^{-3}$

Signal (mV):
- 450
- 470

Lifetime (µs):
- 100
- 200
- 300

$N_{Fe}$ (cm$^{-3}$):
- 4
- 6
- $10^{11}$
- 2
- 4
- 6
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.
Under reverse bias, generation dominates over recombination

**Bulk**

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

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

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

**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 $5 \times 10^{10}$ cm$^{-3}$

13,000 Tons IC Si (2007 Production)
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 Photoluminescence measurement?