Lecture 4 - Carrier generation and recombination

February 12, 2007

Contents:

1. G&R mechanisms
2. Thermal equilibrium: principle of detailed balance
3. G&R rates in thermal equilibrium
4. G&R rates outside thermal equilibrium

Reading assignment:

del Alamo, Ch 3. §§3.1-3.4
Key questions

- What are the physical mechanisms that result in the generation and recombination of electrons and holes?
- Which one of these are most relevant for Si at around temperature?
- What are the key dependencies of the most important mechanisms?
- If there are several simultaneous but independent mechanisms for generation and recombination, how exactly does one define thermal equilibrium?
- What happens to the balance between generation and recombination when carrier concentrations are perturbed from thermal equilibrium values?
1. Generation and recombination mechanisms

a) *Band-to-band G&R*, by means of:

- phonons (thermal G&R)
- photons (optical G&R)

\[ E_c \gg E_g \]

- thermal G&R: very unlikely in Si, need too many phonons simultaneously (about 20)
- optical G&R: unlikely in Si, “indirect” bandgap material, need a phonon to conserve momentum
b) *Auger generation and recombination*, involving a third carrier

- Auger generation: energy provided by "hot" carrier
- Auger recombination: energy given to third carrier; needs lots of carriers; important only in heavily-doped semiconductors
c) Trap-assisted generation and recombination, relying on electronic states in middle of gap ("deep levels" or "traps") that arise from:

- crystalline defects
- impurities

\[ 
\begin{array}{c}
E_c \\
E_t \\
E_v \\
\end{array} \\
\begin{array}{c}
\bullet \\
\circ \\
\circ \\
\end{array} \\
\begin{array}{c}
\text{trap-assisted} \\
\text{thermal generation} \\
\text{trap-assisted} \\
\text{thermal recombination} \\
\end{array} \\
\]

Trap-assisted G/R is:

- dominant in Si
- engineerable: can introduce deep levels to Si to enhance it
d) **Other generation mechanisms**

- **Impact ionization**: Auger generation event triggered by electric-field-heated carrier

- **Zener tunneling or field ionization**: direct tunneling of electron from VB to CB in presence of strong electric field

\[ E_C \quad \rightarrow \quad E_V \]

impact ionization

\[ E_C \quad \rightarrow \quad E_V \]

Zener tunneling

- **Energetic particles**, such as $\alpha$-particles (bad for DRAMs)

- **Energetic electrons** incident from outside: electron microscope characterization techniques
2. Thermal equilibrium: principle of detailed balance

Define:

\[ G_i \equiv \text{generation rate by process } i \ [cm^{-3} \cdot s^{-1}] \]
\[ R_i \equiv \text{recombination rate by process } i \ [cm^{-3} \cdot s^{-1}] \]
\[ G \equiv \text{total generation rate} \ [cm^{-3} \cdot s^{-1}] \]
\[ R \equiv \text{total recombination rate} \ [cm^{-3} \cdot s^{-1}] \]

In thermal equilibrium:

\[ R_o = \Sigma R_{oi} = G_o = \Sigma G_{oi} \]

Actually, *detailed balance* is also required:

\[ R_{oi} = G_{oi} \quad \text{for all } i \]

*In the presence of several paths for } G \text{ & } R, \text{ each has to balance out in detail} \text{ [Principle of Detailed Balance]}. 

[see example in notes illustrating impossibility of TE whithout detailed balance]
3. G\&R rates in thermal equilibrium

a) Band-to-band G\&R

- Will not consider thermal G\&R as it is negligible.
- Optical G\&R

At finite $T$, semiconductor is immersed in "bath" of blackbody radiation $\Rightarrow$ optical generation.

Only a small number of bonds are broken at any one time $\Rightarrow G$ depends only on $T$:

$$G_{o,rad} = g_{rad}(T)$$

A recombination process demands one electron and one hole $\Rightarrow R$ depends of $n_o p_o$:

$$R_{o,rad} = r_{rad}(T) \ n_o p_o$$

In TE, detailed balance implies:

$$g_{rad} = r_{rad} n_o p_o = r_{rad} n_i^2$$
b) *Auger G&R*

- **Involving hot electrons:**

The more electrons there are, the more likely it is to have hot ones capable of Auger generation:

$$G_{o,eeh} = g_{eeh}(T)n_o$$

A recombination event demands *two* electrons and *one* hole:

$$R_{o,ehh} = r_{ehr}n_o^2p_0$$

In TE, detailed balance implies:

$$g_{eeh} = r_{ehr}n_0p_0$$

- **Involving hot holes:** similar but substitute $n_o$ for $p_o$ and $eeh$ by $ehh$ above.
c) *Trap-assisted thermal G\&R:* Shockley-Read-Hall model

Consider a trap at $E_t = E_i$ in concentration $N_t$.

Trap occupation probability:

$$f(E_t) = f(E_i) = \frac{1}{1 + \exp \frac{E_i - E_F}{kT}} = \frac{n_i}{n_i + p_o}$$

Concentration of traps occupied by an electron:

$$n_{to} = N_t f(E_i) = N_t \frac{n_i}{n_i + p_o}$$

Concentration of empty traps:

$$N_t - n_{to} = N_t - N_t \frac{n_i}{n_i + p_o} = N_t \frac{p_o}{n_i + p_o}$$

Trap occupation depends on doping:

- **n-type:** $p_o \ll n_i \rightarrow n_{to} \approx N_t$, most traps are full
- **p-type:** $p_o \gg n_i \rightarrow n_{to} \ll N_t$, most traps are empty

![Energy levels](image)

$n$-type

$p$-type
Four basic processes:

\[ \begin{align*}
&\text{electron capture} \\
&\text{electron emission} \\
&\text{hole capture} \\
&\text{hole emission}
\end{align*} \]

Rates of four subprocesses in TE:

- **electron capture:**
  \[ r_{o,ec} = c_e n_o (N_t - n_{to}) \]

- **electron emission:**
  \[ r_{o,ee} = e_e n_{to} \]

- **hole capture:**
  \[ r_{o,hc} = c_h p_o n_{to} \]

- **hole emission:**
  \[ r_{o,he} = e_h (N_t - n_{to}) \]
In thermal equilibrium, detailed balance demands:

\[ r_{o,ec} = r_{o,ee} \]

\[ r_{o,hc} = r_{o,he} \]

Then, relationships that tie up capture and emission coefficients:

\[ e_e = c_e n_o \frac{N_t - n_{to}}{n_{to}} = c_e n_i \]

\[ e_h = c_h p_o \frac{n_{to}}{N_t - n_{to}} = c_h n_i \]

Capture coefficients can be calculated from first principles, but most commonly they are measured.

Also define:

\[ \tau_{eo} = \frac{1}{N_t c_e} \]

\[ \tau_{ho} = \frac{1}{N_t c_h} \]

\( \tau_{eo} \) and \( \tau_{ho} \) are characteristic of the nature of the trap and its concentration. They have units of \( s \).
All together, rates of communication of trap with CB and VB:

\[ r_{o,ec} = r_{o,ee} = \frac{1}{\tau_{eo} n_i + p_o} n_i^2 \]

\[ r_{o,he} = r_{o,he} = \frac{1}{\tau_{ho} n_i + p_o} n_i p_o \]

Rates depend on trap nature and doping level.
Simplify for n-type semiconductor:

\[ r_{o,ec} = r_{o,ee} \approx \frac{n_i}{\tau_{eo}} \]

\[ r_{o,hc} = r_{o,he} = \frac{p_o}{\tau_{ho}} \]

If \( \tau_{eo} \) not very different from \( \tau_{ho} \),

\[ r_{o,ec} = r_{o,ee} \gg r_{o,hc} = r_{o,he} \]

The rate at which trap communicates with CB much higher than VB.

- lots of electrons in CB and trap \( \Rightarrow \) \( r_{o,ec} = r_{o,ee} \) high
- few holes in VB and trap \( \Rightarrow \) \( r_{o,hc} = r_{o,he} \) small

Reverse situation for p-type semiconductor.
4. G&R rates outside equilibrium

- In thermal equilibrium:

\[
\begin{align*}
n &= n_o \\
p &= p_o \\
G_{oi} &= R_{oi} \\
G_o &= R_o
\end{align*}
\]

- Outside thermal equilibrium (with carrier concentrations disturbed from thermal equilibrium values):

\[
\begin{align*}
n &\neq n_o \\
p &\neq p_o \\
G_i &\neq R_i \\
G &\neq R
\end{align*}
\]

\[\text{Cite as: Jesús del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/), Massachusetts Institute of Technology. Downloaded on [DD Month YYYY].}\]
If $G \neq R$, carrier concentrations change in time.

Useful to define net recombination rate, $U$:

$$U = R - G$$

Reflects imbalance between internal G&R mechanisms:

- if $R > G$ → $U > 0$, net recombination prevails
- if $R < G$ → $U < 0$, net generation prevails
- if $R = G$ → $U = 0$, thermal equilibrium

If there are several mechanisms acting simultaneously, define:

$$U_i = R_i - G_i$$

and

$$U = \Sigma U_i$$

What happens to the G&R rates of the various mechanisms outside thermal equilibrium?
a) Band-to-band optical G&R

\[ G_{\text{rad}} = G_{\text{rad}} = r_{\text{rad}}n_0p_0 \]

- optical generation rate unchanged since number of available bonds unchanged:

- optical recombination rate affected if electron and hole concentrations have changed:

\[ R_{\text{rad}} = r_{\text{rad}}np \]

- define net recombination rate:

\[ U_{\text{rad}} = R_{\text{rad}} - G_{\text{rad}} = r_{\text{rad}}(np - n_0p_0) \]

- if \( np > n_0p_0 \), \( U_{\text{rad}} > 0 \), net recombination prevails
- if \( np < n_0p_0 \), \( U_{\text{rad}} < 0 \), net generation prevails

- note: we have assumed that \( g_{\text{rad}} \) and \( r_{\text{rad}} \) are unchanged from equilibrium
b) *Auger G&R*

- **Involving hot electrons:**

\[
\begin{align*}
\text{E}_c & \quad n_0 \\
\text{E}_v & \quad g_{eeh} = g_{eeh}n \\
\text{E}_c & \quad n > n_0 \\
\text{E}_v & \quad g_{eeh} > g_{0,eeh} \\
\text{E}_v & \quad r_{eeh} > r_{0,eeh}
\end{align*}
\]

thermal equilibrium

with excess carriers

\[
G_{eeh} = g_{eeh}n
\]

\[
R_{eeh} = r_{eeh}n^2p
\]

If relationship between \(g_{eeh}\) and \(r_{eeh}\) unchanged from TE:

\[
U_{eeh} = R_{eeh} - G_{eeh} = r_{eeh}n(np - n_o p_o)
\]

- **Involving hot holes, similarly:**

\[
U_{ehh} = r_{ehh}p(np - n_o p_o)
\]

- **Total Auger:**

\[
U_{Auger} = (r_{eeh}n + r_{ehh}p)(np - n_o p_o)
\]
Key conclusions

- Dominant generation/recombination mechanisms in Si: *trap-assisted* and *Auger*.

- In TE, $G$ and $R$ processes must be balanced *in detail*.

- Auger R rate in TE is proportional to the *square* of the majority carrier concentration and is *linear* on the minority carrier concentration.

- Trap-assisted G/R rates in TE depend on the nature of the trap, its concentration, the doping type and the doping level.

- In n-type semiconductor, midgap trap communicates preferentially with conduction band. In p-type semiconductor, midgap trap communicates preferentially with valence band.