Lecture 6 - Carrier generation and recombination (cont.)

Carrier drift and diffusion

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Contents:

1. Dynamics of excess carriers in uniform situations
2. Thermal motion

Reading assignment:

del Alamo, Ch. 3, §§3.5,3.7, Ch. 4, §4.1.
Key questions

• What governs the carriers dynamics in semiconductors outside equilibrium?

• In particular, if one shines light onto a semiconductor, how do the carrier concentrations evolve in time?

• What happens when the light is turned off?

• How about if the light excitation is turned on and off very quickly?

• Are carriers sitting still in thermal equilibrium?
1. Dynamics of excess carriers in uniform situations

Consider:

- extrinsic uniformly doped semiconductor
- no surfaces nearby

In thermal equilibrium:

\[ n = n_0 \]
\[ p = p_0 \]
\[ G_0 - R_0 = 0 \]

[Diagram showing thermal equilibrium with levels \( E_c \) and \( E_v \), and states \( n_0 \) and \( p_0 \)]
Now add:

- uniform excitation throughout body, $G_{ext}$

If there is imbalance between total generation and recombination, carrier concentrations change in time:

$$\frac{dn}{dt} = \frac{dp}{dt} = G - R$$

- if $G > R \Rightarrow n, p \uparrow$
- if $G < R \Rightarrow n, p \downarrow$

Distinguish between internal and external generation:

$$G = G_{ext} + G_{int}$$
Then:

\[ G - R = G_{\text{ext}} + G_{\text{int}} - R = G_{\text{ext}} - U \]

and:

\[ \frac{dn}{dt} = \frac{dp}{dt} = G_{\text{ext}} - U \]

• if \( G_{\text{ext}} > U \) \( \Rightarrow \) \( n, p \uparrow \)

• if \( G_{\text{ext}} < U \) \( \Rightarrow \) \( n, p \downarrow \)

Under LLI:

\[ U \approx \frac{n'}{\tau} \]

Also:

\[ \frac{dn}{dt} = \frac{dn'}{dt} \]

Then:

\[ \frac{dn'}{dt} = G_{\text{ext}} - \frac{n'}{\tau} \]

Homogeneous solution (\( G_{\text{ext}} = 0 \)) is: \( e^{-t/\tau} \)
• Example 1: Turn-on transient

\[ n'(t) = g_l \tau (1 - e^{-t/\tau}) \quad \text{for } t \geq 0 \]

Define:

*steady-state* \( \equiv \) initial transient died out (need a few \( \tau \)'s)

In steady state:

\[ \text{generation} = \text{recombination} \]

or

\[ g_l = \frac{n'}{\tau} \]

Then

\[ n' = g_l \tau \]
- Example 2: Turn-off transient

\[ n'(t) = g_\tau e^{-t/\tau} \quad \text{for } t \geq 0 \]

Technique to measure \( \tau \):

[Dziewior & Silber, 1977]
Example 3: A pulse of light

\[ n'(t) = g_l \tau (1 - e^{-t/\tau}) \quad \text{for} \ 0 \leq t \leq T \]

\[ n'(t) = g_l \tau (1 - e^{-T/\tau}) e^{-(t-T)/\tau} \quad \text{for} \ T \leq t \]
Two extreme cases:

- If $\tau_1 \gg T$, pulse too short for final value of $n'$ to be reached:
  \[
  n'(t) \approx g_l t \quad \text{for } 0 \leq t \leq T
  \]

- If $\tau_3 \ll T$, final value of $n'$ achieved quickly:
  \[
  n'(t) \approx g_l \tau_3 \quad \text{for } 0 \leq t \leq T
  \]

Shape of $n'(t)$ similar to shape of light pulse: quasi-static situation $\equiv$ no memory effect

\[
\frac{dn'}{dt} = G_{ext} - \frac{n'}{\tau} \Rightarrow n'(t) \simeq G_{ext}(t) \tau
\]
• Example 4: A pulse train

Important point: difference between \textit{quasi-static} and \textit{steady-state}

- \textit{steady-state}: initial transient associated with turn-on of excitation has died off

- \textit{quasi-static}: time derivatives irrelevant in time scale of interest

\[
\begin{align*}
G_{ext} & \uparrow \\
0 & \quad g_l \\
0 & \quad 0 \quad t_1 \quad t_2 \quad t \\
\tau & \quad n'(t)
\end{align*}
\]

\[
\begin{align*}
\tau & \ll t_1, t_2 \\
g_l & \quad 0 \quad 0 \quad t_1 \quad t_2 \quad t \\
\tau & \quad n'(t)
\end{align*}
\]

\[
\begin{align*}
\tau & \gg t_1, t_2 \\
g_l & \quad 0 \quad 0 \quad t_1 \quad t_2 \quad t \\
\tau & \quad n'(t)
\end{align*}
\]
2. Thermal motion

At finite $T$, carriers moving around in a random way suffering frequent collisions with vibrating lattice, ionized impurities, etc.

Define:

- **Thermal velocity**, $v_{th}$: average magnitude of carrier velocity between collisions [cm/s].
- **Mean free path**, $l_c$: average distance travelled between collisions [cm].
- **Scattering time**, $\tau_c$: average time between collisions [s].

Then:

$$l_c = v_{th}\tau_c$$
Thermal velocity depends on material and temperature:

\[ v_{th} = \sqrt{\frac{8 kT}{\pi m^*_c}} \]

Where:

\[ m^*_c \equiv \text{conductivity effective mass \([eV \cdot s^2/cm^2]\)} \]

\( m^*_c \) accounts for all interactions between the carriers and the perfect periodic potential of the lattice.

For electrons in Si at 300 K \((m^*_{ce} = 0.28m_o)\), \(v_{the} \simeq 2 \times 10^7 \text{ cm/s}\).
Scattering mechanisms:

1. **lattice or phonon scattering**: carriers collide with vibrating lattice atoms (phonon absorption and emission)
   \[ \Rightarrow \text{some energy exchanged} \ (\sim \text{tens of } meV) \]

2. **ionized impurity scattering**: Coulombic interaction between charged impurities and carriers
   \[ \Rightarrow \text{no energy exchanged} \]

3. **surface scattering** in inversion layer

4. **neutral impurity scattering** with neutral dopants, interstitials, vacancies, etc

5. **carrier-carrier scattering**

No need for detailed models.

Order of magnitude of \( \tau_c < 1 \text{ ps} \) (will learn to estimate next time).

Then, order of magnitude of \( l_c < 50 \text{ nm} \).
Key conclusions

• Dynamics of carrier concentrations in quasi-neutral low-level injected situations governed by carrier lifetime.

• *Quasi-static situation*: perturbations with time scale much longer than $\tau$.

• *Steady-state situation*: condition established after initial transient has died off.

• At finite temperatures, carriers move around in a random way suffering many collisions (*thermal motion*).

• Dominant scattering mechanisms in Si at 300K: phonon scattering, ionized impurity scattering, and surface scattering (in inversion layer).

• Order of magnitude of key parameters for Si at 300K:
  
  $- v_{th} \sim 2 \times 10^7 \ cm/s$
  
  $- \tau_c < 1 \ ps$
  
  $- l_c < 50 \ nm$