Quiz 1

1. Adding impurities to a semiconductor will not effect (at room temperature)
   A. free carrier concentration
   B. intrinsic carrier concentration
   C. Fermi Level
   D. Concentration of ionized atoms

2. Which of the following is true for a hole as defined in electronics?
   A. the absence of an atom in a semiconductor lattice.
   B. cannot contribute to the conduction of current
   C. behaves exactly like an electron
   D. the absence of an electron in valence band.

3. Which of the following factors do not affect the drift current in a material.
   A. carrier concentration
   B. electric field
   C. carrier concentration gradient
   D. mobility
RECOMBINATION AND GENERATION
DEFINITION

Two processes that affect the currents by changing the carrier densities involved in drift and diffusion are:

Generation: Process of creating new carriers, holes, and electrons.

Recombination: Inverse of generation, whereby an electron and hole disappears simultaneously, or electrons and holes annihilate each other.
THERMAL EQUILIBRIUM

• At thermal equilibrium, no external forces (such as light) or electric field are applied to the semiconductor. For intrinsic and extrinsic non-degenerate semiconductors, $np = n_i^2$ at thermal equilibrium.

• In an intrinsic semiconductor at thermal equilibrium, electrons and holes are continuously generated and continuously recombined. The intrinsic carrier density is determined only by the energy gap and temperature, therefore constant under given conditions, the rates of generation of electron-pairs is balanced by the equal rate of recombination.

• In extrinsic semiconductors, the carrier densities are determined by both the impurity doping densities and the intrinsic carrier densities. The rates of generation and recombination are also equal.
NON-EQUILIBRIUM CONDITIONS

• Recombination rates and Generation rates are not equal:
  \[ np \neq n_i^2 \]

• System must return to equilibrium.

• Example: When excess minority carriers are injected into one end of a semiconductor bar, electron and hole densities will tend to obtain equilibrium by causing rate of recombination to exceed rate of generation.
GENERATION AND RECOMBINATION (G & R) MECHANISM

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

- phonons (thermal G&R)
- photons (optical G&R)
CARRIER RECOMBINATION MECHANISMS IN SEMICONDUCTORS
BAND TO BAND TRANSITION: Direct Generation-Recombination

Recombination occurs when an electron falls from its state in the conduction band into the empty state in the valence band which is associated with a hole. This transition is a radiative transition in direct bandgap semiconductors.
a) Band-to-band G&R

- 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
TRAP-ASSISTED RECOMBINATION: Indirect Recombination-Regeneration

- **Trap-assisted** recombination occurs when an electron falls into a "trap", an energy level within the bandgap caused by the presence of impurities or a lattice imperfection.
- Once the trap is filled it cannot accept another electron.
- The electron occupying the trap energy can in a second step fall into an empty state in the valence band, thereby completing the recombination process.
- This process can either be:
  i. A two-step transition of an electron from the conduction band to the valence band or
  ii. The annihilation of the electron and hole which meet each other in the trap. This process can be referred to as Shockley-Read-Hall (SRH) recombination.
c) *Trap-assisted generation and recombination*, relying on electronic states in middle of gap ("deep levels" or "traps") that arise from:

- crystalline defects

- impurities

\[
\begin{align*}
E_c & \quad \uparrow \quad \bullet \quad \downarrow \\
E_t & \quad \bullet \quad \circ \quad \bullet \\
E_v & \quad \circ \quad \bullet
\end{align*}
\]

- trap-assisted thermal generation

- trap-assisted thermal recombination

- dominant in Si

- engineerable: can introduce deep levels to Si to enhance it
GENERATION MECHANISMS WITH NO ASSOCIATED RECOMBINATION MECHANISMS

Carrier **generation due to light absorption:**

- The photon energy must be large enough (at least equal to bandgap energy) to lift an electron from the valence band into an empty state in the conduction band, generating one electron-hole pair.

- The photon is absorbed in this process and the excess energy, \(E_{ph} - E_g\) is added to the electron and the hole in the form of kinetic energy.
Excess Carrier Concentrations

\[ \Delta n \equiv n - n_0 \]
\[ \Delta p \equiv p - p_0 \]

Charge neutrality condition:
\[ \Delta n = \Delta p \]
“Low-Level Injection”

- Often the disturbance from equilibrium is small, such that the majority-carrier concentration is not affected significantly:
  - For an n-type material:
    \[ |\Delta n| = |\Delta p| \ll n_0 \quad \text{so} \quad n \approx n_0 \]
  - For a p-type material:
    \[ |\Delta n| = |\Delta p| \ll p_0 \quad \text{so} \quad p \approx p_0 \]

- However, the minority carrier concentration can be significantly affected
Indirect Recombination Rate

- Consider hole recombination in n-Si through a number of traps, \( N_T \):
  \[
  \left. \frac{\partial p}{\partial t} \right|_R = -c_p N_T p
  \]

- Since total generation = recombination at equilibrium:
  \[
  \left. \frac{\partial p}{\partial t} \right|_G = -\left. \frac{\partial p}{\partial t} \right|_R = c_p N_T p_0
  \]

- If we introduce excess carriers (e.g. using light) and watch the decay in \( \Delta p \):
  \[
  \left. \frac{\partial p}{\partial t} \right|_{R-G} = -c_p N_T (p - p_0) 
  \equiv -\frac{\Delta p}{\tau_p}
  \]

\[\tau_p = \frac{1}{c_p N_T}\]
Recombination Lifetime

The *minority carrier lifetime* $\tau$ is the average time an excess minority carrier "survives" in a sea of majority carriers.

$\tau$ ranges from 1 ns to 1 ms in Si and depends on the density of metallic impurities (contaminants) such as Au and Pt, and the density of crystalline defects. These *deep traps* capture electrons or holes to facilitate recombination and are called *recombination-generation centers*. 
Example: Photoconductor

Consider a sample of Si doped with $10^{15}$ cm$^{-3}$ boron, with recombination lifetime 10 μs. It is exposed to light such that electron-hole pairs are generated throughout the sample at the rate of $10^{20}$/s·cm$^3$.

Find:
(a) $n_0$ and $p_0$
(b) $\Delta n$ and $\Delta p$
(c) $p$, $n$, and the $np$ product
Solution:

(a) What is $p_0$?

$$p_0 = N_a = 10^{15} \text{ cm}^{-3}$$

(b) What is $n_0$?

$$n_0 = n_i^2/p_0 = 10^5 \text{ cm}^{-3}$$

(c) What is $\Delta p$?

In steady-state, the rate of generation is equal to the rate of recombination.

$$10^{20}/\text{s-cm}^3 = \Delta p/\tau$$

$$\therefore \Delta p = 10^{20}/\text{s-cm}^3 \cdot 10^{-5} \text{s} = 10^{15} \text{ cm}^{-3}$$
(d) What is $\Delta n$?
$\Delta n = \Delta p = 10^{15} \text{ cm}^{-3}$

(e) What is $p$?
$p = p_0 + \Delta p = 10^{15} \text{ cm}^{-3} + 10^{15} \text{ cm}^{-3} = 2 \times 10^{15} \text{ cm}^{-3}$

(f) What is $n$?
$n = n_0 + \Delta n = 10^5 \text{ cm}^{-3} + 10^{15} \text{ cm}^{-3} \sim 10^{15} \text{ cm}^{-3}$ since $n_0 << \Delta n$

(g) What is $np$?
$np \sim 2 \times 10^{15} \text{ cm}^{-3} \cdot 10^{15} \text{ cm}^{-3} = 2 \times 10^{30} \text{ cm}^{-6} \gg n_i^2 = 10^{20} \text{ cm}^{-6}$.

Note: The $np$ product can be very different from $n_i^2$. 
QUASI-FERMI LEVEL

Equilibrium State

\[ n_0 p_0 = n_i^2 \]

When excess carriers are present

\[ np \neq n_i^2 \]

Equilibrium State

\[ n_0 = n_i \exp\left[\frac{(E_F - E_i)}{kT}\right] \]
\[ p_0 = n_i \exp\left[\frac{(E_i - E_F)}{kT}\right] \]

When excess carriers are present, use similar expressions by defining separate quasi-Fermi levels, \( F_n \) and \( F_p \) for electrons and holes.

\[ n = n_i \exp\left[\frac{(F_n - E_i)}{kT}\right] \]
\[ p = n_i \exp\left[\frac{(E_i - F_p)}{kT}\right] \]
A Si sample with $n_0 = 10^{14}$ cm$^{-3}$ and $\tau_n = \tau_p = 2.0 \mu$sec is irradiated with a CW laser and thus every microsecond $10^{13}$ e-h pairs/cm$^3$ are created. What is the position of equilibrium Fermi energy, i.e. what is $E_F - E_i$? What is a steady state concentration of electrons $n$ and holes $p$ under CW laser excitation? Find the position of quasi-Fermi levels for electrons and holes, $F_n - E_i$ and $E_i - F_p$, respectively?

$$n_0 = n_i \exp\left(\frac{(E_F - E_i)}{kT}\right), \text{ and for Si } n_i = 1.5 \times 10^{10} \text{ cm}^{-3},$$

$$E_F - E_i = kT \ln\left(\frac{n_0}{n_i}\right) = 0.0259 \ln\left(\frac{10^{14}}{1.5 \times 10^{10}}\right) = 0.228 \text{ eV}.$$ 

$$\delta n = \delta p = g_{op} \tau_n, \text{ thus}$$

$$n = n_0 + \delta n = n_0 + g_{op} \tau_n = 10^{14} + 10^{13} \times 2.0 = 1.2 \times 10^{14} \text{ cm}^{-3}.$$ 

Since $p_0 \ll \delta p, p \approx \delta p = 2 \times 10^{13} \text{ cm}^{-3}$.

$$F_n - E_i = kT \ln\left(\frac{n}{n_i}\right) = 0.0259 \ln\left(\frac{1.2 \times 10^{14}}{1.5 \times 10^{10}}\right) = 0.233 \text{ eV}.$$ 

$$E_i - F_p = kT \ln\left(\frac{p}{n_i}\right) = 0.0259 \ln\left(\frac{2 \times 10^{13}}{1.5 \times 10^{10}}\right) = 0.186 \text{ eV}.$$