SEMICONDUCTOR III: Carrier generation and recombination in semiconductors

INTRODUCTION

In intrinsic silicon, germanium and GaAs, the generation and recombination rate is slow in dark at room temperature. That is, if access electron hole pairs are generated in the sample, it takes a long time for them to recombine. In real experiments, we can show that the lifetime indeed can be longer than hours. This is because of their relative large bandgap (than kT). In practice, however, we may want to reduce the lifetime of carriers for making the response faster, such as for photodetectors. In addition, the semiconductors may not be very pure after all. There is a need to understand how states in the bandgap promotes generation and recombination.

Drift and diffusion

There are two types of motion that we want to consider: drift and diffusion. Electrons (and holes) can be driven by electric field and we have derived the Ohm’s law based on the Drude model: \( J = \sigma E, \sigma = nq\mu, \) and \( \mu = \frac{e\tau}{m^*}. \) The diffusive motion has the characteristic equation of motion: \( Flux = D\partial n/\partial x, \) i.e., the flux of carrier is proportional to the gradient of carriers, and the proportionality constant is \( D. \)

Homework: We have derived the Einstein relation \( (D = \frac{kT}{q}\mu) \) in class.

Homework: Prove that the Fermi level in the sample at equilibrium is flat, i.e., \( dE_f/dx = 0. \)

Nonequilibrium: low level injection and high level injection

If the access carrier concentration is less than the majority carrier concentration, we call the situation low level injection. For example, in an n-type Si with doping concentration of \( 10^{17}/cm^3, \) an injection of \( 10^{14} \) electron-hole pairs will cause negligible increase to the electron concentration, but the hole concentration will go from \( 10^3/cm^3 \) (coming from \( p = n_i^2/n \)) to \( (10^{14} + 10^3)/cm^3. \)

Generation and recombination at levels in the bandgap

To understand the processes controlling the concentration of electrons and holes with the existence of bandgap states, we consider the following four processes.

1. Electron capture: an electron can be captured from the conduction band to the state.
2. Electron emission: an electron is emitted from the state back to the conduction band.
3. Hole capture: a hole is capture from the valence band to the state.
4. Hole emission: a hole is emitted from the state back to the valence band.

Each process has a rate, and they are defined, in sequence, as \( r_a, r_b, r_c, \) and \( r_d, \) respectively.
We now discuss the overall generation/recombination rate. \( r_a \propto n N_t (1 - f) = V_{th} \sigma_n n N_t (1 - f) \), where \( N_t \) is the trap density, \( f \) is the Fermi-Dirac probability that the trap state is occupied, \( v_{th} \) is the thermal velocity, defined from \( \frac{1}{2} m^* v_{th}^2 = \frac{3}{2} kT \), and \( \sigma_n \) is the capture cross section.

**Homework:** Plug numbers in to convince yourself that the \( v_{th} \) is of the order of \( 10^7 \text{cm/sec} \).

The rate \( r_b \) can be modeled to be expressed as \( r_b = e_n N_t f \), where \( e_n \) is the electron emission rate.

At equilibrium, \( r_a = r_b \), therefore, we can use the terms in \( r_a \) to express \( e_n \):

\[
e_n = \frac{v_{th} \sigma_n N_t n}{N_t} \frac{1 - f}{f} \tag{1}
\]

Now, knowing that, for nondegenerate electrons:

\[
\frac{1 - f}{f} \sim \frac{1}{f} = e^{(E_t - E_f)/kT}, \tag{2}
\]

\[
e_n = \frac{v_{th} \sigma_n N_t N_e e^{-(E_e - E_f)/kT}}{N_t} \left( \frac{1 - f}{f} \right) \tag{3}
\]

\[
\sim v_{th} \sigma_n N_e e^{-(E_e - E_f)/kT} \frac{e^{(E_t - E_f)/kT}}{e^{(E_e - E_f)/kT}}, \tag{4}
\]

\[= v_{th} \sigma_n N_e e^{-(E_e - E_t)/kT} \tag{5}
\]

\[= v_{th} \sigma_n n_i e^{(E_t - E_i)/kT}. \tag{6}
\]

By the same token,

\[
e_p = v_{th} \sigma_p n_i e^{-(E_i - E_t)/kT}. \tag{7}
\]

At steady state,

\[
\frac{\partial n_n}{\partial t} = G_L - r_a + r_b = 0 ; \tag{8}
\]

\[
\frac{\partial p_n}{\partial t} = G_L - r_c + r_d = 0 , \tag{9}
\]

where \( n_n \) (\( p_n \)) stands for the electron (hole) concentration in n-type material, and \( G_{L(\text{light})} \) is the generation rate by photo-excitation. So, at steady state, \( r_a - r_b = r_c - r_d \). This leads to:

\[
v_{th} \sigma_n n N_t (1 - f) - e_n N_t f = v_{th} \sigma_p p N_t f - e_p N_t (1 - f) \tag{10}
\]
\[ f = \frac{\sigma_n n + \sigma_p n_i e^{(E_i - E_t)/kT}}{\sigma_n (n + n_i e^{(E_t - E_i)/kT}) + \sigma_p (p + n_i e^{(E_i - E_t)/kT})} . \]  

(11)

Plugging this equation into \[ U = r_a - r_b, \] we get at steady state:

\[ U = r_a - r_b = r_c - r_d \]  

(12)

\[ U = \frac{\sigma_n \sigma_{vth} N_t (pn - n_i^2)}{\sigma_n (n + N_c e^{-(E_c - E_i)/kT}) + \sigma_p (p + N_v e^{-(E_i - E_v)/kT})} . \]  

(13)

If we let \( \sigma_n = \sigma_p = \sigma \), then

\[ U \sim \sigma v_{th} N_t \frac{(pn - n_i^2)}{n + p + 2n_i \cosh\left(\frac{E_t - E_i}{kT}\right)} . \]  

(14)

\((\cosh(x) = \frac{1}{2}(e^x + e^{-x}).\) For low level injection, i.e., \( p = p_n \gg p_{no}, n = n_n \sim n_{no}, \) and that \( n \gg n_i \gg p \), we obtain that, for n-type material:

\[ pn - n_i^2 = p_n n_n - p_{no} n_{no} \sim n_{no} (p_n - p_{no}) . \]  

(15)

The denominator is approximately \( n_{no} \). So,

\[ U \sim \sigma v_{th} N_t (p_n - p_{no}) \sim \frac{(p_n - p_{no})}{\tau_p} , \]  

(16)

where \( \tau_p \) is defined as the inverse of \( \sigma v_{th} N_t \).

We learn that:

1. The term \( pn - n_i^2 \) is really the driving force, since it is a measure of how much the system deviates from equilibrium.
2. To make \( U \) large, \( n \sim p \).
3. To make \( U \) large, \( E_t \sim E_i \), i.e., the trap level is close to the middle of the bandgap.
4. The concept of lifetime \( \tau \) is for minority carrier only.
5. The rate equation becomes: \( \frac{\partial p_n}{\partial t} = G_L - U \), and the expressions of \( U \) is derived with clear physical meanings. Therefore, to make the photo current large in a photodetector, the sample should be pure.

Homework: Read chapter one of Sze.