ECE MS exam: EDM _ AP depth

1. The energy diagram shown below is a Si sample at room temperature, where $E_F - E_i = E_G/4$ at $x = L$ and $E_i - E_F = E_G/4$ at $x = 0$. Please answer the following questions concisely.

(a) The semiconductor is in equilibrium. How does one deduce this fact from the energy band diagram?

(b) What is the electron current density ($J_n$) and hole current density ($J_p$) at $x = \pm L/2$?

(c) Roughly sketch $n$ and $p$ versus $x$ inside the sample.

(d) Is there an electron diffusion current at $x = L/2$? If there is a diffusion current at a given point, indicate the direction of current flow.

(e) Sketch the electric field ($\mathbf{E}$) inside the semiconductor as a function of $x$.

(f) Is there an electron drift current at $x = \pm L/2$? If there is a drift current at a given point, indicate the direction of current flow.

\[ E_c \quad E_F \quad E_i \quad E_v \]

\[ -L \quad 0 \quad L \quad x \]

2. The carrier concentrations in doped semiconductors depend on the ionization of dopant atoms, which is a function of temperature. Thus the operation temperature is defined as freeze-out region, extrinsic temperature region, and intrinsic temperature region. Suppose we define the low temperature limit ($T_{min}$) and high temperature limit ($T_{max}$) for the extrinsic temperature region to be $n = 0.9 \ N_D$ and $n = 1.1 \ N_D$, respectively. Assuming the semiconductor to be non-degenerately $N_D$ doped with $N_d = 0$, please answer the following questions:

(a) what is a freeze-out region, extrinsic temperature region, and intrinsic temperature region?

(b) Indicate how would proceed in determining $T_{min}$ for a given donor doping.

(c) Indicate how you would proceed in determining $T_{max}$ for a given doping concentration.

(d) Since solid-state devices are normally operated in extrinsic temperature region, what do you conclude about the use of Si and GaAs devices at elevated temperatures?
A-1. Known: Si at room temperature; \( E_f - E_i = \frac{E_g}{4} \) at \( x=L \);
\( E_i - E_p = \frac{E_g}{4} \) at \( x=0 \).

(a) This semiconductor is under equilibrium, because in the energy band diagram, the Fermi level is constant as a function of position \( x \). \( \frac{dE_f}{dx} = 0 \).

(b) \( J_n = 0 \), \( J_p = 0 \) at \( x=\pm L/2 \). We know that under equilibrium conditions, the total currents must be identically zero.

\[ J_n |_{\text{diff}} + J_p |_{\text{diff}} = 0 \]
\[ J_n |_{\text{drift}} + J_p |_{\text{drift}} = 0. \]

(c) We know \( n = n_i \exp \left( \frac{E_f - E_i}{kT} \right) \)
\[ p = n_i \exp \left( \frac{E_i - E_f}{kT} \right) \]
(a) Yes! \( \text{J}_e = e \cdot D_e \frac{\partial n}{\partial x} > 0 \) at \( x = \frac{L}{2} \), the electron diffuses toward \( +x \) direction and \( \text{J}_i = 0 \) at \( x \) direction; At \( x = -\frac{L}{2} \), electron diffuses toward \( -x \) direction and \( \text{J}_i = 0 \) at \( -x \) direction.

(c) A nonzero electric field is established inside non-uniformly doped semiconductors under equilibrium conditions.

\[ \mathcal{E} = \frac{1}{e} \frac{d\mathcal{E}}{dx} \text{ in one dimensional semiconductor} \]

(\( \text{E} \)) Yes! There are electron drift current at both \( x = -\frac{L}{2} \) and \( x = \frac{L}{2} \) because of nonzero \( \mathcal{E} \). \( \text{J}_i \text{drift} = q \cdot n \cdot v \cdot \mathcal{E} \). At \( x = -\frac{L}{2} \), \( \text{J}_i \text{drift} \) flows along \( +x \) direction and at \( x = \frac{L}{2} \), \( \text{J}_i \) is along \( -x \) direction. Electrons flow in the opposite direction of currents.

A-2. For a non-degenerately doped semiconductor, \( \text{ND} \). As shown in the carrier concentration vs temperature plot, there are freeze-out region, extrinsic temperature region, and intrinsic temperature region. Note that temperature dependence is material specific. In other words, different materials will have different \( T_{\text{min}}, T_{\text{max}} \) for freeze-out/extrinsic and extrinsic/intrinsic region/transition.

(a) At certain low temperature, the energy available is not sufficient to create a significant number of electrons.
from the valence band into the conduction band or even to ionize the donor sites, hence the number of mobile electrons at low temperature is equal to the number of ionized donors, \( n = N_D^+ \). In this region of temperature, it is considered "freeze-out region".

As temperature is increased, almost complete ionization can be achieved, \( N_D \gg N_i \), therefore the contribution to the electron population from band-to-band excitation remains negligible at least up to room temperature. \( N_D = N_D^+ \), which leads to \( n = N_D \) constant over the temperature at which \( N_D > n_i \). This temperature region is referred to be "extrinsic" region as the electrons contribution from extrinsic dopants is dominant.
At high temperature, the electrons excited across the band-gap eventually approach, reach, and exceed, ultimately swamp the fixed number of electrons from the donor sites. The temperature range when \( n \approx n_i \) is referred as the intrinsic temperature region.

(b) \( T_{\text{min}} \) is defined as the temperature limit for free-electron and extrinsic temperature region transition. For the Donor sites with \( E_D \) energy level, the ratio of ionized dopants to total dopants \( (N_{D^+}/N_D) \) corresponds to the ratio of empty to total states at the donor energy \( E_D \) .

\[
N_{D^+}/N_D = 1 - f(E_D) = \\
1 / \left[ 1 + g_D \exp \left( \frac{(E_F - E_D)}{kT_{\text{min}}} \right) \right]
\]

where \( g \) is the donor site degeneracy factor. To determine \( T_{\text{min}} \), we know at which temperature \( n = 0.1 n_i \), and in the freeze-out region, \( n = N_{D^+} \), therefore,

\[
N_{D^+}/N_D = \frac{n}{N_D} = \frac{1}{1 + 2 \exp \left( \frac{(E_F - E_D)}{kT_{\text{min}}} \right)} = 0.9 \Rightarrow 0.1 = 1.8 \exp \left( \frac{(E_F - E_D)}{kT_{\text{min}}} \right)
\]

\[
(E_F - E_D)/kT_{\text{min}} = \ln \frac{1}{0.1} \Rightarrow kT_{\text{min}} = \frac{1}{\ln \frac{1}{0.1}} (E_F - E_D) \Rightarrow T_{\text{min}} = \frac{T}{\ln \frac{1}{0.1}} (E_F - E_D).
\]

(c) \( T_{\text{max}} \) is defined as extrinsic/intrinsic temperature.

In extrinsic region, \( n = N_D \), which approaches to \( n = n_i \) in the intrinsic region as temperature increases. Here there \( T_{\text{max}} \) is defined as \( n = 0.1 N_D \). Charge neutrality remains true.

\[
p - n = N_D - N_{A^+} = \frac{h^2}{2m} \n + \frac{1}{1.1} n - 0 = \frac{h^2}{2m} + \frac{1}{1.1} n = 0 \Rightarrow
\]

\[
\frac{h^2}{2m} = \frac{1}{2m} \Rightarrow \text{not \_\_\_ extrinsic/intrinsic}_3
\]

Because \( n = n_i \exp \left( \frac{(E_F - E_D)}{kT} \right) \)
\( E_x - E_i = kT \ln \left( \frac{n}{n_i} \right) \)  (true for extrinsic/intrinsic regions)

\[ T_{\text{max}} = \frac{E_x - E_c}{k \cdot T} = \frac{E_x - E_i}{k \cdot T} \quad \text{EF - EI can be easily found from semiconductor property charts & books.} \]

(a). Solid-state devices, such as p/n diode, BiT, Mosfet, etc. are all normally operated in the extrinsic region, when the extrinsic dopant dominates the free carrier population, device function is accomplished through the selective doping and control over properties by doping. 

for Si and Ge at high temperature, the intrinsic carrier concentration dominant, \( n = p = n_i \), there will not be \( p/n \) junctions and not diode, transistor, etc. functions can be sustained. 

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