

EE 221 Device Physics

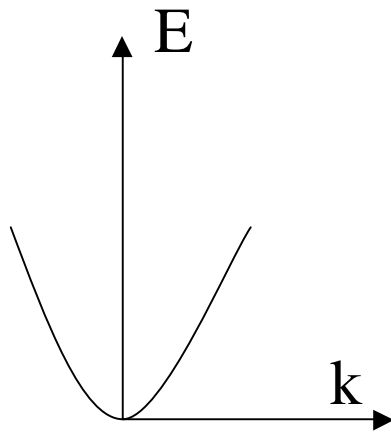
Class 6 Carrier Mobility and Energy Band Diagram

Charge carriers in semiconductors

- Effective mass
 - Electrons in a crystal are not totally free.
 - The periodic crystal affects how electrons move through the lattice.
 - We use an effective mass to modify the mass of an electron in the crystal and then use the E+M equations that describe free electrons.

Charge carriers in semiconductors

- Effective mass



$$p = mv = \hbar k$$

$$E = \frac{1}{2}mv^2 = \frac{\hbar^2}{2m}k^2$$

$$\frac{d^2 E}{dk^2} = \frac{\hbar^2}{m}$$

$$m^* = \frac{\hbar^2}{\frac{d^2 E}{dk^2}}$$

Strain can change the lattice constant, thus m !

Charge carriers in semiconductors

- Effective mass
 - The double derivative of E is a constant
 - Not all semiconductors have a perfectly parabolic band structure
 - The different atomic spacing in each direction gives rise to different effective masses in different crystal directions. This can be compensated by using an average value of effective mass.

Strain can change the lattice constant, thus m ! (Nitride, SiGe)

Drift of carriers in electric and magnetic fields

- Mobility
 - Impurity scattering $T^{3/2}$ (affects highly doped samples more than lowly doped samples)
 - Lattice scattering $T^{-3/2}$ (affects can be seen in lowly doped samples)
 - Depends on effective mass as well
 - in Si the electron mobility is higher than the hole mobility, thus PMOS channel widths have to be twice that of NMOS channel widths

What doping would you use for a resistor in an environment that the temperature changed dramatically?

Drift of carriers in electric and magnetic fields

- Mobility
 - At high electric field the mobility can saturate or even become smaller.

Charge carriers in semiconductors

- Effective mass (for density of states calculation)

| | Ge | Si | GaAs |
|---------|------------|-----------|-------------|
| m_n^* | 0.55 m_0 | 1.1 m_0 | 0.067 m_0 |
| m_p^* | 0.37 m_0 | .56 m_0 | 0.48 m_0 |

Charge carriers in semiconductors

- Intrinsic material
 - A perfect semiconductor crystal
 - no impurities or defects
 - No charge carriers at 0K
 - valence band is filled, conduction band empty
 - Heat (lattice vibrations can break a covalent bond and push an electron into the conduction band (EHP)
 - This electron is moving several lattice constants away in a QM probability distribution.

Charge carriers in semiconductors

- Intrinsic material
 - Each electron pumped up to the valence band leaves an empty state behind, thus for intrinsic material the electron concentration in the conduction band ($n \text{ e/cm}^3$)=the hole concentration in the valence band ($p \text{ h/cm}^3$)

$$n = p = n_i$$

Charge carriers in semiconductors

- Intrinsic material
 - If this relation is to hold then the generation rate of EHP's must equal the recombination rate of EHP's

$$n = p = n_i$$

$$r_i = g_i$$

$$r_i = \mathbf{a}_r n_0 p_0 = \mathbf{a}_r n_i^2 = g_i$$

Charge carriers in semiconductors

- Extrinsic material
 - Intrinsic material is not very useful except for devices which change their conductivity based on optical or thermal excitation. There is no gain mechanism involved and thus large areas are needed to detect the effect, thus are slow.
 - One can create extrinsic material by replacing semiconductor atoms in the lattice with atoms from different groups in the periodic table.

Charge carriers in semiconductors

- Extrinsic material.

| II | III | IV | V | VI |
|----|-----|----|----|----|
| | B | C | | |
| | Al | Si | P | S |
| Zn | Ga | Ge | As | Se |
| Cd | In | | Sb | Te |

Charge carriers in semiconductors

- Extrinsic material.
 - Elements from group V give rise to energy levels close to the conduction band in Si and Ge and is completely filled at 0K. It only takes a little energy to make an electron jump from this level to the conduction band. This new energy level donates an electron and so group V elements are known as donors (with respect to Si and Ge)

Charge carriers in semiconductors

- Extrinsic material.
 - Elements from group III give rise to energy levels close to the valence band in Si and Ge and is completely empty at 0K. It only takes a little energy to make an electron jump from the valence band to this new level. This new energy level accepts an electron and so group III elements are known as acceptors (with respect to Si and Ge)

Charge carriers in semiconductors

- Extrinsic material.
 - Not all group III and V elements make good dopant sources, if the new energy level is near the middle of the band gap then it takes more energy to accept or donate an electron.
 - In III-VI semiconductors it is more complex
 - group VII elements on a VI site will donate an electron
 - group II elements on a III site will accept an electron
 - group IV elements can go on either a III or VI and thus are amphoteric

Charge carriers in semiconductors

- Electrons and holes in a quantum well
 - A quantum well consists of a thin ($\sim 100\text{\AA}$) semiconductor layer sandwiched between two semiconductor layers with larger band gaps.
 - In the one dimensional case this gives rise to discrete energy levels above the conduction band and below the valence band.
 - This well serves as a trap for EHP's and when an EHP recombines in a direct band semiconductor, a photon is emitted.

Charge carriers in semiconductors

- Electrons and holes in a quantum well
 - This trapping effect increases the probability of an electron hole pair recombining between these new energy levels compared to the bulk semiconductor. This leads to more efficient lasers due to the fact that the energy spread of the photons generated is tighter than compared to bulk material.

Carrier concentrations

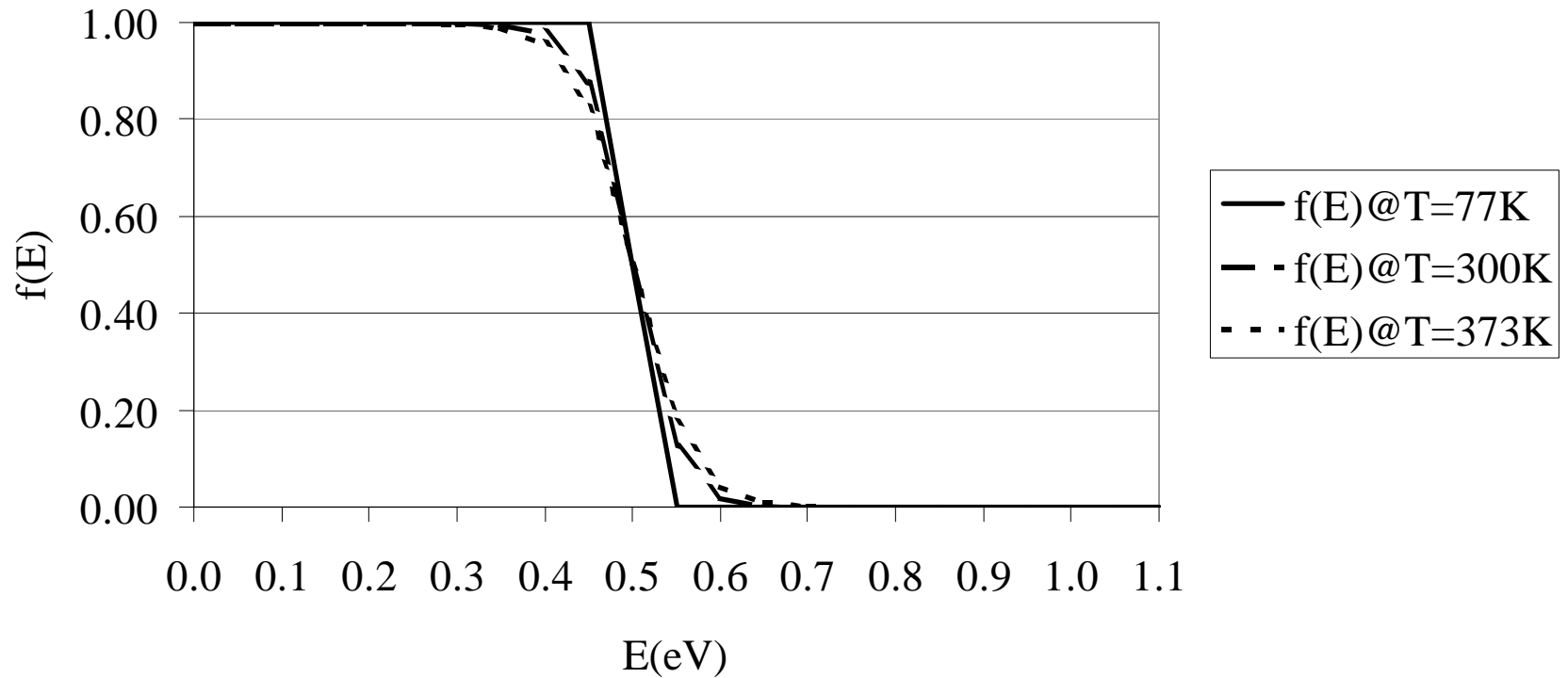
- The Fermi level
 - Indistinguishability of electrons
 - Wave nature of electrons
 - Pauli exclusion principle

$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

$$f(E_F) = \frac{1}{1+1} = \frac{1}{2}$$

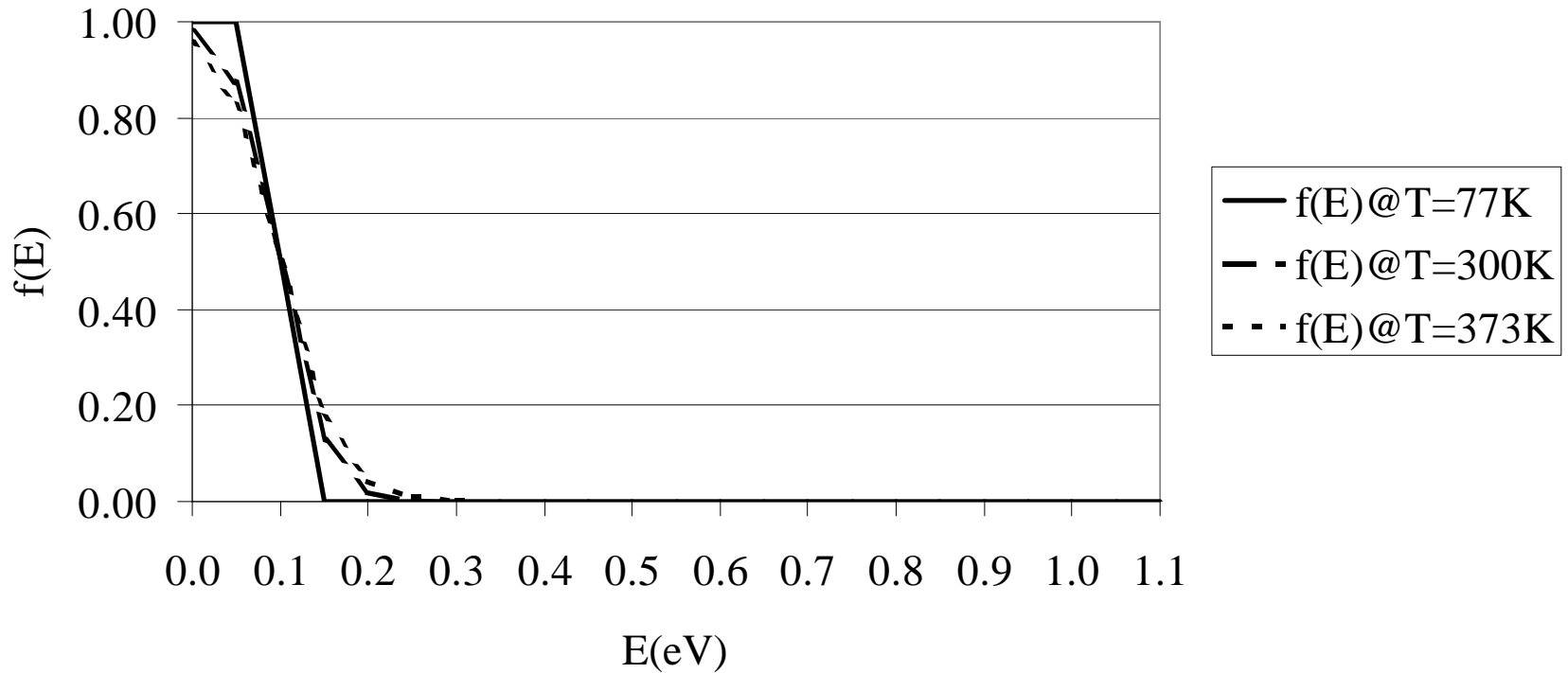
Carrier concentrations

Intrinsic $E_F = 0.5$



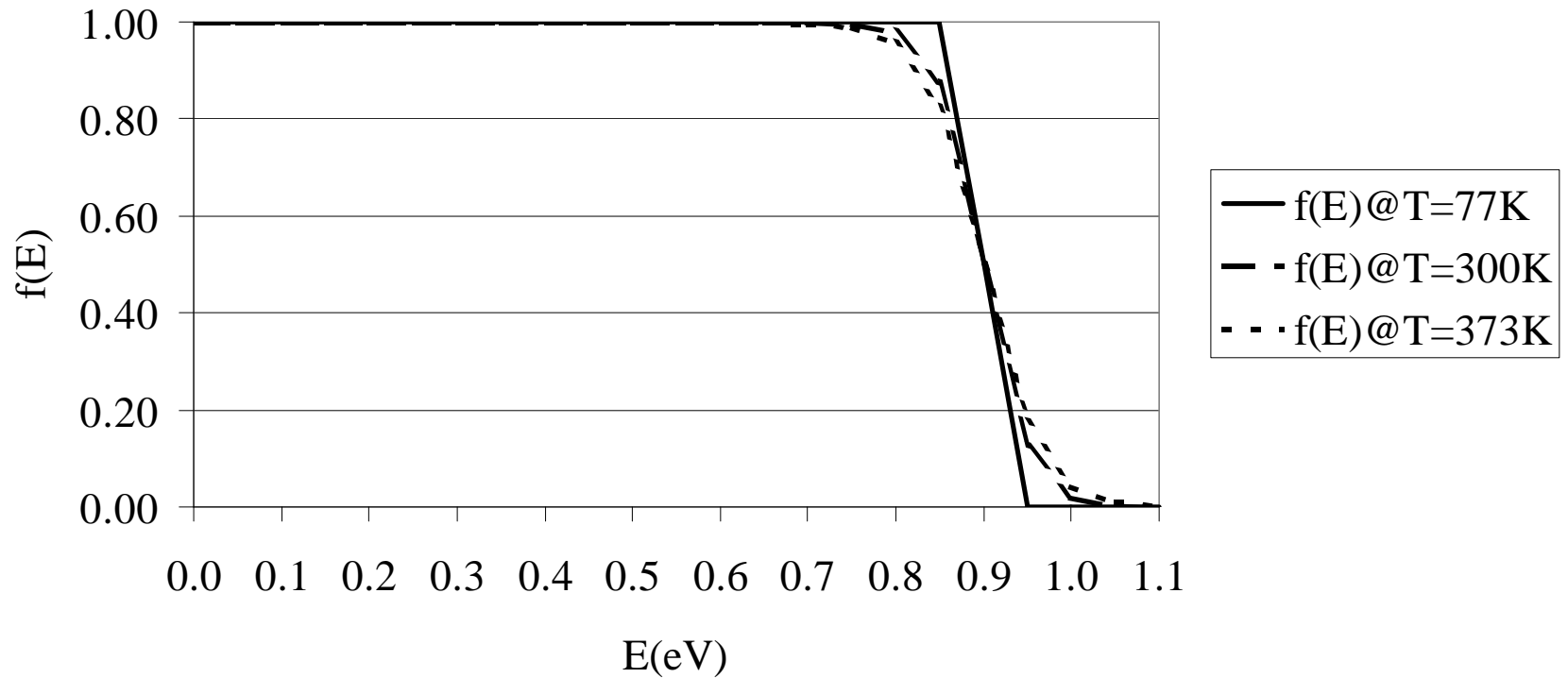
Carrier concentrations

p-type ($E_F = .1\text{eV}$)



Carrier concentrations

n-type ($E_F=0.9$)



Carrier concentrations

- The Fermi distribution only shows the probability of an available state being filled it does not allow states to form.
- The probability of a state being filled with an electron is $f(E)$.
- The probability of a state being empty $1 - f(E)$ (probability of finding a hole).

Carrier concentrations

$$n_o = N_C f(E_c)$$

$$f(E_c) = \frac{1}{1 + e^{(E_c - E_F)/kT}} \approx e^{-(E_c - E_F)/kT}, E_F < E_C - 2kT$$

$$n_o = N_C e^{-(E_c - E_F)/kT}$$

$$N_C = 2 \left(\frac{2\mathbf{p}m_n^* kT}{h^2} \right)^{\frac{3}{2}}$$

Carrier concentrations

$$p_o = N_V (1 - f(E_c))$$

$$1 - f(E_v) = 1 - \frac{1}{1 + e^{(E_v - E_F)/kT}} \approx e^{-(E_F - E_v)/kT}, E_F > E_v + 2kT$$

$$p_o = N_V e^{(-E_F - E_v)/kT}$$

$$N_V = 2 \left(\frac{2pm_p^* kT}{h^2} \right)^{\frac{3}{2}}$$

Carrier concentrations

$$n_o p_o = n_i^2$$

$$n_i = \sqrt{N_C N_V} e^{-E_g / 2kT}$$

$$n_i = 2 \left(\frac{2pkT}{h^2} \right)^{\frac{3}{2}} \left(m_n^* m_p^* \right)^{\frac{3}{4}} e^{-E_g / 2kT}$$

Carrier concentrations PE:

Calculate n_i for Si at 300K

$$n_i = 2 \left(\frac{2pkT}{h^2} \right)^{\frac{3}{2}} \left(m_n^* m_p^* \right)^{\frac{3}{4}} e^{-E_g/2kT}$$

Carrier concentrations PE:

$$n = 2 \left(\frac{2p * 1.38E^{-23} J / K * 300K}{(6.63E^{-34} J - s)^2} \right)^{\frac{3}{2}}$$

$$\left(1.1 * .56 * 9.11E^{-31} kg^2 \right)^{\frac{3}{4}} e^{-1.11/2/.0259}$$

$$n_i = 2 \left(5.91771E^{46} / J - s^2 \right)^{\frac{3}{2}} \left(5.112E^{-61} kg^2 \right)^{\frac{3}{4}} e^{-21.236}$$

$$n_i = 2 * 1.4396E^{70} \frac{1}{kg^{3/2} m^3} * 6.04593E^{-46} kg^{3/2} * 5.99143E^{-10}$$

$$n_i = 1.043E^{16} m^{-3} = 1.043E^{10} cm^{-3}$$

Carrier concentrations

- Space charge neutrality

- $p_o + N_d^+ = n_o + N_a^-$

- $n_o = N_d^+ - N_a^-$, for strongly n-type

- $p_o = N_a^- - N_d^+$, for strongly p-type

Drift of carriers in electric and magnetic fields

- The carriers are in constant random motion due to heat and there is no net motion.
- Under an electric field there is net motion.

$$J_x = -qn \langle v_x \rangle$$

$$J_x = \mathbf{s}E_x$$

$$\mathbf{s} = qn\mathbf{m}_n$$

$$J_x = qn\mathbf{m}_n E_x$$

$$J_x = q(n\mathbf{m}_n + p\mathbf{m}_p)E_x$$

Fermi level

- Qualitatively
 - At thermal equilibrium there can be no discontinuity or gradient in the Fermi level.
 - Assume two dissimilar semiconductors
 - There can be no net charge transport at thermal equilibrium, therefore no net charge transfer
 - The charges must balance each other. This leads to:

$$\frac{dE_F}{dx} = 0$$