Lecture 4: Electrons in semiconductors III

- Carrier freezeout
- Heavy doping
- Scattering in semiconductors
- Low Electric fields
  - mobility and drift velocity
- High electric fields
- Very high electric fields– breakdown
  - Zener Tunnelling

Carrier Freezeout

- How do we know that a donor atom electron will occupy an energy level E_d below the conduction band or become a free electron in the conduction band?

i. At low temperature the electrons are confined to the donor atom. The free electron density is zero, we have carrier **freezeout**.

ii. With increasing temperature, the fraction of ionised donors increases until the free carrier density is equal to the donor density. This region is known as the **saturation region**.

iii. With further increase in temperature, the carrier density starts to increase because of the intrinsic carrier density exceeding the donor density. We have the **intrinsic region**.

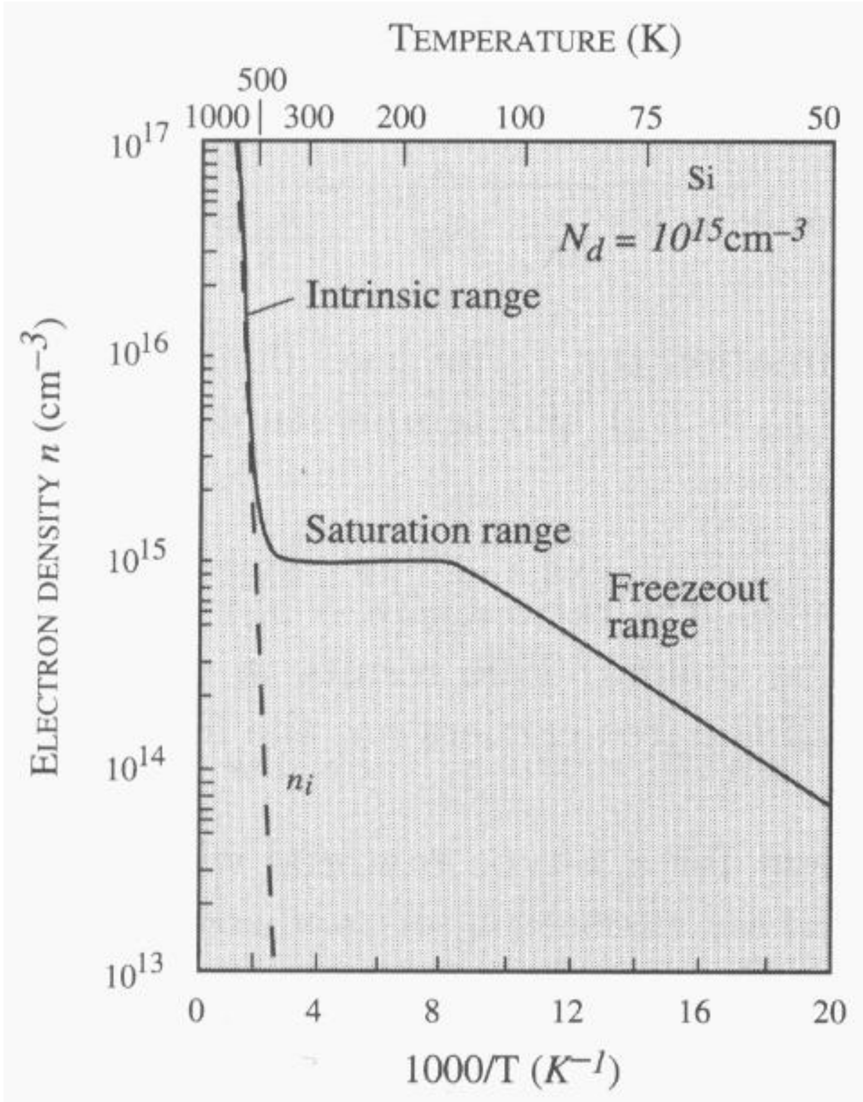
Carrier Freezeout

n = total free electrons in conduction band

n_d = electrons bound to donors

p = total free holes in the valence band

p_a = holes bound to the acceptors



Carrier Freezeout

- The fraction of electrons tied to donor levels in an n-type material with doping density N_d is:

$$\frac{n_d}{n+n_d} = \frac{1}{\frac{N_C}{2N_d}\exp\left[-\frac{(E_C - E_d)}{k_B T}\right]+1}$$

- The donor ionization energy (E_c-E_d) and temperature determine the fraction of bound electrons.
- At low temperatures the ratio $n_d/(n+n_d) \rightarrow 1$ so that all electrons are bound to donors.
- A similar result can be produced for p-type material:

$$\frac{p_a}{p+p_a} = \frac{1}{\frac{N_V}{4N_a}\exp\left[-\frac{(E_a - E_v)}{k_B T}\right]+1}$$

- For electronic devices at room temperature it will be assumed the $n=N_d$ and $p=P_a$ for n and p-type materials respectively

Carrier Freezeout: Example

- A sample of silicon is doped with phosphorus at a doping density of 10^{16}cm^{-3}. What is:
  - The fraction of ionised donors at 300K.
  - The change if the doping density is 10^{18}cm^{-3}
- For Si N_d=10^{16}cm^{-3} (donor BE=45meV)

$$\frac{n_d}{n+n_d}=\frac{1}{\frac{2.8\times10^{19}}{2(10^{16})}\exp\left(-\frac{0.045}{0.026}\right)+1}=0.004$$

- n_d is only 0.4% of the total electron concentration and almost all donors are ionised.
- For a donor level of 10^{18} $\frac{n_d}{n+n_d}=0.29$
- Heavy doping and only 71% of dopants are ionised.

Heavily Doped Semiconductors

- We have assumed the doping levels are low in our theory so far which means:
  - The bandstructure of the host crystal is not seriously perturbed and the bandedges are still described by simply parabolic bands.
  - The dopants are independent of each other and therefore their potential is a simple Coulombic potential.
- This is not valid when the spacing of the impurity atoms reaches ~10nm
- At high doping levels we will get impurity bands.
- The bandgap will narrow resulting in poor performance for a number of electronic devices

Scattering in semiconductors

- The equation of motion for a free electron is:

$$\hbar \frac{dk}{dt} = F$$

- Quantum mechanics states that in a perfect semiconductor there is no scattering of electrons as they move through the periodic lattice structure.
- The presence of lattice imperfections will cause electron scattering.
- If a beam of electrons is incident on a semiconductor, the average time it takes to lose coherence of the initial state values is called the relaxation time (τ_{sc}). The average distance between collisions is called the mean free path.

Scattering in semiconductors

- Under thermal equilibrium, the average thermal energy of a conduction electron can be obtained from the theorem of equipartition of energy.
- *1/2kT* units of energy per degree of freedom.
- The electrons in a semiconductor have three degrees of freedom; they can move about in three dimensional space.
- The kinetic energy of electrons is hence given by:

$$\frac{1}{2}m^* v_{th}^2 = \frac{3}{2}kT$$

- v_{th} is the average thermal velocity of electrons.
- At room temperature the thermal velocity is about 10^7cm/s for Si and GaAs.

Sources of scattering

Ionised impurities	Due to dopants in the semiconductor
Phonons	Due to lattice vibrations at finite temperatures $\rightarrow$ result in bandedge variations
Alloy	Random potential fluctuations in alloy semiconductors (MOSFET)
Interface roughness	Important in heterostructure devices
Chemical impurities	Due to unintentional impurities

A total scattering rate can be defined:

$$R_{Tot} = \sum_i R_i \qquad \frac{1}{\tau_{sc}} = \sum_i \frac{1}{\tau_{sc}^{(i)}}$$

τ^{i}_{sc} is the scattering time of the electrons due to each individual scattering process.

For a typical value of 10^{-5}cm for the mean free path, $\tau^{(I\imath}_{sc}$ is about 1ps

E-fields in semiconductors

- With the application of an E-field, the electrons move under the external force.
- A steady state is established in which the electrons have a net drift velocity in the field direction.
- In the absence of any applied field the electron distribution is given by the Fermi-Dirac distribution.
- When a field is applied a new distribution which is a function of the scattering rates and field strength is introduced – it is determined by solving the Boltzmann transport equation.
- The response of electrons to the field can be represented by a velocity-field relationship.

Low field response

- Macroscopic transport properties:
  - Mobility
  - Conductivity
- Microscopic properties:
  - Scattering rate
  - Relaxation time
- At low fields the above quantities can be related.
- Assumptions:
  - The electrons in the semiconductor do not interact with each other $\rightarrow$ the independent electron approximation.
  - Electrons suffer collisions from various scattering sources. τ_{sc} describes the mean time between respective collisions.
  - In between collisions electrons move according the equation of motion for a free electron.
  - After a collision the electrons lose all their excess energy

Low field response

- Assuming immediately after a collision the electron velocity is zero and that the electron gains velocity in between collisions for time τ_{sc}.
- The average velocity gain is:

$$v_{avg} = -\frac{eE\tau_{sc}}{m^*} = v_d$$

- v_d is the drift velocity. The current density is hence:

$$J = -nev_d = \frac{ne^2\tau_{sc}}{m^*}E \quad \text{or} \quad J = \sigma E$$

- Recall the mobility (μ) defines the proportionality factor between the drift velocity and the applied E field:

$$v_d = -\mu E$$

Low field: Mobilities

- If both electrons and holes are present, the conductivity of the material becomes:

1/*m** dependence

$$\sigma = ne\mu_n + pe\mu_p$$

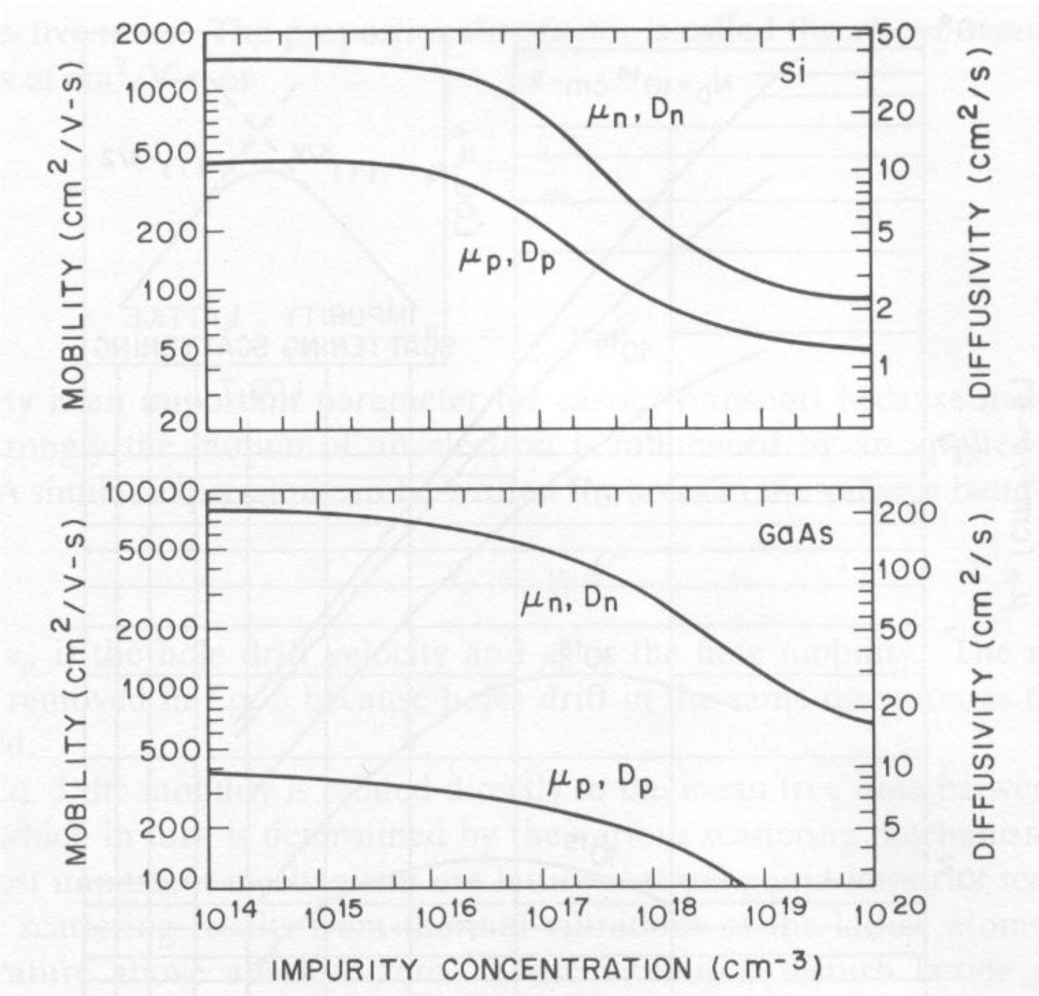
- μ_n and μ_p are the electron and hole mobilities and n and p are their densities.

Mobility at 300K (cm^2/V•s)		
Semiconductor	Electrons	Holes
Si	1500	450
Ge	3900	1900
GaAs	8500	400

Mobility at low E field

Mobility reaches a maximum value at low impurity concentration; this corresponds to the lattice-scattering limitation.

The mobility of electrons is greater than that of holes. Greater electron mobility is due mainly to the smaller effective mass of electrons.

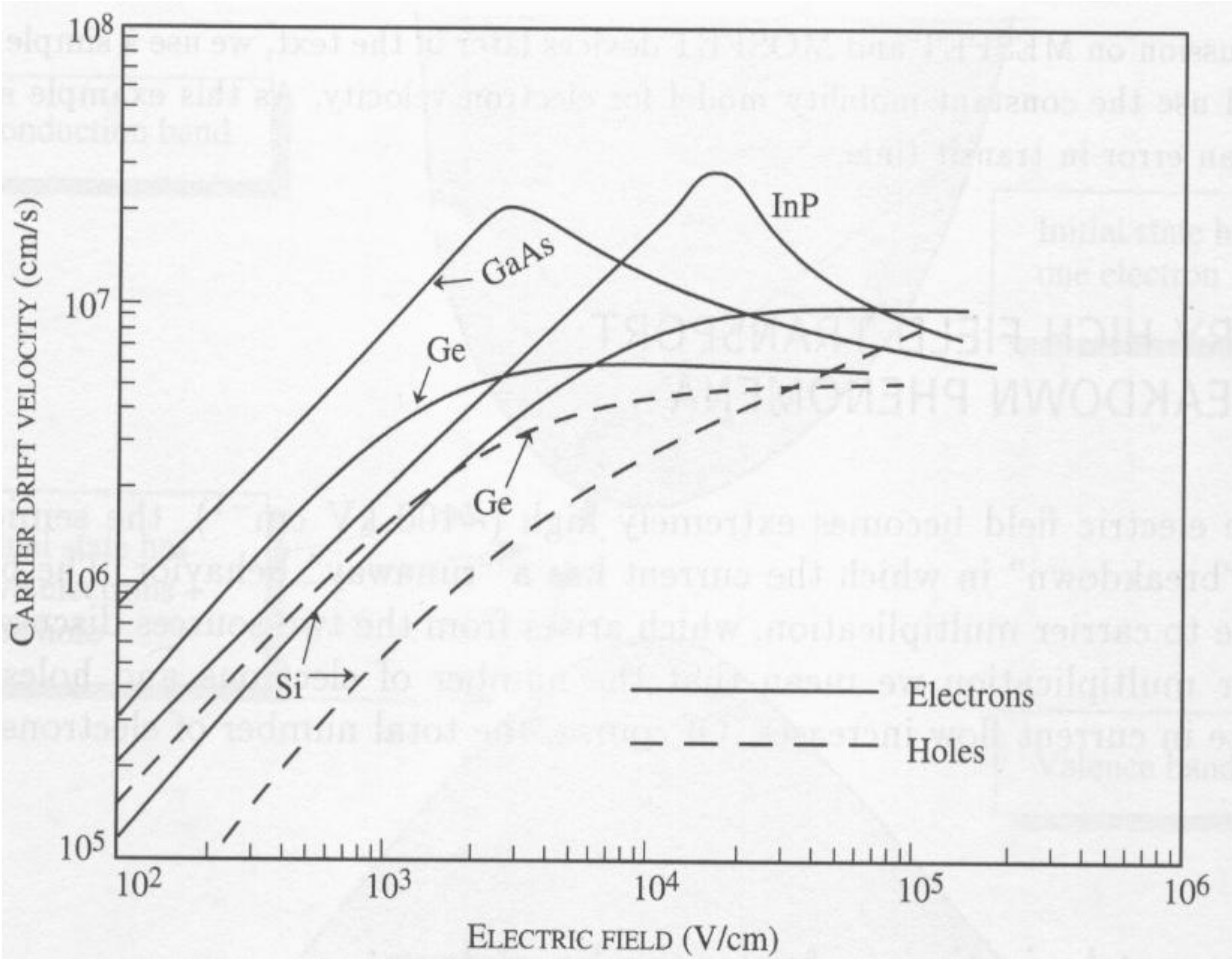


- Mobility as a function of impurity concentration at room temperature.

High E-fields

- Important in most electronic devices.
- At high fields (~1-100kV/cm) electrons acquire a high average energy.
- As the carriers gain energy they suffer greater scattering and the mobility starts to decrease.
- At very high fields the drift velocity becomes saturated and therefore independent of the E-field.
- The drift velocities for most materials saturates to a value of ~10^7cm/s.
- This fact is important in the understanding of current flow in semiconductors.

Carrier velocity E-field relationship



Charge transport: Example

- Calculate the relaxation time of electrons in silicon with E-fields of 1kV/cm and 100kV/cm at 300K.
- 1kV/cm v_d=1.4×10^{6}cm s and 100kV/cm v_d=1.0×10^{7}cm s.
- The mobilities are:

$$\mu(1kV/cm) = \frac{v_d}{E} = \frac{1.4 \times 10^6}{1 \times 10^3} = 1400 cm^2/V \cdot s$$

$$\mu(100kv.cm) = 100 cm^2/V \cdot s$$

- The corresponding relaxation times are hence:

$$\tau_{sc}(1kV/cm) = \frac{m^* \mu}{e} = \frac{(0.26 \times 9.1 \times 10^{-31} kg)(1400 \times 10^{-4} m^2/V)}{1.6 \times 10^{-19}}$$

$$= 2.1 \times 10^{-13} s$$

$$\tau_{sc}(100kV/cm) = 1.48 \times 10^{-14} s$$

- The scattering rate is increased at higher E-field.

Very high E-field

- For E-fields >100kV/cm^{-1}, the semiconductor material will suffer a breakdown, with runaway current behaviour.
- Occurs due to carrier multiplication.
  - Avalanche breakdown
  - Zener Tunneling
- At very high E-fields the electron (hole) does not remain in the same band during transport. For example, an electron can scatter with an electron which is in the valence band an knock it into the conduction band.
- The initial electron energy must be slightly larger than the bandgap energy in order for this to happen.
- In the final state there are two electron in the conduction band and one hole in the valence band. This process is referred to as **avalanching**.

Zener Tunnelling

- Recall quantum mechanical tunnelling probabilities responsible for our understanding of nuclear decay.
- In high E-fields electrons in the valence band can tunnel into unoccupied states in the conduction band.
- The tunnelling probability through the potential barrier (triangular) is given by:

$$T \cong \exp\left(\frac{-4\sqrt{2m^*}E_g^{3/2}}{3e\hbar E}\right)$$

- In narrow bandgap material this band-to-band tunnelling (Zener tunnelling) is important.
- This is the basis of the Zener diode where the current is essentially zero until the tunnelling starts, and the current increases very sharply.
- A tunnelling probability $\sim 10^{-6}$ is necessary to start the breakdown process.

Summary of lecture 4

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