Lecture 10 Doping semiconductors

Consider silicon semiconductor with some Si atom replaced by the atom of group V, like N, P, As, Sb. These atoms have five valent electrons s^2p^3. Four of them will form bonds with four silicon neighbors and the fifth electron will go away. Thus these atoms act as <u>donors</u> giving additional carriers (electrons) to semiconductor. Analogously replacing Si atom by the atom of group <u>III</u>, like B, Al, Ga, In will produce holes. These impurities are called <u>acceptors</u> since they accept electrons from the valence band to form the covalent bonds, leaving holes in the band. The deliberate addition of impurities to a semiconductor is called <u>doping</u>

Consider donor impurity (like P in Si)

An additional electron leaves in the conduction band with a spectrum

$$\mathcal{E}(k) = \frac{\hbar^2 k^2}{2m_c} + E_g .$$

For simplicity we consider a single isotropic band with effective mass m_c

With one electron left phosphorus (P) ion produces electric field. that can trap electron

Schrödinger equation is

$$\left(-\frac{\hbar^2 \nabla^2}{2m_c} - \frac{e^2}{\varepsilon |r|} \right) \psi(r) = E \psi(r)$$

This is just the Schrödinger equation for the hydrogen like atom. The energy spectrum is

$$E_n - E_g = -\frac{m_c e^4}{2\hbar^2 \varepsilon^2 n^2} = -\frac{m_c}{m_0 \varepsilon^2 n^2} Ry$$

Similarly to excitons its energy is strongly reduced compared to the hydrogen atom

With $\varepsilon \approx 12$ and $m_c \simeq 0.2\, m_e$ we get

$E_1 \simeq -$ 20 meV.

The effective radius of the state (analog of Bohr radius) is

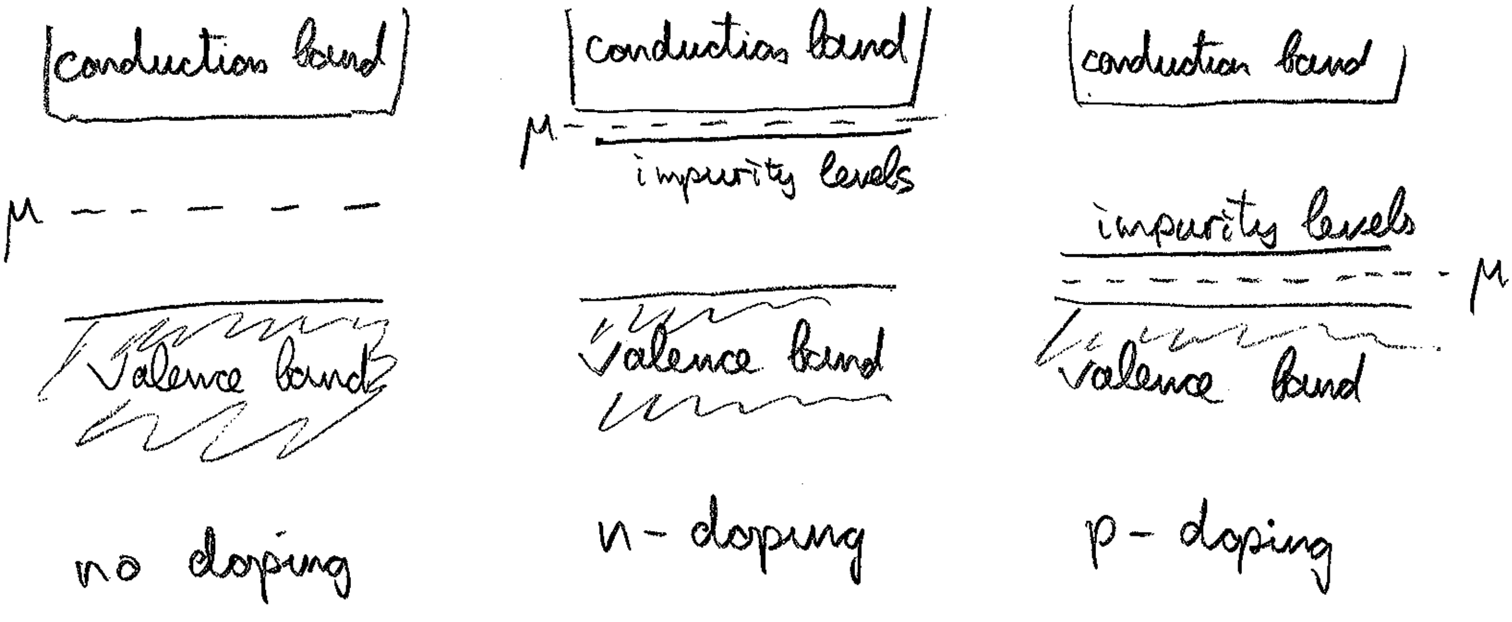
$$r_1 = \frac{\hbar^2 \varepsilon}{m^* e^2} = \frac{\varepsilon m}{m_c} a_B \simeq 30 \text{ Å}$$

This radius strongly exeeds interatomic distance. Thus weakly bound electron spreads far away from the P ion, thus certifying our use of band spectrum and ε to describe its behavior.

Because of the large radii the donor orbits overlap at relatively low donor concentation thus forming "impurity band". The semiconductor can conduct in the impurity band by electron hoping from donor to donor

Because of the low binding energy these states can be easily ionized to the conduction band at room temperature. One speakes about an <u>n-doped</u> semiconductor (n = negative charge). In the same way group III impurities like Al produce weably bound holes. This case is called <u>p-doping</u> (p = positive charge).

In both cases the chemical potential is attached to the dopand levels (it lies between the dopand level and the conduction band for n-doping and between the dopand level and the valence band for p-doping)



In the Lecture 9 we derived the electron density

$$n_e = e^{\frac{\mu - E_g}{T}} \left(\frac{2\pi m_c T}{4\pi^3} \right)^{3/2}$$

and the hole density

$$n_h = e^{-\frac{\mu}{T}} \left(\frac{2\pi m_v T}{4\pi^3} \right)^{3/2}$$

Their product does not depend on position of chemical potential

$$n_e n_h = n_0^2 \left(\frac{T}{T_0} \right)^3 e^{-\frac{E_g}{T}} = n^2(T)$$

For intrinsic Si semiconductor we have

$n_e = n_h \simeq 10^{10}\ \mathrm{cm}^{-3}$ at room temperature

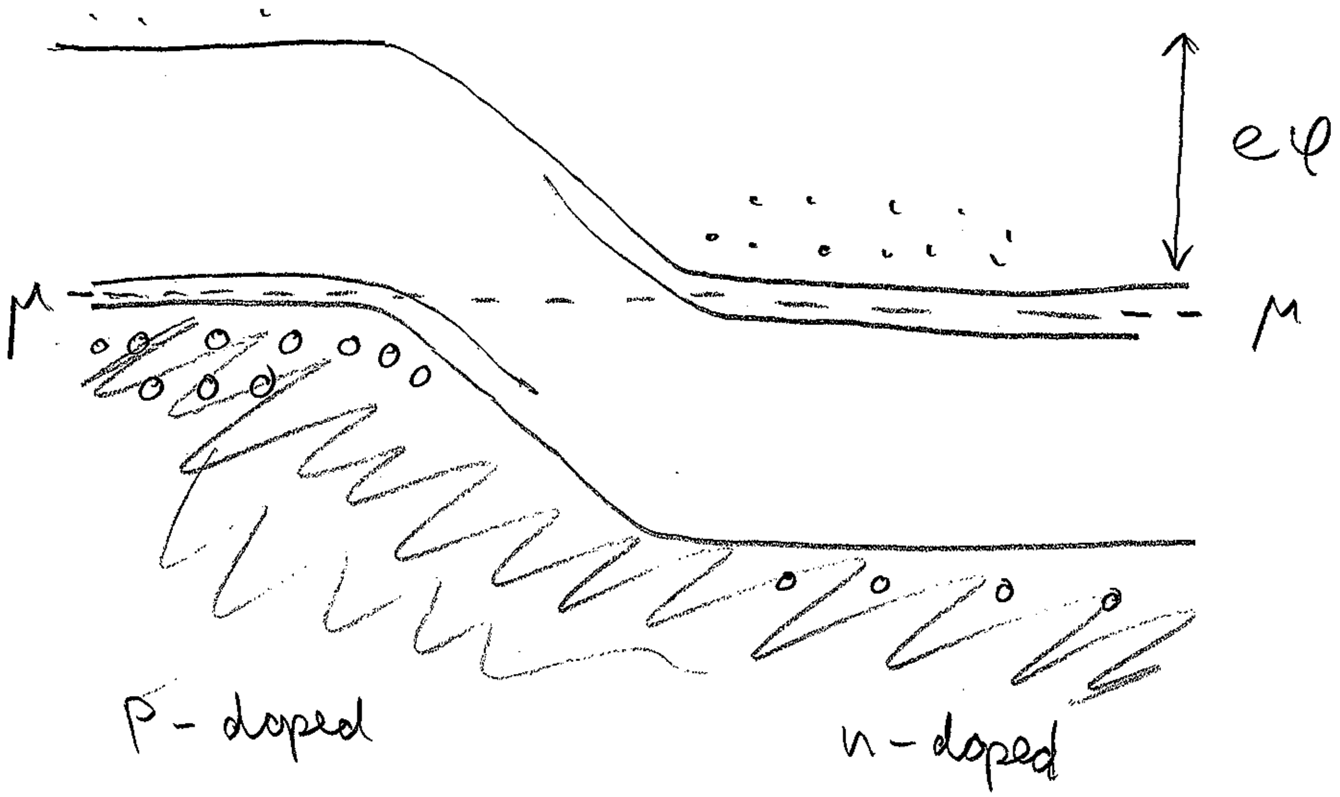
For n-doped Si with a typical donor concentration $n_d \simeq 10^{17}\ \mathrm{cm}^{-3}$ assuming that most of the donors are ionized we will get $n_e \simeq n_d \simeq 10^{17}\ \mathrm{cm}^{-3}$ and

$$n_h = \frac{n^2(T)}{n_e} \simeq 10^3\ \mathrm{cm}^{-3}.$$

Semiconductor devices

pn-junctions are made by bringing in contact a p-doped and n-doped version of the same semiconductor.

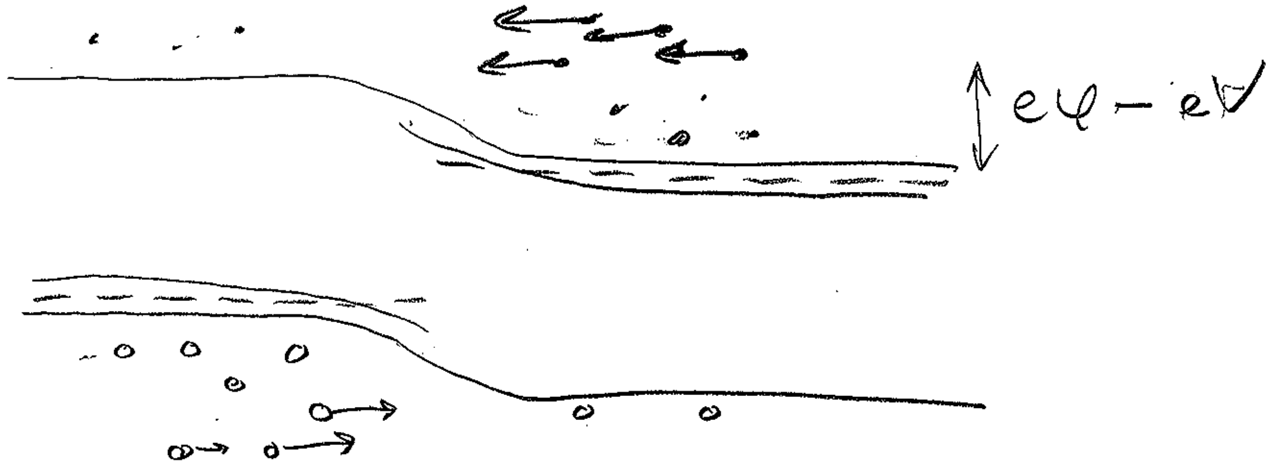
The chemical potential is pinned to the impurity levels. In equilibrium the chemical potential is constant across the sample. Then we have a "band bending"



Between the p and n-doped parts there is an electrostatic potential drop and depletion layer with low carrier density

There is larger number of electrons on the n-side They are diffusing to the p-side producing diffusion current. The same happens with holes that diffuse in the opposite direction Since electrons and holes have opposite charge these current add up. This diffusion of carriers produce dipole layer at the interface In equilibrium the drift current produced by this dipole field is compensated by the diffusion current due to the gradient of carrier concentration.

Applying voltage that reduces this dipole field will enhace the diffusion current without changing the drift current



Then we have current flowing through the junction. Applying the opposite voltage will only change the width of the deplition layer without producing significant current.

To get an IV curve we note that in equilibrium both drift and diffusion currents are $\propto e^{-\frac{E_g}{T}}$. For the drift current this exponent comes from the low carrier concentration in the deplition layer.

For the diffusion current the same exponent describes the thermal activation over the dipole barrier that strongly depends on the applied voltage $j_{diff} = C\, e^{-\frac{(E_g - eV)}{T}}$.

- The drift current is unchanged

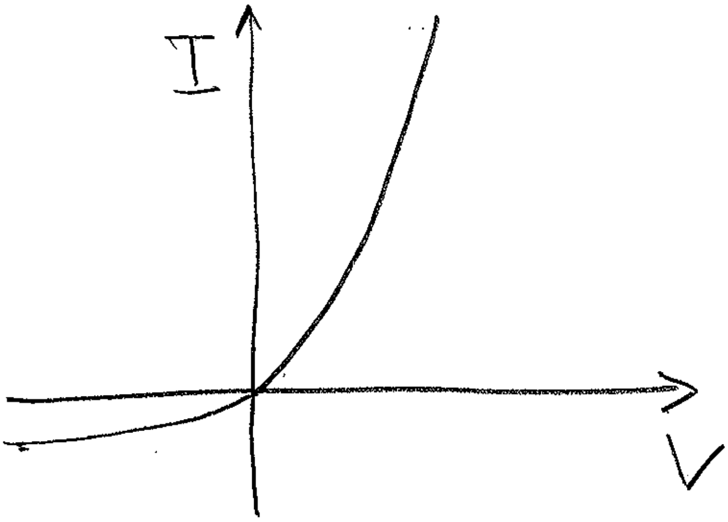
$$j_{drift} = -C\, e^{-\frac{E_g}{T}}$$

Combining both we obtain the Shockley diode equation

$$J_{tot} = C e^{-\frac{E_g}{T}} \left(e^{\frac{eV}{T}} - 1\right)$$

Reversing voltage we reduce diffusion current without changing the drift current that will dominate in this case

$$J_{tot} = -Ce^{-\frac{E_g}{T}}\left(e^{-\frac{eV}{T}}-1\right)$$



Thus we have diode that can rectify the alternating current

Light emitting diodes

The recombination of electrons and holes can lead to the emission of photons with the frequency E_g. An excess of electron-hole pairs can be produced in pn-diodes by applying current. Using different semiconductor with different gaps allows to tune the color of the emitted light.

		wave length	
$GaAs$	-	940 nm	infrared
$GaAs_{0.6}P_{0.4}$		660 nm	red
$GaAs_{0.4}P_{0.6}$		620 nm	yellow
GaP		550 nm	green
GaN		340	blue

Solar cell

The charge carriers can be induced by the light absorption. If the n-side of a diode is exposed to irradiation this will create hole carriers. These holes will diffuse to the pn interface and produce the current $-J_L$. Then the total current

$$J = J_{pn} - J_L = J_0\left(e^{\frac{eV}{T}} - 1\right) - J_L$$

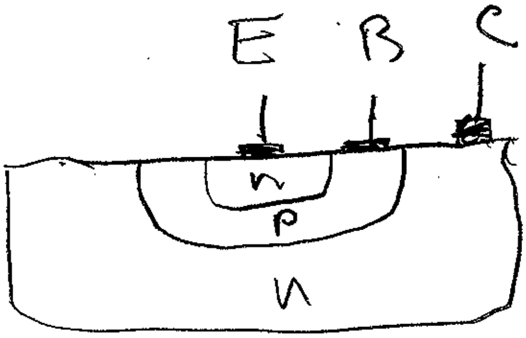
For $J = 0$ we have voltage drop

$$V_L = \frac{T}{e} \ln\left(\frac{J_L}{J_0} + 1\right)$$

Transistors

Bipolar junction transistor   Shockley 1948

npn or pnp junctions

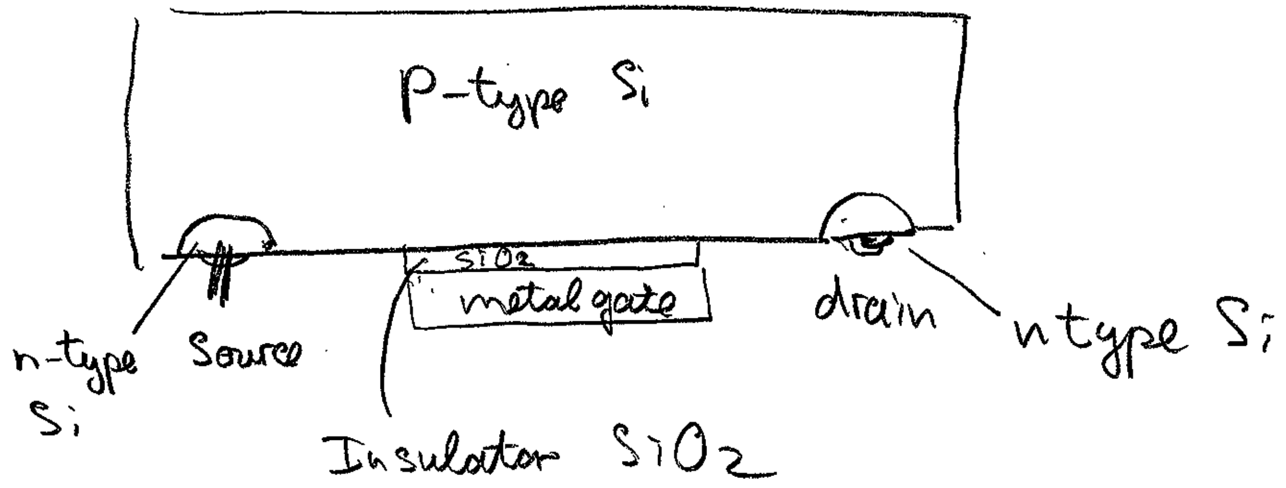


P electrode is the Base between emitter and collector.

In the active mode E B np junction is open and pn -BC junction is closed in this way one gets maximum amplification of the base current

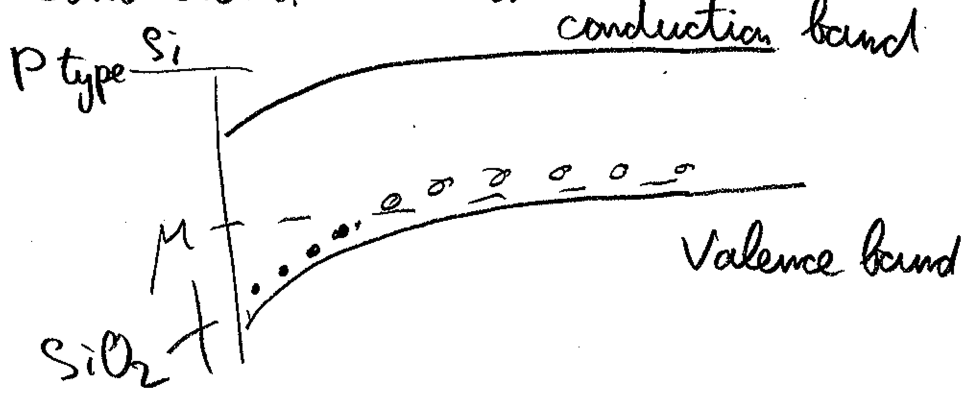
MOSFET

Metal - Oxide - Semiconductor - Field - Effect - Transistor

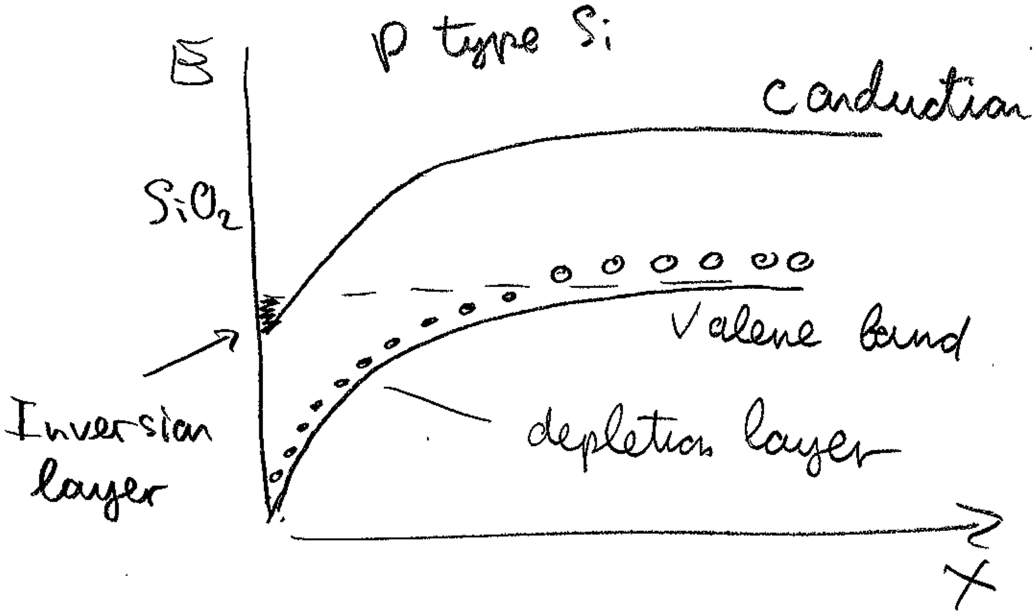


One applies gate voltage to the metal gate that is separated from the p-type Si by insulating SiO_2. Insulator is needed to have no current from the gate to semiconductor

Applying gate voltage bends down the conduction band



For sufficiently large voltage $eV_g > E_g$ inversion layer is created



In this inversion layer conduction band is bent below the valence band. The electrons in the inversion layer provide carriers that connect n-type source and the drain electrons producing large current