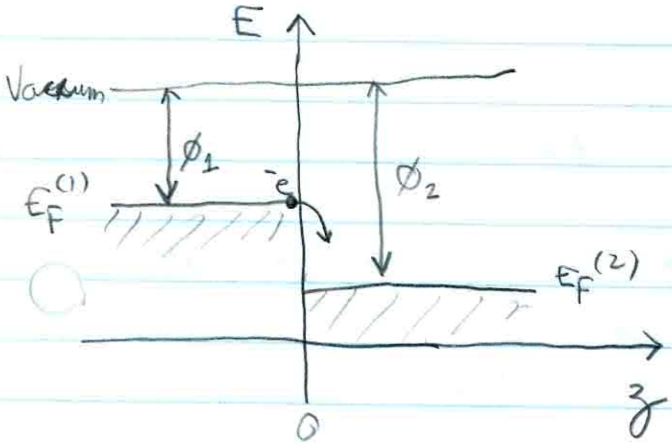
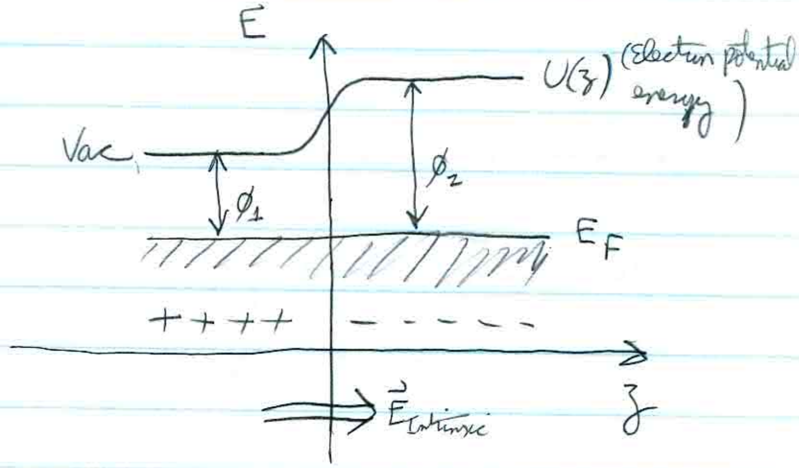
Lecture #9 :

Contact between two materials "HETERO JUNCTIONS"

Main Concept: Energy bands will "bend" so that chemical potential becomes equal for both materials.

Metal to Metal junctions





Immediately after contact: Different Fermi levels, electrons from left metal "diffuse" into metal at right.

After equilibrium is reached: Charge transfer across junction stops when Fermi levels are equal. The work fns do not change, implying that vacuum potential varies across junction. "Band Bending".

Determine thickness of band bending region:
Poisson eqn:

$$\nabla^2 V(z) = -\frac{\rho}{\varepsilon} \Rightarrow \frac{\partial^2 V}{\partial z^2} = -\frac{\rho(z)}{\varepsilon}$$

$$\rho(z) = \begin{cases} 0, & z < -d \\ -en, & -d < z < 0 \\ +en, & 0 < z < d \\ 0, & z > d \end{cases} \quad \underset{\text{here}}{(e<0)}$$

$\Rightarrow \rho(z) = \text{Const}$ so

$V(z) = \text{Const}\, z^2 + \text{Const}\, z + \text{Const}$

Initial cond: $V(-\infty) = V_0$, $V'(-\infty) = 0$.

②

$$V(z) = \begin{cases} V_0 & , z < -d \\ V_0 + \left(\frac{en}{2\varepsilon}\right)(z+d)^2 & , -d < z < 0 \\ V_0 + \Delta - \frac{en}{2\varepsilon}(z-d)^2 & , 0 < z < d \\ V_0 + \Delta & , z > d \end{cases}$$

} continuous

} continuous

Here $\boxed{e}\Delta \approx E_F^{(1)} - E_F^{(2)}$

$n \sim n_{\text{initial}}$

(A more sophisticated approach is needed to find $E_{F\,\text{final}}$ and n)

To find d, impose continuity at $z = 0$:

$$\left(\frac{en}{2\varepsilon}\right) d^2 = \Delta - \left(\frac{en}{2\varepsilon}\right) d^2 \Rightarrow 2\left(\frac{en}{2\varepsilon}\right) d^2 = \Delta \Rightarrow \boxed{d = \sqrt{\frac{\varepsilon}{en}\Delta}}$$

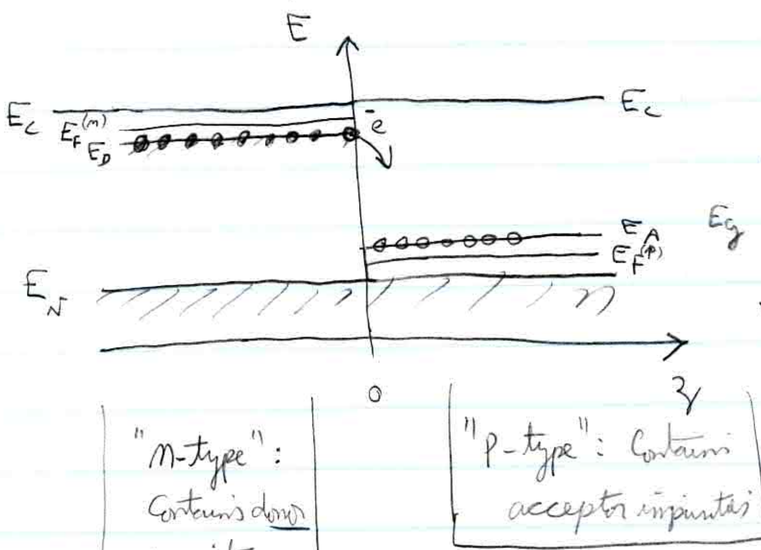
For $e\Delta \sim eV$ and $n \sim 10^{21} cm^{-3}$ $\Rightarrow \boxed{d \sim \text{few } Å}$.

$\Rightarrow$ Putting two metals in contact produces a voltage difference.

This is how the thermocouple (or thermopair) works: For $T > 0$, μ shifts, so Δ will be temperature dependent $\Rightarrow$ Voltage difference across junction changes and can be used as a thermometer.

Junction between two doped semiconductors

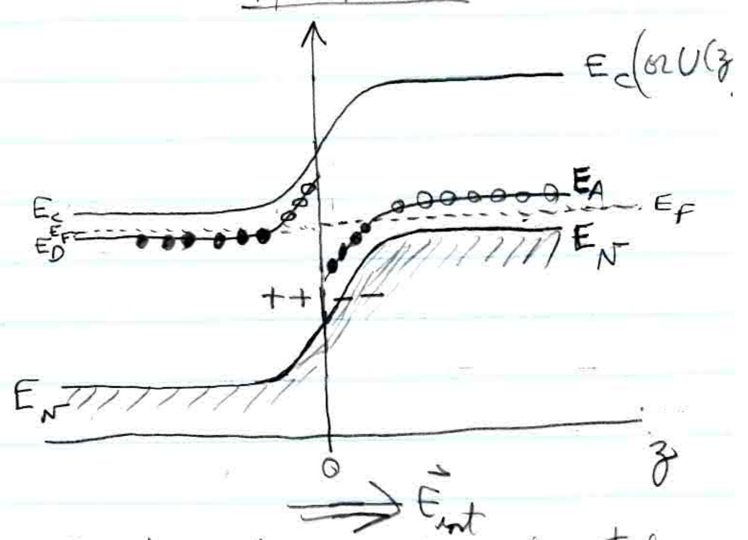
Before equilibrium



"n-type": Contains donor impurities

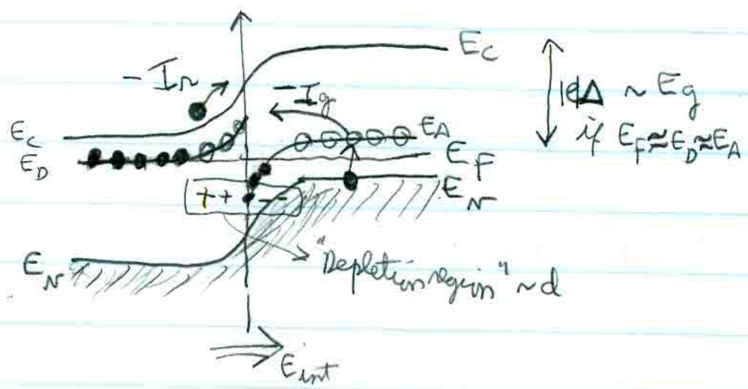
"p-type": Contains acceptor impurities

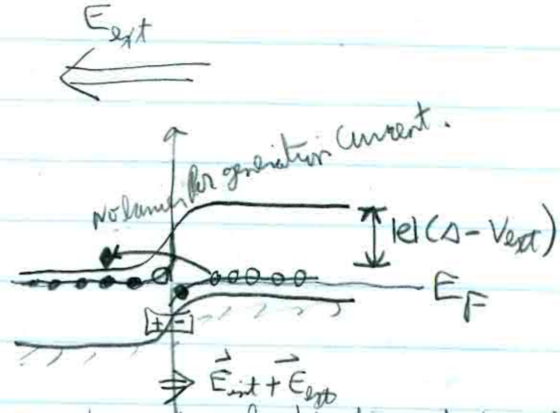
After equilibrium



Bands bend so that chemical potentials match and E_g (gap) remains the same.

pn junction: A current "rectifier"





V_{ext} reduces band bending and reduces depletion region.

If there happens to be an electron on the left side, it will "jump up the barrier" with probability proportional to $e^{-|e|\frac{(\Delta - V_{ext})}{k_B T}}$

This gives rise to a recombination current: $I_r = I_0 e^{-\frac{|e|(\Delta - V_{ext})}{k_B T}}$
(called recombination because electron recombines once it reaches right side).

There is also a "generation current" I_g due to electrons going from right to left. It's called generation because it generates carriers on the n side.

I_g is quite small (electron on the right has to jump into acceptor and then jump into the left conduction band), and, I_g does not depend on V_{ext}. Because even for $V_{ext}>0$, $E_C^{(n)} \approx E_A^{(P)}$.

At equilibrium these two currents generation and recombination must be equal:

$$V_{ext} = 0 \Rightarrow I_g = I_r \Rightarrow I_g = I_0 e^{-\frac{|e|\Delta}{k_B T}} \Rightarrow \boxed{I_0 = I_g e^{\frac{|e|\Delta}{k_B T}}}$$

The total current is then:

$$I = I_r - I_g = \underbrace{I_0 e^{-\frac{|e|(\Delta - V_{ext})}{k_B T}}}_{I_g e^{\frac{|e| V_{ext}}{k_B T}}} - I_g = I_g\left(e^{\frac{|e| V_{ext}}{k_B T}} - 1\right)$$

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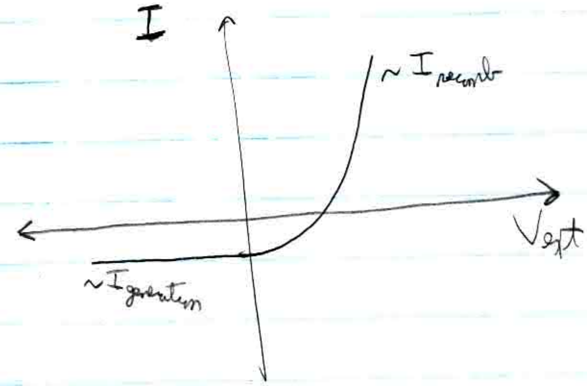
$$\boxed{I = I_g \left(e^{\frac{|e| V_{ext}}{k_B T}} - 1 \right)}$$



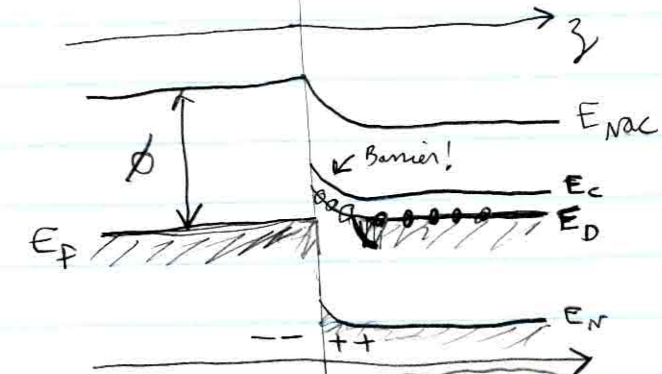
rectification! pn junction works as a diode, a "valve" for current.

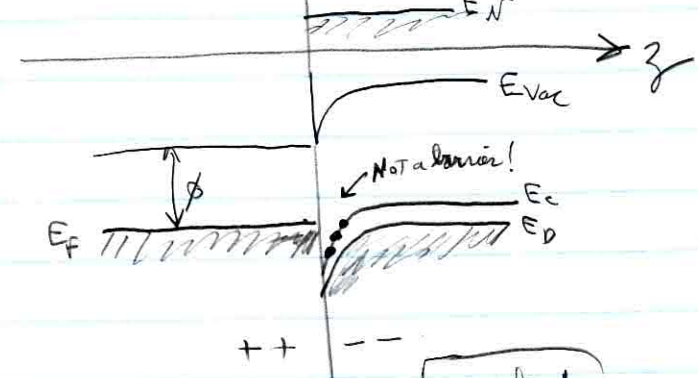
<u>Metal – Semiconductor heterojunctions</u>

Very important: Metal can act as a gate to "tune" electron density in semiconductor.

Two (very different) cases:

$$\begin{cases} E_F^{metal} < E_F^{semicond} \Rightarrow \text{"Schottky barrier" } \underline{\text{no conduction}} \\ \qquad \text{(or Schottky contact).} \\ E_F^{metal} > E_F^{semiconductor} \Rightarrow \text{"Ohmic contact"} \Rightarrow \text{conducts} \end{cases}$$





Schottky contact $\boxed{\text{SM Band "Bends down"}}$ z

Ohmic contact $\boxed{\text{SM band "bends up"}}$

Useful for confinement, e.g. making quantum dots.