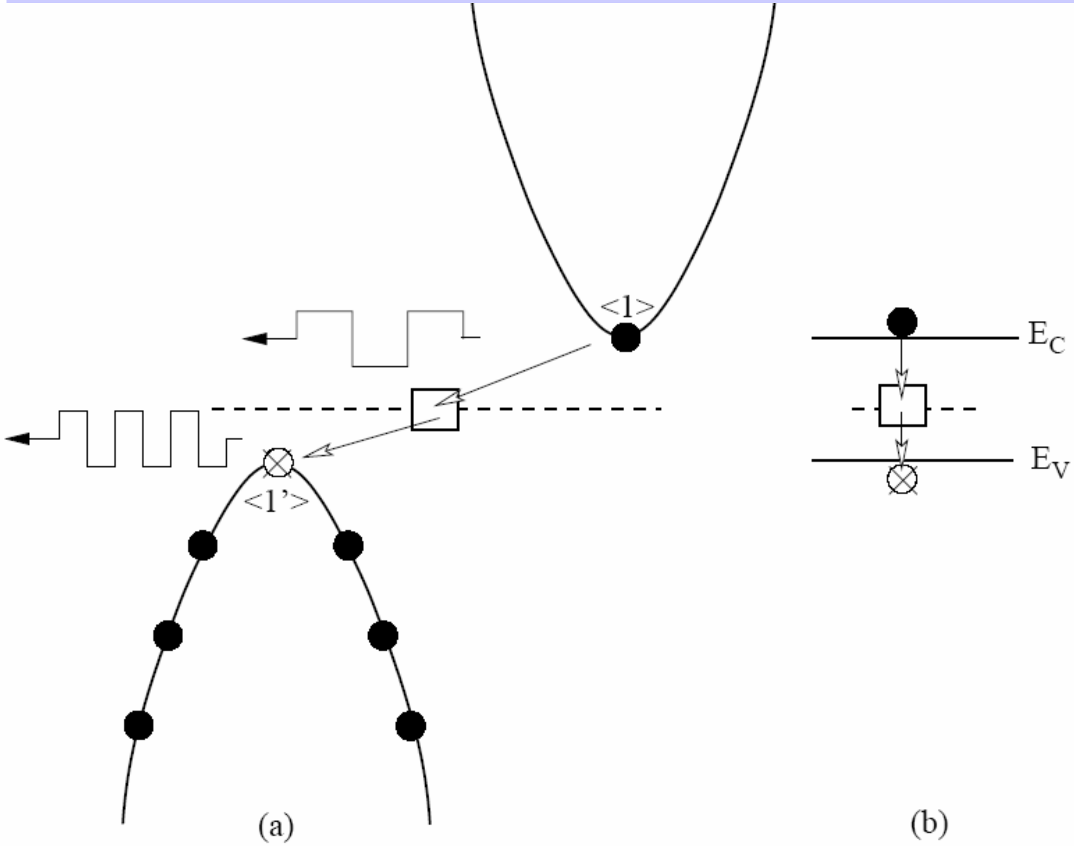
Thermal equilibrium, *pn*-junction

LECTURE 5

- Recombination-Generation centre recombination
- Conditions for thermal equilibrium
- Fermi-Dirac distribution function
- Fermi level
- Energy band diagram for *pn*-junction at equilibrium

Sec. 3.2.2

R-G-centre recombination

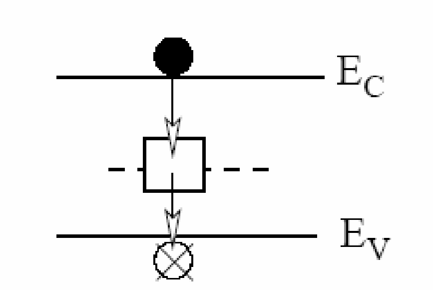


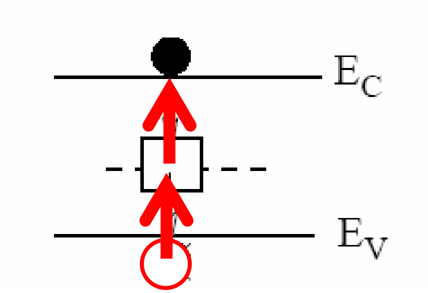
Rate of recombination for p-type material: $\longrightarrow$ $R_{RG,} \approx r N_T n \equiv \square\, n$

"A" depends on the quality of material. For high-grade Si, A = $\square$

Sec. 3.2.2

Generation and recombination via R-G centres





For p-type material: $R_{RG} = An$ $G_{RG,th} = An_0$

Net rate of R-G-centre recombination: $U = R - R_0 \equiv R - G_{th,0}$

What is the significance of the different symbols: n and n_0 ?

What are the units of U?

Secs. 3.2.4, 4.1

Thermal equilibrium

Two conditions need to be satisfied:

1. No net rate of recombination $U = R - G_{th} = 0$

e.g., for R-G-centre recombination in [ ] material

$$R - G = A(n_0 + \Delta n) - An_0$$

$$= A\Delta n \equiv \frac{\Delta n}{\tau} \longrightarrow \tau_{e,\mathrm{RG}} = \frac{1}{A}$$

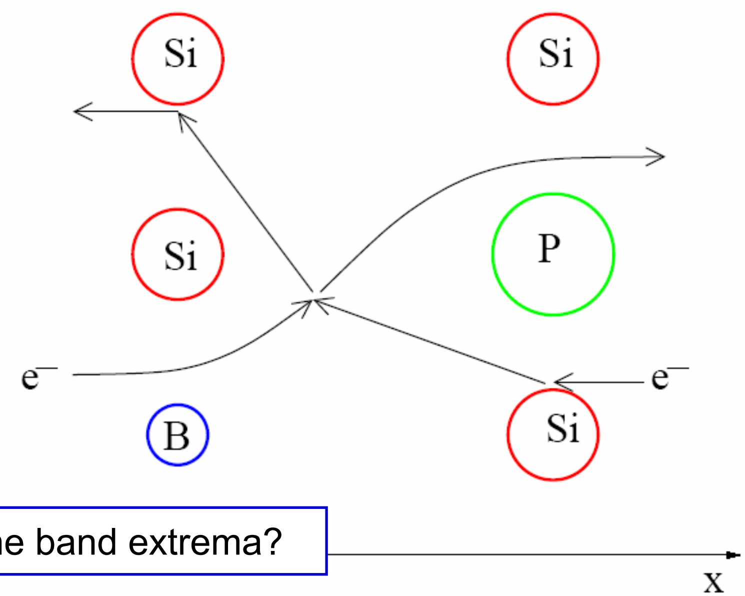
i.e., $\Delta n =$ [ ] in equilibrium

What is τ called?

2. Collisions randomize a carrier's momentum

What's another verb for `collide'?

Collisions keep electrons and holes near the [ ]

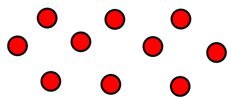


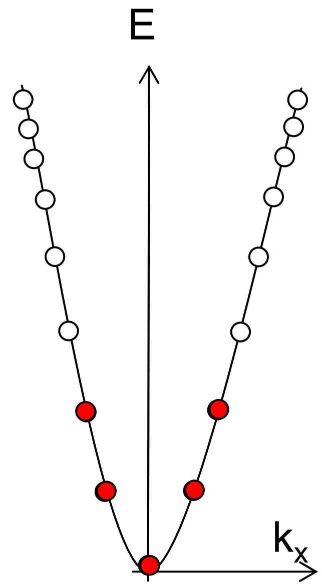
Now do you see the usefulness of a parabolic fit to the band extrema?

Sec. 4.2

Filling states at equilibrium

How are these electrons accommodated in the CB?





Notice that the density of states in energy, g(E), is not constant.

For the distribution function is

$$f_{FD}(E) =$$

E_F is the Fermi (energy) level
k_B is Boltzmann's constant

What is k_BT at 300K?

Sec. 4.2

Fermi-Dirac distribution function

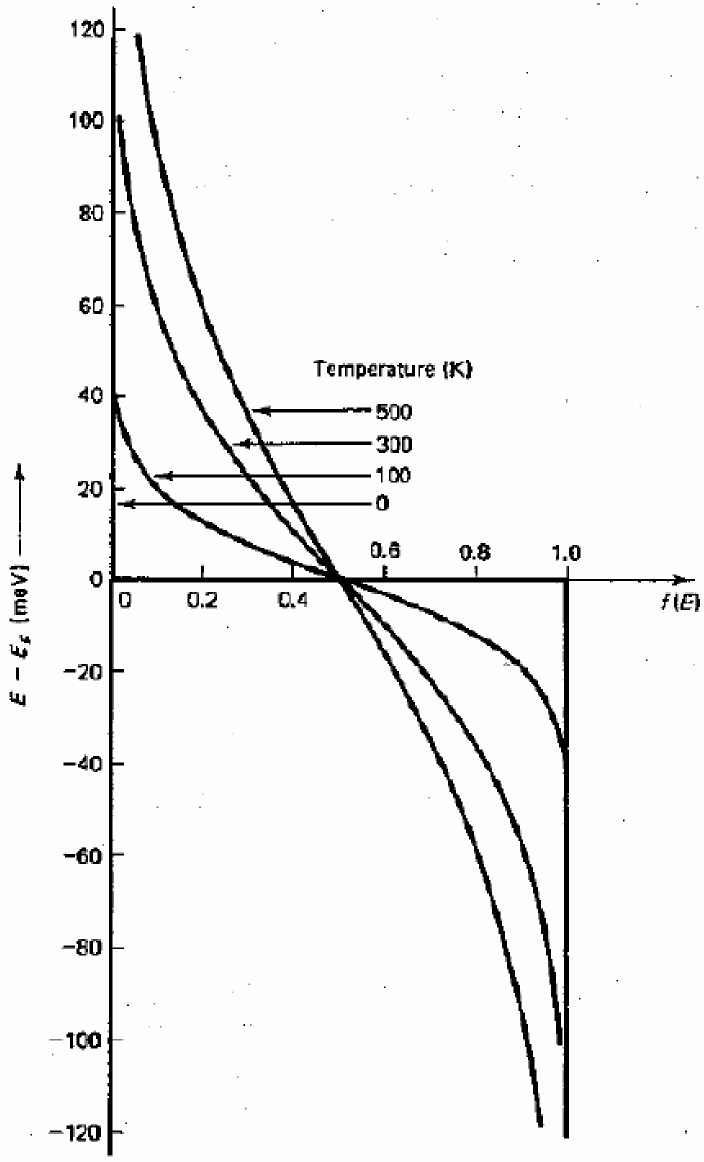
$$f_{FD}(E) = \frac{1}{1 + \exp[(E - E_F)/k_B T]}$$

What is the probability of an electron occupying a state at $E=E_F$?

What is the probability of an electron occupying a state at E when $(E-E_F)=k_BT$?

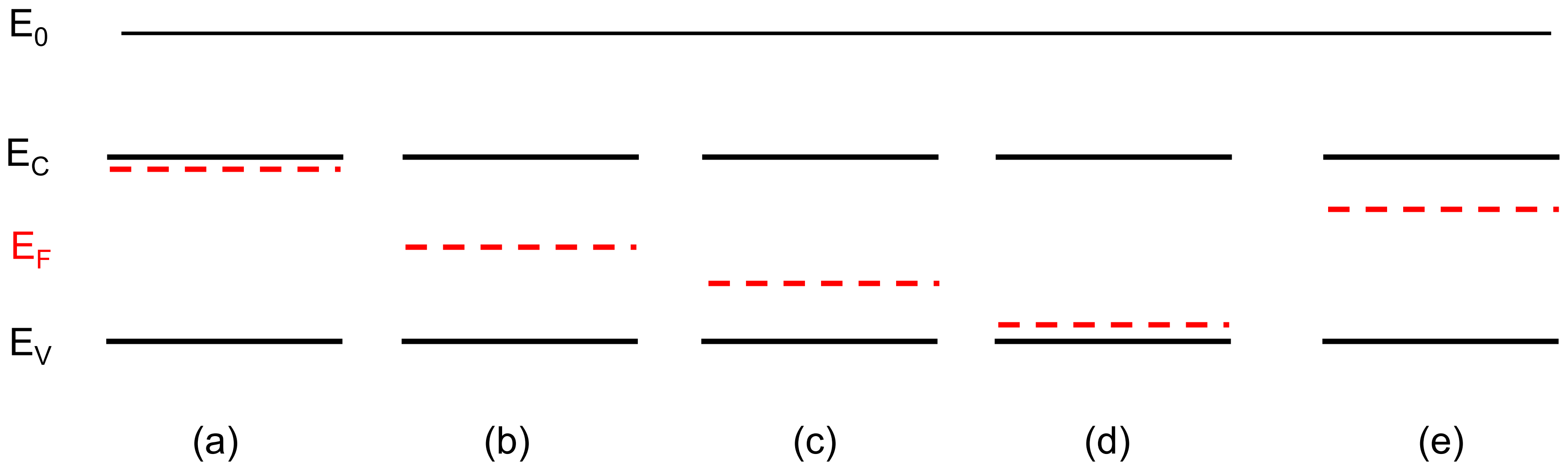
What is the probability of an electron occupying a state at E when $(E-E_F)=10k_BT$?

View E_F as a [ ] for electrons (or holes).



Secs. 4.2, 6.1

The Fermi level



Identify the cases where the material is: n^+, n, intrinsic, p, p^+

- What is E_0 ?
- What material property is defined by E_0-E_C ?
- What is the value for this property in Si?
- What does the energy band diagram look like when n-type and p-type materials are joined together?

Sec. 6.1.2

np-junction band diagram: step 1

- Consider separate *n*- and *p*-material

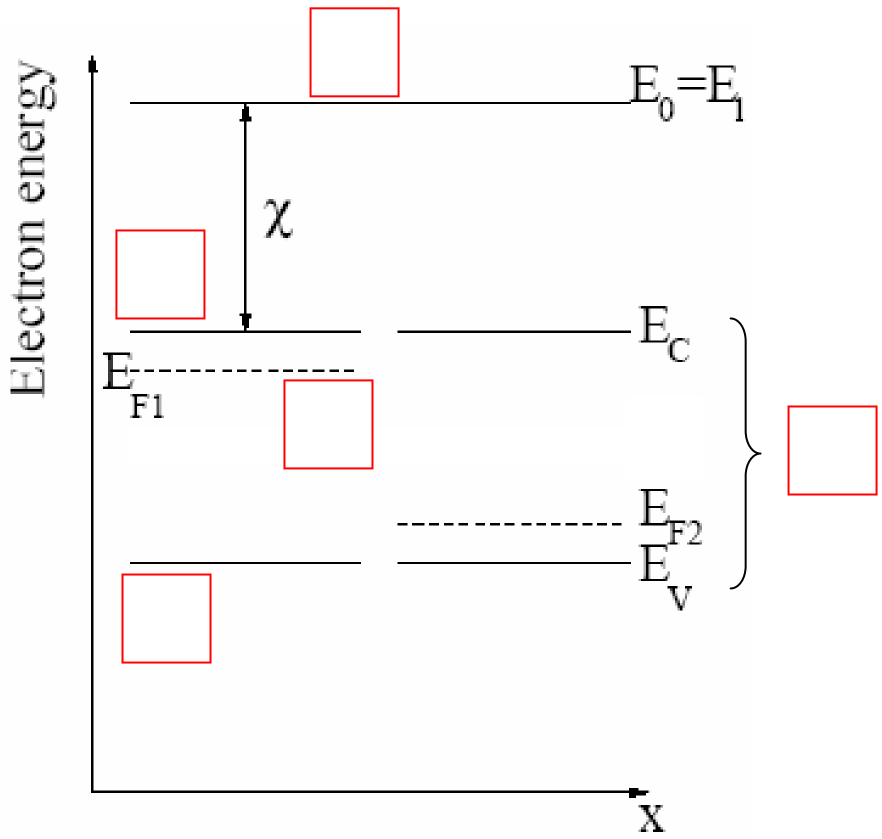
- All energies on the diagram are negative wrt E_0.

- Construct the diagram in the order shown by the numbers.

- Leave a gap between the n- and p-regions

- The difference in E_F is a difference in chemical potential energy*.

* Just as in a battery, it provides a driving force for mobile charges.



np-junction: equilibrium

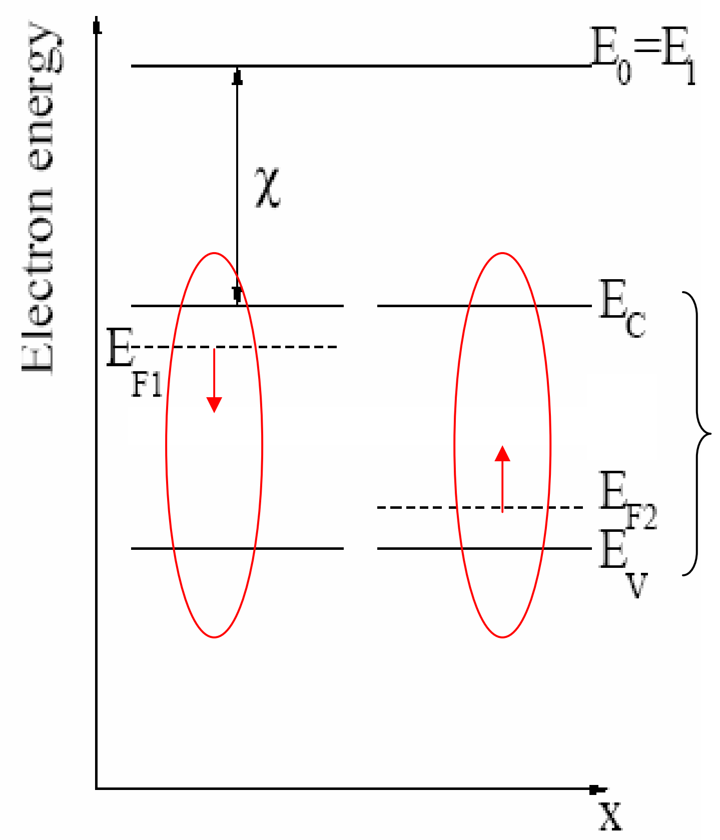
n- and p-materials brought together

drives electrons from n- to p-side

E_F on the n-side drops

E_F on the p-side rises

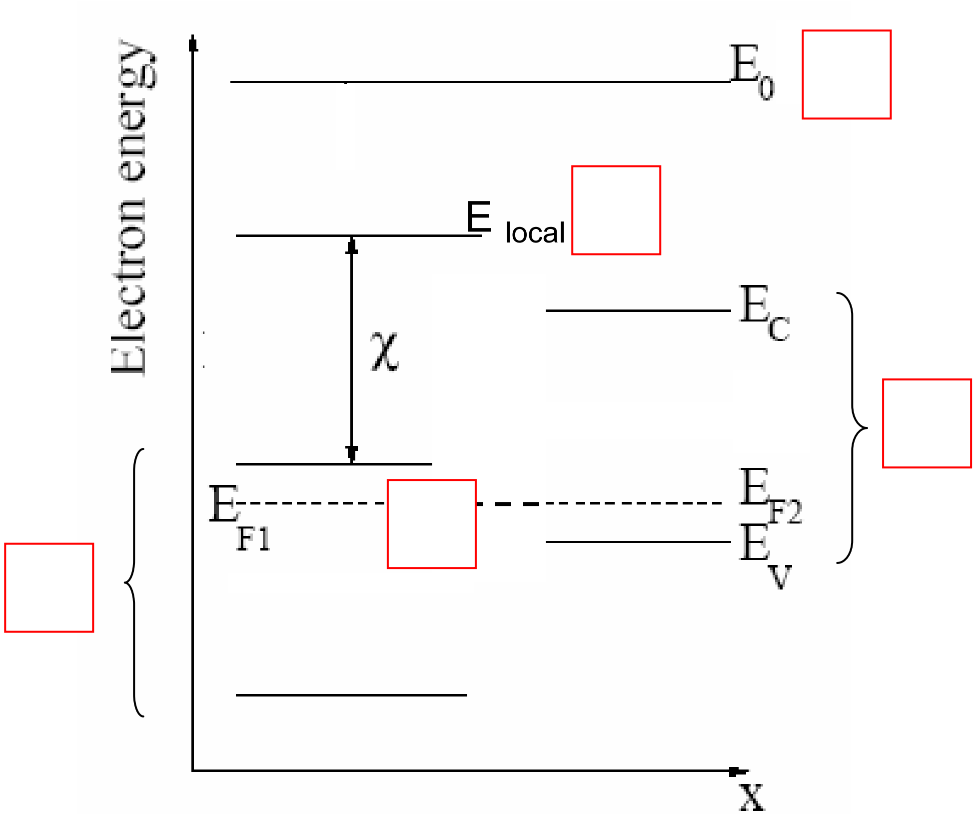
Transfer stops when



Sec. 6.1.2

np-junction band diagram: step 2

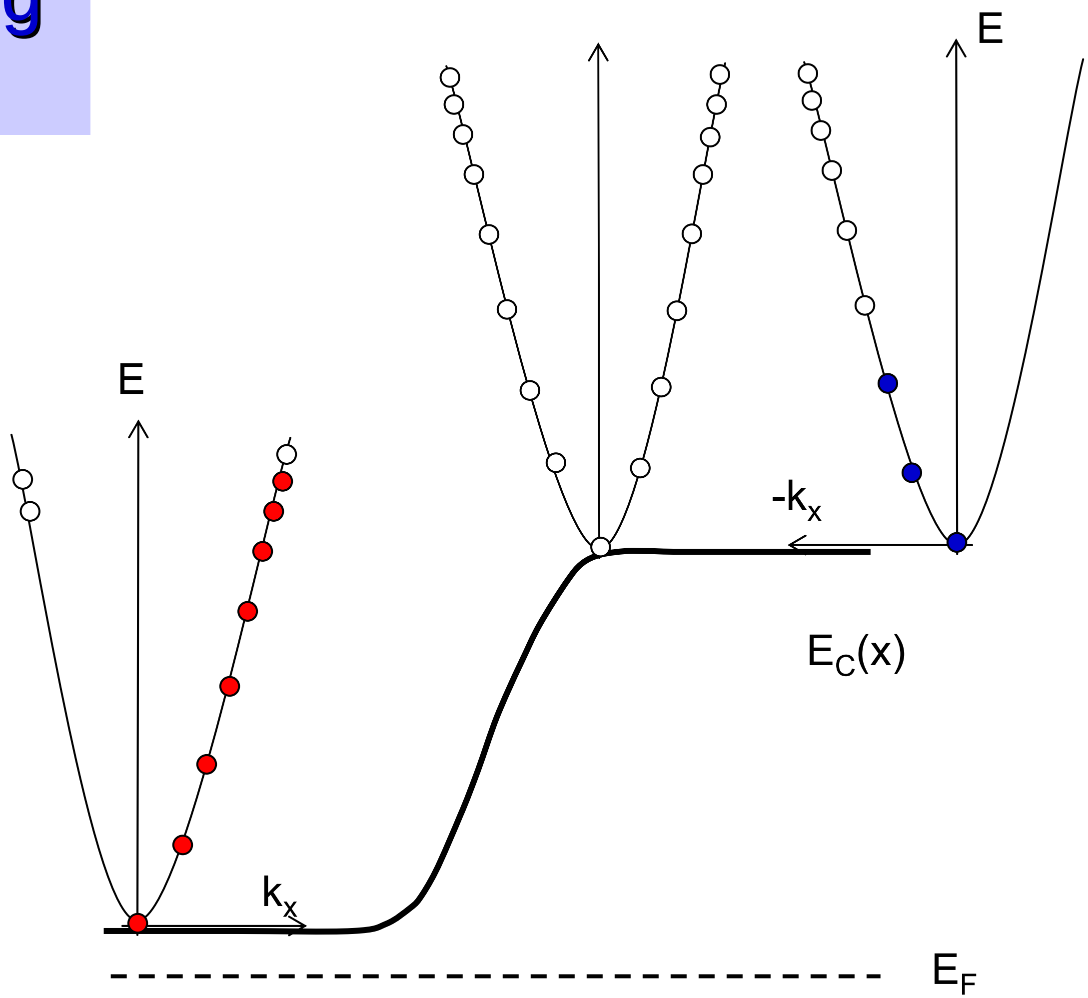
- Keep the *n*- and *p*-materials separate, but align the Fermi levels.
- Construct the diagram in the order shown by the numbers.
- Where the vacuum level is displaced from it's zero-field value it is called the local vacuum level.
- The displacement defines the electrostatic potential.
- The overall potential difference at equilibrium is the built-in voltage.
- E_F is now the electrochemical potential energy.



Identify $-qV_{bi}$. Can it be measured?
Join up E_C, E_V, and E_0 with smooth curves. Why smooth?
Are there any charge flows in this case?
What is the net current in this case?

Current balancing at equilibrium

Sec. 6.1



How many electrons flow from the n-side to the p-side?
How many electrons flow from the p-side to the n-side?
How can this lead to no net current?

Current bala
at equilibr

Sec. 6.1

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