Metal-Semiconductor Junctions

This can have similar behavior to pn junctions, but much easier to fabricate.

Two types

Schottky (Rectifying) barriers

Ohmic (non-rectifying) contacts
Schottky Barriers

What happens when a metal & a semiconductor are brought into contact?

metal work function = energy required to remove an electron at the Fermi level to the outside.

What do you think will happen to the energy bands?

The schottky device is a rectifier (or diode)
$q \Phi_B = q(\Phi_m - \chi)$

barrier for electron injection from metal to semiconductor

$E_{Fm}$

Fermi levels align

$E_{Fs}$

$E_c$

$E_v$

uncompensated donors

equilibrium contact potential (prevents electron diffusion)

Also, the junction capacitance is

$C_j = \frac{\varepsilon A}{W}$

depletion region width (similar to a p+n junction)

permittivity of the semiconductor

$W = \left[ \frac{2 \varepsilon V_0}{q \left( \frac{N_d + N_a}{N_d N_a} \right)} \right]^{1/2} = \left[ \frac{2 \varepsilon V_0}{q \left( \frac{1}{N_d} + \frac{1}{N_a} \right)} \right]^{1/2}$

$q(\Phi_m - \Phi_s) = qV_0$
Metal p-type semiconductor contact

What is the electron injection barrier from metal to semiconductor?
The schottky device is a rectifier (or diode)

At equilibrium

\[ q\Phi_B = q(\Phi_m - \chi) \]

\[ q(\Phi_m - \Phi_s) = qV_0 \]

\[ E_c \]

\[ E_{Fm} \]

\[ E_{F_S} \]

\[ W \]

\[ E_v \]

\[ + \quad V \quad - \]

n-type

barrier lowered -->
electrons can go across

barrier increased -->
electron flow impeded

Forward bias

\[ q(V_r + V) \]

\[ E_c \]

\[ E_{Fm} \]

\[ E_{F_s} \]

\[ E_v \]

\[ I = I_0(e^{\frac{qV}{kT}} - 1) \]

The reverse saturation current depends upon electron barrier from metal to semiconductor

\[ I_0 \propto e^{-\frac{q\Phi_B}{kT}} \]

This is independent of bias voltage.
What happens for the metal p-type semiconductor junction?

Draw the energy bands for:
- forward bias
- reverse bias

\[ q(\Phi_s - \Phi_m) = qV_0 \]
In schottky-barrier devices, current is due to majority-carrier injection.

There is no minority carrier injection and no charge storage delay ---> extremely fast operation.

- high-frequency operation
- small-area so high density applications integrated circuits.
- Easier to fabricate than pn junction.
Ohmic contacts are non-rectifying.

Important application: connections between transistors in ICs.
Fermi levels align by electrons moving from metal to semiconductor

small barrier for electron flow from metal to semiconductor

majority carriers accumulate at boundary of semiconductor

No depletion region.

What is the barrier? How can it be controlled?
With p-type semiconductor, fermi levels align by flow of holes from metal to semiconductor.

Holes carry current and the barrier to cross from metal to semiconductor again is small.
Al provides the acceptor impurities for the p+ semiconductor & forms the ohmic contact.

Here Au forms an ohmic contact with Si. Alloys are used for adhesion promotion. The semiconductor is heavily doped near the contact to reduce depletion region width.
Another example from research (2011). Goal to avoid gold (to make it CMOS compatible).
Heterojunctions

Two different materials forming a junction.

Important applications: bipolar junction transistors, field-effect transistors & semiconductor lasers.
In practice, the band bending must be solved numerically by solving Poisson's equations with correct boundary conditions: \( \varepsilon_1 \varepsilon_1 = \varepsilon_2 \varepsilon_2 \)

Fermi levels align

The contact potential is split between the two materials as here.

\[
\frac{V_{01}}{V_{02}} = \frac{\varepsilon_2 N_{d2}}{\varepsilon_1 N_{a1}}
\]

Note that the holes see a different energy barrier than the electrons.

What is the electron energy barrier (from n to p)?
What is the hole energy barrier (from p to n)?

global vacuum level must be the same everywhere.

local vacuum level incorporates location of electron relative to the junction; how much energy does it take to remove an electron from inside the semiconductor to just outside = electron affinity.
How to draw the band diagram for heterojunctions?

1. Align fermi levels

$E_c$  
$E_F$  
$E_v$

2. Mark experimentally (or numerically) determined values at junction boundary

$\Delta E_c$  
$\Delta E_v$

3. Connect the bands

This shape requires solving Poisson's equation.

An important example: 2D electron gas in a quantum well structure: AlGaAs/GaAs

- barrier for electrons
  - $qV_n$
  - $\Delta E_c$
  - lightly-doped n-type GaAs
  - This discontinuity forms a potential well.

- barrier for holes
  - $qV_p$

- AlGaAs
- GaAs

- The extra electrons move the fermi level above the conduction band.

- Electrons spill over & get trapped here.

If the electron conduction is out-of-plane, then we have a 2D electron gas with extremely high mobility (electrons provided by AlGaAs but located in the GaAs portion). Low dopant density in GaAs - so low scattering & high mobility.