VE 320 Fall 2021

Introduction to Semiconductor Devices

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Lecture 10

Schottky Contact (Chapter 9)

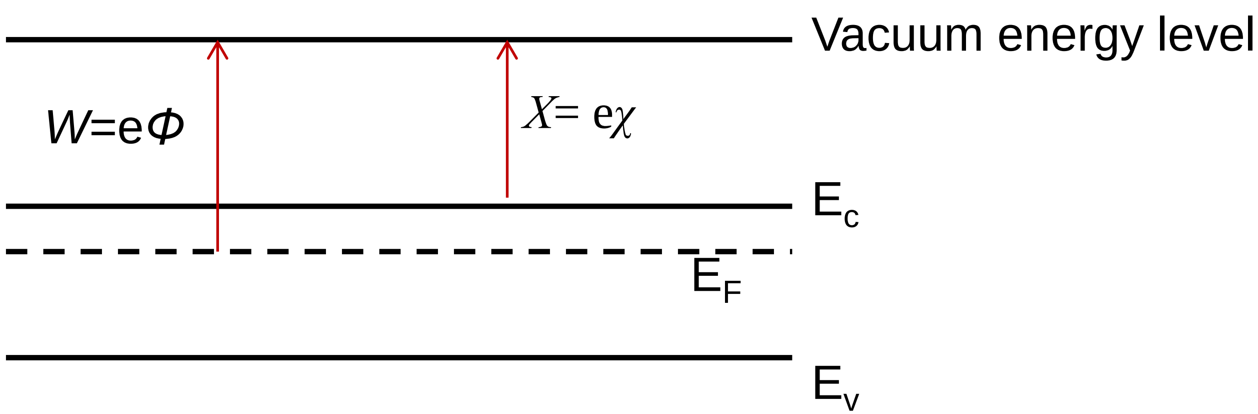
Metal-semiconductor contact

- Real semiconductor devices and ICs always contain metals. Why?
  - Contacts & Interconnects!
- Metals are actually easier to treat than semiconductors:
  - 1) No band gap, only Fermi level matters
  - 2) ~100-1000x more electrons than highly doped silicon (no internal E-fields → flat energy bands in metals!)
- Heterojunction: different material
  - pn junction: homojunction, same material

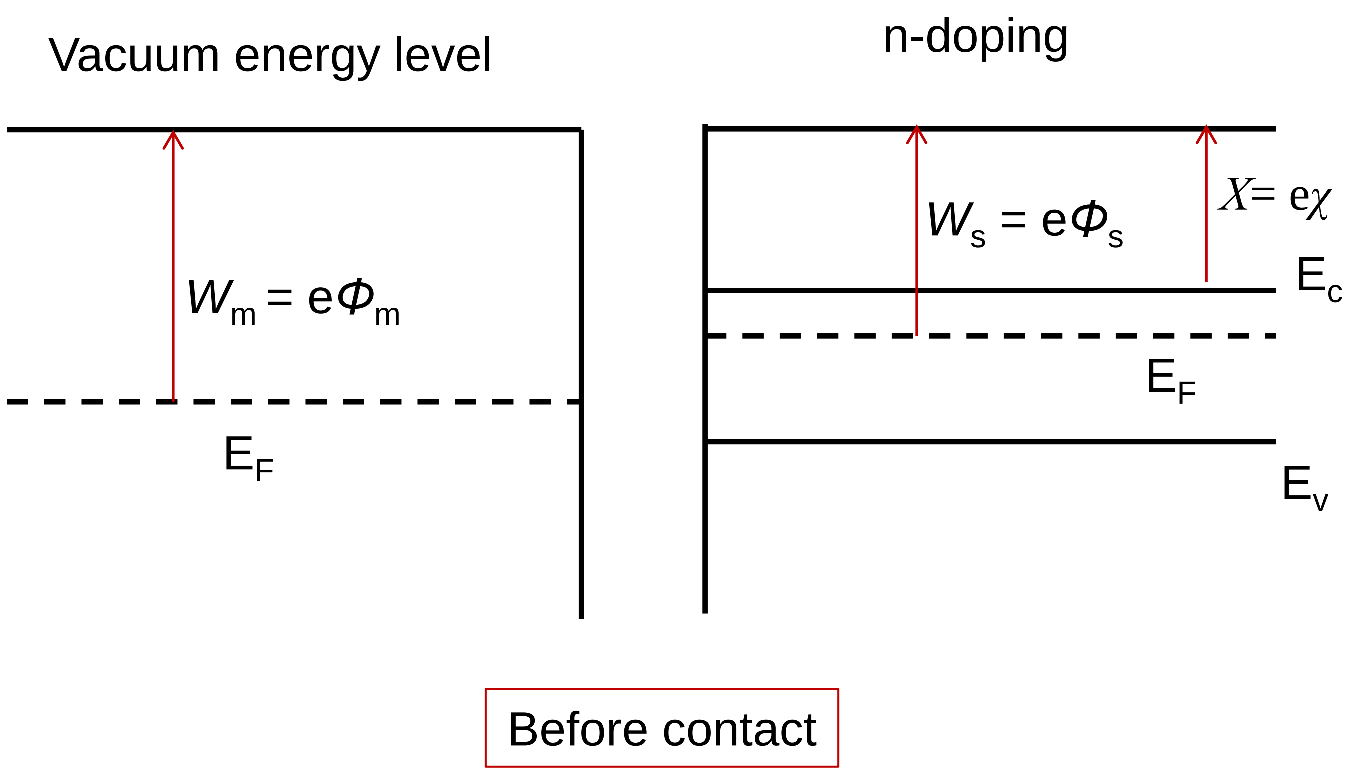
Work function and electron affinity

Work function: energy difference between the vacuum energy level and the Fermi level

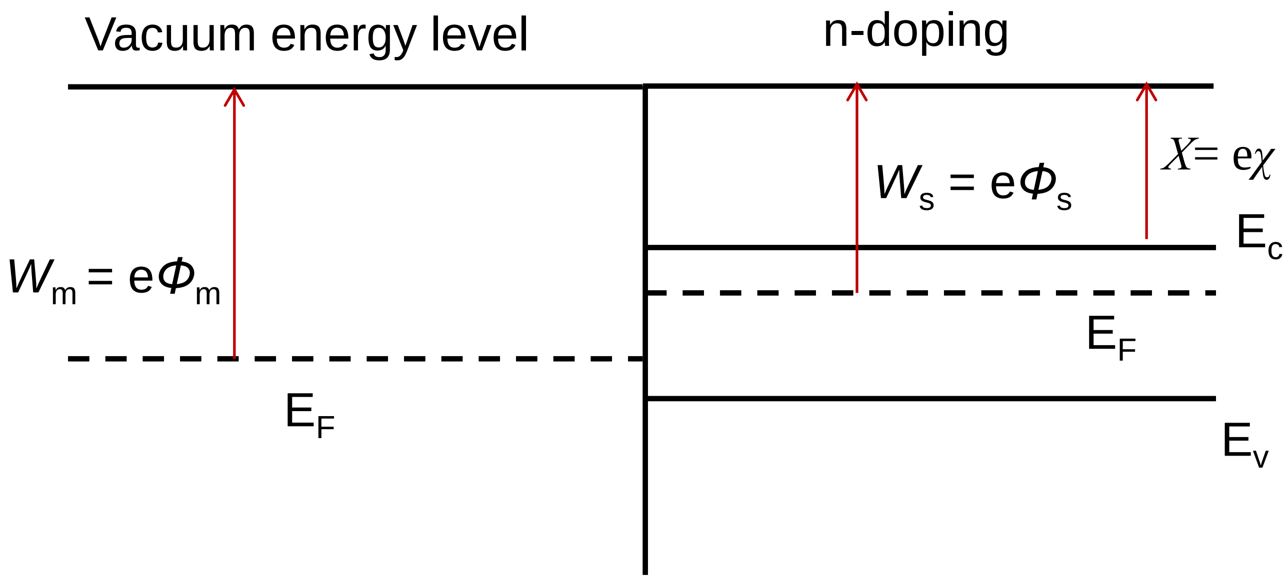
Electron affinity: energy difference between the vacuum energy level and conduction band bottom edge



Metal and semiconductor in contact



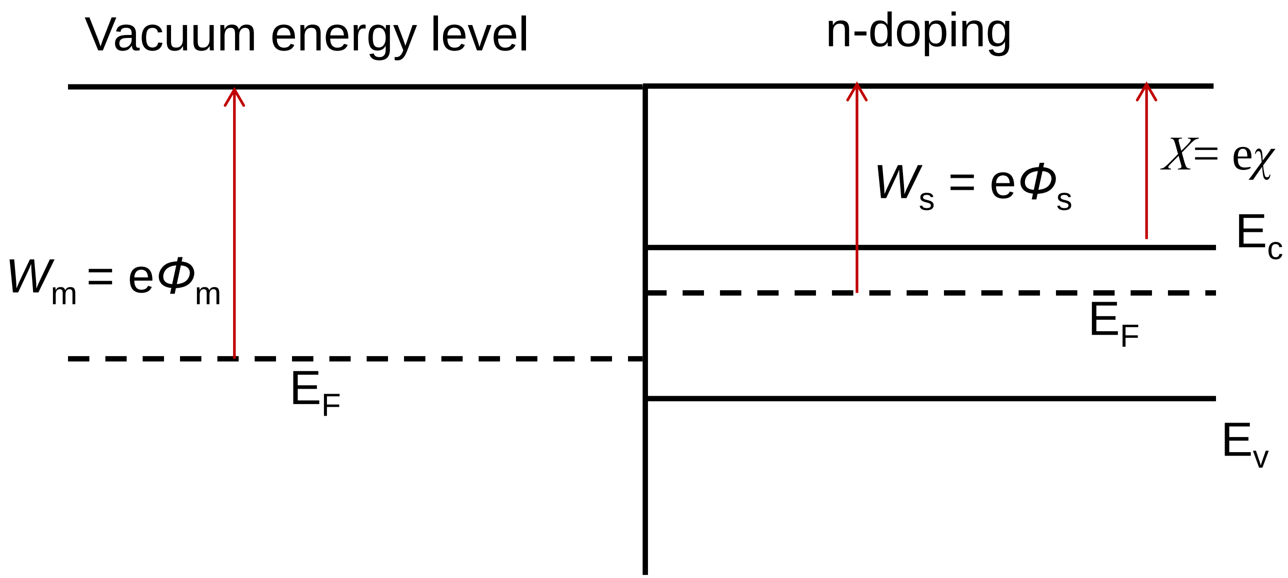
Metal and semiconductor in contact



After contact

Fermi level of the semiconductor is above the metal

Metal and semiconductor in contact

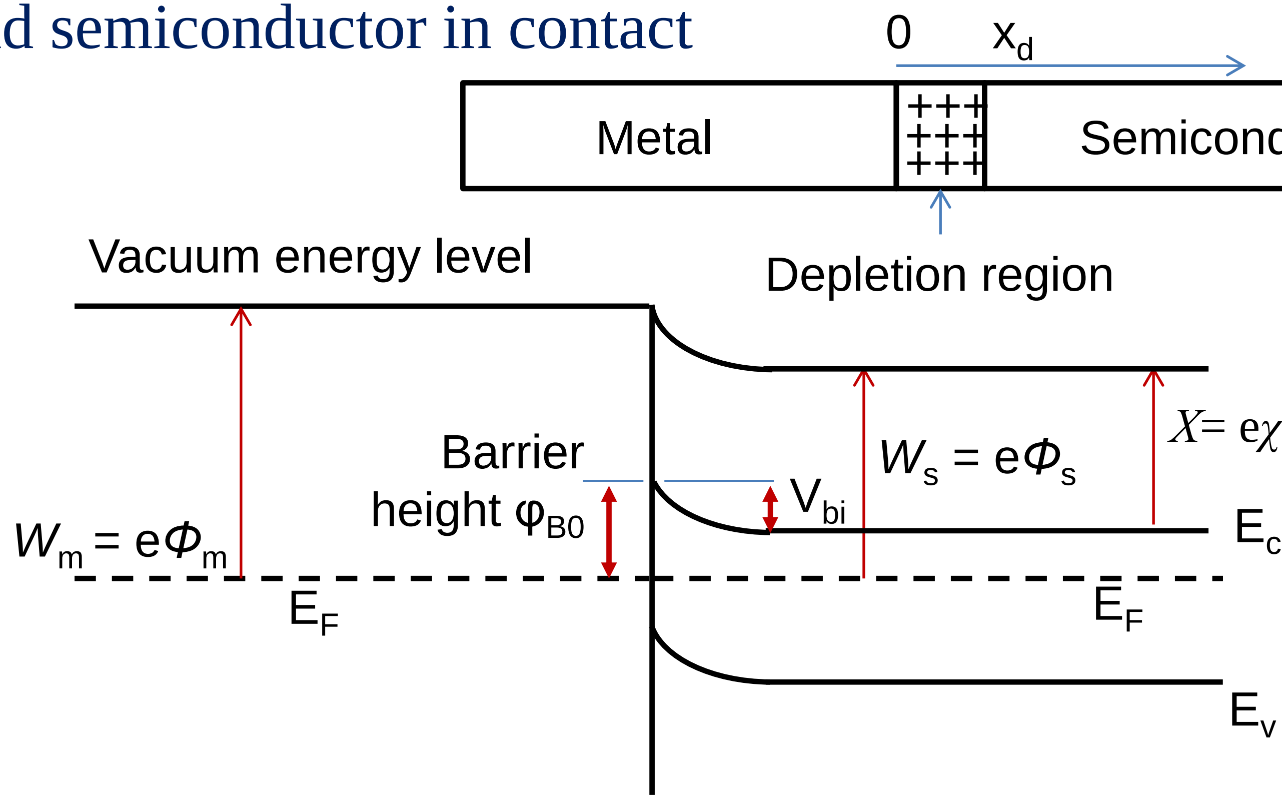


After contact

Fermi level of the semiconductor is above the metal

Electrons from the semiconductor flow to the lower energy states in the metal → Fermi level becomes a constant

Metal and semiconductor in contact



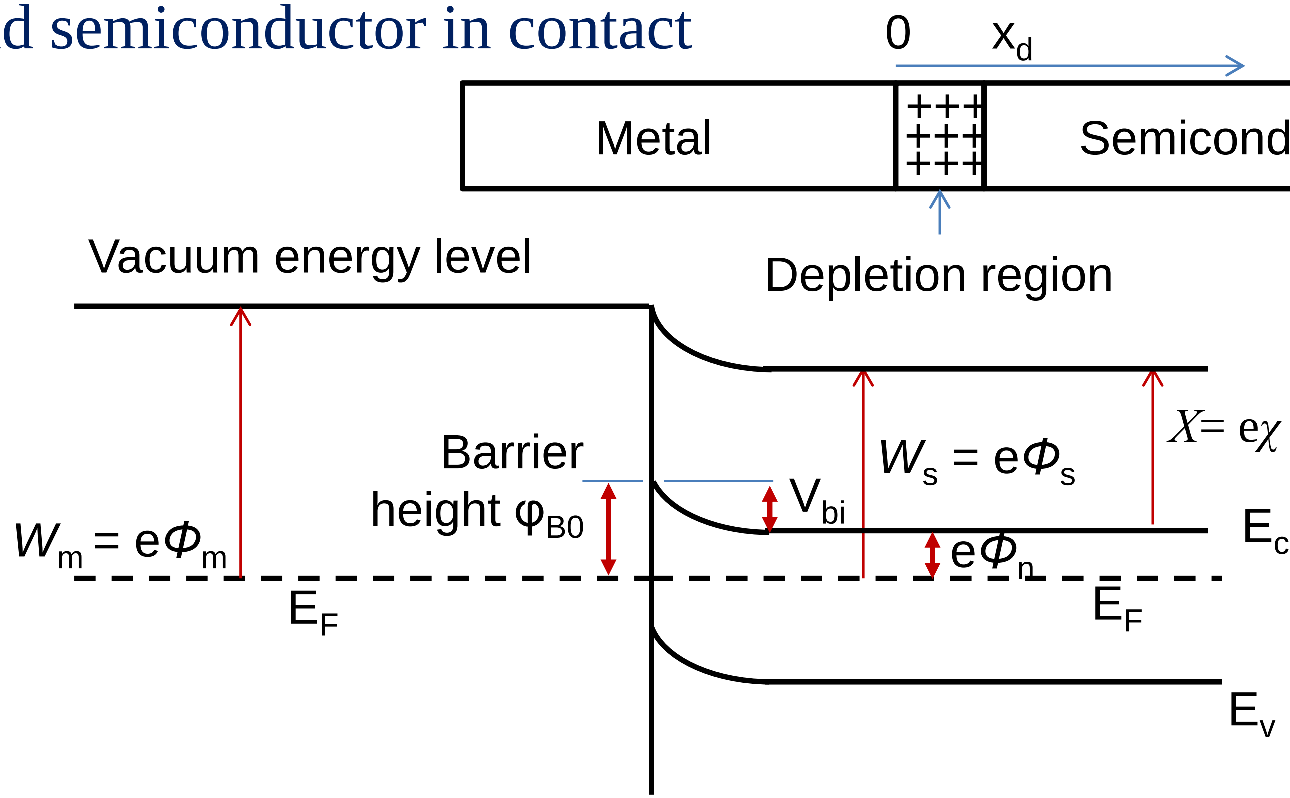
After contact

Why no band bending in metal?

Schottky barrier $\phi_{B0} = (\phi_m - \chi)$

For electrons in the metal trying to flow into the semiconductor

Metal and semiconductor in contact



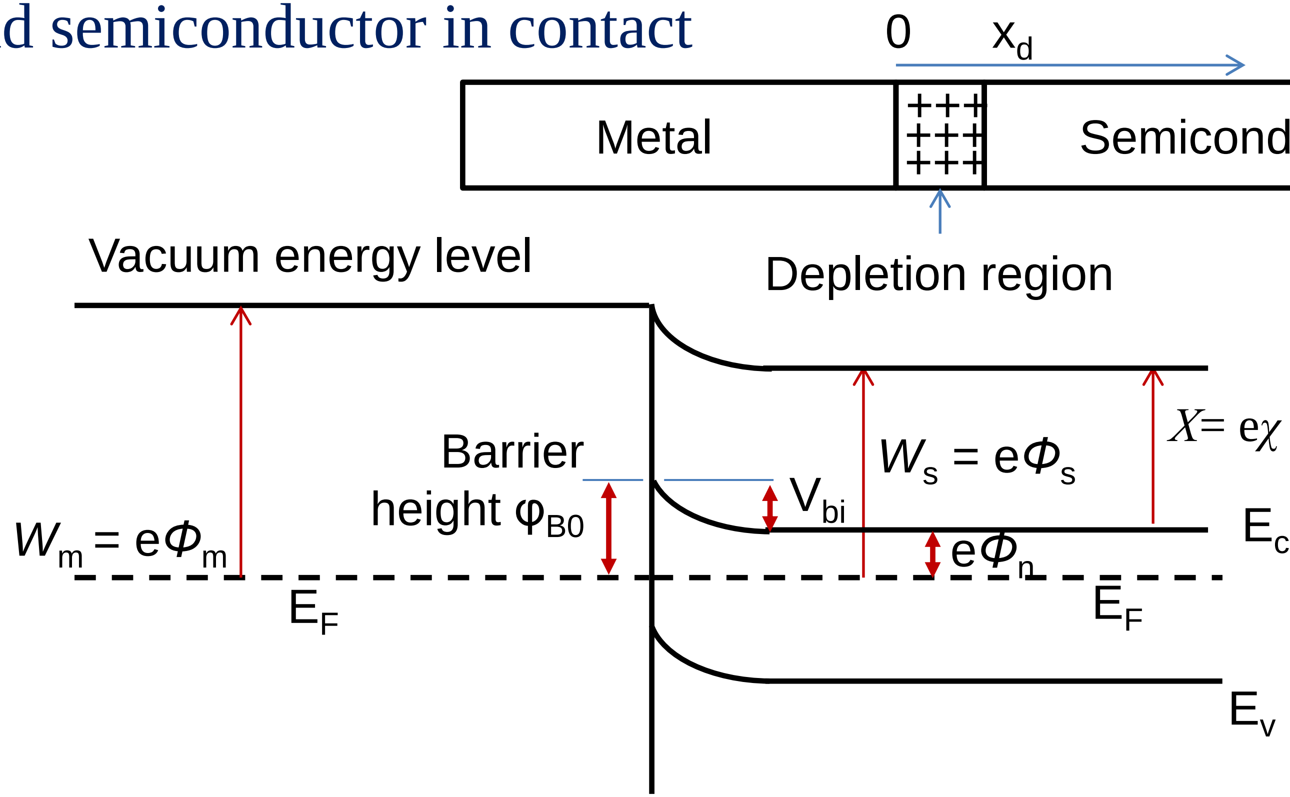
After contact

$$\Phi_n = \Phi_s - \chi$$

Built-in potential barrier $V_{bi} = \phi_{B0} - \phi_n$

For electrons in the conduction band of the semiconductor trying to flow into the metal

Metal and semiconductor in contact



Electric field in the space charge region: Poisson's equation, again! Like in pn junction

$$\frac{d\mathrm{E}}{dx} = \frac{\rho(x)}{\epsilon_s}$$

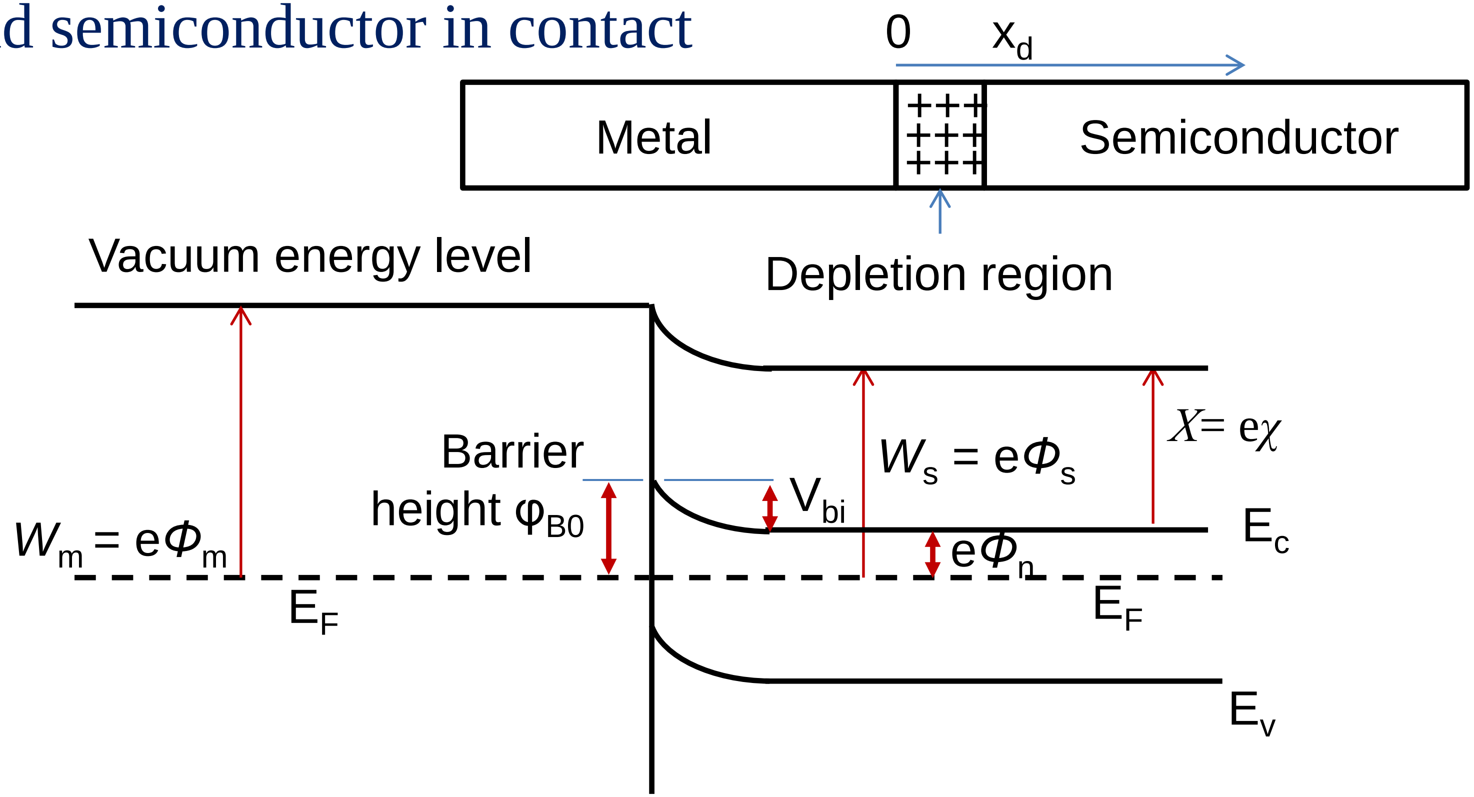
$\rho(x)$: space charge density

$$\mathrm{E} = \int \frac{eN_d}{\epsilon_s} dx = \frac{eN_d x}{\epsilon_s} + C_1$$

E is zero in the space charge edge

$$C_1 = -\frac{eN_d x_n}{\epsilon_s}$$

Metal and semiconductor in contact



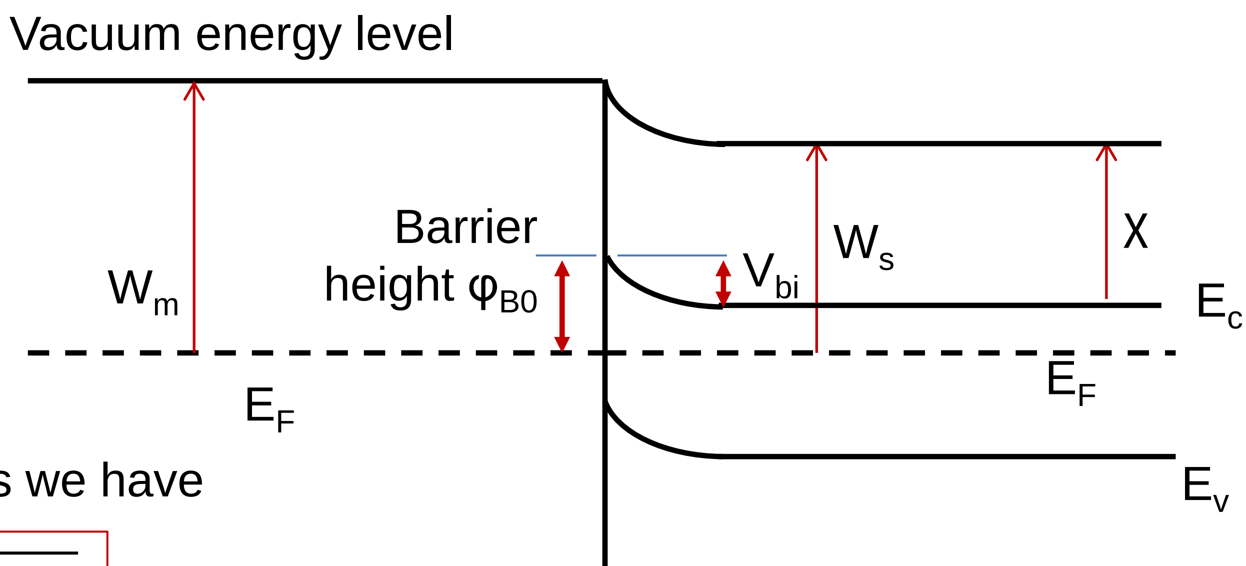
Electric field in the space charge region: Poisson's equation, again! Like in pn junction

Electric field:

$$\mathrm{E} = -\frac{eN_d}{\epsilon_s}(x_n - x)$$

Metal and semiconductor in contact

- electrostatics

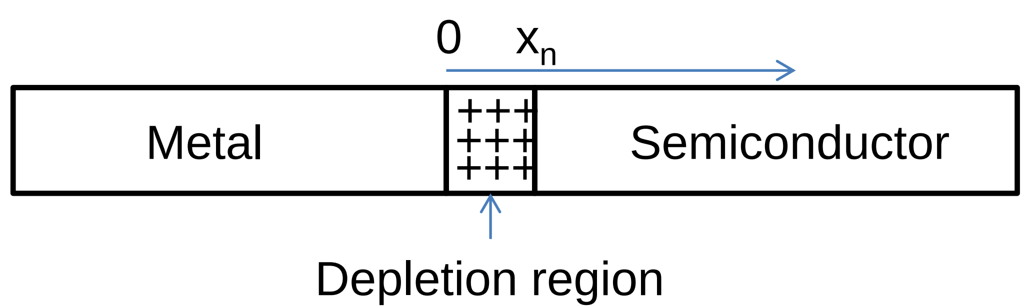


Remember for pn junctions we have

$$W = a + b = \sqrt{\frac{2\varepsilon V_{bi}}{e}\frac{N_d + N_a}{N_a N_d}}$$

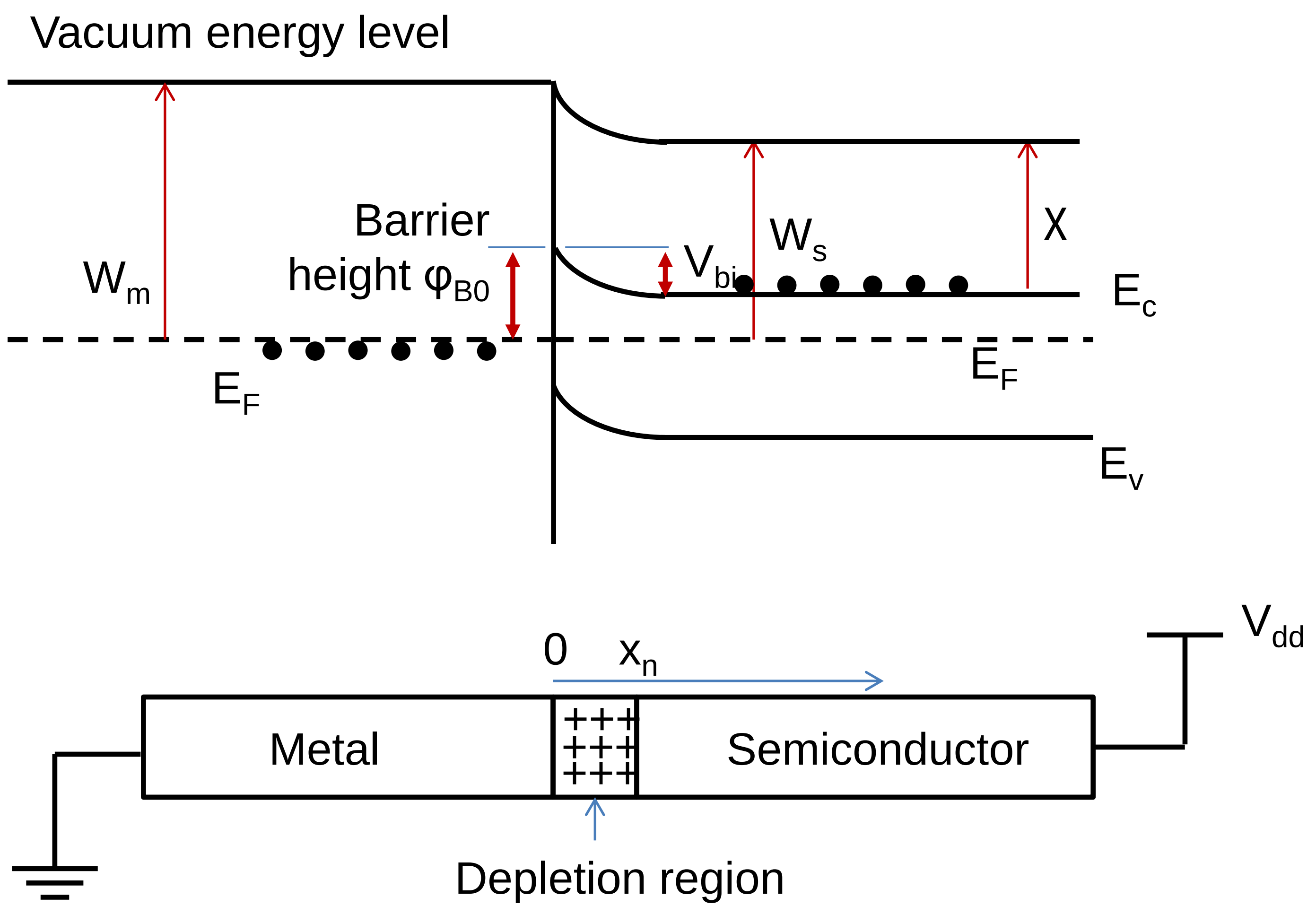
For Schottky barrier junction: like a one-sided p^+n junction

$$x_n = \sqrt{\frac{2\epsilon_s(V_{bi} + V)}{eN_d}}$$



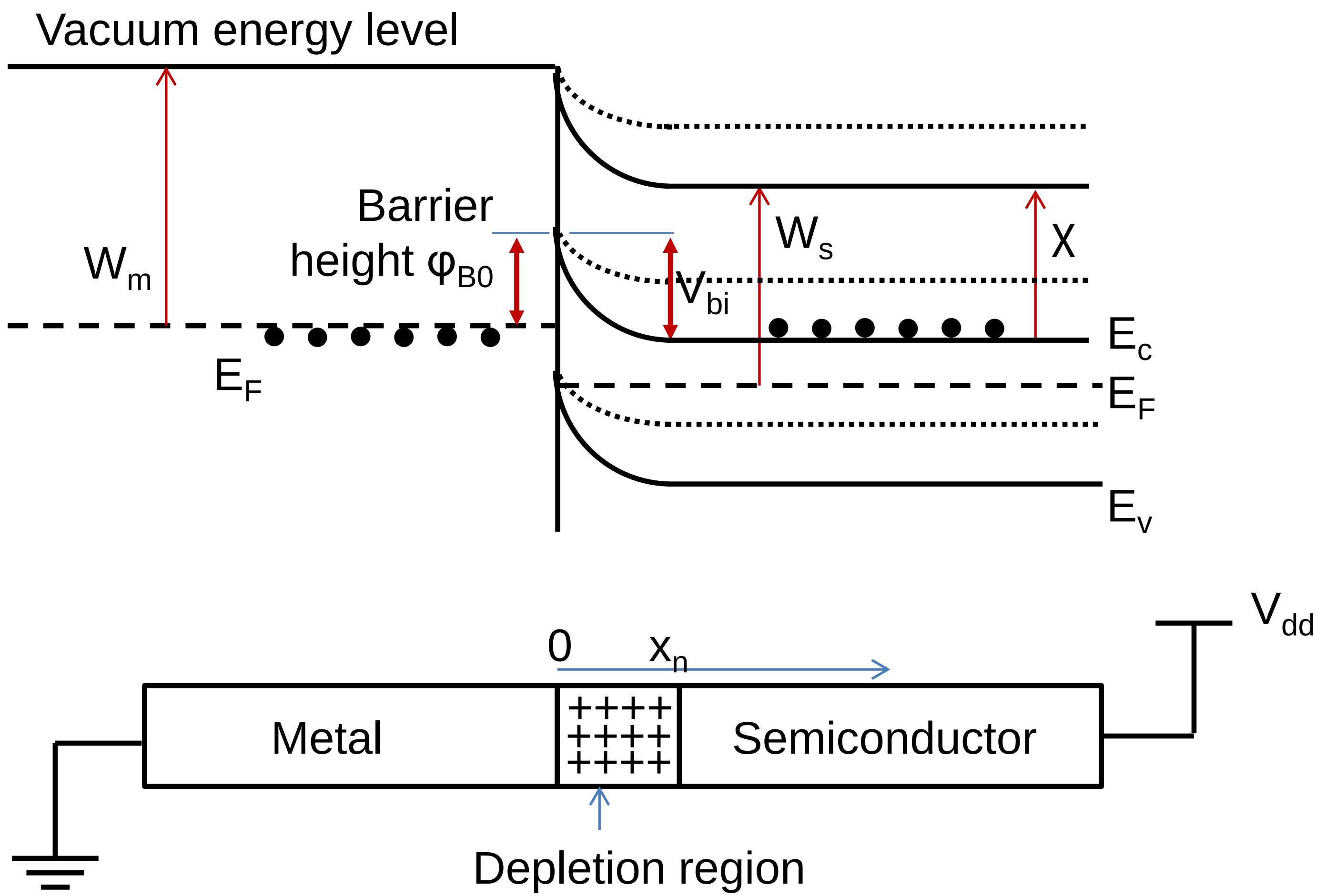
Metal and semiconductor in contact

- No bias



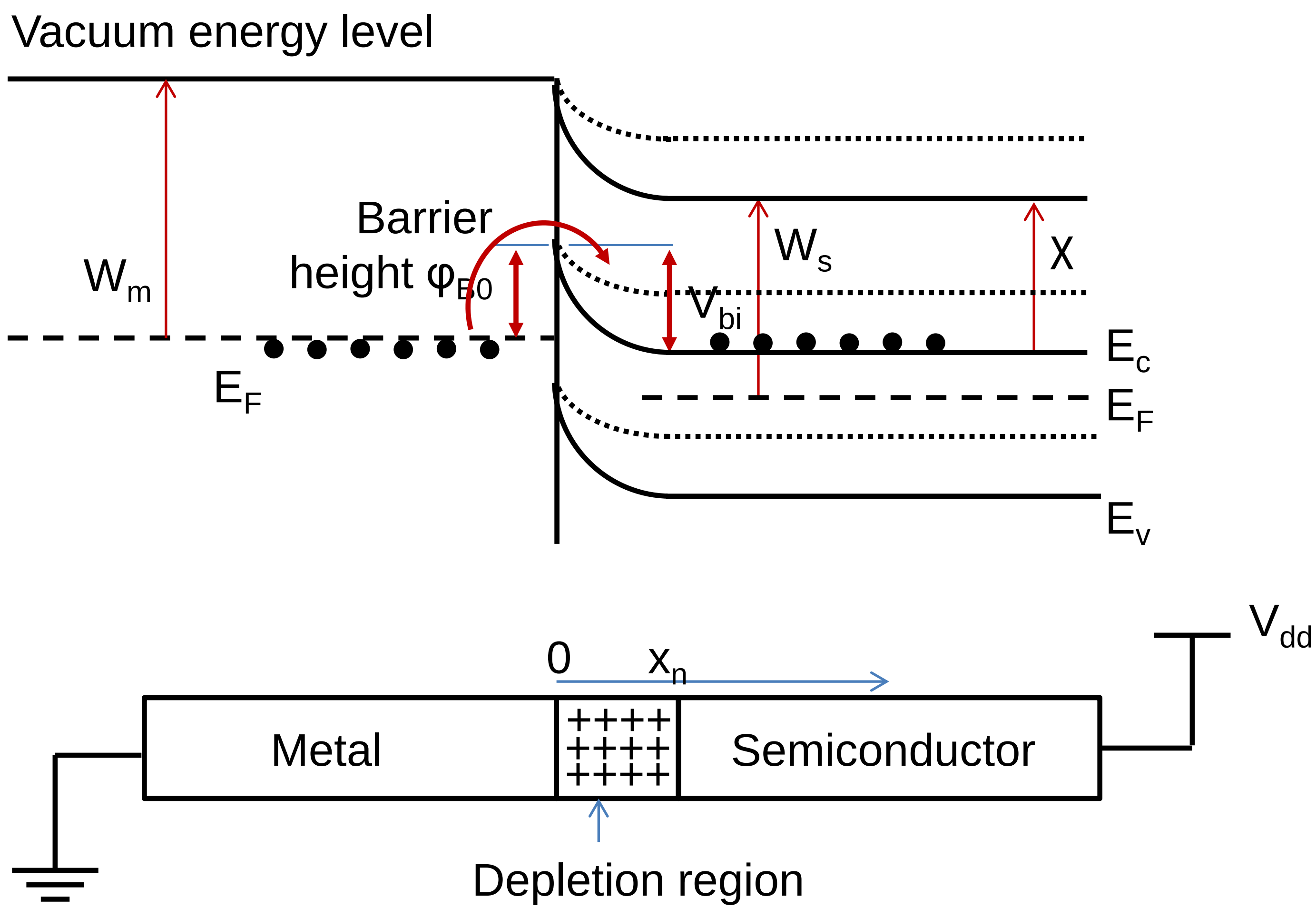
Metal and semiconductor in contact

- Reverse bias



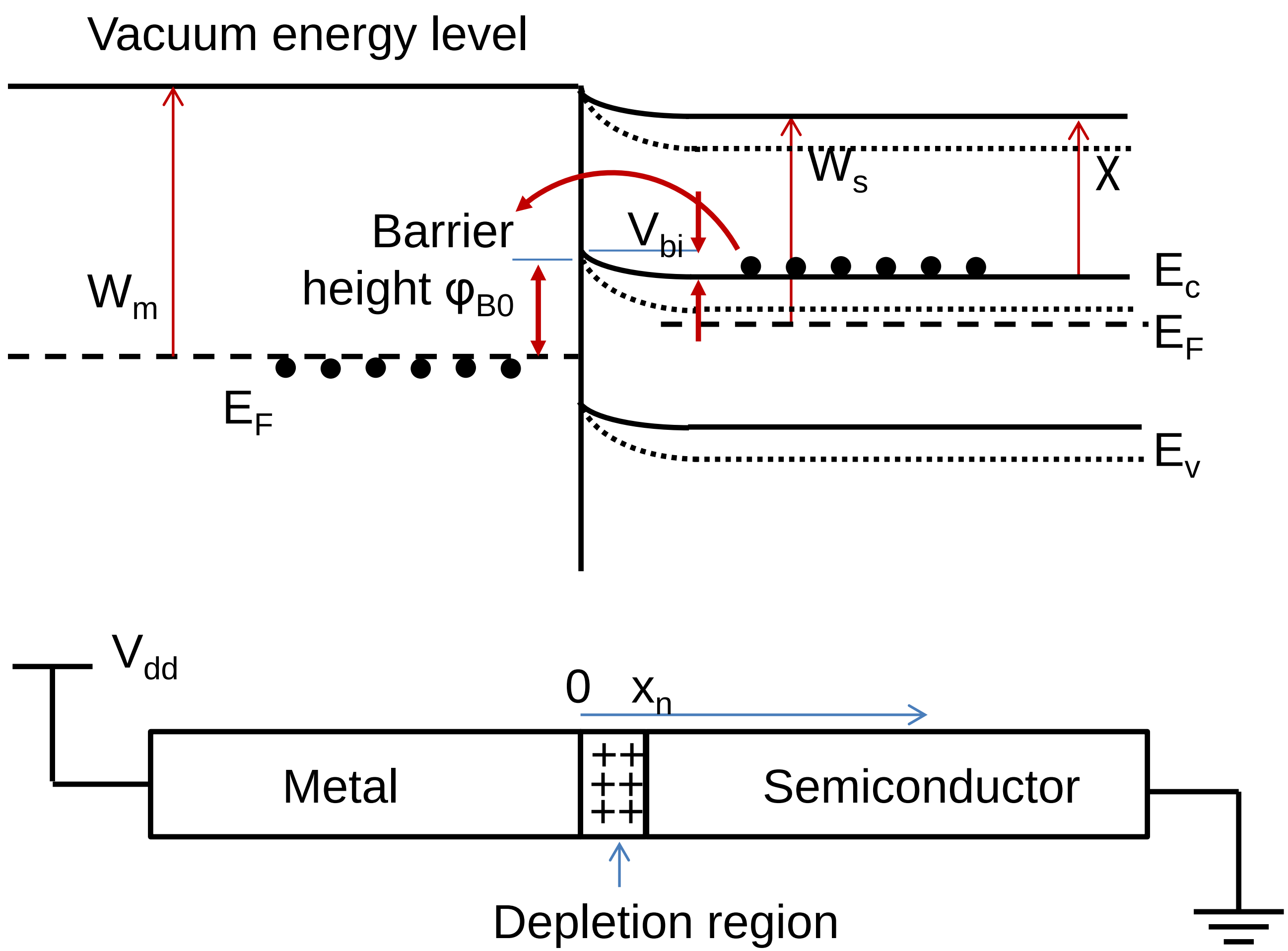
Metal and semiconductor in contact

- Reverse bias



Metal and semiconductor in contact

- Forward bias



Metal and semiconductor in contact

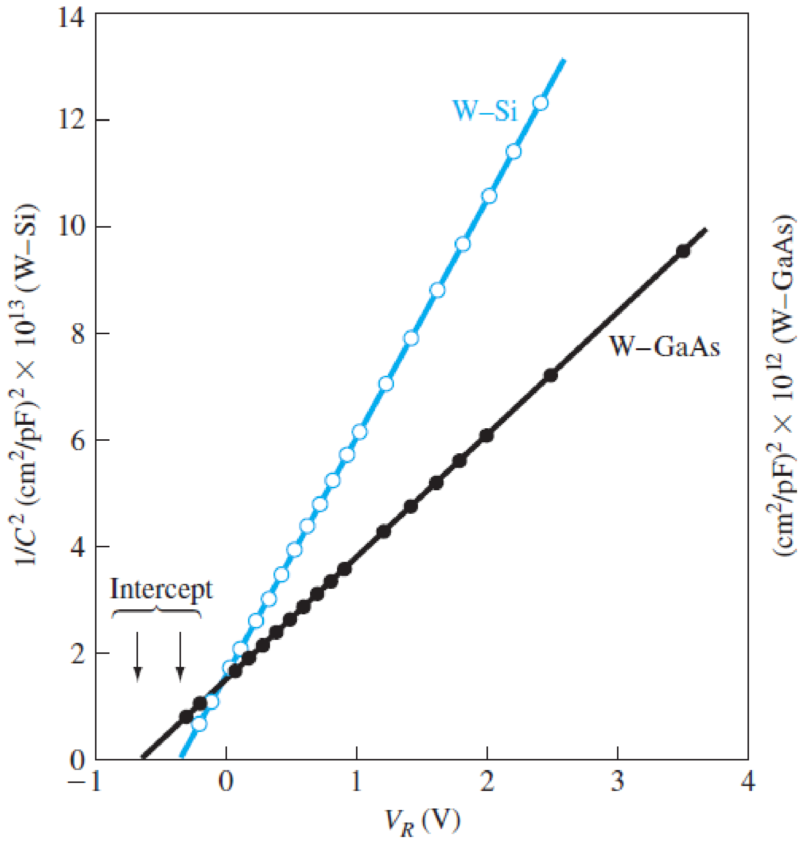
Junction capacitance (per unit area):

$$C' = eN_d \frac{dx_n}{dV_R} = \left[\frac{e\epsilon_s N_d}{2(V_{bi} + V_R)}\right]^{1/2}$$

Similar to pn junction

$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d}$$

Can obtain V_{bi} and doping N_d
Then, we can calculate Φ_n and Φ_{B0}



Metal and semiconductor in contact

Nonideal effects:

1. Schottky effect, or image-force-induced lowering of the potential barrier

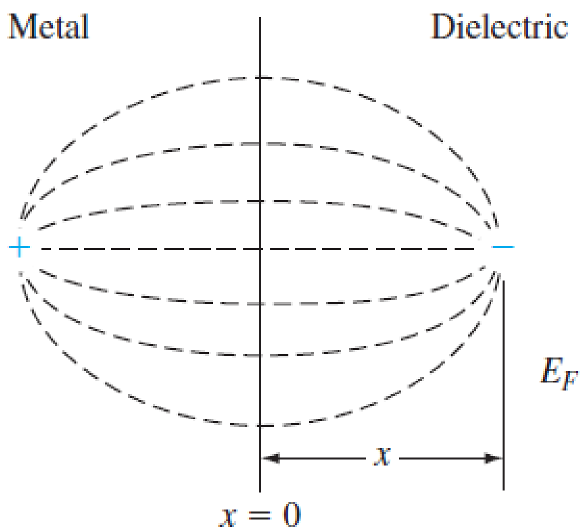
$$F = \frac{-e^2}{4\pi\epsilon_s(2x)^2} = -e\mathrm{E}$$

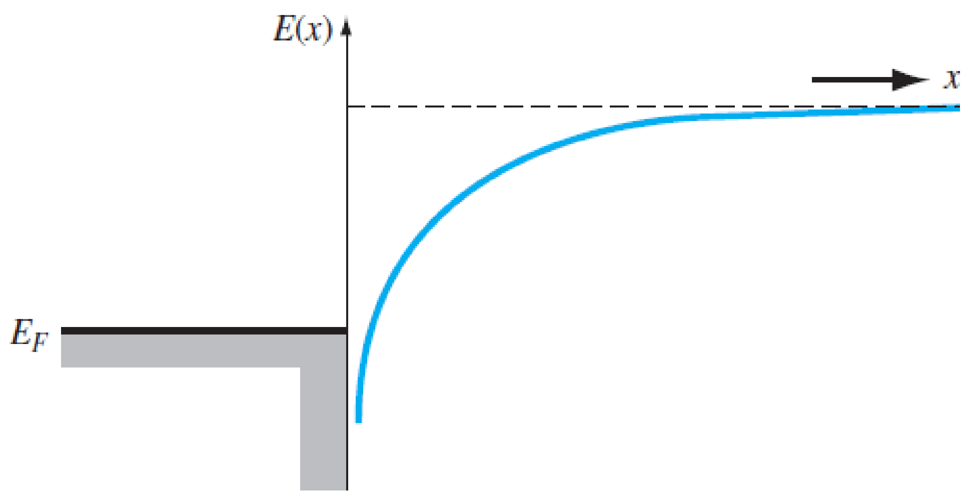
An electron in a dielectric material at a distance *x* from the metal will create an electric field. The electric field can be determined by adding an image charge, +*e*, inside the metal located at the same distance, *x*, from the interface

The E–field lines are perpendicular to the metal surface, no external field

$$-\phi(x) = +\int_x^\infty \mathrm{E}\,dx' = +\int_x^\infty \frac{e}{4\pi\epsilon_s \cdot 4(x')^2}\,dx' = \frac{-e}{16\pi\epsilon_s x}$$

Potential is 0 at ∞





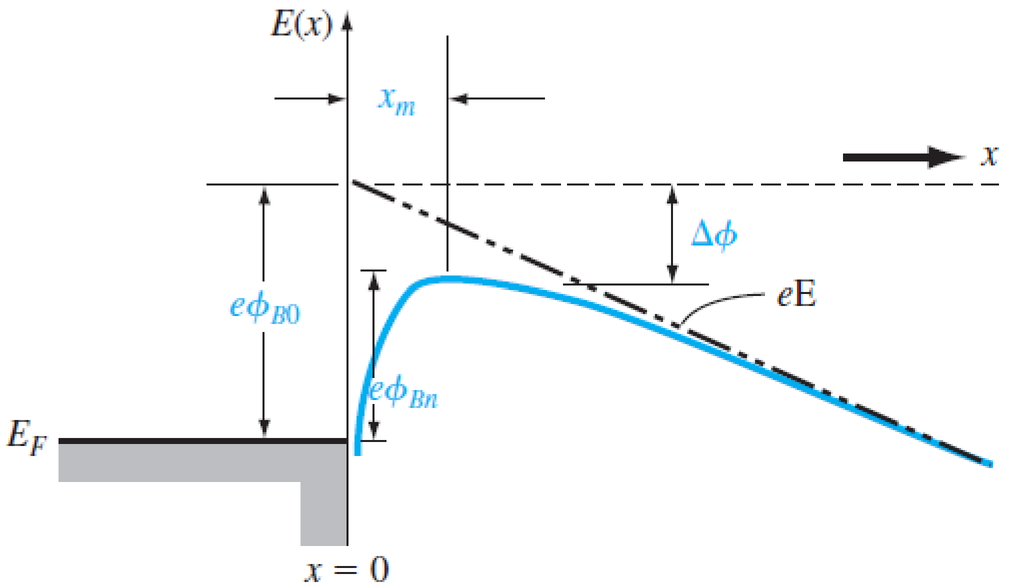
Metal and semiconductor in contact

With a constant electric field in the dielectric:

$$-\phi(x) = \frac{-e}{16\pi\epsilon_s x} - \mathrm{E}x$$

Find the maximum of the barrier

$$\frac{d[e\phi(x)]}{dx} = 0 \qquad x_m = \sqrt{\frac{e}{16\pi\epsilon_s \mathrm{E}}}$$



Metal and semiconductor in contact

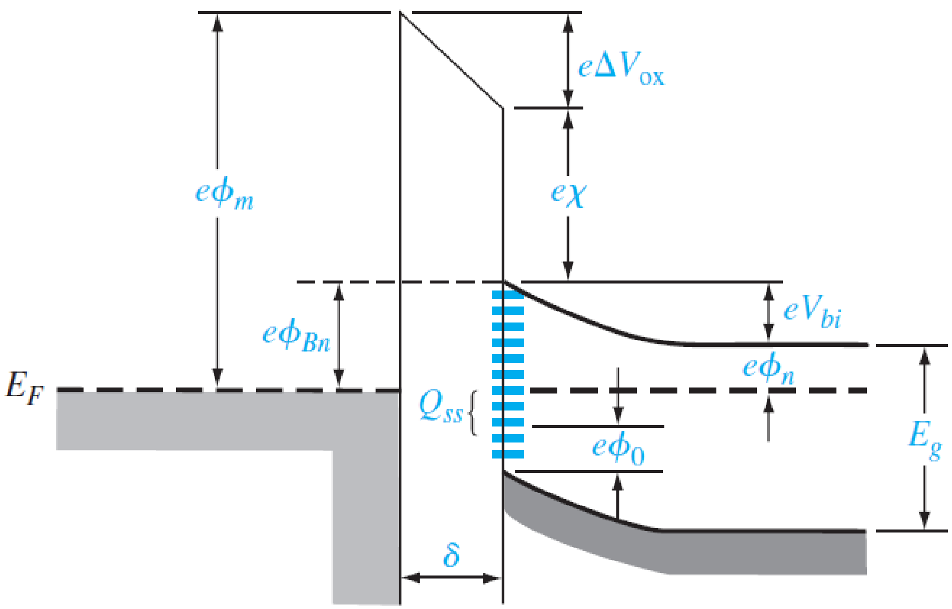
Nonideal effects:

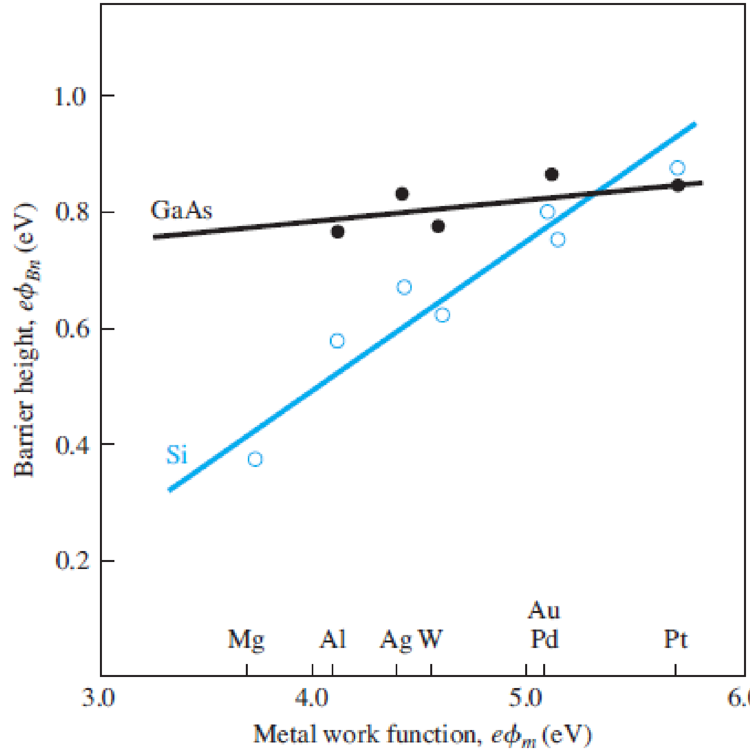
2. Interface states

Cannot fit to $\phi_{B0} = (\phi_m - \chi)$

Interface or surface states

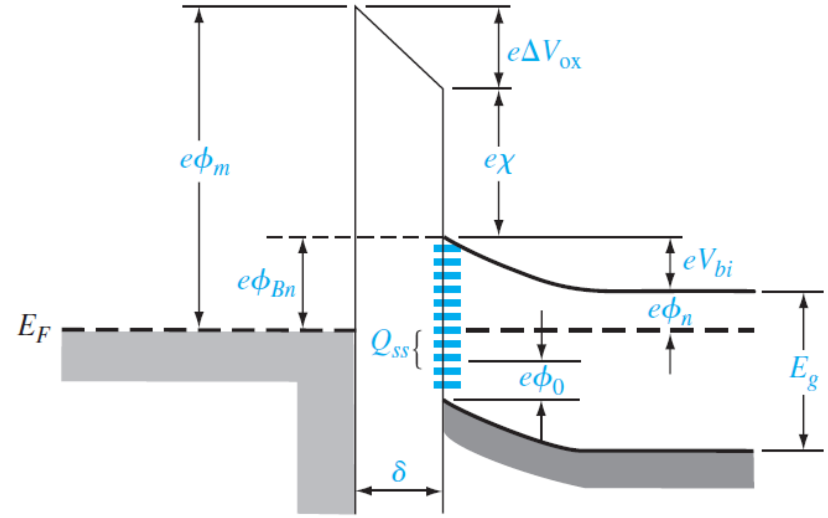
A narrow interfacial layer of insulator exists between the metal and semiconductor





Metal and semiconductor in contact

Nonideal effects:
2. Interface states



Surface state density D_{it} states/cm^{2}eV,
Acceptor states above surface potential Φ_0 and below E_F
Acceptor states tend to contain electrons and are negatively charged

$$(E_g - e\phi_0 - e\phi_{Bn}) = \frac{1}{eD_{it}}\sqrt{2e\epsilon_s N_d(\phi_{Bn} - \phi_n)} - \frac{\epsilon_i}{eD_{it}\delta}[\phi_m - (\chi + \phi_{Bn})]$$

If D_{it} is large, $$\phi_{Bn} = \frac{1}{e}(E_g - e\phi_0)$$

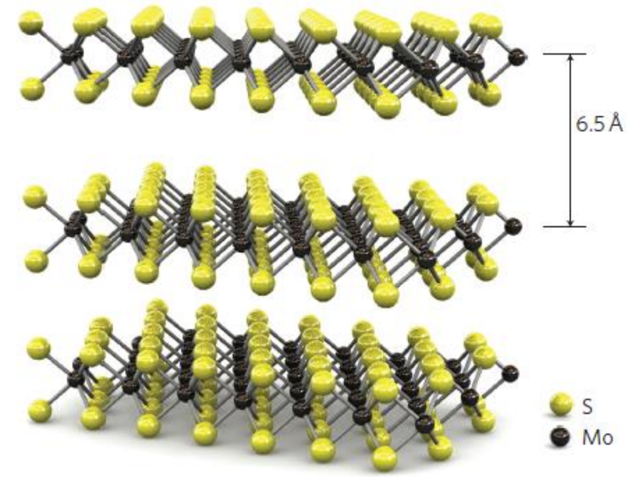
The barrier height is no longer dependent on the metal work function and semiconductor electron affinity!
The Fermi level becomes "pinned" at the surface, at the surface potential Φ_0

If D_{it} is small, $$\phi_{Bn} = (\phi_m - \chi)$$
Original equation

Metal and semiconductor in contact

Nonideal effects:
2. Interface states
Example:
Application in 2D material devices

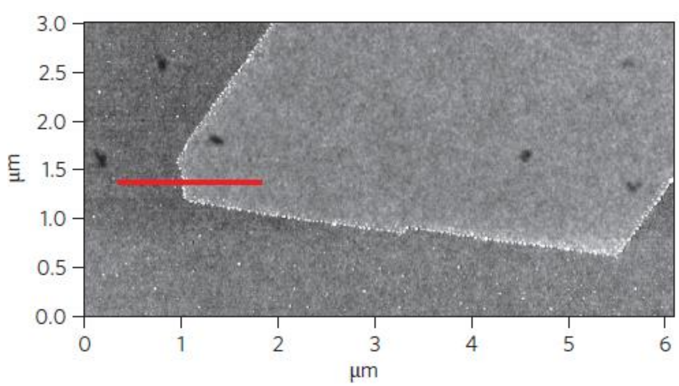
Molybdenum disulfide (MoS_2):
2D semiconductor
Bandgap: 1.8eV for single layer, 1.2eV for bulk

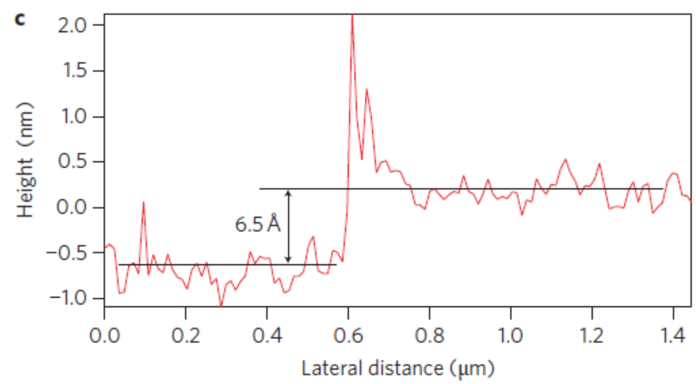


nature nanotechnology
LETTERS
PUBLISHED ONLINE: 30 JANUARY 2011 | DOI: 10.1038/NNANO.2010.279

Single-layer MoS_2 transistors

B. Radisavljevic[1], A. Radenovic[2], J. Brivio[1], V. Giacometti[1] and A. Kis[1]*





Ref: *Nature Nanotechnol.* **6**, 147-150 (2011)

Metal and semiconductor in contact

Nonideal effects:
2. Interface states
Example:
Application in 2D material devices

Molybdenum disulfide (MoS_2):

NANO LETTERS

Letter

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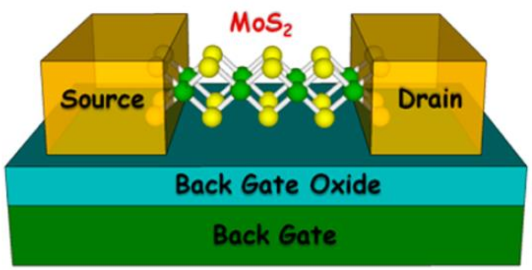
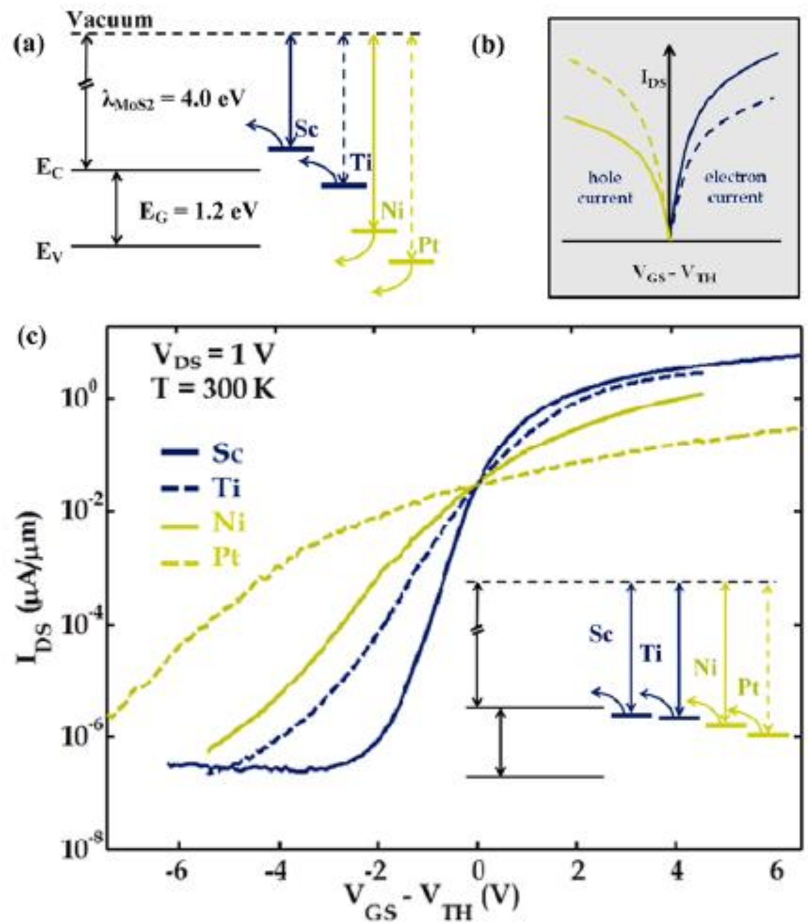
High Performance Multilayer MoS_2 Transistors with Scandium Contacts





Ref: *Nano Lett.* **13**, 100-105 (2013)

Metal and semiconductor in contact

Nonideal effects:
2. Interface states
Example:
Application in 2D material devices

Molybdenum disulfide (MoS_2):

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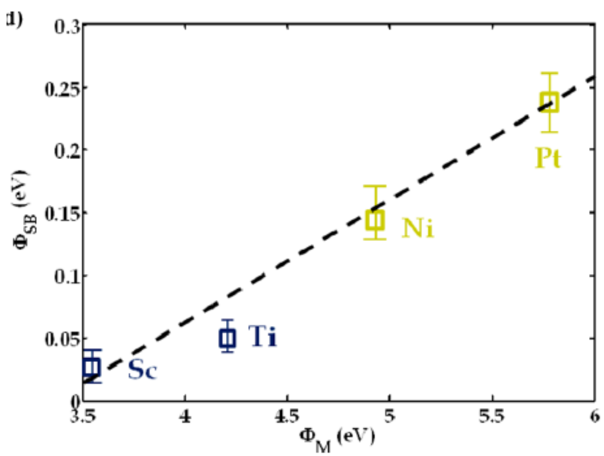
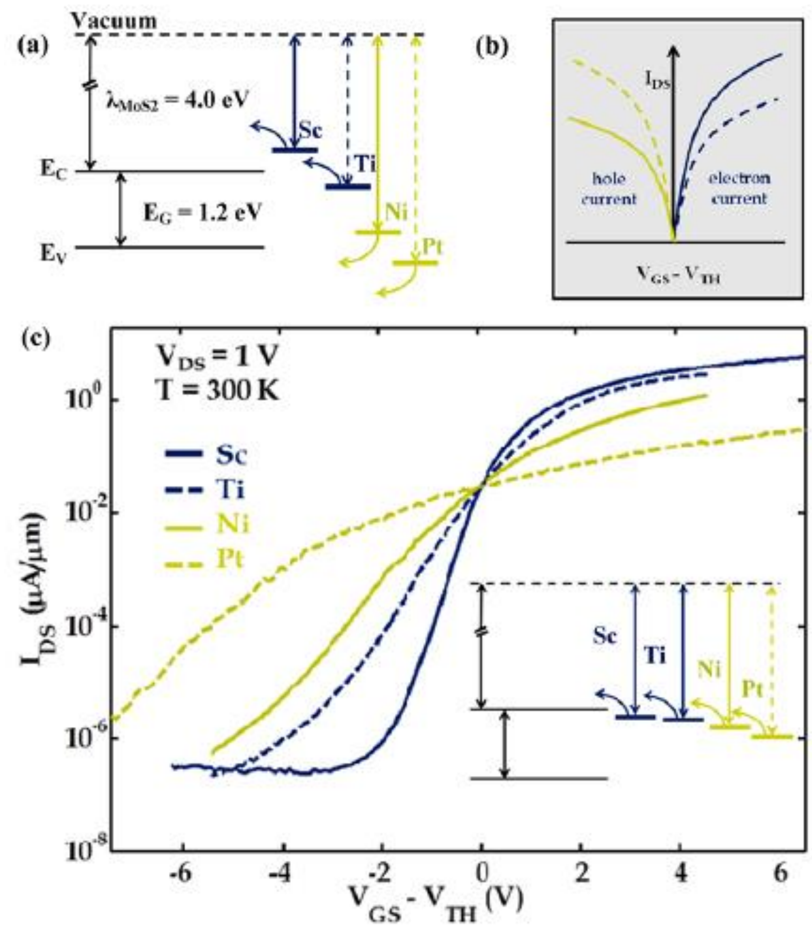
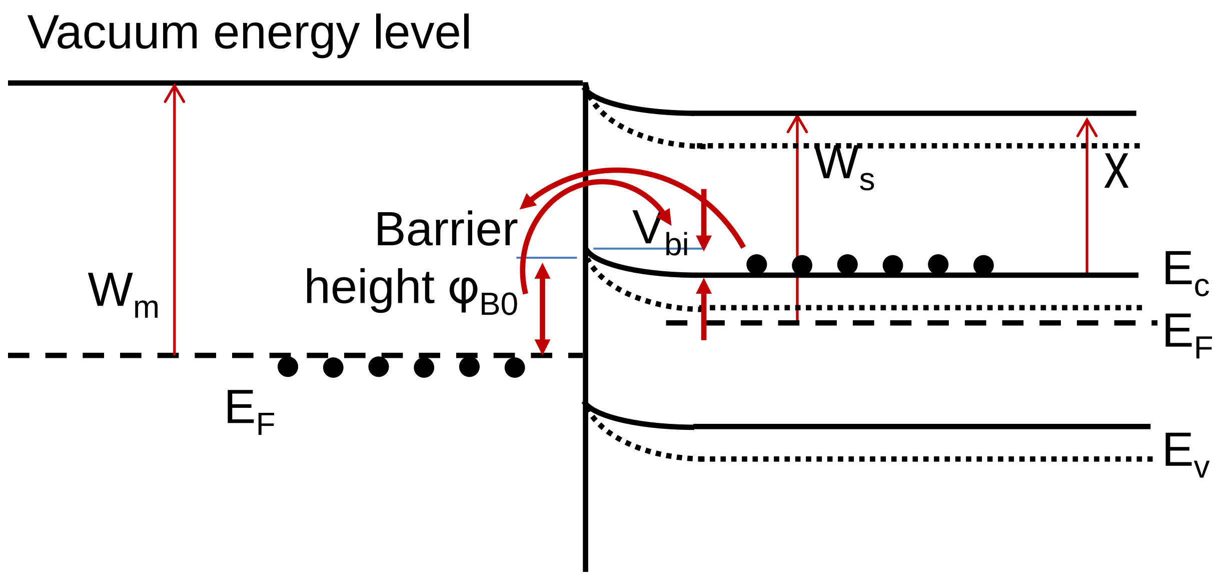




Ref: *Nano Lett.* **13**, 100-105 (2013)

Metal and semiconductor in contact

- Forward bias



Current: due to majority carriers
Different from pn junction (due to minority carriers)
n-type semiconductor in contact with metal: transport of electrons over the potential barrier

1. Thermionic emission theory
2. Tunneling

Metal and semiconductor in contact

- Forward bias

Conduction mechanism:
1. Thermionic emission theory
Assuming Boltzmann approximation
Velocity sufficient to overcome the potential barrier

$$J_{s\to m} = e\int_{E_c'}^{\infty} v_x\,dn$$

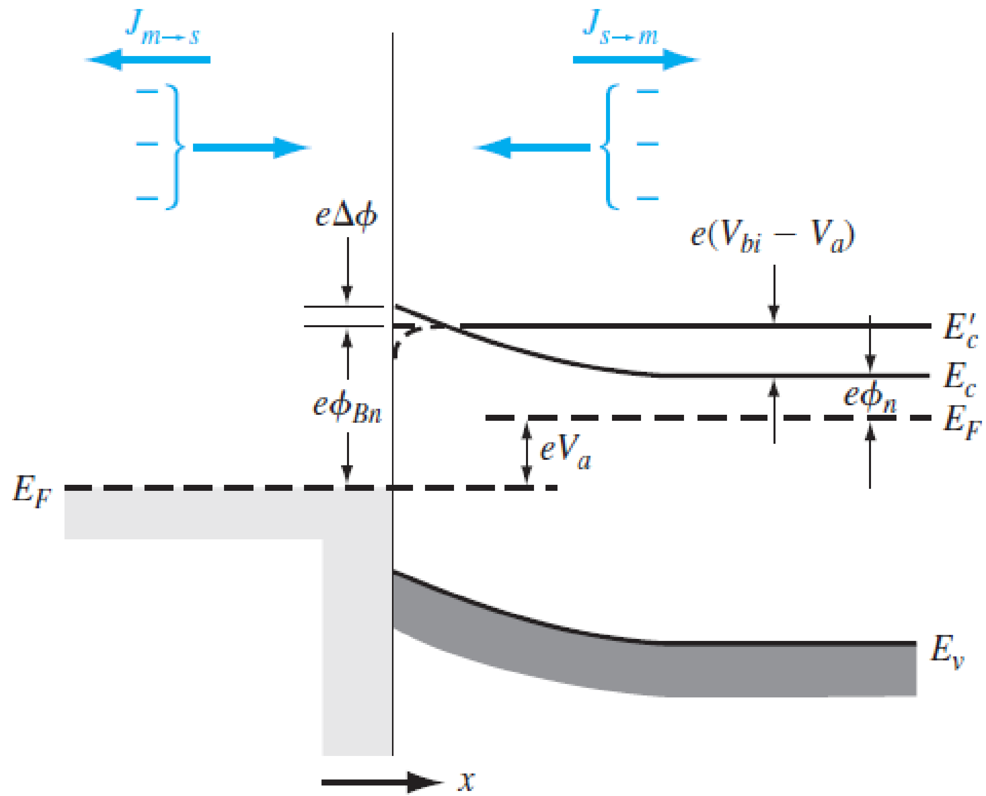
E_c' is the minimum energy required for thermionic emission into the metal

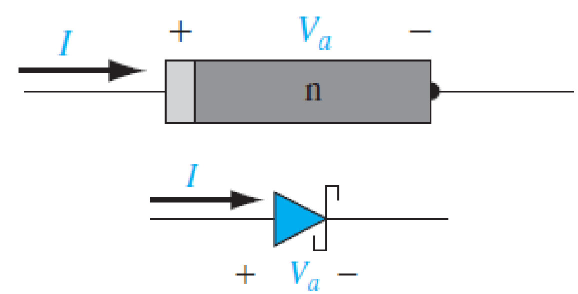
$$dn = g_c(E)\,f_F(E)\,dE$$

$$dn = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E-E_c}\,\exp\left[\frac{-(E-E_F)}{kT}\right]dE$$

Assume that all the electron energy above E_c is kinetic energy

$$\frac{1}{2}m_n^* v^2 = E - E_c$$





Metal and semiconductor in contact

- Forward bias

Thermionic emission theory:
Assuming Boltzmann approximation

$$J = J_{s\to m} - J_{m\to s}$$

$$J = \left[A^* T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)\right]\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

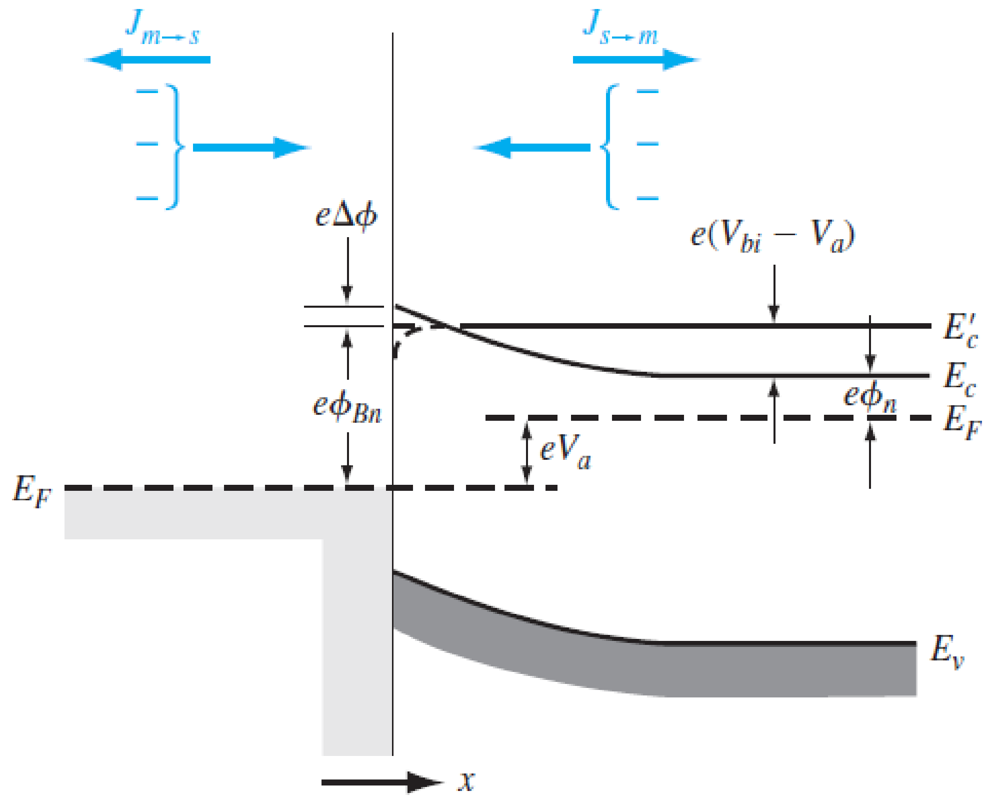
$$A^* \equiv \frac{4\pi e m_n^* k^2}{h^3}$$

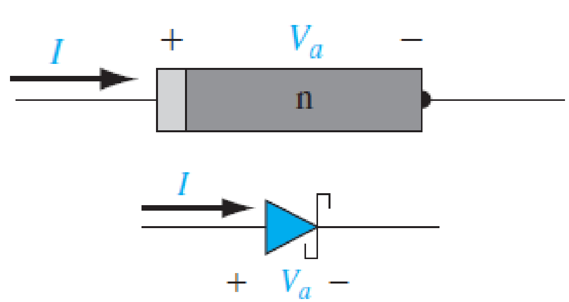
A^* is called the effective Richardson constant for thermionic emission

$$J = J_{sT}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

J_{sT} is the reverse-saturation current density

$$J_{sT} = A^* T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)$$





Metal and semiconductor in contact

- Forward bias

Thermionic emission theory:
Assuming Boltzmann approximation

$$J = J_{sT}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$J_{sT} = A^*T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)$$

Image-force lowering

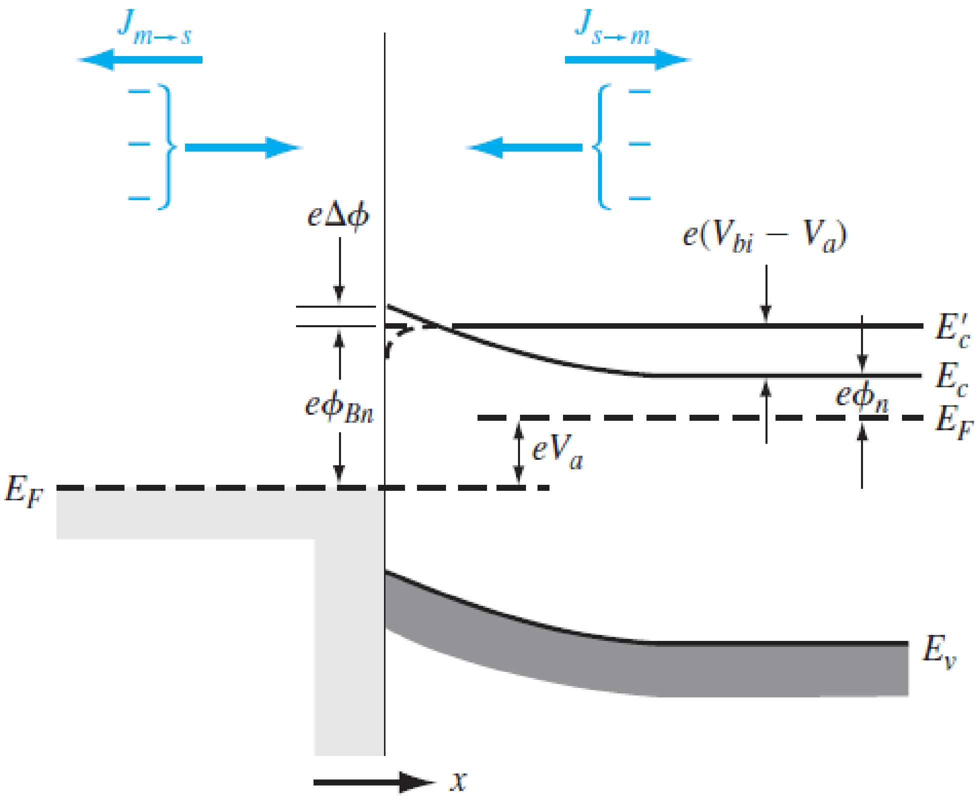
$$\phi_{Bn} = \phi_{B0} - \Delta\phi$$

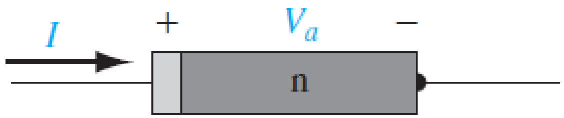
$$\Delta\phi = \sqrt{\frac{e\mathrm{E}}{4\pi\epsilon_s}}$$

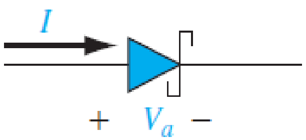
$$J_{sT} = A^*T^2 \exp\left(\frac{-e\phi_{B0}}{kT}\right)\exp\left(\frac{e\Delta\phi}{kT}\right)$$

pn junction diode:

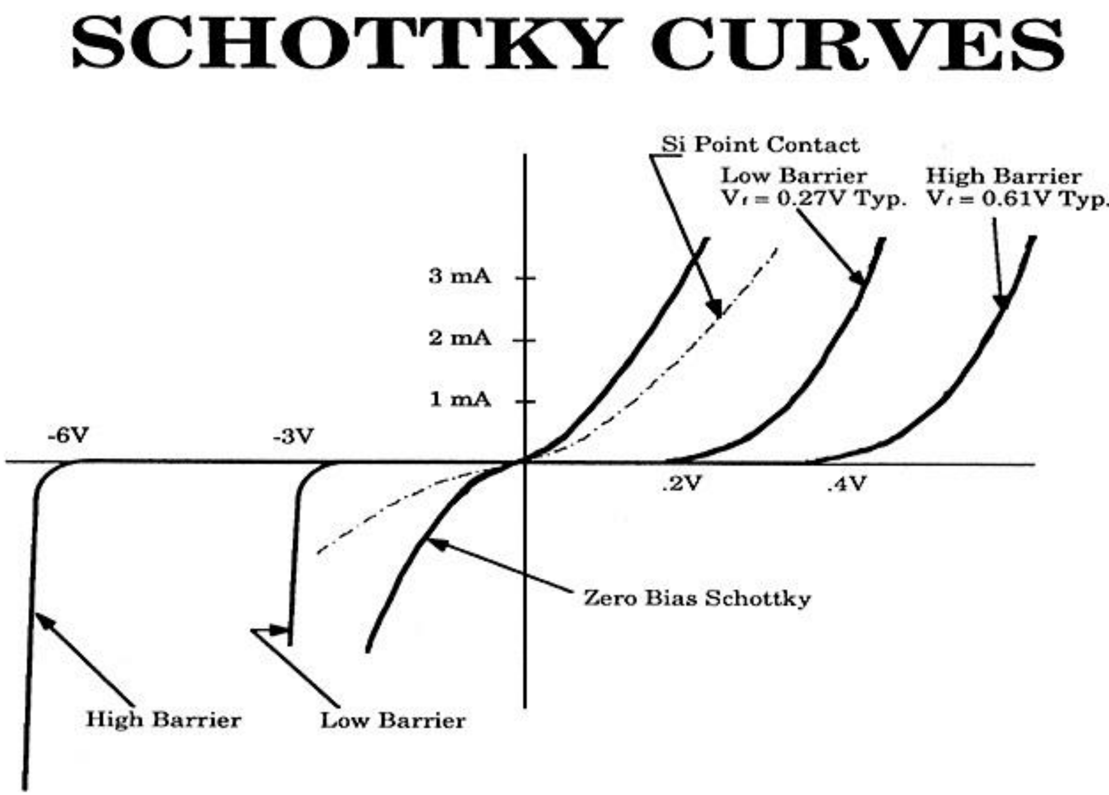
$$J_s = \frac{eD_n n_{po}}{L_n} + \frac{eD_p p_{no}}{L_p}$$







Metal and semiconductor in contact

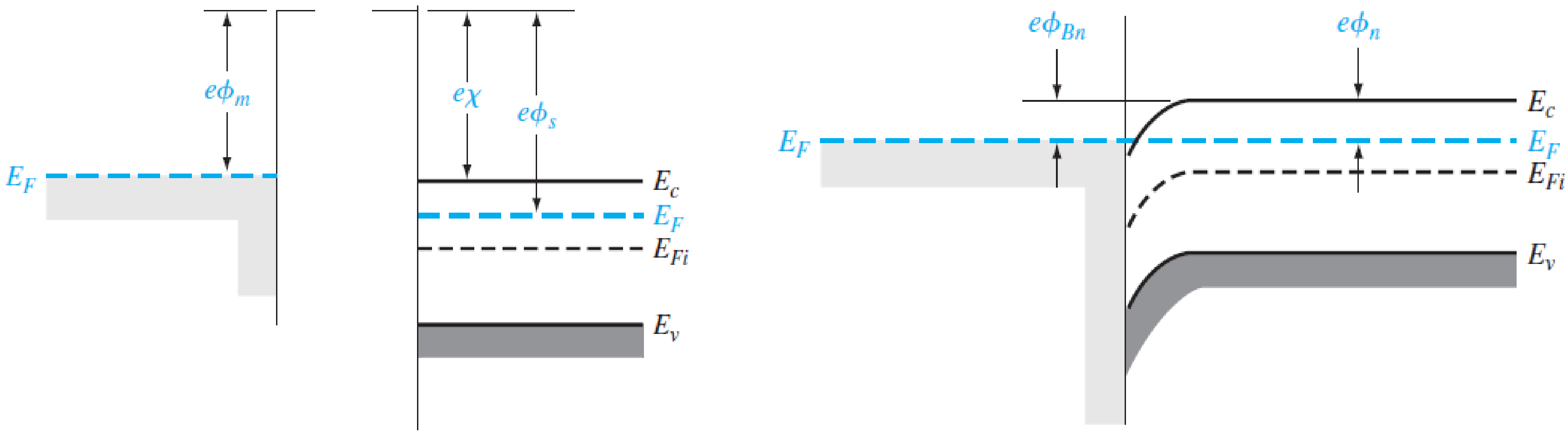


$$J = A^* T^2 \exp\left(-\frac{e\phi_{Bn}}{kT}\right)\left[\exp\left(-\frac{eV_a}{kT}\right) - 1\right]$$

Metal and semiconductor in contact

Ohmic contact: $\Phi_m < \Phi_s$ for n-type semiconductor

Before contact After contact

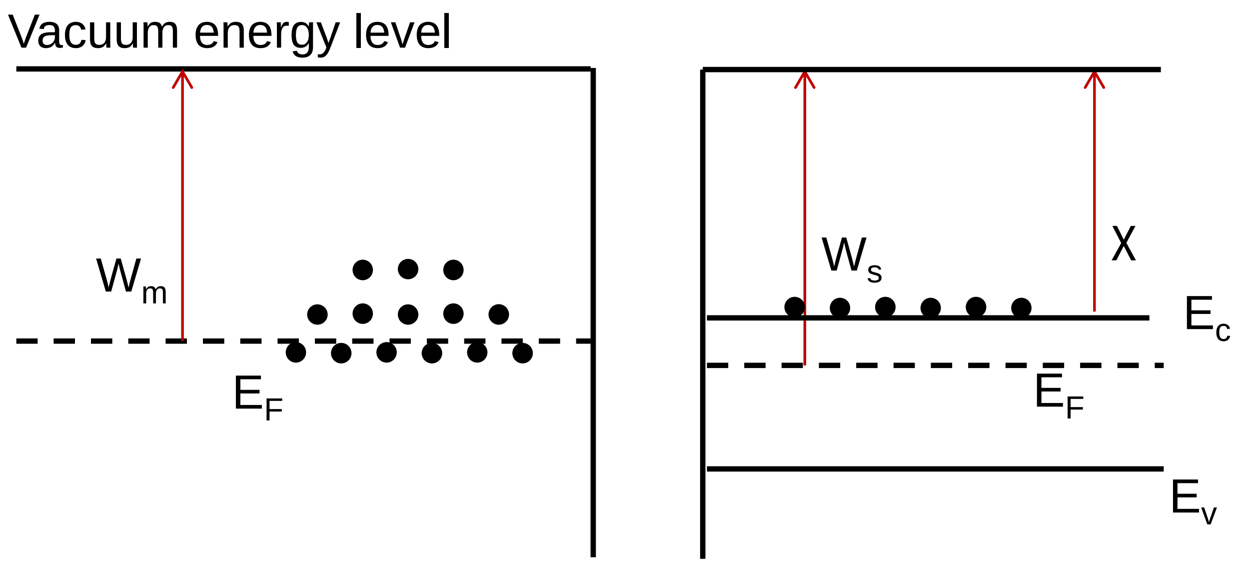


Electrons flow from the metal into the lower energy states in the semiconductor
More electrons at the surface of the semiconductor
n-type semiconductor and metal
More n-type near the metal

Metal and semiconductor in contact

- To avoid Schottky barrier: work function

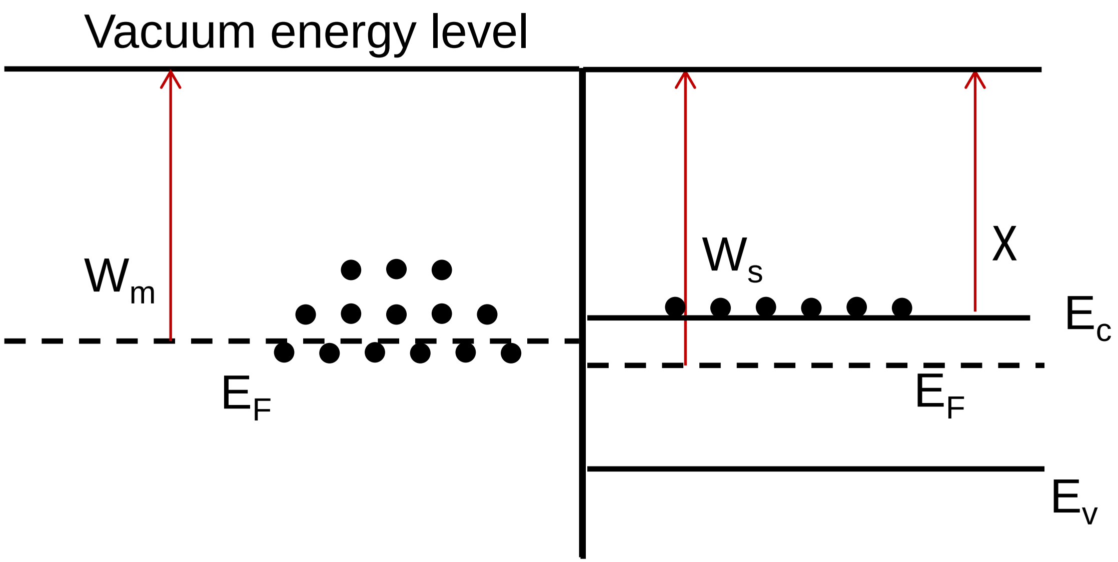
$W_m < W_s$ for n-type material



Metal and semiconductor in contact

- To avoid Schottky barrier: work function

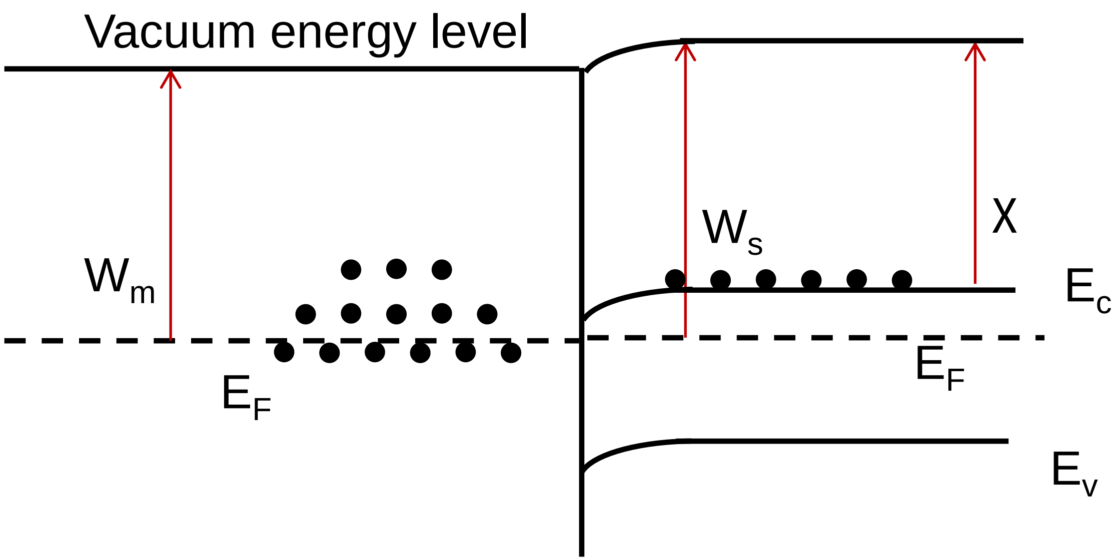
$$\boxed{W_m < W_s}$$



Metal and semiconductor in contact

- To avoid Schottky barrier: work function

$$\boxed{W_m < W_s}$$

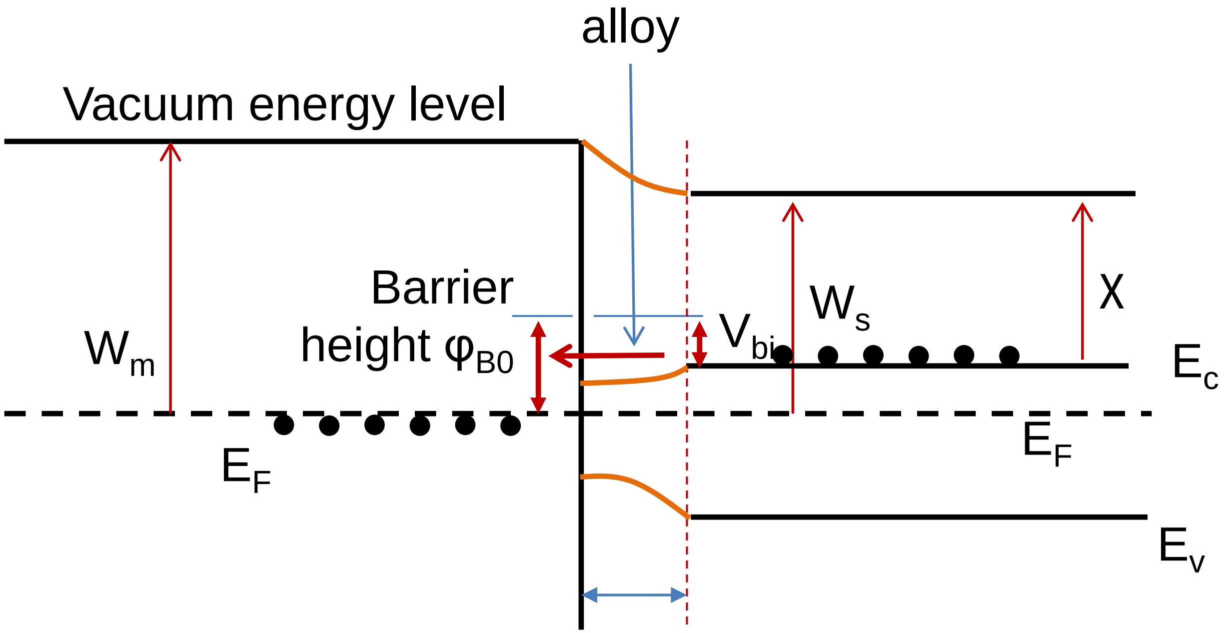


Metal and semiconductor in contact

- To avoid Schottky barrier: silicide (metal-semiconductor alloy)

Nickel silicide, NiSi

Titanium silicide, $TiSi_2$

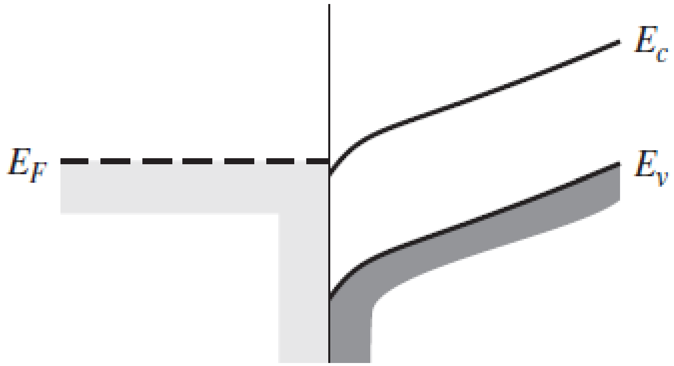


Highly doped region

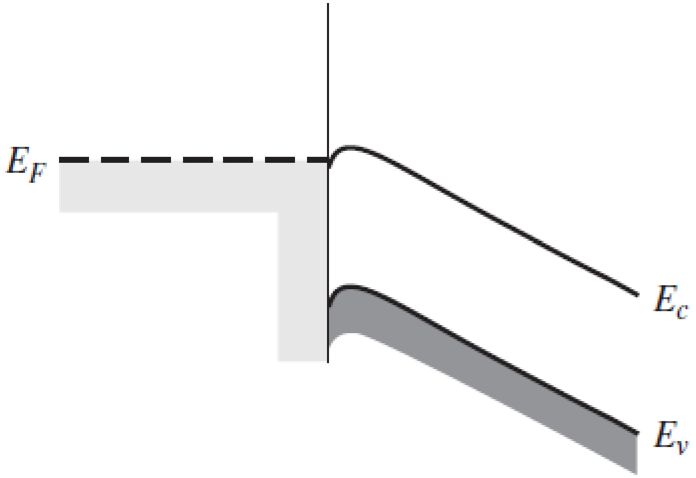
Metal and semiconductor in contact

Ohmic contact: $\Phi_m < \Phi_s$

Positive voltage applied to the metal



Positive voltage applied to the semiconductor



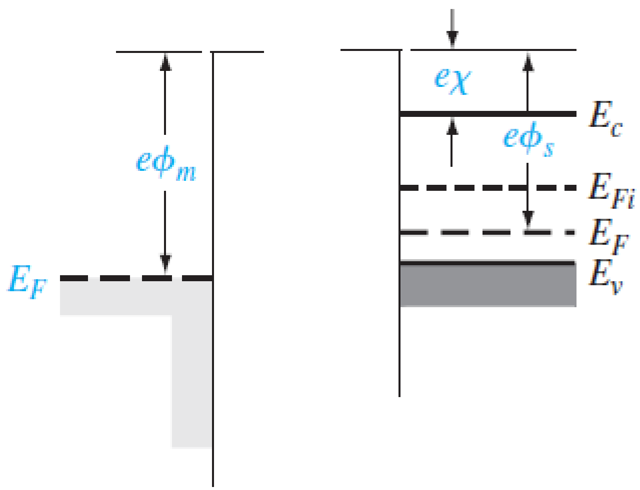
Positive voltage applied to the metal: electrons easily flow from semiconductor to metal “downhill”
Positive voltage applied to the semiconductor: electrons flow from the metal, through the small potential barrier $\phi_{Bn} = \phi_n$

Ohmic contact: conductive both ways, like resistor

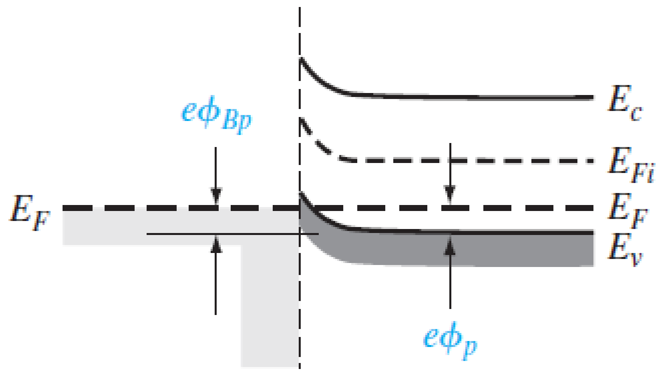
Metal and semiconductor in contact

Ohmic contact: $\Phi_m > \Phi_s$ for a p-type semiconductor

Before contact



After contact



Electrons from the semiconductor flow into the metal to reach thermal equilibrium
Leaving behind more holes (majority carriers), so more p-type near the metal.

Surface states and interface states: may prevent formation of Ohmic contact

Metal and semiconductor in contact

Conduction mechanism:

2. Tunneling barrier

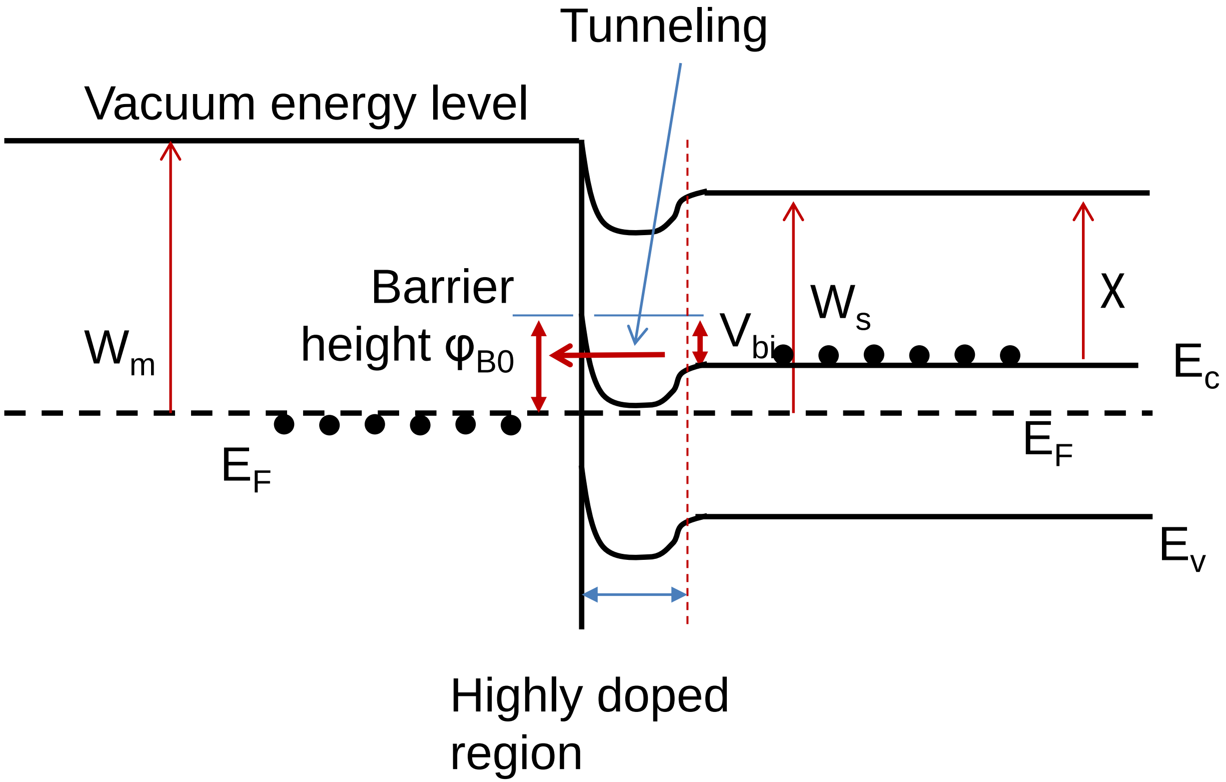
Large doping concentration: small depletion region width

Tunneling current density

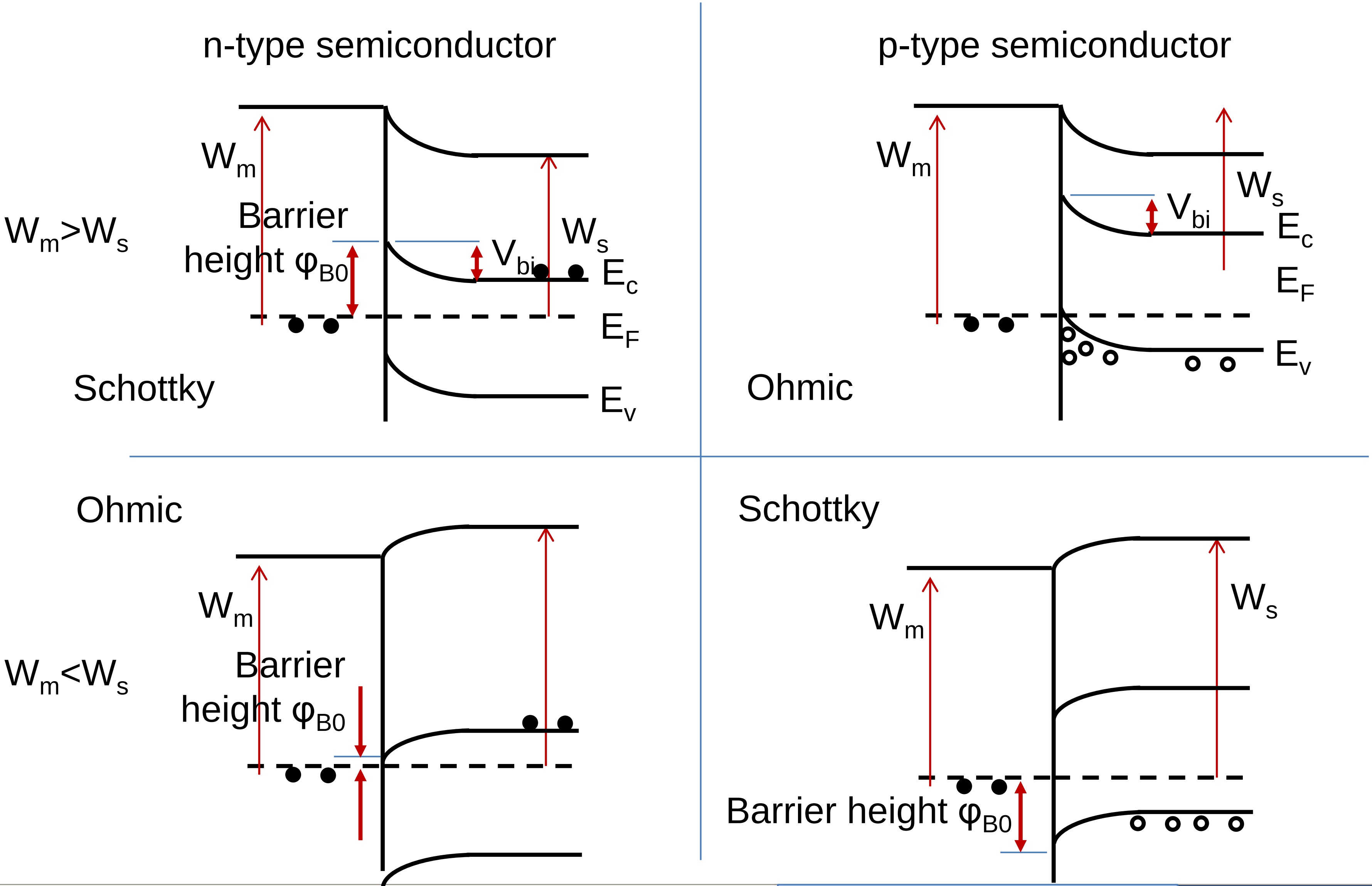
$$J_t \propto \exp\left(\frac{-e\phi_{Bn}}{E_{oo}}\right)$$

where

$$E_{oo} = \frac{e\hbar}{2}\sqrt{\frac{N_d}{\epsilon_s m_n^*}}$$



Schottky junction and Ohmic contact

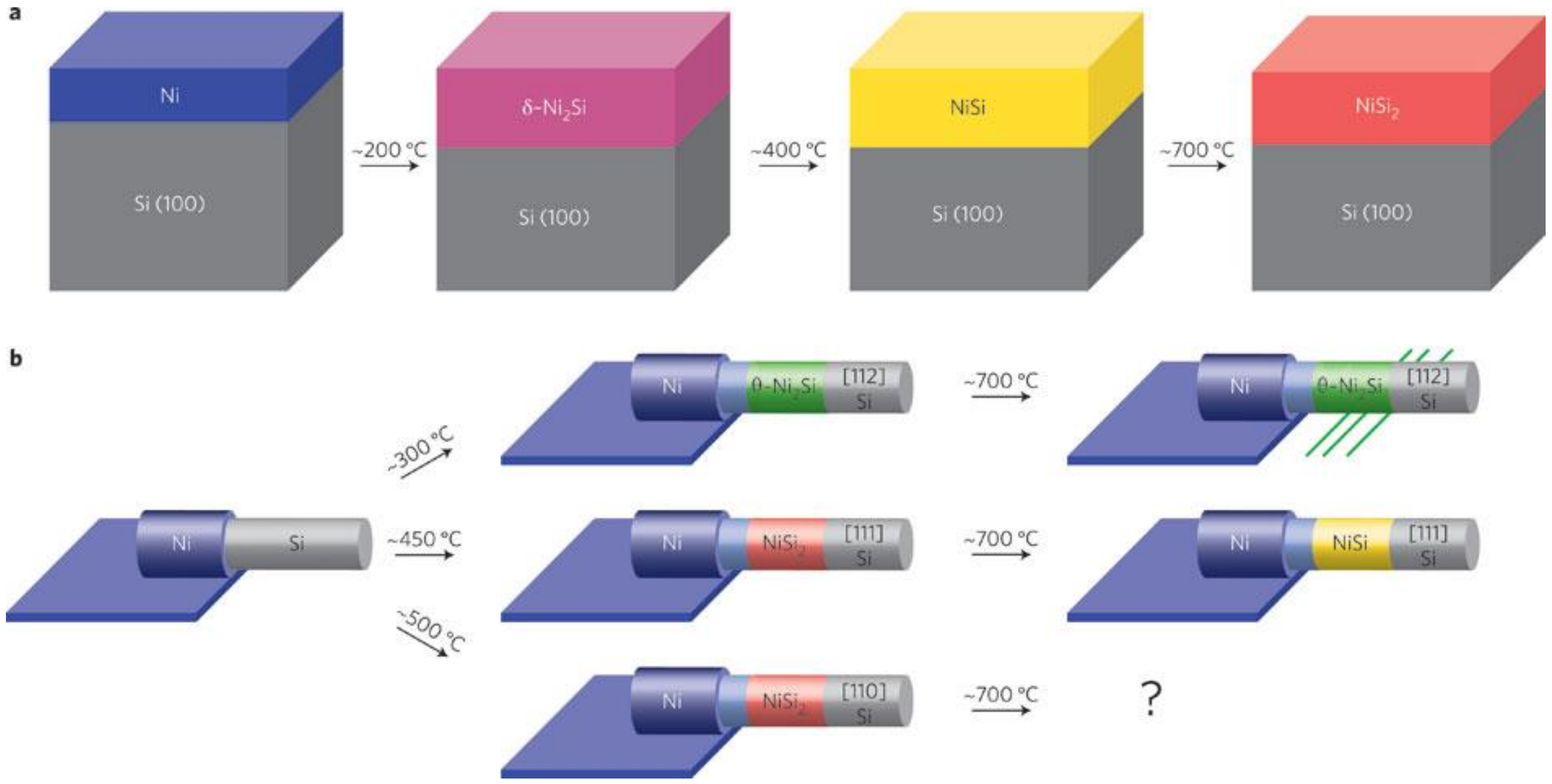


Metal and semiconductor in contact

- To avoid Schottky barrier: silicide (metal-semiconductor alloy)

Nickel silicide, NiSi

Titanium silicide, $TiSi_2$



Metal and semiconductor in contact

Contact resistance

$$R_c = \left(\frac{\partial J}{\partial V}\right)^{-1}\bigg|_{V=0} \qquad \Omega\text{-cm}^2$$

We want R_c to be as small as possible

$$J_n = A^*T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

When thermionic emission is dominant:

$$R_c = \frac{\left(\frac{kT}{e}\right)\exp\left(\frac{+e\phi_{Bn}}{kT}\right)}{A^*T^2}$$

When tunneling is dominant:

$$R_c \propto \exp\left(\frac{+2\sqrt{\epsilon_s m_n^*}}{\hbar}\cdot\frac{\phi_{Bn}}{\sqrt{N_d}}\right)$$

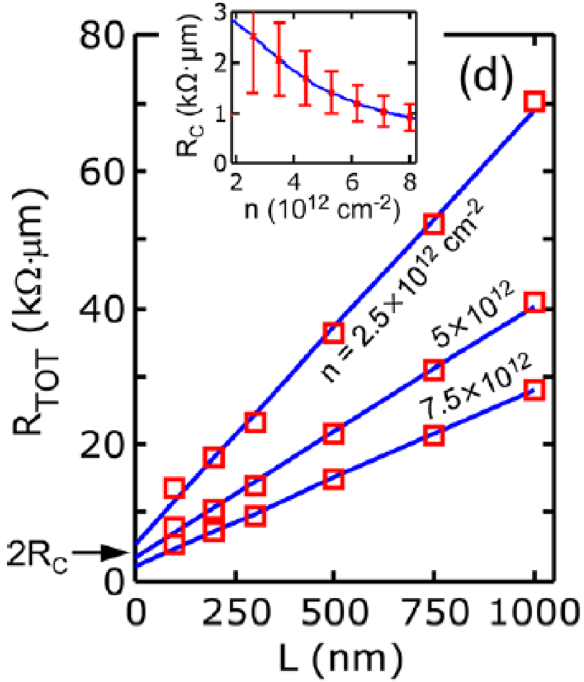
Metal and semiconductor in contact

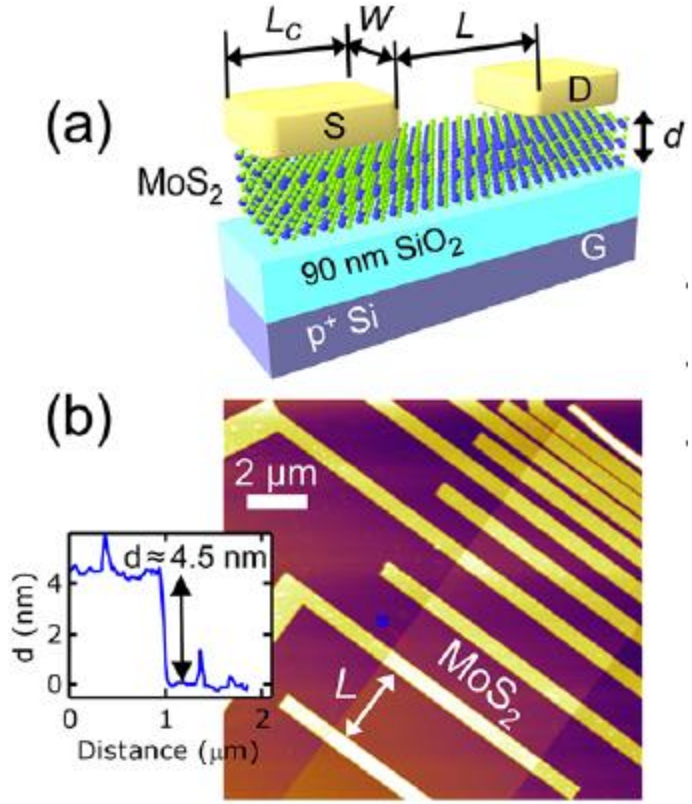
Example: how to measure contact resistance

NANO LETTERS Letter pubs.acs.org/NanoLett

Improved Contacts to MoS_2 Transistors by Ultra-High Vacuum Metal Deposition

Transfer length method (TLM) measurements





Ref: *Nano Lett.* **16**, 3824-3830 (2016)

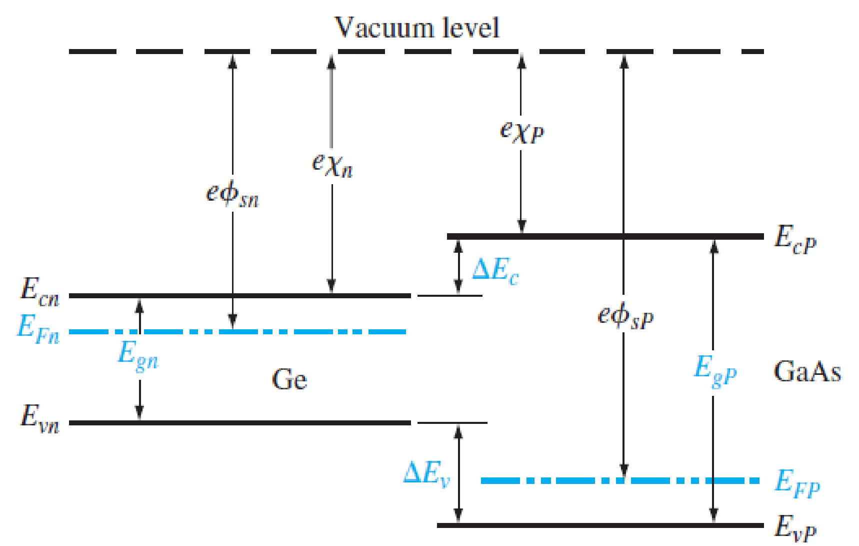
Heterojunction

Two different semiconductor materials: semiconductor heterojunction
Lattice matched: 0.14% percent for GaAs and AlGaAs

Straddling Staggered Broken gap

$$\Delta E_c = e(\chi_n - \chi_P)$$

$$\Delta E_c + \Delta E_v = E_{gP} - E_{gn} = \Delta E_g$$



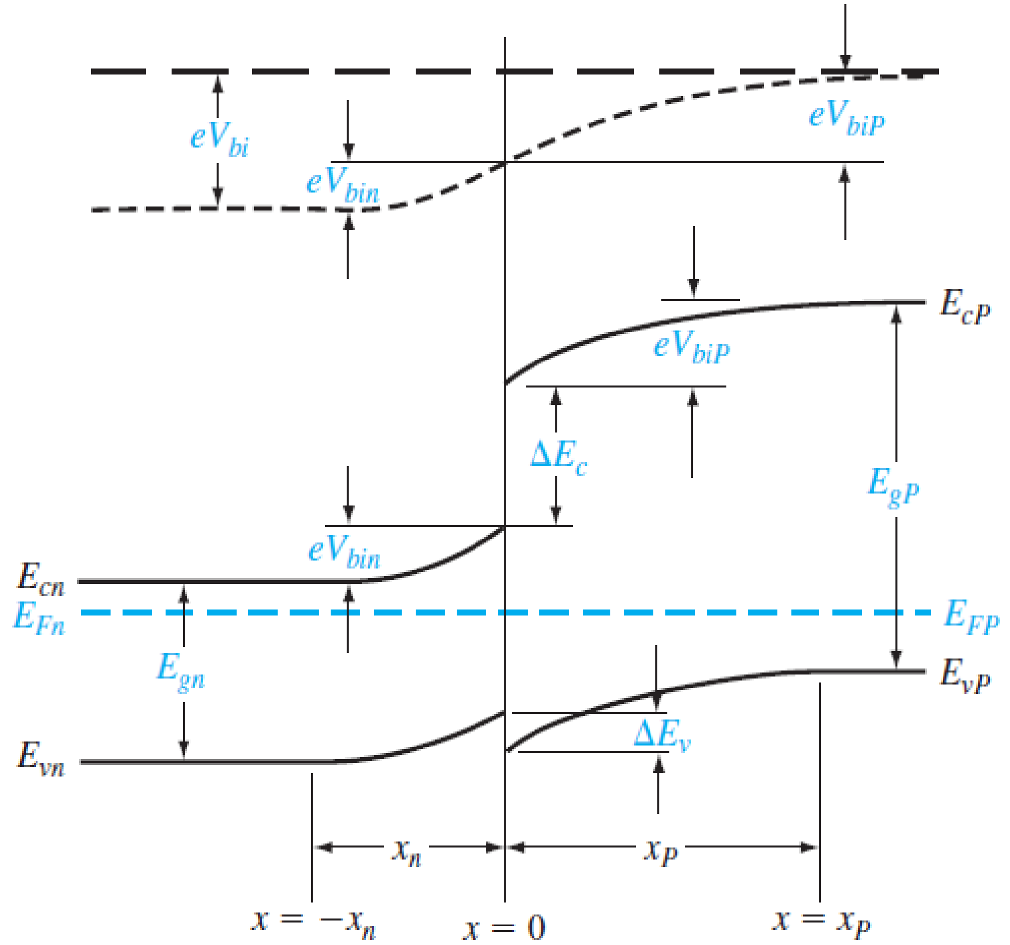
Heterojunction

Two different semiconductor materials: semiconductor heterojunction
Lattice matched: 0.14% percent for GaAs and AlGaAs

nP heterojunction

n: small bandgap
P: large bandgap

Electrons and holes flow
Forming depletion region



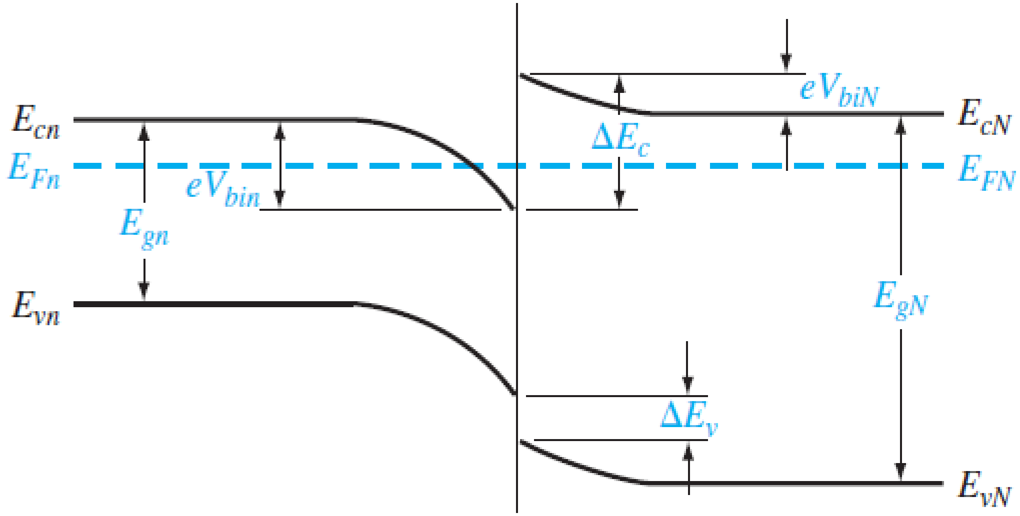
Heterojunction

Two different semiconductor materials: semiconductor heterojunction
Lattice matched: 0.14% percent for GaAs and AlGaAs

More interesting case:
nN heterojunction
GaAs-AlGaAs

GaAs lightly doped or intrinsic

Electrons from the wide-bandgap
AlGaAs flow into the GaAs



Many electrons in the potential well adjacent to the interface in GaAs
Energy of an electron contained in a potential well is quantized
Two-dimensional electron gas (2DEG): electrons have quantized energy levels in one spatial direction (perpendicular to the interface), but are free to move in the other two spatial directions

Heterojunction

Two different semiconductor materials: semiconductor heterojunction
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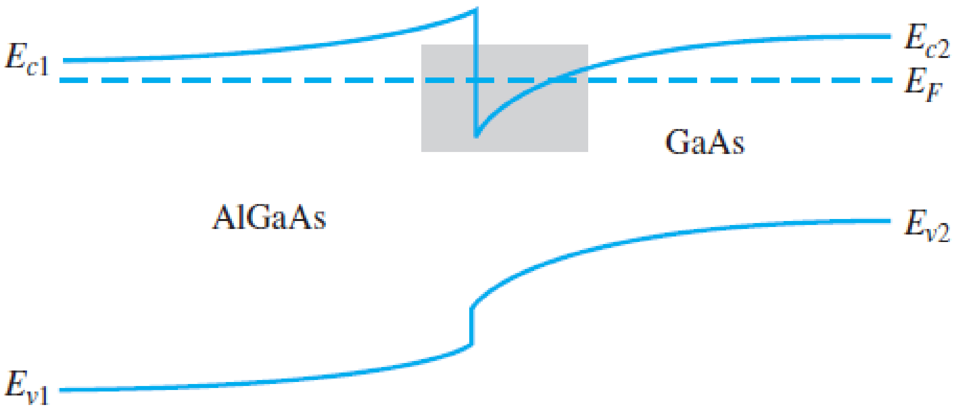
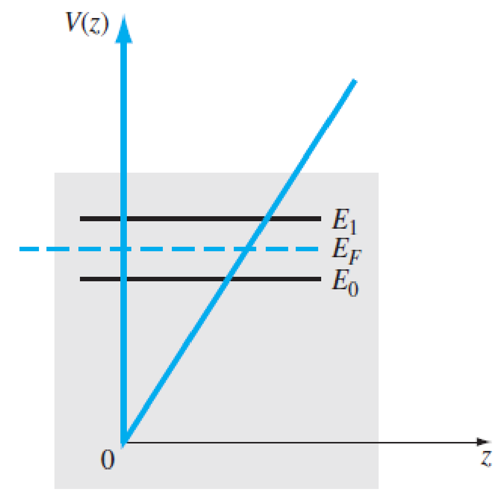


Two-dimensional electron gas (2DEG)

Triangular potential well

$$V(x) = e\mathrm{E}z \qquad z > 0$$

$$V(z) = \infty \qquad z < 0$$



Small impurity scattering in GaAs, due to low doping level or intrinsic

Large carrier mobility