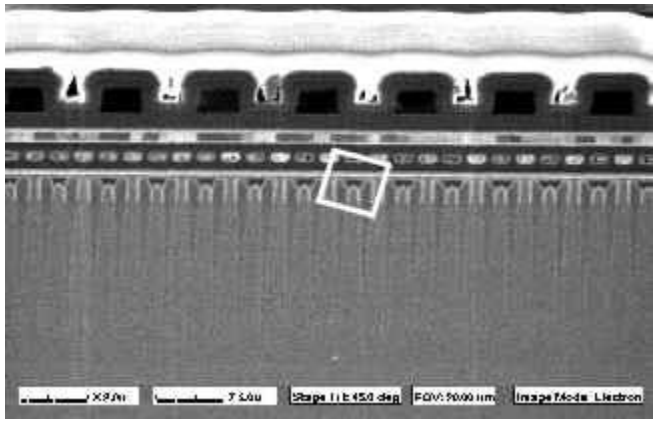
Metal-Semiconductor Junctions

EECS 320

Introduction to Semiconductor Devices

Metal-Semiconductor Junctions

- Metals are used for:
  - Device-level interconnects
  - Component-level interconnects
  - Devices



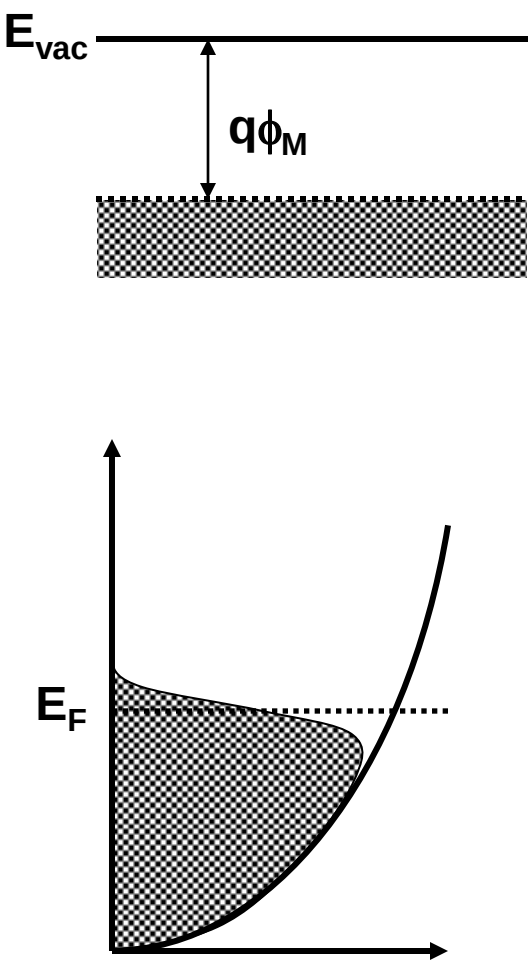
http://www.fibics.com/LargeEELS.html

64 Mbit DRAM X-section

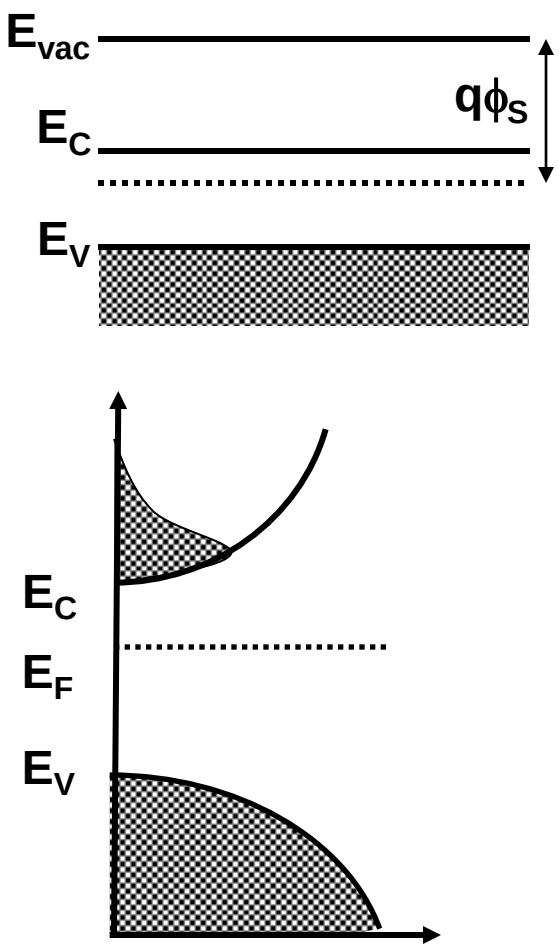
Microprocessor Top View

Metal-Semiconductor Junction

Metal



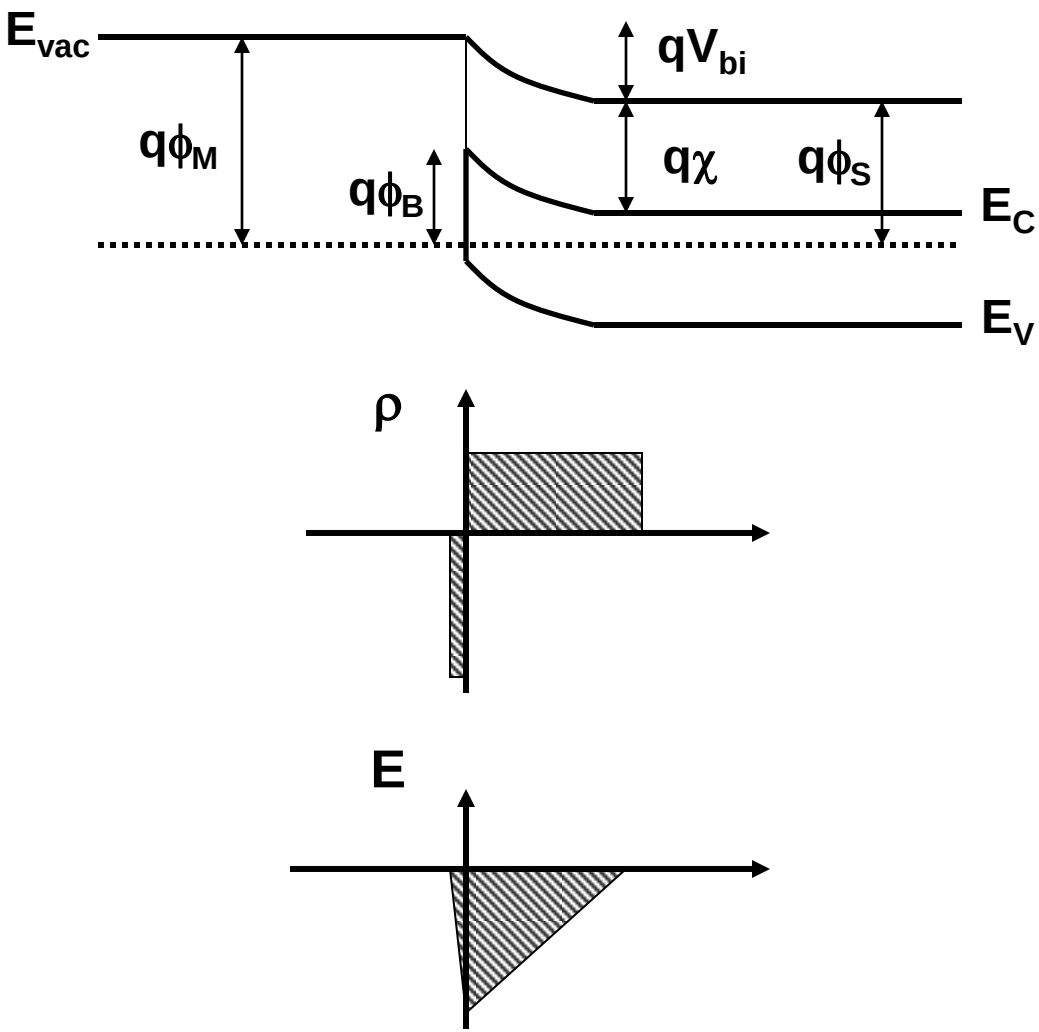
Semiconductor



Band Diagram For Metal-Semiconductor

Sketch what you would expect for the band diagram of a metal-semiconductor junction with n-type material and the cases $\phi_M > \phi_S$ and $\phi_M < \phi_S$

Equilibrium Band Diagram



Charge redistribution near junction, Fermi level flat in equilibrium

$$Q = qN_d x_d$$

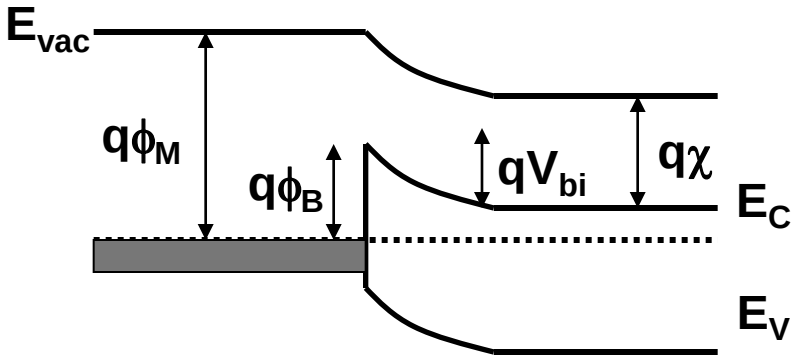
$$x_d = \sqrt{\frac{2\varepsilon_S V_{bi}}{qN_D}}$$

$$E_{\max} = -\frac{qN_d x_d}{\varepsilon_S}$$

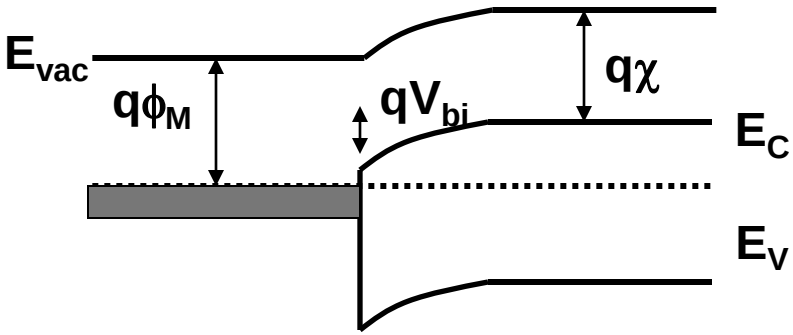
Built-In Potential

$$V_{bi} = \phi_M - \phi_S = \phi_M - \left[\chi + \frac{1}{q}\left(E_C - E_f\right) \right]$$

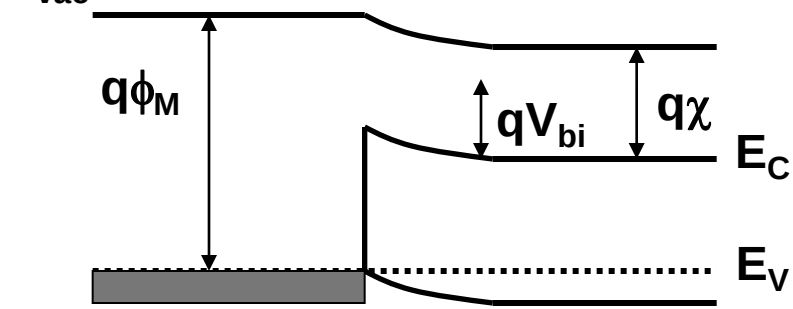
$\phi_M > \phi_S$, n-type



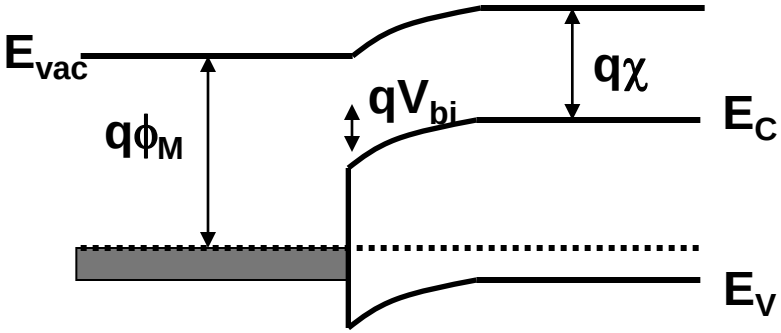
$\phi_M < \phi_S$, n-type



$\phi_M > \phi_S$, p-type

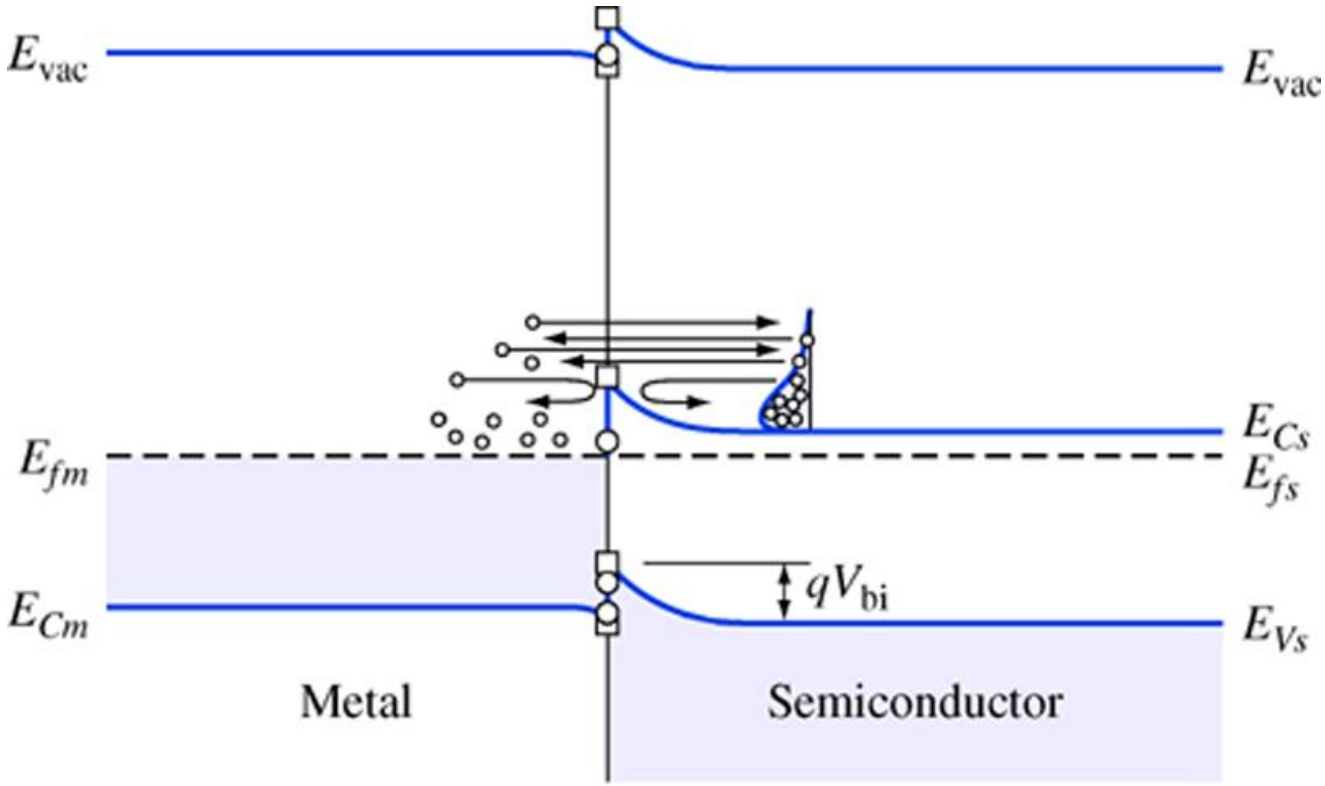


$\phi_M < \phi_S$, p-type

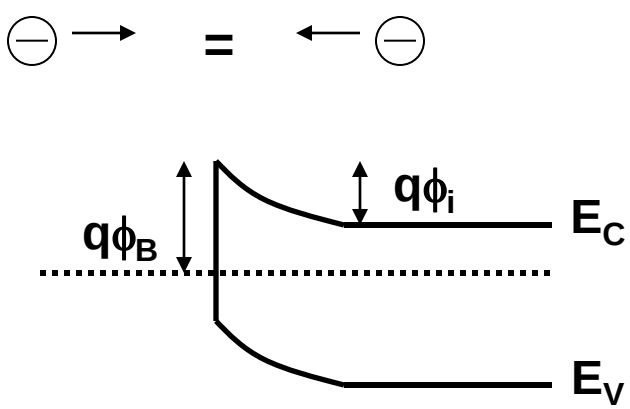


Equilibrium Band Diagram

Current flow balanced



Current at Zero Bias



Carrier density at semiconductor interface

$$n_s = N_C \exp\left(-\frac{q\phi_B}{kT}\right)$$

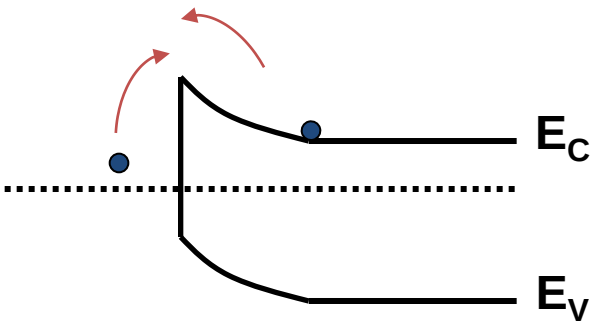
Current proportional to carrier density
Current flow balanced at zero bias

$$\left|J_{MS}\right| = \left|J_{SM}\right| = KN_C \exp\left(-\frac{q\phi_B}{kT}\right)$$

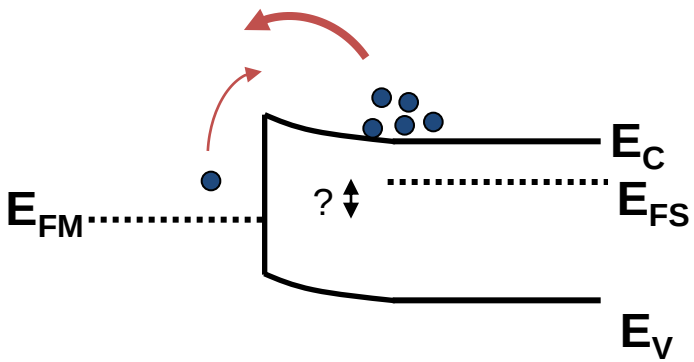
Current flow is due to *majority carriers* through thermionic emission process

Forward Bias Current

$V_A = 0$, $J_{MS} = J_{SM}$



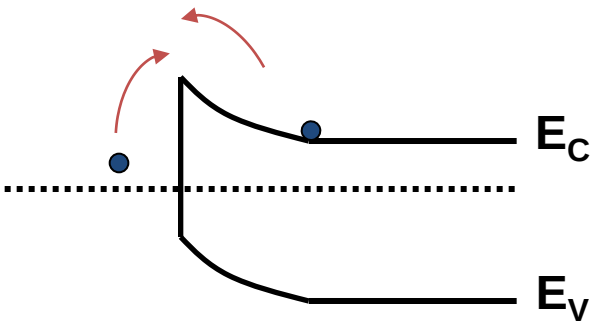
$V_A > 0$, $J_{MS} < J_{SM}$



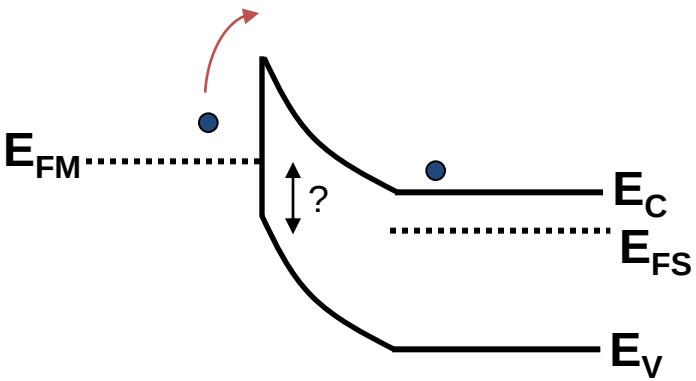
Barrier for current flow from semiconductor to metal decreases with forward bias, while barrier for current flow from metal to semiconductor stays fixed at the Schottky barrier height (Φ_B)

Reverse Bias Current

$V_A = 0$, $J_{MS} = J_{SM}$



$V_A < 0$, $J_{MS} > J_{SM}$



As a reverse bias is applied to the MS junction, the barrier for current from the semiconductor to the metal is increased, while the barrier from the metal to the semiconductor remains the same

Thermal Velocity Distribution: Ideal Gas

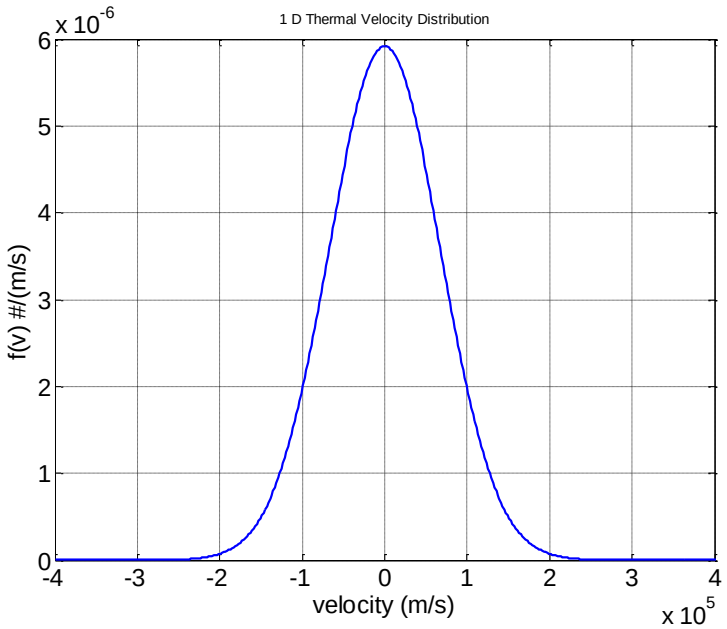
- Maxwellian Distribution

$$f\left(v_x, v_y, v_z\right) = \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-\frac{m\left(v_x^2 + v_y^2 + v_z^2\right)}{2kT}\right)$$

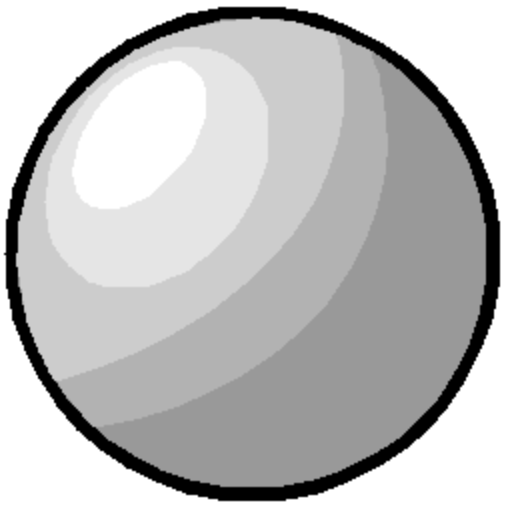
$$= \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-\frac{m\left|\vec{v}\right|^2}{2kT}\right)$$

$$1-D$$

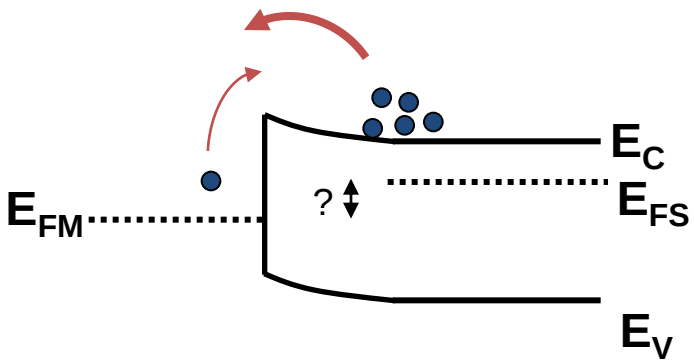
$$f\left(v_x\right) = \left(\frac{m}{2\pi kT}\right)^{1/2} \exp\left(-\frac{mv_x^2}{2kT}\right)$$

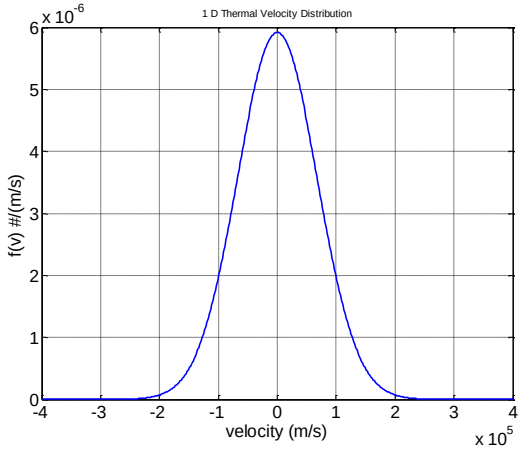


Surface Breaks Symmetry



$V_A > 0, J_{MS} < J_{SM}$





Schottky Diode Under Applied Bias

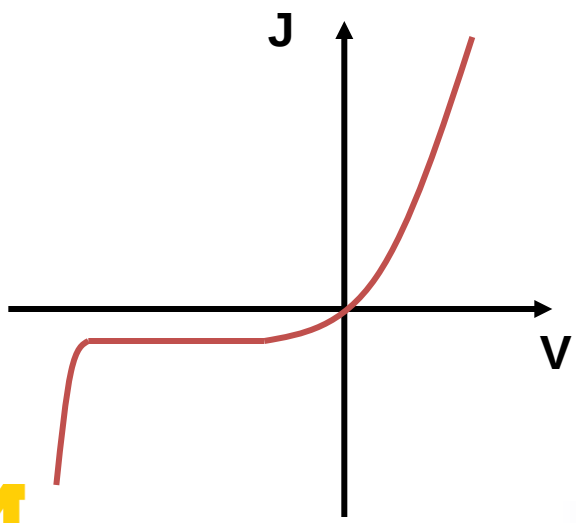
Rectifying behavior like p-n diode

$$J = J_S\left[\exp\left(\frac{qV_a}{\underline{n}kT}\right)-1\right]$$

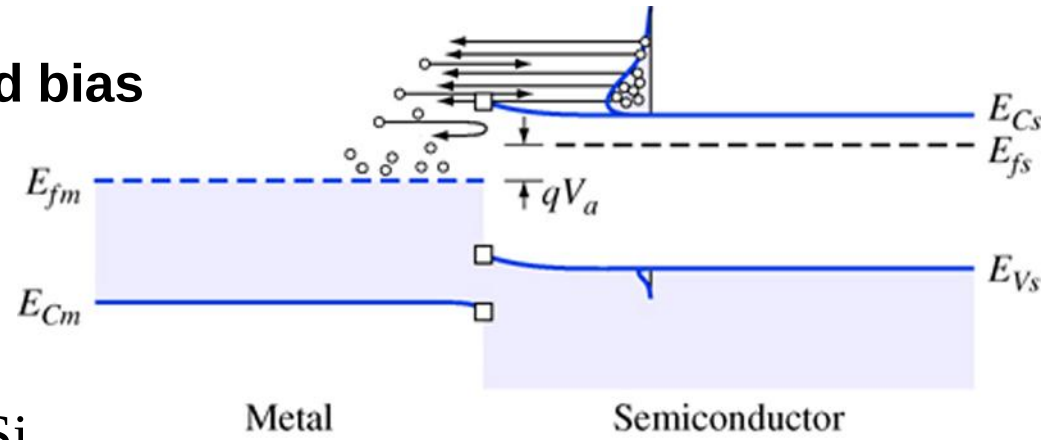
$$J_S = A^{**}T^2\exp\left(-\frac{q\varphi_B}{kT}\right)$$

$A^{**} = 1.12\text{x}10^6\,\text{A m}^{-2}\,\text{K}^{-2}$ for n-type Si

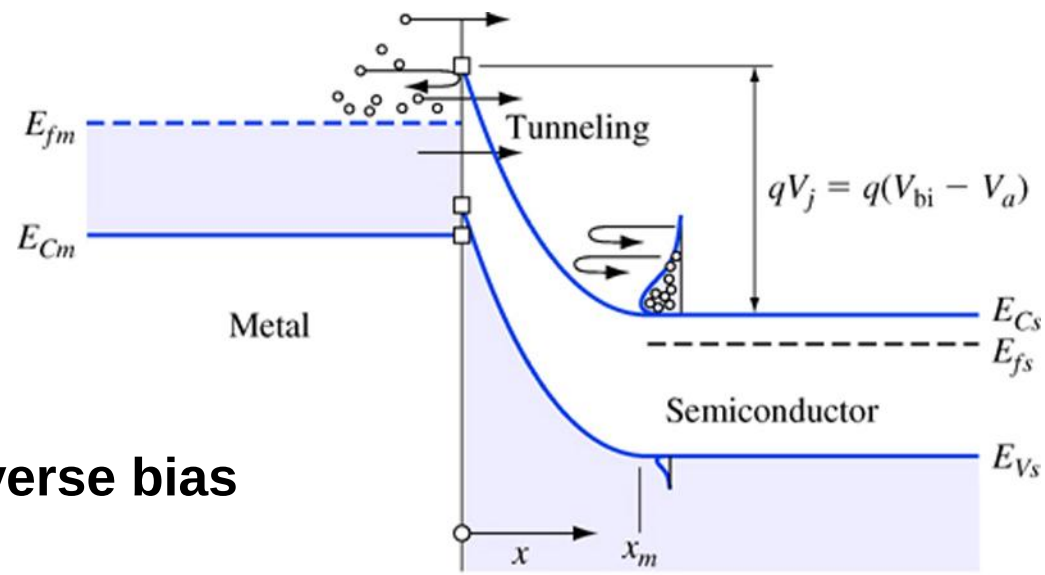
Effective Richardson's Constant



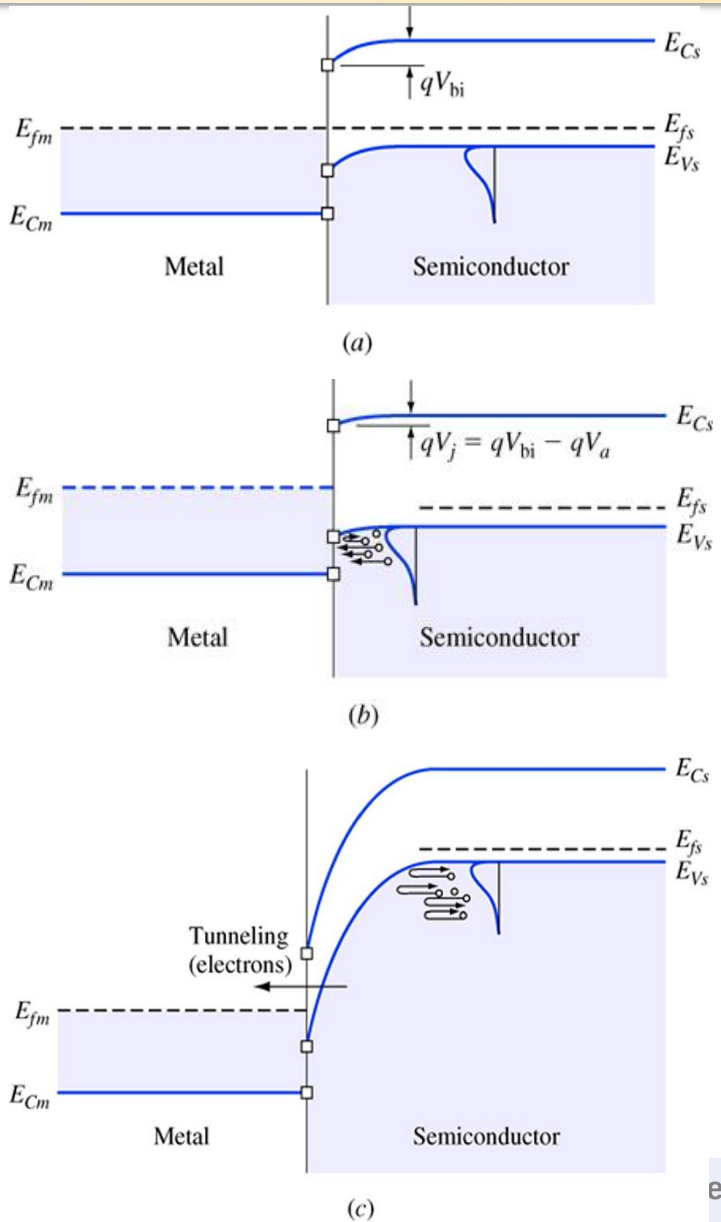
Forward bias



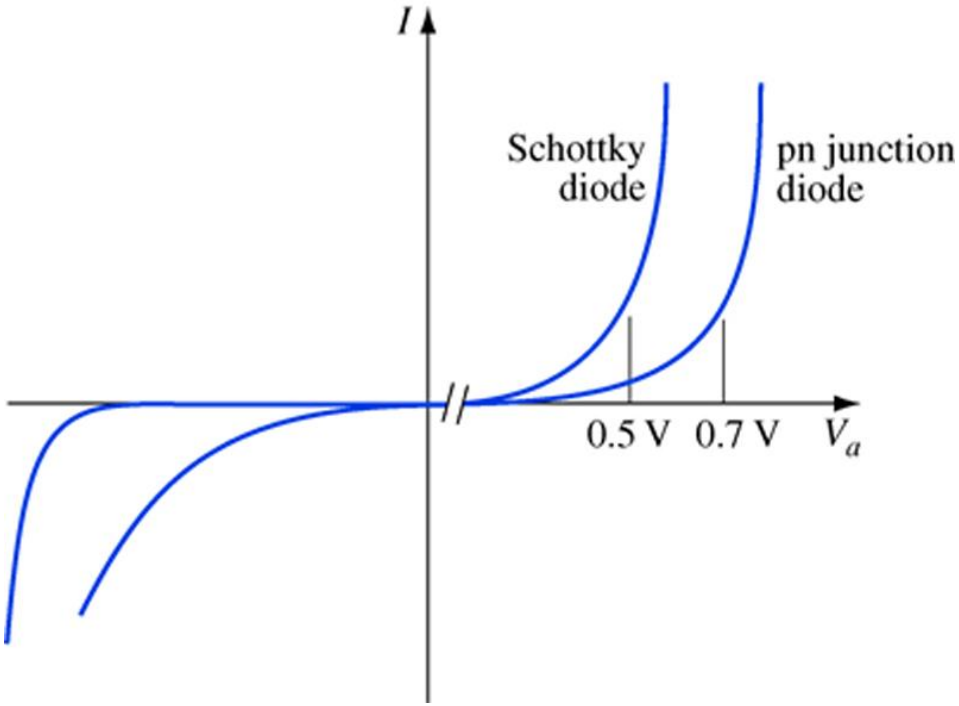
Reverse bias



Reverse Bias Tunneling



Tunneling distance typically smaller in M-S



Ohmic Contacts

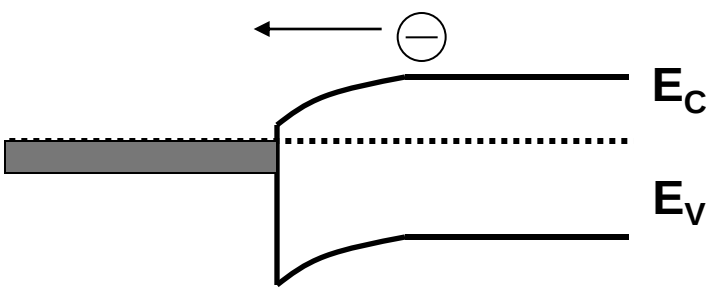
Ohmic: linear I-V, negligible resistance desired

- Allows current to flow freely
- Voltage drop across contact negligible in comparison to voltage drops elsewhere
- Power dissipation minimal
- Contacts critical for every device, often just as challenging as realizing the device itself!

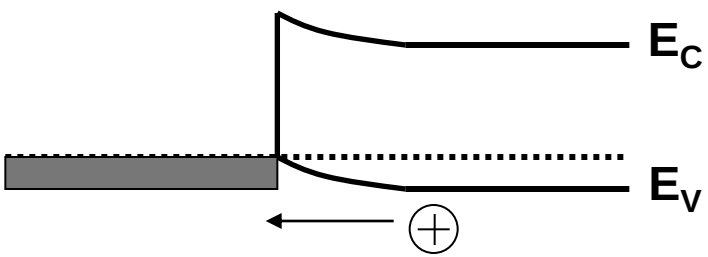
Schottky Ohmic Contacts

Reverse Work Function

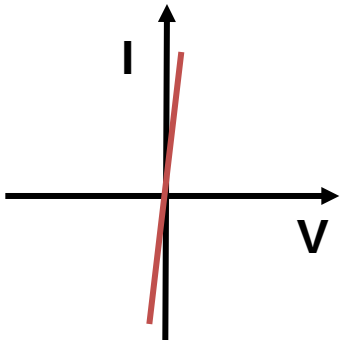
$\phi_M < \phi_S$, n-type



$\phi_M > \phi_S$, p-type

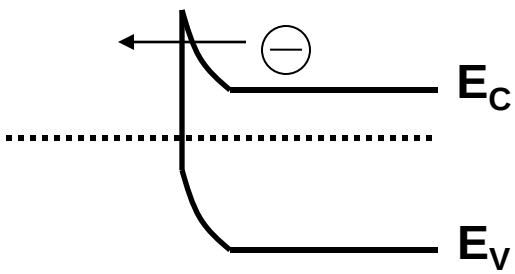


- No barrier to majority carrier current flow
- Very few metal/semiconductor materials have this lineup

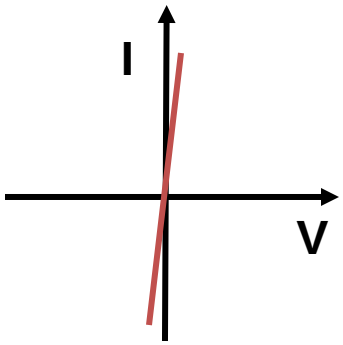


Tunnel Contacts

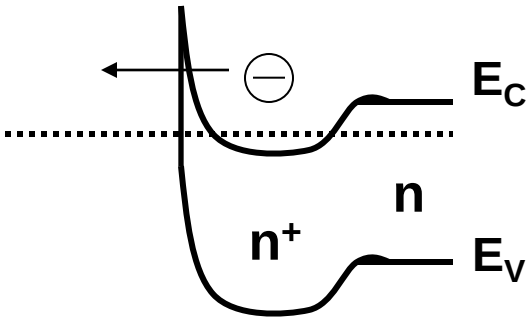
Reduction in depletion layer width to permit quantum mechanical electron tunneling



$$x_d = \sqrt{\frac{2\varepsilon_S \phi_{bi}}{qN_D}}$$

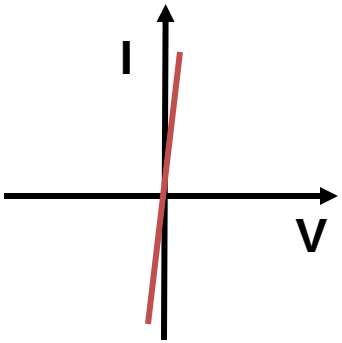


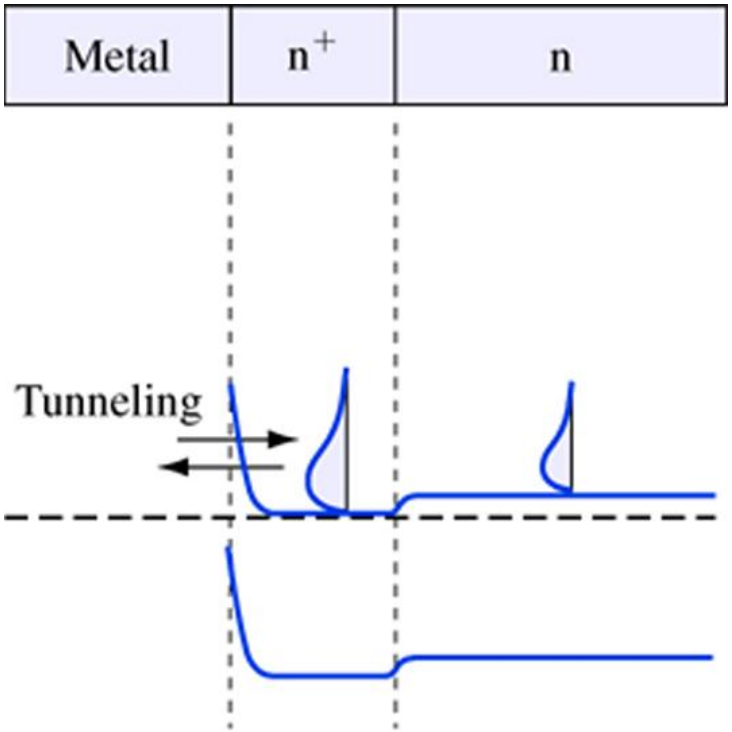
High doping (degenerate) typically used in practice, and/or annealing to alloy contacts

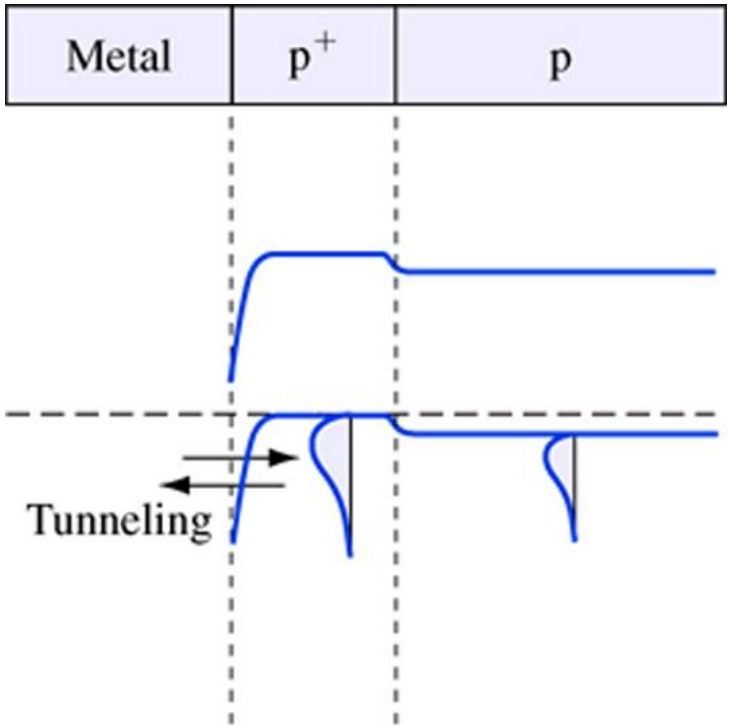


Ohmic Contacts

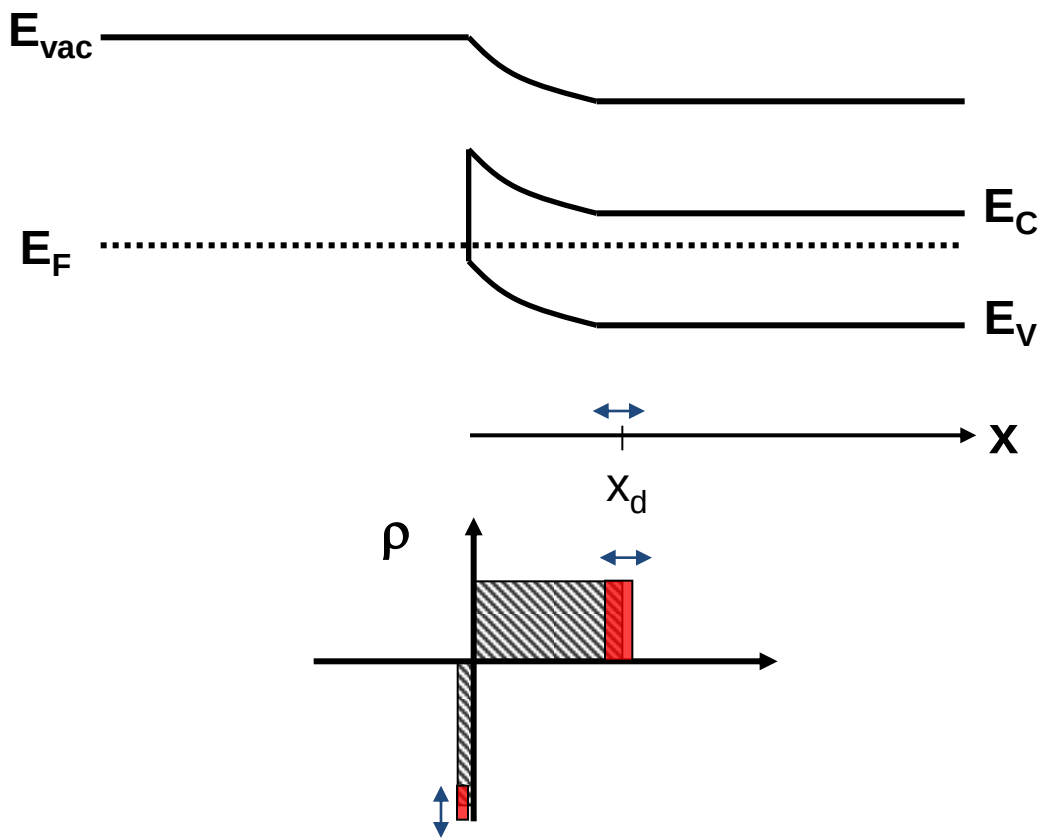
Reduction in depletion layer width to permit quantum mechanical electron tunneling







Depletion Capacitance



$$C = \frac{\varepsilon A}{\sqrt{\frac{2\varepsilon}{qN_D}\left(V_{bi} - V_A\right)}}$$

$$\frac{1}{C^2} = \frac{2}{qN_D \varepsilon A^2}\left(V_{bi} - V_A\right)$$

- In response to a small ac signal, a Schottky junction acts like a parallel plate capacitor as the depletion width changes with the ac signal