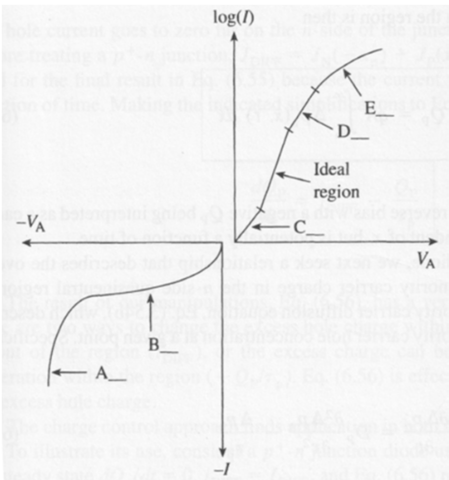
University of Michigan – Shanghai Jiao Tong University Joint Institute
Center of Optics and Optoelectronics

VE 320 – Summer 2012
Introduction to Semiconductor Device

Schottky Diode

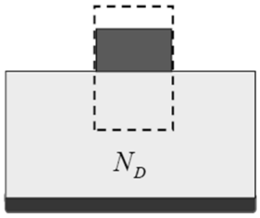
Instructor: Professor Hua Bao

PN Junction Diode, non-ideal

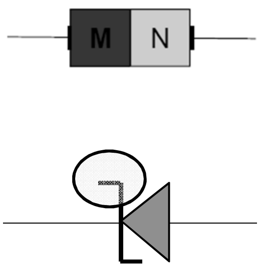


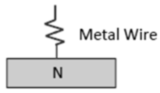
1. Photogeneration
2. Thermal recombination in the depletion region
3. Avalanching and/or Zener process
4. Low-level injection
5. Depletion approximation
6. Thermal generation in the depletion region
7. Band bending
8. Series resistance
9. $V_A > V_{bi}$
10. High-level injection

Metal-semiconductor Diode



Symbols





Electrostatic and DC

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

Electrostatic

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N\mathcal{E} + qD_N\nabla n$$

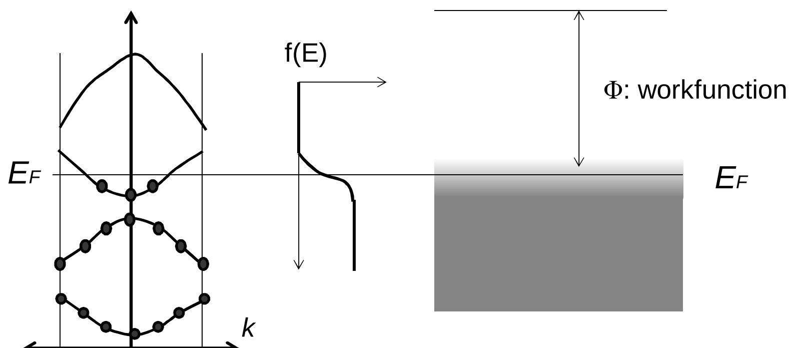
$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P\mathcal{E} - qD_P\nabla p$$

DC/AC/Transient

Metal

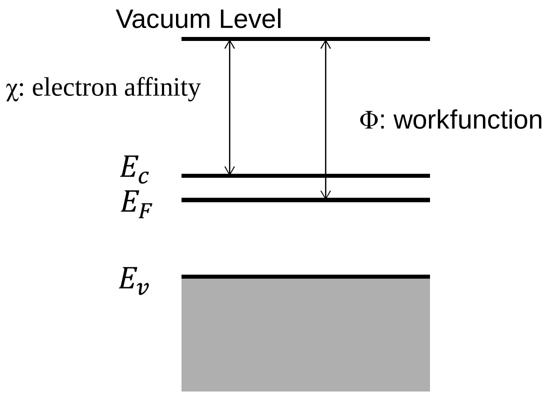
Vacuum Level:
the energy of a stationary electron
outside the metal



A lot of states are available around E_F

Φ: workfunction, material property 3.66 ~ 5.15 eV

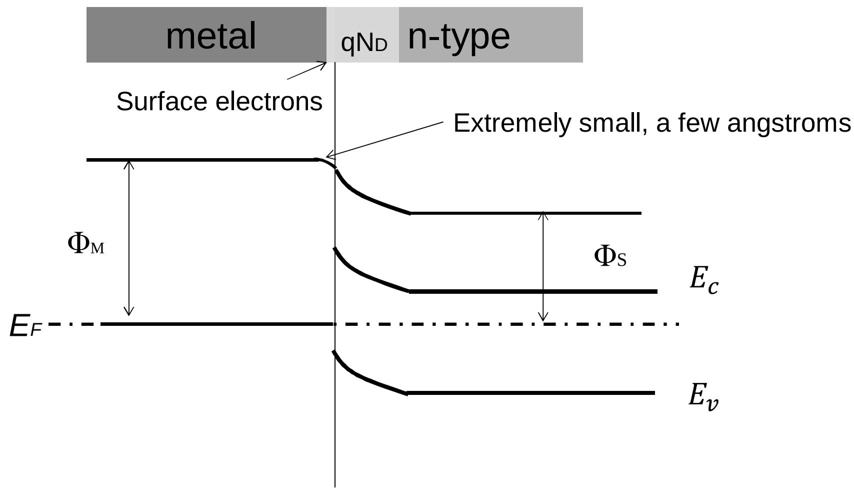
Semiconductor



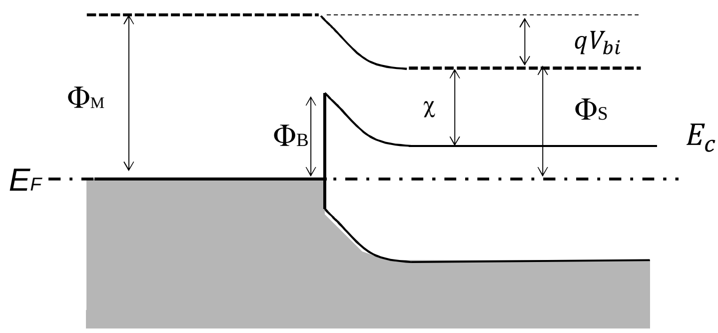
χ: electron affinity is a material property. 4.03 eV for silicon.
Workfunction of semiconductor depends on doping level

$$\Phi_S = \chi + (E_c - E_F)$$

Form a Diode/Band Diagram



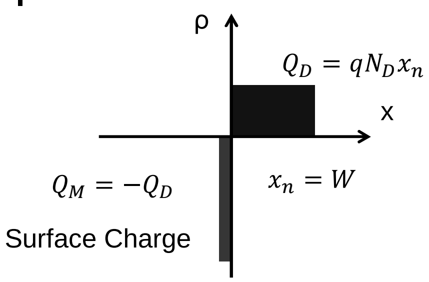
Band Diagram

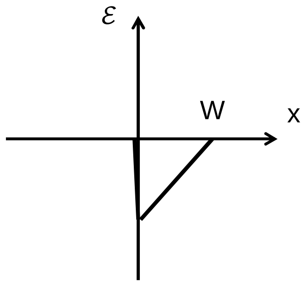


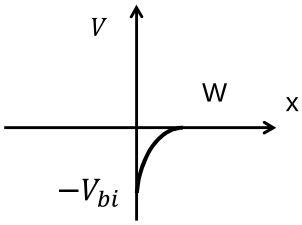
$$\Phi_B = \Phi_M - \chi$$

$$V_{bi} = \frac{1}{q}\left[\Phi_B - (E_c - E_F)_{FB}\right]$$

Analytical Solution





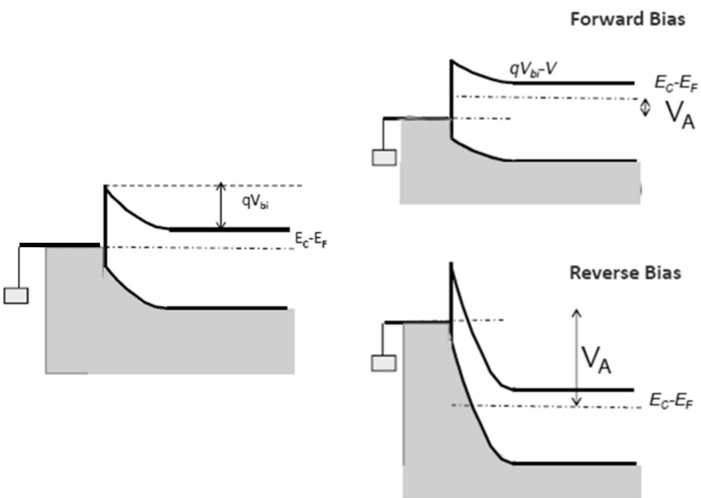


$$\frac{d\mathscr{E}}{dx} = \frac{\rho}{K_S\varepsilon_0} \approx \frac{qN_D}{K_S\varepsilon_0} \qquad 0 \le x \le W$$

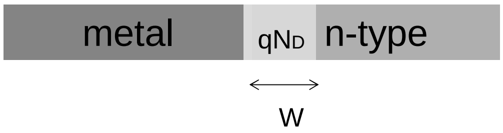
$$\mathscr{E}(x) = -\frac{qN_D}{K_S\varepsilon_0}(W - x)$$

$$V(x) = -\frac{qN_D}{2K_S\varepsilon_0}(W - x)^2$$

Band Diagram with Bias



Depletion Width



Depletion width varies with the applied potential V_A

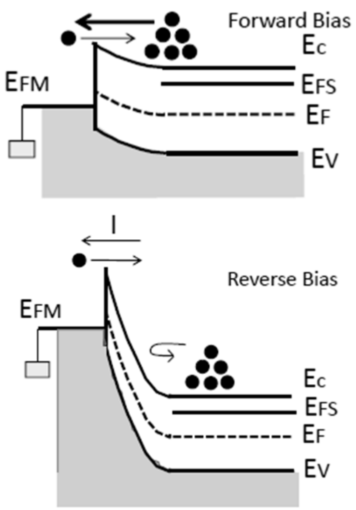
$$-(V_{bi} - V_A) = -\frac{qN_D}{2K_S\varepsilon_0}W^2$$

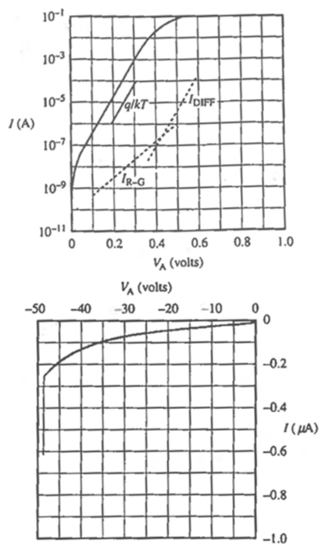
$$W = \left[\frac{2K_S\varepsilon_0}{qN_D}(V_{bi} - V_A)\right]^{1/2}$$

This solution is similar to a $p^+ - n$ junction

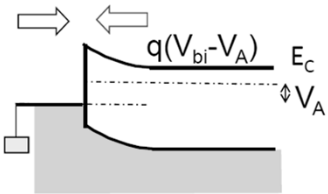
$$W = \sqrt{\frac{2K_s\varepsilon_0}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)(V_{bi} - V_A)}$$

I-V Characteristics





Simple Approach

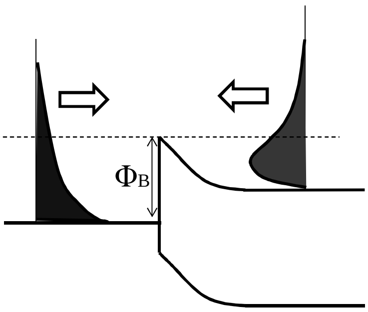


$$J_T(V_A) = J_{m\to s}(V_A) - J_{s\to m}(V_A)$$
$$= J_{m\to s}(0) - J_{s\to m}(V_A)$$
$$J_T(V_A = 0) = 0 = J_{m\to s}(0) - J_{s\to m}(0)$$ (detailed balance)
$$\Rightarrow J_{m\to s}(0) = J_{s\to m}(0)$$
$$J_T(V_A) = J_{s\to m}(0) - J_{s\to m}(V_A)$$

Semiconductor to Metal Flux

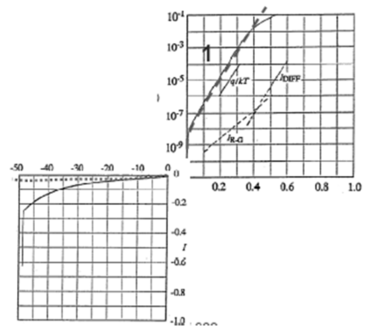
$$J_{m\to s}(V_A) = -q\frac{n_m}{2}e^{-\frac{q\Phi_B}{kT}}\upsilon_{th}$$

$$J_{s\to m}(V_A) = -q\frac{n_s}{2}e^{-q\frac{V_{bi}-V_A}{kT}}\upsilon_{th}$$
$$= -q\frac{n_s\upsilon_{th}}{2}e^{-\frac{qV_{bi}}{kT}} \times e^{\frac{qV_A}{kT}}$$
$$= -q\frac{n_m\upsilon_{th}}{2}e^{-\frac{q\Phi_B}{kT}}e^{\frac{qV_A}{kT}}$$



Total Flux

$$J_T = J_{s\to m}(0) - J_{s\to m}(V_A) = \frac{q n_m \upsilon_{th}}{2} e^{\frac{-q\Phi_m}{kT}} \left[e^{\frac{qV_A}{kT}} - 1 \right]$$



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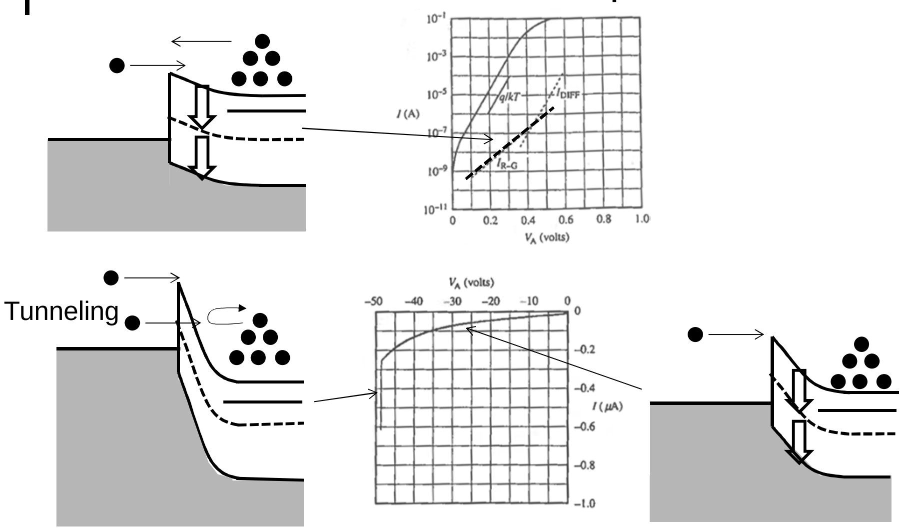
Recombination/Generation/Impact-ionization



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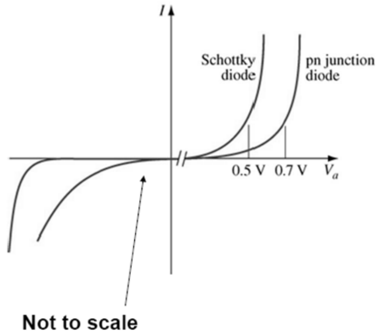
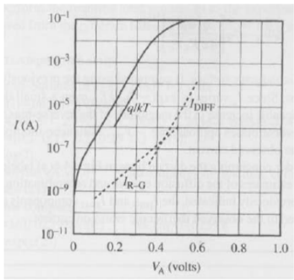
Comparing to PN Junction Diode

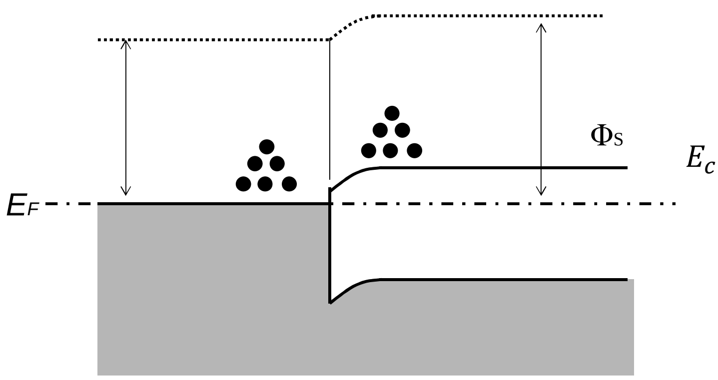




- smaller V_{bi}
- faster in charging/discharging during transient as no accumulation of minority carrier necessary
- no high-level injection problem
- ideality factor close to 1 (ideal case)
- lower breakdown voltage

Ohmic Contact

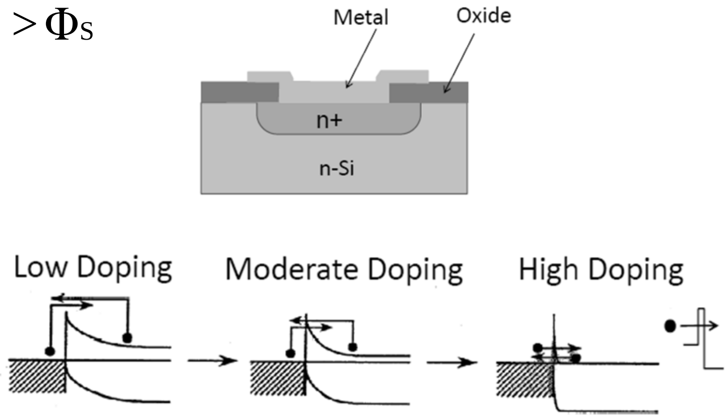
We have assumed $\Phi_M > \Phi_S$, what happens if $\Phi_M < \Phi_S$



No barrier from semiconductor to metal.
Small barrier vanishes with even relatively small reverse bias.
This is non-rectifying or ohmic-like.

Tunneling Ohmic Contacts

$\Phi_M > \Phi_S$



Summary

- M-S contact can be rectifying or ohmic-like.
- M-S diode electrostatics is similar to a p-n junction diode with one-side heavy doping.