Semiconductor Device Physics

Lecture 8

http://zitompul.wordpress.com

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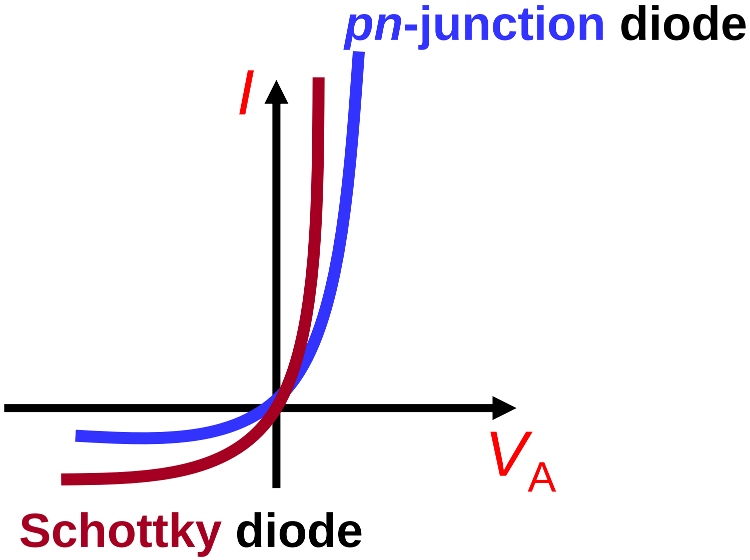
Chapter 14

MS Contacts and Schottky Diodes

MS Contact

- The metal-semiconductor (MS) contact plays a very important role in solid-state devices.
  - When in the form of a *rectifying contact*, the MS contact is referred to as the Schottky.
  - When in the from of a *non-rectifying* or *ohmic contact*, the MS contact is the critical link between the semiconductor and the outside.

- The reverse-bias saturation current I_S of a Schottky diode is 10^3 to 10^8 times larger than that of a *pn*-junction diode, depending on the type of material.
  - Schottky diodes are proffered rectifiers for low-voltage high-current applications.

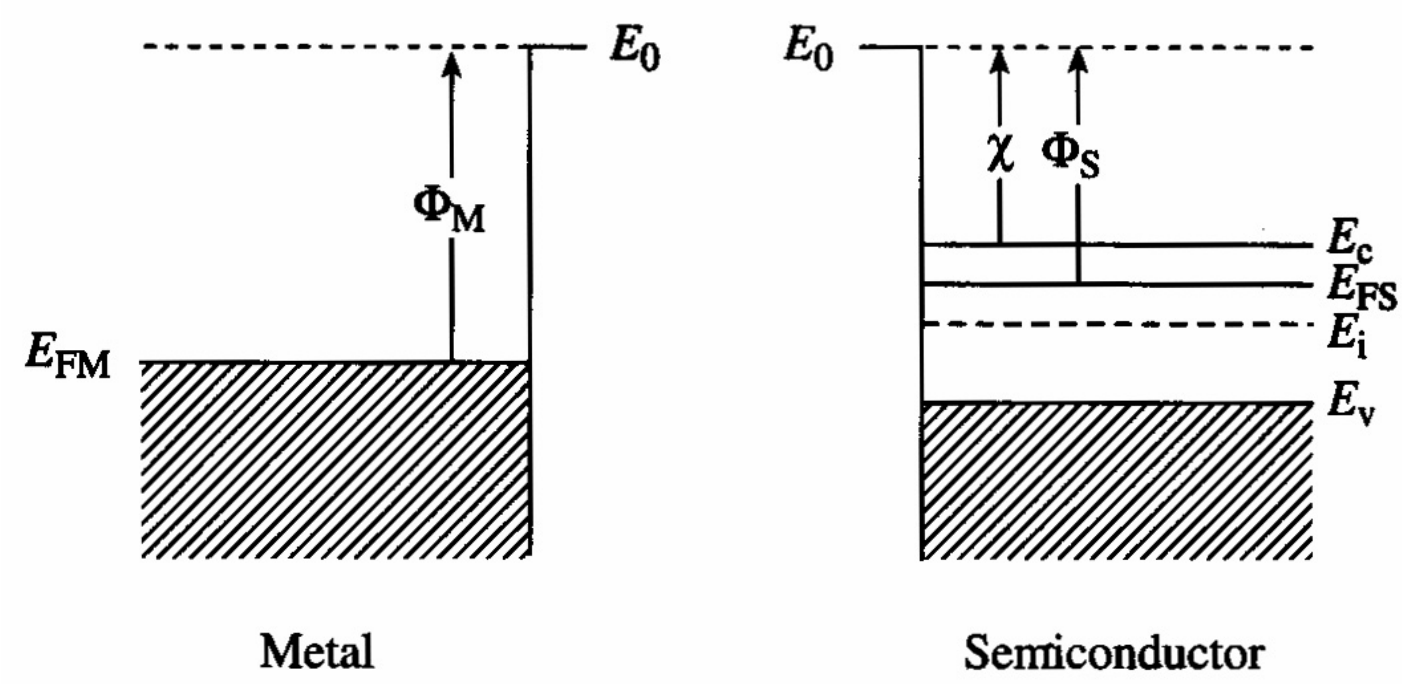


MS Contact

- A vacuum energy level, E_0, is defined as the minimum energy an electron must possess to completely free itself from the material.
- The energy difference between E_0 and E_F is known as the workfunction (Φ).

Workfunction

E_0: vacuum energy level



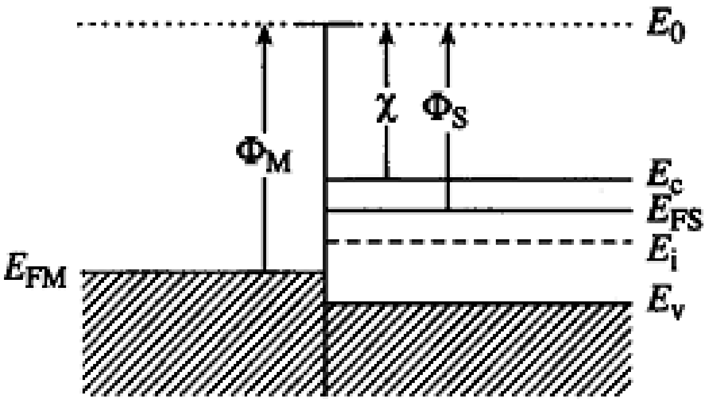
$\chi_{Si} = 4.03\text{eV}$

Φ_M: Metal workfunction
E_{FM}: Fermi level in metal

Φ_S: Semiconductor workfunction
E_{FS}: Fermi level in semiconductor
χ: electron affinity

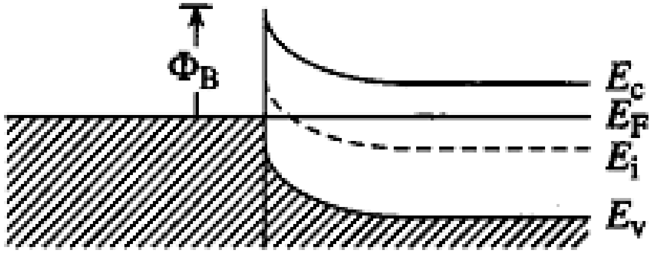
Ideal MS Contact: $\Phi_M > \Phi_S$, n-type

- Band diagram instantly after contact formation



- E_0 is continuous

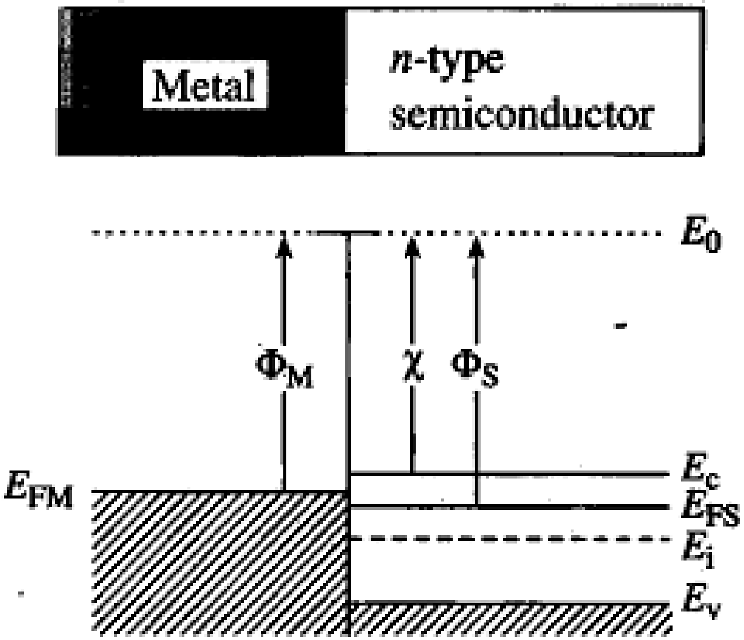
- Band diagram under equilibrium condition



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

- Surface potential-energy barrier

Ideal MS Contact: $\Phi_M < \Phi_S$, n-type



- E_0 is continuous

- Band diagram instantly after contact formation

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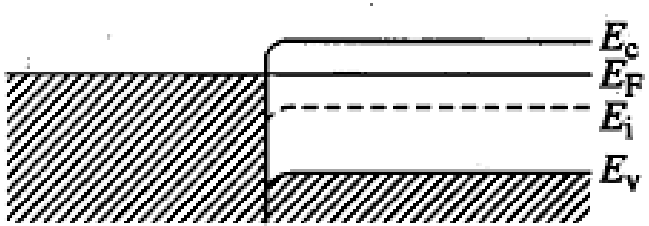
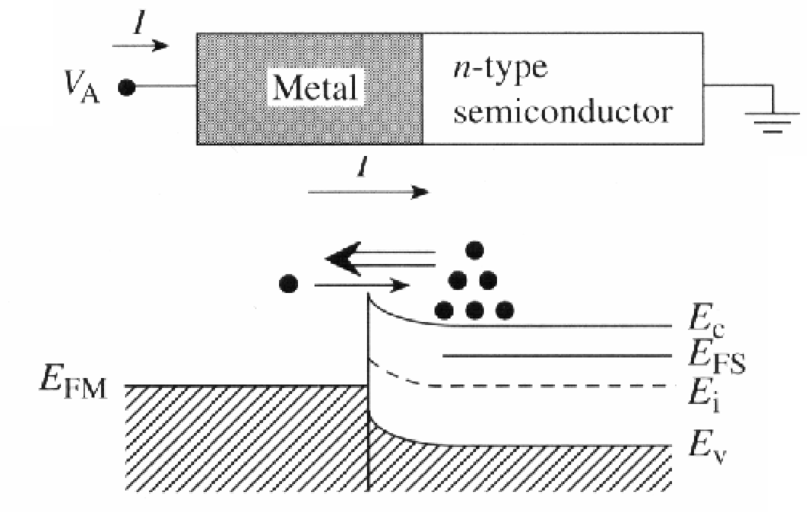
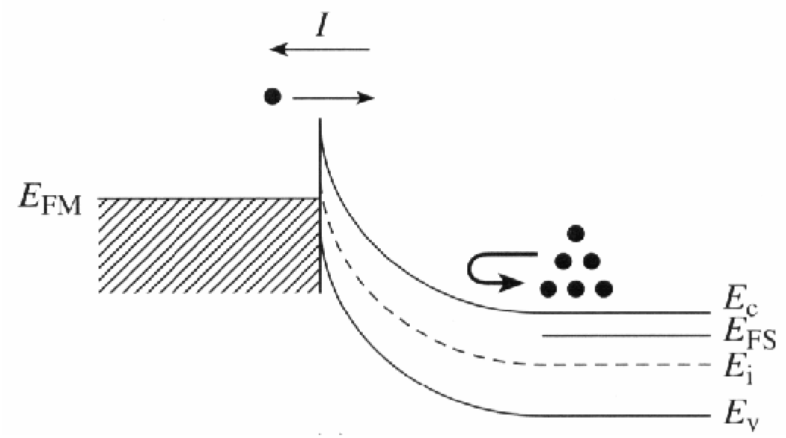


n-type MS Contact

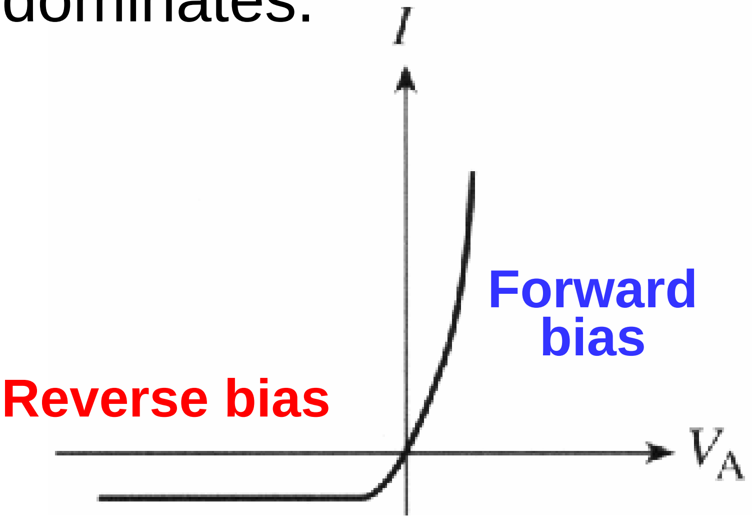


Forward Bias



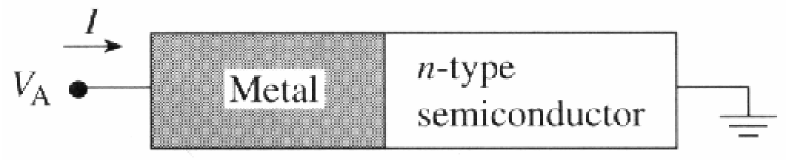
Reverse Bias

- Current is determined by majority-carrier flow across the MS junction.
  - Under forward bias, majority-carrier diffusion from the semiconductor into the metal dominates.
  - Under reverse bias, majority-carrier diffusion from the metal into the semiconductor dominates.

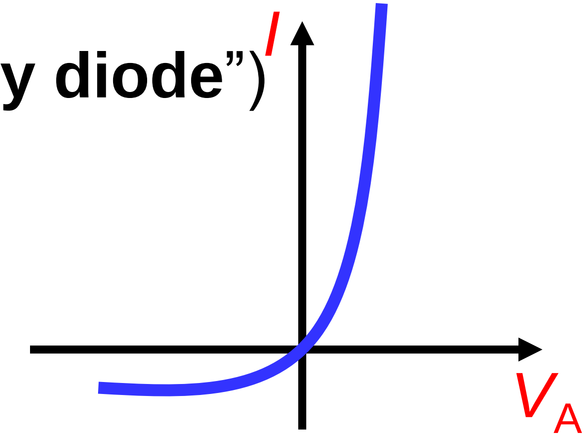


Metal-Semiconductor Contacts

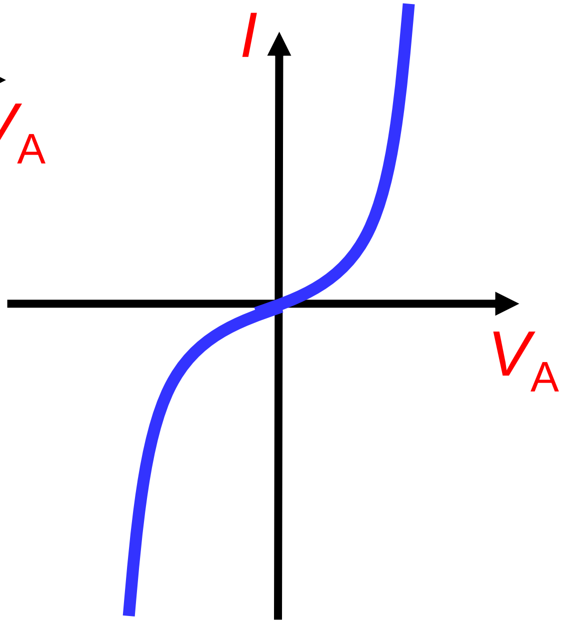
- There are 2 kinds of metal-semiconductor (MS) contact:



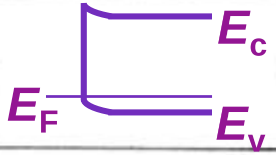
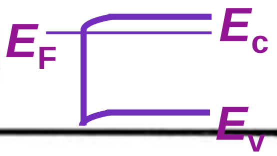
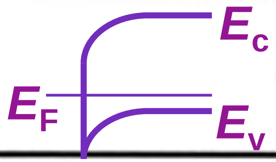
  - Rectifying (“**Schottky diode**”)



  - Non-rectifying (“**Ohmic contact**”)



Metal-Semiconductor Contacts

	n-type Semiconductor	*p-type Semiconductor*
$\Phi_M > \Phi_S$	 Rectifying	 Ohmic
$\Phi_M < \Phi_S$	 Ohmic	 Rectifying

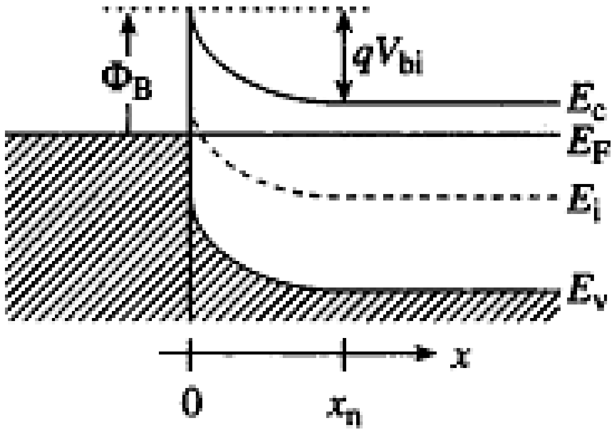
The Depletion Approximation

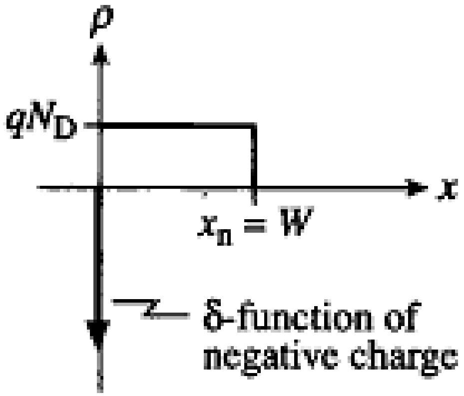
- The semiconductor is depleted to a depth *W*:
  - In the depleted region ($0 \le x \le W$):

$$\boxed{\begin{aligned} &\rho = q(N_\mathrm{D} - N_\mathrm{A}) \\ &n = 0,\ p = 0 \end{aligned}}$$

  - Beyond the depleted region ($x > W$):

$$\boxed{\begin{aligned} &\rho = 0 \\ &n = n_0,\ p = p_0 \end{aligned}}$$





$$V_\mathrm{bi} = \frac{1}{q}\left[\Phi_\mathrm{B} - (E_\mathrm{c} - E_\mathrm{F})_\mathrm{FB}\right]$$

V_bi : “built-in” voltage

Poisson's Equation

- According to Gauss's Law:

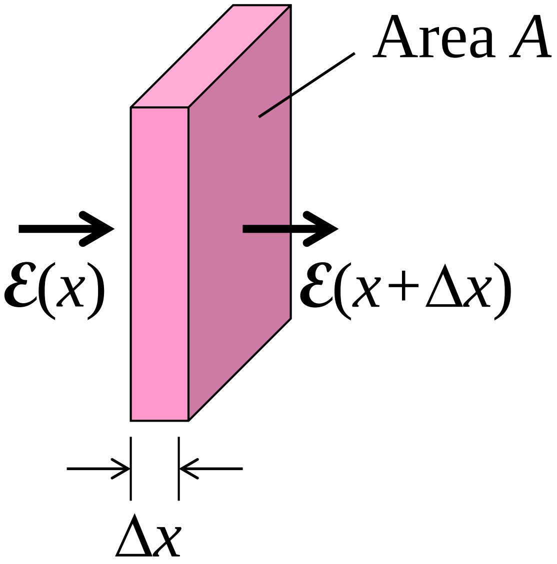
$$\varepsilon_S\left[\mathcal{E}(x+\Delta x)-\mathcal{E}(x)\right]A=\rho\Delta xA$$

- Or:

$$\frac{\left[\mathcal{E}(x+\Delta x)-\mathcal{E}(x)\right]}{\Delta x}=\frac{\rho}{\varepsilon_S}$$

$$\frac{d\mathcal{E}}{dx}=\frac{\rho}{\varepsilon_S}$$

$$-\frac{d^2V}{dx^2}=\frac{\rho}{\varepsilon_S}$$



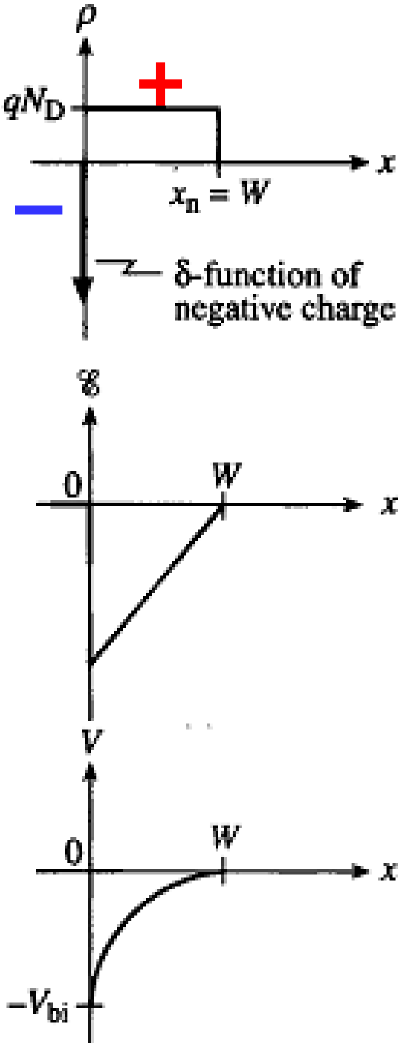
- $\mathcal{E}$: electric field intensity (V/m)
- ε_S : relative permittivity (F/cm)
- ρ : charge density (C/cm^3)

- $\varepsilon_S = K_S\varepsilon_0$
- ε_0 = 8.854 × 10–14 F/cm
- For Si, $K_S = 11.8$

MS Contact Electrostatics

- Poisson's equation:

$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{\varepsilon_{\mathrm{S}}} \approx \frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{S}}}$$



- The solution is:

$$\int_{\mathcal{E}(x)}^{0} d\mathcal{E} = \int_{x}^{W} \frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{S}}}\, dx$$

$$\mathcal{E}(x) = -\frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{S}}}(W - x)$$

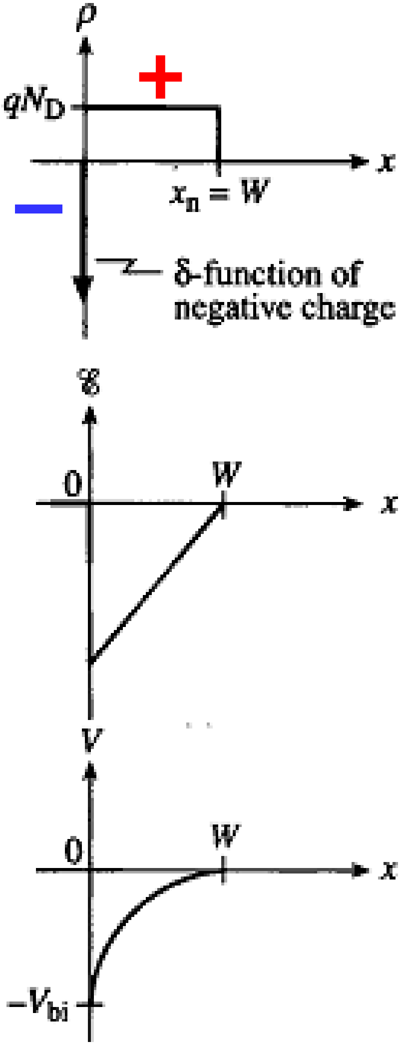
- Furthermore:

$$V(x) = -\int_{x}^{W} \mathcal{E}(x)dx = \int_{x}^{W} \frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{S}}}(W - x)dx$$

$$= -\frac{qN_{\mathrm{D}}}{2\varepsilon_{\mathrm{S}}}(W - x)^2$$

Depletion Layer Width *W*

$$V(x) = -\frac{qN_\mathrm{D}}{2\varepsilon_\mathrm{S}}(W - x)^2$$



- The potential in the semiconductor side is chosen to be the zero reference.
- At $x = 0$, $V = -V_\mathrm{bi}$
- The depletion width is given by

$$W = \sqrt{\frac{2\varepsilon_\mathrm{S} V_\mathrm{bi}}{qN_\mathrm{D}}}$$

  - *W* decreases as N_D increases

Depletion Layer Width W for $V_A \neq 0$

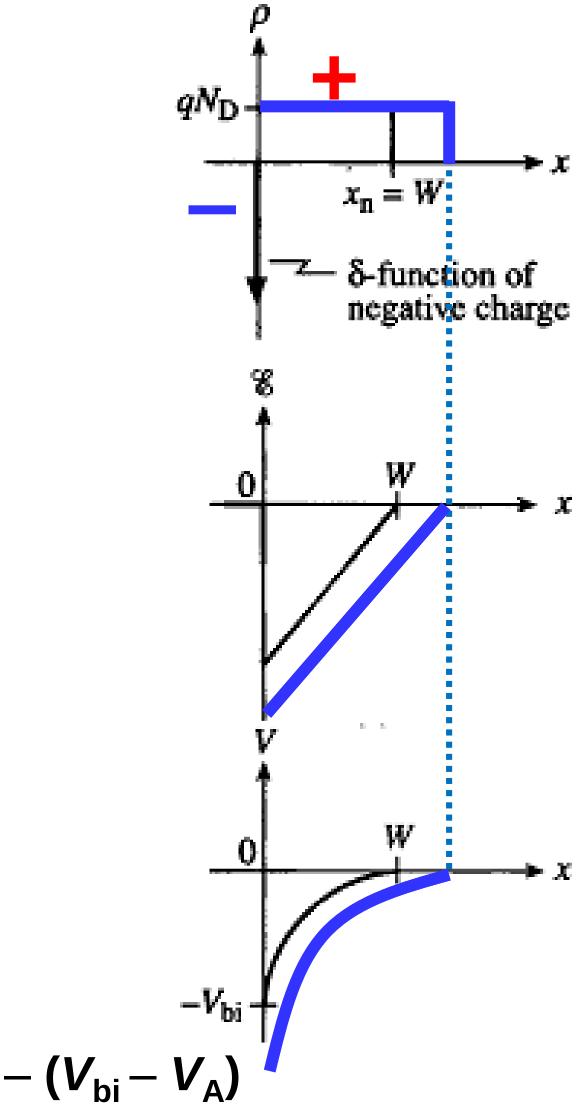
- Previously,

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

- At $x = 0$, now $V = -(V_{bi} - V_A)$

$$W = \sqrt{\frac{2\varepsilon_S(V_{bi} - V_A)}{qN_D}}$$

  - W decreases as N_D increases
  - W increases as $-V_A$ increases



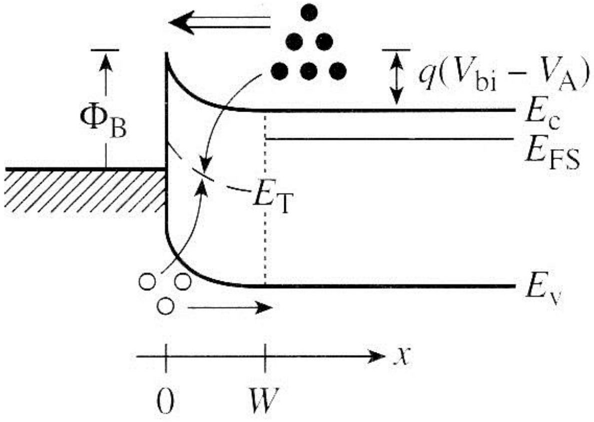
Thermionic Emission Current

- Thermionic emission current results from majority carrier injection over the potential barrier.
- Electrons can cross the junction into the metal if:

$$\mathrm{KE_x} = \frac{1}{2} m_\mathrm{n}^* v_\mathrm{x}{}^2 \ge q(V_\mathrm{bi} - V_\mathrm{A})$$

- Or:

$$|v_\mathrm{x}| \ge v_\mathrm{min} = \sqrt{\frac{2q}{m_\mathrm{n}^*}(V_\mathrm{bi} - V_\mathrm{A})}$$



- The current for electrons at a certain velocity is:

$$I_{\mathrm{S}\bullet\to\mathrm{M},v_\mathrm{x}} = -qAv_\mathrm{x} n(v_\mathrm{x})$$

- The total current over the potential barrier is:

$$I_{\mathrm{S}\bullet\to\mathrm{M}} = -qA \int_{-\infty}^{-v_\mathrm{min}} v_\mathrm{x} n(v_\mathrm{x}) dv_\mathrm{x}$$

I –*V* Characteristics

- For a non-degenerate semiconductor, it can be shown that:

$$n(v_x) = \left[\frac{4\pi kTm_n^{*2}}{h^3}\right] e^{(E_F - E_c)/kT} e^{-(m_n^*/2kT)v_x^2}$$

- We can then obtain

$$I_{S\bullet\rightarrow M} = A\mathscr{B}^* T^2 e^{-\Phi_B/kT} e^{qV_A/kT}$$

- Where $\mathscr{B}^* = \left(\frac{m_n^*}{m_0}\right)\mathscr{B}$

- And $\mathscr{B} = \frac{4\pi q m_0 k^2}{h^3} = 120\ \mathrm{A}/(\mathrm{cm}^2 \cdot \mathrm{K}^2)$

I –*V* Characteristics

- In the reverse direction and equilibrium condition, the electrons always see the same barrier Φ_B, so

- Therefore

$$I_{\mathrm{M}\bullet\to\mathrm{S}}(V_{\mathrm{A}}=0)=-I_{\mathrm{S}\bullet\to\mathrm{M}}(V_{\mathrm{A}}=0)$$

$-I_S$:reverse bias saturation current

- Finally, combining the total current at an arbitrary V_A,

$$\boxed{I=I_{\mathrm{S}}(e^{qV_{\mathrm{A}}/kT}-1)}$$

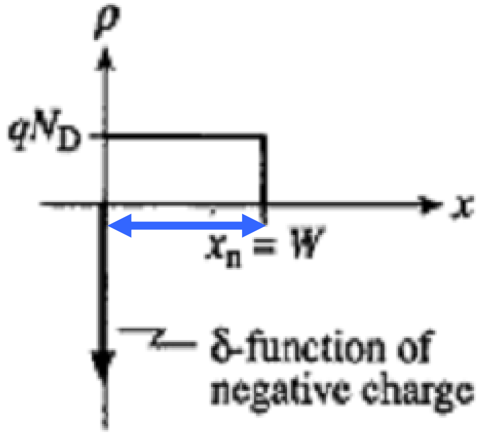
- Where

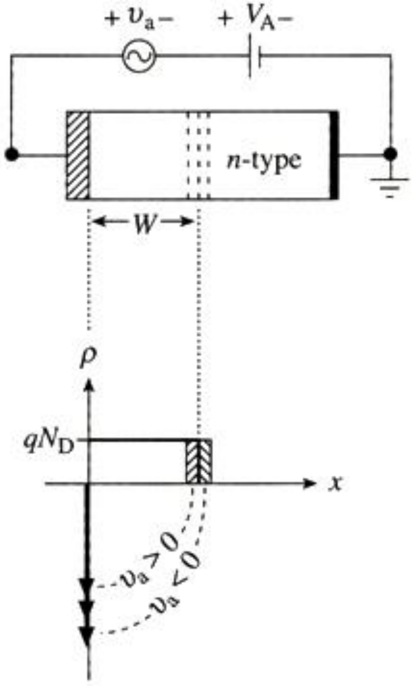
$$I_{\mathrm{S}}=A\mathscr{B}^{*}T^{2}e^{-\Phi_{\mathrm{B}}/kT}$$

Small-Signal Capacitance

- In an MS contact, charge is stored on either side of the MS junction.
  - The applied bias V_A affects this charge and varies the depletion width.
- If an a.c. voltage v_a is applied in series with the d.c. bias V_A, the charge stored in the MS contact will be modulated at the frequency of the a.c. voltage.
  - Displacement current will flow.

$$i = C\frac{dv_a}{dt} \Rightarrow C = A\frac{\varepsilon_s}{W}$$





Small-Signal Capacitance

- Since in general

$$W = \sqrt{\frac{2\varepsilon_\mathrm{S}(V_\mathrm{bi} - V_\mathrm{A})}{qN_\mathrm{D}}}$$

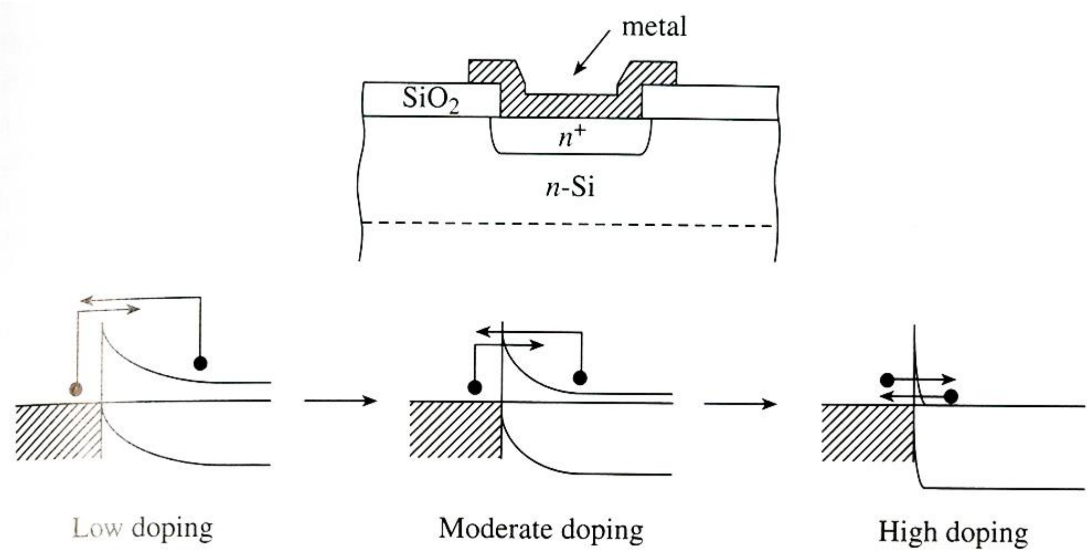
- Then

$$C = A\frac{\varepsilon_\mathrm{S}}{W} = A\frac{\varepsilon_\mathrm{S}}{\sqrt{\frac{2\varepsilon_\mathrm{S}}{qN_\mathrm{D}}(V_\mathrm{bi} - V_\mathrm{A})}} = A\sqrt{\frac{qN_\mathrm{D}\varepsilon_\mathrm{S}}{2(V_\mathrm{bi} - V_\mathrm{A})}}$$

- Or $\dfrac{1}{C^2} = \dfrac{2}{qN_\mathrm{D}\varepsilon_\mathrm{S}A^2}(V_\mathrm{bi} - V_\mathrm{A})$

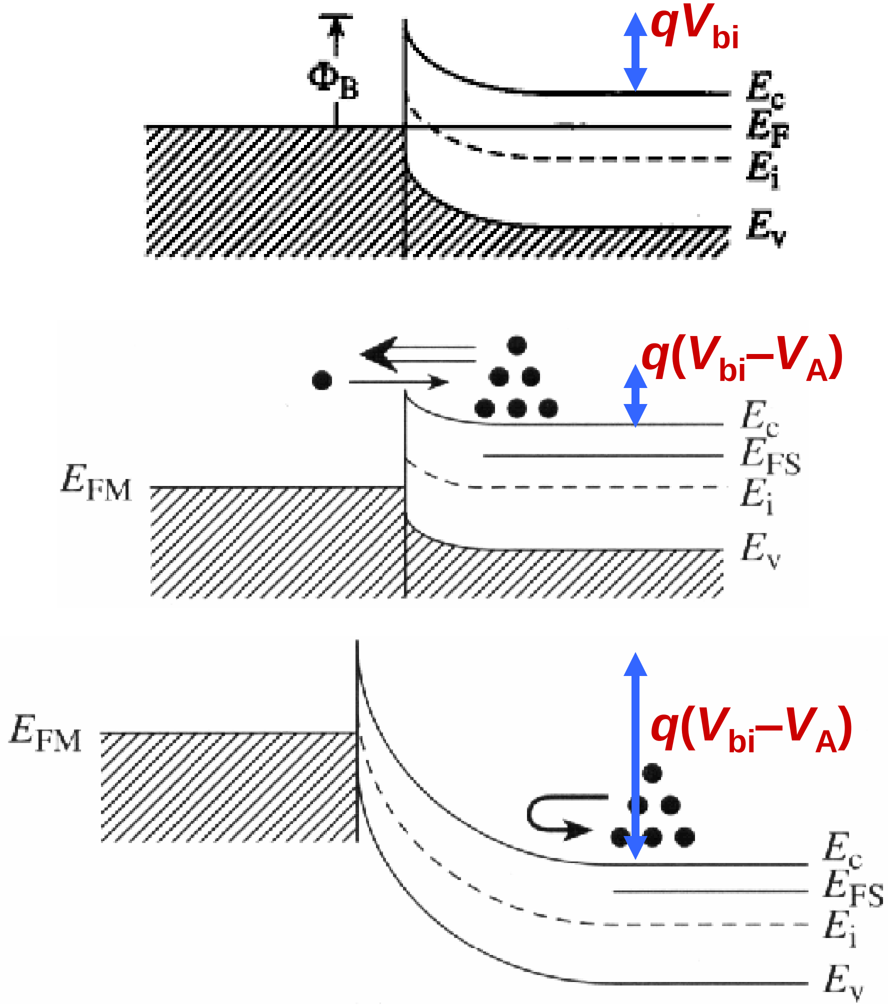
Practical Ohmic Contact

- In practice, most MS-contacts are rectifying.
- In order to achieve a contact that can conduct easily in both directions, the semiconductor is to be doped very heavily.
  - Depletion width W becomes so narrow that the carriers can tunnel directly through the barrier.



Voltage Drop Across the MS Contact

- Under equilibrium conditions ($V_A = 0$), the voltage drop across the semiconductor depletion region is the built-in voltage V_{bi}.
- If $V_A \neq 0$, the voltage drop across the semiconductor depletion region is $V_{bi} - V_A$.



MS Contact with *p*-type Semiconductor

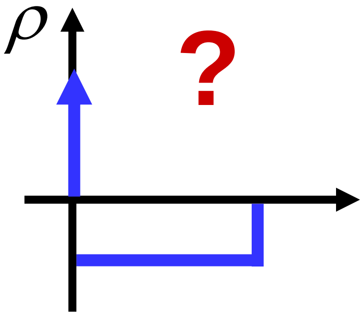
- If *p*-type semiconductor is used, the depletion layer width W of the MS contact for $V_A \neq 0$ is given by

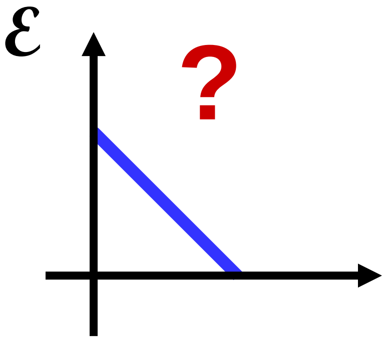
$$V(x) = \frac{qN_A}{2\varepsilon_S}(W - x)^2$$

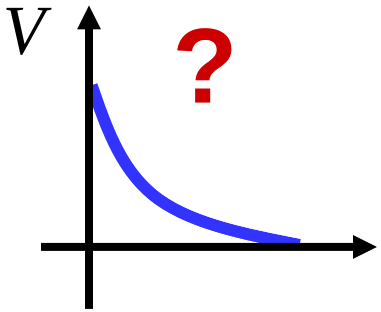
- At $x = 0$, $V = V_{bi} + V_A$,

$$W = \sqrt{\frac{2\varepsilon_S (V_A + V_{bi})}{qN_A}}$$

  - W increases as V_A increases
  - W decrease as N_A increases







Homework 9

- 1. (Nea.EC.10.27)

  An MS-junction is formed between a metal with a work function of 4.3 eV and *p*-type Si with an electron affinity of 4 eV. The doping concentration in semiconductor is 5×10^{16} cm^{-3}. Assume T = 300 K.

  (a) Sketch the thermal equilibrium energy band diagram;
  (b) Determine the height of the Schottky barrier;
  (c) Sketch the energy band diagram with an applied reverse-bias voltage of V_A = –3V;
  (d) Sketch the energy band diagram with an applied forward-bias voltage of V_A = 0.25 V.