Lecture 17 - Metal-Semiconductor Junction

March 14, 2007

Contents:

1. Ideal metal-semiconductor junction in TE
2. Ideal metal-semiconductor junction outside equilibrium

Reading assignment:

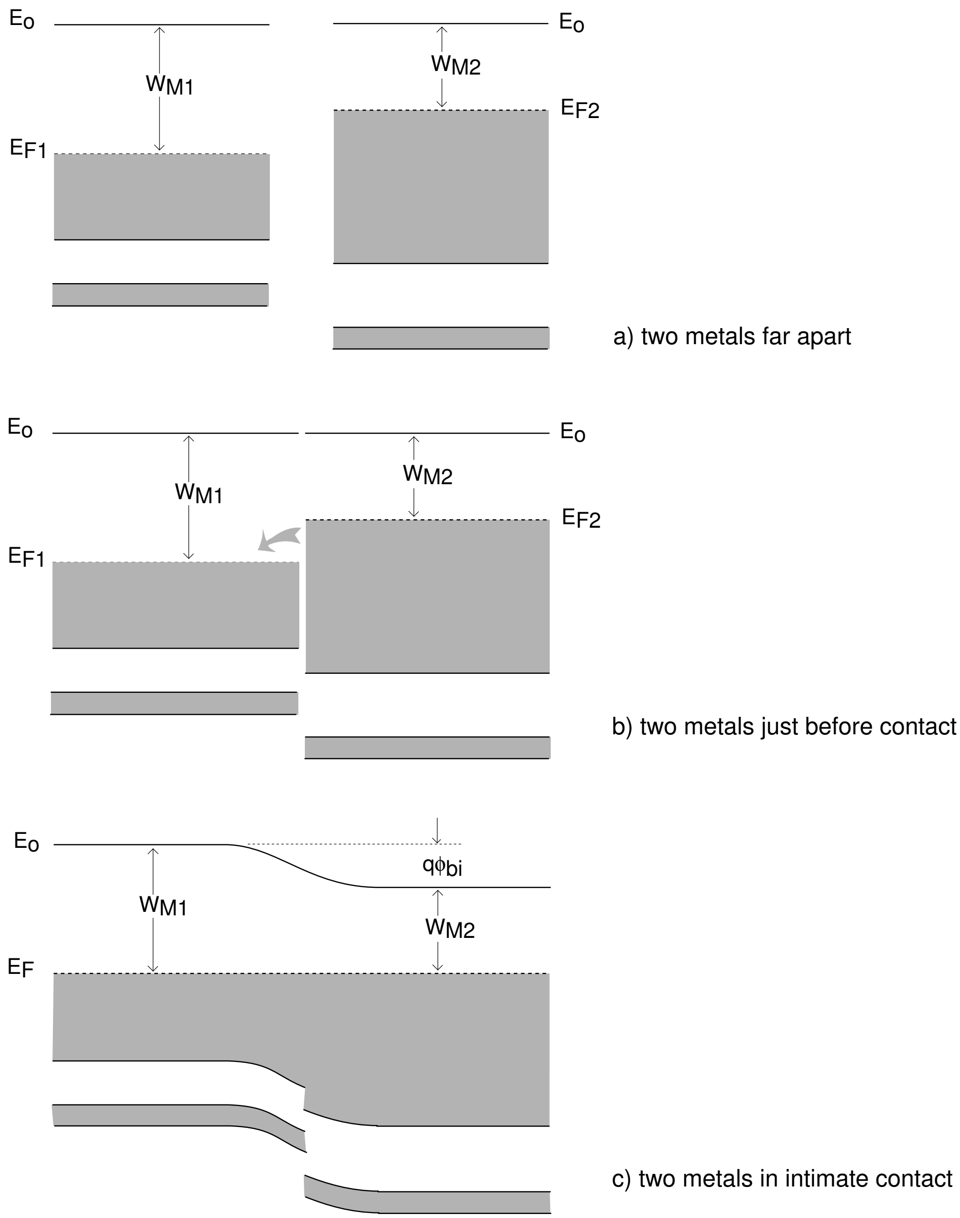
del Alamo, Ch. 7, §§7.1, 7.2

Key questions

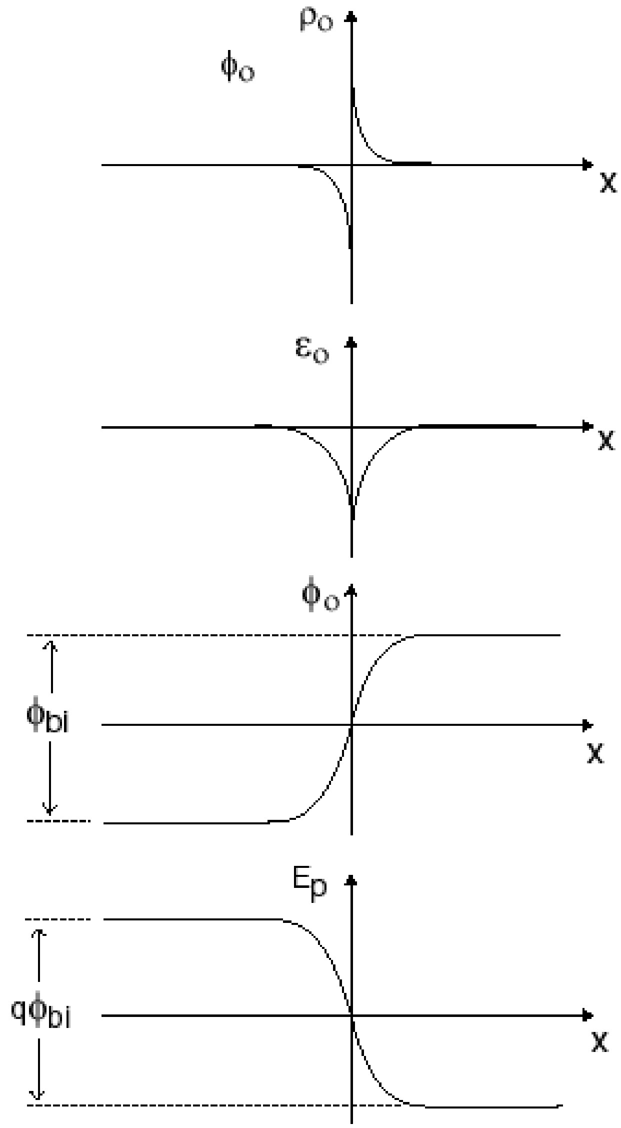
- What happens when you bring together a metal and a semiconductor in intimate contact?
- What happens in a metal-semiconductor junction when you apply a voltage to the metal with respect to the semiconductor?
- In a metal-semiconductor junction under bias, is there current flow? If so, how exactly does it happen?

1. Ideal metal-semiconductor junction in TE

□ First, ideal *metal-metal junction* in TE:



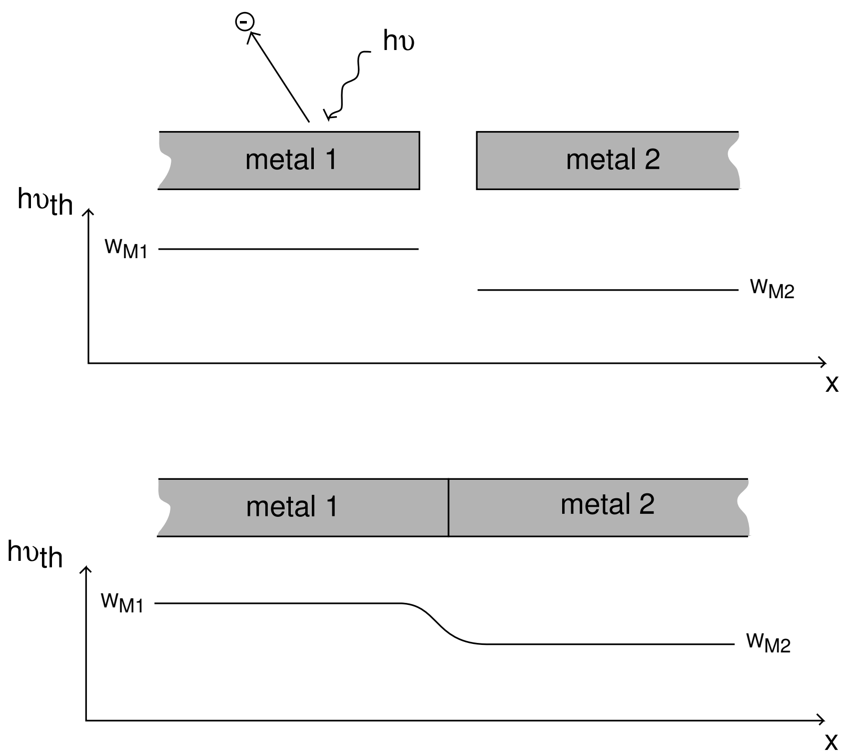
dipole charge at interface → *built-in potential*



Spatial extent of SCR in MM junction: a few nm

Can define *local work function*

Think of photoelectric experiment vs. position:



Can define *local vacuum energy* E_o

Shape of E_o identical to potential energy ⇒

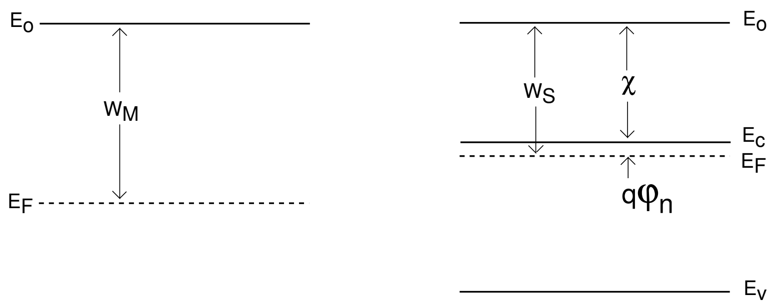
$$\phi_{bi} = \frac{1}{q}(W_{M1} - W_{M2})$$

□ Ideal *metal-semiconductor junction* in TE

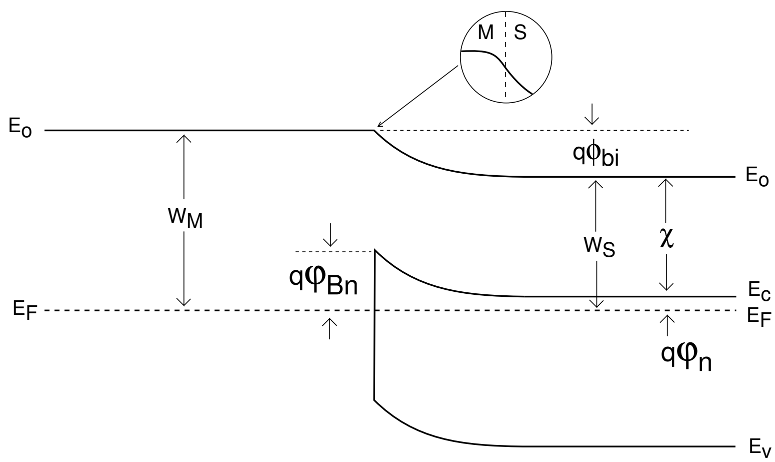
Energy band line up depends on choice of metal and semiconductor.

Do metal/n-type semiconductor with $W_M > W_S$:

$$W_S = \chi + q\varphi_n$$

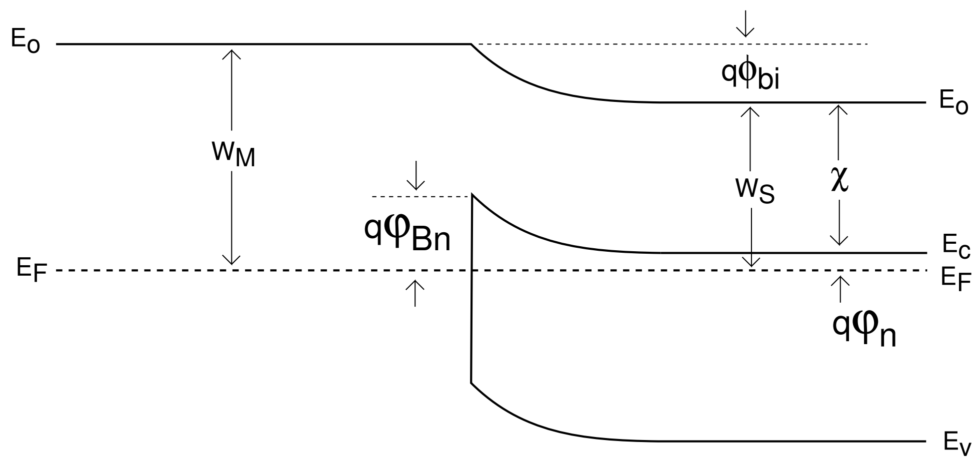


a) metal and semiconductor far apart



b) metal and semiconductor in intimate contact

$$\phi_{bi} = \frac{1}{q}(W_M - W_S)$$



Most important parameter of MS junction: *Schottky barrier height*:

$$q\varphi_{Bn} = W_M - \chi$$

Also:

$$q\varphi_{Bn} = q\phi_{bi} + q\varphi_n$$

Warning: simple theory not followed due to *surface states*
$\Rightarrow$ In practice, rely on measurements for $q\varphi_{Bn}$.

Still can use:

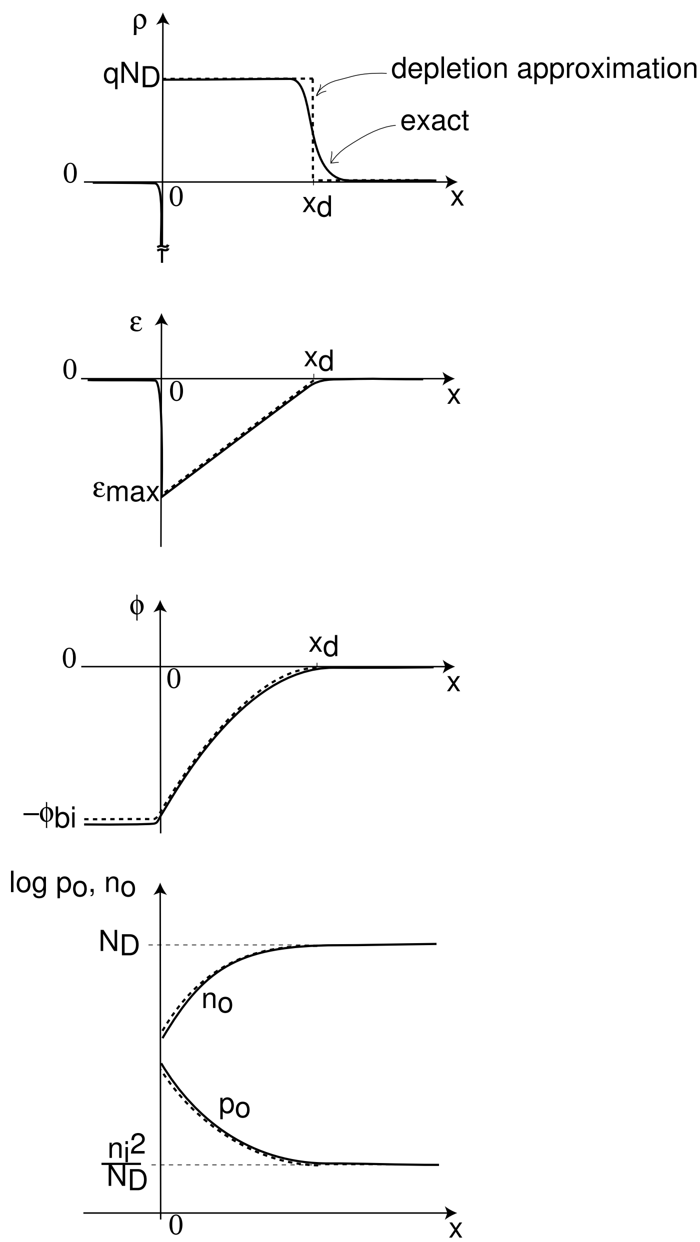
$$q\varphi_{Bn} = q\phi_{bi} + q\varphi_n$$

Typical Schottky barrier height: $q\varphi_B \sim 0.4 - 0.8\ eV$ (depends on metal and doping type).

□ Electrostatics in TE

In semiconductor:

- close to the M-S interface: *space-charge region*
- farther away: *quasi-neutral region*



Do *depletion approximation:*

- Volume charge density:

$$\rho(x) \simeq qN_D \qquad \text{in SCR: } 0 \le x < x_d$$
$$\rho(x) \simeq 0 \qquad \text{in QNR: } x_d < x$$

- Electric field:

$$\mathcal{E}(x) \simeq \frac{qN_D}{\epsilon}(x - x_d) \qquad \text{in SCR: } 0 \le x \le x_d$$
$$\mathcal{E}(x) \simeq 0 \qquad \text{in QNR: } x_d \le x$$

- Electrostatic potential, with $\phi(bulk) = 0$:

$$\phi(x) = -\frac{qN_D}{2\epsilon}(x^2 - 2x_d x + x_d^2) \qquad \text{in SCR: } 0 \le x \le x_d$$
$$\phi(x) = 0 \qquad \text{in QNR: } x_d \le x$$

x_d obtained by demanding $\phi(0) = -\phi_{bi}$:

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

Maximum field:

$$|\mathcal{E}_{max}| = \frac{qN_D x_d}{\epsilon} = \sqrt{\frac{2qN_D\phi_{bi}}{\epsilon}}$$

Key dependencies:

- $N_D \uparrow \rightarrow \ x_d \downarrow \rightarrow \ |\mathcal{E}_{max}| \uparrow$
- $\phi_{Bn} \uparrow \rightarrow \ x_d \uparrow \rightarrow \ |\mathcal{E}_{max}| \uparrow$

Also in TE, Boltzmann relation:

$$n_o(x) = N_D \exp\frac{q\phi(x)}{kT}$$

At $x = 0$:

$$n_o(0) = N_D \exp\frac{-q\phi_{bi}}{kT}$$

Depletion approximation valid if $n_o(0) \ll N_D$, or $\phi_{bi} \gg 3\frac{kT}{q}$, easy!

2. Metal-semiconductor junction outside equilibrium

Apply voltage across:

- forward bias: metal positive with respect to semiconductor
- reverse bias: metal negative with respect to semiconductor

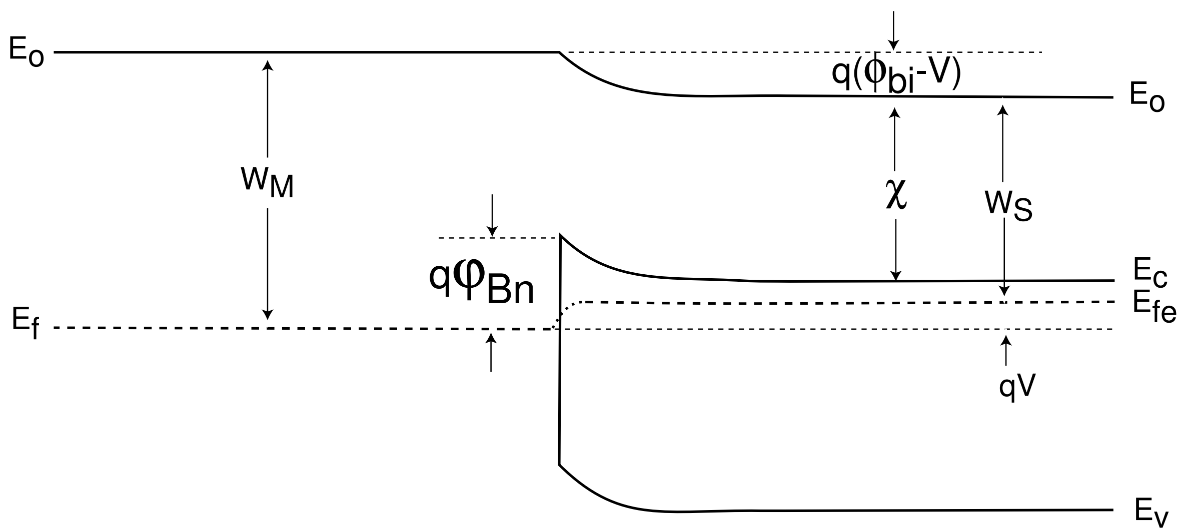
[notation reversed for metal/p-semiconductor junction]

Voltage can drop in four distinct regions:

- metal
- metal-semiconductor interface on metal side
- semiconductor SCR
- semiconductor QNR

Key to drawing energy band diagram: battery grabs on majority-carrier quasi-Fermi level [will see when we discuss ohmic contacts].

□ Forward bias ($V > 0$):



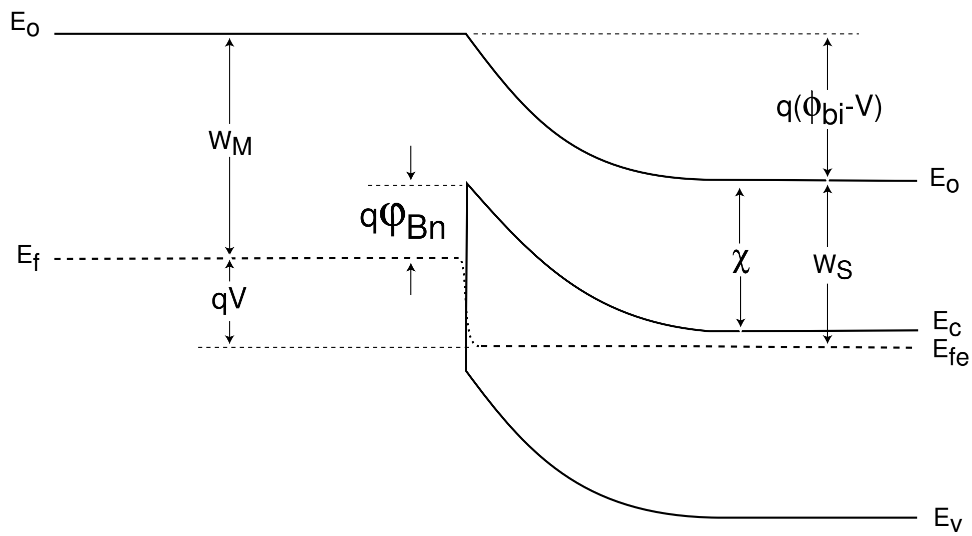
Main consequence of voltage application:

$$\phi_{bi} \rightarrow \phi_{bi} - V < \phi_{bi}$$

Then:

$$x_d(V) < x_d(V = 0)$$

□ Reverse bias ($V < 0$):



Also:

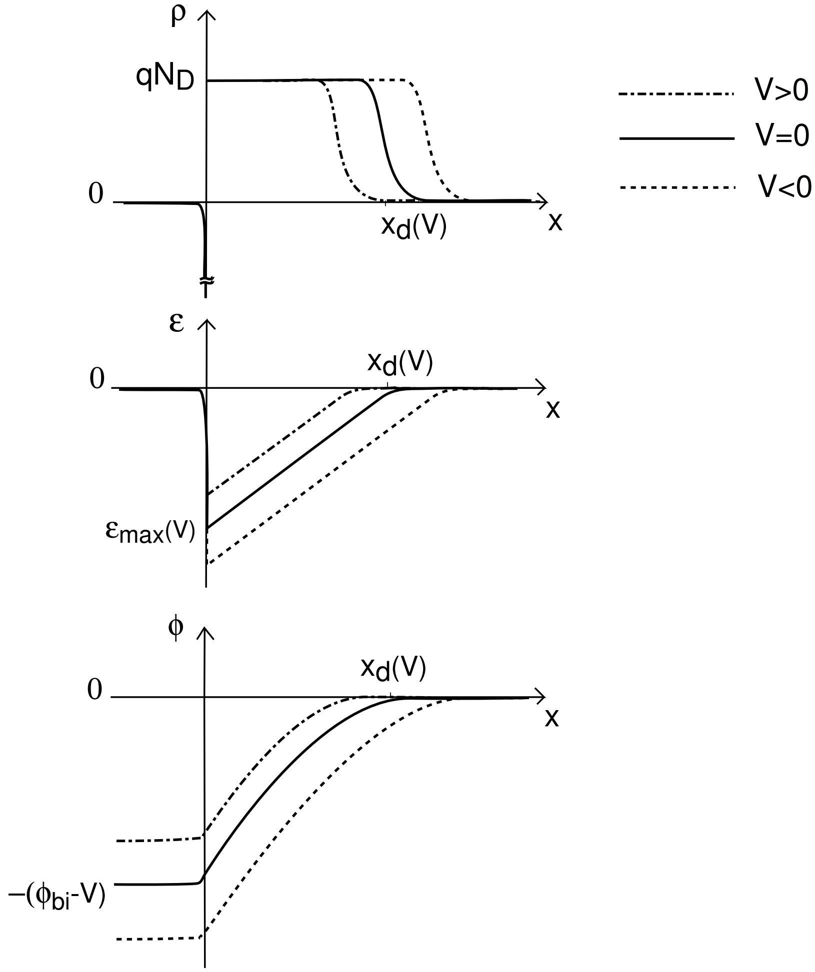
$$\phi_{bi} \rightarrow \phi_{bi} - V > \phi_{bi}$$

Then:

$$x_d(V) > x_d(V = 0)$$

Otherwise, electrostatics not substantially changed.

□ Summary of electrostatics under bias:



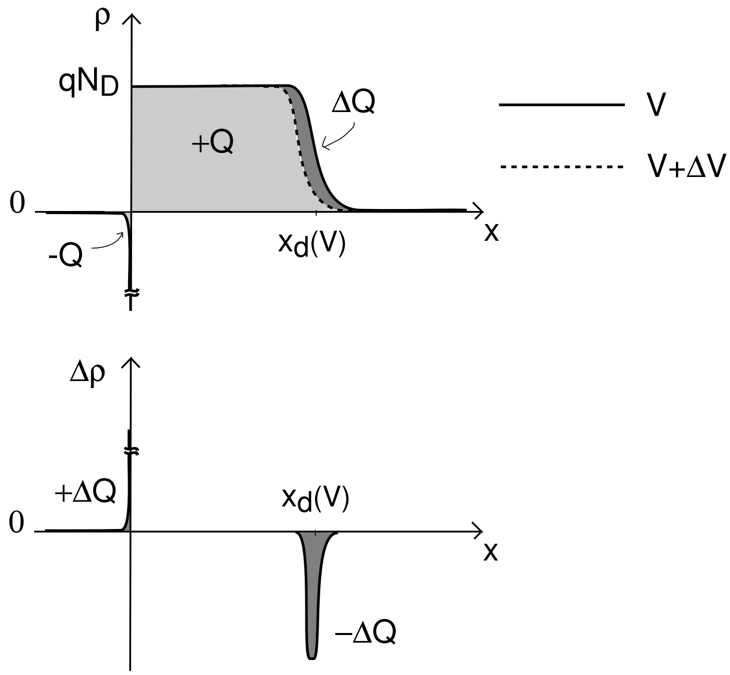
Reuse main results from TE but $\phi_{bi} \rightarrow \phi_{bi} - V$:

$$x_d(V) = \sqrt{\frac{2\epsilon(\phi_{bi} - V)}{qN_D}} = x_d(V = 0)\sqrt{1 - \frac{V}{\phi_{bi}}}$$

$$|\mathcal{E}_{max}(V)| = \frac{qN_D x_d(V)}{\epsilon} = \sqrt{\frac{qN_D(\phi_{bi} - V)}{\epsilon}} = |\mathcal{E}_{max}(V = 0)|\sqrt{1 - \frac{V}{\phi_{bi}}}$$

□ Depletion capacitance

Examine change in SCR charge *differentially*:



SCR behaves as capacitor of capacitance per unit area:

$$C(V) = \frac{\epsilon}{x_d(V)}$$

Or:

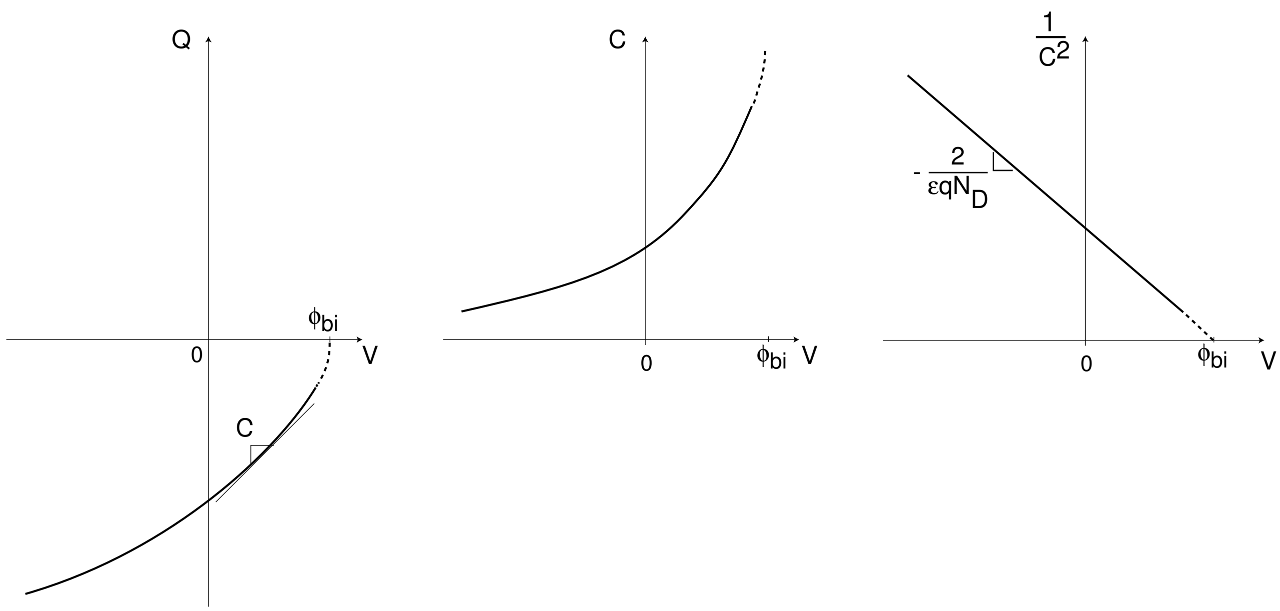
$$C(V) = \sqrt{\frac{\epsilon q N_D}{2(\phi_{bi} - V)}} = \frac{C(V=0)}{\sqrt{1 - \frac{V}{\phi_{bi}}}}$$

Same result obtained if:

$$C = \frac{dQ}{dV}$$

with:

$$Q(V) = qN_D x_d(V) = \sqrt{2qN_D\epsilon(\phi_{bi} - V)}$$



C-V technique to extract ϕ_{bi} and N_D:

$$\frac{1}{C^2} = \frac{2(\phi_{bi} - V)}{\epsilon q N_D}$$

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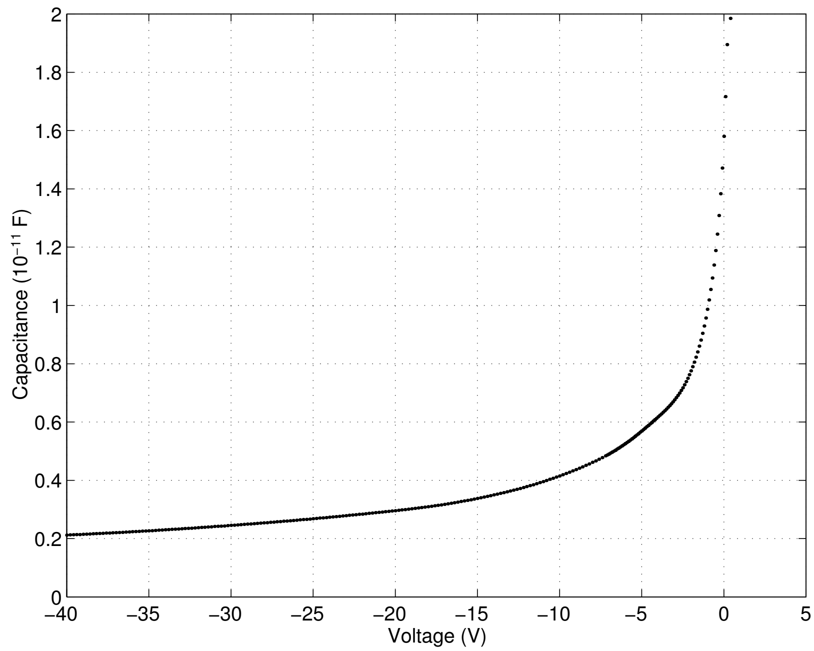

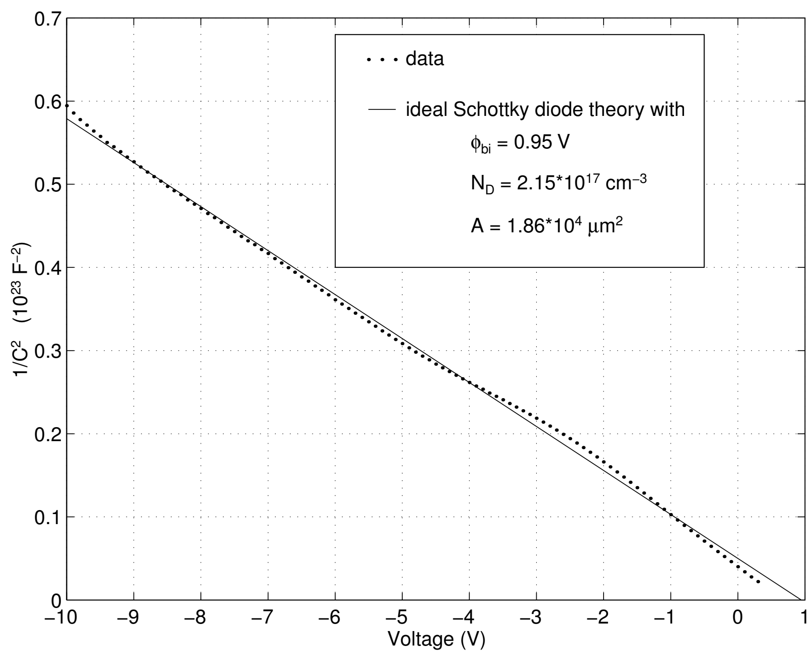

Key conclusions

- Junction of dissimilar materials ⇒ dipole charge at interface ⇒ built-in potential.
- Relative band alignment between metal and semiconductor characterized by *Schottky barrier height*, $q\varphi_{Bn}$.
- Simple theory for $q\varphi_{Bn}$ does not apply ⇒ must use experimentally determined values.
- In M-S junction, charge dipole occurs at interface; typically a depletion region is created on semiconductor side.
- Built-in potential of M-S junction:

$$\phi_{bi} = \varphi_{Bn} - \phi_n$$

- Application of voltage to M-S junction impacts ϕ_{bi} directly ⇒ $x_d(V)$, $\mathcal{E}(V)$.
- Modulation of depletion region width with voltage gives rise to *capacitive effect*.
- Order of magnitude of key parameters in Si at $300K$:
  - Schottky barrier height: $q\varphi_B \sim 0.4 - 0.8\ eV$ (depends on metal and doping type).