

# Lecture 14 - Metal-Semiconductor Junction (*cont.*)

October 4, 2002

## Contents:

1. Ideal metal-semiconductor junction in TE (*cont.*)
2. Ideal metal-semiconductor junction outside equilibrium

## Reading assignment:

del Alamo, Ch. 6, §6.2

## Announcements:

Quiz 1: October 10, Rm. 50-340 (Walker), 7:30-9:30 PM; lectures #1-13 (up to metal-semiconductor junction, no space-charge-region transport). Open book. *Calculator required.*

## Key questions

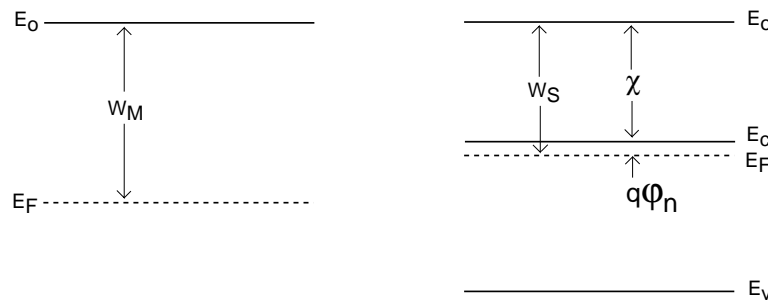
- What happens when you bring together a metal and a semiconductor in intimate contact?
- What happens in a metal-semiconductor junction when you apply a voltage to the metal with respect to the semiconductor?

# 1. Ideal metal-semiconductor junction in TE (*cont.*)

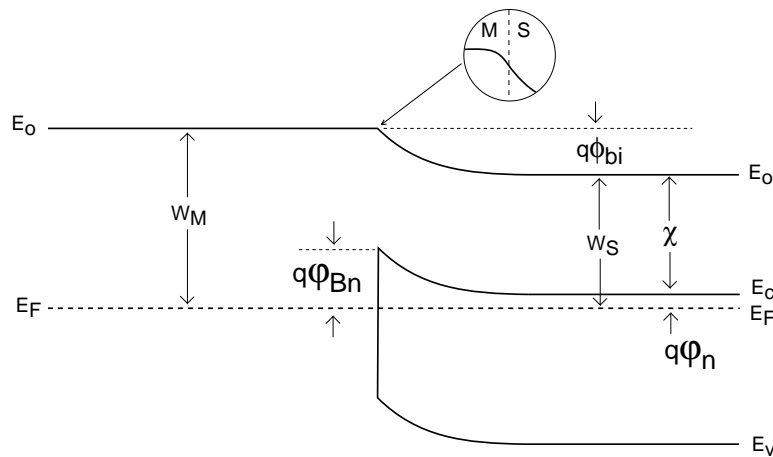
□ Ideal *metal-semiconductor junction* in TE

Energy band line up depends on choice of metal and semiconductor.  
Do metal/n-type semiconductor with  $W_M > W_S$ :

$$W_S = \chi + q\phi_n$$

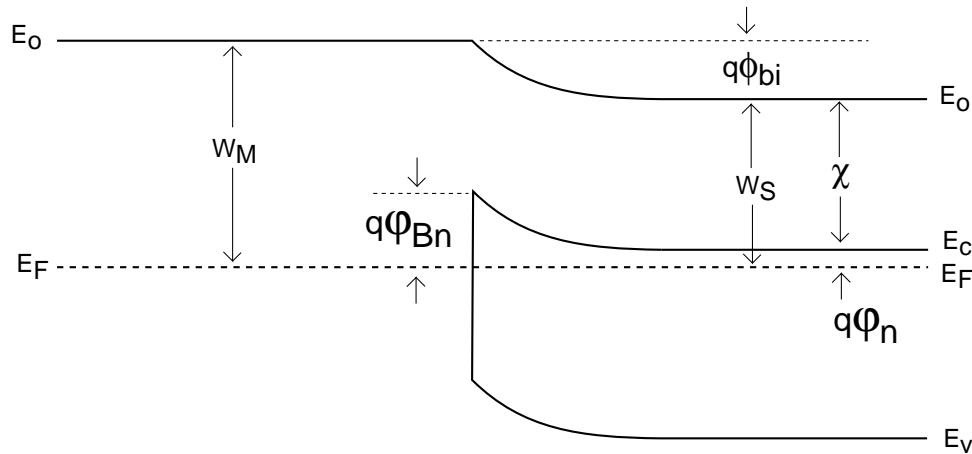


a) metal and semiconductor far apart



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*:

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

Also:

$$q\phi_{Bn} = q\phi_{bi} + q\phi_n$$

*Warning*: simple theory not followed due to *surface states*

$\Rightarrow$  In practice, rely on measurements for  $q\phi_{Bn}$ .

Still can use:

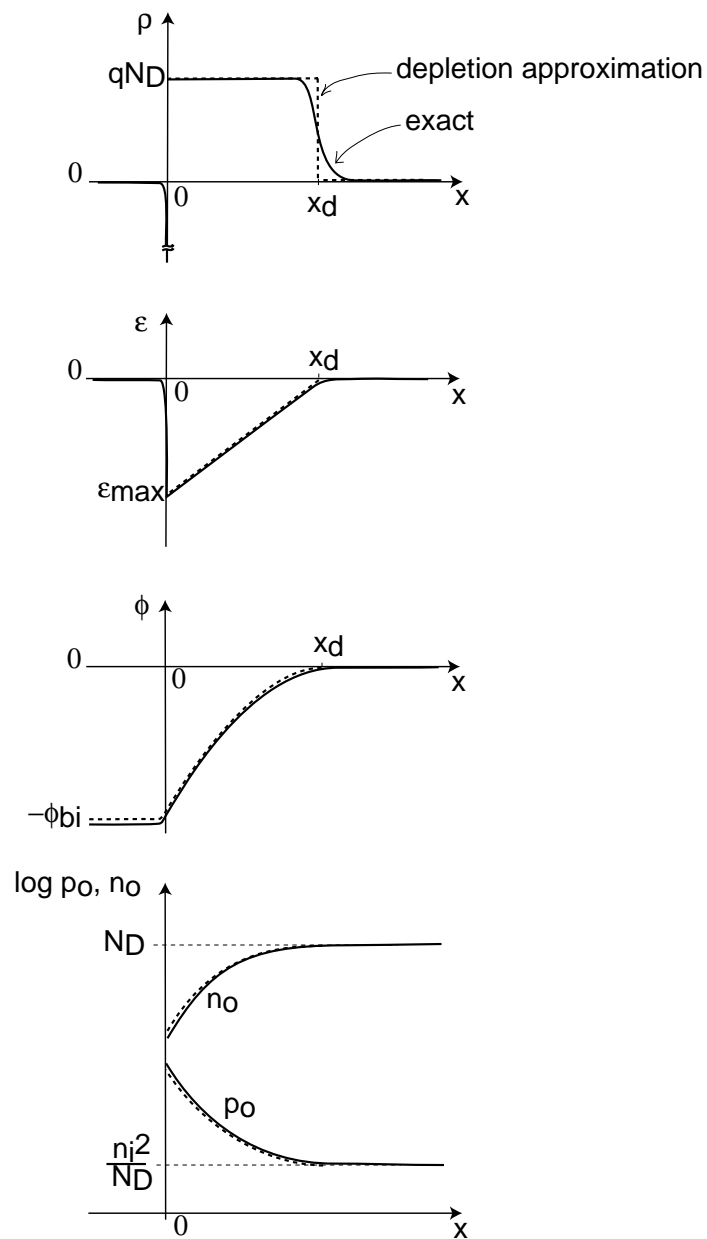
$$q\phi_{Bn} = q\phi_{bi} + q\phi_n$$

Typical Schottky barrier height:  $q\phi_B \sim 0.4 - 0.8 \text{ eV}$  (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:

$$\begin{aligned} \rho(x) &\simeq qN_D && \text{in SCR: } 0 \leq x < x_d \\ \rho(x) &\simeq 0 && \text{in QNR: } x_d < x \end{aligned}$$

- Electric field:

$$\begin{aligned} \mathcal{E}(x) &\simeq \frac{qN_D}{\epsilon}(x - x_d) && \text{in SCR: } 0 \leq x \leq x_d \\ \mathcal{E}(x) &\simeq 0 && \text{in QNR: } x_d \leq x \end{aligned}$$

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

$$\begin{aligned} \phi(x) &= -\frac{qN_D}{2\epsilon}(x^2 - 2x_d x + x_d^2) && \text{in SCR: } 0 \leq x \leq x_d \\ \phi(x) &= 0 && \text{in QNR: } x_d \leq x \end{aligned}$$

$x_d$  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:

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

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]

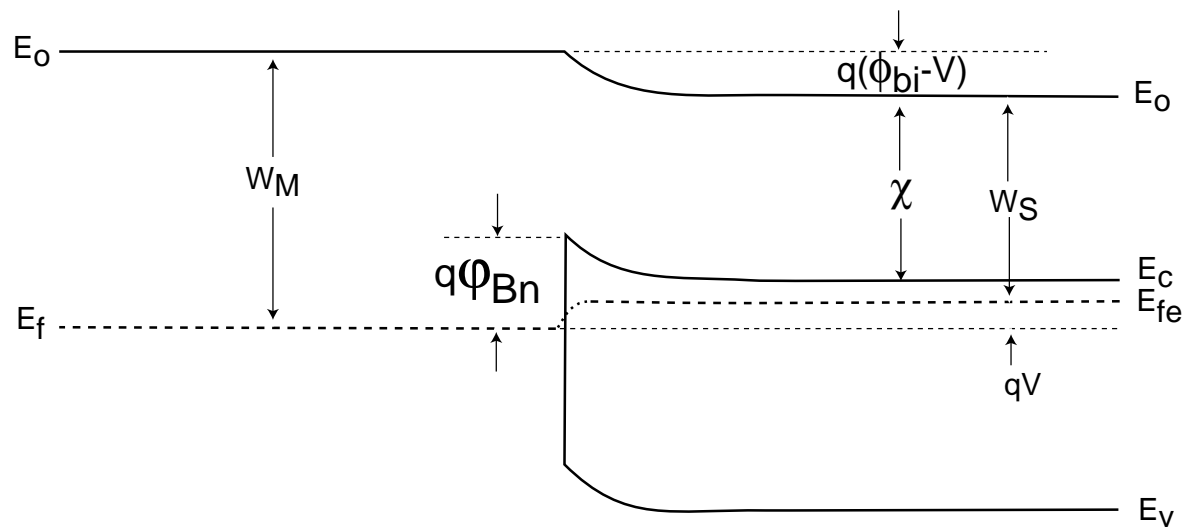
Voltage can drop in four distinct regions:

- 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 ( $V > 0$ ):



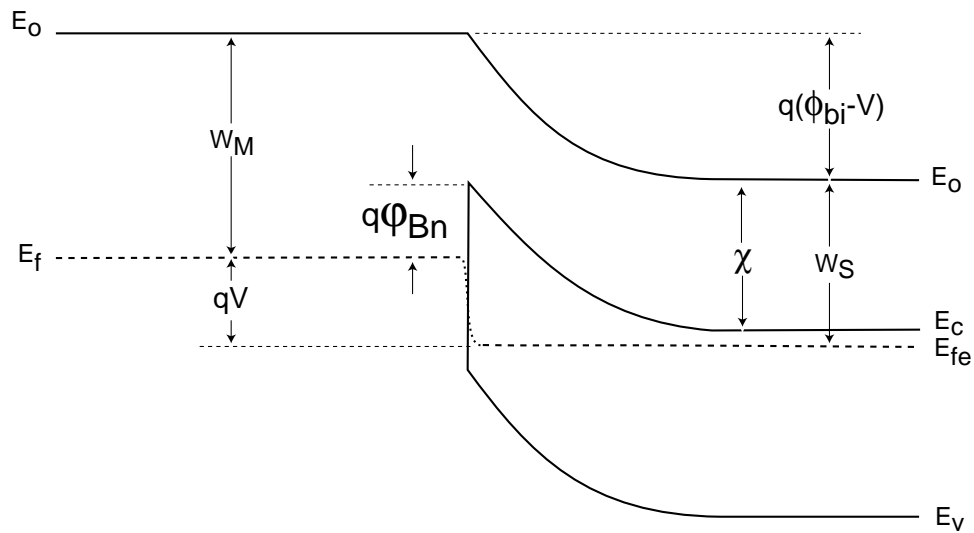
Main consequence of voltage application:

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

Then:

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

□ Reverse bias ( $V < 0$ ):



Also:

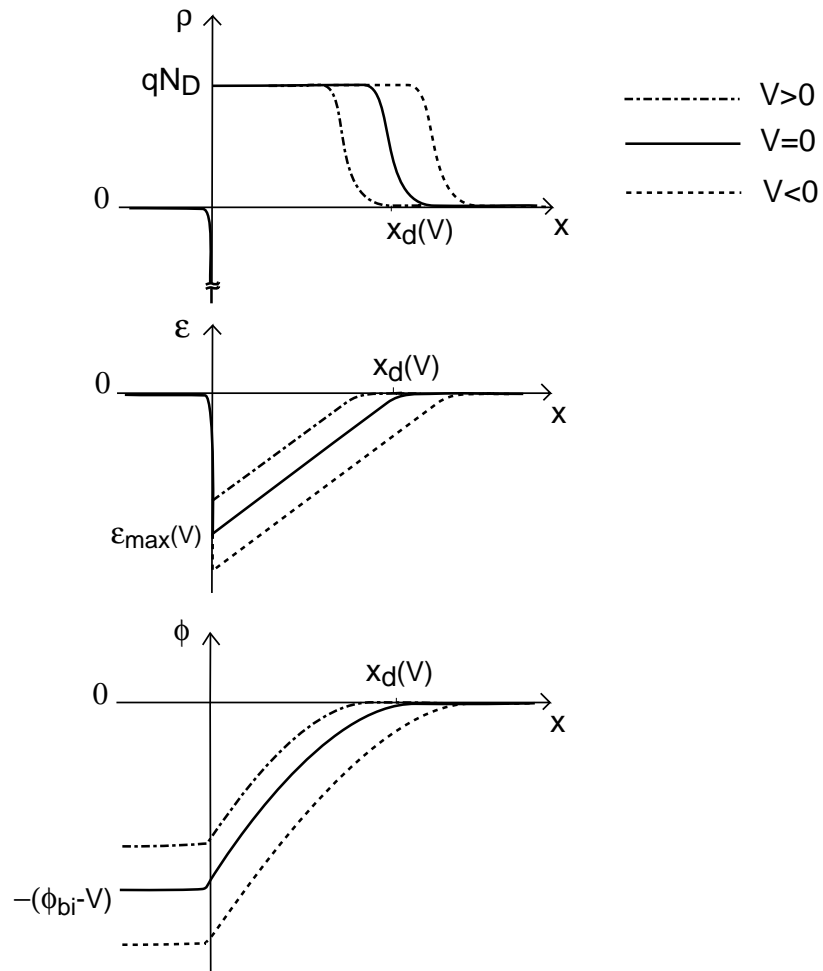
$$\phi_{bi} \rightarrow \phi_{bi} - V > \phi_{bi}$$

Then:

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

Otherwise, electrostatics not substantially changed.

□ Summary of electrostatics under bias:



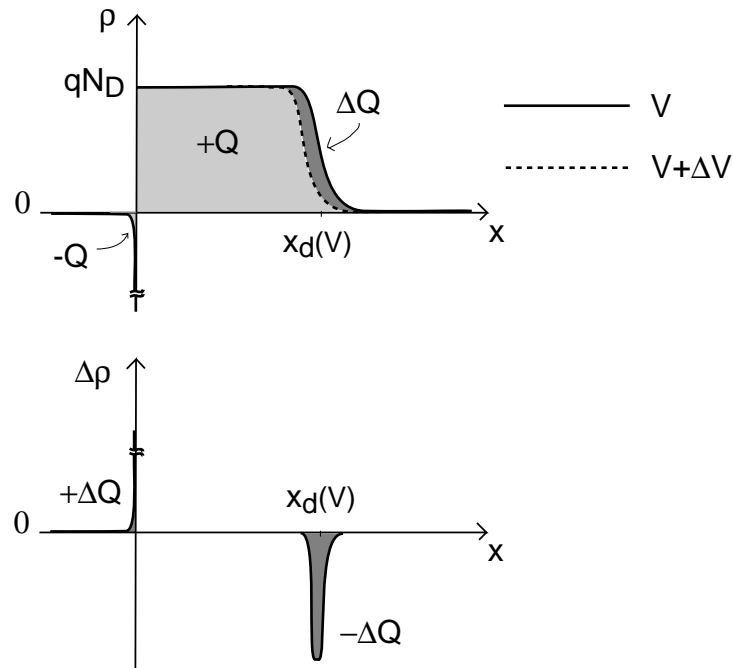
Reuse main results from TE but  $\phi_{bi} \rightarrow \phi_{bi} - V$ :

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

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

## □ 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:

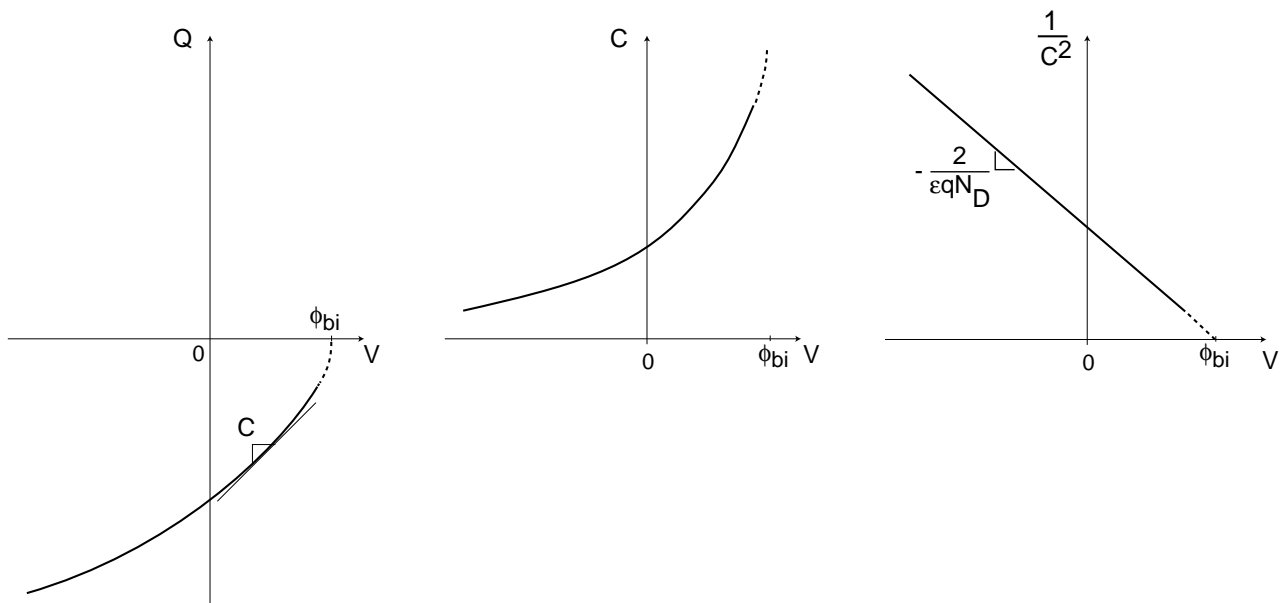
$$C(V) = \sqrt{\frac{\epsilon q N_D}{2(\phi_{bi} - V)}} = \frac{C(V=0)}{\sqrt{1 - \frac{V}{\phi_{bi}}}}$$

Same result obtained if:

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

with:

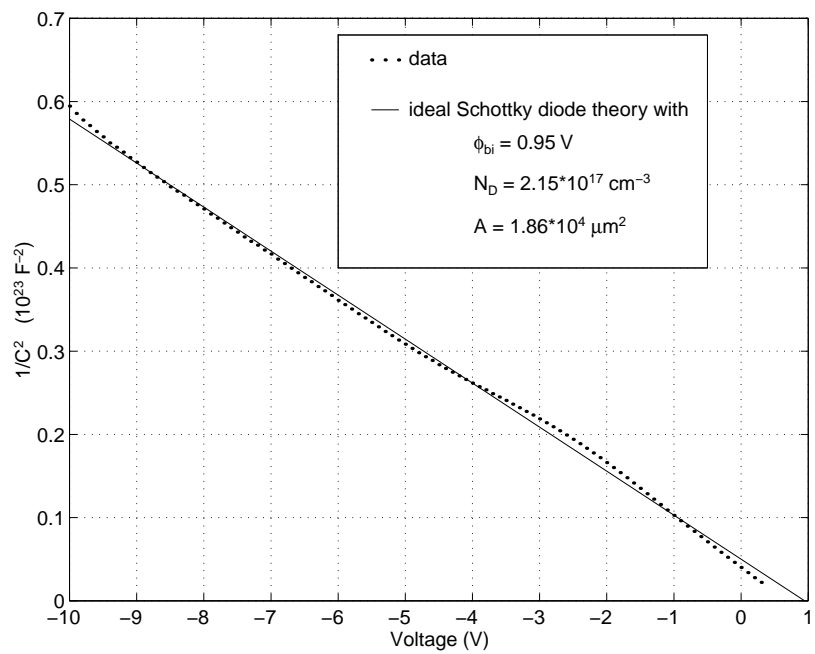
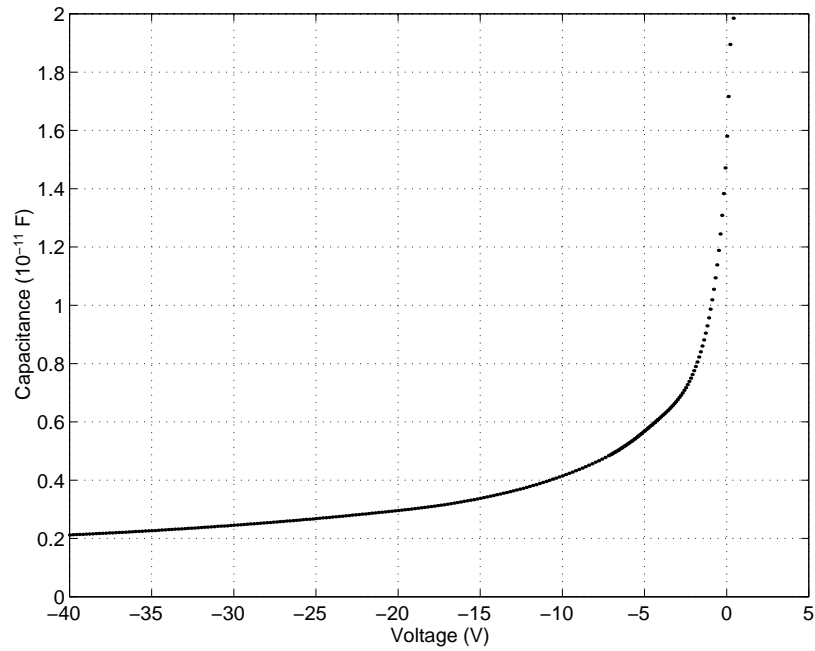
$$Q(V) = qN_D x_d(V) = \sqrt{2qN_D \epsilon (\phi_{bi} - V)}$$



*C-V technique to extract  $\phi_{bi}$  and  $N_D$ :*

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

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



## Key conclusions

- Relative band alignment between metal and semiconductor characterized by *Schottky barrier height*,  $q\varphi_{Bn}$ .
- Simple theory for  $q\varphi_{Bn}$  does not apply  $\Rightarrow$  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  $\phi_{bi}$  directly  $\Rightarrow x_d(V)$ ,  $\mathcal{E}(V)$ .
- 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:  $q\varphi_B \sim 0.4 - 0.8 \text{ eV}$  (depends on metal and doping type).