

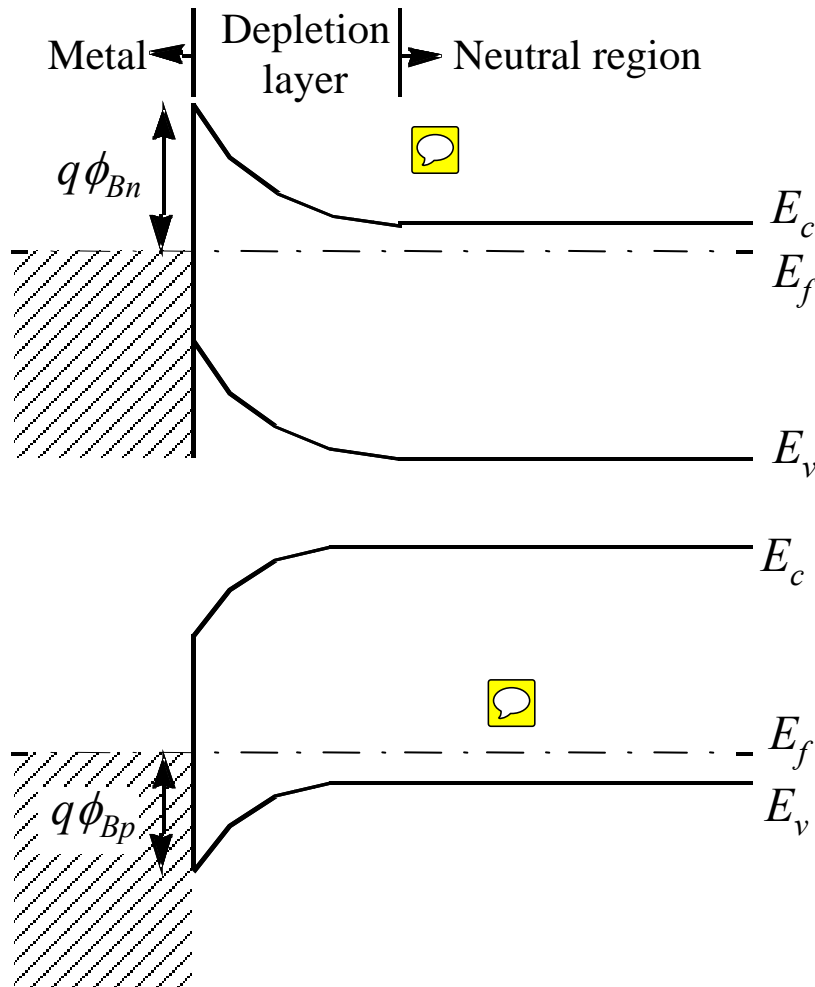
## *Chapter 9 Metal-Semiconductor Contacts*

Two kinds of metal-semiconductor contacts:

- *metal on lightly doped silicon* —
- *rectifying Schottky diodes*
- *metal on heavily doped silicon* —
- *low-resistance ohmic contacts*

## 9.1 Schottky Barriers

*Energy Band Diagram of Schottky Contact*



- Schottky barrier height,  $\phi_B$ , is a function of the metal material.

- $\phi_B$  is the single most important parameter. The sum of  $q\phi_{Bn}$  and  $q\phi_{Bp}$  is equal to  $E_g$ .

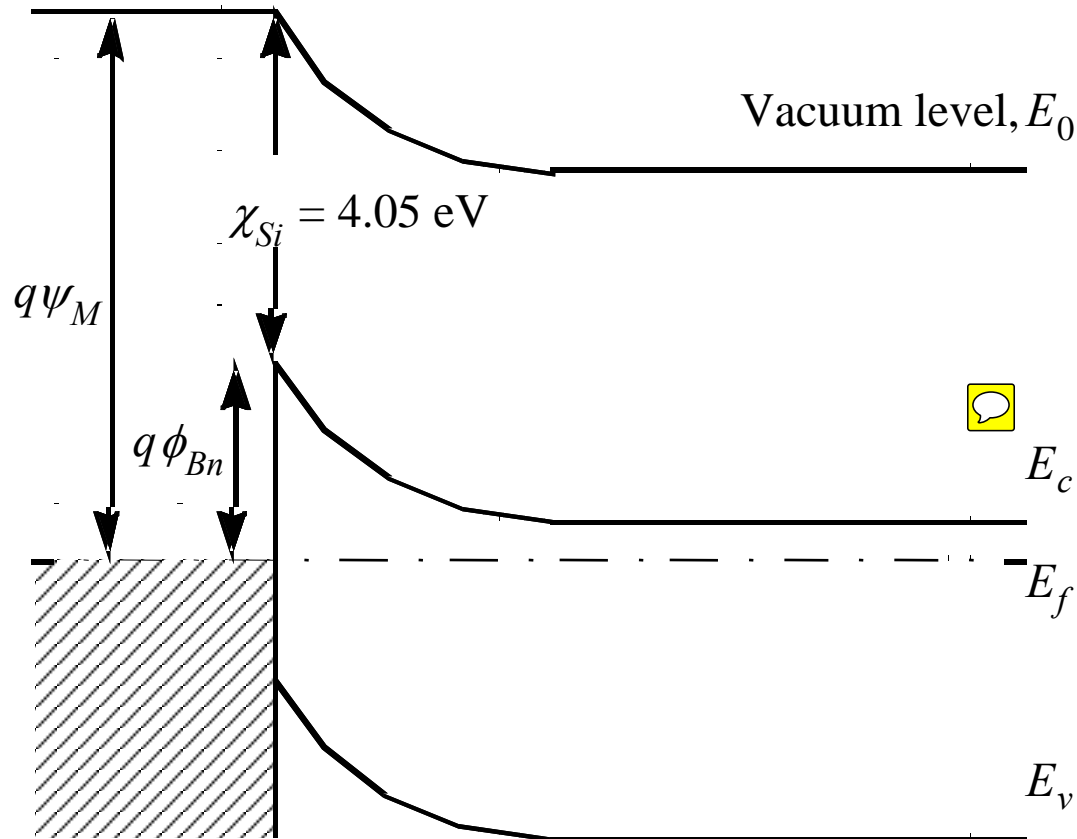
## *Schottky barrier heights for electrons and holes*

Metal	Mg	Ti	Cr	W	Mo	Pd	Au	Pt
$\phi_{Bn}$ (V)	0.4	0.5	0.61	0.67	0.68	0.77	0.8	0.9
$\phi_{Bp}$ (V)		0.61	0.5		0.42		0.3	
Work Function $\psi_m$ (V)	3.7	4.3	4.5	4.6	4.6	5.1	5.1	5.7

$$\phi_{Bn} + \phi_{Bp} \approx 1.1 \text{ V}$$

$\phi_{Bn}$  increases with increasing metal work function

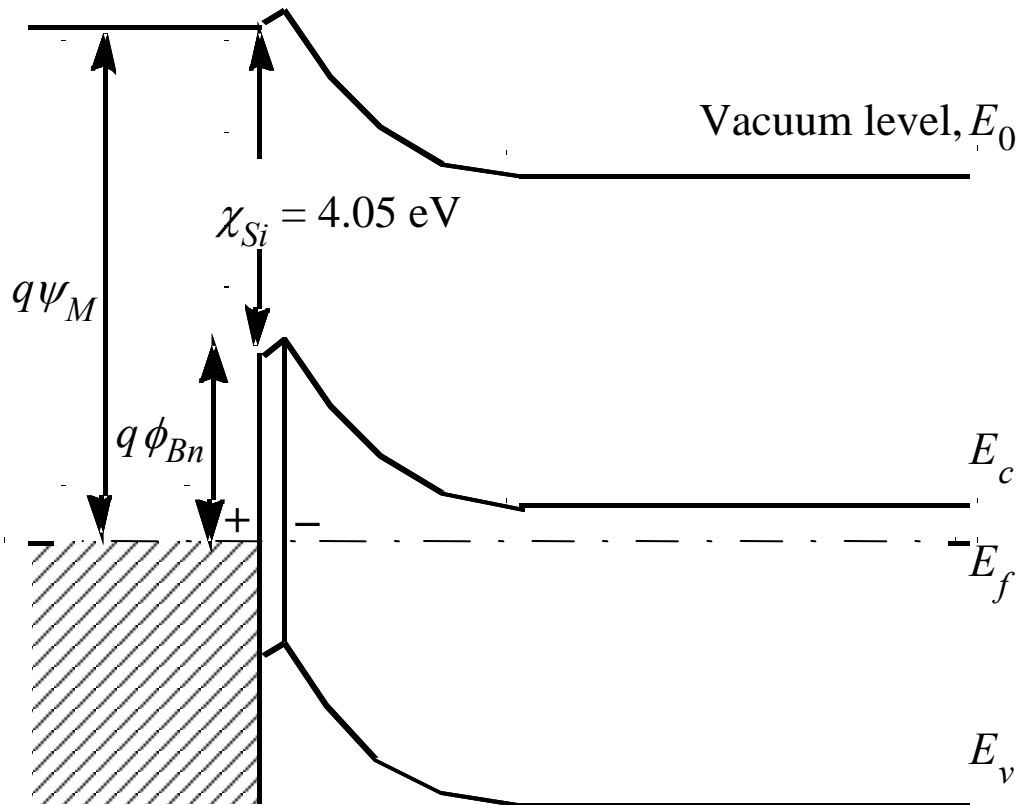
***$\phi_{Bn}$  Increases with Increasing Metal Work Function***



Ideally,

$$q\phi_{Bn} = q\psi_M - \chi_{Si}$$

$\phi_{Bn}$  is typically 0.4 to 0.9 V



- A high density of energy states in the bandgap at the metal-semiconductor interface pins  $E_f$  to a range of 0.4 eV to 0.9 eV below  $E_c$

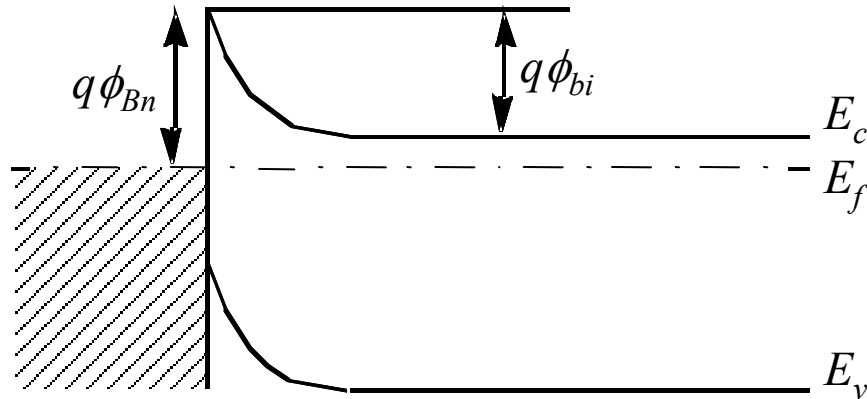
• **Question:** What is the typical range of  $\phi_{Bp}$ ?

## *Schottky barrier heights of metal silicide on Si*

Silicide	ErSi <sub>1.7</sub>	HfSi	MoSi <sub>2</sub>	ZrSi <sub>2</sub>	TiSi <sub>2</sub>	CoSi <sub>2</sub>	WSi <sub>2</sub>	NiSi <sub>2</sub>	Pd <sub>2</sub> Si	PtSi
$\phi_{Bn}$ (V)	0.28	0.45	0.55	0.55	0.61	0.65	0.67	0.67	0.75	0.87
$\phi_{Bp}$ (V)			0.55	0.49	0.45	0.45	0.43	0.43	0.35	0.23

Silicide-Si interfaces are more stable than metal-silicon interfaces. After metal is deposited on Si, an annealing step is applied to form a silicide-Si contact. The term *metal-silicon contact* includes silicide-Si contacts.

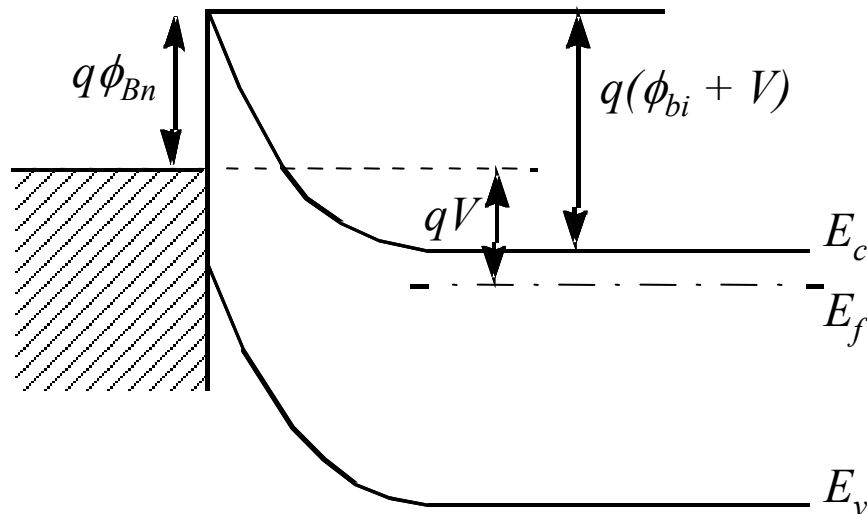
## Using CV Data to Determine $\phi_B$



$$\begin{aligned} q\phi_{bi} &= q\phi_{Bn} - (E_c - E_f) \\ &= q\phi_{Bn} - kT \ln \frac{N_c}{N_d} \end{aligned}$$

$$W_{dep} = \sqrt{\frac{2\epsilon_s (\phi_{bi} + V)}{qN_d}}$$

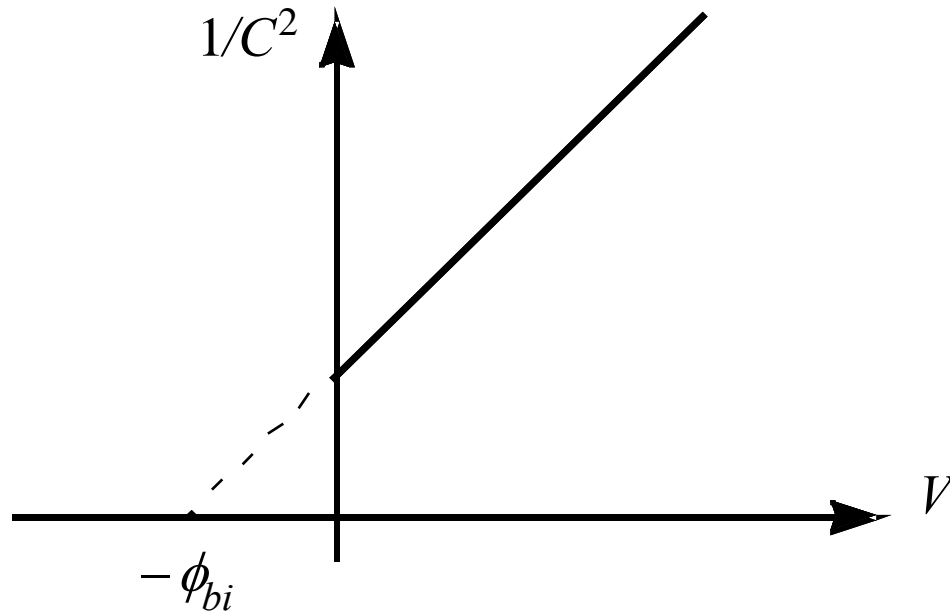
$$C = \frac{\epsilon_s}{W_{dep}} A$$



### **Question:**

*How should we plot the CV data to extract  $\phi_{bi}$ ?*

## *Using CV Data to Determine $\phi_B$*



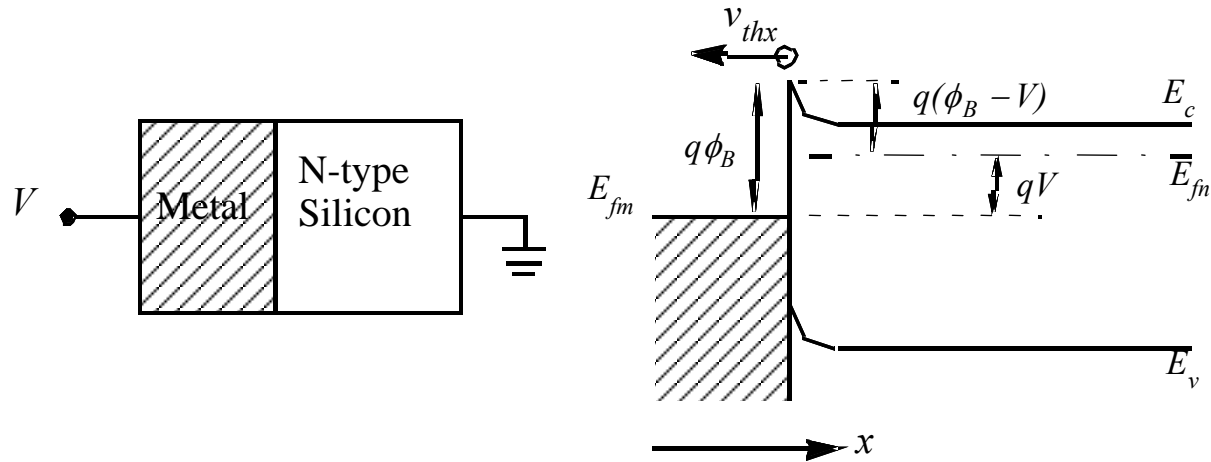
$$\frac{1}{C^2} = \frac{2(\phi_{bi} + V)}{qN_d\epsilon_s A^2}$$

Once  $\phi_{bi}$  is known,  $\phi_B$  can be determined using

$$q\phi_{bi} = q\phi_{Bn} - (E_c - E_f) = q\phi_{Bn} - kT \ln \frac{N_c}{N_d}$$



## 9.2 Thermionic Emission Theory



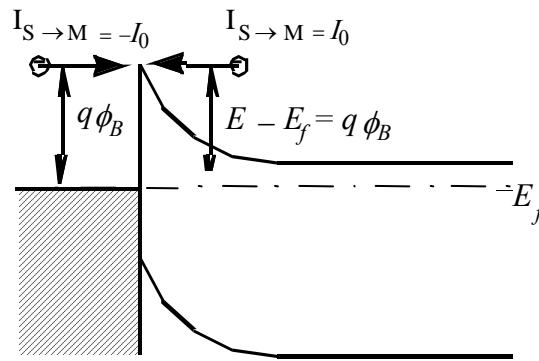
$$n = N_c e^{-q(\phi_B - V)/kT} = 2 \left[ \frac{2\pi m_n kT}{h^2} \right]^{3/2} e^{-q(\phi_B - V)/kT}$$

$$v_{th} = \sqrt{3kT / m_n} \quad v_{thx} = -\sqrt{2kT / \pi m_n}$$

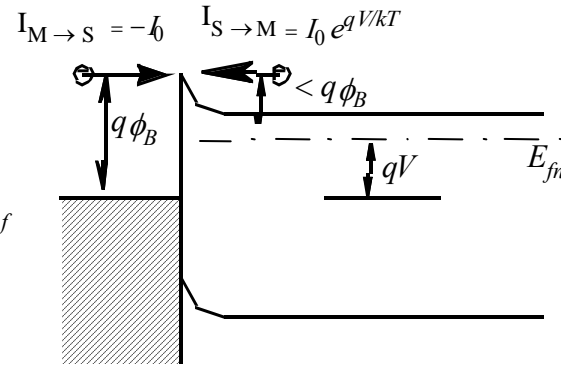
$$J_{S \rightarrow M} = -\frac{1}{2} q n v_{thx} = \frac{4\pi q m_n k^2}{h^3} T^2 e^{-q\phi_B/kT} e^{qV/kT}$$

$$= J_0 e^{qV/kT}, \text{ where } J_0 \approx 100 e^{-q\phi_B/kT} \text{ A/cm}^2$$

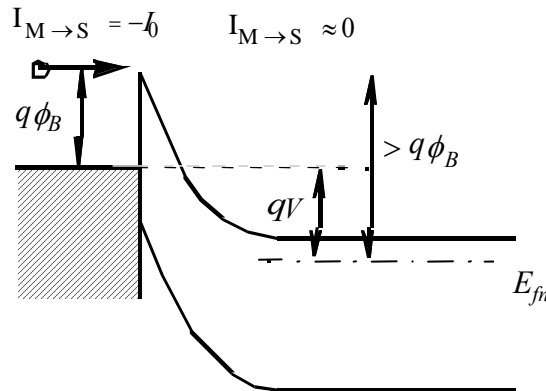
## 9.3 Schottky Diode



(a)  $V = 0$ .  $I_{S \rightarrow M} = |I_{M \rightarrow S}| = I_0$

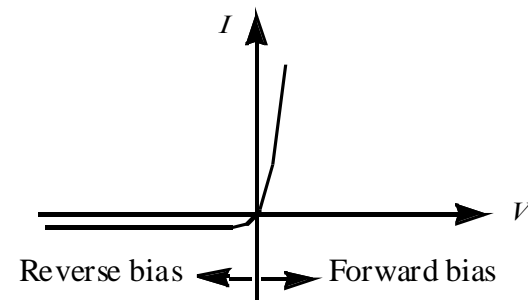


(b) Forward bias. Metal is positive wrt Si.  $I_{S \rightarrow M} \gg |I_{M \rightarrow S}| = I_0$



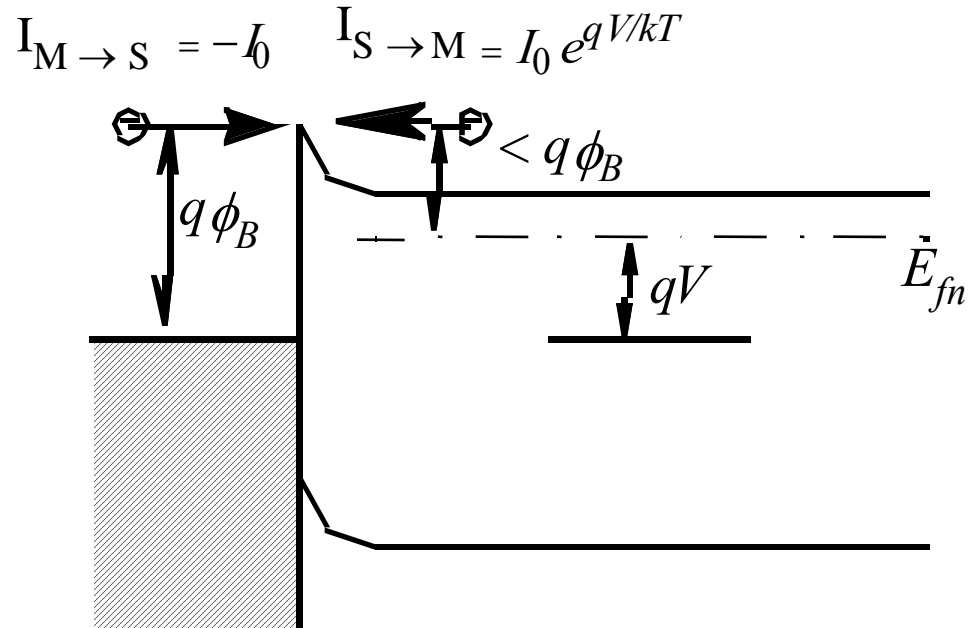
(c) Reverse bias. Metal is negative wrt Si.

$$I_{S \rightarrow M} \ll |I_{M \rightarrow S}| = I_0$$



(d) Schottky diode IV.

## 9.3 Schottky Diode

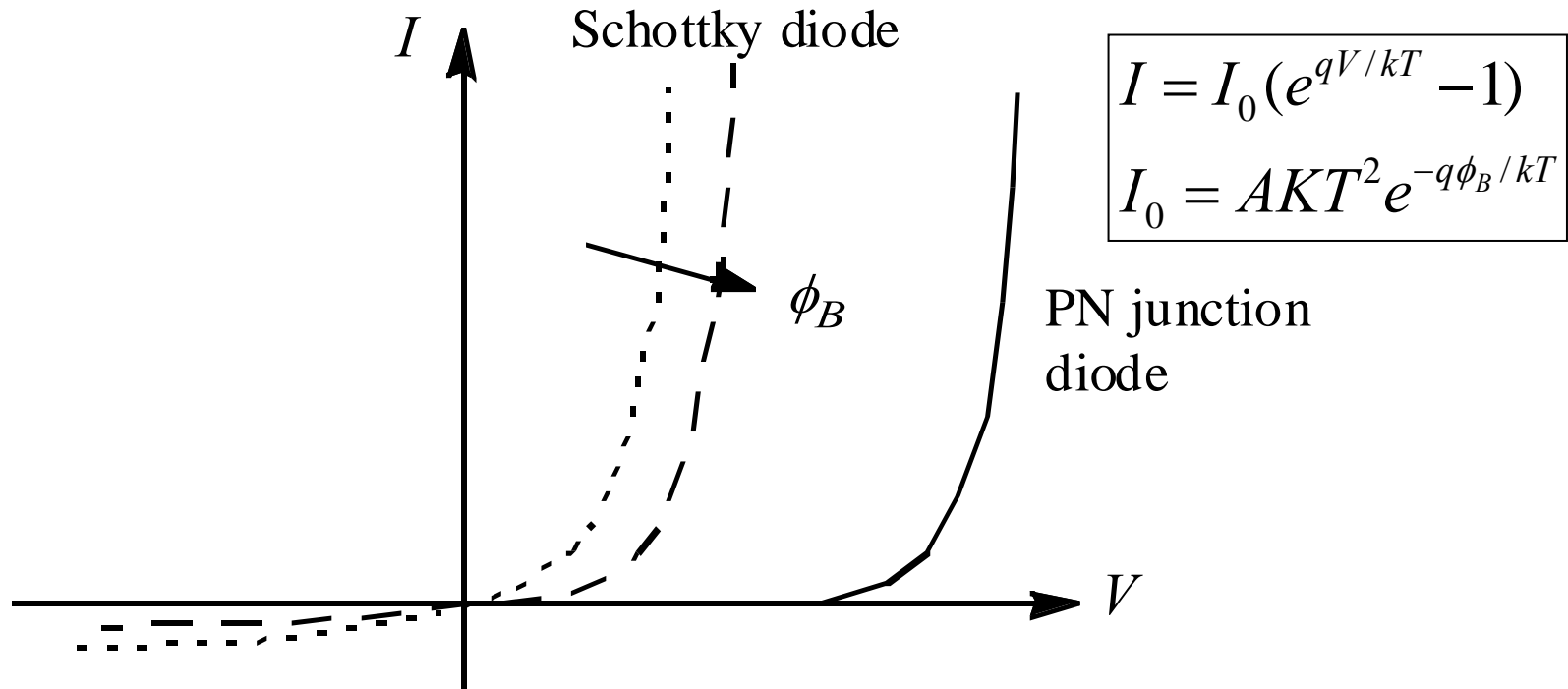


$$I_0 = AKT^2 e^{-q\phi_B/kT}$$

$$K = \frac{4\pi q m_n k^2}{h^3} \approx 100 \text{ A}/(\text{cm}^2 \cdot \text{K}^2)$$

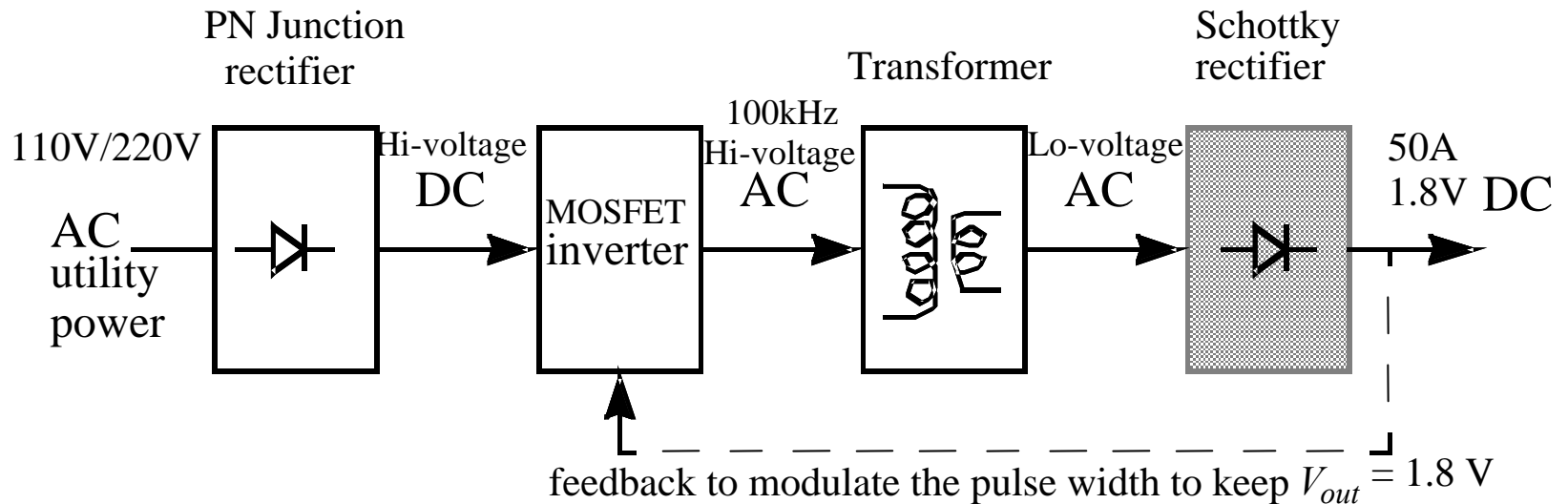
$$I = I_{S \rightarrow M} + I_{M \rightarrow S} = I_0 e^{qV/kT} - I_0 = I_0 (e^{qV/kT} - 1)$$

## 9.4 Applications of Schottky Diodes



- $I_0$  of a Schottky diode is  $10^3$  to  $10^8$  times larger than a PN junction diode, depending on  $\phi_B$ . A larger  $I_0$  means a smaller forward drop  $V$ .
- A Schottky diode is the preferred rectifier in low voltage, high current applications.

## Switching Power Supply



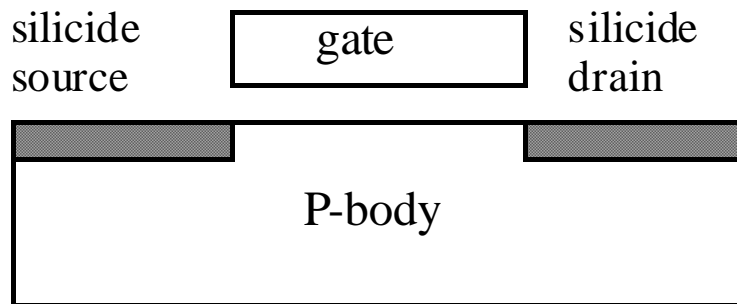
**Question:** What sets the lower limit in a Schottky diode's forward drop?

**Synchronous Rectifier:** For an even lower forward drop, replace the diode with a wide-W MOSFET which is not bound by the tradeoff between diode  $V$  and  $I_0$ :  $I = I_0 e^{qV/kT}$

## 9.4 Applications of Schottky Diodes

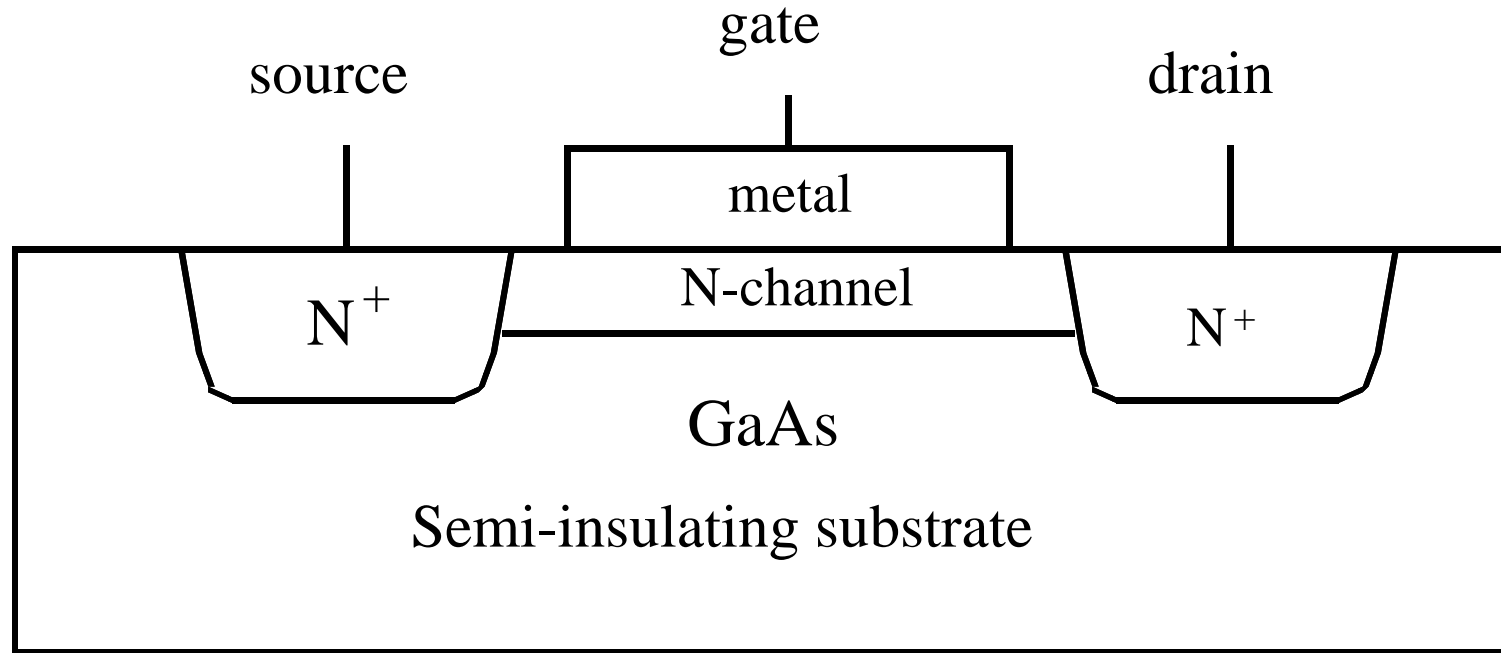
There is no minority carrier injection at the Schottky junction. Thus, the CMOS latch-up problem can be eliminated by replacing the source/drain of the NFET with Schottky junctions.

In addition, the Schottky S/D MOSFET would have shallow junctions and low series resistance. So far, Schottky S/D MOSFETs have lower performance.



***No excess carrier storage.  
What application may benefit  
from that?***

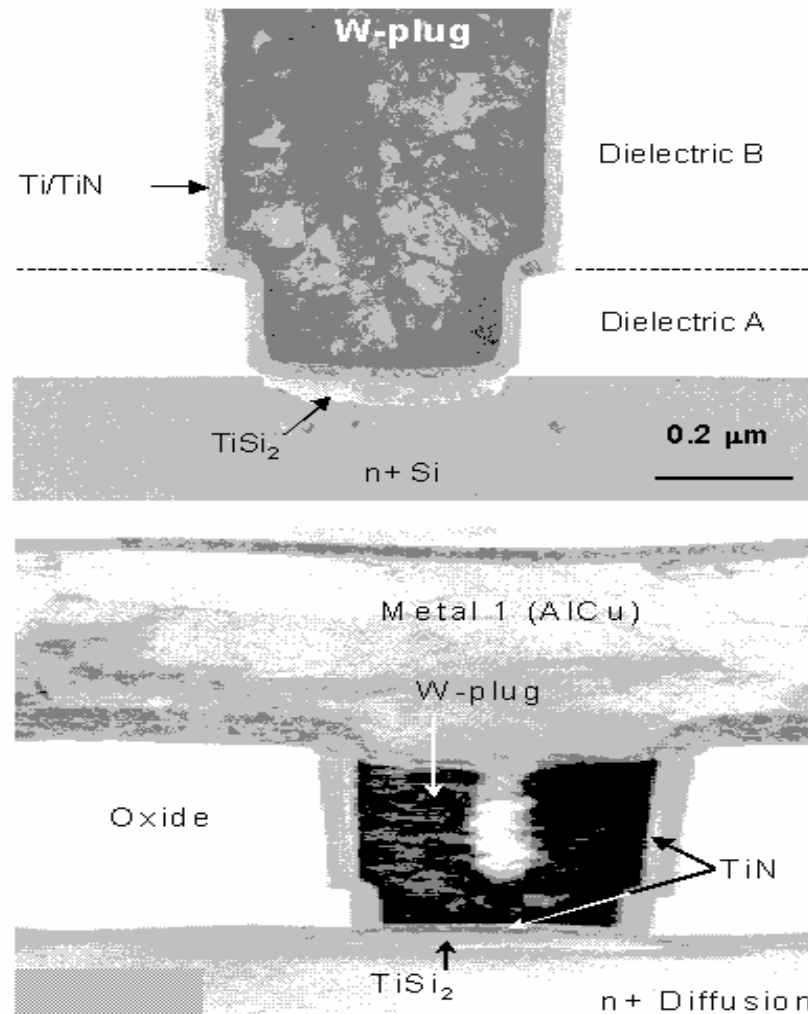
## *GaAs MESFET*



The MESFET has similar IV characteristics as the MOSFET, but does not require a gate oxide.

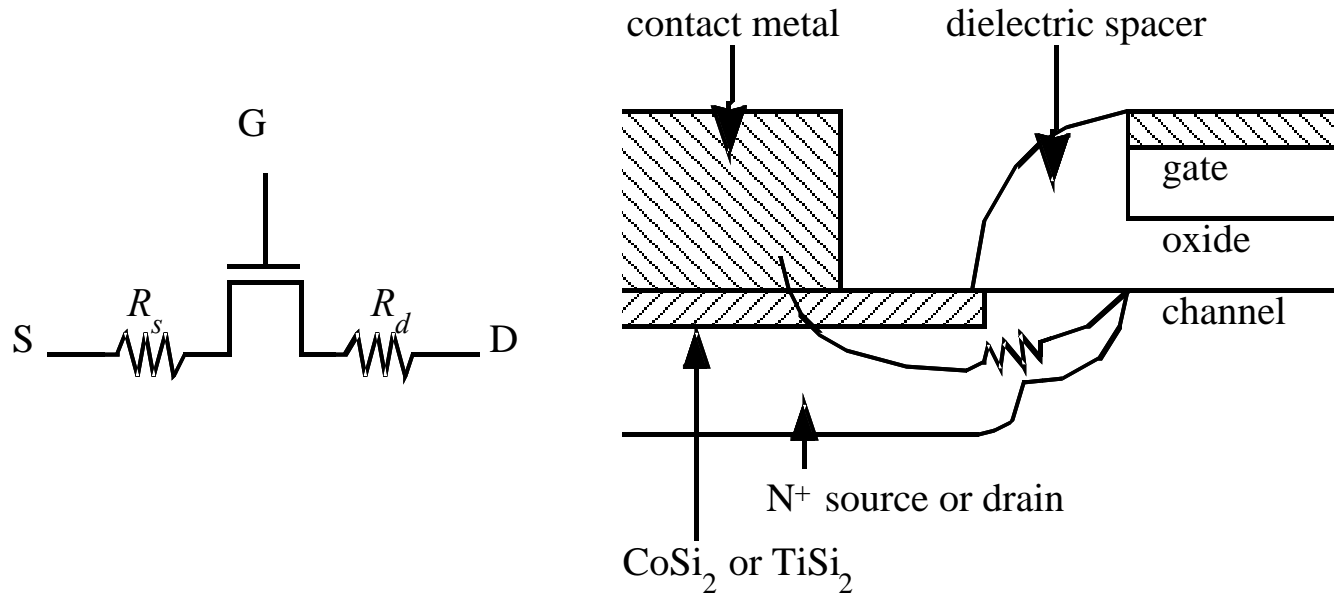
***Question:*** What is the advantage of GaAs over Si?

## 9.5 Ohmic Contacts





## ***SALICIDE (Self-Aligned Silicide) Source/Drain***



After the spacer is formed, a Ti or Mo film is deposited. Annealing causes the silicide to be formed over the source, drain, and gate. Unreacted metal (over the spacer) is removed by wet etching.

### ***Question:***

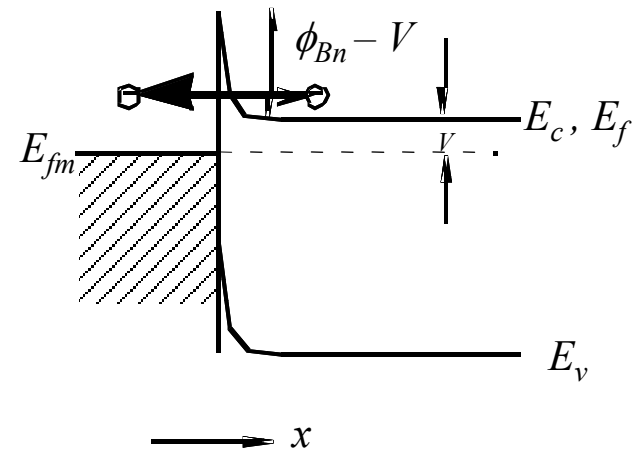
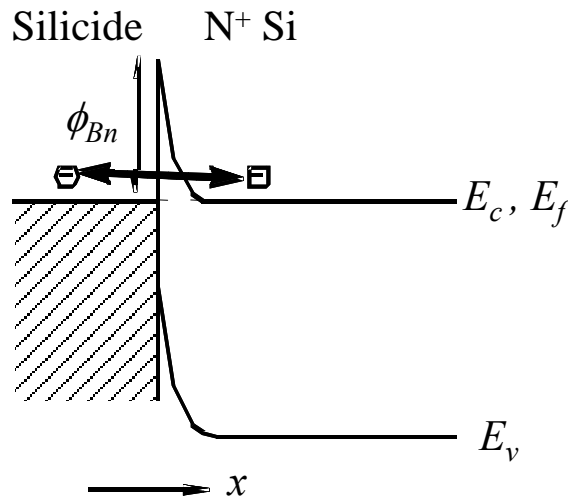
- What is the purpose of siliciding the source/drain/gate?
- What is self-aligned to what?

## 9.5 Ohmic Contacts

$$W_{dep} = \sqrt{\frac{2\epsilon_s \phi_{Bn}}{qN_d}}$$

Tunneling  
probability:

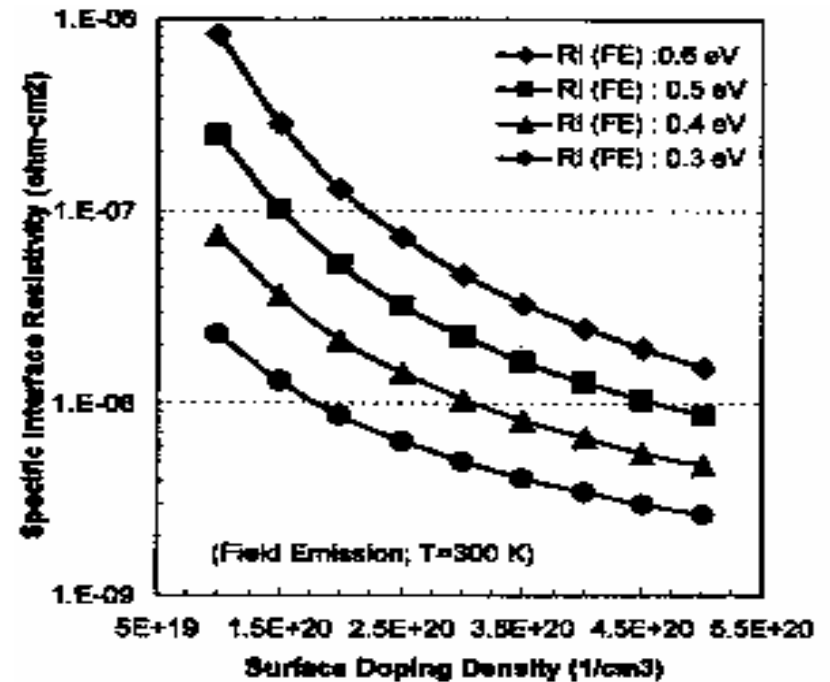
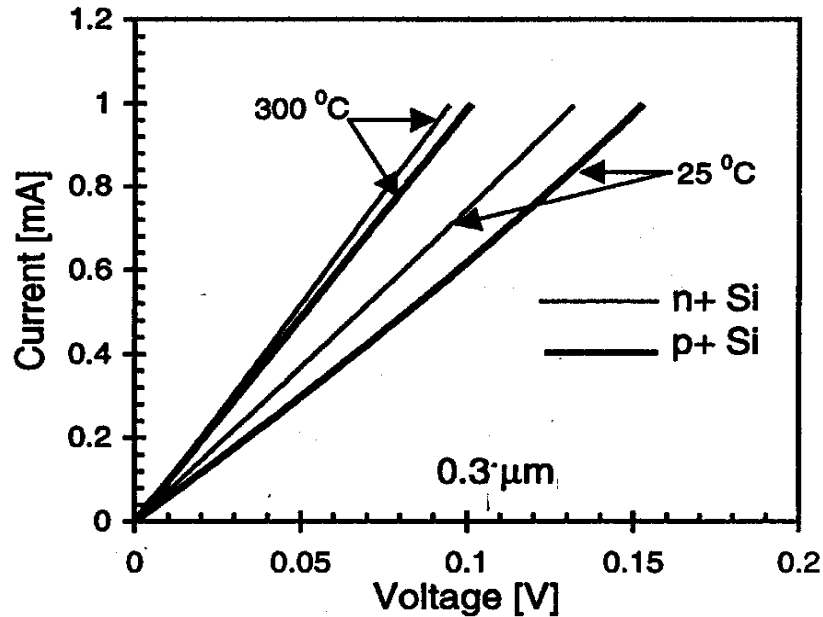
$$P = e^{-H\phi_{Bn}/\sqrt{N_d}}$$



$$H = 4\pi\sqrt{\epsilon_s m_n} / h = 5.4 \times 10^9 \sqrt{m_n / m_o} \text{ cm}^{-3/2} \text{ V}^{-1}$$

$$J_{S \rightarrow M} \approx \frac{1}{2} q N_d v_{thx} P = q N_d \sqrt{kT / 2\pi m_n} e^{-H(\phi_{Bn} - V) / \sqrt{N_d}}$$

## 9.5 Ohmic Contacts



$$R_c \equiv \left( \frac{dJ_{S \rightarrow M}}{dV} \right)^{-1} = \frac{e^{H\phi_{Bn}/\sqrt{N_d}}}{qv_{thx} H \sqrt{N_d}} \propto e^{H\phi_{Bn}/\sqrt{N_d}} \Omega \cdot \text{cm}^2$$