# Metal Semiconductor Junction

Basics of Schottky Diode

➤ It is a metal-semiconductor diode, also called a *point contact diode.*

➤ The ideal energy-band diagram for a particular metal and n-type semiconductor before making contact is shown.

(a) Energy-band diagram of a metal and semi-conductor before contact; (b) ideal energy-band diagram of a metal–n-semiconductor junction for $\phi_m > \phi_s$

The parameter ϕ_m is the metal work function (measured in volts), ϕ_s is the semiconductor work function, and χ is known as the *electron affinity*

Basics of Schottky Diode

➢ Before contact, the Fermi level in the semiconductor was above that in the metal.

➢ In order for the Fermi level to become a constant through the system in thermal equilibrium, electrons from the semiconductor flow into the lower energy states in the metal.

➢ Positively charged donor atoms remain in the semiconductor, creating a space charge region.

➢ The parameter ϕ_{B0} is the ideal barrier height of the semiconductor contact, the potential barrier seen by electrons in the metal trying to move into the semiconductor. This barrier is known as the *Schottky barrier.*

➢ This barrier is known as the *Schottky barrier*

$$\phi_{B0} = (\phi_m - \chi)$$

➢ On the semiconductor side, *Vbi* is the built-in potential barrier. This barrier, similar to the case of the pn junction, is the barrier seen by electrons in the conduction band trying to move into the metal. The built-in potential barrier is given by

$$V_{bi} = \phi_{B0} - \phi_n$$

$$x_n = \left[\frac{2\epsilon_s V_{bi}}{eN_d} \right]^{1/2}$$

$$|E_{max}| = \frac{eN_d x_n}{\epsilon_s}$$

Objective: Determine the theoretical barrier height, built-in potential barrier, and maximum electric field in a metal–semiconductor diode for zero applied bias.

Consider a contact between tungsten and n-type silicon doped to $N_d = 10^{16}$ cm^{-3} at $T = 300$ K.

■ **Solution**

The metal work function for tungsten (W) from Table 9.1 is $\phi_m = 4.55$ V and the electron affinity for silicon from Table 9.2 is $\chi = 4.01$ V. The barrier height is then

$$\phi_{B0} = \phi_m - \chi = 4.55 - 4.01 = 0.54 \text{ V}$$

where ϕ_{B0} is the ideal Schottky barrier height. We can calculate ϕ_n as

$$\phi_n = \frac{kT}{e} \ln\left(\frac{N_c}{N_d}\right) = 0.0259 \ln\left(\frac{2.8 \times 10^{19}}{10^{16}}\right) = 0.206 \text{ V}$$

Then

$$V_{bi} = \phi_{B0} - \phi_n = 0.54 - 0.206 = 0.334 \text{ V}$$
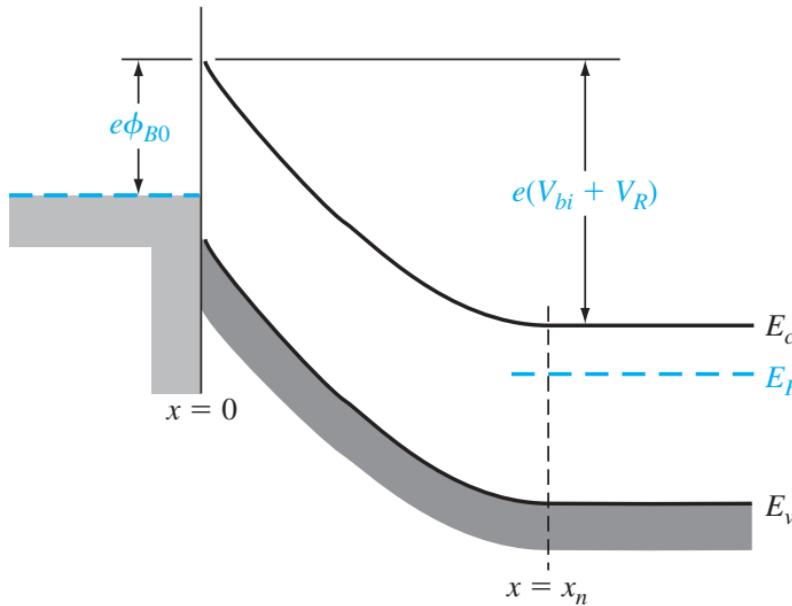
$$x_n = \left[\frac{2\epsilon_s V_{bi}}{eN_d}\right]^{1/2} = \left[\frac{2(11.7)(8.85 \times 10^{-14})(0.334)}{(1.6 \times 10^{-19})(10^{16})}\right]^{1/2} \qquad |E_{max}| = \frac{eN_d x_n}{\epsilon_s} = \frac{(1.6 \times 10^{-19})(10^{16})(0.208 \times 10^{-4})}{(11.7)(8.85 \times 10^{-14})}$$
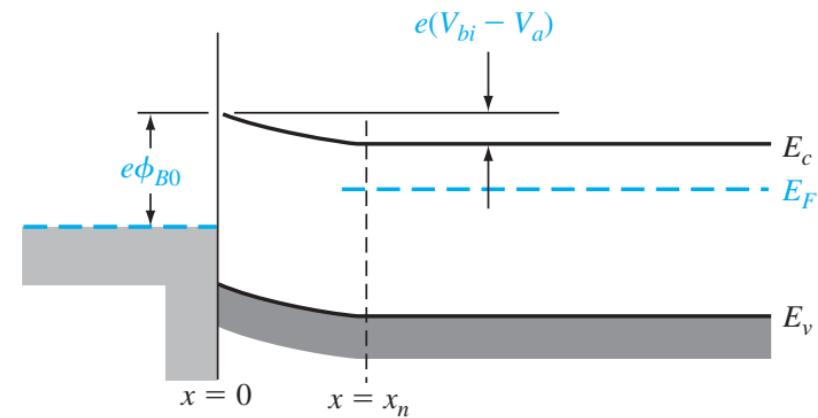
$$x_n = 0.208 \times 10^{-4} \text{ cm} \qquad\qquad\qquad |E_{max}| = 3.21 \times 10^4 \text{ V/cm}$$

Basics of Schottky Diode

➤ If we apply a positive voltage to the semiconductor with respect to the metal, the semiconductor-to-metal barrier height increases, while ϕ_{B0} remains constant in this idealized case. This bias condition is the reverse bias.

(a)   (b)

Ideal energy-band diagram of a metal–semiconductor junction (a) under reverse bias and (b) under forward bias.

➤ If a positive voltage is applied to the metal with respect to the semiconductor, the semiconductor-to-metal barrier V_{bi} is reduced.

➤ In this situation, electrons can more easily flow from the semiconductor into the metal since the barrier has been reduced. This bias condition is the forward bias.

Basics of Schottky Diode

➢ The current mechanism here, however, is due to the flow of majority carrier electrons.

➢ In forward bias, the barrier seen by the electrons in the semiconductor is reduced, so majority carrier electrons flow more easily from the semiconductor into the metal.

➢ The forward-bias current is in the direction from metal to semiconductor: It is an exponential function of the forward-bias voltage Va .

➢ The electric field can then be written as $E = -\dfrac{eN_d}{\epsilon_s}(x_n - x)$

➢ Electric field is a linear function of distance, for the uniformly doped semiconductor, and reaches a peak value at the metal–semiconductor interface i.e. at x=0.

➢ The space charge region width, W, may be calculated as

$$W = x_n = \left[\frac{2\epsilon_s(V_{bi} + V_R)}{eN_d}\right]^{1/2} \qquad C' = eN_d\frac{dx_n}{dV_R} = \left[\frac{e\epsilon_s N_d}{2\,(V_{bi} + V_R)}\right]^{1/2} \qquad \left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d}$$

Table 9.1 | Work functions of some elements

Element	Work function, ϕ_m
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

Table 9.2 | Electron affinity of some semiconductors

Element	Electron affinity, χ
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminum arsenide	3.5

Basics of Schottky Diode
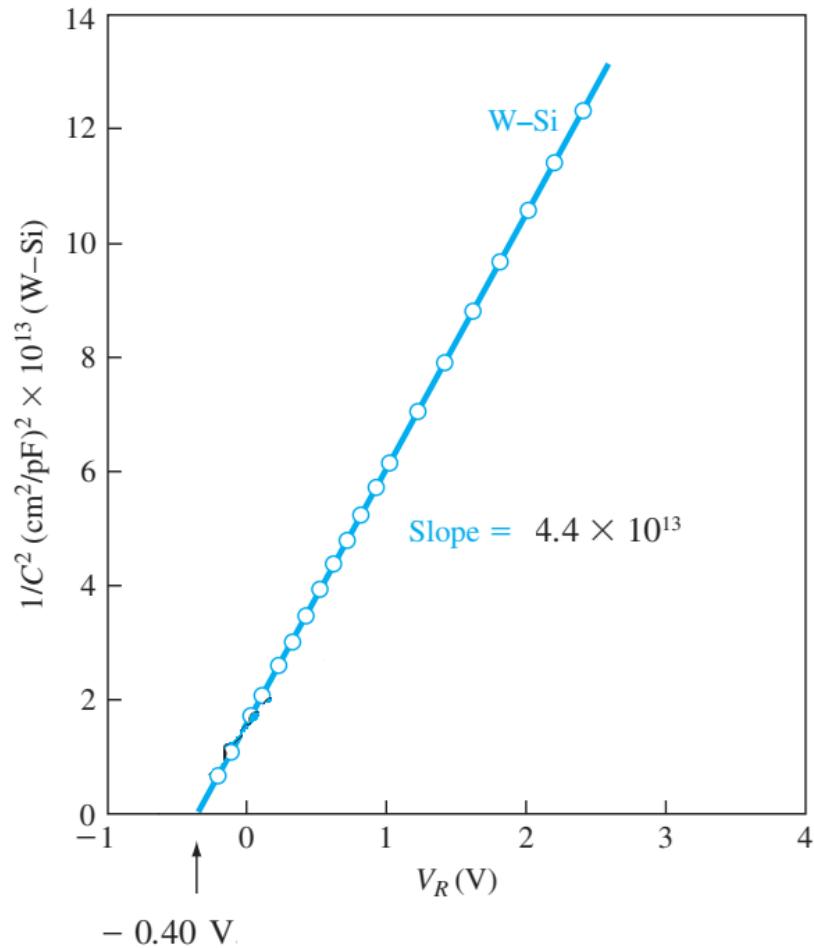
Consider an ideal tungsten-to-n-type GaAs junction. Assume the GaAs is doped to a concentration of $N_d = 5 \times 10^{15}$ cm^{-3} . Determine the theoretical barrier height, the built-in potential barrier, and maximum electric field for the case of zero applied bias.

(Ans. $\phi_{B0} = 0.48$ V, $V_{bi} = 0.3623$ V, $\left| E_{max} \right| = 2.24 \times 10^4$ V/cm)

Gold is deposited on n-type silicon forming an ideal rectifying junction. The doping concentration is $N_d = 10^{16}$ cm^{-3}. Assume $T = 300$ K. Determine the theoretical values of (a) ϕ_{B0}, (b) V_{bi}, and (c) x_n and $\left| E_{max} \right|$ at (i) $V_R = 1$ V and (ii) $V_R = 5$ V.

(a) ϕ_{BO} 1.09 V;
(b) $V_{bi} = 0.8844$ V;
(c) (i) $x_n = 0.4939$ μm, $\left| E_{max} \right| = 7.63 \times 10^4$ V/cm;
   (ii) $x_n = 0.8728$ μm, $\left| E_{max} \right| = 1.35 \times 10^5$ V/cm

Prob: Calculate the semiconductor doping concentration and Schottky barrier height for W-Si diode. Assume T=300K
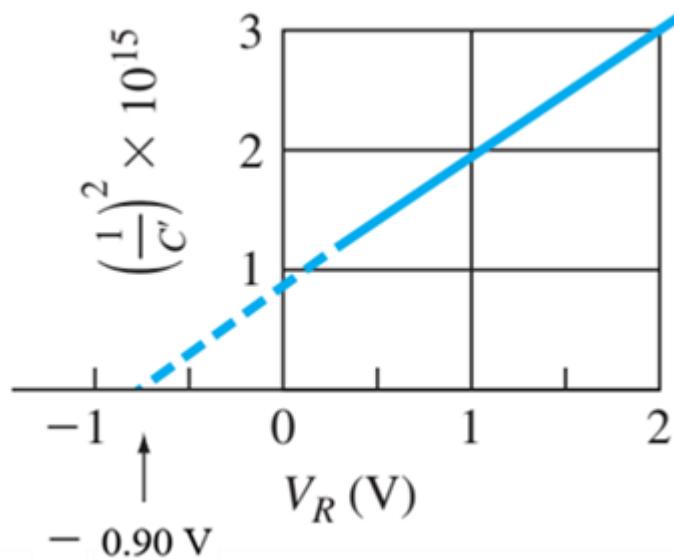

$$N_d = \frac{2}{(1.6 \times 10^{-19})(11.7)(8.85 \times 10^{-14})(4.4 \times 10^{13})}$$

$$N_d = 2.7 \times 10^{17} \text{ cm}^{-3}$$

$$\phi_n = \frac{kT}{e} \ln\left(\frac{N_c}{N_d}\right) = (0.0259) \ln\left(\frac{2.8 \times 10^{19}}{2.7 \times 10^{17}}\right) = 0.12 \text{ V}$$

$$\phi_{Bn} = V_{bi} + \phi_n = 0.40 + 0.12 = 0.52 \text{ V}$$

Prob: A Schottky diode with n-type GaAs at $T=300$ K yields the following plot, where C' is the capacitance per cm^2. Determine (a) V_{bi}, (b) N_d (c) ϕ_n, and (d) ϕ_{B0}.

(a) From the figure, $V_{bi} = 0.90$ V

(b) We find

$$\frac{\Delta\left(\dfrac{1}{C'}\right)^2}{\Delta V_R} = \frac{3\times10^{15} - 0}{2 - (-0.90)} = 1.034\times10^{15}$$

and

$$1.034\times10^{15} = \frac{2}{e\,\epsilon_s\,N_d}$$

We can then write

$$N_d = \frac{2}{\left(1.6\times10^{-19}\right)\left(13.1\right)\left(8.85\times10^{-14}\right)\left(1.034\times10^{15}\right)}$$

or

$$N_d = 1.04\times10^{16}\ \text{cm}^{-3}$$

(c)

$$\phi_n = V_t\,\ln\left(\frac{N_c}{N_d}\right)$$

$$= (0.0259)\ln\left(\frac{4.7\times10^{17}}{1.04\times10^{16}}\right)$$

or

$$\phi_n = 0.0986\,\text{V}$$

(d)
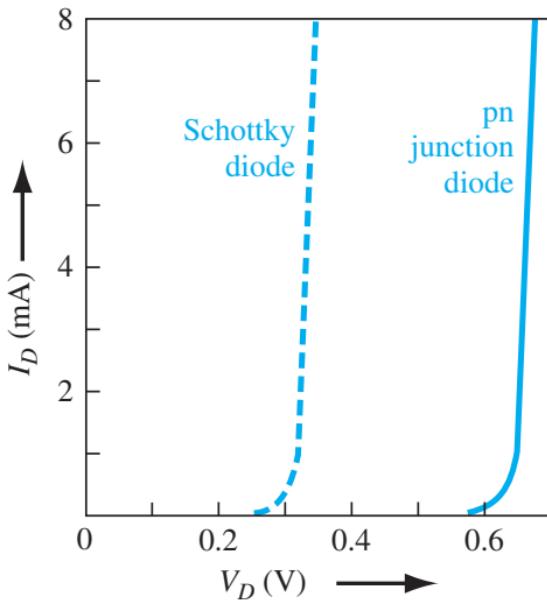
$$\phi_{Bn} = V_{bi} + \phi_n = 0.90 + 0.0986$$

or

$$\phi_{Bn} = 0.9986\,\text{V}$$

# Comparison of the Schottky Barrier Diode and the p-n Junction Diode
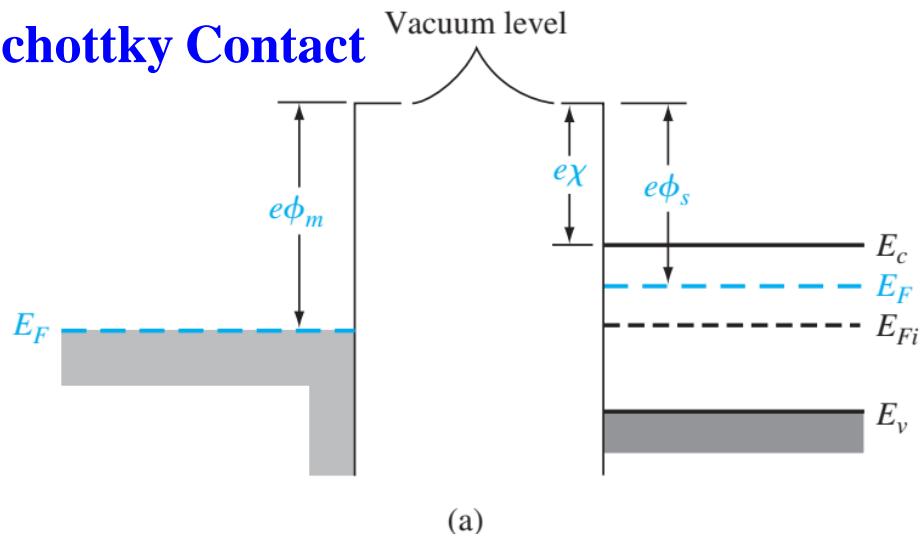
➤ The current in a p-n junction is determined by the diffusion of minority carriers while the current in a Schottky barrier diode is determined by the thermionic emission of majority carriers over a potential barrier.

➤ Reverse saturation current in the Schottky diode is higher as compared to normal p-n junction diode.

➤ The effective turn-on voltage of the Schottky diode is less than that of the p-n junction diode.
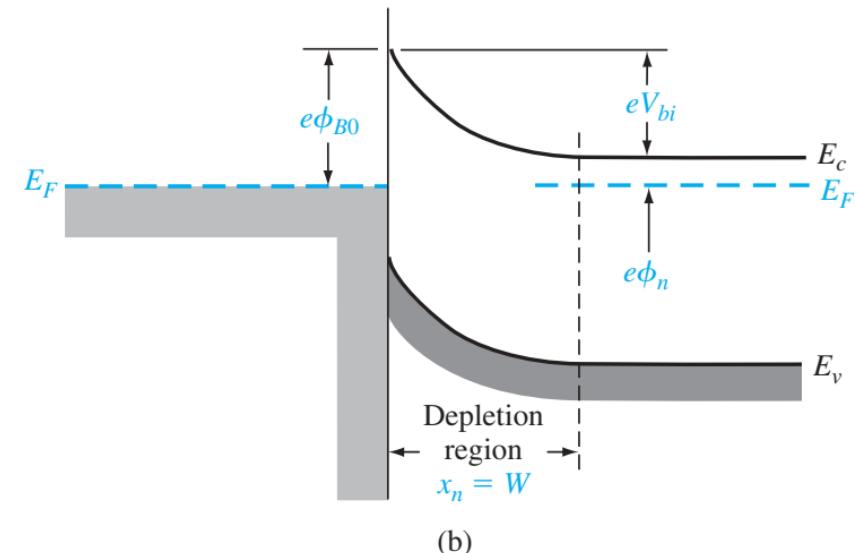
➤ The Schottky barrier diode, is a majority carrier device.

➤ When switching a Schottky diode from forward to reverse bias, there is no minority carrier stored charge to remove, as is the case in the p-n junction diode. Since there is no minority carrier storage time, the Schottky diodes can be used in fast-switching applications

➤ A typical switching time for a Schottky diode is in the picosecond range, while for a p-n junction it is normally in the nanosecond range.

# N-type Semiconductor ($\phi_m > \phi_s$)

Schottky Contact
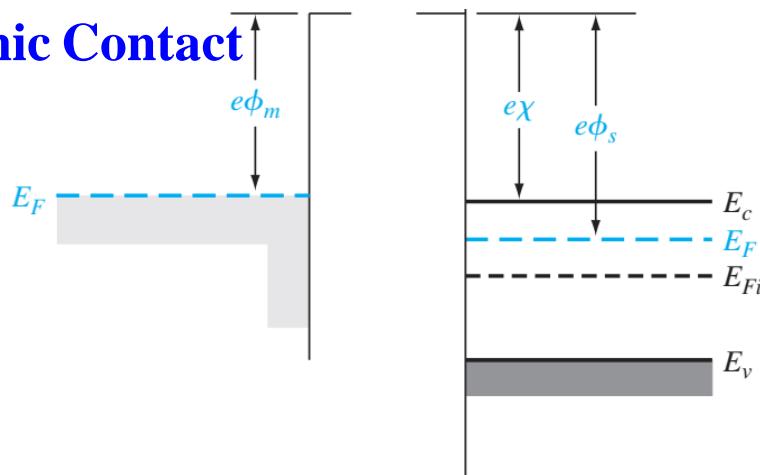
(a) Energy-band diagram of a metal and semi-conductor before contact; (b) ideal energy-band diagram of a metal–n-semiconductor junction for $\phi_m > \phi_s$

➤ To achieve thermal equilibrium in this junction, electrons flow from the semiconductor into the lower energy states in the metal, which makes the surface of the semiconductor less n-type.

➤ If a positive voltage is applied to the metal with respect to the semiconductor, electrons can easily flow from the semiconductor into the metal since the barrier has been reduced

➤ If positive voltage to the semiconductor with respect to the metal, the semiconductor-to-metal barrier height increases

N-type Semiconductor ($\phi_s > \phi_m$)

Ohmic Contact

(a)   (b)

(a) Energy-band diagram of a metal and semi-conductor before contact; (b) ideal energy-band diagram of a metal–n-semiconductor junction for $\phi s > \phi m$

➢ To achieve thermal equilibrium in this junction, electrons flow from the metal into the lower energy states in the semiconductor, which makes the surface of the semiconductor more n-type.

➢ If a positive voltage is applied to the metal, there is no barrier to electrons flowing from the semiconductor into the metal.

➢ If a positive voltage is applied to the semiconductor, the effective barrier height for electrons flowing from the metal into the semiconductor will be small and, electrons can easily flow from the metal into the semiconductor.

Semiconductor	Work Function	Contact
N-Type	$\phi_m > \phi_s$	Schottky
	$\phi_m < \phi_s$	Ohmic
P-Type	$\phi_m > \phi_s$	Ohmic
	$\phi_m < \phi_s$	Schottky

1. Draw the structure of an n-channel JFET and qualitatively discuss the I–V characteristics, including current directions and voltage polarities.

2. Calculate the internal pinch-off voltage and pinch-off voltage of n-channel JFET. Assume that the p-n junction of a uniformly doped silicon n-channel JFET at T=300 K has doping concentrations of $N_a=10^{18}$ cm^{-3} and $N_d=10^{16}$ cm^{-3}. Assume that the metallurgical channel thickness, a, is 0.75 µm.

3. Design the channel doping concentration and metallurgical channel thickness to achieve a given pinch-off voltage. Consider a silicon p-channel p-n JFET at T=300 K. Assume that the gate doping concentration is $N_d=10^{18}$ cm^{-3}. Determine the channel doping concentration and channel thickness so that the pinch-off voltage is 2.25 V.

4. Consider a GaAs n-channel p-n JFET at T=300 K with $Na=10^{18}$ cm^{-3}, $Nd=3\times10^{15}$cm^{-3}, and a=0.70 µm. Determine the forward-bias gate voltage required to open a channel region that is 0.10 µm thick with zero drain voltage.

5. Calculate the maximum current in an n-channel JFET Consider a silicon n-channel JFET at T = 300 K with the following parameters: $N_a =10^{18}$ cm^{-3}, $N_d =10^{16}$ cm^{-3}, a =0.75 µm, L =10 µm, W =30 µm, and $\mu_n =1000$ cm^2/V-s.

6. Describe the basic operation of the MESFET and the mechanism of current saturation in it.

7. Consider an n-channel GaAs MESFET at T=300 K with a gold Schottky barrier contact. Assume the barrier height is ϕ_{Bn}= 0.89 V. The n-channel doping is $N_d=2\times10^{15}$ cm^{-3}. Design the channel thickness such that V_T=0.25 V.

8. The Schottky barrier height, ϕ_{Bn}, of a metal–n-GaAs MESFET is 0.90 V. The channel doping is $N_d=1.5\times10^{16}$ cm^{-3}, and the channel thickness is a=0.5 μm. T=300 K.

    (a) Calculate the internal pinch-off voltage V_{p0} and the threshold voltage V_T.

    (b) Determine whether the MESFET is a depletion type or enhancement type.

9. Consider an n-channel GaAs MESFET at T=300 K with ϕ_{Bn}=0.85 V and a=0.25 μm. Determine the channel doping concentration such that V_T=0.5 V

10. Consider an n-channel GaAs MESFET with a gate barrier height of ϕ_{Bn}=0.85 V. The channel doping concentration is $N_d = 5\times10^{15}$ cm^{-3} and the channel thickness is a = 0.40 μm. Calculate the internal pinch-off voltage and the threshold voltage.

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