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(b) The part (a) charge diagram is in agreement with the \( \rho/qN_A \) versus \( x \) plot in Fig. 16.8(c). To obtain the total charge in the semiconductor at each point one adds the separate block charges shown in part (a).

![Charge Diagram]

The spike near \( x = 0 \) in the Fig. 16.8(c) plot simply reflects the forming inversion layer of electrons at the surface. By definition, at the onset of inversion \( n_{\text{surface}} = N_A \). Thus, at the special \( V_T \) bias point \( \rho_S = -q(n_{\text{surface}} + N_A) = -2qN_A \), or \( \rho/qN_A = -2 \) at \( x = 0 \) at the onset of inversion.

(c) Since \( \phi_F/(kT/q) = 12 \), inverting Eq.(16.8a) yields

\[
N_A = n_i e^{\phi_F/(kT/q)} = 1.00 \times 10^{10} \text{ } e^{12} = 1.63 \times 10^{15} / \text{cm}^3
\]

\[
W_T = \left[ \frac{2KS\phi_0}{qN_A} \right]^{1/2} = \left[ \frac{(2)(11.8)(8.85 \times 10^{-14})(24)(0.0259)}{(1.6 \times 10^{-19})(1.63 \times 10^{15})} \right]^{1/2} = 0.706 \mu\text{m}
\]

(From Fig. 16.9 one also reads \( W_T \equiv 0.7 \mu\text{m}. \))

The above \( W_T \) is indeed consistent with the positioning of the end of the approximate charge distribution (the dashed-line distribution) in Fig. 16.8(c).
16.3

The required $W_T$ versus doping plot appropriate for GaAs and the MATLAB program script that generated the plot are reproduced below.

MATLAB program script...

%WT versus NA or ND for GaAs at 300K
%Initialization
clear; close;

%Constants and parameters
q=1.6e-19;
e0=8.85e-14;
ni=2.25e6;
KS=12.85;
kT=0.0259;
NB=logspace(14,18); %NB = NA or ND

%WT calculation
EF=kT.*log(NB./ni);
WT=sqrt(4*KS*e0.*EF./(q.*NB));
WT=(1.0e4).*WT; %WT in micrometers

%Plotting result
loglog(NB,WT); grid
xlabel('NA or ND (cm^-3)');
ylabel('WT (micrometers)');
text(1.0e17,2.3,'GaAs, 300K')
16.4
(a) \[
\frac{\phi_F}{kT/q} = -\ln \left( \frac{N_D/n_i}{10^{10}} \right) = -11.51
\]
\[
\phi_F = -11.51 \ (kT/q) = -(11.51)(0.0259) = -0.298 \text{V}
\]
(b) Using Eq.(16.16) with \(N_A \rightarrow -N_D\),
\[
W = W_T = \left[ \frac{2K_S \varepsilon_0}{-qN_D} (2\phi_F) \right]^{1/2} = \left[ \frac{(2)(11.8)(8.85 \times 10^{-14})(2)(0.298)}{(1.6 \times 10^{-19})(10^{15})} \right]^{1/2} = 0.882 \mu \text{m}
\]
(c) Evaluating Eq.(16.12) at \(x = 0\) yields \(E_S\). Thus, with \(N_A \rightarrow -N_D\) in Eq. (16.12),
\[
E_S = -\frac{qN_D}{K_S \varepsilon_0} W = -\frac{(1.6 \times 10^{-19})(10^{15})(0.882 \times 10^{-4})}{(11.8)(8.85 \times 10^{-14})} = -1.35 \times 10^4 \text{ V/cm}
\]
(d) Substituting into Eq.(16.26) gives
\[
V_G = 2\phi_F + \frac{K_S}{K_O} x_0 E_S \quad \ldots E_S \text{ evaluated at } \phi_S = 2\phi_F
\]
\[
= -(2)(0.298) - \frac{(11.8)(10^{-5})(1.35 \times 10^4)}{3.9}
\]
\[
= -1.00 \text{ V}
\]
Except for the doping type, the parameters used in this problem are identical to those assumed in constructing Fig. 16.10. Since \(\phi_S = 2\phi_F\), the \(|V_G|\) calculated in part (d) should correspond to the depletion/inversion transition point in Fig. 16.10. Indeed, in the figure \(V_T \equiv 1 \text{V}\).

(e) The MATLAB program script yielding a computer generated computation of \(\phi_F\), \(W\), \(E_S\), and \(V_G\) is listed on the next page and included on the Instructor's disk as m-file P_16_04.m. Note that a normalized \(\phi_S\), \(\phi_S/2\phi_F\), is taken to be one of the input variables. Also, donor dopings must be input as a negative concentration in running the program.
MATLAB program script...

```matlab
%Autocalculation of $\phi_F$, $W$, $ES$ and $VG$
%Initialization
clear; close;
format compact

%Constants and parameters
q=1.6e-19;
e0=8.85e-14;
ni=1.0e10;
KS=11.8;
KO=3.9;
kT=0.0259;

%Input variables
xo=input('Please input xo in cm, xo = ');
N=input('Please input NA or -ND in cm^-3, N = ');
r=input('Please input $\phi_S/2\phi_F$, $\phi_S/2\phi_F = ');
NB=abs(N); s=N/NB;

%$\phi_F$ and $WT$ calculation
$\phi_F=s*kT*log(NB/n1)$
$\phi_S=r*2*\phi_F$;
$W_0=sqrt(2*KS*e0*\phi_S/(q*N))$; %$W_0$ in cm
$W=(1.8e4)*W_0$ %$W$ in micrometers

%Surface Electric Field ($ES$) calculation
$ES=(q*N*W0)/(KS*e0)$

%$VG$ calculation
$VG=\phi_S+KS*xo*ES/KO$
```

16.5
(a) In general we can write

Also $V_G = \phi_S + \frac{KS}{KO} x_0 E_S$ ...Eq.(16.26)

$\phi_S = \frac{kT}{q} U_S$ ...Eq.(B.2)

and Eq.(B.16) evaluated at the surface gives

$E_S = \frac{\tilde{U}_S}{q} \frac{kT F(U_S,U_F)}{L_D}$

Substituting the above $\phi_S$ and $E_S$ expressions into the general $V_G-\phi_S$ relationship yields the desired result;

16 - 5
\[ V_G = \frac{kT}{q} \left[ U_S + \hat{U}_S \frac{K_{sxo}}{K_{OLD}} F(U_S,U_F) \right] \]

(b) The required \( V_G \) versus \( U_S \) computation is performed by the MATLAB m-file listed below. Setting \( x = 0.1 \mu m \) and \( N_D = 10^{15}/cm^2 \) yields a plot identical to Fig. 16.10 except the entire plot is reflected through the origin of coordinates.

MATLAB program script...

```matlab
% VG versus US Calculation

% Initialization
clear; close
format compact

% Universal and System Constants
q=1.60e-19;
e0=8.85e-14;
kT=0.0259;

% Device and Material Constants
KS=11.8;
KO=3.9;
ni=1.00e10;
LD=sqrt((KS*e0*kT)/(2*q*ni));
s=input('Employ xo=1.0e-5cm and ND=1.0e15/cm3? 1-Yes, 2-No...');
   if s==1
      Net=1.0e15;
      xo=1.0e-5;
   else
      Net=input('Input the net semi doping in cm^-3, ND-NA = ');
      xo=input('Input the oxide thickness in cm, xo = ');
   end
N=abs(Net); sign=-Net/N;
UF=sign*log(N/ni);

% Computation Proper
US=UF-21.1:UF+21;
S=US./abs(US);
F=sqrt(exp(UF).*exp(-US)+US-1)+exp(-UF).*exp(US-US-1));
VG=kT*(US+S*(KS*xo)/(KO*LD).*F);

% Plot result
plot(US,VG); grid
   if s==1
      axis([-40, 10, -4, 4]);
   end
   xlabel('US'); ylabel('VG (volts)');
```

16-6
16.6

(a) Eq.(16.28) may be viewed as a quadratic equation with $\sqrt{\phi_S}$ as the variable.

$$\left(\sqrt{\phi_S}\right)^2 + \frac{K_S}{K_O} x_0 \sqrt{\frac{2qN_A}{K_S\varepsilon_0}} \sqrt{\phi_S} - V_G = 0$$

Introducing

$$b = \frac{K_S}{K_O} x_0 \sqrt{\frac{2qN_A}{K_S\varepsilon_0}}$$

and choosing the (+) root solution so that $\sqrt{\phi_S} > 0$, one obtains,

$$\sqrt{\phi_S} = -\frac{b}{2} + \left(\frac{b}{2}\right)^2 + V_G \right)^{1/2} = \frac{b}{2} \left[1 + \frac{V_G}{(b/2)^2}\right]^{1/2} - 1$$

or

$$\sqrt{\phi_S} = \left(\frac{K_S}{K_O} x_0 \sqrt{\frac{qN_A}{2K_S\varepsilon_0}}\right) \left[1 + \frac{V_G}{(b/2)^2}\right]^{1/2} - 1$$

Substituting the $\sqrt{\phi_S}$ result into Eq.(16.15) then yields

$$W = \frac{K_S x_0}{K_O} \left[\sqrt{1 + \frac{V_G}{V_\delta}} - 1\right]$$

if

$$V_\delta = \left(\frac{b}{2}\right)^2 = \frac{q}{2} \frac{K_S x_0^2}{K_O \varepsilon_0} N_A$$

We have indeed obtained the text result.

(b) (i) $\phi_T = -\frac{kT}{q} \ln(N_D/n_i) = -(0.0259) \ln\left[\frac{10^{15}}{10^{10}}\right] = -0.298V$

$$W_T = \left[\frac{2K_S \varepsilon_0}{-qN_D}(2\phi_T)\right]^{1/2} = \left[\frac{(2)(11.8)(8.85 \times 10^{-14})(2)(0.298)}{(1.6 \times 10^{-19})(10^{15})}\right]^{1/2} = 0.882 \mu m$$

(From Fig. 16.9 with $N_D = 10^{15}/cm^3$ one would estimate $W_T \approx 0.9 \mu m$.)

16 - 7
(ii) From Eq.(16.34d),

\[ \frac{C}{C_0} = \frac{1}{1 + \frac{K_0 W_T}{K_S x_0}} \quad \ldots \text{inv}(\omega \to \infty) \]

\[ = \frac{1}{1 + \frac{(3.9)(0.882)}{(11.8)(0.1)}} = 0.255 \]

(iii) Some care must be exercised in working this part of the problem. An acceptable approach is to proceed as in Problem 16.4, first calculating \( E_S \) using Eq.(16.12) and then substituting into Eq.(16.26). In fact, the parameters are the same as in Prob. 16.4 and thus the expected answer is \( V_T = -1.00 \text{V} \). Alternatively, one might consider substituting into Eq.(16.28) directly; \( V_G = V_T \) when \( \phi_S = 2\phi_F \). However, Eq.(16.28) is only valid for \( p \)-type devices and simply changing \( N_A \) to \( -N_D \) will not yield the correct \( V_T \). [For an \( n \)-type device the "+" between the two right-hand terms in Eq.(16.28) is replaced with a "-" sign.] Nevertheless, Eq.(16.28) can be used if we first act as if the doping was \( p \)-type, and then just change the sign of the result noting the voltage symmetry between ideal \( n \)- and \( p \)-type devices.

\[ V_T = -\left[ \frac{K_S}{K_O} x_0 \sqrt{\frac{2qN_A}{K_S e_0}} (2\phi_F) \right] \quad (\phi_F > 0) \]

\[ = -\left\{ (2)(0.298) + \frac{(11.8)(10^{-5})}{3.9} \left[ \frac{(2)(1.6\times10^{-19})(10^{15})(2)(0.298)}{(11.8)(8.85\times10^{-14})} \right]^{1/2} \right\} \]

\[ = -1.00 \text{ V} \leftarrow \text{expected result} \]

(iv) The parameters used in this problem are identical to those assumed in constructing Fig. 16.13. Thus the part (ii) \( C/C_0 \) value should correspond to the high-frequency inversion value on the figure and the \( V_T \) calculated in part (iii) should be the depletion/inversion transition voltage shown in the figure. This is indeed the case.
16.7
(a) $\phi$ has the same shape as the "upside down" of the bands.

![Diagram of potential energy profile]

(b) $E$ is proportional to the slope of the bands. Also, as emphasized in a footnote on p. 581, $E_{ox} \equiv 3E_S$ in an ideal MOS-C.

![Diagram of electric field profile]

(c) **Yes.** Inside the semiconductor $E_F$ is position independent.

(d) Noting \[ n = n_i e^{(E_F - E_i)/kT} \]
we conclude

![Graph of ln(n) vs. x]

(e) Since $E_F = E_i$ at the Si–SiO$_2$ interface, \[ n|_{x=0} = n_i = 10^{10}/\text{cm}^3 \].

(f) \[ N_D \equiv n_{bulk} = n_i e^{(E_F - E_i(\text{bulk}))/kT} = (10^{10}) e^{0.29/0.0259} = 7.29 \times 10^{14}/\text{cm}^3 \]

(g) \[ \phi_S = (1/q)[E_i(\text{bulk}) - E_i(\text{surface})] = -0.29 \text{ V} \]
(h) Some care must be exercised in completing this part of the problem. Simply employing Eq. (16.28) with \( N_A \) replaced by \( -N_D \) yields an incorrect result because \( \xi_S < 0 \) when an \( n \)-bulk MOS-C is depletion biased. Specifically, for an \( n \)-bulk device

\[
\xi_S = - \left[ \frac{2qN_D}{K_S\varepsilon_0} (-\phi_S) \right]^{1/2}
\]

and

\[
V_G = \phi_S - \frac{K_S x_0}{K_O} \sqrt{\frac{2qN_D}{K_S\varepsilon_0} (-\phi_S)}
\]

Thus here

\[
V_G = -0.29 - \frac{(11.8)(2\times10^{-5})}{(3.9)} \left[ \frac{(2)(1.6\times10^{-19})(7.29\times10^{14})}{(11.8)(8.85\times10^{14})} (0.29) \right]^{1/2}
\]

or

\[
V_G = -0.78 \text{ V}
\]

(i) \( V_G = \Delta \phi_{ox} + \phi_S \)

\[
\Delta \phi_{ox} = V_G - \phi_S = -0.78 + 0.29 = -0.49 \text{ V}
\]

(j) \( V_\delta = -\frac{q}{2} \frac{K_S x_0^2}{K_O^2 \varepsilon_0} N_D = - \frac{(1.6\times10^{-19})(11.8)(2\times10^{-5})^2(7.29\times10^{14})}{(3.9)^2(8.85\times10^{14})} = 0.2045 \text{ V} \)

\[
\frac{C}{C_O} = \frac{1}{1 + V_G/V_\delta} = \frac{1}{1 + 0.78/0.20} = 0.45
\]

(Eqs. 16.15 and 16.34b may alternatively be used to compute \( C/C_O \).)

16.8

Inversion \( \ldots \) e, 4

Depletion \( \ldots \) c, 3

Flat band \( \ldots \) b, 1

\( V_G = V_T \) \( \ldots \) d, 2

Accumulation \( \ldots \) a, 5
(a) [Yes]. The Fermi level inside the semiconductor is position independent.

(b) \( \phi_F = (1/q)[E_i(\text{bulk}) - E_F] = 0.3 \text{ V} \)

(c) \( \phi_S = (1/q)[E_i(\text{bulk}) - E_i(\text{surface})] = \phi_F = 0.3 \text{ V} \)

(d) \( E_F(\text{metal}) - E_F(\text{semi}) = -qV_G \quad \text{Eq. (2.1)} \)
\[ V_G = (1/q)[E_F(\text{semi}) - E_F(\text{metal})] = 0.6 \text{ V} \]

(e) Based on the delta-depletion approximation,
\[ V_G = \phi_S + \frac{K_S x_0}{K_0} \sqrt{2qN_A} \frac{\phi_S}{K_S \varepsilon_0} \quad \text{Eq.(16.28)} \]

where from prior parts of the problem \( V_G = 0.6 \text{V} \) and \( \phi_S = 0.3 \text{V} \). Also,
\[ \phi_F = (kT/q) \ln(N_A/n_i) \]
or
\[ N_A = n_i e^{\phi_F/(kT/q)} = (10^{10})e^{0.3/0.0259} = 1.073 \times 10^{15}/\text{cm}^3 \]

Thus
\[ x_0 = \frac{V_G - \phi_S}{K_S \sqrt{2qN_A} \phi_S} = \frac{0.6 - 0.3}{(11.8)^{3.9}} \left[ \frac{(2)(1.6 \times 10^{-19})(1.073 \times 10^{15})(0.3)}{(11.8)(8.85 \times 10^{-14})} \right]^{1/2} \]

(f) 

\[ W = \frac{W_T}{\sqrt{2}} \]

16-11
(h) Expressions (i) and (iv) are clearly wrong because they do not apply to depletion. Employing Eq. (16.28), we conclude $V_T \approx 1V$ and $V_G \approx 0.6V_T$. Thus referring to Eq. (16.37), expression (ii) is close but not the correct expression. Finally, noting that at the specified bias point,

$$\phi_S = \phi_F \quad \text{and} \quad W = \left[ \frac{2K_S \phi_0}{qN_A} \phi_F \right]^{1/2} = W_{\text{TNA}}$$

we conclude

$$C = \frac{C_O}{1 + \frac{K_Q W}{K_S x_0}} = \frac{C_O}{1 + \frac{K_Q W_T}{\sqrt{2K_S x_0}}} \quad \Rightarrow \text{Expression (iii)}$$
16.10

(a)

(b)

(c)

Justification: When $V_G > 0$, electrons pile-up in the Si immediately adjacent to the oxide giving rise to a low-frequency $C = C_O$. Similarly, when $V_G < 0$, holes pile-up in the Si immediately adjacent to the oxide giving rise to a low-frequency $C = C_O$. (Actually, $C \equiv C_O$, but in the delta-depletion formulation the carrier layers are taken to be δ-functions at the Si surface.) Note that, within the framework of the delta-depletion formulation, there is no "depletion" or depletion-like region inside the given device.
(i) $V_G = 0$

(ii) $V_G > 0$ but small

(iii) $V_G > 0$ and large

(iv) $V_G < 0$ but small — (ii) answer with semiconductor regions interchanged.

(v) $V_G < 0$ and large — (iii) answer with semiconductor regions interchanged.
16.12

(a) [Curves a and b] are standard low- and high-frequency $C$-$V$ curves that result when the semiconductor component of the MOS-C is in equilibrium under d.c. biasing conditions. Curve c is a nonequilibrium deep-depletion characteristic.

(b) In accumulation $C \rightarrow C_0 = K_0 \varepsilon_0 A_G / x_0$. Since both devices exhibit the same capacitance in accumulation, the two devices have the same oxide thickness. With $x_0$ being the same, the lower capacitance of device b in inversion indicates this device has a lower doping. ($W_T$ increases with decreasing doping, thereby giving rise to a smaller capacitance; also see Fig. 16.14b.)

16.13

(a) [p-type] ...For p-type devices accumulation ($C_{\text{max}}$) occurs for negative $V_G$ and inversion ($C_{\text{min}}$) occurs at positive $V_G$. The exact opposite is true for n-type devices.

(b) At point (2) the p-type MOS-C is far into inversion. Thus

(c) At point (1) the MOS-C is clearly deep into accumulation.
(d) From Fig. P16.13, \( C_{\text{max}} = 100\, \text{pF} \). However,
\[
C_{\text{max}} = C_O = \frac{K_O \varepsilon_0 AG}{x_o}
\]
\[
x_o = \frac{K_O \varepsilon_0 AG}{C_{\text{max}}} = \frac{(3.9)(8.85 \times 10^{-14})(3 \times 10^{-3})}{(10^{-10})} = 0.104 \, \mu\text{m}
\]

(c) In the delta-depletion formulation
\[
C = \frac{C_O}{1 + \frac{K_O W_T}{K_S x_o}} \quad \text{inv (} \omega \to \infty \text{)}
\]

Thus
\[
W_T = \frac{K_S x_o}{K_O} \left( \frac{C_O}{C} - 1 \right) = \frac{(11.8)(0.104)}{(3.9)} \left( \frac{100}{20} - 1 \right) = 1.26 \, \mu\text{m}
\]

Employing Fig. 16.9, we conclude \( N_A \equiv 5 \times 10^{14}/\text{cm}^3 \).

16.14
(a)

\[
\begin{array}{c}
\text{C} \\
\downarrow \\
V_G
\end{array}
\]

(b) \( C_{\text{MAX}} = C_O = \frac{K_O \varepsilon_0 AG}{x_o} = \frac{(3.9)(8.85 \times 10^{-14})(10^{-3})}{10^{-5}} = 34.5 \, \text{pF} \)

(c) \( \phi_F = -(kT/q) \ln(N_D/n_i) = -0.0259 \ln(2 \times 10^{15}/10^{10}) = -0.316 \)

\[
W_T = \left[ \frac{2K_S \varepsilon_0}{qN_D} (-2\phi_F) \right]^{1/2} = \left[ \frac{(2)(11.8)(8.85 \times 10^{-14})(2)(0.316)}{(1.6 \times 10^{-19})(2 \times 10^{15})} \right]^{1/2} = 6.42 \times 10^{-5} \, \text{cm}
\]
\[ C_{\text{MIN}} = \frac{C_O}{1 + \frac{K_O W_T}{K_S x_0}} = \frac{34.5}{1 + \frac{(3.9)(6.42 \times 10^{-5})}{(11.8)(10^{-5})}} = 11.1 \text{ pF} \]

(d) By definition, if \( V_G = V_T \ldots \phi_S = 2\phi_F = -0.632 \text{ V} \)

(e) \[ V_T = (2\phi_F) - \frac{K_S x_0}{K_O} \sqrt{\frac{2qND}{K_S \epsilon_0} (-2\phi_F)} \] (Also see Prob. 16.7h.)

\[ = -2(0.316) - \frac{(11.8)(10^{-5})}{(3.9)} \left[ \frac{(2)(1.6 \times 10^{-19})(2 \times 10^{15})(0.632)}{(11.8)(8.85 \times 10^{-14})} \right]^{1/2} = 1.23 \text{ V} \]

(f)

(g) \( |\phi_S| = |5\phi_F/2| > |2\phi_F| \) and the MOS-C is therefore inversion biased with \( W = W_T \).

(h) Under the specified operating conditions, the MOS-C is expected to exhibit a total deep-depletion characteristic exemplified by the dashed line in the part (a) answer.
16.15

(a) [p-type] ...There is an inversion-layer of negative charge — electrons — shown in the block charge diagram. The semiconductor must therefore be p-type. (Also, the depletion-region charge is negative or clearly due to acceptor ions.)

(b) [Inversion biased] ...As noted in part (a), there is an inversion layer with \( n_s > N_A \) shown on the diagram.

(c)

(d)

-\( \Delta Q \) due to ac signal at high-frequency
NOTE: Because the added depletion-layer charge is farther from the surface than the inversion layer charge, there is NOT a one-to-one correspondence between the two charges. Also, the charge on the metal will be slightly different than under equilibrium inversion conditions at the same $V_G$ bias.
16.16
The MATLAB program script yielding deep-depletion p-type MOS-C C–V characteristics and a sample plot (\(x_0 = 0.2 \mu m\), \(N_A = 7.8 \times 10^{14}/cm^3\)) are reproduced below. Note that the sample plot has been extended to \(V_G = 5V_T\) (as opposed to stopping at \(V_G = 3V_T\) per the directions in the first printing of the book). If the sample C–V curve is converted to an \(n\)-type characteristic AND translated approximately 2V along the voltage axis in the negative direction, the sample plot becomes a very good match to the experimental total-deep-depletion data displayed in Fig. 16.17.

MATLAB program script...

```matlab
% p-type Deep Depletion MOS-C C-V Characteristics
% Initialization and Input
clear; close
format compact

NA=input('Please input the bulk doping in /cm3, NA=');
xo=input('Please input the oxide thickness in cm, xo=');

% Constants and Parameters
e0=8.85e-14;
qu=1.6e-19;
k=8.617e-5;
KS=11.8;
KO=3.9;
ni=1.0e10;
T=300;
kT=k*T;

% Computed Constants
UF=log(NA/ni);
LD=sqrt((kT*KS*e0)/(2*q*ni));

% C-V Computation for US < UF (or VG < VI)
US=UF-21.0:0.5:UF;
F=sqrt(exp(UF).*exp(-US)+US-1)+exp(-UF).*exp(UF-US-1));
VGL=kT*(US./abs(US)).*(KS*xo)/(KO*LD).*F);
DENOM1=exp(UF).*exp(-US)+exp(UF-1).*exp(UF-1);
W1=(US./abs(US)).*LD.*(2*F)./DENOM1;
c1=1.0./(1+(KO*W1)./(KS*xo));

% C-V Computation for US > UF (or VI < VG < 5VT)
FI=sqrt(exp(UF).*exp(-UF)+UF-1)+exp(-UF).*exp(UF-UF-1));
VI=kT*(US+(KS*xo)/(KO*LD).*FI);
\( \phi_F = k_T * UF \);
\( VT = 2 * \phi_F + (KS * xo / KO) * sqrt((4 * q * NA * \phi_F) / (KS * e0)) \);
Vdelta=(qu/2)*(KS*xo^2*NA)/(KO^2*e0);
VG2=VI+0.1:0.1:5*VT;
c2=1./sqrt(1+VG2./Vdelta);
```
% Combining and Plotting results

c=[c1,c2];
VG=[VG1,VG2];
plot(VG,c); grid
axis([-3*VT,5*VT,0,1.1])
xlabel('VG (volts)'); ylabel('C/CO')
16.17

(a) 
\[ C_0 = \frac{K_0 e_0 A_G}{x_0} \quad \Rightarrow \quad x_0 = \frac{K_0 e_0 A_G}{C_0} \]
\[ x_0 = \frac{(3.9)(8.85 \times 10^{-14})(4.75 \times 10^{-3})}{82 \times 10^{-12}} = 0.200 \mu m \]

(b) From Fig. 16.17, \( C/C_0(\text{inv}) \approx 0.39. \)

\[ C(\text{inv}) = \frac{C_0}{1 + \frac{K_0 W_{\text{eff}}(\text{inv})}{K_S x_0}} \]
\[ W_{\text{eff}}(\text{inv}) = \frac{K_S x_0}{K_0} \left[ \frac{C_0}{C(\text{inv})} - 1 \right] = \frac{(11.8)(0.2)}{(3.9)} \left( \frac{1}{0.39} - 1 \right) \]
\[ = 0.946 \mu m \]

and
\[ \frac{W_{\text{eff}}(\text{inv})}{L_D} = \frac{9.46 \times 10^{-5}}{2.91 \times 10^{-3}} = 3.25 \times 10^{-2} \]

(c) If \( W_{\text{eff}}(\text{inv}) \) is equated to \( W_T \), one estimates from Fig. 16.9 that \( N_D \equiv 8.5 \times 10^{14}/\text{cm}^3 \) or \( U_F = -\ln(N_D/n_i) = -\ln(8.5 \times 10^{14}/1.00 \times 10^{10}) = -11.35 \). Substituting \( U_F = -11.35 \) into the expression for \( W_{\text{eff}}/L_D \) one computes \( W_{\text{eff}}/L_D = 3.374 \times 10^{-2} \). \( W_{\text{eff}}/L_D \) is too large implying \( N_D \) and \( U_F \) are somewhat larger. Trying \( U_F = -11.45 \) yields \( W_{\text{eff}}/L_D = 3.223 \times 10^{-2} \); trying \( U_F = -11.40 \) yields \( W_{\text{eff}}/L_D = 3.298 \times 10^{-2} \). Clearly \( U_F \) is bracketed between \(-11.40 \) and \(-11.45 \). Subsequent calculations give \( W_{\text{eff}}/L_D = 3.268 \times 10^{-2}, \ 3.253 \times 10^{-2}, \ 3.238 \times 10^{-2} \) when \( U_F = -11.42, -11.43, \) and \(-11.44, \) respectively. The best value appears to be

\[ U_F = -11.43 \quad \text{and} \quad N_D = n_i e^{-U_F} = (10^{10}) e^{11.43} = 9.20 \times 10^{14}/\text{cm}^3 \]

NOTE: We actually pushed the calculation here beyond the accuracy of the data to illustrate the procedure.