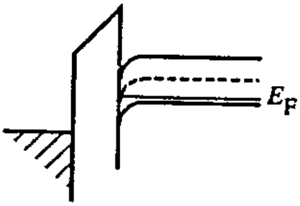
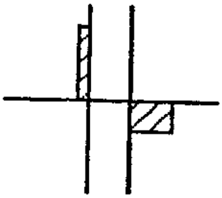
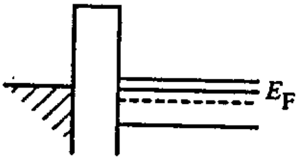
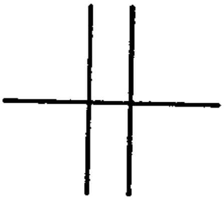
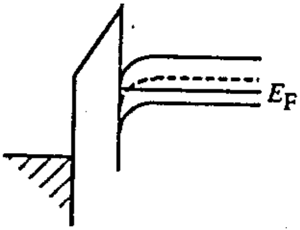
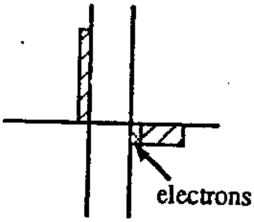
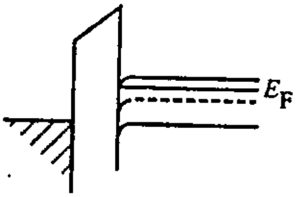
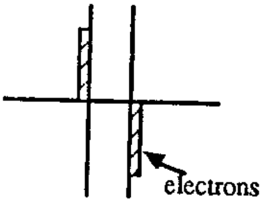
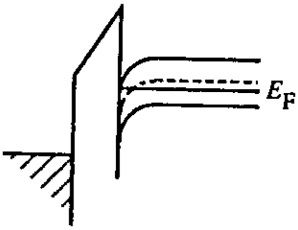
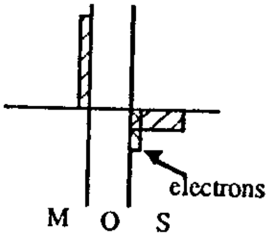
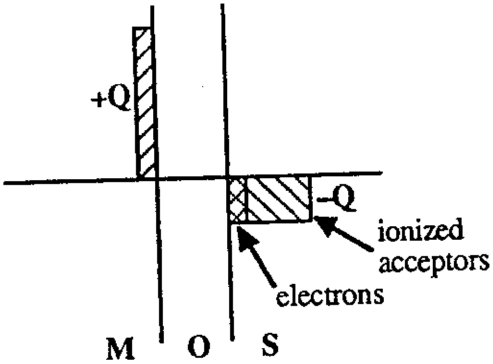
CHAPTER 16

16.1

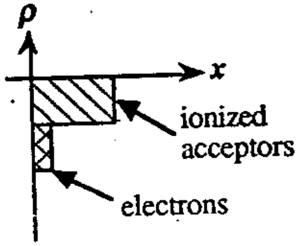
Part	Doping	Biasing Condition	Energy Band Diagram	Block Charge Diagram
(a)	p	depletion		
(b)	n	flat band		
(c)	p	depl/inv transition		
(d)	n	accumulation		
(e)	p	inversion		

16.2

(a)



(b) The part (a) charge diagram is in agreement with the ρ/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).



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 $n_{surface} = N_A$. Thus, at the special V_T bias point $\rho_S = -q(n_{surface} + N_A) = -2qN_A$, 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

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

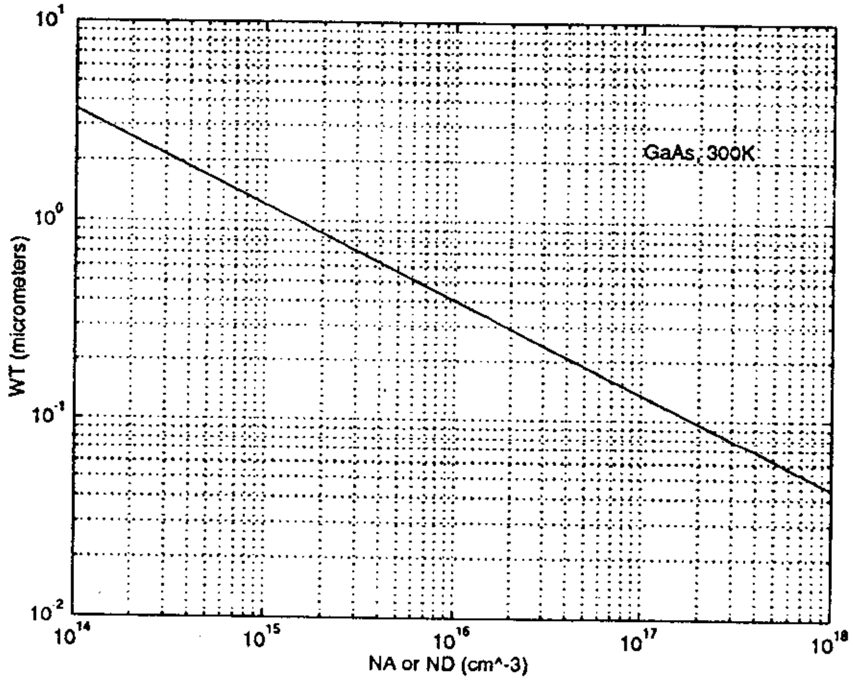
$$W_T = \left[\frac{2K_S\varepsilon_0}{qN_A}(2\phi_F)\right]^{1/2} = \left[\frac{(2)(11.8)(8.85\times10^{-14})(24)(0.0259)}{(1.6\times10^{-19})(1.63\times10^{15})}\right]^{1/2} = \mathbf{0.706\mu m}$$

(From Fig. 16.9 one also reads $W_T \cong 0.7\mu$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
øF=kT.*log(NB./ni);
WT=sqrt(4*KS*e0.*øF./(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)

$$\frac{\phi_F}{kT/q} = -\ln(N_D/n_i) = -\ln\left(\frac{10^{15}}{10^{10}}\right) = -11.51$$

$$\phi_F = -11.51\,(kT/q) = -(11.51)(0.0259) = \mathbf{-0.298V}$$

(b) Using Eq.(16.16) with $N_A \rightarrow -N_D$,

$$W = W_T = \left[\frac{2K_S\varepsilon_0}{-qN_D}(2\phi_F)\right]^{1/2} = \left[\frac{(2)(11.8)(8.85\times10^{-14})(2)(0.298)}{(1.6\times10^{-19})(10^{15})}\right]^{1/2} = \mathbf{0.882\mu m}$$

(c) Evaluating Eq.(16.12) at $x = 0$ yields $\mathcal{E}_S$. Thus, with $N_A \rightarrow -N_D$ in Eq. (16.12),

$$\mathcal{E}_S = -\frac{qN_D}{K_S\varepsilon_0}W = -\frac{(1.6\times10^{-19})(10^{15})(0.882\times10^{-4})}{(11.8)(8.85\times10^{-14})} = \mathbf{-1.35\times10^4\ V/cm}$$

(d) Substituting into Eq.(16.26) gives

$$V_G = 2\phi_F + \frac{K_S}{K_O}x_o\mathcal{E}_S \qquad \text{...}\mathcal{E}_S \text{ evaluated at } \phi_S = 2\phi_F$$

$$= -(2)(0.298) - \frac{(11.8)(10^{-5})(1.35\times10^4)}{3.9}$$

$$= \mathbf{-1.00\ V}$$

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 $V_T \cong 1$V.

(e) The MATLAB program script yielding a computer generated computation of ϕ_F, W, $\mathcal{E}_S$, 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 ϕ_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...

```
%Autocalculation of øF, 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 øS/2øF, øS/2øF = ');
NB=abs(N);   s=N/NB;

%øF and WT calculation
øF=s*kT*log(NB/ni)
øS=r*2*øF;
W0=sqrt(2*KS*e0*øS/(q*N));   %W0 in cm
W=(1.0e4)*W0  %W in micrometers

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

%VG calculation
VG=øS+KS*xo*ES/KO
```

16.5

(a) In general we can write

Also $$V_G = \phi_S + \frac{K_S}{K_O} x_o \mathcal{E}_S \qquad \text{...Eq.(16.26)}$$

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

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

$$\mathcal{E}_S = \hat{U}_S \frac{kT}{q} \frac{F(U_S,U_F)}{L_D}$$

Substituting the above ϕ_S and $\mathcal{E}_S$ expressions into the general V_G–ϕ_S relationship yields the desired result;

$$V_G = \frac{kT}{q}\left[U_S + \hat{U}_S \frac{K_S x_o}{K_O L_D} F(U_S,U_F)\right]$$

(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 $N_D = 10^{15}/cm^3$ yields a plot identical to Fig. 16.10 except the entire plot is reflected through the origin of coordinates.

MATLAB program script...

```
%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

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

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

Introducing

$$b \equiv \frac{K_S}{K_O} x_o \sqrt{\frac{2qN_A}{K_S\varepsilon_0}}$$

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

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

or

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

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

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

if

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

We have indeed obtained the text result.

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

$$W_T = \left[\frac{2K_S\varepsilon_0}{-qN_D}(2\phi_F)\right]^{1/2} = \left[\frac{(2)(11.8)(8.85\times10^{-14})(2)(0.298)}{(1.6\times10^{-19})(10^{15})}\right]^{1/2} = \mathbf{0.882\mu m}$$

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

(ii) From Eq.(16.34d),

$$\frac{C}{C_O} = \frac{1}{1+\frac{K_O W_T}{K_S x_o}} \qquad \text{...inv}(\omega \to \infty)$$

$$= \frac{1}{1+\frac{(3.9)(0.882)}{(11.8)(0.1)}} = \mathbf{0.255}$$

(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 $\mathcal{E}_S$ 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 $V_T = -1.00$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.

$$V_T = -\left[(2\phi_F) + \frac{K_S}{K_O} x_o \sqrt{\frac{2qN_A}{K_S \varepsilon_0}(2\phi_F)}\,\right] \qquad (\phi_F > 0)$$

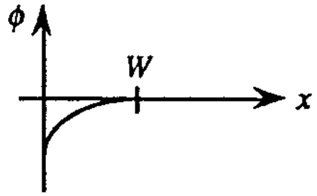
$$= -\left\{(2)(0.298) + \frac{(11.8)(10^{-5})}{3.9}\left[\frac{(2)(1.6\times10^{-19})(10^{15})(2)(0.298)}{(11.8)(8.85\times10^{-14})}\right]^{1/2}\right\}$$

$$= -1.00 \text{ V} \leftarrow \text{expected result}$$

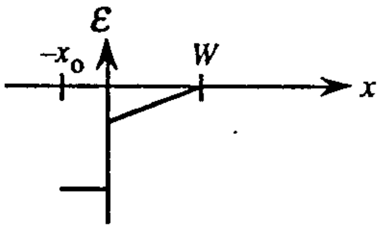
(iv) The parameters used in this problem are identical to those assumed in constructing Fig. 16.13. Thus the part (ii) C/C_O value should correspond to the high-frequency inversion value on the figure and the V_T calculated in part (iii) should be the depletion/inversion transition voltage shown in the figure. This is indeed the case.

16.7

(a) ϕ has the same shape as the "upside down" of the bands.



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

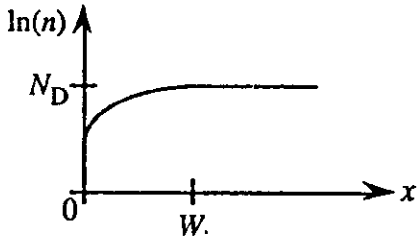


(c) $\boxed{\text{Yes}}$. *Inside the semiconductor* E_F is position independent.

(d) Noting

$$n = n_i e^{(E_F - E_i)/kT}$$

we conclude



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

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

(g) $\phi_S = (1/q)[E_i(\text{bulk}) - E_i(\text{surface})] = \mathbf{-0.29\ V}$

(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 $\mathcal{E}_S < 0$ when an n-bulk MOS-C is depletion biased. Specifically, for an n-bulk device

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

and

$$V_G = \phi_S - \frac{K_S x_o}{K_O}\sqrt{\frac{2qN_D}{K_S\varepsilon_0}(-\phi_S)}$$

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

$$V_G = \mathbf{-0.78\ V}$$

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

$$\Delta\phi_{ox} = V_G - \phi_S = -0.78 + 0.29 = \mathbf{-0.49\ V}$$

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

$$\frac{C}{C_O} = \frac{1}{\sqrt{1+V_G/V_\delta}} \cong \frac{1}{\sqrt{1+0.78/0.20}} = \mathbf{0.45}$$

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

<u>16.8</u>

Inversion	. . . e, 4
Depletion	. . . c, 3
Flat band	. . . b, 1
$V_G = V_T$	. . . d, 2
Accumulation	. . . a, 5

16.9

(a) $\boxed{\text{Yes}}$. The Fermi level *inside the semiconductor* is position independent.

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

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

(d)... $E_F(\text{metal}) - E_F(\text{semi}) = -qV_G$ ...Eq. (2.1)

$V_G = (1/q)[E_F(\text{semi}) - E_F(\text{metal})] = \mathbf{0.6\ V}$

(e) Based on the delta-depletion approximation,

$$V_G = \phi_S + \frac{K_S x_o}{K_O}\sqrt{\frac{2qN_A}{K_S\varepsilon_0}\phi_S} \qquad \Leftarrow \text{Eq.(16.28)}$$

where from prior parts of the problem $V_G = 0.6\text{V}$ and $\phi_S = 0.3\text{V}$. Also,

$$\phi_F = (kT/q)\ln(N_A/n_i)$$

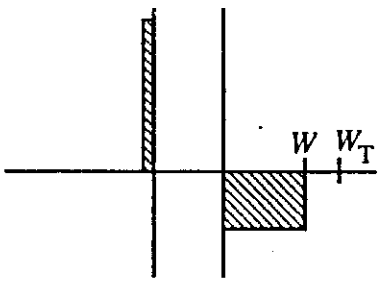
or

$$N_A = n_i e^{\phi_F/(kT/q)} = (10^{10})e^{0.3/0.0259} = 1.073\times10^{15}/\text{cm}^3$$

Thus

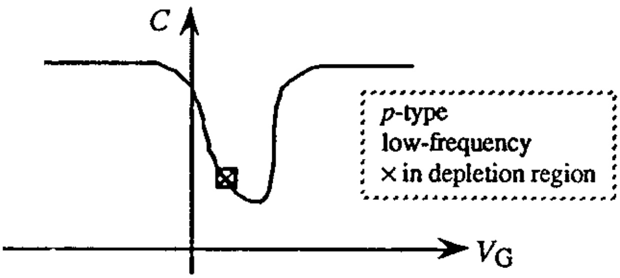
$$x_o = \frac{V_G - \phi_S}{\frac{K_S}{K_O}\sqrt{\frac{2qN_A}{K_S\varepsilon_0}\phi_S}} = \frac{0.6-0.3}{\left(\frac{11.8}{3.9}\right)\left[\frac{(2)(1.6\times10^{-19})(1.073\times10^{15})(0.3)}{(11.8)(8.85\times10^{-14})}\right]^{1/2}} = \mathbf{0.10\mu m}$$

(f)



$$\left(W = \frac{W_T}{\sqrt{2}}\right)$$

(g)



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

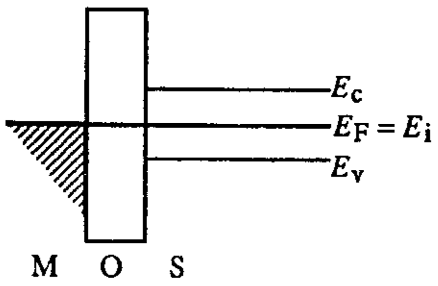
$$\phi_S = \phi_F \quad \text{and} \quad W = \left[\frac{2K_S\varepsilon_0}{qN_A}\phi_F\right]^{1/2} = W_T/\sqrt{2}$$

we conclude

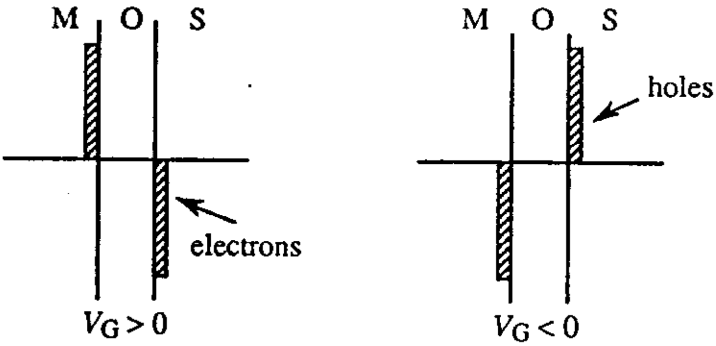
$$C = \frac{C_O}{1+\dfrac{K_O W}{K_S x_o}} = \frac{C_O}{1+\dfrac{K_O W_T}{\sqrt{2}K_S x_o}} \qquad \Leftarrow \boxed{\text{Expression (iii)}}$$

16.10

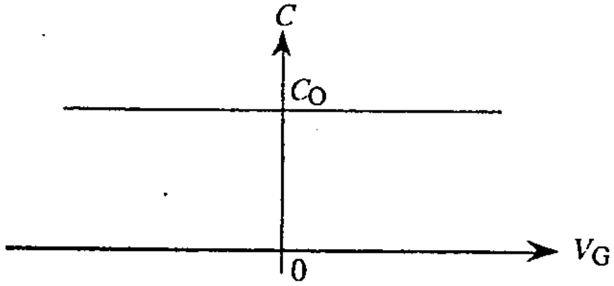
(a)



(b)



(c)

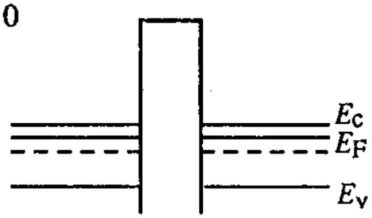


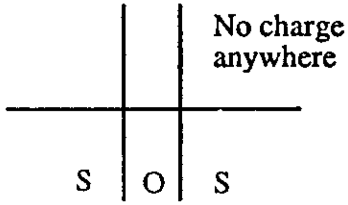
Justification: When $V_G > 0$, electrons pile-up in the Si immediately adjacent to the oxide giving rise to a low-frequency $C = C_O$. Similarly, when $V_G < 0$, holes pile-up in the Si immediately adjacent to the oxide giving rise to a low-frequency $C = C_O$. (Actually, $C \cong C_O$, but in the delta-depletion 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.

16.11

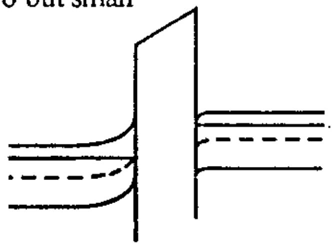
Part (a) ↓ Part (b) ↓

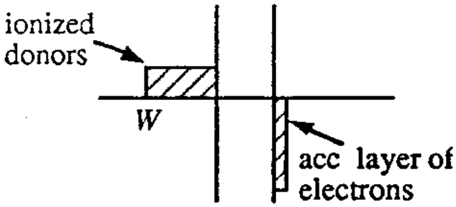
(i) $V_G = 0$



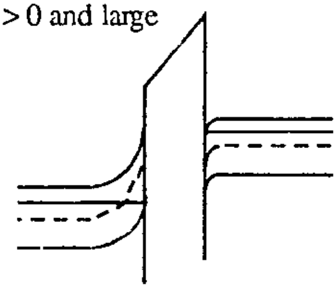


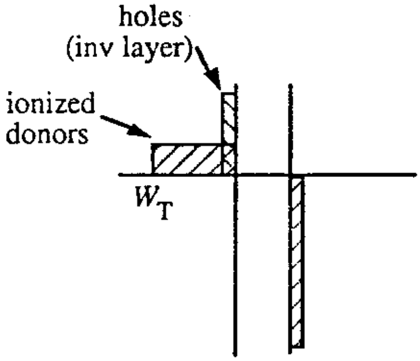
(ii) $V_G > 0$ but small





(iii) $V_G > 0$ and large

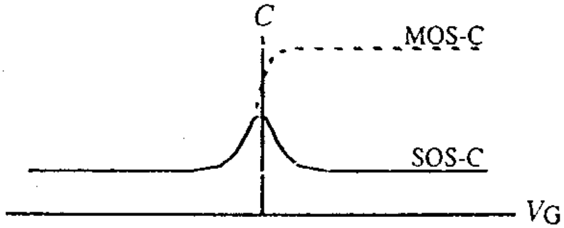




(iv) $V_G < 0$ but small — (ii) answer with semiconductor regions interchanged.

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

(c)



16.12

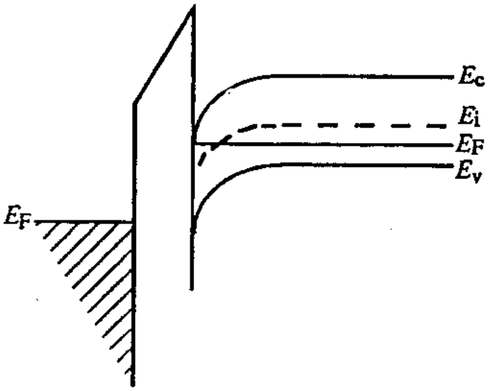
(a) $\boxed{\text{Curves } a \text{ and } b}$ are standard low- and high-frequency C–V curves that result when the semiconductor component of the MOS-C is in equilibrium under d.c. biasing conditions. Curve c is a nonequilibrium deep-depletion characteristic.

(b) In accumulation $C \rightarrow C_O = K_O\varepsilon_0 A_G/x_o$. Since both devices exhibit the same capacitance in accumulation, the two devices have the same oxide thickness. With x_o 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.)

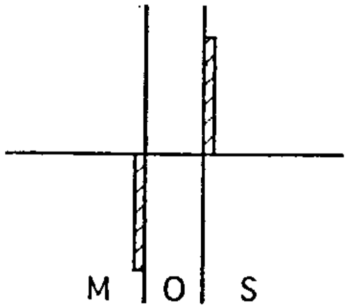
16.13

(a) $\boxed{p\text{-type}}$ ...For p-type devices accumulation (C_{max}) occurs for negative V_G and inversion (C_{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_{max} = 100pF. However,

$$C_{max} = C_O = \frac{K_O\varepsilon_0 A_G}{x_o}$$

$$x_o = \frac{K_O\varepsilon_0 A_G}{C_{max}} = \frac{(3.9)(8.85\times10^{-14})(3\times10^{-3})}{(10^{-10})} = \mathbf{0.104\mu m}$$

(e) In the delta-depletion formulation

$$C = \frac{C_O}{1+\dfrac{K_O W_T}{K_S x_o}} \qquad \text{inv } (\omega\to\infty) \tag{16.34d}$$

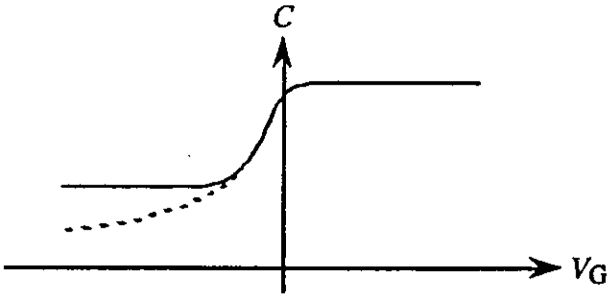
Thus

$$W_T = \frac{K_S x_o}{K_O}\left(\frac{C_O}{C}-1\right) = \frac{(11.8)(0.104)}{(3.9)}\left(\frac{100}{20}-1\right) = \mathbf{1.26\mu m}$$

Employing Fig. 16.9, we conclude $N_A \cong \mathbf{5\times10^{14}/cm^3}$.

16.14

(a)



(b) $$C_{MAX} = C_O = \frac{K_O\varepsilon_0 A_G}{x_o} = \frac{(3.9)(8.85\times10^{-14})(10^{-3})}{10^{-5}} = \mathbf{34.5\ pF}$$

(c) $$\phi_F = -(kT/q)\ln(N_D/n_i) = -0.0259\ln(2\times10^{15}/10^{10}) = -0.316$$

$$W_T = \left[\frac{2K_S\varepsilon_0}{qN_D}(-2\phi_F)\right]^{1/2} = \left[\frac{(2)(11.8)(8.85\times10^{-14})(2)(0.316)}{(1.6\times10^{-19})(2\times10^{15})}\right]^{1/2} = 6.42\times10^{-5}\text{ cm}$$

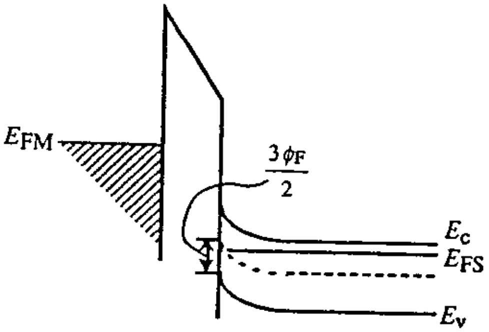
$$C_{MIN} = \frac{C_O}{1+\frac{K_O W_T}{K_S x_o}} = \frac{34.5}{1+\frac{(3.9)(6.42\times10^{-5})}{(11.8)(10^{-5})}} = \mathbf{11.1\ pF}$$

(d) By definition, if $V_G = V_T$. . . $\phi_S = 2\phi_F = \mathbf{-0.632\ V}$

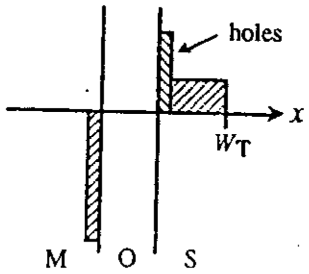
(e) $V_T = (2\phi_F) - \frac{K_S x_o}{K_O}\sqrt{\frac{2qN_D}{K_S\varepsilon_0}(-2\phi_F)}$ (Also see Prob. 16.7h.)

$$= -2(0.316) - \frac{(11.8)(10^{-5})}{(3.9)}\left[\frac{(2)(1.6\times10^{-19})(2\times10^{15})(0.632)}{(11.8)(8.85\times10^{-14})}\right]^{1/2} = \mathbf{1.23\ V}$$

(f)



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



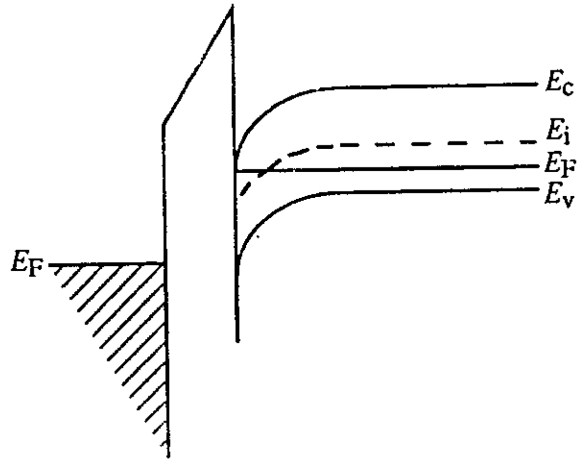
(h) Under the specified operating conditions, the MOS-C is expected to exhibit a total deep-depletion characteristic exemplified by the dashed line in the part (a) answer.

16.15

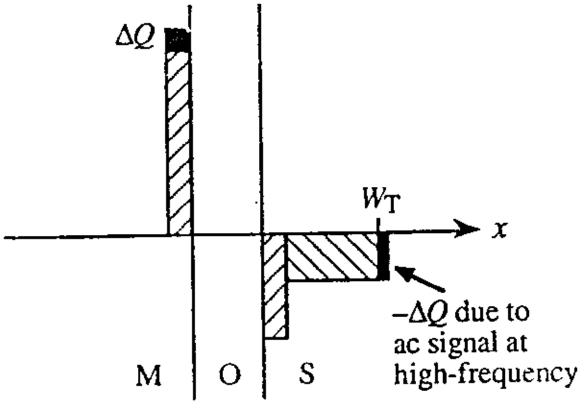
(a) $\boxed{p\text{-type}}$ ...There is an inversion-layer of negative charge — electrons — shown in the block charge diagram. The semiconductor must therefore be p-type. (Also, the depletion-region charge is negative or clearly due to acceptor ions.)

(b) $\boxed{\text{Inversion biased}}$ ...As noted in part (a), there is an inversion layer with $n_s > N_A$ shown on the diagram.

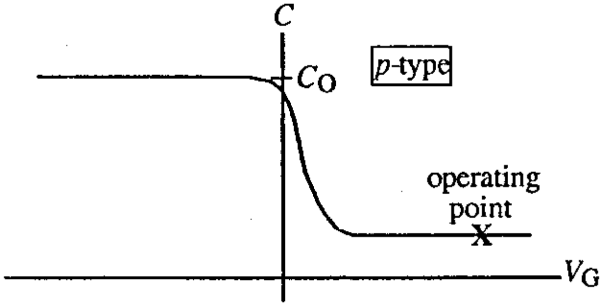
(c)



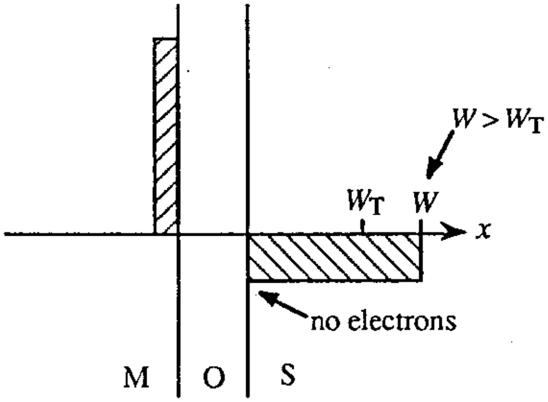
(d)



(e)



(f)



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.

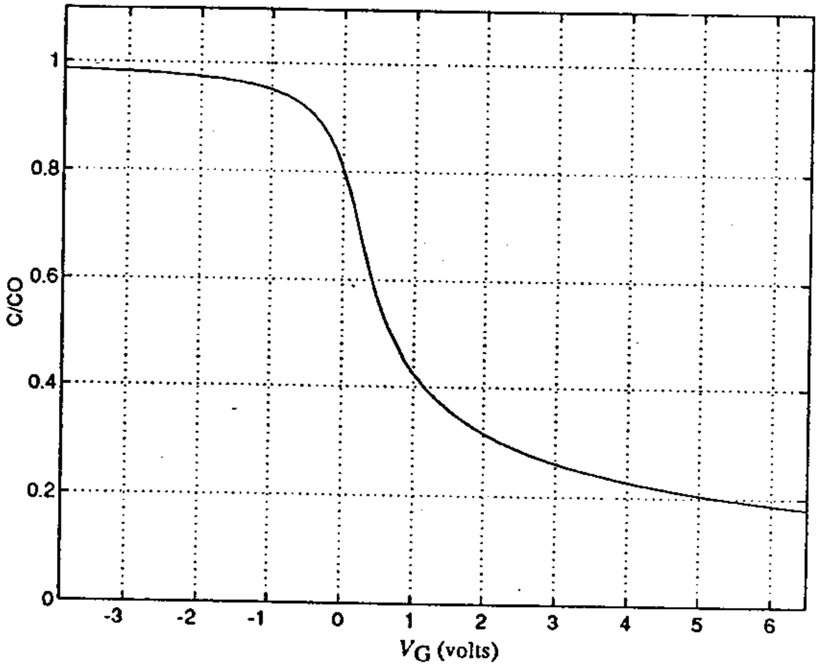
16.16

The MATLAB program script yielding deep-depletion p-type MOS-C C–V characteristics and a sample plot ($x_o = 0.2\mu$m, $N_A = 7.8\times10^{14}$/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...

```
%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;
q=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-21:0.5:UF;
F=sqrt(exp(UF).*(exp(-US)+US-1)+exp(-UF).*(exp(US)-US-1));
VG1=kT*(US+(US./abs(US)).*(KS*xo)/(KO*LD).*F);
DENOM1=exp(UF).*(1-exp(-US))+exp(-UF).*(exp(US)-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*(UF+(KS*xo)/(KO*LD).*FI);
øF=kT*UF;
VT=2*øF+(KS*xo/KO)*sqrt((4*q*NA*øF)/(KS*e0));
Vdelta=(q/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)

$$C_O = \frac{K_O \varepsilon_0 A_G}{x_o} \quad \Rightarrow \quad x_o = \frac{K_O \varepsilon_0 A_G}{C_O}$$

$$x_o = \frac{(3.9)(8.85\times10^{-14})(4.75\times10^{-3})}{82\times10^{-12}} = \mathbf{0.200\mu m}$$

(b) From Fig. 16.17, $C/C_O(\text{inv}) \cong 0.39$.

$$C(\text{inv}) = \frac{C_O}{1+\dfrac{K_O W_{\text{eff}}(\text{inv})}{K_S x_o}}$$

$$W_{\text{eff}}(\text{inv}) = \frac{K_S x_o}{K_O}\left[\frac{C_O}{C(\text{inv})} - 1\right] = \frac{(11.8)(0.2)}{(3.9)}\left(\frac{1}{0.39} - 1\right)$$

$$= \mathbf{0.946\mu m}$$

and

$$\frac{W_{\text{eff}}(\text{inv})}{L_D} = \frac{9.46\times10^{-5}}{2.91\times10^{-3}} = 3.25 \times 10^{-2}$$

(c) If $W_{\text{eff}}(\text{inv})$ is equated to W_T, one estimates from Fig. 16.9 that $N_D \cong 8.5\times10^{14}/\text{cm}^3$ or $U_F = -\ln(N_D/n_i) = -\ln(8.5\times10^{14}/1.00\times10^{10}) = -11.35$. Substituting $U_F = -11.35$ into the expression for W_{eff}/L_D one computes $W_{\text{eff}}/L_D = 3.374\times10^{-2}$. W_{eff}/L_D is too large implying N_D and $|U_F|$ are somewhat larger. Trying $U_F = -11.45$ yields $W_{\text{eff}}/L_D = 3.223\times10^{-2}$; trying $U_F = -11.40$ yields $W_{\text{eff}}/L_D = 3.298\times10^{-2}$. Clearly U_F is bracketed between -11.40 and -11.45. Subsequent calculations give $W_{\text{eff}}/L_D = 3.268\times10^{-2}$, 3.253×10^{-2}, 3.238×10^{-2} when $U_F = -11.42$, -11.43, and -11.44, respectively. The best value appears to be

$$\boxed{U_F = -11.43 \qquad \text{and} \qquad N_D = n_i e^{-U_F} = (10^{10})e^{11.43} = 9.20\times10^{14}/\text{cm}^3}$$

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