CHAPTER 14

14.1

(a) MS, Schottky, and Hot Carrier are just alternative names for a rectifying metal-semiconductor contact. Hot Carrier diodes are typically small area devices.

(b) If $\Phi_M = \chi$ in an ideal MS contact, the contact is borderline rectifying/ohmic independent of the semiconductor doping.

(c)...V_{bi} is computed differently.

...In *pn* junction analyses it is common practice to take $V = 0$ on the *p*-side of the junction. In MS work the semiconductor bulk is typically employed as the zero-voltage reference point.

(d) Thermionic emission current — majority carrier injection over the surface potential-energy barrier.

(e) Since $I_{M\bullet\to S}(V_A) = I_{M\bullet\to S}(0) = -I_{S\bullet\to M}(0)$, the M•→S component is obtained by evaluating the S•→M component at zero bias.

(f) The diffusion capacitance and conductance arise from the fluctuation of the minority carriers stored in a quasineutral region adjacent to the depletion region. The minority carrier storage is large in a forward-biased *pn* junction diode and leads to a significant diffusion admittance. In an MS diode there is minimal minority carrier storage for operational forward biases.

(g) There is a minimal number of stored minority carriers to be removed in going from the forward-bias "on" condition to the reverse-bias "off" condition.

(h) It is a special circuit or fabricated-in arrangement where an MS (Schottky) diode is connected between the base and collector of a BJT. The arrangement leads to a significant reduction in the turn-off time when the BJT is used as a switch.

(i) Ohmic contacts are usually produced in practice by heavily doping the surface region of the semiconductor immediately beneath the contact. The device structure is also routinely annealed (heated in an inert atmosphere) to minimize the contact resistance.

(j) "Spiking" is the nonuniform penetration of Al into Si beneath an Al-Si contact. (See Fig. 14.11a.)

14.2

(NOTE: In the first printing, all of the semiconductors were erroneously identified as n-type. Combinations B, D, and F should have been labeled as N_A doped.)

For a given combination, it is first necessary to determine the nature of the contact. This requires that we compute Φ_S using

$$\Phi_S = \chi + (E_c - E_F)_{FB} \cong \chi + E_G/2 - (E_F - E_i)_{FB}$$

$$(E_F - E_i)_{FB} = \begin{cases} kT\ln(N_D/n_i) & \text{... } n\text{-type} \\ -kT\ln(N_A/n_i) & \text{... } p\text{-type} \end{cases}$$

Combo	Mat	Type	Doping (cm^{-3})	n_i (cm^{-3})	$E_F - E_i$ (eV)	$E_G/2$ (eV)	Φ_S (eV)
A	Ge	n	10^{16}	2.5×10^{13}	0.155	0.33	4.18
B	Ge	p	10^{15}	2.5×10^{13}	−0.096	0.33	4.43
C	Si	n	10^{15}	10^{10}	0.298	0.56	4.29
D	Si	p	10^{16}	10^{10}	−0.358	0.56	4.95
E	GaAs	n	10^{16}	2.25×10^{6}	0.575	0.71	4.21
F	GaAs	p	10^{17}	2.25×10^{6}	−0.635	0.71	5.42

Noting the semiconductor type and whether $\Phi_M > \Phi_S$ or $\Phi_M < \Phi_S$, the ideal nature of the contact is deduced by referring to Table 14.1.

Combo	Type	Φ_M ? Φ_S	ideal nature	Part (a) diagram similar to	Part (b) argument similar to that in
A	n	$\Phi_M > \Phi_S$	Rectifying	Fig. 14.2(b)	Section 14.1
B	p	$\Phi_M > \Phi_S$	Ohmic	Fig. (b), Exer. 14.1	Exercise 14.1
C	n	$\Phi_M < \Phi_S$	Ohmic	Fig. 14.2(d)	Section 14.1
D	p	$\Phi_M < \Phi_S$	Rectifying	Fig. (a), Exer. 14.1	Exercise 14.1
E	n	$\Phi_M > \Phi_S$	Rectifying	Fig. 14.2(b)	Section 14.1
F	p	$\Phi_M < \Phi_S$	Rectifying	Fig. (a), Exer. 14.1	Exercise 14.1

14.3

(a) $\Phi_B = \Phi_M - \chi = 5.10 - 4.03 = \mathbf{1.07\ eV}$

(b)
$$(E_c - E_F)_{FB} \cong E_G/2 - (E_F - E_i)_{FB} = E_G/2 - kT\ln(N_D/n_i)$$
$$= 0.56 - (0.0259)\ln(10^{15}/10^{10})$$
$$= 0.26\ \text{eV}$$

$$V_{bi} = \frac{1}{q}[\Phi_M - (E_c{-}E_F)_{FB}] = 1.07 - 0.26 = \mathbf{0.81\ V}$$

(c) $V_A = 0$ under equilibrium conditions and

$$W = \left[\frac{2K_S\varepsilon_0}{qN_D}V_{bi}\right]^{1/2} = \left[\frac{2(11.8)(8.85\times10^{-14})(0.81)}{(1.6\times10^{-19})(10^{15})}\right]^{1/2} = \mathbf{1.03\times10^{-4}\ cm}$$

(d) $$|\mathcal{E}|_{max} = |\mathcal{E}_{|x=0}| = \frac{qN_D}{K_S\varepsilon_0}W = \frac{(1.6\times10^{-19})(10^{15})(1.03\times10^{-4})}{(11.8)(8.85\times10^{-14})} = \mathbf{1.58\times10^{4}\ V/cm}$$

14.4

The computations were performed employing Eq. (14.12) with $V_A = 0$, Eq. (14.3), and

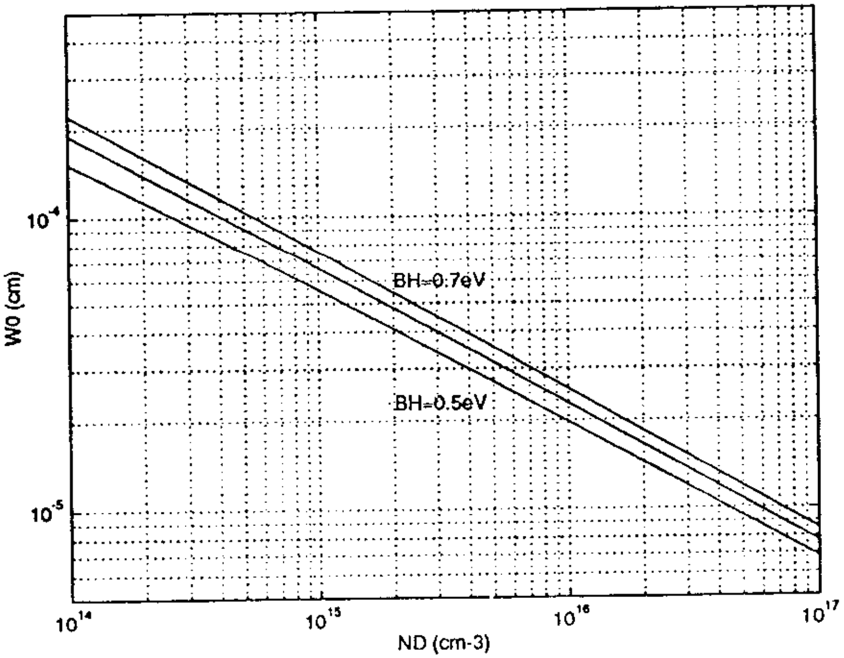
$$(E_c - E_F)_{FB} \cong E_G/2 - kT\ln(N_D/n_i)$$

The resultant plot and associated MATLAB m-file are displayed below.

MATLAB program script...

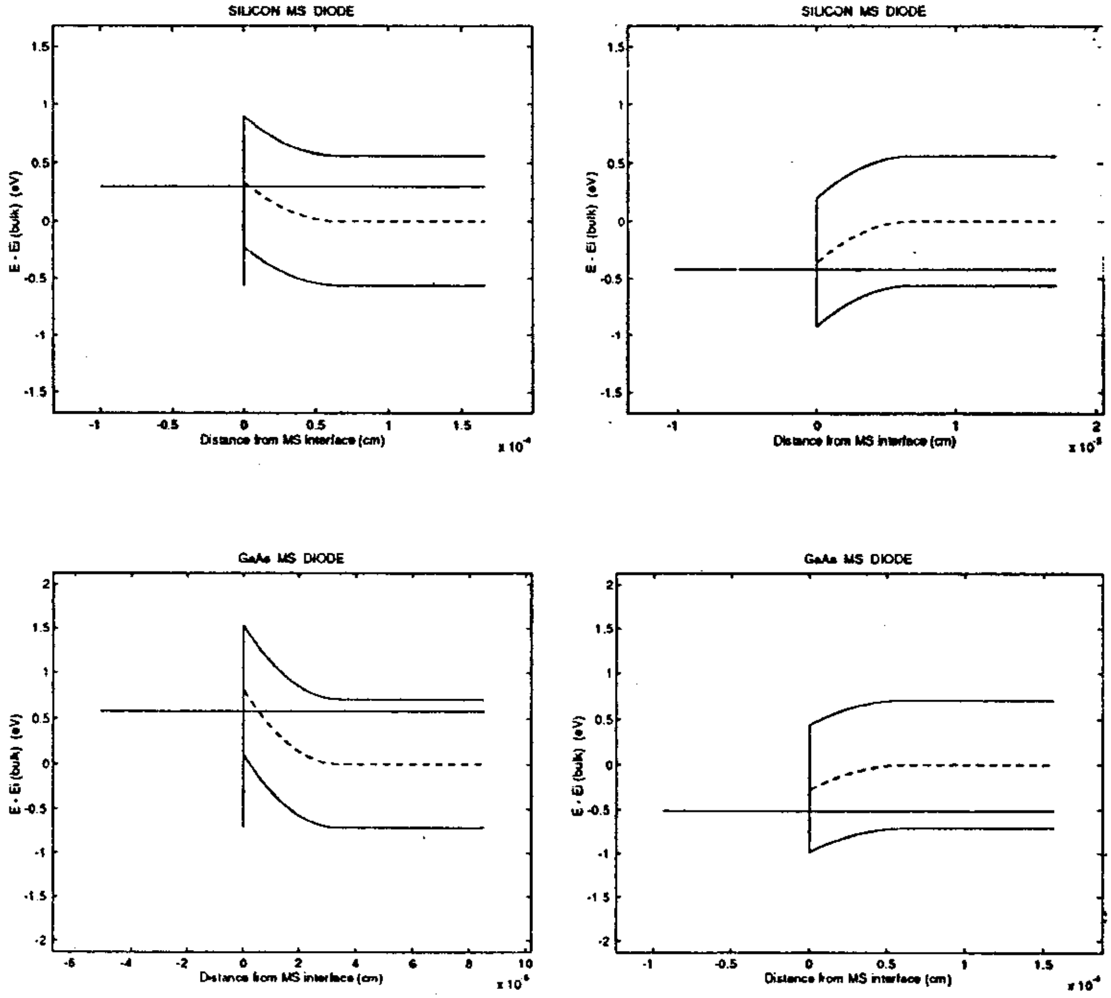
```
%Equilibrium Depletion Width (Problem 14.4)
%Initialization
clear; close
%Constants and Parameters
q=1.6e-19;
e0=8.85e-14;
kT=0.0259;
```

```
EG=1.12;
ni=1.0e10;
KS=11.8;
BH=[0.5,0.6,0.7];  %Barrier Height
ND=logspace(14,17);
%Depletion Width Calculation
ECF=EG/2-kT*log(ND./ni);
W0=[];
for i=1:3,
  Vbi=BH(i)-ECF;
  W=sqrt((2*KS*e0.*Vbi)./(q.*ND));
  W0=[W0;W];
end
%Plot result
loglog(ND,W0);
axis([1.0e14,1.0e17,5e-6,5e-4]);  grid
xlabel('ND (cm-3)');  ylabel('W0 (cm)')
text(2e15,2.3e-5,'BH=0.5eV')
text(2e15,6e-5,'BH=0.7eV')
```



14.5

(a)/(b)/(c) A sample MATLAB program that generates MS diode energy band diagrams (equilibrium, 300 K) is included on the instructor's disk as m-file P_14_05.m. The program can generate both *n*- and *p*-type Si diagrams plus *n*- and *p*-type GaAs diagrams. Sample plots are displayed below.



14.6

Substituting Eq. (14.17) into Eq. (14.16) gives

$$I_{S\bullet\to M} = -qA\left(\frac{4\pi kTm_n^{*2}}{h^3}\right)e^{(E_F-E_c)/kT}\int_{-\infty}^{-\upsilon_{min}} \upsilon_x\, e^{-(m_n^*/2kT)\upsilon_x^2}\, d\upsilon_x$$

$$= qA\left(\frac{4\pi kTm_n^{*2}}{h^3}\right)e^{(E_F-E_c)/kT}\int_{\upsilon_{min}}^{\infty} \upsilon_x\, e^{-(m_n^*/2kT)\upsilon_x^2}\, d\upsilon_x$$

where the second form of the above equation is obtained by interchanging the limits on the integral and changing variables from υ_x to $-\upsilon_x$. Next evaluating the integral yields

$$\int_{\upsilon_{min}}^{\infty} \upsilon_x\, e^{-(m_n^*/2kT)\upsilon_x^2}\, d\upsilon_x = -\left(\frac{kT}{m_n^*}\right)e^{-(m_n^*/2kT)\upsilon_x^2}\Bigg|_{\upsilon_{min}}^{\infty} = \left(\frac{kT}{m_n^*}\right)e^{-(m_n^*/2kT)\upsilon_{min}^2}$$

Thus, noting from Eq. (14.14) that $\upsilon_{min}^2 = (2q/m_n^*)(V_{bi}-V_A)$, we obtain .

$$I_{S\bullet\to M} = qA\left(\frac{4\pi k^2T^2m_n^*}{h^3}\right)e^{(E_F-E_c)/kT}\, e^{-q(V_{bi}-V_A)/kT}$$

But

$$qV_{bi}/kT = \Phi_B/kT + (E_F-E_c)/kT$$

and

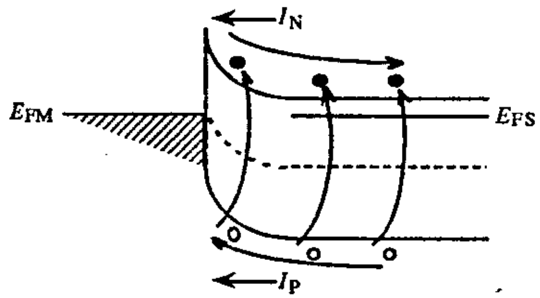
$$qA\left(\frac{4\pi k^2T^2m_n^*}{h^3}\right) = A\left(\frac{m_n^*}{m_0}\right)\left(\frac{4\pi qm_0k^2}{h^3}\right)T^2 = A\mathcal{A}^*T^2$$

leading to the conclusion

$$I_{S\bullet\to M} = A\mathcal{A}^*T^2\, e^{-\Phi_B/kT}\, e^{qV_A/kT}$$

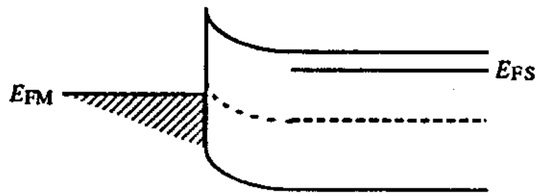
14.7

(a) With positive current flow as defined in Fig. 14.3(a), the short-circuit photocurrent is negative. (Note that $E_{FM} = E_{FS}$ in the energy band diagram because the device is short-circuited. However, both F_N and F_P deviate from E_{FS} near the M–S interface.)



(Short-circuit diagram)

(b) A forward bias must be developed under open-circuit conditions so that the negative-going photocurrent is precisely balanced by a positive-going thermionic emission current.

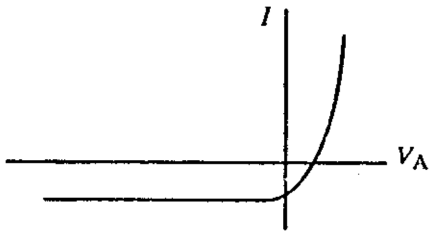


(Open-circuit diagram)

(c) Paralleling the approach presented in Subsection 9.2.1, the photocurrent (I_L) will be equal to $-q$ times the electron-hole pairs photogenerated per second in the volume $A(W+L_P)$, or

$$I_L = -qA(W + L_P)G_L$$

(d) The I–V sketch should be similar to one of the $G_0 \neq 0$ curves in Fig. 9.3; i.e., a constant value is subtracted from the dark I–V characteristic to obtain the light-on characteristic. Consistent with the part (a) and (b) answers, $I < 0$ if the device is short-circuited ($V_A = 0$) and $V > 0$ if the device is open circuited ($I = 0$).



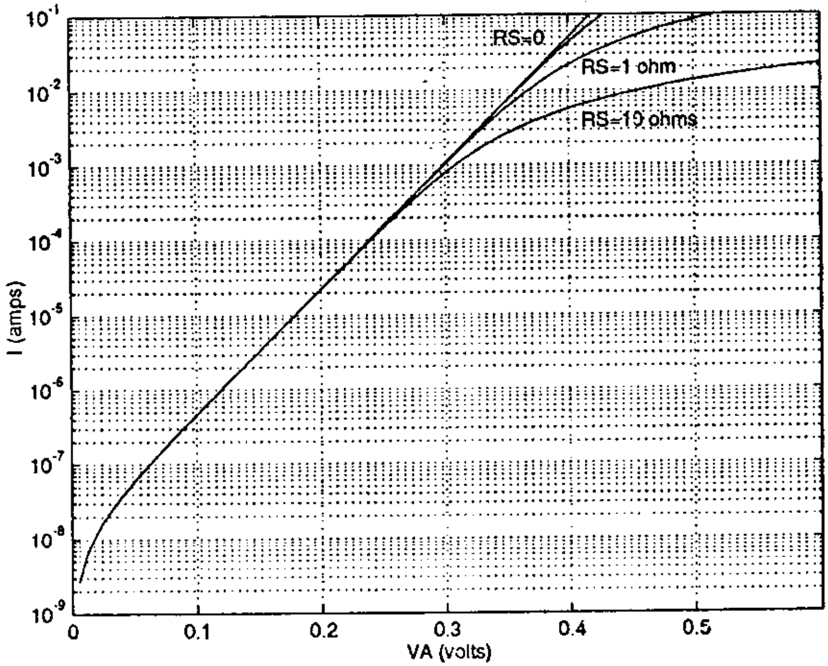
14.8
When the series resistance cannot be ignored, Eq. (14.24) assumes the modified form

$$I = I_S(e^{qV_J/kT} - 1)$$

where

$$V_J = V_A - IR_S \quad \text{or} \quad V_A = V_J + IR_S$$

The I–V relationships here are totally analogous to the high-current *pn* junction relationships presented in Subsection 6.2.4. In performing computations, it is convenient to first choose a value for V_J, compute I, and then compute V_A. The requested I–V characteristics illustrating the effect of the series resistance are reproduced below.



MATLAB program script...

```
%Effect of RS on MS diode I-V Characteristics

%Initialization
clear;  close

%Constants and Parameters
kT=0.0259;
```

```
Is=1.0e-8;
RS=[0,0.1,1.0,10];
VJ=linspace(0,0.6);
%Calculate I versus VA
I=Is.*(exp(VJ/kT)-1);
VA=[];
for i=1:4,
VA=[VA;VJ+I.*RS(i)];
end
%Plot result
semilogy(VA,I,'w');
axis([0,0.6,1.0e-9,1.0e-1]);  grid
xlabel('VA (volts)');  ylabel('I (amps)')
text(0.34,5.0e-2,'RS=0');  text(0.41,2.0e-2,'RS=1 ohm')
text(0.41,4.0e-3,'RS=10 ohms')
```

14.9

For a p^+-n junction...

$$I_{\mathrm{DIFF}} = I_0(e^{qV_A/kT} - 1) = qA\frac{D_P}{L_P}\frac{n_i^2}{N_D}(e^{qV_A/kT} - 1)$$

and employing Eqs. (14.24/14.25),

$$I_{\mathrm{TE}} = I_s(e^{qV_A/kT} - 1) = A\mathcal{A}^*T^2e^{-\Phi_B/kT}(e^{qV_A/kT} - 1)$$

Thus noting

$$\frac{D_P}{L_P} = \sqrt{\frac{D_P}{\tau_p}} = \sqrt{\frac{(kT/q)\mu_p}{\tau_p}}$$

$$\frac{I_{\mathrm{DIFF}}}{I_{\mathrm{TE}}} = \frac{I_0}{I_s} = \frac{qA\dfrac{D_P}{L_P}\dfrac{n_i^2}{N_D}}{A\mathcal{A}^*T^2e^{-\Phi_B/kT}} = \frac{q\sqrt{\dfrac{(kT/q)\mu_p}{\tau_p}}\dfrac{n_i^2}{N_D}}{\mathcal{A}^*T^2e^{-\Phi_B/kT}}$$

$$= \frac{(1.6\times10^{-19})\left[\dfrac{(0.0259)(437)}{(10^{-6})}\right]^{1/2}\left(\dfrac{10^{20}}{10^{16}}\right)}{(140)(300)^2e^{-(0.72)/(0.0259)}} = \mathbf{5.05 \times 10^{-7}}$$

14.10

(a)/(b) The computational results for parts (a) and (b) and the associated MATLAB m-file are included after the part (c) comments. The primary relationships employed in the computations were:

For part (a)...

$$\Delta\Phi_B = \left(\frac{q|\mathcal{E}_S|}{4\pi K_S\varepsilon_0}\right)^{1/2} \qquad \text{... } (\Delta\Phi_B \text{ in eV})$$

$$|\mathcal{E}_S| = \frac{qN_D}{K_S\varepsilon_0}W = \left[\frac{2qN_D}{K_S\varepsilon_0}(V_{bi}-V_A)\right]^{1/2}$$

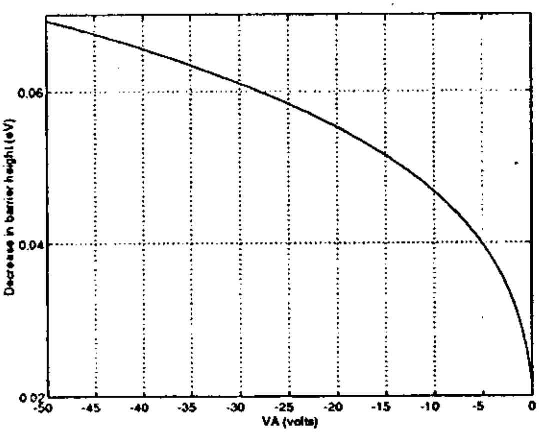
$$V_{bi} = \frac{1}{q}\left[\Phi_B - (E_c - E_F)_{FB}\right]$$

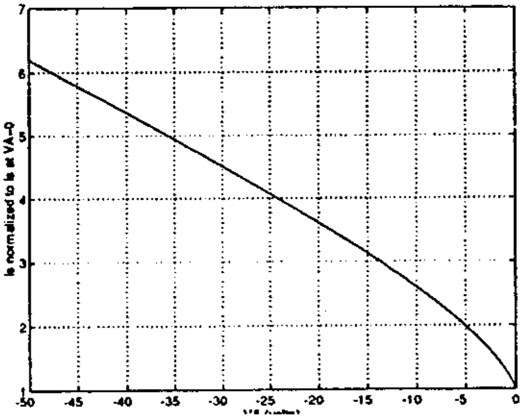
$$(E_c - E_F)_{FB} \cong E_G/2 - (E_F - E_i)_{FB} = E_G/2 - kT\ln(N_D/n_i)$$

For part (b)...

$$\frac{I_s(V_A)}{I_s(V_A{=}0)} = \frac{e^{-\Phi_B(V_A)/kT}}{e^{-\Phi_B(0)/kT}} = e^{[\Phi_B(0)-\Phi_B(V_A)]/kT} = e^{[\Delta\Phi_B(V_A)-\Delta\Phi_B(0)]/kT}$$

(c) The $\Delta\Phi_B$(eV) versus V_A plot shows that the change in $\Delta\Phi_B$ tends to be quite small, only 0.047 eV corresponding to a $\Delta V_A = 50$V in the given calculation. However, because I_s depends exponentially on the barrier height, the effect of a small $\Delta\Phi_B$ change on I_s is very significant.— I_s changes by more than a factor of 6 over the examined voltage range!





MATLAB program script...

```
%Schottky Barrier Lowering Computation
%Initialization
clear;  close
%Constants and Parameters
q=1.6e-19;
e0=8.85e-14;
kT=0.0259;
KS=11.8;
EG=1.12;
ni=1.0e10;
ND=1.0e16;
BH=0.72;     %BH=barrier height in eV
%Computation of ΔBH
VA=linspace(-50,0);
ECF=EG/2-kT*log(ND/ni);
Vbi=BH-ECF;
ES=sqrt((2*q*ND)/(KS*e0).*(Vbi-VA));
ΔBH=sqrt((q.*ES)./(4*pi*KS*e0));
plot(VA,ΔBH);  grid
xlabel('VA (volts)');  ylabel('Decrease in barrier height (eV)');
pause
%Computation of Is/Is(0)
Isn=exp((ΔBH-ΔBH(100))./kT);
plot(VA,Isn); grid
xlabel('VA (volts)');  ylabel('Is normalized to Is at VA=0');
```

14.11

If not explicitly given in the problem statement, the device area ($A = 1.5 \times 10^{-3}$ cm^2) may be obtained from Exercise 14.4. Effecting the fit employing the MATLAB program listed below, one finds:

Fit Results	Exercise 14.4
$N_D = 9.62 \times 10^{15}/\text{cm}^3$	$N_D \cong 9.7 \times 10^{15}/\text{cm}^3$
$V_{bi} = 0.613$ V	$V_{bi} \cong 0.6$ V
$\Phi_B = 0.816$ eV	$\Phi_B \cong 0.8$ eV

The fit results obviously compare very favorably with the approximate results obtained in Exercise 14.4.

MATLAB program script...

```
% Determination of Vbi, ND, and BH of MS diode
% employing P14.11 C-V data

%Initialization
clear;  close
format compact;  format short e

%Input data...Y=1/CJ2
VA= -[1.09,2.08,3.07,4.06,5.05,6.04,7.03,8.02,9.01,10];
Y=1.0e21*[0.953,1.494,2.035,2.579,3.125,3.673,4.217, ...
4.763,5.320,5.890];

%Fit
p=polyfit(VA,Y,1)
ND=2./(1.6e-19*11.8*8.85e-14*(1.5e-3)^2*(-p(1)))
Vbi=-p(2)/p(1)

%Barrier Height Computation
EG=1.12;  ni=1.0e10;  kT=0.0259;
ECF=EG/2-kT*log(ND/ni);
BH=Vbi+ECF

%1/CJ2 vs. VA plot (not required)
plot(VA,Y,'+')
axis([-11,2,0,1.1*max(Y)]);  grid
xlabel('VA (volts)');  ylabel('1/CJ^2  (1/F^2)')
```

14.12

In general the development of relationships for the electrostatic variables in a linearly graded MS diode closely parallels the uniformly doped analysis in Subsection 14.2.1. The results obtained are analogous to the linearly graded *pn* junction relationships established in Subsection 5.2.5.

(a) With $N_D(x) = ax$ for $x \geq 0$, invoking the depletion approximation yields

$$\boxed{\rho(x) = qax \qquad \ldots 0 \leq x \leq W}$$

Substituting into Poisson's equation gives

$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{K_S\varepsilon_0} \cong \frac{qa}{K_S\varepsilon_0}x \qquad \ldots 0 \leq x \leq W$$

and

$$\int_{\mathcal{E}(x)}^{0} d\mathcal{E}' = \frac{qa}{K_S\varepsilon_0}\int_{x}^{W} x'dx'$$

or

$$\boxed{\mathcal{E}(x) = -\frac{qa}{2K_S\varepsilon_0}(W^2 - x^2) \qquad \ldots 0 \leq x \leq W}$$

Turning to the electrostatic potential, we can write

$$\frac{dV}{dx} = -\mathcal{E}(x) = \frac{qa}{2K_S\varepsilon_0}(W^2 - x^2)$$

and

$$\int_{V(x)}^{0} dV' = \frac{qa}{2K_S\varepsilon_0}\int_{x}^{W} (W^2 - x'^2)\, dx'$$

or

$$\boxed{V(x) = -\frac{qa}{6K_S\varepsilon_0}(2W^3 - 3W^2x + x^3) \qquad \ldots 0 \leq x \leq W}$$

Finally, $V = -(V_{bi} - V_A)$ at $x = 0$, and therefore

$$-(V_{bi} - V_A) = -\frac{qa}{3K_S\varepsilon_0} W^3$$

$$\boxed{W = \left[\frac{3K_S\varepsilon_0}{qa} (V_{bi}-V_A)\right]^{1/3}}$$

(b) Paralleling the development for the linearly graded *pn* junction in Subsection 5.2.5, the Eq. (14.3) expression for V_{bi} must be modified to read

$$V_{bi} = \frac{1}{q}\left[\Phi_B - (E_c - E_F)|_{x=W_0}\right]$$

where W_0 is the depletion width when $V_A = 0$. Since approximate charge neutrality applies for $x > W_0$, it follows that

$$n|_{x=W_0} = n_i e^{[(E_F-E_i)|_{x=W_0}]/kT} \cong N_D(x=W_0) = aW_0$$

or

$$(E_c-E_F)|_{x=W_0} \cong E_G/2 - kT \ln\left(\frac{aW_0}{n_i}\right)$$

Thus, to determine V_{bi}, one must simultaneously solve the following two equations employing numerical techniques.

$$W_0 = \left[\frac{3K_S\varepsilon_0}{qa} V_{bi}\right]^{1/3}$$

$$V_{bi} = \frac{1}{q}\left[\Phi_B - E_G/2 + kT \ln\left(\frac{aW_0}{n_i}\right)\right]$$

(c) $$C_J = \frac{K_S\varepsilon_0 A}{W} = \frac{K_S\varepsilon_0 A}{\left[\frac{3K_S\varepsilon_0}{qa} (V_{bi}-V_A)\right]^{1/3}}$$