18.1

(a) In theory the two quantities are numerically identical.

(b) The MOS–C or MOSFET under test is heated to an elevated temperature and a bias is applied to the gate of the device. Typical conditions for a bias–temperature stress to detect sodium ion contamination would be $T = 150^\circ \text{C}$, $V_G$ such that $E_{\text{ox}} < 10^6 \text{ V/cm}$, and $t = 5$ minutes.

(c) The fixed oxide charge is thought to be due to excess ionic silicon that has broken away from the silicon proper and is waiting to react in the vicinity of the Si–SiO$_2$ interface when the oxidation process is abruptly terminated.

(d) $D_{\Gamma T}$ is greatest on {111} Si surfaces, smallest on {100} Si surfaces, and the ratio of midgap states on the two surfaces is approximately 3:1.

(e) MOS device structures exhibit both an increase in the apparent fixed charge within the oxide and an increase in the interfacial trap concentration.

(f) In response to BT stressing, the negative–bias instability causes a shifting of the $C$–$V$ curve toward negative biases. Alkali ion contamination leads to a $C$–$V$ curve voltage translation in the direction opposite to the applied bias.

(g) The $V_T = V_T' + V_{FB}$ relationship was derived assuming $Q_{\Gamma T}$ changes little over the range of surface potentials between $\phi_S = 0$ and $\phi_S = 2\phi_F$. This becomes a poor assumption if the device contains a large density of interfacial traps — if the device is unannealed, for example.

(h) A depletion–mode transistor is a MOSFET that is "on" or conducting when $V_G = 0$.

(i) The field-oxide lies outside the active region in MOS devices and integrated circuits; the gate-oxide lies directly beneath the MOS gates. The field-oxide is typically much thicker than the gate-oxide.

(j) Simply stated, the "body effect" refers to the deep depletion condition that is created beneath the gate when the back or body of a MOSFET is reverse biased relative to the source. The body effect is utilized to adjust the threshold voltage.
(b) $\phi_{MS} = \frac{1}{q} (\Phi_M - \Phi_S) = [\chi' - (E_F - E_c)_{\text{poly-Si}}] - [\chi' + (E_c - E_F)_{\text{FB,crystalline-Si}}]$

$$= \frac{1}{q} [(E_c - E_F)_{\text{poly-Si}} - (E_c - E_F)_{\text{FB, crystalline-Si}}]$$

$$= -0.4 \text{V}$$

(Note that the computational equation developed here is the same as Eq. 18.24.)

(c) [Accumulation] biased. When $V_G = 0$ the polysilicon side of the part (a) diagram is lowered, yielding
In general

\[ \phi_{MS} = \frac{1}{q} \left[ \Phi_{M'} - \chi' - (E_c - E_F)_{FB} \right] \]

where

\[ \Phi_{M'} - \chi' = \begin{cases} 
-0.03 \text{eV} & \text{Al (See Fig. 18.3 caption.)} \\
-0.18 \text{eV} & \text{\ldots n\textsuperscript{+} poly (See Fig. 18.3 caption.)} \\
(E_0 - E_F)_{\text{p\textsuperscript{+} poly}} - \chi' = (\chi' + E_G) - \chi' = E_G = 1.12 \text{eV} & \text{\ldots p\textsuperscript{+} poly} 
\end{cases} \]

Also

\[ (E_c - E_F)_{FB} = (E_c - E_i) + (E_i - E_F)_{FB} \equiv E_G / 2 + (E_i - E_F)_{FB} \]

or

\[ (E_c - E_F)_{FB} = \begin{cases} 
E_G / 2 - (kT/q) \ln(N_D/n_i) & \text{n-type crystalline Si} \\
E_G / 2 + (kT/q) \ln(N_A/n_i) & \text{p-type crystalline Si} 
\end{cases} \]

The results of the p\textsuperscript{+} polycrystalline-gate computation based on the above relationships are presented in the following plot. The MATLAB program script used to generate the plot is also listed on the next page. Although it leads to only a minor difference, it should be mentioned that, instead of employing \( E_c - E_i \equiv E_G / 2 \), the more accurate value of \( E_c - E_i = 0.57 \text{eV} \) was used in constructing Fig. 18.3.
MATLAB program script...

% Metal-Semiconductor Workfunction Difference
% Initialization
clear; close
% Constants and Parameters
ni=1.0e10;
Eg=1.12;
kT=0.0259;
s=menu('Specify the gate material', 'Al', 'n+ poly', 'p+ poly');
if s==1,
    A=-0.03;
elseif s==2,
    A=-0.18;
else
    A=Eg;
end
% Calculate M-S Workfunction Difference
% EcEF=(Ec-EF)FB
NB=logspace(14,18);
EcEFn=Eg/2-kT.*log(NB./ni);
EcEFp=Eg/2+kT.*log(NB./ni);
φMSn=A-EcEFn;
φMSp=1-A-EcEFp;
% Plotting result
semilogx(NB,φMSn,NB,φMSp); grid
xlabel('NA or ND (cm^-3)'); ylabel('φMS (volts)')
18.5

(a) \( \Delta V_G(\text{fixed charge}) = -\frac{Q_F}{C_0} \) \hspace{1cm} \text{...Eq. (18.15)}

(b) We are given

\[
\rho_{\text{ox}} = \begin{cases} 
  0 & \quad 0 \leq x \leq x_0 - \Delta x \\
  \frac{2Q_F}{\Delta x^2} x' & \quad 0 \leq x' \leq \Delta x, \text{ where } x' = x - x_0 + \Delta x
\end{cases}
\]

or mathematically

\[
\rho_{\text{ox}} = \begin{cases} 
  0 & \quad 0 \leq x \leq x_0 - \Delta x \\
  \frac{2Q_F}{\Delta x^2} x' & \quad 0 \leq x' \leq \Delta x
\end{cases}
\]

Substituting \( \rho_{\text{ox}} \) into Eq. (18.11) gives

\[
\Delta V_G = -\frac{1}{K_0 \varepsilon_0} \int_0^{x_0} x \rho_{\text{ox}} dx = -\frac{1}{K_0 \varepsilon_0} \left( \frac{2Q_F}{\Delta x} \right) \int_0^{\Delta x} x'(x' + x_0 - \Delta x) dx'
\]

and

\[
\Delta V_G = -\frac{Q_F}{C_0} \left( 1 - \frac{\Delta x}{3x_0} \right)
\]

(c) \( \frac{\Delta V_G(\text{part b})}{\Delta V_G(\text{part a})} = 1 - \frac{\Delta x}{3x_0} \)

If \( \Delta x = 10^{-7}\text{cm} \) and \( x_0 = 10^{-5}\text{cm} \) \( \rightarrow \) \( \Delta V_G(\text{b})/\Delta V_G(\text{a}) = 0.997 \)

If \( \Delta x = 10^{-7}\text{cm} \) and \( x_0 = 10^{-6}\text{cm} \) \( \rightarrow \) \( \Delta V_G(\text{b})/\Delta V_G(\text{a}) = 0.967 \)

Provided \( x_0 \gg \Delta x \), it is essentially impossible to distinguish between charge distributed a
short distance into the oxide and charge right at the interface. For very thin oxides the
difference becomes detectable, but not all that significant, even when \( x_0 \) is only \( 10\Delta x \).
(a) Given \( \rho_{\text{ion}} = \rho_0 = \text{constant} \),

\[
\Delta V_G^{(\text{ions})} = -\frac{1}{K_0 \varepsilon_0} \int_0^{x_0} x \rho_0 dx = -\frac{\rho_0 x_0^2}{2 K_0 \varepsilon_0}
\]

\[
= -\frac{(1.6 \times 10^{-19})(10^{18})(10^{-5})^2}{(2)(3.9)(8.85 \times 10^{-14})}
\]

\[= - 23.2 \text{V} \]

(b) Here

\[ \rho_{\text{ion}} = Q_M \delta(x_0) \]

where

\[ Q_M = \int_0^{x_0} \rho_{\text{ion}}(x) dx = \rho_0 x_0 \]

Substituting \( \rho_{\text{ion}} = Q_M \delta(x_0) \) into Eq.(18.13) gives

\[
\Delta V_G^{(\text{ions})} = \frac{Q_M}{C_0} = \frac{x_0}{K_0 \varepsilon_0} \rho_0 x_0 = -\frac{\rho_0 x_0^2}{K_0 \varepsilon_0}
\]

Clearly the \( \Delta V_G \) here is twice that in part (a).

\[ \Delta V_G = -46.4 \text{V} \]
18.6

(a) If the MOS-C is ideal except for $\phi_{MS} \neq 0$ and $Q_F \neq 0$, then

$$V_{FB} = \phi_{MS} - \frac{Q_F}{C_0} = \phi_{MS} - \frac{x_0}{K_0 \varepsilon_0} Q_F.$$  

A plot of $V_{FB}$ versus $x_0$ data should be a straight line with an extrapolated $V_{FB}$-axis intercept equal to $\phi_{MS}$ and a slope of $-Q_F/K_0 \varepsilon_0$.

(b) The given $V_{FB}$ versus $x_0$ data is plotted below. A least squares fit through the data yields

$$V_{FB} = -0.596 - (3.02 \times 10^4)x_0 \quad \text{...} x_0 \text{ in cm}$$

Thus

$$\phi_{MS} = -0.596 \text{ V}$$

$$Q_F/q = -K_0 \varepsilon_0 \text{(slope)}/q = \frac{(3.9)(8.85 \times 10^{-14})(3.02 \times 10^4)}{1.6 \times 10^{-19}} = 6.52 \times 10^{10}/\text{cm}^2$$

![Graph showing the relationship between $V_{FB}$ and $x_0$.]
18.7

(a) $[Q_M \not= 0]$. If there is no charge in the oxide, if $\rho_{ox} = 0$, then $\varepsilon_{ox} = \text{constant}$ and the oxide energy bands are a linear function of position. However, if $\rho_{ox} \not= 0$, $\varepsilon_{ox}$ becomes a function of position and the oxide energy bands in turn exhibit curvature. A concave curvature as pictured in Fig. P18.7 is indicative of a significant positive charge, alkali ions, in the oxide.

(b) $[Q_F \not= 0]$. The normal component of the $D$–field, where $D = \varepsilon E$, must be continuous if there is no plane of charge at an interface between two dissimilar materials (see Subsection 16.3.2). When a plane of charge does exist, there is a discontinuity in the $D$–field equal to the charge/cm$^2$ along the interface. Note from Fig. P18.7 that the slope of the bands is zero and therefore $\varepsilon = (1/q)(dE_x/dx) = 0$ on the oxide side of the interface. On the semiconductor side of the interface $\varepsilon$ is decidedly nonzero and positive. Thus, there must be a plane of charge at or near the interface. For the pictured situation we in fact require $Q_{\text{interface}} = K_S \varepsilon_0 \varepsilon_S$ and the interface charge must be positive. The interfacial charge could arise from alkali ions, interfacial traps, or the fixed charge. In real devices, alkali ions typically give rise to a spread-out volume charge, making alkali ions an unlikely source of $Q_{\text{interface}}$. Moreover, the interfacial trap charge is assumed to be negligible in the statement of the problem. That leaves the fixed charge which closely approximates a plane of positive charge at the Si–SiO$_2$ interface. We conclude $Q_F \not= 0$.

Although a conclusion has been reached, we need to address an apparent inconsistency. In this problem and in Exercise 18.3, we have indicated that the fixed charge will cause a discontinuity in the interfacial $D$–field at the Si–SiO$_2$ interface. However, in deriving Eq.(18.11), the $D$–field was explicitly assumed to be continuous across the Si–SiO$_2$ interface. Eq. (18.11) in turn was used to establish the $\Delta V_G$(fixed charge) expression. This apparent inconsistency is resolved if the mathematical development is examined carefully. To be precise, by including $Q_F$ in $\rho_{ox}$ in the Eq. (18.11) derivation, we actually took the fixed charge to be slightly inside the oxide. The $D$–field discontinuity then occurs at $x = x_0^-$ instead of exactly at $x = x_0$. Whether the discontinuity occurs exactly at the interface or an imperceptible distance into the oxide cannot be detected physically, and clearly does not affect the mathematical results.
18.8
(a) In an ideal version of an MOS-C, flat band always occurs at \( V_G = 0 \), with the ideal device exhibiting the same value of \( C \) at flat band as the non-ideal device. Because \( Q_{IT} = 0 \), the ideal \( C-V \) curve is obtained by simply translating the given \( C-V \) curve along the voltage axis until the flat band point is at \( V_G = 0 \).

\[
C_{MAX} = C_O = \frac{K_{Ox0}A_G}{x_0}
\]

we conclude

\[
x_0 = \frac{K_{Ox0}A_G}{C_O} = \frac{(3.9)(8.85 \times 10^{-14})(2.9 \times 10^{-3})}{200 \times 10^{-12}} = 5.00 \times 10^{-6} \text{ cm}
\]

Also

\[
C_{MIN} = \frac{C_O}{1 + \frac{K_{GW}}{K_{Sx_0}}}
\]

making

\[
W_T = \frac{K_Sx_0}{K_O} \left( \frac{C_O}{C_{MIN}} - 1 \right) = \frac{(11.8)(5 \times 10^{-6})}{(3.9)} \left( \frac{200}{67} - 1 \right) = 3.00 \times 10^{-5} \text{ cm} = 0.3 \mu \text{m}
\]

Referring to Fig. 16.9, the plot of \( W_T \) versus \( N_A \) or \( N_D \), we conclude a \( W_T = 0.3 \mu \text{m} \) results when

\[
N_D \equiv 10^{16} / \text{cm}^3
\]

(c) Since \( Q_M = 0 \) and \( Q_{IT} = 0 \),

\[
\Delta V_C \big|_{\text{flat band}} = V_{FB} = \phi_{MS} - \frac{Q_F}{C_O}
\]

\( V_{FB} = -0.71 \) in the statement of the problem. Also, for an \( N_D = 10^{16} / \text{cm}^3 \) Al(n-Si) device, we conclude from Fig. 18.3 that \( \phi_{MS} = -0.24 V \). Thus

\[
Q_F = C_O(\phi_{MS} - V_{FB}) = \frac{C_O}{A_G} (\phi_{MS} - V_{FB}) = \frac{200 \times 10^{-12}}{2.9 \times 10^{-3}} (-0.24 + 0.71)
\]

\[
= 3.24 \times 10^{-8} \text{ coul/cm}^2
\]
18.9
We infer from the $C-V$ characteristics that the MOS-C is a p-bulk device. Also, we know that acceptor-like traps are negatively charged when filled with an electron and neutral when empty. For a p-bulk MOS-C the effect of biasing on the occupation and charge state of the acceptor-like traps is summarized in the following figure.

We also note

$$\Delta V_G = -\frac{Q_T}{C_0}$$

Thus, relative to the "after" or negligible $Q_T$ situation, the "before" characteristics will be shifted positively ($Q_T$ is negative) and the displacement will systematically increase as one progresses from accumulation, through depletion, to inversion. The deduced "before" characteristics are pictured below.

18.10
From the answer to Problem 1.5 (see Solutions Manual pages 1-2 and 1-3), we know that there are $6.78 \times 10^{14}$ atoms/cm$^2$ and $9.59 \times 10^{14}$ atoms/cm$^2$ on the (100) and (110) surface planes, respectively. If one assumes the number of residual "dangling bonds" is proportional to the number of Si surface atoms, then the [(110) surface] should exhibit the higher density of residual "dangling bonds" or interfacial traps. (Experiments confirm the above conclusion.)
18.11
(a) We note that the interfacial traps will be neutral when the MOS–C is accumulation or lightly depletion biased, but become positively charged when the device is \(|\phi_S| > |\phi_F|\) depletion biased or inversion biased.

Clearly, there is no shift in the \(C-V\) curve when the device is accumulation and \(|\phi_S| < |\phi_F|\) depletion biased. However, when \(|\phi_S| > |\phi_F|\) depletion biased or inversion biased, the characteristics are translated \(\Delta V_G = -Q_{IT}/C_0\) = constant negative value along the voltage axis.

(b) For acceptor-like interfacial traps

<table>
<thead>
<tr>
<th>Bias</th>
<th>Position of (E_F)</th>
<th>Trap Occupation</th>
<th>Charge State</th>
<th>(\Delta V_G) shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>acc, (</td>
<td>\phi_S</td>
<td>&lt;</td>
<td>\phi_F</td>
<td>) depl</td>
</tr>
<tr>
<td>(</td>
<td>\phi_S</td>
<td>&gt;</td>
<td>\phi_F</td>
<td>) depl, inv</td>
</tr>
</tbody>
</table>
From the preceding one concludes,

(c) If the states are very close to $E_c$ they retain the same charge over the non-constant capacitance portion of the $C-V$ characteristic. Since the states are donor-like and always empty for all depletion biasing, one expects a positive $Q_{IT}$ and a negative shifting for the entire depletion part of the $C-V$ characteristic.

(d) A donor-like level very close to $E_v$ is always filled and neutral for the non-constant capacitance portion of the $C-V$ curve. There will be no observable $C-V$ shift due to such states.

*Note:* This problem points out the difficulty of detecting $E_{IT}$ states that are very close to the band edges.
18.12
The two halves of the MOS-C may be viewed as separate capacitors.

Before irradiation, each half will contribute precisely one-half of the observed capacitance, each yielding a $C-V$ characteristic like that labeled "$\frac{1}{2}$ before" in the figure below. After irradiation, the $C-V$ characteristic of the affected half (labeled "$\frac{1}{2}$ after" in the figure below) will be shifted toward negative voltages due to the apparent $Q_F$. Graphically combining the "$\frac{1}{2}$ before" and "$\frac{1}{2}$ after" curves yields the total expected "after" curve.

18.13
(a) The shift in the $g_d - V_G$ characteristic after +BT stressing is symptomatic of mobile ions in the oxide.

(b) Conceptually extrapolating the $g_d - V_G$ curves into the $V_G$ axis, we conclude that the turn-on voltage has shifted negatively ~ 2V after +BT stressing. The device is now obviously "off" when $V_G = -2V$ and $V_G = -3V$. Moreover, the $V_G = -4V$ state after stressing is equivalent to the $V_G = -2V$ state before stressing. Thus,
(a) \( V_T \) will shift in the \(-V_G\) direction. Since \( Q_F \) is positive, an apparent \( Q_F \) causes a negative shift in the threshold voltage.

\[ V_T \leftarrow V_{T0} \rightarrow +V_G \text{ (apparent } Q_F \neq 0) \]

(b) The gate material affects \( \phi_{MS} \). With \( \Phi_M' - \chi' = -0.03 \text{ eV for Al (see the Fig. 18.3 caption)} \) and \( \Phi_M' - \chi' = 0.63 \text{ eV for Cu (from Table 18.1)} \), \( \phi_{MS} \) and hence \( V_T \) will increase by 0.66V in going from an Al to a Cu gate.

\[ V_{T0} \rightarrow V_T \rightarrow +V_G \text{ (Al } \rightarrow \text{ Cu gate)} \]

(c) The substrate doping affects both \( \phi_{MS} \) and \( V_T' \). As given by Eq.(18.22),

\[ V_T' = 2\phi_F + \frac{K_S}{K_O} x_0 \sqrt{\frac{4qN_A}{K_S} \phi_F} \]

where \( \phi_F = \frac{kT}{q} \ln \left( \frac{N_A}{n_i} \right) \)

Also

\[ (E_C - E_F)_{FB} = E_G/2 - (E_I - E_F)_{FB} = E_G/2 + q\phi_F \]

and

\[ \phi_{MS} = (1/q)[\Phi_M' - \chi' - (E_C - E_F)_{FB}] = (1/q)[\Phi_M' - \chi' - E_G/2] - \phi_F \]

Since \( \phi_T \) increases with doping, \( \phi_{MS} \) decreases and \( V_T' \) increases with increasing \( N_A \). However, the increase in \( V_T' \) is greater than the decrease in \( \phi_{MS} \), and \( V_T = V_T' + \phi_{MS} \) increases with an increase in substrate doping.

\[ V_{T0} \rightarrow V_T \rightarrow +V_G \text{ (increased } N_A) \]

(d) In general, \( x_0 \) enters into the determination of both \( V_T' \) and \( V_{FB} \). However, because the MOSFET is specified to be ideal except for \( \phi_{MS} \neq 0 \), \( x_0 \) in this problem affects only \( V_T' \).

Inspecting the \( V_T' \) expression quoted in part (b), one rapidly concludes \( V_T' \), and therefore \( V_T \), decrease with decreasing \( x_0 \).

\[ V_T \leftarrow V_{T0} \rightarrow +V_G \text{ (decreased } x_0) \]

(e) To first order, the implantation of Boron into the near surface region of the Si is equivalent to adding a negative fixed charge to the system. — The threshold voltage shifts in the \(+V_G\) direction.

\[ V_{T0} \rightarrow V_T \rightarrow +V_G \text{ (Boron implantation)} \]
(a) Adding the voltage shift due to the ion implanted charge (Eq. 18.25) to the regular flat band expression (Eq. 18.20), one obtains

\[
V_{FB} = \phi_{MS} - \frac{Q_F}{C_0} - \frac{Q_{MY}}{C_0} - \frac{Q_{TT(0)}}{C_0} - \frac{Q_I}{C_0}
\]

\[
= \phi_{MS} - q \frac{x_0}{K_0 \varepsilon_0} \left[ \frac{Q_F}{q} + \frac{Q_{MY}}{q} + \frac{Q_{TT(0)}}{q} + \frac{Q_I}{q} \right]
\]

For the given device

\[
V_{FB} = -0.46 - \frac{(1.6 \times 10^{-19})(5 \times 10^{-6})}{(3.9)(8.85 \times 10^{-14})} (2 \times 10^{11} + 0 + 0 - 4 \times 10^{11}) \approx 0
\]

(b)

\[
\dot{V}_T = 2\phi_F - \frac{K_s}{K_O} x_0 \sqrt{\frac{4qN_D}{K_S \varepsilon_0}} (\phi_F)
\]

\[
\phi_F = - \frac{kT}{q} \ln(N_D/n_i) = -0.0259 \ln(10^{15}/10^{10}) = -0.298V
\]

\[
V_T = - (2)(0.298) - \frac{(11.8)}{(3.9)} (5 \times 10^{-6}) \left[ \frac{(4)(1.6 \times 10^{-19})(10^{15})(0.298)}{(11.8)(8.85 \times 10^{-14})} \right]^{1/2}
\]

\[
= -0.80V
\]

and

\[
V_T = V_T^\prime + V_{FB} = V_T^\prime = -0.80V
\]

(c) Enhancement mode device. For the given p-channel device there is no inversion-layer at zero bias and therefore no drain current when \(V_G = 0\). A MOSFET which is "off" at zero bias is referred to as an enhancement mode device.
Combining Eqs.(18.21), (18.20), and (18.25), one can write

\[ V_T = V'_T + \phi_{MS} - \frac{Q_F}{C_0} - \frac{Q_M Y_M}{C_0} - \frac{Q_{IT(0)}}{C_0} - \frac{Q_I}{C_0} \]

Since there are no interfacial traps and no mobile ions in the oxide, \( Q_M = 0 \) and \( Q_{IT} = 0 \). Also \( C_0 = K_0 \epsilon_0 / x_0 \) and \( Q_I = -q N_I \). Thus the \( V_T \) expression simplifies to

\[ V_T = V'_T + \phi_{MS} - q \frac{x_0}{K_0 \epsilon_0} (Q_F/q - N_I) \]

Solving the preceding equation for \( N_I \) then gives

\[ N_I = \frac{Q_F}{q} + \frac{1}{q} \frac{K_0 \epsilon_0}{x_0} (V_T - V'_T - \phi_{MS}) \]

\( Q_F/q \) and \( V_T \) are specified in the statement of the problem. However, we need to determine \( \phi_{MS} \) and \( V_T' \). Because the MOSFET is an Al–SiO\(_2\)–Si device, we can read \( \phi_{MS} \) directly from Fig. 18.3. For \( N_A = 10^{17}/\text{cm}^3 \), one finds \( \phi_{MS} = -1.02\text{V} \). The ideal-device threshold voltage can be computed using Eq.(18.22).

\[ V_T' = 2 \phi_F + \frac{K_S}{K_O} x_0 \sqrt{\frac{4 q N_A}{K_S \epsilon_0}} \phi_F \]

\[ \phi_F = \frac{kT}{q} \ln(N_A/n_t) = 0.0259 \ln(10^{17}/10^{10}) = 0.417\text{V} \]

\[ V_T' = (2)(0.417) + \frac{(11.8)}{(3.9)} (10^{-6}) \left[ \frac{(4)(1.6 \times 10^{-19})(10^{17})(0.417)}{(11.8)(8.85 \times 10^{-14})} \right]^{1/2} \]

\[ = 1.32\text{V} \]

Finally, substituting into the \( N_I \) expression, we obtain

\[ N_I = 10^{11} + \frac{(3.9)(8.85 \times 10^{-14})}{(1.6 \times 10^{-19})(10^{-6})} (0.5 - 1.32 + 1.02) \]

or

\[ N_I = 5.31 \times 10^{11} \text{ boron ions/cm}^2 \]