CHAPTER 18

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 $T = 150^\circ C$, V_G such that $\mathcal{E}_{ox} < 10^6$ 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_{IT} 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_{IT} 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.

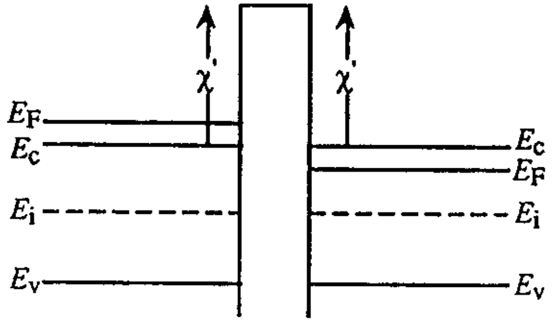
(h) A depletion–mode transistor is a MOSFET that is "on" or conducting when $V_G = 0$.

(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.

18.2

(a)



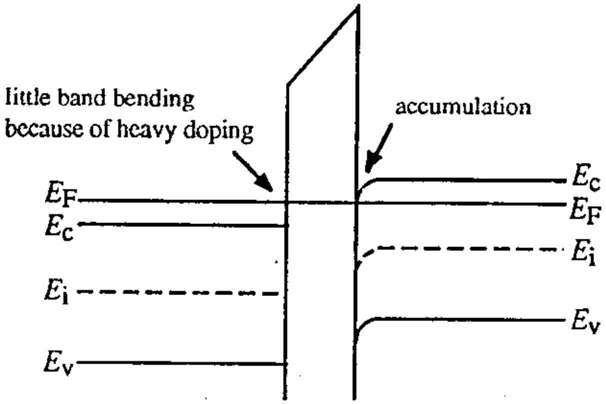
(b) $$\phi_{MS} = \frac{1}{q}(\Phi_M - \Phi_S) = [\chi' - (E_F - E_c)_{\text{poly-Si}}] - [\chi' + (E_c - E_F)_{\text{FB,crystalline-Si}}]$$

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

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

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

(c) $\boxed{\text{Accumulation}}$ biased. When $V_G = 0$ the polysilicon side of the part (a) diagram is lowered, yielding



18.3

In general

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

where

$$\Phi_M' - \chi' = \begin{cases} -0.03\text{eV} & \text{...Al} \quad \text{(See Fig. 18.3 caption.)} \\ -0.18\text{eV} & \text{...}n^+\text{ poly} \quad \text{(See Fig. 18.3 caption.)} \\ (E_0 - E_F)_{p+\text{ poly}} - \chi' = (\chi' + E_G) - \chi' = E_G = 1.12\text{eV} & \text{...}p^+\text{ poly} \end{cases}$$

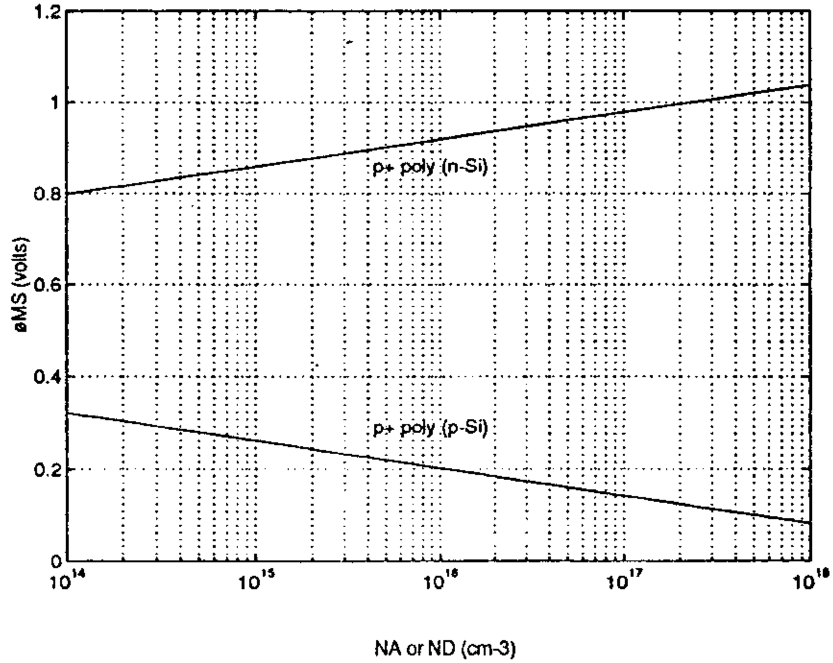
Also

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

or

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

The results of the p^+ 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 $E_c - E_i \cong E_G/2$. the more accurate value of $E_c - E_i = 0.57\text{eV}$ was used in constructing Fig. 18.3.



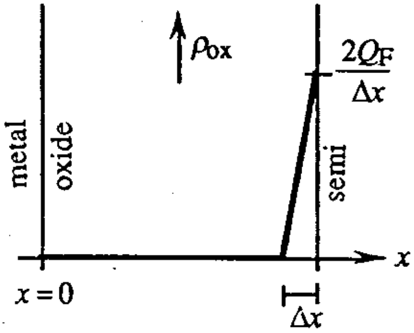
MATLAB program script...

```
%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);
øMSn=A-EcEFn;
øMSp=A-EcEFp;

%Plotting result
semilogx(NB,øMSn,NB,øMSp);  grid
xlabel('NA or ND (cm-3)');  ylabel('øMS (volts)')
```

18.5

(a) $\Delta V_G(\text{fixed charge}) = -Q_F/C_o$ ...Eq. (18.15)

(b) We are given



or mathematically

$$\rho_{ox} = \begin{cases} 0 & \text{...}0 \le x \le x_o\text{-}\Delta x \\ \dfrac{2Q_F}{\Delta x^2}x' & \text{...}0 \le x' \le \Delta x, \text{ where } x' = x\text{-}x_o\text{+}\Delta x \end{cases}$$

Substituting ρ_{ox} into Eq.(18.11) gives

$$\Delta V_G = -\frac{1}{K_O\varepsilon_0}\int_0^{x_o} x\rho_{ox}dx = -\frac{1}{K_O\varepsilon_0}\left(\frac{2Q_F}{\Delta x^2}\right)\int_0^{\Delta x} x'(x'+x_o-\Delta x)dx'$$

and

$$\boxed{\Delta V_G = -\frac{Q_F}{C_o}\left(1-\frac{\Delta x}{3x_o}\right)}$$

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

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

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

Provided $x_o >> \Delta x$, 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_o is only $10\Delta x$.

18.4

(a) Given $\rho_{ion} = \rho_0 = \text{constant}$,

$$\Delta V_G\begin{pmatrix}\text{mobile}\\\text{ions}\end{pmatrix} = -\frac{1}{K_O\varepsilon_0}\int_0^{x_o} x\rho_0 dx = -\frac{\rho_0 x_o^2}{2K_O\varepsilon_0}$$

$$= -\frac{(1.6\times10^{-19})(10^{18})(10^{-5})^2}{(2)(3.9)(8.85\times10^{-14})}$$

$$= -\ 23.2\text{V}$$

(b) Here

$$\rho_{ion} = Q_M\delta(x_o)$$

where

$$Q_M = \int_0^{x_o}\rho_{ion}(x)dx = \rho_0 x_o$$

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

$$\Delta V_G\begin{pmatrix}\text{mobile}\\\text{ions}\end{pmatrix} = -\frac{Q_M}{C_o} = -\frac{x_o}{K_O\varepsilon_0}\rho_0 x_o = -\frac{\rho_0 x_o^2}{K_O\varepsilon_0}$$

Clearly the ΔV_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

$$V_{FB} = \phi_{MS} - \frac{Q_F}{C_o} = \phi_{MS} - \frac{x_o}{K_O\varepsilon_0}Q_F$$

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

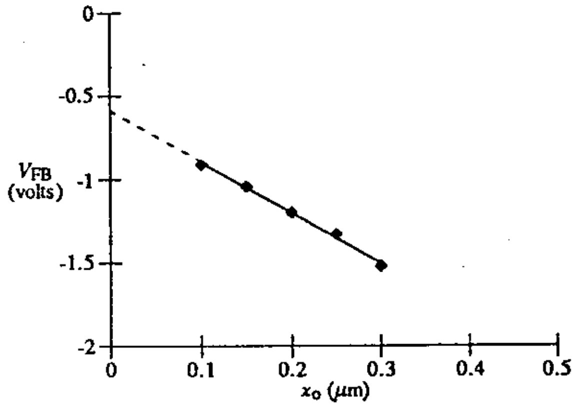
(b) The given V_{FB} versus x_o data is plotted below. A least squares fit through the data yields

$$V_{FB} = -0.596 - (3.02\times10^4)x_o \qquad ...x_o \text{ in cm}$$

Thus

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

$$Q_F/q = -K_O\varepsilon_0(slope)/q = \frac{(3.9)(8.85\times10^{-14})(3.02\times10^4)}{1.6\times10^{-19}} = \mathbf{6.52\times10^{10}/cm^2}$$



18.7

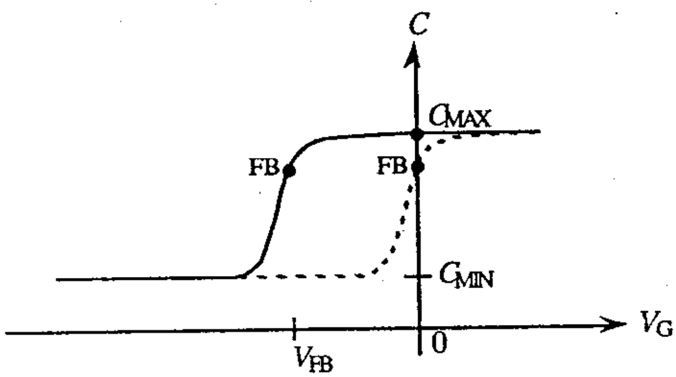
(a) $\boxed{Q_M \neq 0}$. If there is no charge in the oxide, if $\rho_{ox} = 0$, then $\mathcal{E}_{ox}$ = constant and the oxide energy bands are a linear function of position. However, if $\rho_{ox} \neq 0$, $\mathcal{E}_{ox}$ becomes a function of position and the oxide energy bands in turn exhibit curvature. A concave curvature as pictured in Fig. P18.7 is indicative of a significant positive charge, alkali ions, in the oxide.

(b) $\boxed{Q_F \neq 0}$. The normal component of the D–field, where $D = \varepsilon\mathcal{E}$, 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 $\mathcal{E} = (1/q)(dE_c/dx) = 0$ on the oxide side of the interface. On the semiconductor side of the interface $\mathcal{E}$ 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 $Q_{\mathrm{interface}} = K_S\varepsilon_0\mathcal{E}_S$ and the interface charge must be positive. The interfacial charge could arise from alkali ions, iterfacial 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 $Q_{\mathrm{interface}}$. 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 $Q_F \neq 0$.

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 ΔV_G(fixed charge) expression. This apparent inconsistency is resolved if the mathematical development is examined carefully. To be precise, by including Q_F in ρ_{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 $V_G = 0$.



(b) Given $\quad C_{MAX} = C_O = \dfrac{K_O \varepsilon_0 A_G}{x_o}$

we conclude

$$x_o = \frac{K_O \varepsilon_0 A_G}{C_O} = \frac{(3.9)(8.85\times10^{-14})(2.9\times10^{-3})}{200\times10^{-12}} = 5.00\times10^{-6}\text{ cm}$$

Also

$$C_{MIN} = \frac{C_O}{1 + \dfrac{K_O W_T}{K_S x_o}}$$

making $\quad W_T = \dfrac{K_S x_o}{K_O}\left(\dfrac{C_O}{C_{MIN}} - 1\right) = \dfrac{(11.8)(5\times10^{-6})}{(3.9)}\left(\dfrac{200}{67} - 1\right) = 3.00\times10^{-5}\text{cm} = 0.3\mu\text{m}$

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

$$N_D \cong 10^{16}/\text{cm}^3$$

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

$$\Delta V_G\Big|_{\text{flat band}} = V_{FB} = \phi_{MS} - \frac{Q_F}{C_o}$$

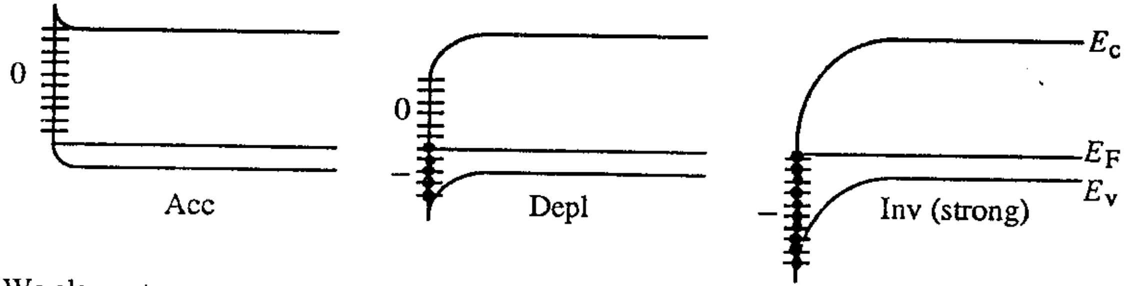
$V_{FB} = -0.71$ in the statement of the problem. Also, for an $N_D = 10^{16}/\text{cm}^3$ Al(n-Si) device, we conclude from Fig. 18.3 that $\phi_{MS} = -0.24$V. Thus

$$Q_F = C_o(\phi_{MS} - V_{FB}) = \frac{C_O}{A_G}(\phi_{MS} - V_{FB}) = \frac{200\times10^{-12}}{2.9\times10^{-3}}(-0.24+0.71)$$

$$= 3.24\times10^{-8}\text{ coul/cm}^2$$

18.9

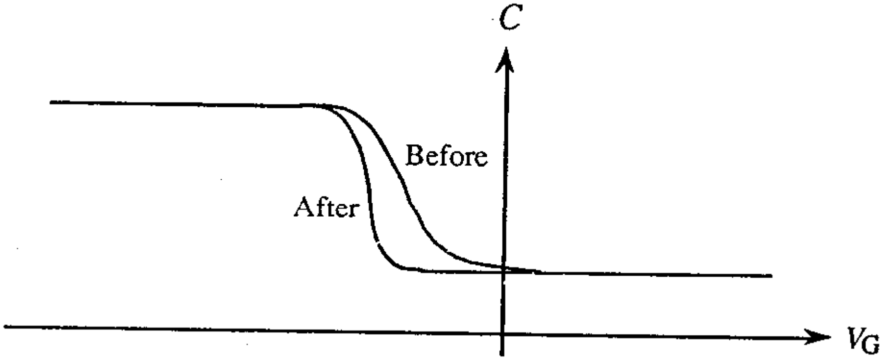
We infer from the C–V characteristics that the MOS-C is a p-bulk device. Also, we know that acceptor-like traps are negatively charged when filled with an electron and neutral when empty. For a p-bulk MOS-C the effect of biasing on the occupation and charge state of the acceptor-like traps is summarized in the following figure.



We also note

$$\Delta V_G = -\frac{Q_{IT}}{C_o}$$

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

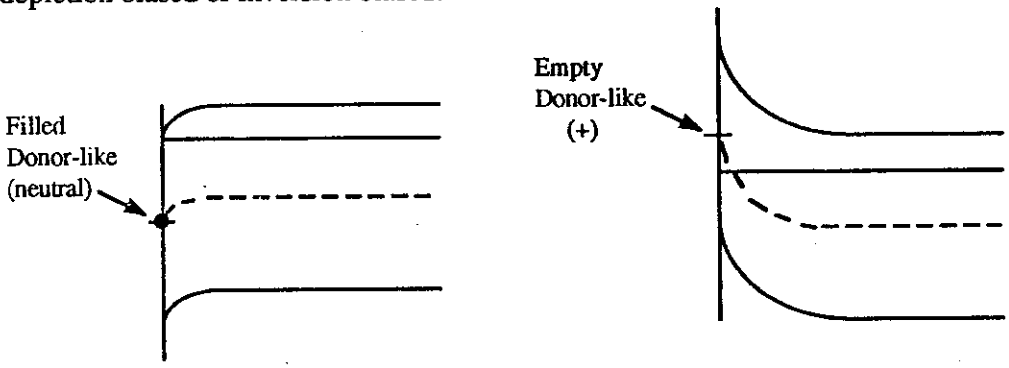


18.10

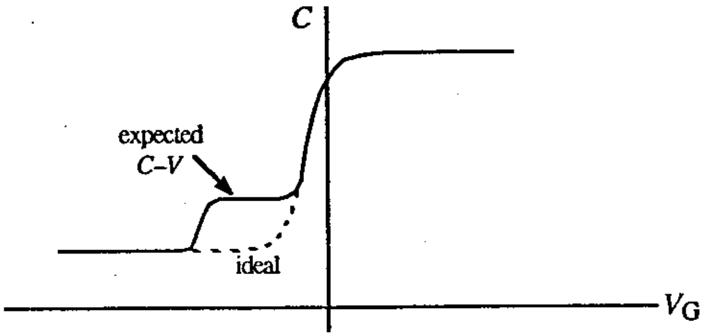
From the answer to Problem 1.5 (see Solutions Manual pages 1-2 and 1-3), we know that there are 6.78×10^{14} atoms/cm^2 and 9.59×10^{14} atoms/cm^2 on the (100) and (110) surface planes, respectively. If one assumes the number of residual "dangling bonds" is proportional to the number of Si surface atoms, then the $\boxed{\text{(110) surface}}$ 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.



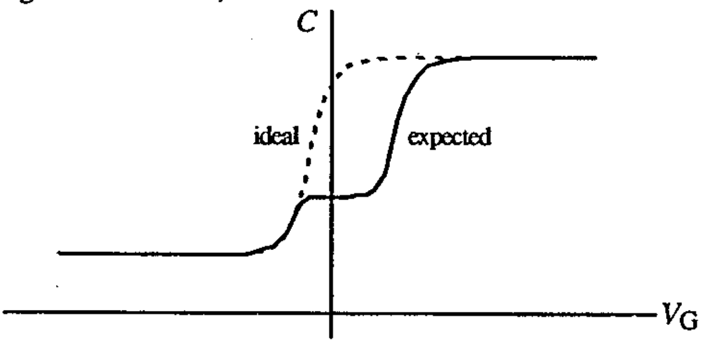
Clearly, there is no shift in the C–V curve when the device is accumulation and $|\phi_S| < |\phi_F|$ depletion biased. However, when $|\phi_S| > |\phi_F|$ depletion biased or inversion biased, the characteristics are translated $\Delta V_G = -Q_{IT}/C_0$ = constant negative value along the voltage axis.



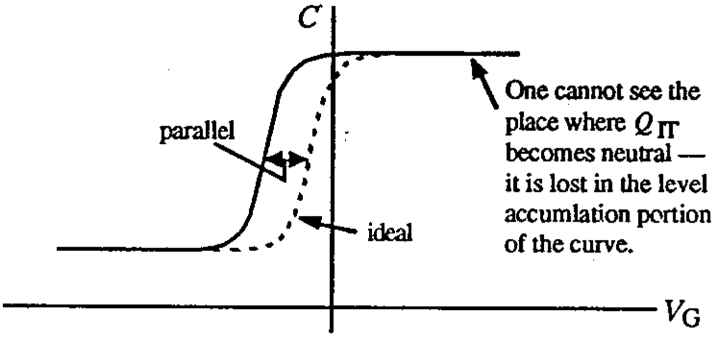
(b) For acceptor-like interfacial traps

Bias	Position of E_F	Trap Occupation	Charge State	ΔV_G shift
acc, $|\phi_S| < |\phi_F|$ depl	above E_{IT}	filled	negative	toward $+V_G$
$|\phi_S| > |\phi_F|$ depl, inv	below E_{IT}	empty	neutral	none

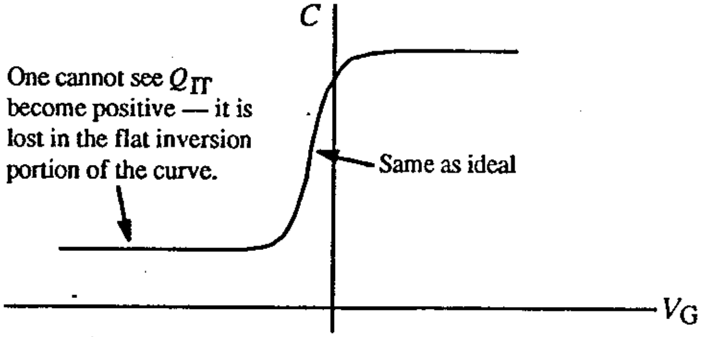
From the preceding one concludes,



(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.



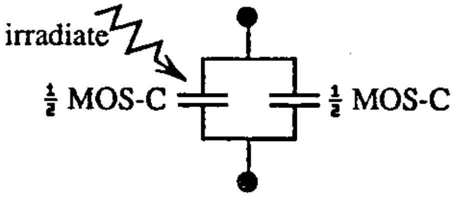
(d) A donor-like level very close to E_v is always filled and neutral for the non-constant capacitance portion of the C–V curve. There will be no observable C–V shift due to such states.



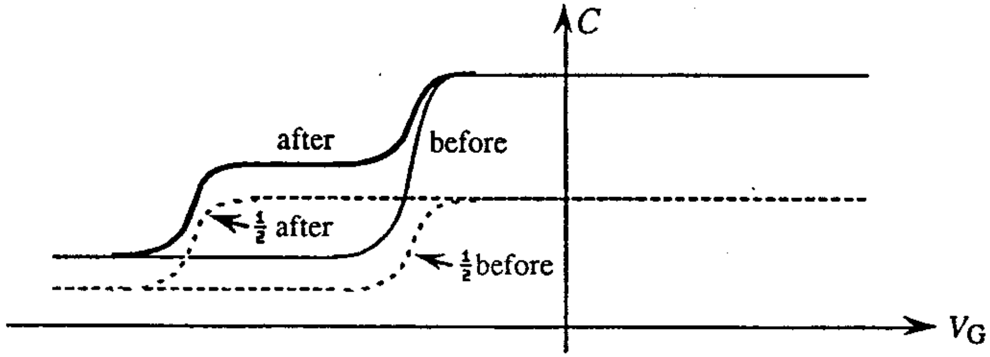
Note: This problem points out the difficulty of detecting E_{IT} states that are very close to the band edges.

18.12

The two halves of the MOS-C may be viewed as separate capacitors.



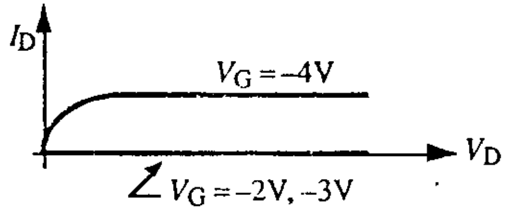
Before irradiation, each half will contribute precisely one-half of the observed capacitance, each yielding a C–V characteristic like that labeled "½ before" in the figure below. After irradiation, the C–V characteristic of the affected half (labeled "½ after" in the figure below) will be shifted toward negative voltages due to the apparent Q_F. Graphically combining the "½ before" and "½ 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,



18.14

(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.

$$V_T \leftarrow V_{T0} \longrightarrow +V_G \quad (\text{apparent } Q_F \neq 0)$$

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

$$V_{T0} \rightarrow V_T \longrightarrow +V_G \quad (\text{Al} \rightarrow \text{Cu gate})$$

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

$$V_T' = 2\phi_F + \frac{K_S}{K_O} x_o \sqrt{\frac{4qN_A}{K_S\varepsilon_0}\phi_F} \qquad \text{where} \qquad \phi_F = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

Also

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

and

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

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

$$V_{T0} \rightarrow V_T \longrightarrow +V_G \quad (\text{increased } N_A)$$

(d) In general, x_o 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_o 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_o.

$$V_T \leftarrow V_{T0} \longrightarrow +V_G \quad (\text{decreased } x_o)$$

(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.

$$V_{T0} \rightarrow V_T \longrightarrow +V_G \quad (\text{Boron implantation})$$

18.15

(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

$$V_{FB} = \phi_{MS} - \frac{Q_F}{C_o} - \frac{Q_M\gamma_M}{C_o} - \frac{Q_{IT}(0)}{C_o} - \frac{Q_I}{C_o}$$

$$= \phi_{MS} - q\frac{x_o}{K_O\varepsilon_0}\left[\frac{Q_F}{q} + \frac{Q_M\gamma_M}{q} + \frac{Q_{IT}(0)}{q} + \frac{Q_I}{q}\right]$$

For the given device

$$V_{FB} = -0.46 - \frac{(1.6\times10^{-19})(5\times10^{-6})}{(3.9)(8.85\times10^{-14})}\left(2\times10^{11} + 0 + 0 - 4\times10^{11}\right) \cong \mathbf{0}$$

(b)

$$V_T' = 2\phi_F - \frac{K_S}{K_O}x_o\sqrt{\frac{4qN_D}{K_S\varepsilon_0}(-\phi_F)}$$

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

$$V_T' = -(2)(0.298) - \frac{(11.8)}{(3.9)}(5\times10^{-6})\left[\frac{(4)(1.6\times10^{-19})(10^{15})(0.298)}{(11.8)(8.85\times10^{-14})}\right]^{1/2}$$

$$= -0.80\text{V}$$

and

$$V_T = V_T' + V_{FB} = V_T' = -\ \mathbf{0.80V}$$

(c) $\boxed{\text{Enhancement mode}}$ 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.

18.16

Combining Eqs.(18.21), (18.20), and (18.25), one can write

$$V_T = V_T' + \phi_{MS} - \frac{Q_F}{C_o} - \frac{Q_M\gamma_M}{C_o} - \frac{Q_{IT}(0)}{C_o} - \frac{Q_I}{C_o}$$

Since there are no interfacial traps and no mobile ions in the oxide, $Q_M = 0$ and $Q_{IT} = 0$. Also $C_o = K_O\varepsilon_0/x_o$ and $Q_I = -qN_I$. Thus the V_T expression simplifies to

$$V_T = V_T' + \phi_{MS} - q\frac{x_o}{K_O\varepsilon_0}(Q_F/q - N_I)$$

Solving the preceding equation for N_I then gives

$$\boxed{N_I = \frac{Q_F}{q} + \frac{1}{q}\frac{K_O\varepsilon_0}{x_o}(V_T - V_T' - \phi_{MS})}$$

Q_F/q and V_T are specified in the statement of the problem. However, we need to determine ϕ_{MS} and V_T'. Because the MOSFET is an Al–SiO_2–Si device, we can read ϕ_{MS} directly from Fig. 18.3. For $N_A = 10^{17}/cm^3$, one finds $\phi_{MS} = -1.02V$. The ideal-device threshold voltage can be computed using Eq.(18.22).

$$V_T' = 2\phi_F + \frac{K_S}{K_O}x_o\sqrt{\frac{4qN_A}{K_S\varepsilon_0}\phi_F}$$

$$\phi_F = \frac{kT}{q}\ln(N_A/n_i) = 0.0259\ln(10^{17}/10^{10}) = 0.417V$$

$$V_T' = (2)(0.417) + \frac{(11.8)}{(3.9)}(10^{-6})\left[\frac{(4)(1.6\times10^{-19})(10^{17})(0.417)}{(11.8)(8.85\times10^{-14})}\right]^{1/2}$$

$$= 1.32V$$

Finally, substituting into the N_I expression, we obtain

$$N_I = 10^{11} + \frac{(3.9)(8.85\times10^{-14})}{(1.6\times10^{-19})(10^{-6})}(0.5 - 1.32 + 1.02)$$

or

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