8.40 Consider a silicon pn junction with parameters as described in Problem 8.8. (*a*) Calculate and plot the depletion capacitance and diffusion capacitance over the voltage range $-10 \le V_a \le 0.75$ V. (*b*) Determine the voltage at which the two capacitances are equal.

****

8.8 A one-sided p⁺n silicon diode has doping concentrations of $N_a = 5 \times 10^{17}$ cm^{-3} and $N_d = 8 \times 10^{15}$ cm^{-3}. The minority carrier lifetimes are $\tau_{n0} = 10^{-7}$ s and $\tau_{p0} = 8 \times 10^{-8}$ s. The cross-sectional area is $A = 2 \times 10^{-4}$ cm^2.

****

- a) Plot C_j & C_d (pF) for $0 \le V_a \le 0.75$ V. Then, plot C_j (pF) for $-10 \le V_a \le 0.75$ V. For both plots use a vertical scale of 0 to 25 pF. Also, tabulate C_j & C_d for V_a = -8, -4, 0, 0.4, 0.5, and 0.6 V. [Three columns- V_a, C_j, & C_d.]

$V_a = V_0$, Table B.4 $n_i = 1.5\times10^{10}$ cm^{-3}

a) $C_j = C'(A)$ where, using (7.42),

$$C' = \left\{ \frac{e \epsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)} \right\}^{1/2} \quad \text{where } V_R = -V_a.$$

Per (8.105), $C_d = \frac{1}{2V_t}\left[I_{p0}\tau_{p0} + I_{n0}\tau_{n0}\right]$

$$(8.94) \quad I_{p0} = \frac{eAD_p p_{n0}}{L_p} e^{V_0/(k_BT/e)} \qquad L_p = \sqrt{D_p \tau_{p0}}$$

$$(8.97) \quad I_{n0} = \frac{eAD_n n_{p0}}{L_n} e^{V_0/(k_BT/e)} \qquad L_n = \sqrt{D_n \tau_{n0}}$$

per Note on page 323, $D_p = 10 \frac{cm^2}{s}$ & $D_n = 25 \frac{cm^2}{s}$

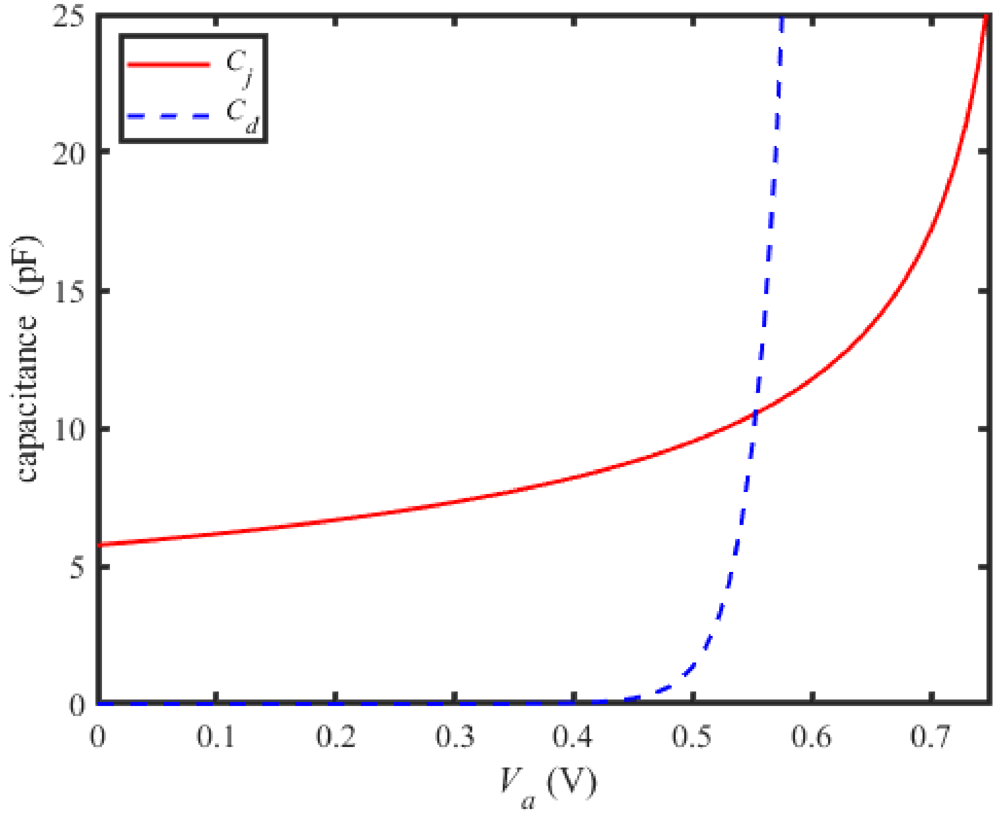
n-region $n_{n0} \simeq N_d = 8\times10^{15}$ cm^{-3} $= 8\times10^{21}$ m^{-3}

$$(4.43) \quad p_{n0} = \frac{n_i^2}{n_{n0}} = \frac{(1.5\times10^{10})^2}{8\times10^{15}} = 28125 \text{ cm}^{-3} = 2.8125\times10^{10} \text{ m}^{-3}$$

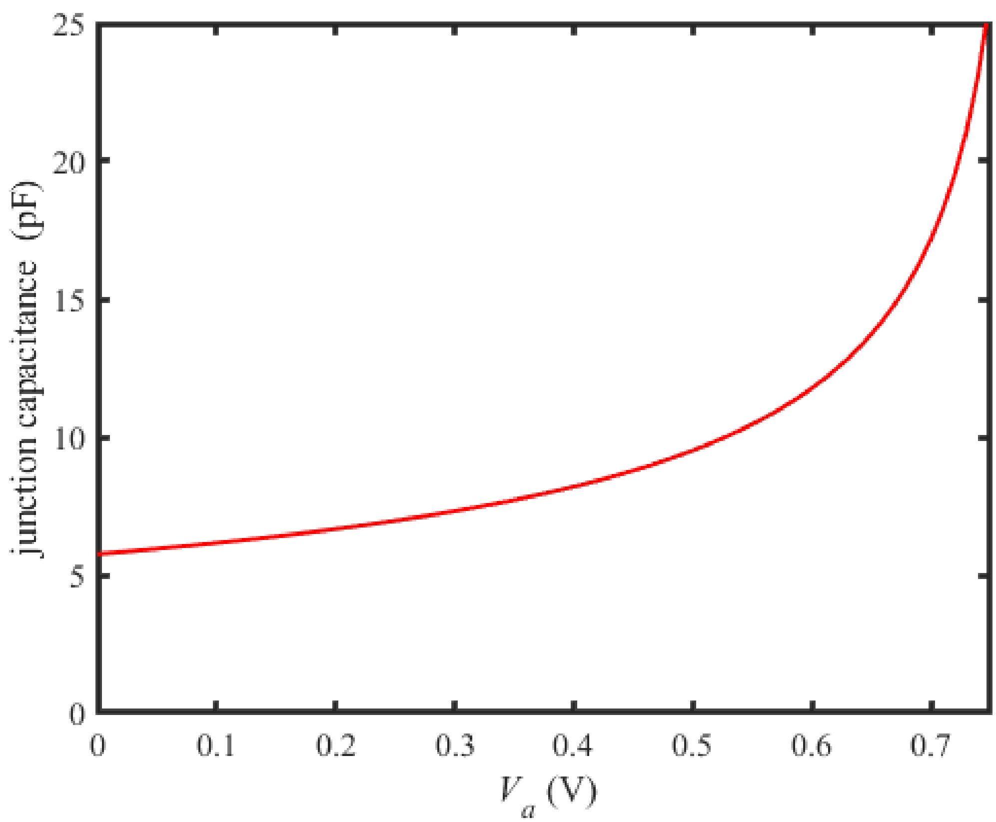
p-region $p_{p0} \simeq N_a = 5\times10^{17}$ cm^{-3} $= 5\times10^{23}$ m^{-3}

$$n_{p0} = \frac{n_i^2}{p_{p0}} = \frac{(1.5\times10^{10})^2}{5\times10^{17}} = 450 \text{ cm}^{-3} = 4.5\times10^{8} \text{ m}^{-3}$$

a) cont.



C_j
C_d
capacitance (pF)
25
20
15
10
5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
V_a (V)



junction capacitance (pF)
25
20
15
10
5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
V_a (V)

V_a (V)	C_j (F)	C_d (F)
-8	1.72454e-12	2.16757e-155
-4	2.33629e-12	3.41205e-88
0	5.75672e-12	5.37104e-21
0.4	8.200085e-12	2.81684e-14
0.5	9.51478e-12	1.347996e-12
0.6	1.17687e-11	6.45081e-11

```
% EE 362 problem 8.40(p8_40.m)
% Plot Cj and Cd for a silicon pn junction.
clear; clc; close all;
kB = 1.380649e-23; % Boltzmann constant (J/K)
qe = 1.602176634e-19; % magnitude of electron charge (C)
T = 300; % temperature (K)
Na = 5e23; Nd = 8e21; % doping concentrations (m^-3)
A = 2e-8; % junction areas (m^2)
tp0 = 8e-8; tn0 = 1e-7; % minority carrier lifetimes (s)
Dp = 1e-4; Dn = 2.5e-3; % diffusion coefficients (p. 323 note)
ni = 1.5e16; % intrinsic charge conc. Si at 300 K (m^-3) Table B.4
es = 11.7*8.8541878e-12; % Si electrical permittivity (F/m) Table B.4
Vt = kB*T/qe;  % thermal voltage (V)
pn0 = ni^2/Nd; np0 = ni^2/Na; % therm. equil. minority carr. conc.(m^-3)
Ln = sqrt(Dn*tn0); Lp = sqrt(Dp*tp0); % diffusion lengths (m)
Vbi = Vt*log(Na*Nd/ni^2); % built in voltage (V) per (7.10)
Va = -10:0.01:0.75; % vector of applied voltages (V)
Vat = [-8,-4,0,0.4,0.5,0.6]; % vector of applied voltages for table (V)
% Calculate junction capacitance.  Note VR = -Va in (7.42)
Cj = A*sqrt(qe*es*Na*Nd/2/(Na+Nd)./(Vbi-Va)); % (F)
Cjt = A*sqrt(qe*es*Na*Nd/2/(Na+Nd)./(Vbi-Vat)); % (F)
% Calc. diff. capacit. w/ (8.94), (8.97), & (8.105). Note V0 = Va
Cd = qe*A/2/Vt*(Dp*pn0*tp0/Lp + Dn*np0*tn0/Ln)*exp(Va/Vt); % (F)
Cdt = qe*A/2/Vt*(Dp*pn0*tp0/Lp + Dn*np0*tn0/Ln)*exp(Vat/Vt); % (F)
% ******* Plot Cj & Cd in linear format *******
plot(Va,Cj*1e12,'r-',Va,Cd*1e12,'b--');
axis([0 0.75 0 25]), % define ranges for horizontal & vertical axes
xlabel('{\it V_a} (V)','fontsize',14,'fontname','times'),
ylabel('capacitance  (pF)','fontsize',14,'fontname','times'),
legend('\it C_j','\it C_d','location','NW');
% ******* Plot  Cj & Cd in semilog format *******
figure; plot(Va,Cj*1e12,'r-')
axis([0 0.75 0 25]), % define ranges for horizontal & vertical axes
```

```
xlabel('{\it V_a} (V)','fontsize',14,'fontname','times'),
ylabel('junction capacitance  (pF)','fontsize',14,'fontname','times'),
set(findobj('type','axes'),'fontsize',12,'fontname','times')
set(findobj('type','line'),'linewidth',1.5)
set(findobj('type','axes'),'linewidth',2)
```

b) Using MathCad, $C_j = C_d$ when **$V_a = 0.5233407$ V**.

Constants $kB := 1.380649 \cdot 10^{-23}$ J/K $\quad \varepsilon 0 := 8.8541878 \cdot 10^{-12}$ F/m

$qe := 1.602176634 \cdot 10^{-19}$ C

Given $T := 300$ K $\quad A := 2 \cdot 10^{-8}$ m^2 $\quad Na := 5 \cdot 10^{23}$ m^{-3} $\quad Nd := 8 \cdot 10^{21}$ m^{-3}

$\tau p0 := 8 \cdot 10^{-8}$ s $\quad \tau n0 := 1 \cdot 10^{-7}$ s

per note p. 323 $\quad Dp := 10 \cdot 10^{-4}$ m^2/s $\quad Dn := 25 \cdot 10^{-4}$ m^2/s

Table B.4, Si at 300 K $\quad ni := 1.5 \cdot 10^{16}$ m^{-3} $\quad \varepsilon s := 11.7 \cdot \varepsilon 0$

(4.43) $\quad pn0 := \dfrac{ni^2}{Nd} \qquad pn0 = 2.8125 \times 10^{10}$ m^{-3}

$np0 := \dfrac{ni^2}{Na} \qquad np0 = 4.5 \times 10^{8}$ m^{-3}

(6.63) $\quad Ln := \sqrt{Dn \cdot \tau n0} \qquad Ln = 1.58114 \times 10^{-5}$ m

(8.9) $\quad Lp := \sqrt{Dp \cdot \tau p0} \qquad Lp = 8.94427 \times 10^{-6}$ m

(7.10) $\quad Vt := \dfrac{kB \cdot T}{qe} \qquad Vt = 0.025852$ V $\qquad Vbi := Vt \cdot \ln\left(\dfrac{Na \cdot Nd}{ni^2}\right) \qquad Vbi = 0.788718$ V

Use (7.42), $V_R = -V_a$, & $C_j = C'(A)$ $\qquad Cj(Va) := \sqrt{\dfrac{qe \cdot \varepsilon s \cdot Na \cdot Nd}{2 \cdot (Vbi - Va) \cdot (Na + Nd)}} \cdot A$

Use (8.94), (8.97), (8.105), & $V_0 = V_a$

$$Cd(Va) := \frac{1}{2 \cdot Vt} \cdot \left(\frac{qe \cdot A \cdot Dp \cdot pn0}{Lp} \cdot e^{\frac{Va}{Vt}} \cdot \tau p0 + \frac{qe \cdot A \cdot Dn \cdot np0}{Ln} \cdot e^{\frac{Va}{Vt}} \cdot \tau n0 \right)$$

b) $\boxed{Cj(0.5233407) = 9.92439 \times 10^{-12}}$ F $\qquad \boxed{Cd(0.5233407) = 9.92439 \times 10^{-12}}$ F