A silicon pn junction at 300 K has uniform doping concentrations of 5×10^{16} cm^{-3} acceptor atoms on p side and 8×10^{16} #/cm^3 donor atoms on n side. The minority carrier lifetimes are $\tau_{n0} = 0.5$ µs and $\tau_{p0} = 0.4$ µs. The cross-sectional area is $0.18\,\text{mm} \times 40\,\mu\text{m}$. a) Plot C_j & C_d (pF) for $0 \le V_a \le 0.7$ V. b) Plot C_j (pF) for $-8 \le V_a \le 0.7$ V. For both plots use a vertical scale of 0 to 12 pF. c) Tabulate C_j & C_d for V_a = -8, -4, 0, 0.3, 0.5, and 0.6 V with three columns- V_a, C_j, & C_d. d) Find the voltage V_a where $C_j = C_d$. See **Note**. Recommend use of MATLAB.

Per Table B.4, $n_i = 1.5 \times 10^{10}$ cm^{-3} and $\varepsilon_s = 11.7\varepsilon_0$ for silicon at 300 K.

The junction capacitance $C_j = C'(A) = C'(0.18{\times}10^{-3})\,40{\times}10^{-6} = 7.2{\times}10^{-9}\,C'$ where, per (7.42),

$$C' = \sqrt{\frac{e\varepsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)}} \text{ where } V_{bi} = \frac{k_B T}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

from (7.10). Note that $V_R = -V_a$.

The diffusion capacitance (8.105) $C_d = \frac{1}{2V_t}\left(I_{p0}\tau_{p0} + I_{n0}\tau_{n0}\right)$ where (8.94) $I_{p0} = \frac{eAD_p p_{n0}}{L_p} e^{V_0/V_t}$ and (8.97) $I_{n0} = \frac{eAD_n n_{p0}}{L_n} e^{V_0/V_t}$ with $L_p = \sqrt{D_p \tau_{p0}}$ & $L_n = \sqrt{D_n \tau_{n0}}$. Note that $V_0 = V_a$.

Per the **Note** on p. 323 of the text, $D_n = 25$ cm^2/s and $D_p = 10$ cm^2/s for silicon at 300 K.

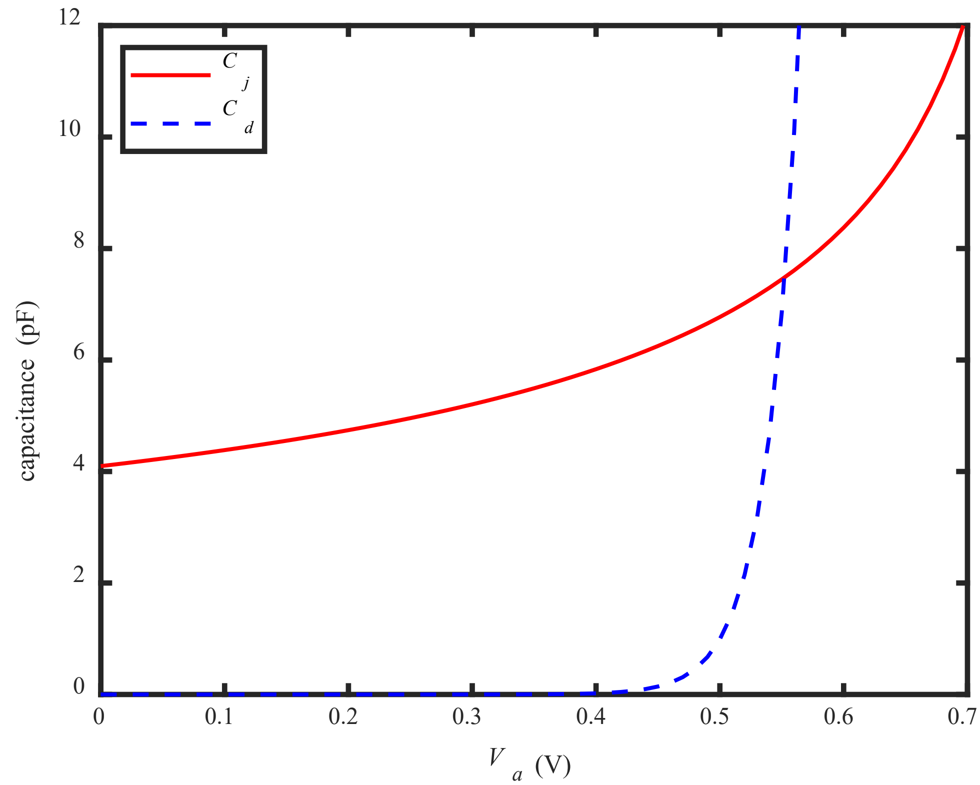
For the **<u>p-region</u>**- $p_{p0} \cong N_a = 5 \times 10^{16}$ cm^{-3} and (4.43) $n_{p0} = n_i^2 / p_{p0} = (1.5{\times}10^{10})^2/5{\times}10^{16} \Rightarrow n_{p0} \cong 4500$ cm^{-3}.

For the **<u>n-region</u>**- $n_{n0} \cong N_d = 8 \times 10^{16}$ cm^{-3} and (4.43) $p_{n0} = n_i^2 / n_{n0} = (1.5{\times}10^{10})^2/8{\times}10^{16} \Rightarrow p_{n0} \cong 2812.5$ cm^{-3}.

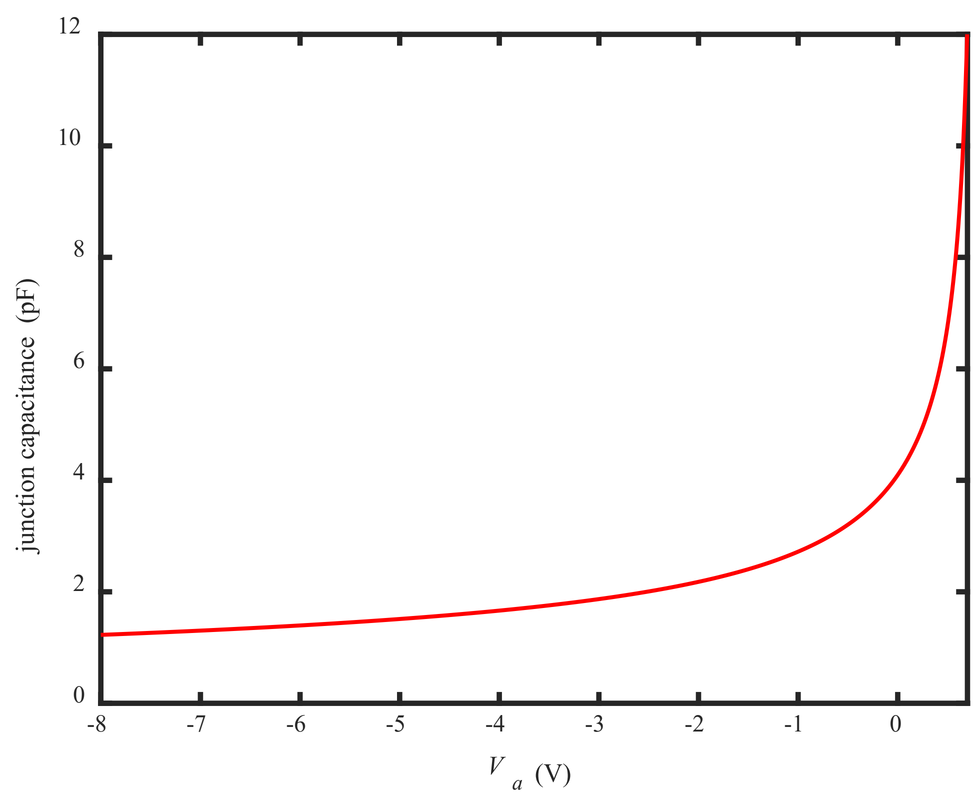
To get the results for parts a) to d), these equation and constants (in MKS units) were put into a MATLAB m-file (next) and the capacitances were calculated as V_a was stepped from -8 to 0.7 V.

```
% EE 362 problem (Si_pn_junc_capacitance.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 = 5e22; Nd = 8e22; % doping concentrations (m^-3)
A = 0.18e-3*40e-6; % junction area (m^2)
tn0 = 0.5e-6; tp0 = 0.4e-6; % 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 = -8:0.01:0.7; % applied voltages (V) for parts a) & b) plots
%Va = 0.55226:0.000001:0.55229; % applied voltages (V) for part d)
Vat = [-8,-4,0,0.3,0.5,0.6]; % applied voltages (V) for part c) table
% Calculate junction capacitance.  Note VR = -Va in (7.42)
Cj = A*sqrt(qe*es*Na*Nd/2/(Na+Nd)./(Vbi-Va)); % (F) for plots
Cjt = A*sqrt(qe*es*Na*Nd/2/(Na+Nd)./(Vbi-Vat)); % (F) for table
% 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 0.7 0 12]), % define ranges for horizontal & vertical axes
%plot(Va,Cj*1e12,'r.',Va,Cd*1e12,'b*'); % part d
%axis([0.55226 0.55229 7.481 7.483]), % part d
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([-8 0.7 0 12]), % 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)
```

a)


C j
C d
capacitance (pF)
V a (V)
12
10
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

b)


junction capacitance (pF)
V a (V)
12
10
8
6
4
2
0
-8
-7
-6
-5
-4
-3
-2
-1
0

c) Go to MATLAB variable editor to get:

V_a (V)	**C_j (F)**	**C_d (F)**
-8	1.2273e-12	1.5927e-155
-4	1.6626e-12	2.5071e-88
0	4.0967e-12	3.9465e-21
0.3	5.2044e-12	4.3251e-16
0.5	6.7711e-12	9.9048e-13
0.6	8.3751e-12	4.7399e-11

d) From graph in part a), we see that $C_d = C_j \sim 7.5$ pF when V_a is between 0.5 V and 0.6 V.

Use MATLAB m-file to determine: $C_d = C_j = 7.48229$ pF at **$V_a = 0.552276$ V**.