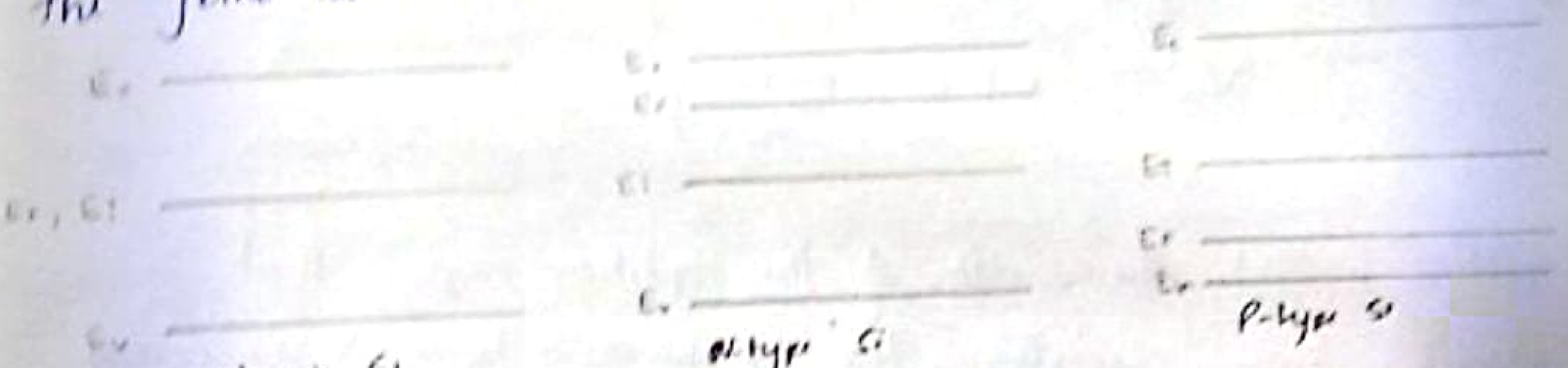
EE313
MICROELECTRONICS LABORATORY
EXPERIMENT 2
ELECTROSTATICS OF PN JUNCTION

OBJECTIVE

To simulate Si PN junction using the SIAPS 3D software, to understand its electrostatics.

THEORY

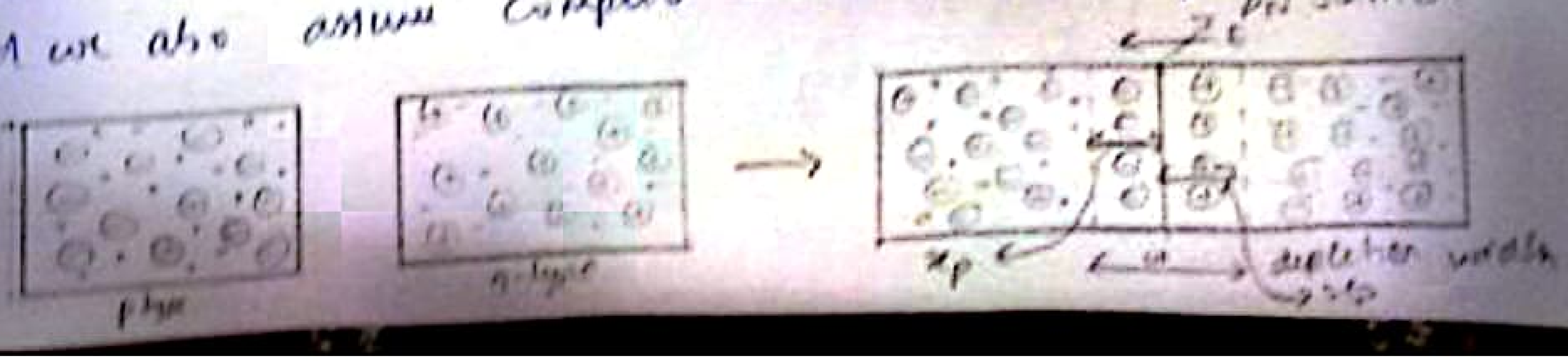
Effect of doping: when an intrinsic semiconductor is doped, its fermi level changes and gets closer to either E_v or E_c level depending on the kind of doping. Doping with donor atoms (N-type) causes the fermi level to be closer to E_c while doping with acceptor atoms (P-type) causes the fermi level to be closer to E_v.



intrinsic Si N-type Si P-type Si

PN Junction: When a P-type Si and an N-type Si are joined together, they form a junction and reach a dynamic equilibrium where diffusion current becomes same as drift current in magnitude. Moreover, the electric field becomes equal and opposite to potential gradient.

* In theoretical analysis, we assume it to be a step junction and we also assume complete ionisation takes place.



when p-type and n-type semiconductors are brought in contact, the difference in concentration of majority charge carriers causes diffusion and holes move from p-side to n-side and electrons move from n-side to p-side. These charge carriers recombine with the host carriers. This causes p-side to become -vely charged due to excess e^- and n-side to become +vely charged due to excess h^+.
This causes an electric field between n and p side which opposes the diffusion of charge carriers. This phenomenon is called drift.
At equilibrium, drift current equals diffusion current

<u>Built-in voltage</u>: Due to the electric field that develops, there is a potential difference between the n and p sides. This potential is called built in potential (V_{bi})
It is given by;

$$V_{bi} = kT \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

<u>Depletion width</u>: the width of the depletion region that is formed upon connecting the p and n type Si is called depletion width. It is the sum of depletion width of p-side and n side

$$\underset{\text{(depletion width)}}{W} = x_n + x_p$$ where, x_n = depl. width of n-side
x_p = depl. width of p-side

where $$x_n = \sqrt{\frac{2\varepsilon_s V_{bi}}{N_D\left(1+\frac{N_D}{N_A}\right)}}$$

$$x_p = \sqrt{\frac{2\varepsilon_s V_{bi}}{N_A\left(1+\frac{N_A}{N_D}\right)}}$$

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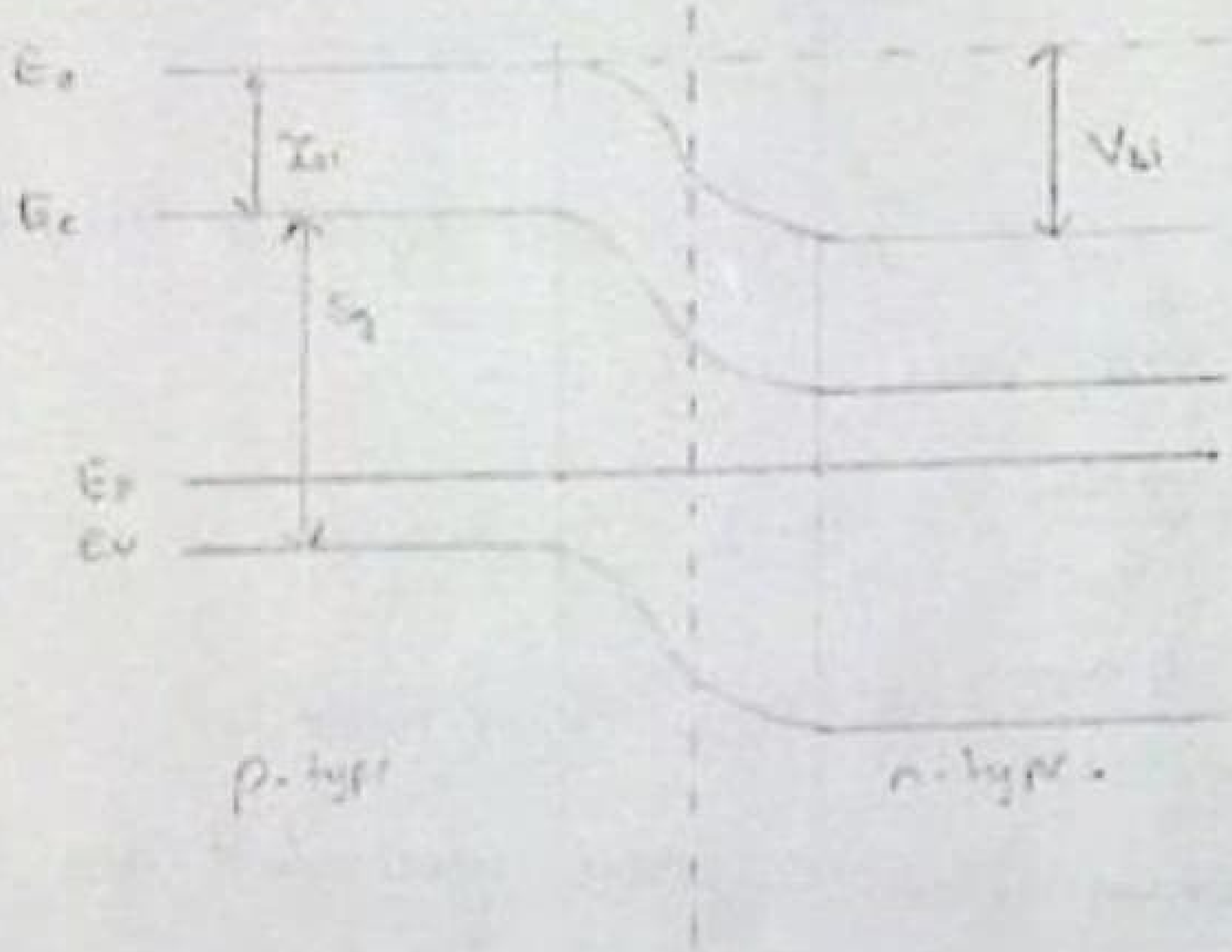
$$W = \left[\frac{2\varepsilon_{si}(V_{bi})}{q}\left(\frac{N_A+N_D}{N_AN_D}\right)\right]^{1/2}.$$

where ε_{si} = permittivity of si , N_A : Acceptor conc. N_D : Donor conc.
q - charge of e^-.

The band diagram of a typical PN junction is as follows.



Capacitance at 0V : As the junction have charges trapped inside them in the depletion region, it leads to some capacitance being generated. This capacitance per unit area at 0V is called C_0.

$$\frac{C_0}{A} = \frac{\varepsilon_{si}}{W}$$, where A - area of semiconductor cross section.

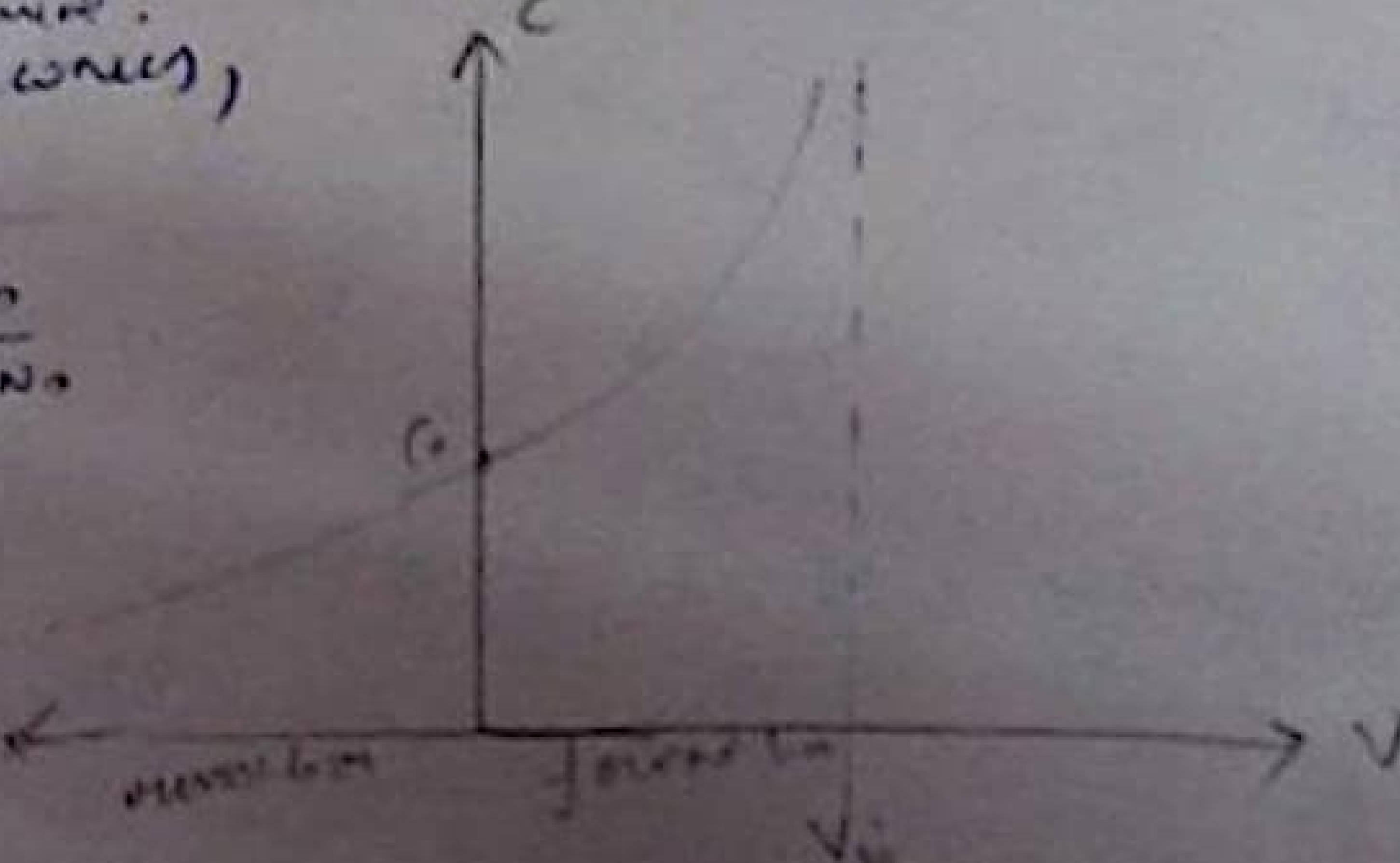
since we know that value of W, we can plug it in.

$$\frac{C_0}{A} = \sqrt{\frac{q\varepsilon_{si}}{2V_{bi}}\frac{N_AN_D}{N_A+N_D}} ,$$

If there is some external voltage (V) applied (bias), then the eqn for capacitance per unit area becomes,

$$\frac{C}{A} = \sqrt{\frac{q\varepsilon_{si}}{2(V_{bi}-V)}\frac{N_AN_D}{N_A+N_D}}$$

we see that the $C \propto \frac{1}{(V_{bi}-V)}$



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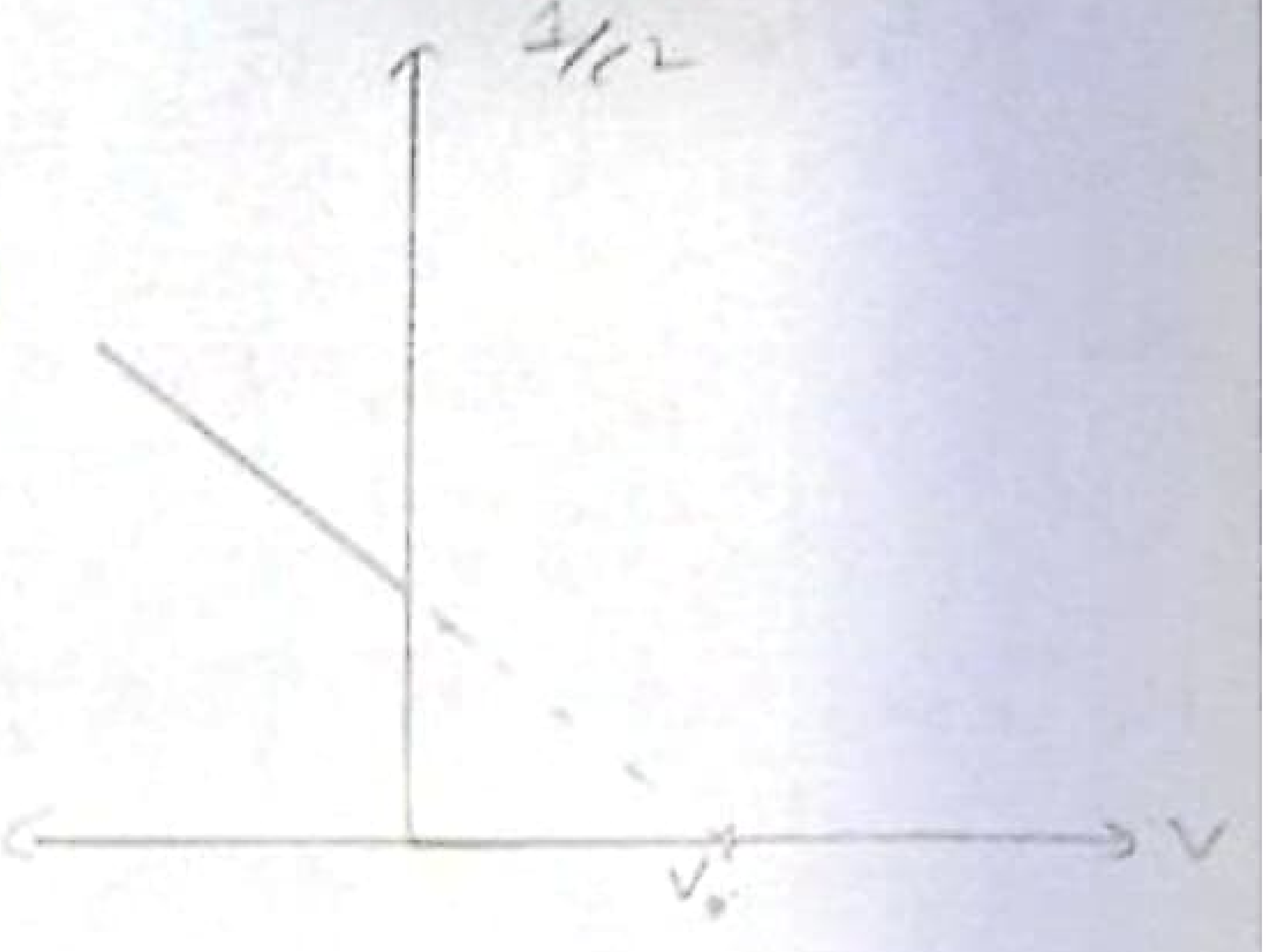
Also, we notice that,



$$\frac{A^2}{C^2} = \frac{2}{q\varepsilon_0} \frac{N_A + N_D}{N_A N_D} (V_{bi} - V)$$

$$\therefore \frac{1}{C^2} \propto (V_{bi} - V)$$

Electric field: The electric field inside the depletion region as a function of x is given as:

$$E = \begin{cases} \frac{qN_D}{\varepsilon_n}(x - x_{n0}) & ; \text{ n-side} \\ \frac{-qN_A}{\varepsilon_{s}}(x - x_{p0}) & ; \text{ p-side} \end{cases}$$

* E_{max} is the maximum electric field generated in a material. E_{max} in PN diode is given as:

$$\frac{2V_{bi}}{W} = E_{max} = -\left[\frac{2q \cdot V_{bi}}{\varepsilon_0}\left(\frac{N_A N_D}{N_A + N_D}\right)\right]^{1/2}$$

Graded P^+N junction: In general case the N side doping of a p+n junction is given as $N_D(x) = Gx^M$.
when $M=0$, its a step junction, when $M=1$, its a linear junction.
the field expression for this case is given as

$$\mathcal{E}(x) = \frac{qG}{\varepsilon(m+1)}(x^{m+1} - W^{m+1})$$

and $V_{bi} - V$ is found out by integrating field w.r.t x.

$$V_{bi} - V = \frac{qG}{\varepsilon_s}\left(\frac{W^{M+2}}{M+2}\right)$$

the charge enclosed is given by

$$Q = \frac{qAGW^{M+1}}{M+1} = \frac{qAG}{M+1}\left[\frac{(V_{bi}-V)\,\varepsilon\,(M+2)}{qG}\right]^{M+1/M+2}$$

and the capacitance,

$$C \propto (V_{bi} - V)^{-2/m+2}$$

CALCULATIONS:

Parameters:

$T = 300K$, $\varepsilon_{si} = \varepsilon_r \varepsilon_0$, $\varepsilon_r = 11.9$, $\varepsilon_0 = 8.85 \times 10^{-14} F cm^{-1}$

$q = 1.6 \times 10^{-19} C$, $n_i = 10^{10} cm^{-3}$, $A = 4 \times 10^{-8} m^2$

Part 1 - Step Junction

(i) $N_A = 10^{14} cm^{-3}$, $N_D = 10^{15} cm^{-3}$

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i}\right) = (0.026)\left(\ln\left(\frac{10^{14}\,10^{15}}{10^{20}}\right)\right)$$

$$\underline{V_{bi} = 0.54\,V}$$

$$W = \left[\frac{2\,\varepsilon_{si} V_{bi}}{q}\left(\frac{N_A + N_D}{N_D N_A}\right)\right]^{1/2}$$

$$W = \left[\frac{2 \times 11.9 \times 8.85 \times 10^{-14} \times 0.54}{1.6 \times 10^{-19}}\left(\frac{10^{15} + 10^{14}}{10^{15} \cdot 10^{14}}\right)\right]^{1/2}$$

$$\underline{W = 2.8\,\mu m}$$

$$\varepsilon_m = \frac{2V_{bi}}{W} = \frac{2 \times 0.54}{2.8} \times 10^{6} = \underline{3.8 \times 10^{5}\,V/m}$$

$$\frac{C_0}{A} = \frac{\varepsilon}{W} = \frac{11.9 \times 8.85 \times 10^{-14}}{2.8 \times 10^{-6}} = \underline{3.77\,nF/cm^2}$$

The relation b/w C and V is given by:

$$\frac{1}{C^2} = \frac{2}{q\varepsilon}\,\frac{N_A + N_D}{N_A N_D}\,(V_{bi} - V)$$

putting values,

$$\frac{1}{C^2} = \frac{1.375 \times 10^{5}}{\varepsilon} \times (V_{bi} - V)$$

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COMPARISON TABLE

Parameter	Calculated	Simulated
V_{bi}	0.54 V	0.55 V
W	2.79 µm	2.26 µm
C_o/A	3.77 nF/cm²	3.92 nF/cm²
E_{max}	0.35 V/µm	0.38 V/µm

(ii) $N_A = 10^{15}\ cm^{-3}$, $N_D = 10^{15}\ cm^{-3}$

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = (0.026)\ln\left(\frac{10^{15}\,10^{15}}{10^{20}}\right)$$

$$V_{bi} = \underline{0.598V}$$

$$W = \left[\frac{2\varepsilon_s V_{bi}}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)\right]^{1/2} = \cancel{1.25}\ \mu m$$

$$W = \underline{1.25\ \mu m}$$

$$E_{max}\quad \frac{2V_{bi}}{W} = \underline{0.95\ V/\mu m} \qquad \frac{C_o}{A} = \frac{\varepsilon}{W} = \underline{8.4\ nF/cm^2}$$

COMPARISON TABLE

Parameter	Calculated	Simulated
V_{bi}	0.6 V	0.61 V
W	1.25 µm	1.02 µm
C_o/A	8.4 nF/cm²	8.66 nF/cm²
E_m	0.95 V/µm	~~1.96~~ V/µm 0.927 V/µm

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(iii) $N_A = 10^{16} cm^{-3}$, $N_D = 10^{15} cm^{-3}$

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.026 \ln\left(\frac{10^{15} \cdot 10^{16}}{10^{20}}\right) = 0.66V$$

$$W = \left[\frac{2\varepsilon_s V_{bi}}{q} \frac{(N_A + N_D)}{N_A N_D}\right]^{1/2} = \left(\frac{2\times 11.9 \times 8.85\times 10^{-14} \times 0.66}{1.6\times 10^{-19}} \left(\frac{10^{15}+10^{16}}{10^{15} \cdot 10^{16}}\right)\right)^{1/2} = 0.98\mu m$$

$$\mathcal{E}_{max} = \frac{2V_{bi}}{W} = \frac{2\times 0.66V}{0.98\mu m} = 1.34\ V/\mu m$$

$$\frac{C_0}{A} = \frac{\varepsilon}{W} = \frac{8.85\times 10^{-14} \times 11.9}{0.98\mu m} = 10.78\ nF/cm^2$$

COMPARISON TABLE

Parameter	Calculated	Simulated
V_{bi}	0.66V	0.67V
W	0.98μm	0.79μm
$\mathcal{E}_{max}$	1.34 V/μm	1.32V/μm
C_0/A	10.78nF/cm²	11.1nF/cm²

(iv) $N_A = 10^{17} cm^{-3}$, $N_D = 10^{15} cm^{-3}$

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.026 \ln\left(\frac{10^{15} \cdot 10^{17}}{10^{20}}\right) = 0.72V$$

$$W = \left[\frac{2\varepsilon_s V_{bi}}{q} \left(\frac{N_A + N_D}{N_A N_D}\right)\right]^{1/2} = \left[\frac{2\times 11.9 \times 8.85\times 10^{-14} \times 0.72}{1.6\times 10^{-19}} \left(\frac{10^{17}+10^{15}}{10^{17} \cdot 10^{15}}\right)\right]^{1/2} = 0.98\mu m$$

$$\mathcal{E}_{max} = \frac{2V_{bi}}{W} = \frac{2\times 0.72}{0.98\mu m} = 1.47\ V/\mu m$$

$$C_0 = \frac{\varepsilon}{W} = \frac{8.85\times 11.9 \times 10^{-14}}{0.98\mu m} = 10.77\ nF/cm^2$$

COMPARISON TABLE

Parameter	Calculated	Simulated
V_{bi}	0.72V	0.73V
W	0.98μm	0.78μm
$\mathcal{E}_{m}$	1.47V/μm	2.07 V/μm
C_0/A	10.77nF/cm²	11.3nF/cm²

(v) $N_A = 10^{18}\ cm^{-3}$, $N_D = 10^{15}\ cm^{-3}$

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.026 \ln\left(\frac{10^{18} \cdot 10^{15}}{10^{20}}\right) = 0.78V$$

$$W = \left[\frac{2\varepsilon_s V_{bi}}{q}\left[\frac{N_A + N_D}{N_A N_D}\right]\right]^{1/2} = \left[\frac{2 \times 11.9 \times 8.85 \times 10^{-14} \times 0.78}{1.6 \times 10^{-19}}\left(\frac{10^{18} + 10^{15}}{10^{18} \cdot 10^{15}}\right)\right]^{1/2} = 1.01\ \mu m$$

$$E_{max} = \frac{2V_{bi}}{W} = \frac{2 \times 0.78V}{1.01\ \mu m} = 1.53\ V/\mu m$$

$$C_0 = \frac{\varepsilon}{W} = \frac{11.9 \times 8.85 \times 10^{-14}}{1.01\ \mu m} = 10.40\ nF/cm^2$$

COMPARISON TABLE

Parameter	Calculation	Simulation.
V_{bi}	0.78V	0.79V
W	1.01 µm	0.71 µm
E_{max}	1.53 V/µm	5.53 V/µm
C_0/A	10.40 nF/cm²	11.4 nF/cm²

Temperature Variance.

$N_A = 10^{15}$, $N_D = 10^{15}$, $V_{bi}(\text{theoretical}) = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$

T	V_{bi} (Simulated)	V_{bi} (theoretical)
250	0.710	0.49
260	0.692	0.51
270	0.673	0.53
280	0.652	0.55
290	0.634	0.57
300	0.616	0.59
310	0.595	0.61
320	0.572	0.63
330	0.551	0.65
340	0.533	0.67

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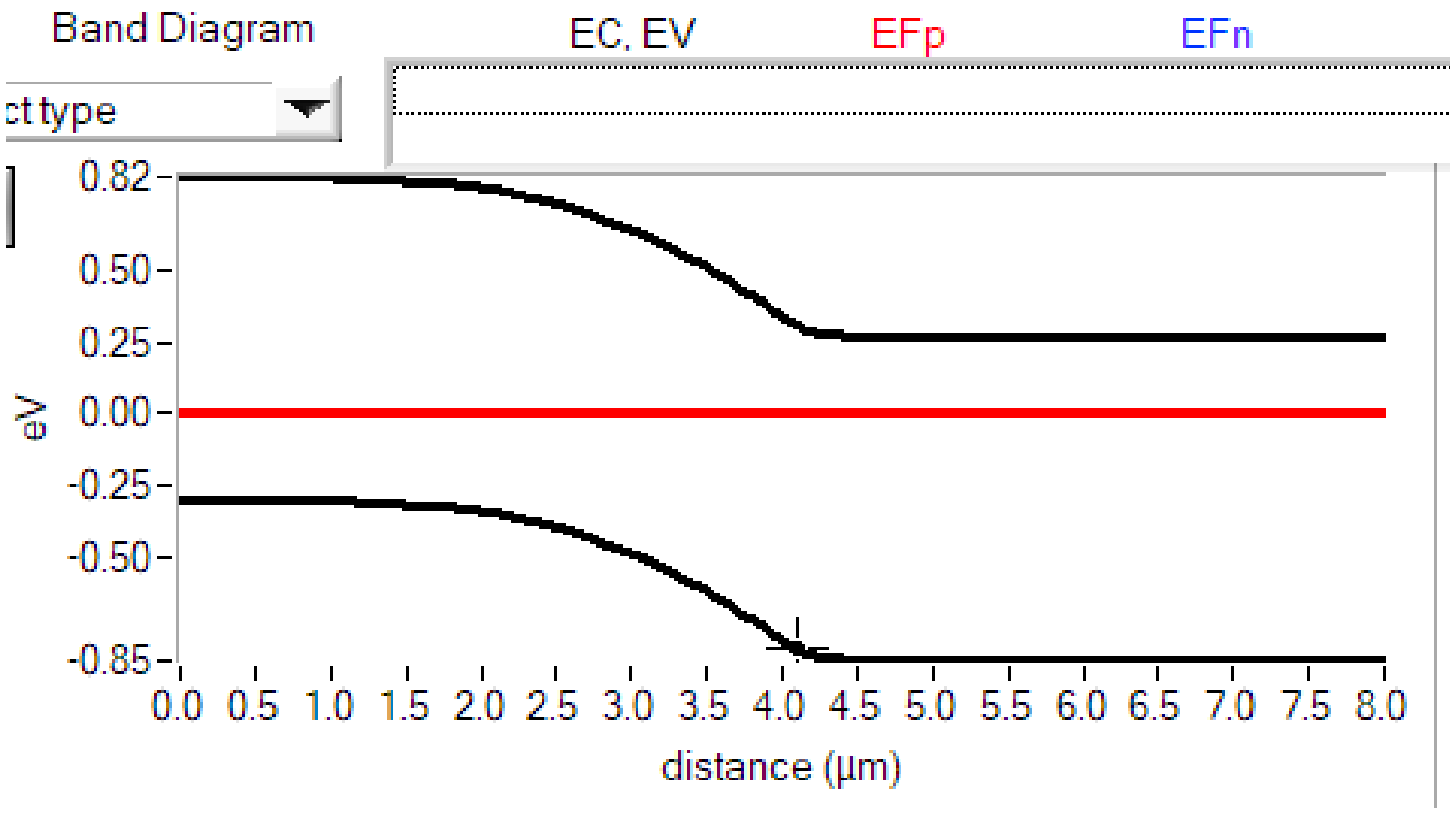
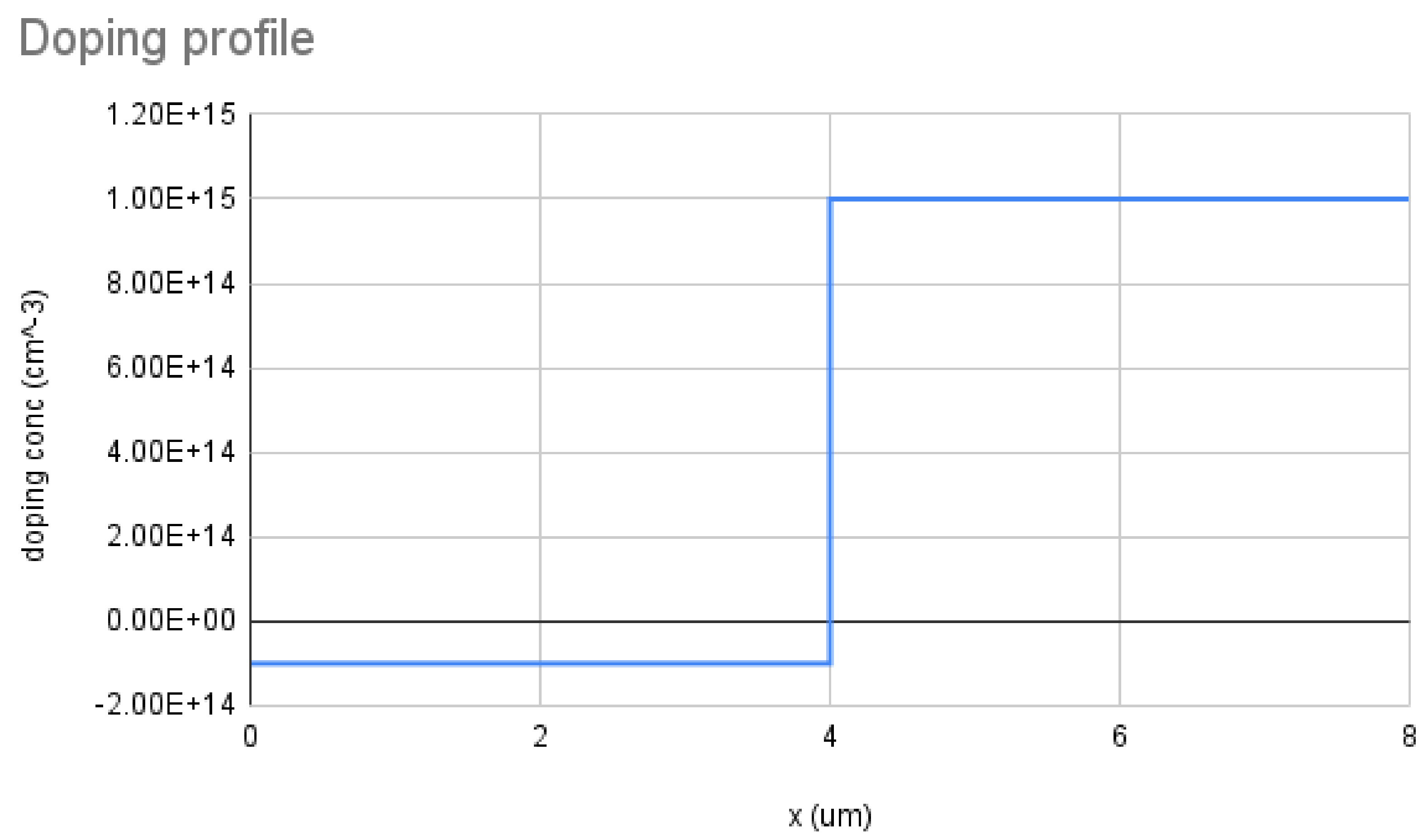
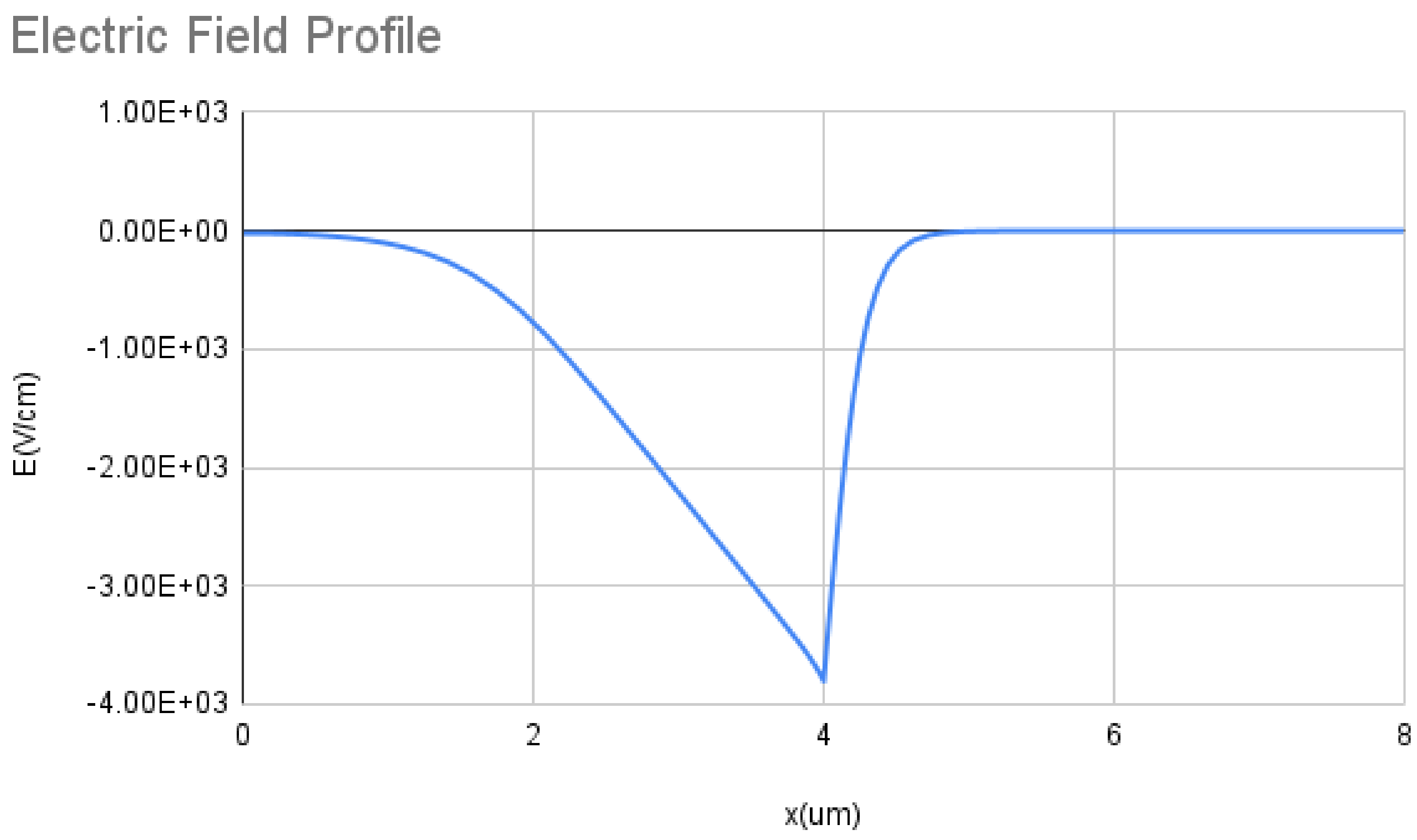
PLOTS

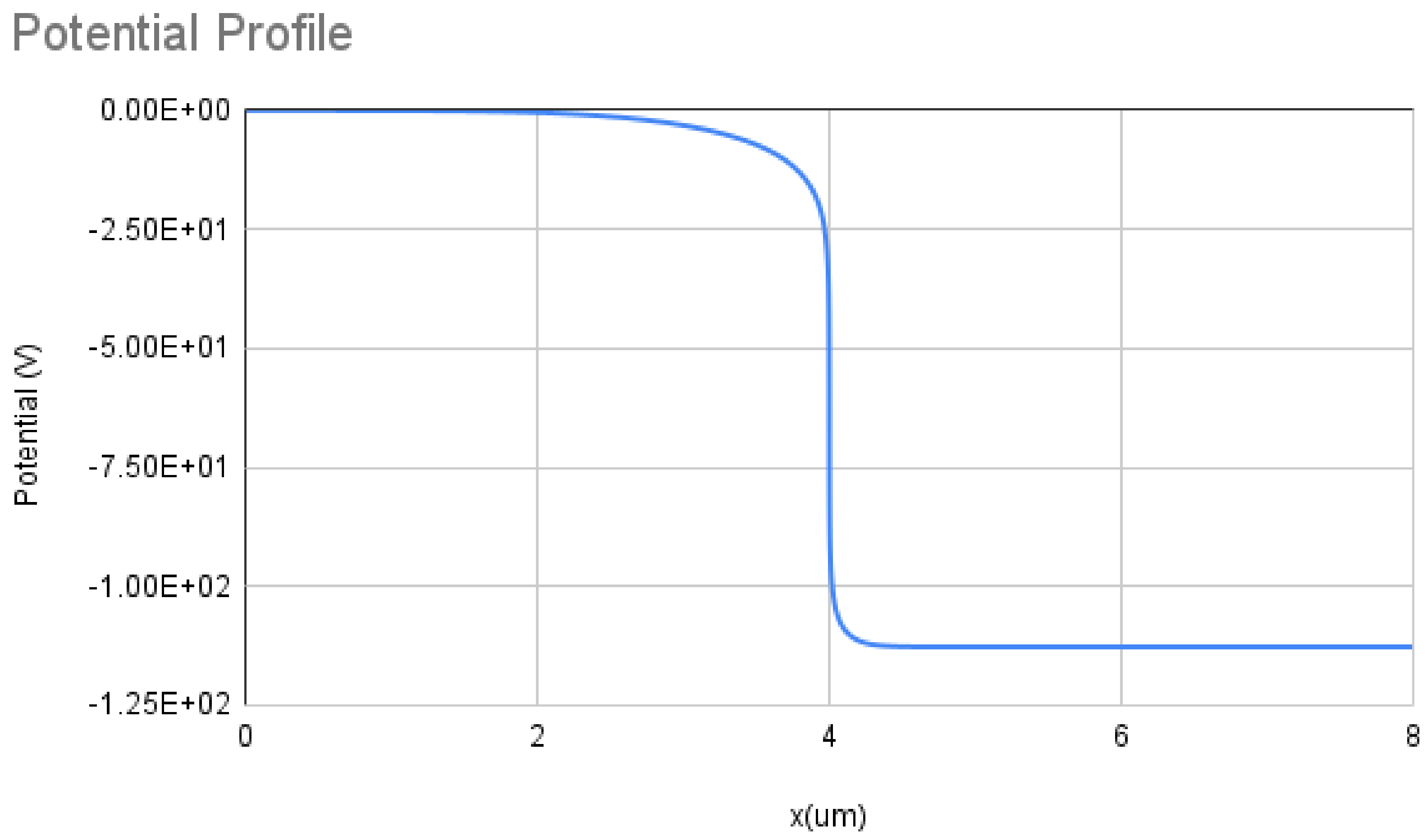
Part 1

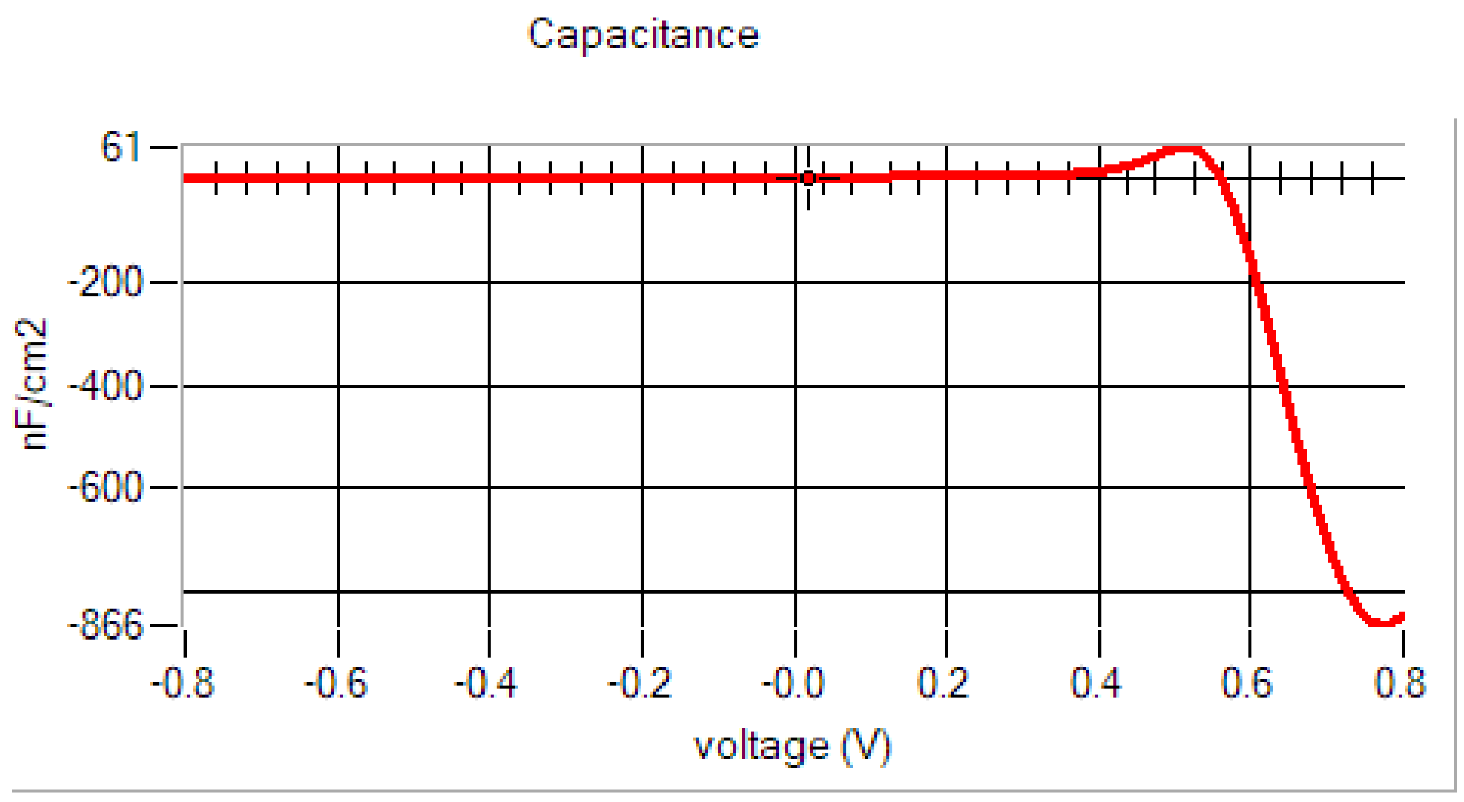
(i) Na = 10^14 cm-3

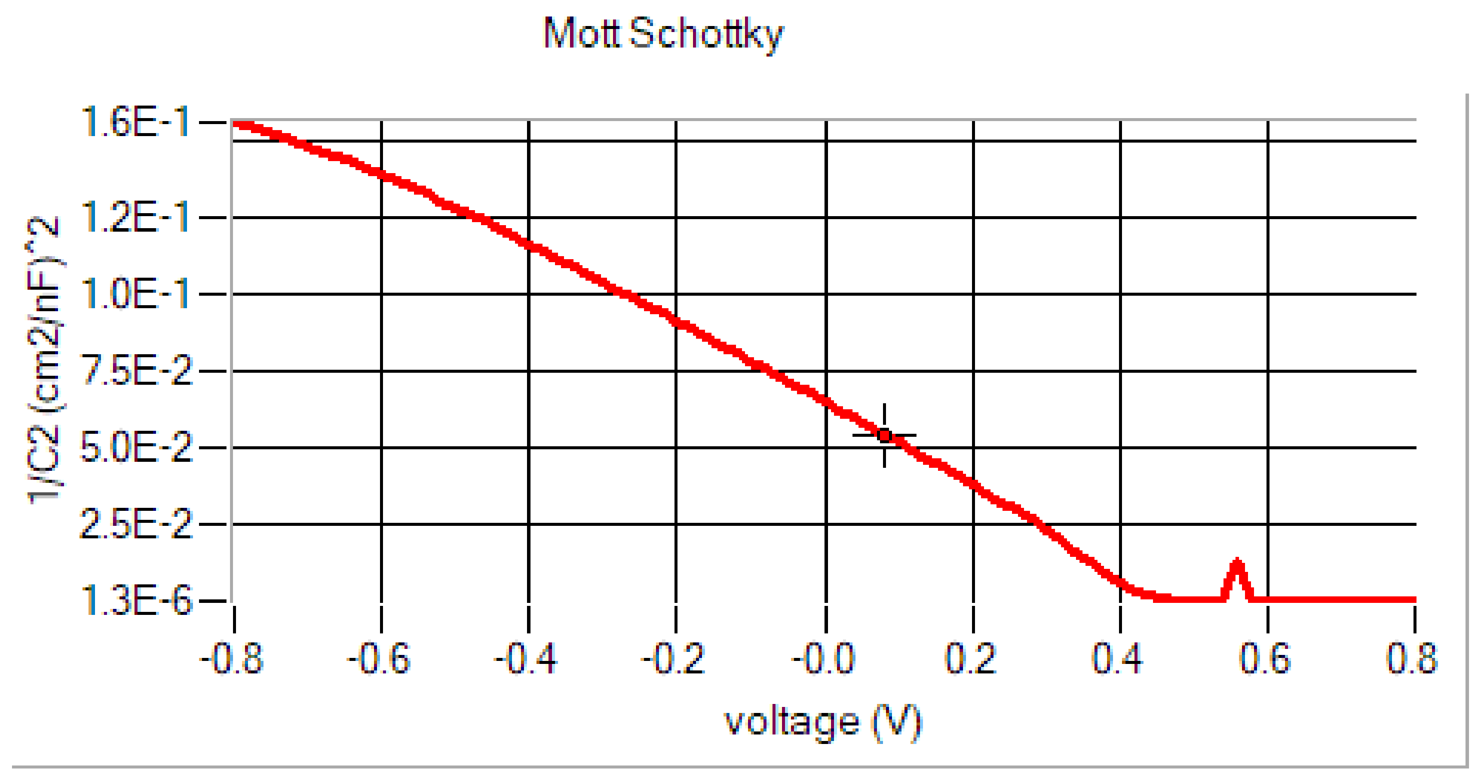




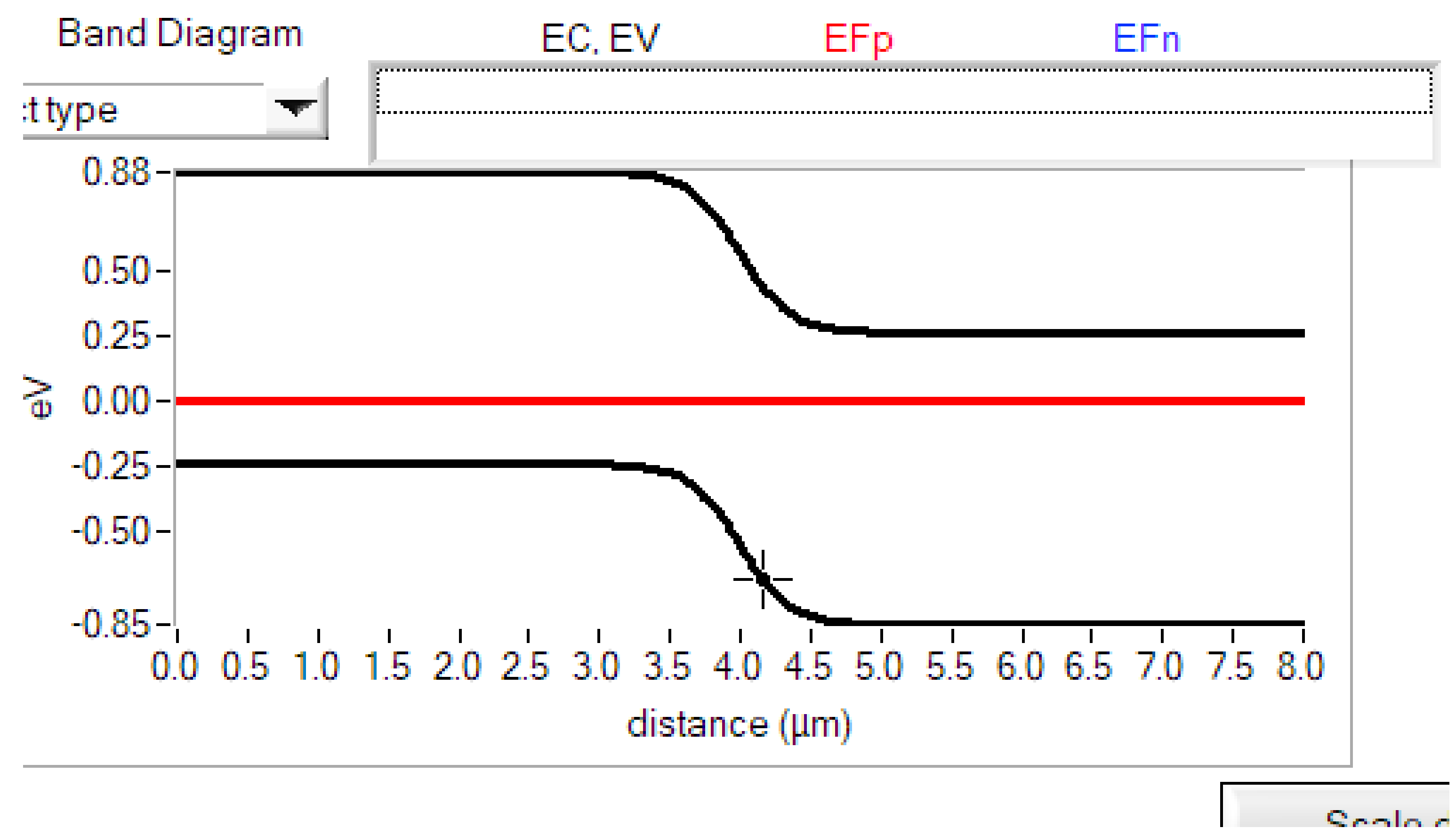


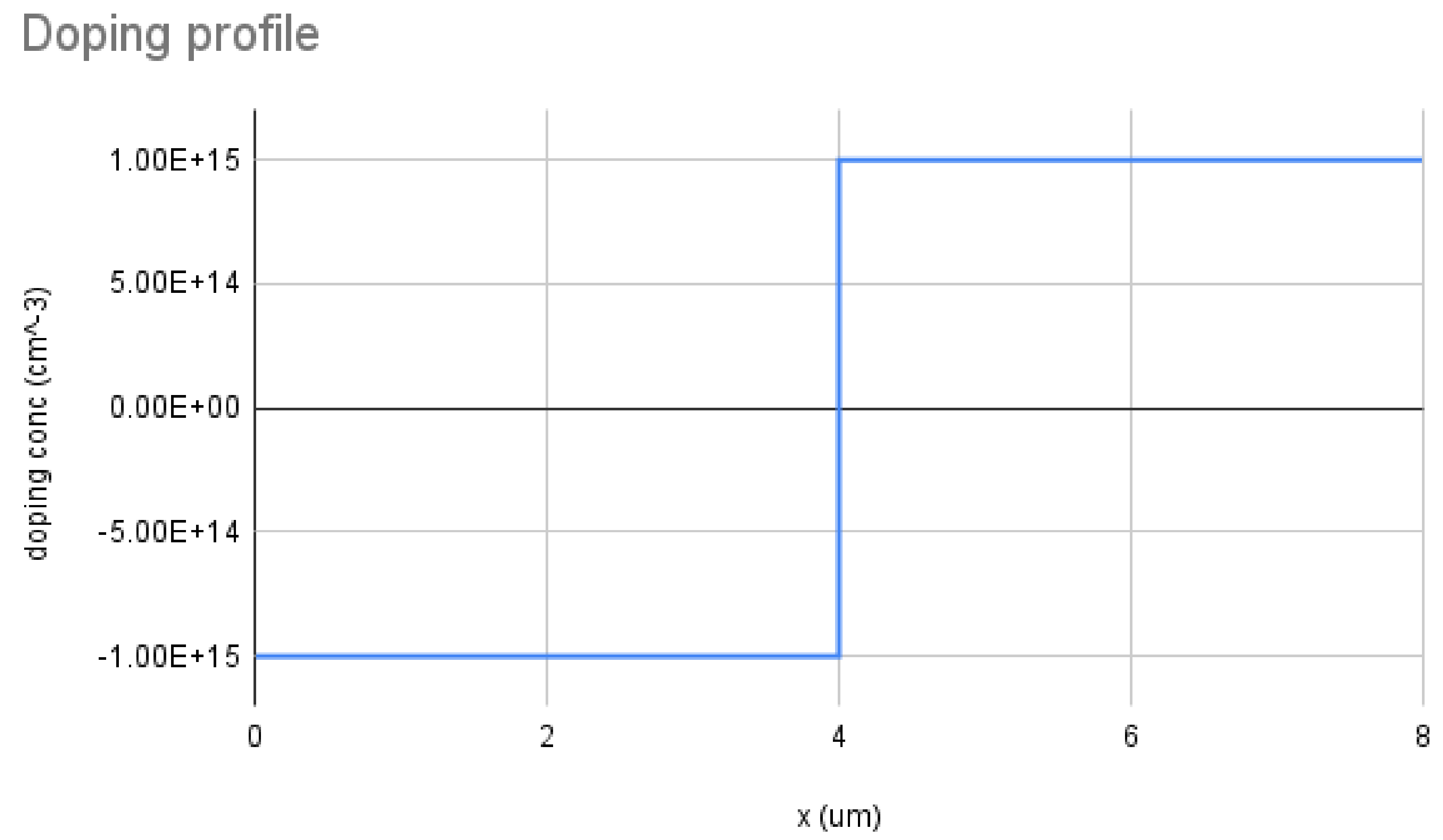


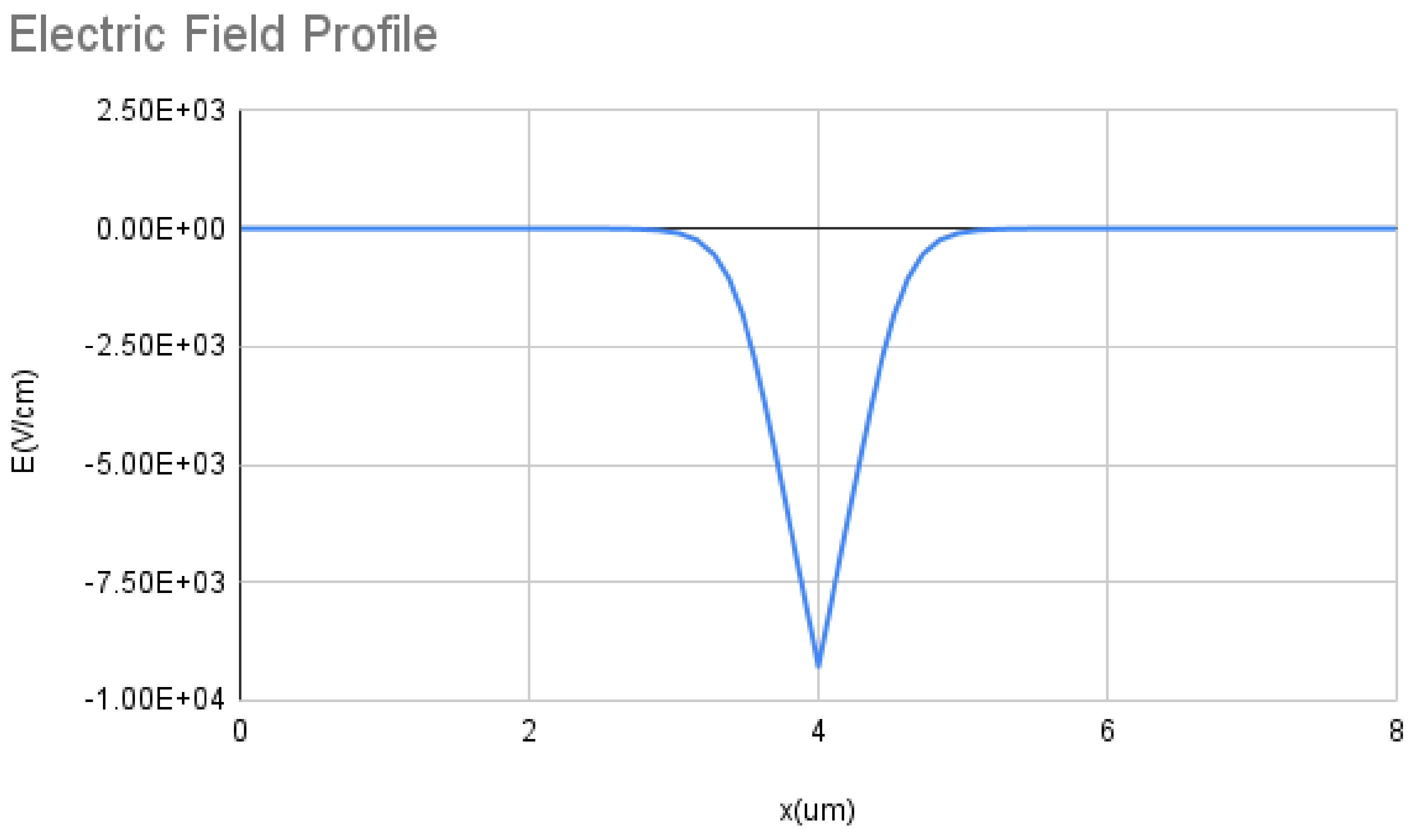


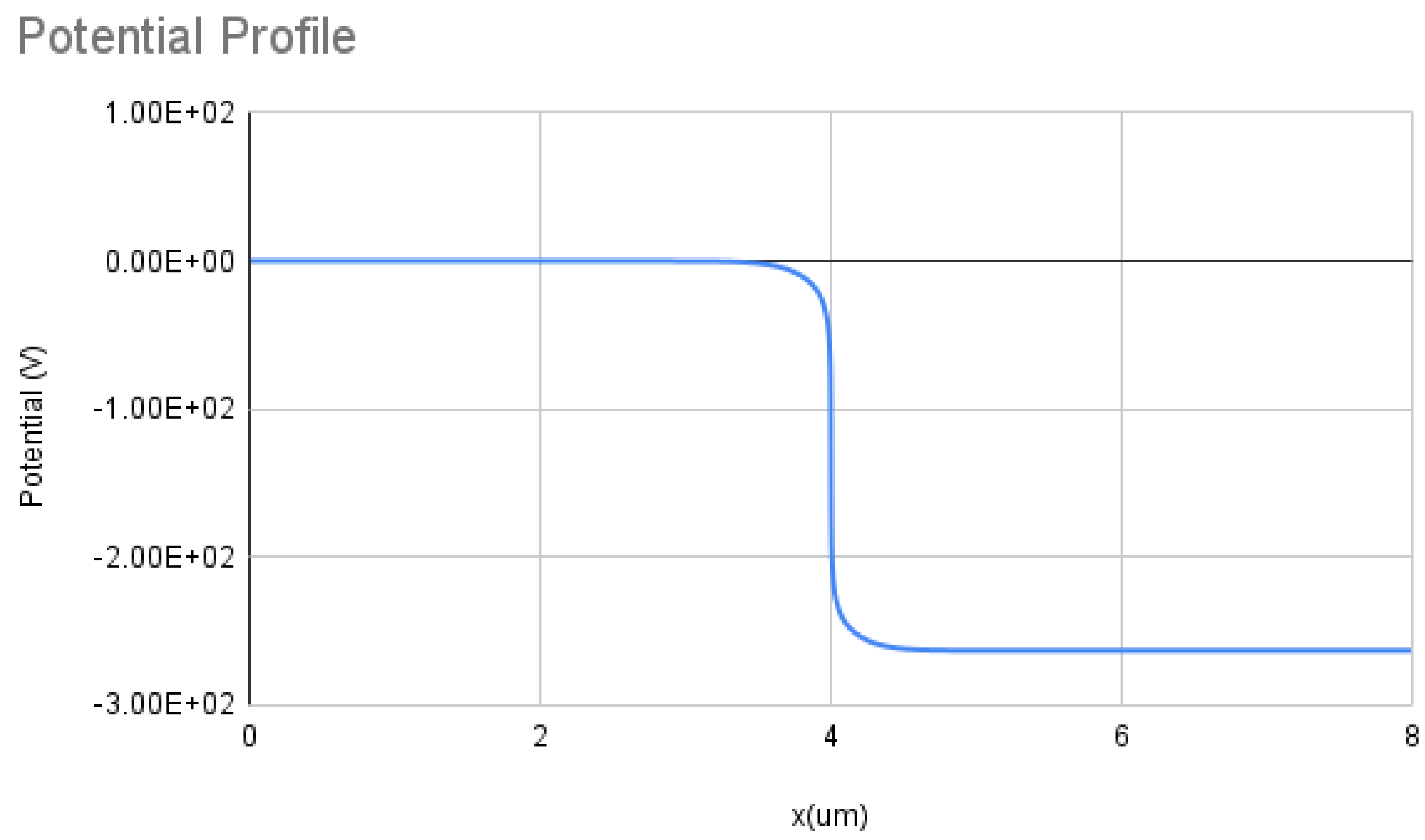


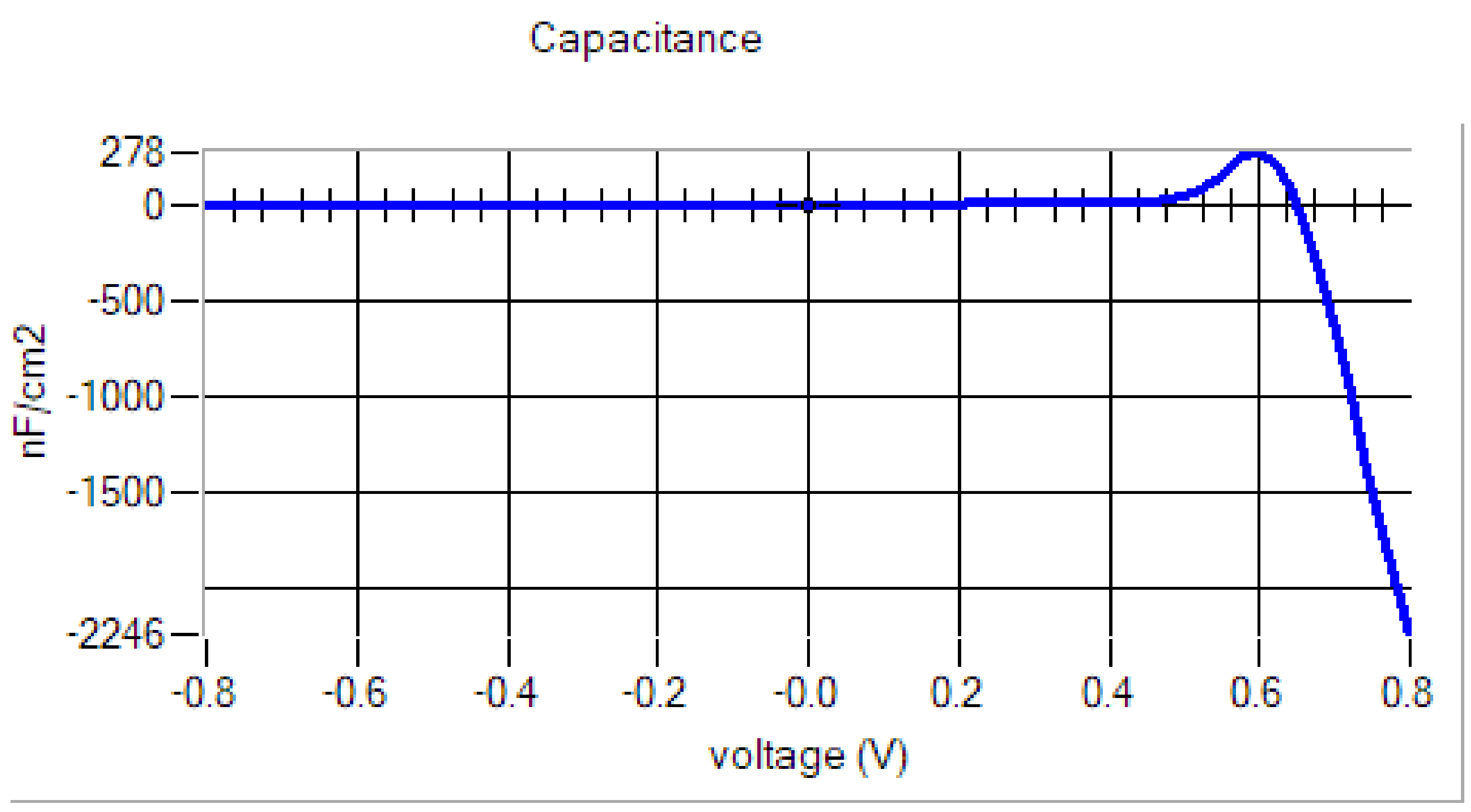
(ii) Na = 10^15 cm-3

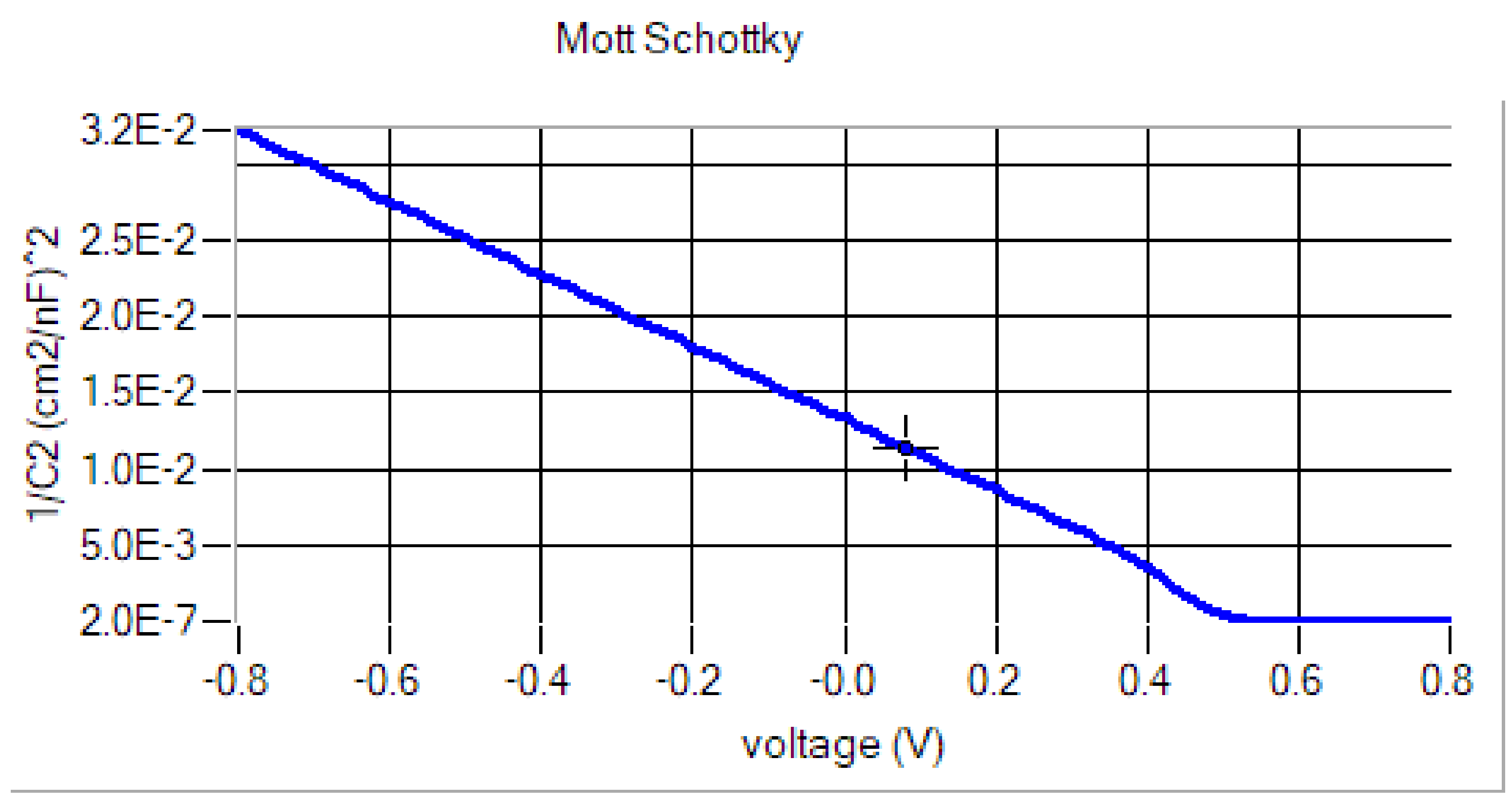




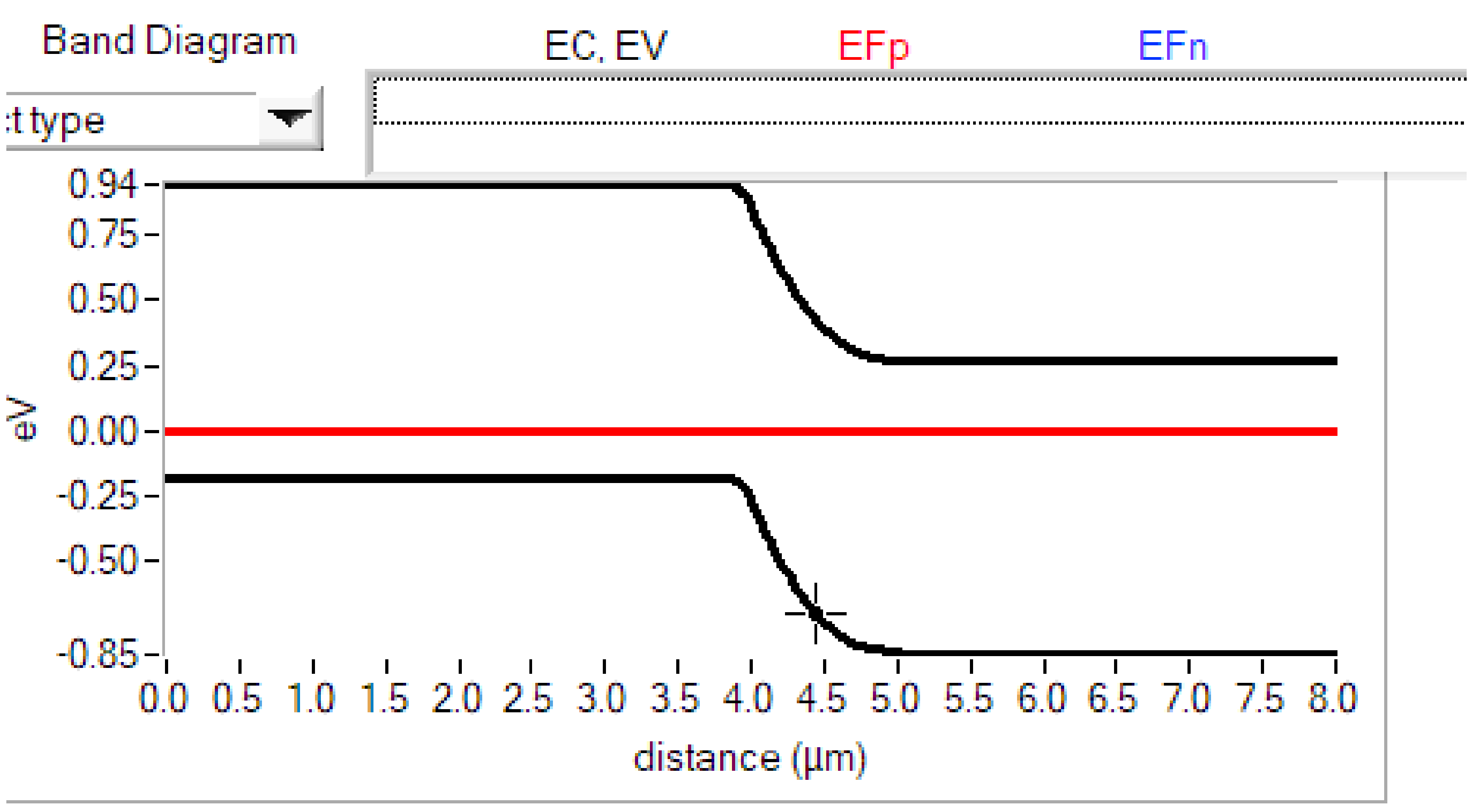


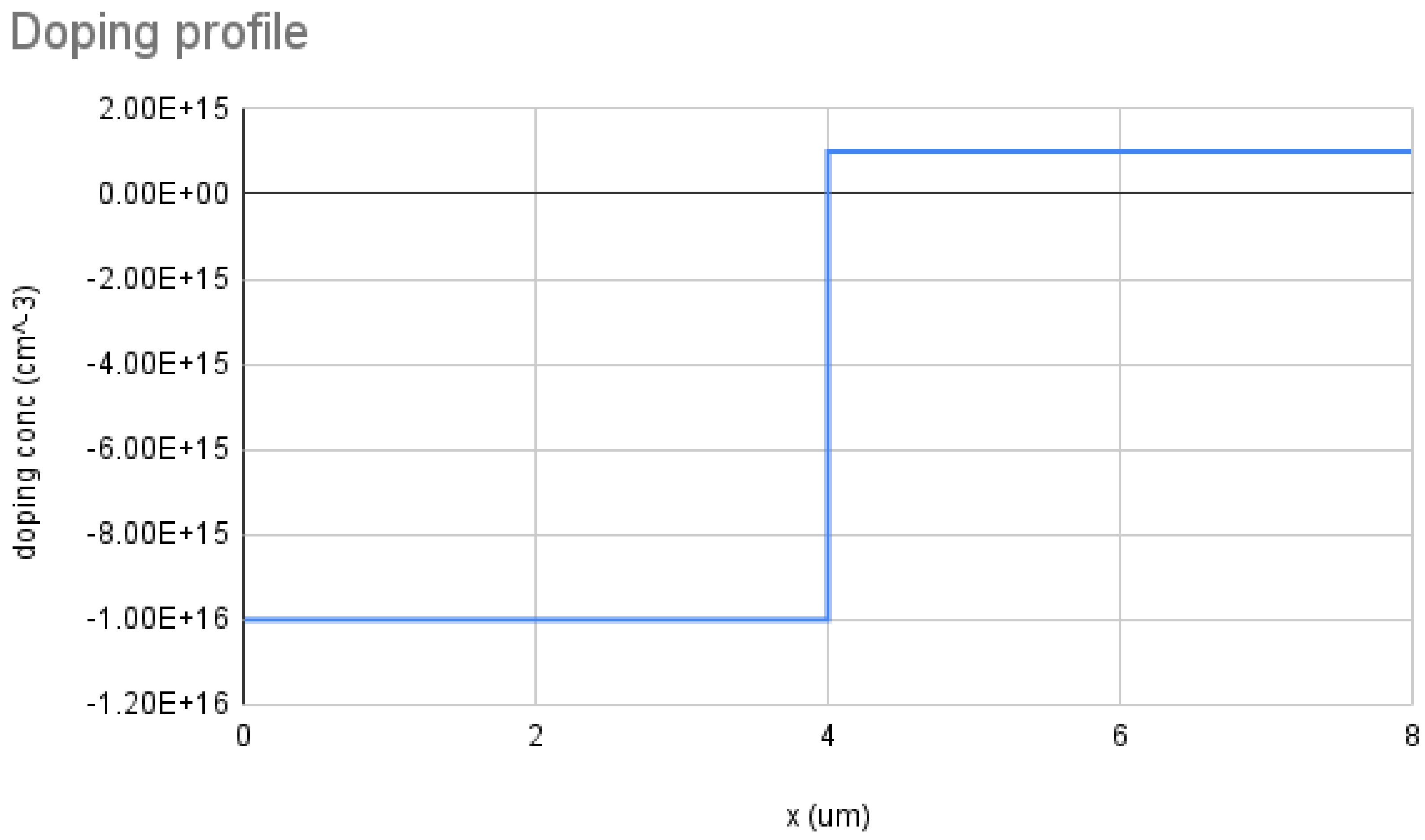


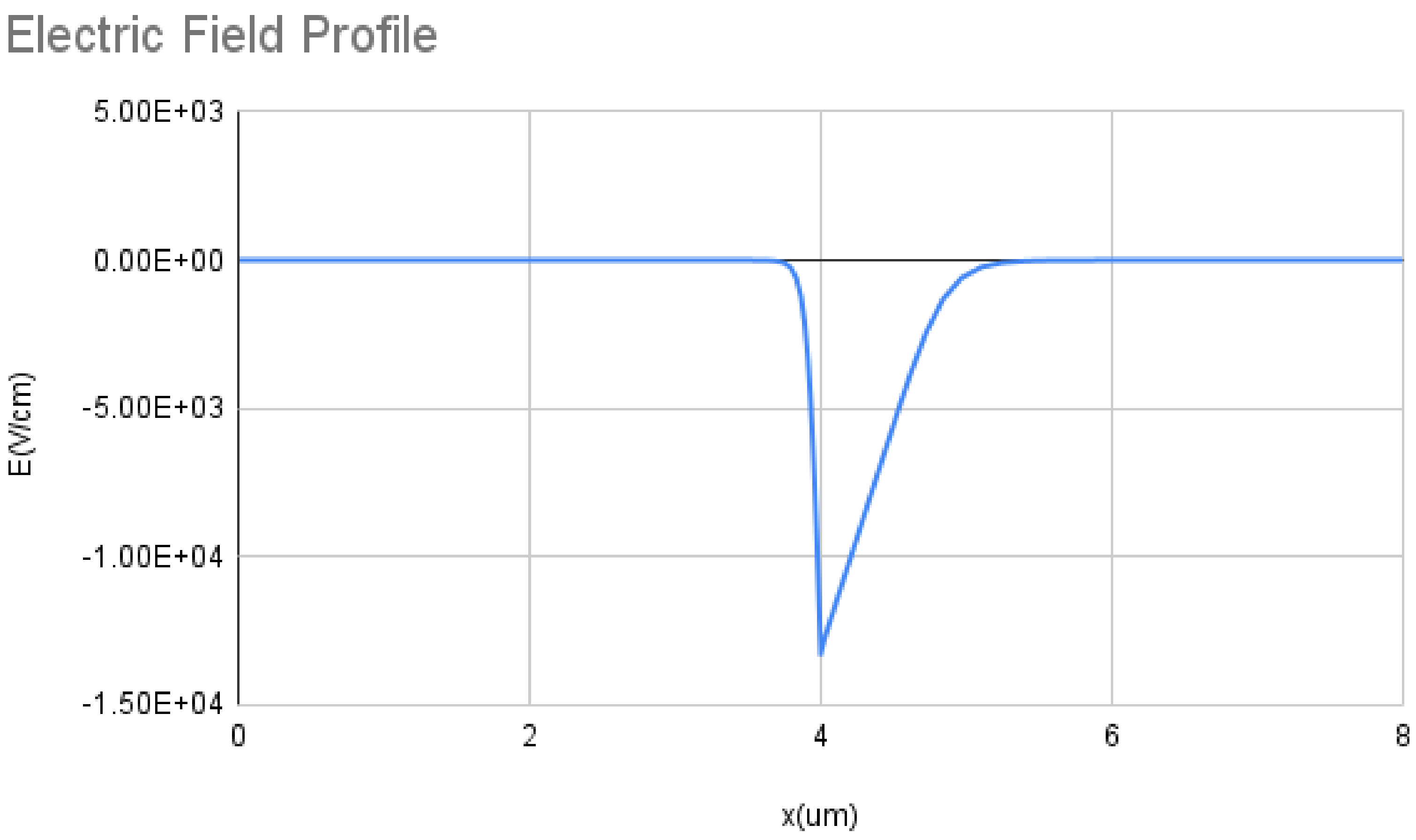


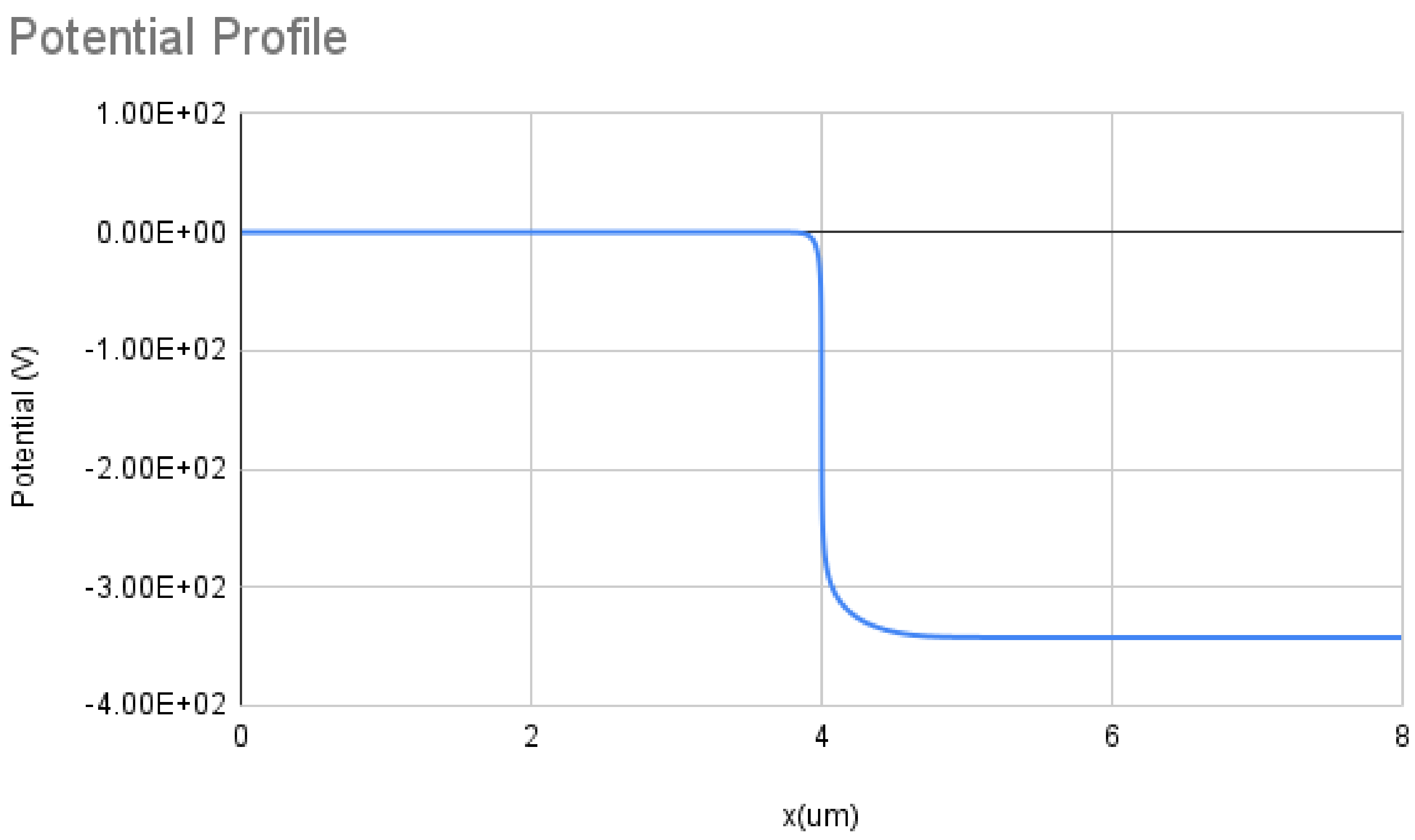


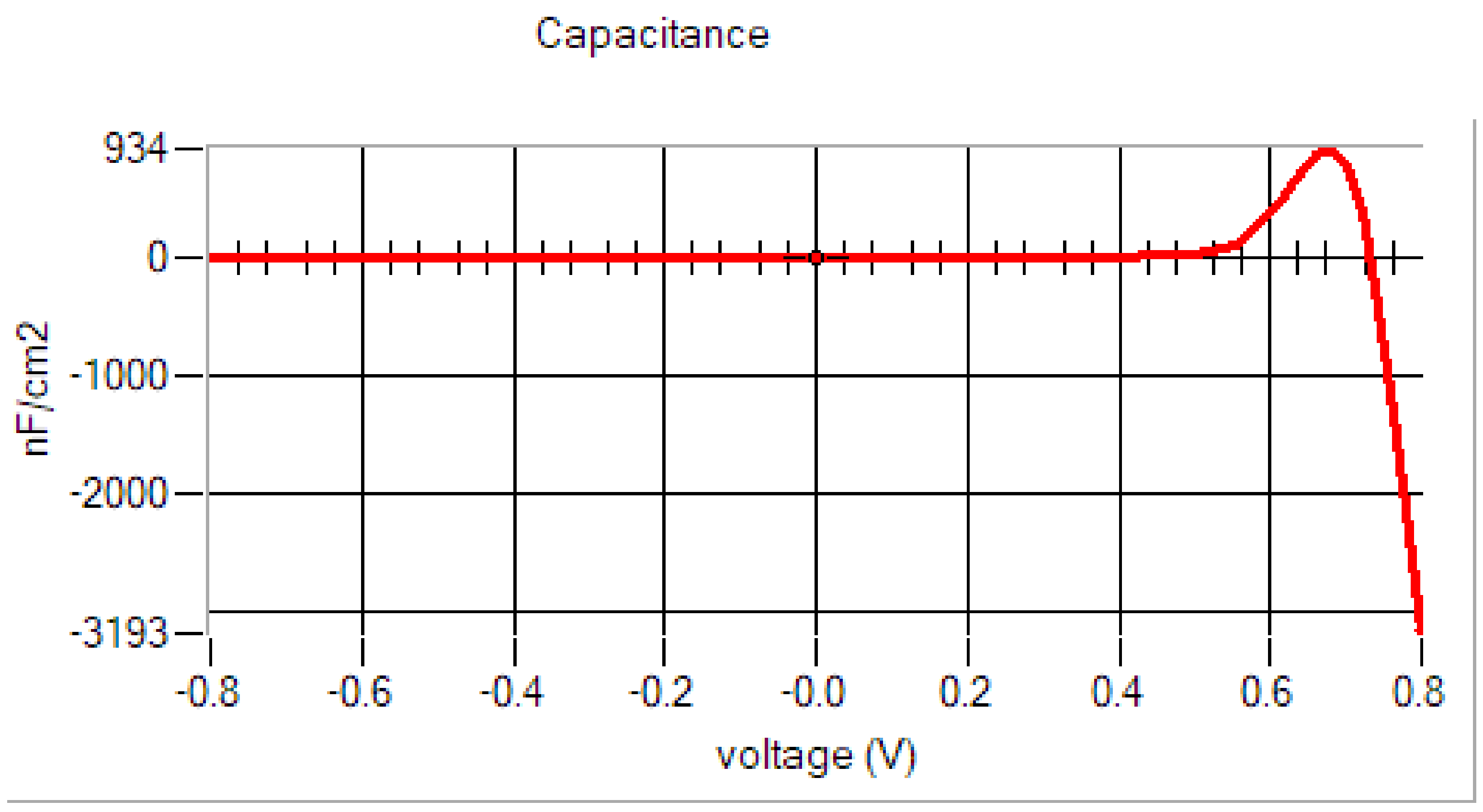
(iii) Na = 10^16 cm-3

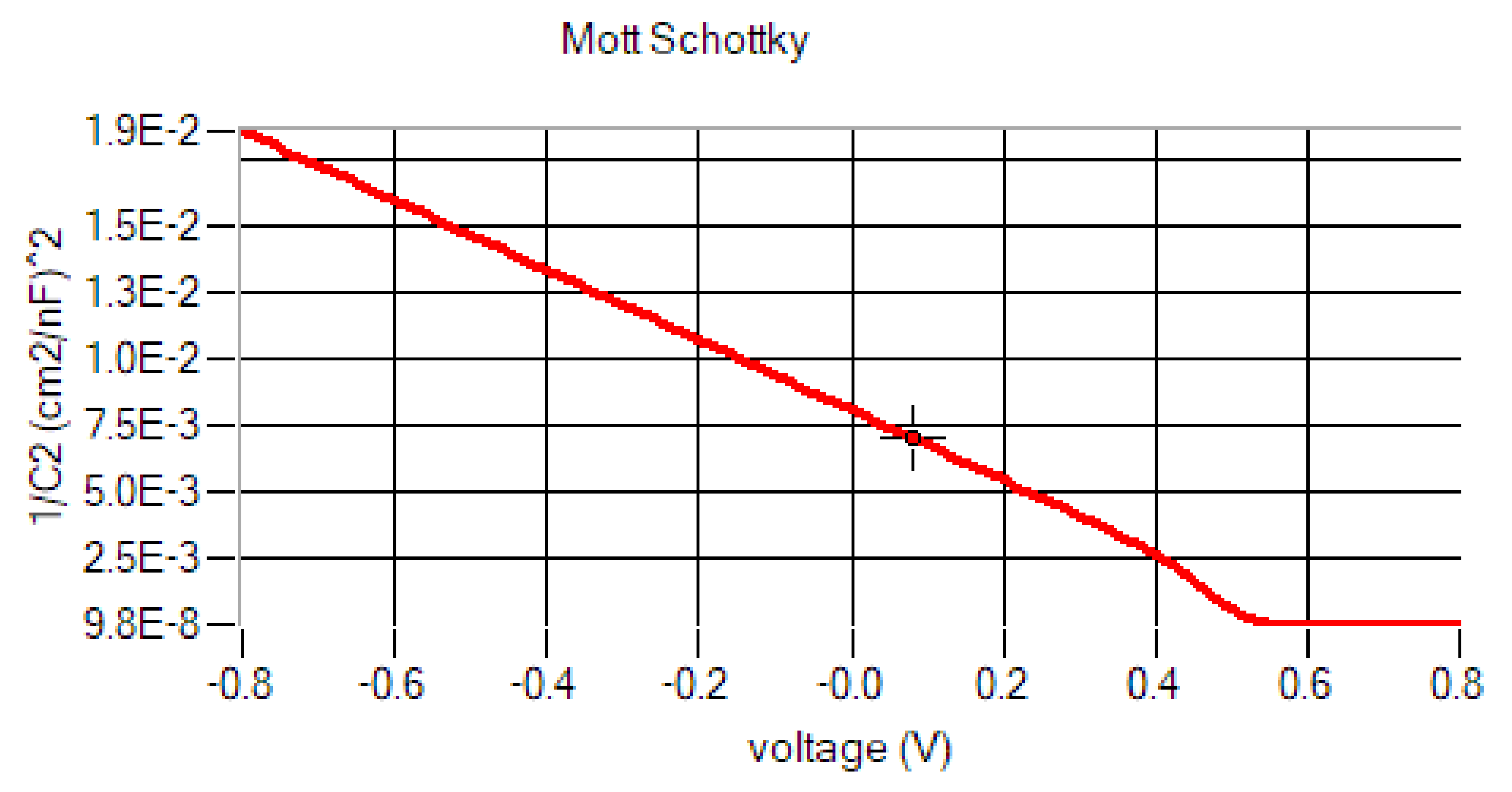




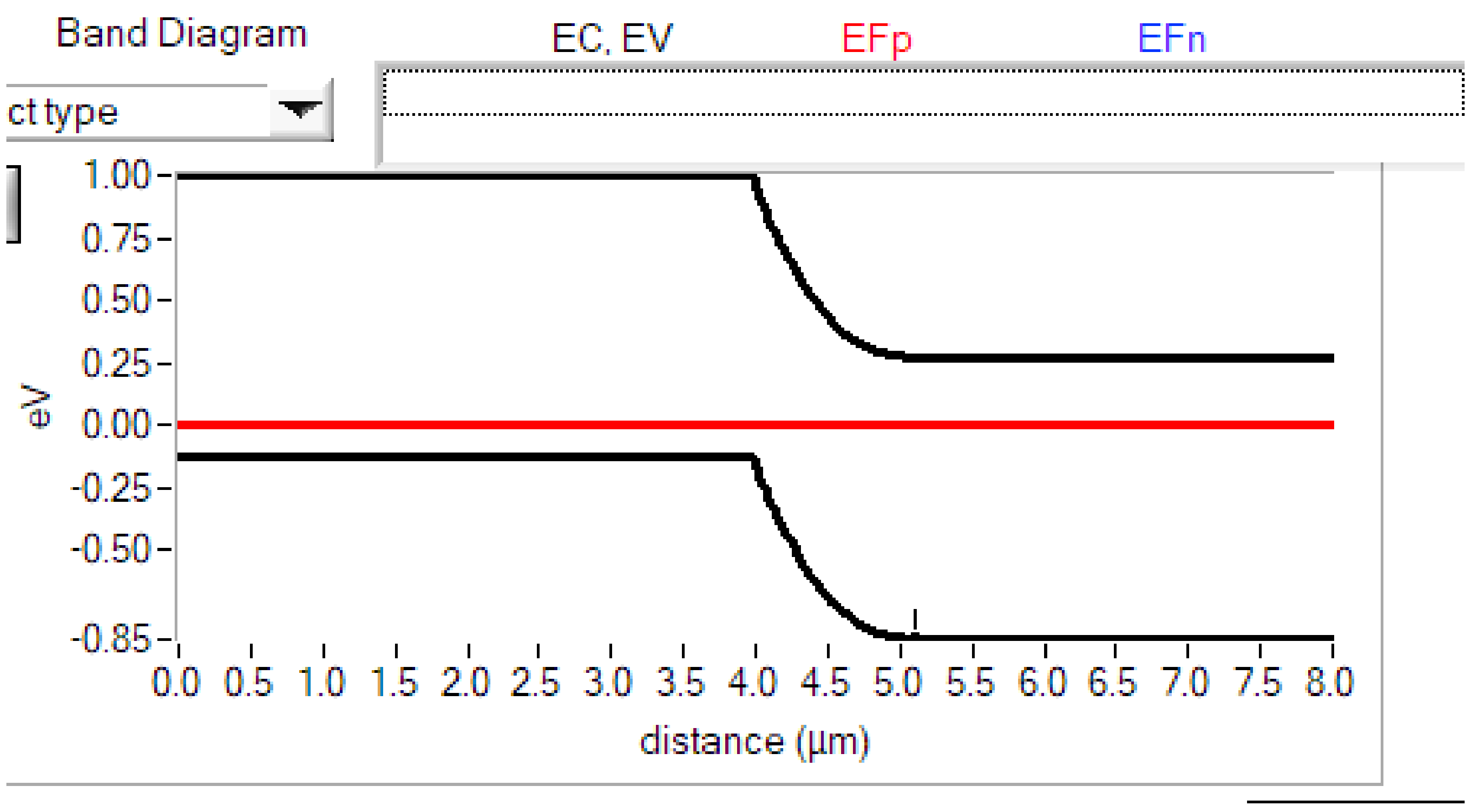


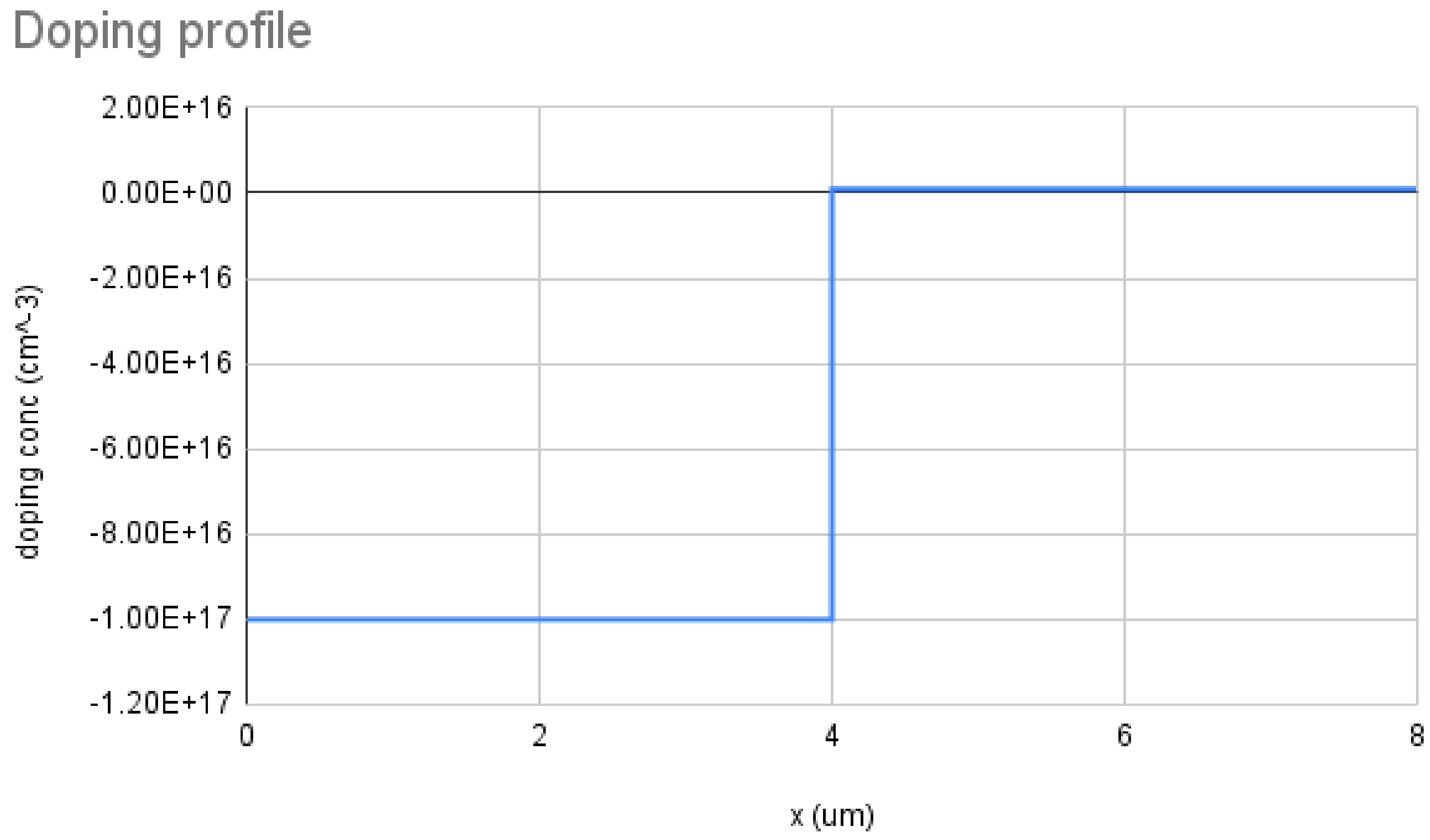


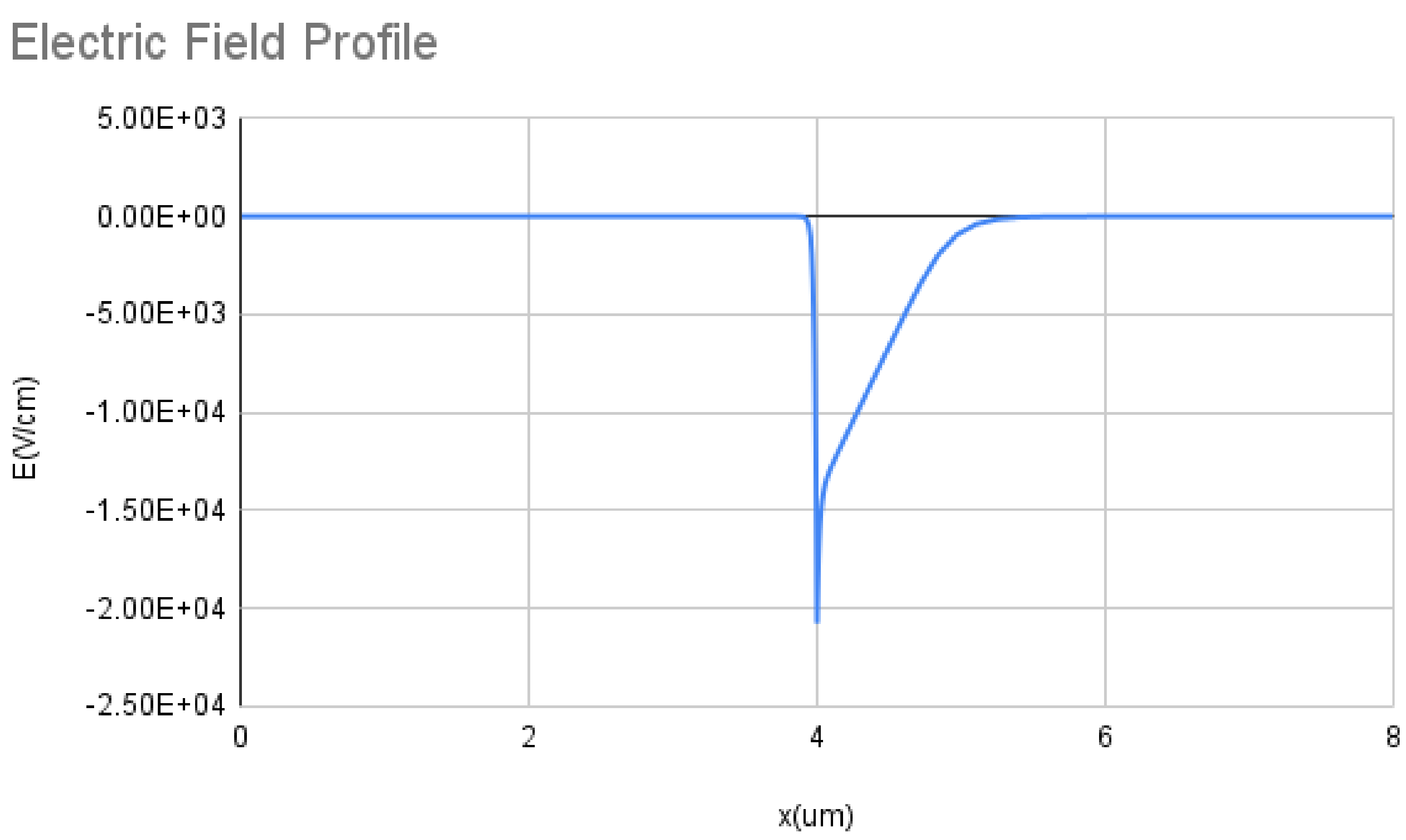


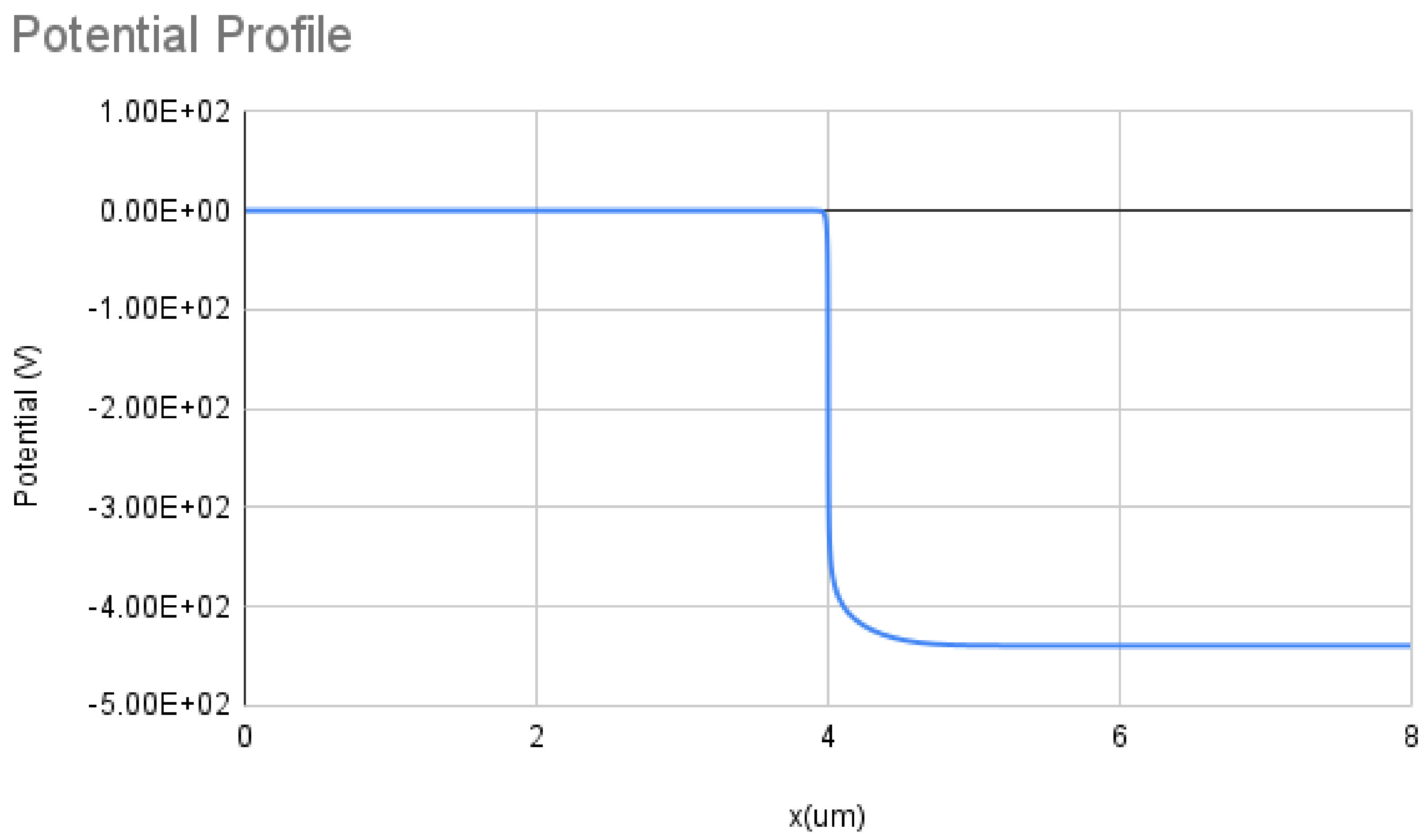


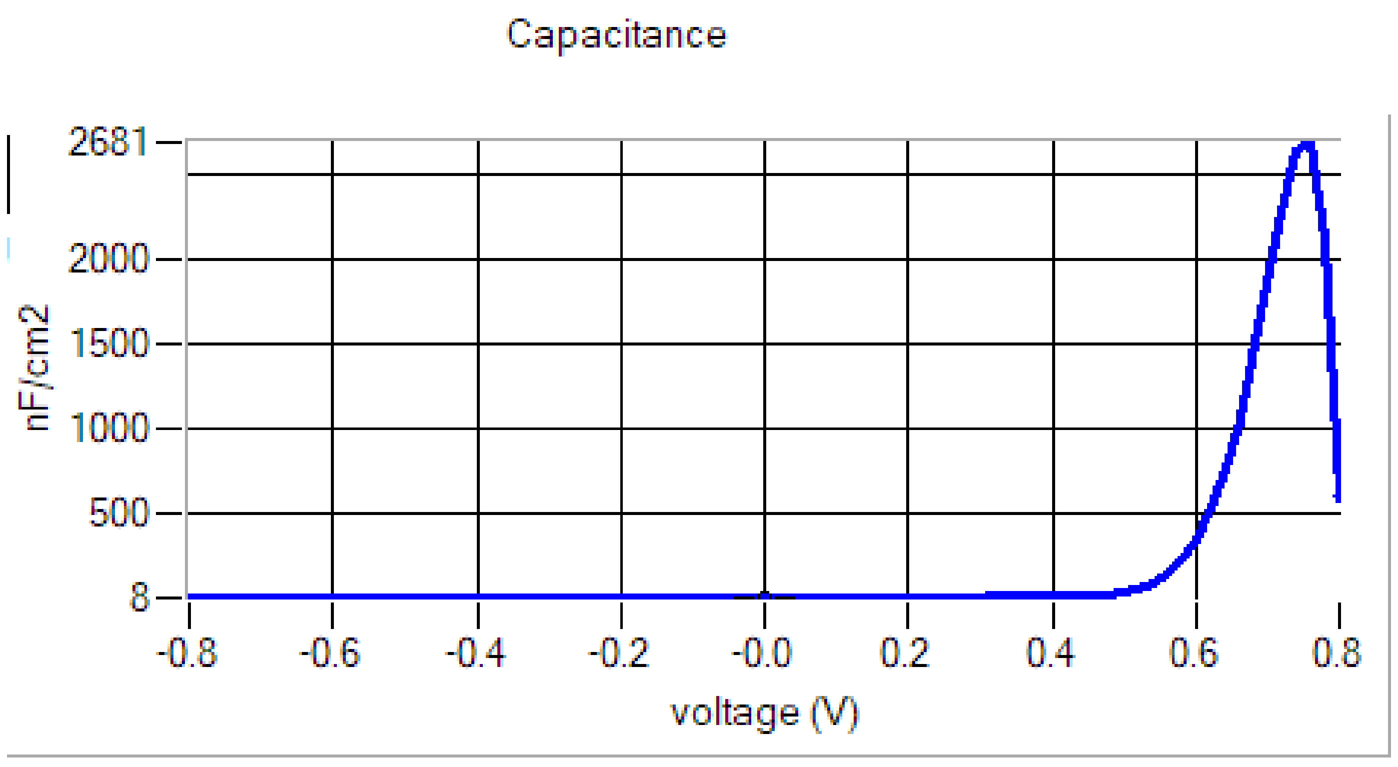
(iv) Na = 10^17 cm-3

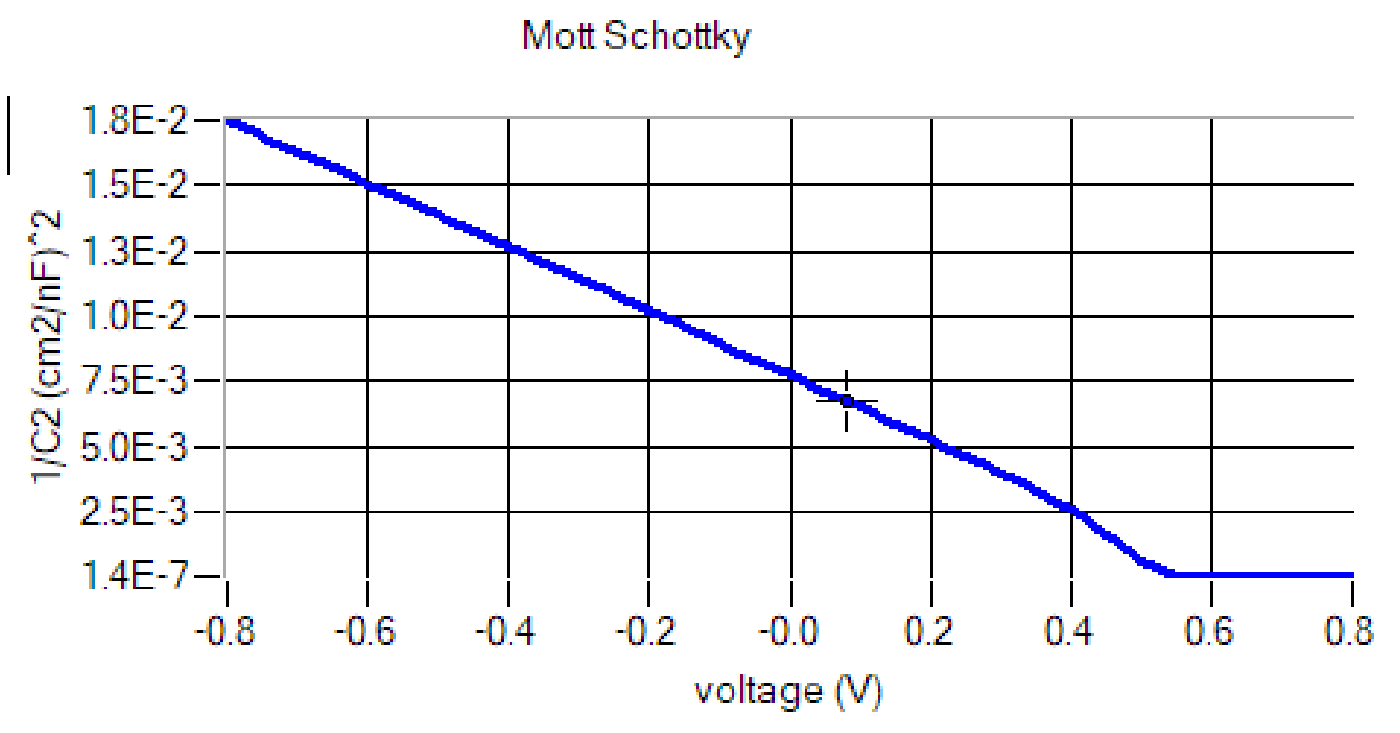




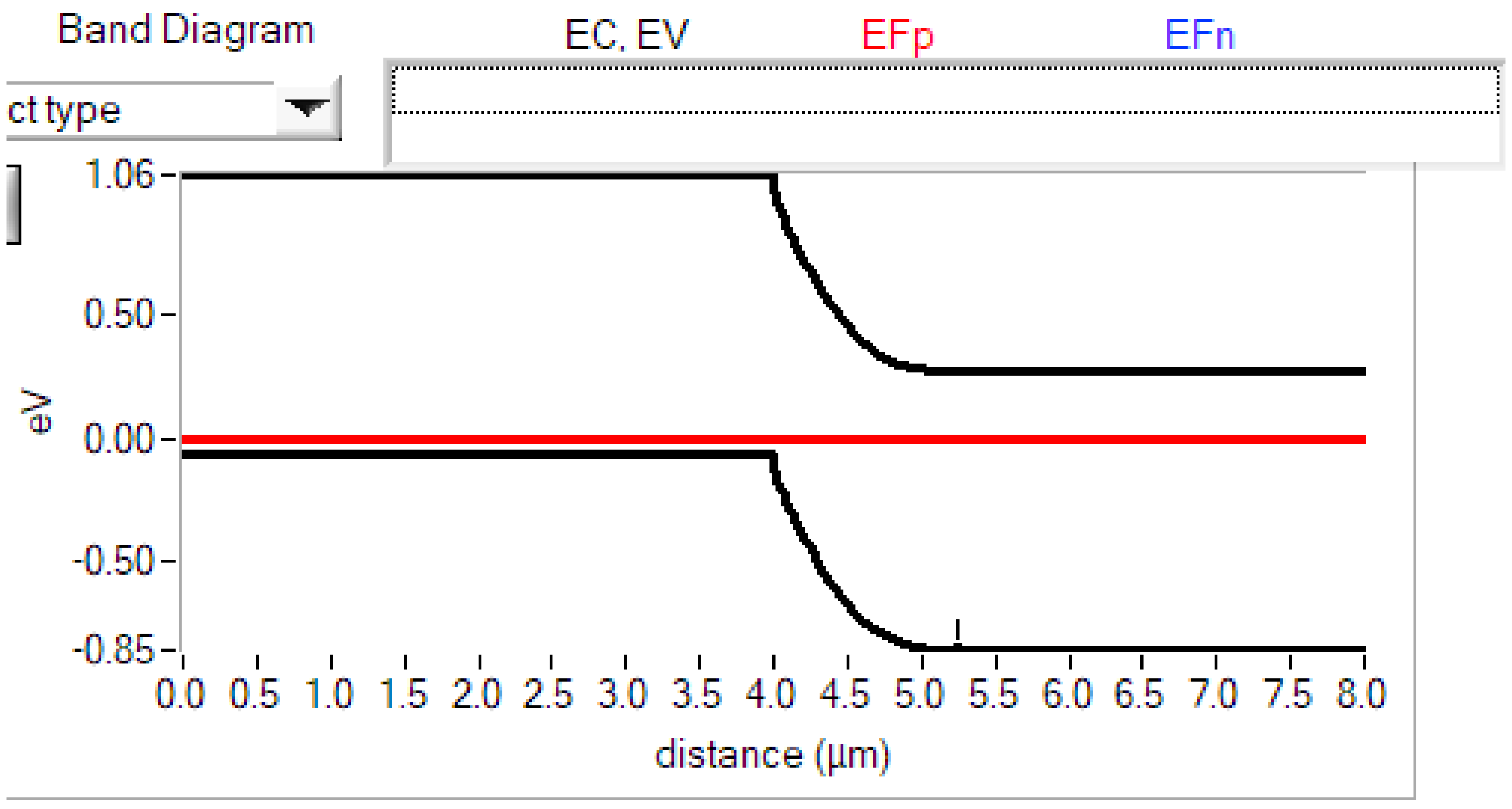


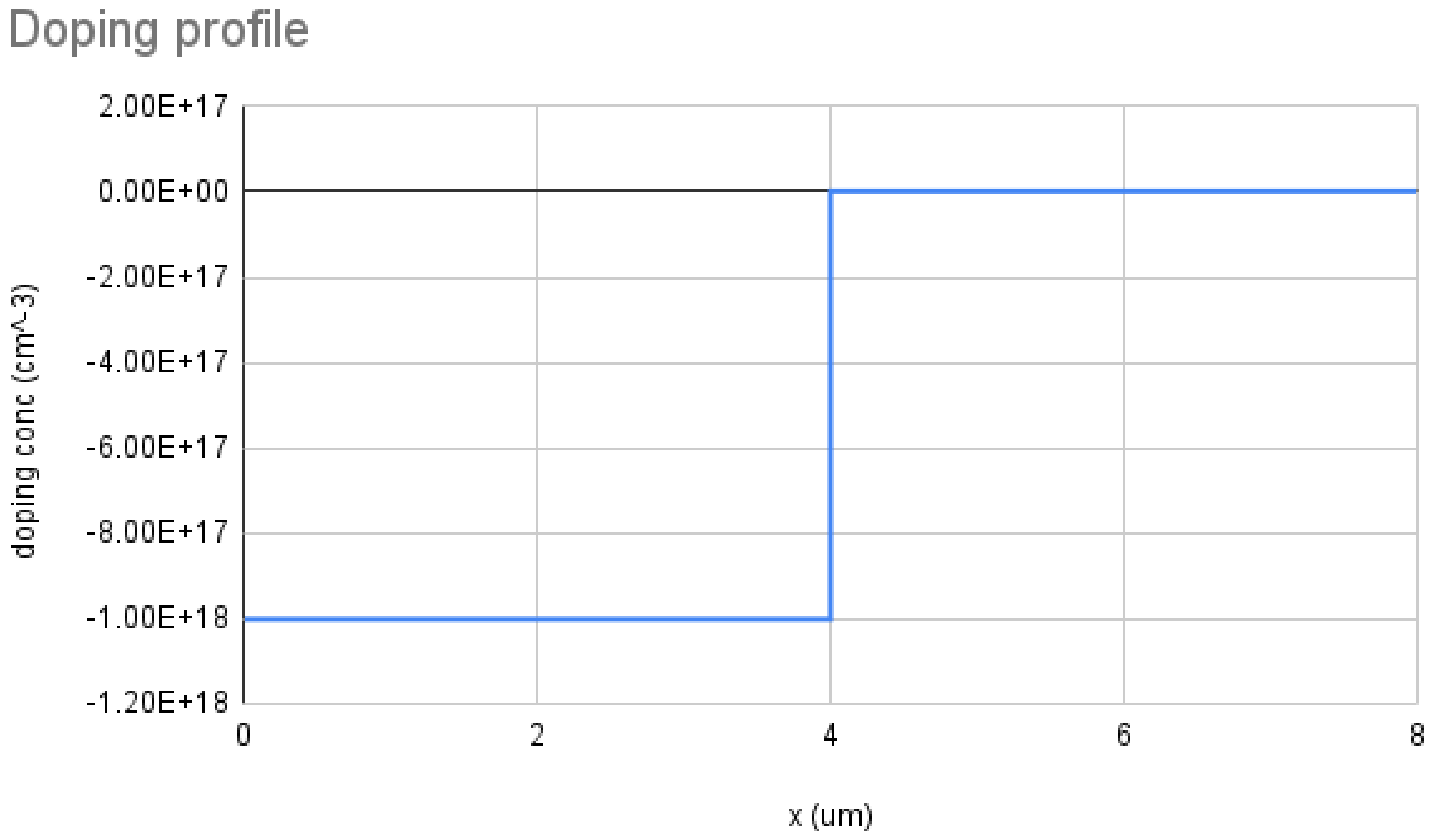


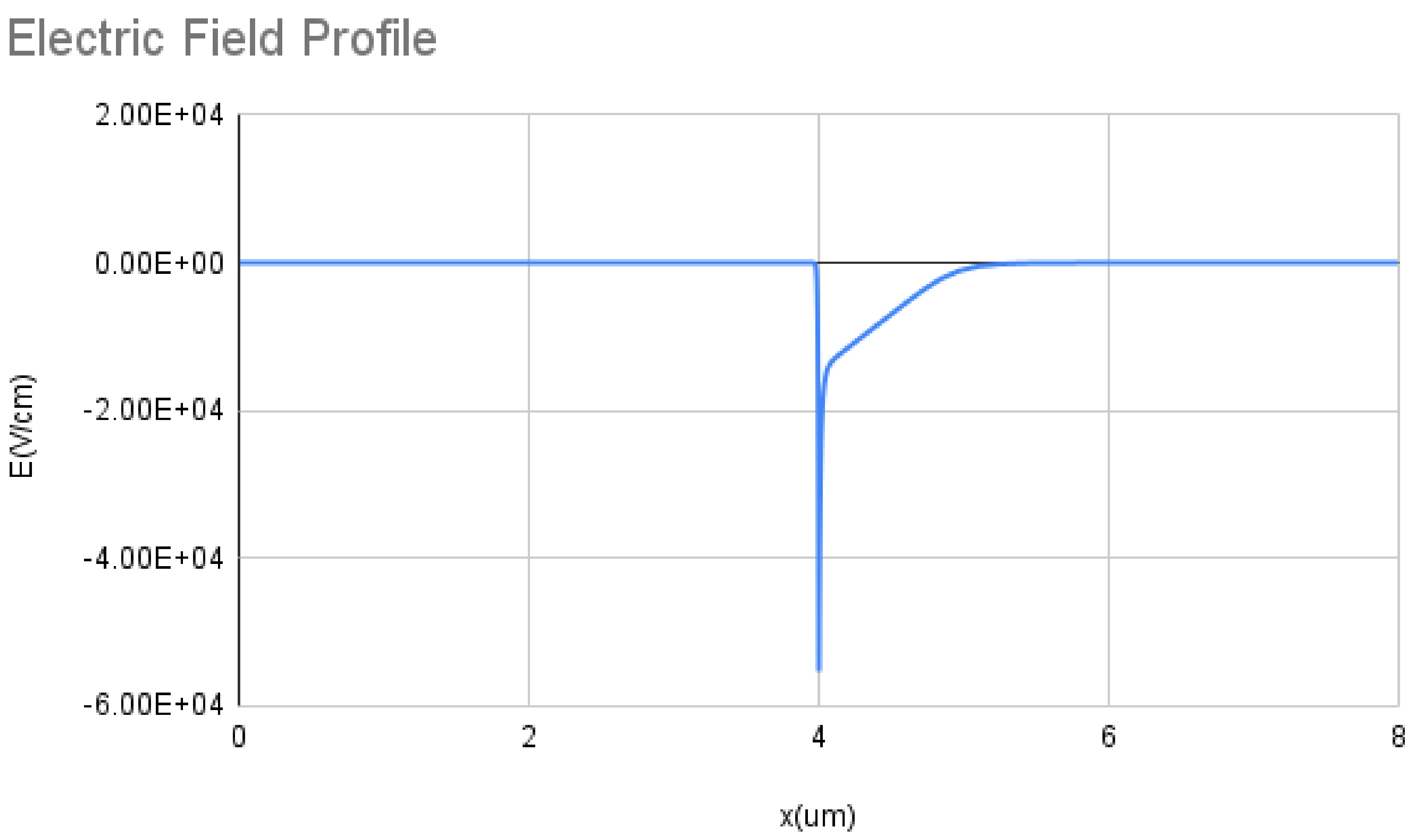


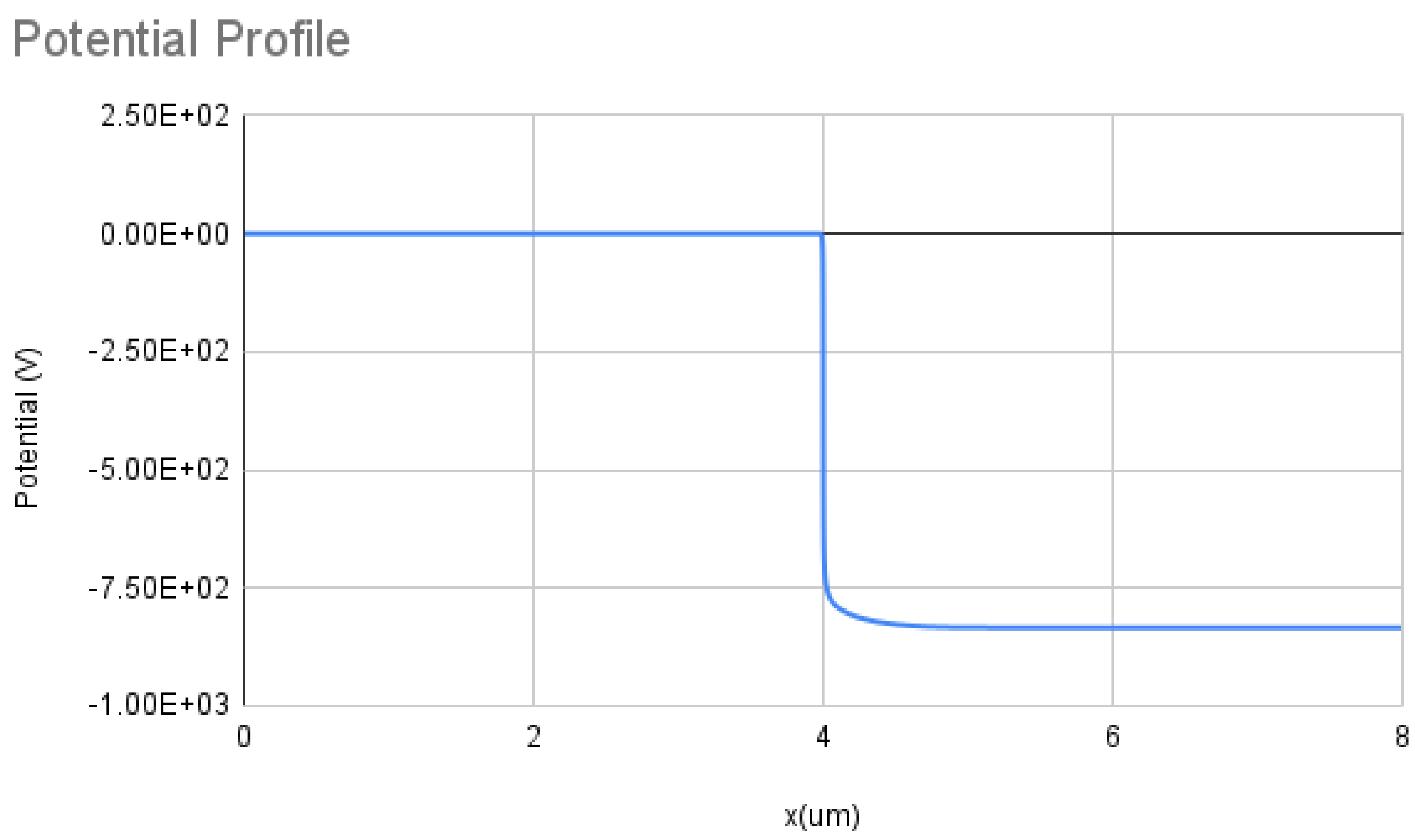


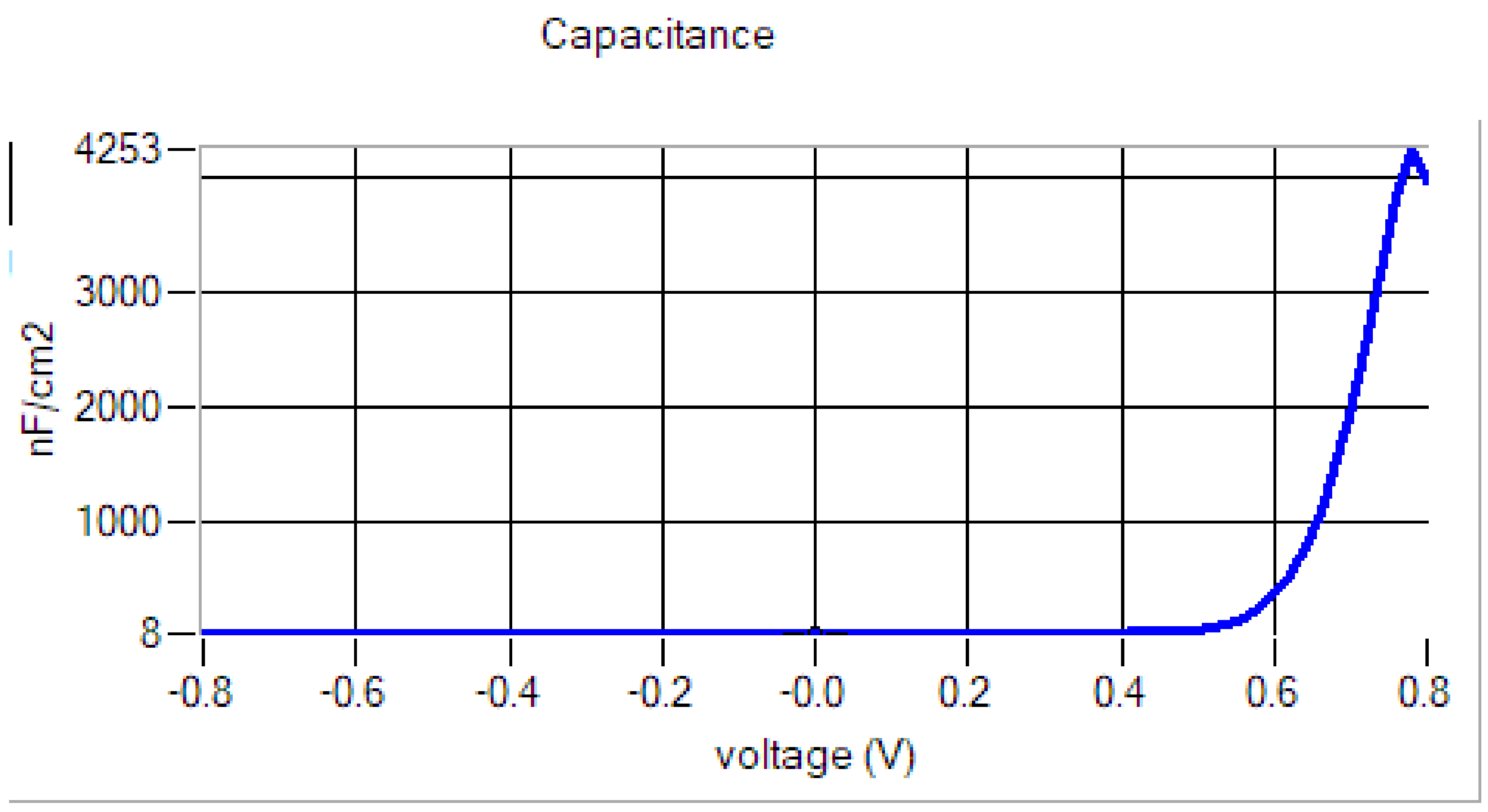
(v) Na = 10^18 cm-3

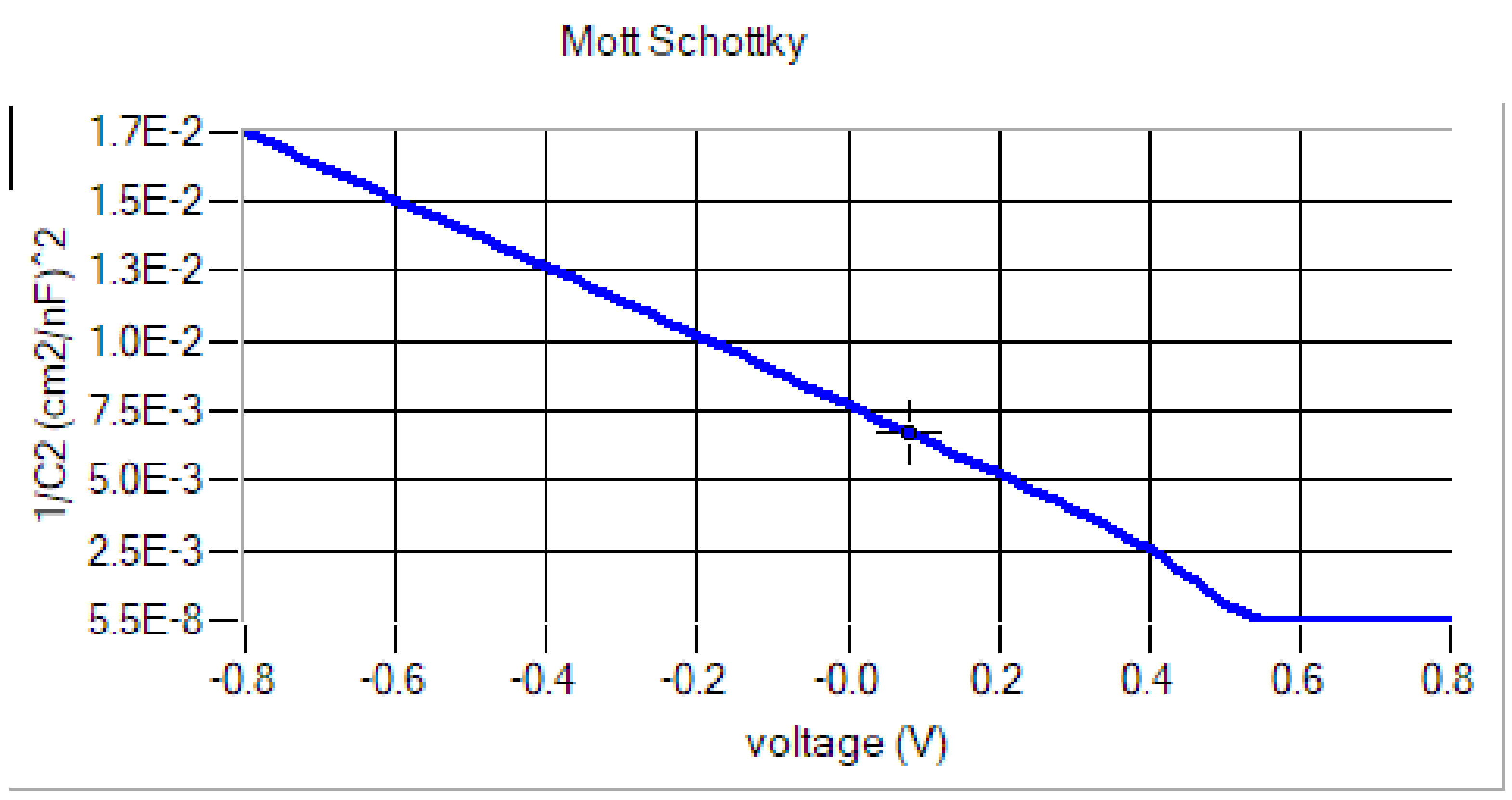

Band Diagram
ct type
EC, EV
EFp
EFn
1.06
0.50
0.00
-0.50
-0.85
eV
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0
distance (µm)


Doping profile
2.00E+17
0.00E+00
-2.00E+17
-4.00E+17
-6.00E+17
-8.00E+17
-1.00E+18
-1.20E+18
doping conc (cm^-3)
0
2
4
6
8
x (um)

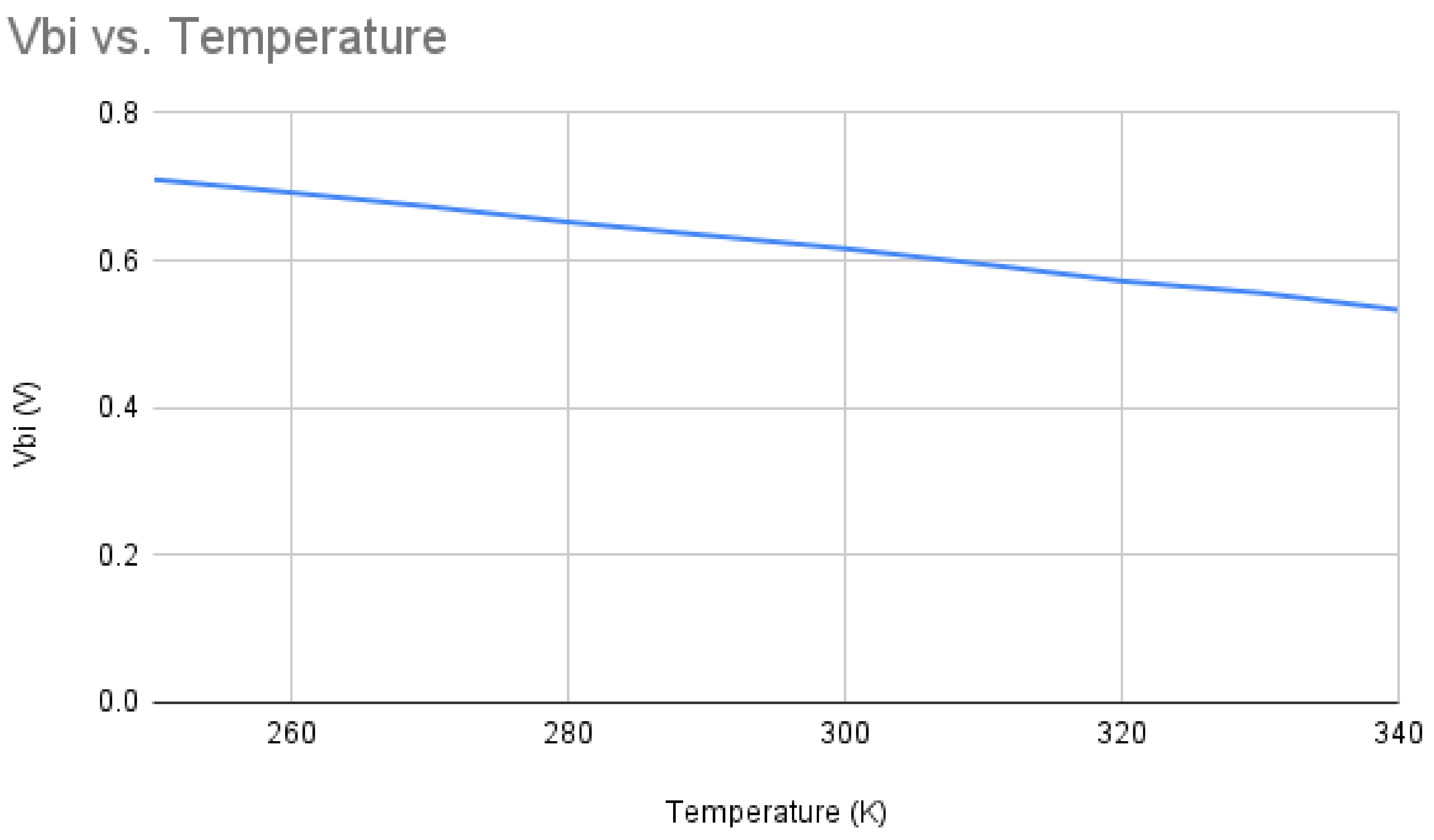

Electric Field Profile
2.00E+04
0.00E+00
-2.00E+04
-4.00E+04
-6.00E+04
E(V/cm)
0
2
4
6
8
x(um)


Potential Profile
2.50E+02
0.00E+00
-2.50E+02
-5.00E+02
-7.50E+02
-1.00E+03
Potential (V)
0
2
4
6
8
x(um)


Capacitance
4253
3000
2000
1000
8
nF/cm2
-0.8 -0.6 -0.4 -0.2 -0.0 0.2 0.4 0.6 0.8
voltage (V)


Mott Schottky
1.7E-2
1.5E-2
1.3E-2
1.0E-2
7.5E-3
5.0E-3
2.5E-3
5.5E-8
1/C2 (cm2/nF)^2
-0.8 -0.6 -0.4 -0.2 -0.0 0.2 0.4 0.6 0.8
voltage (V)

Temperature dependence (Vbi vs T)



ANALYSIS

o) Vbi vs doping density,

Vbi was found to increase ~~exponentially~~ logarithmically ~~for~~ with increase in doping concentration.
The plot of Vbi vs log(Na) was a straight line.

o) W vs doping density.

We observe that w first decreases then stays nearly same and then increases slightly.
this is because W is dependent on both Vbi and $\frac{N_D}{N_A}$.

when N_D and N_A are comparable, w decreases with increase in Na. $w \propto N_a^{-0.5}$

when $N_A >> N_D$, then $w \propto V_{bi}^{0.5}$, hence it increases.

o) Co vs doping density.

Co is inversally ~~exponentially~~ proportional to depletion width.

i.e $C_o \propto \frac{1}{w}$.

Hence Co first increases, then decreases.

o) Emax vs doping density.

Emax depends on both W and Vbi

we find that Emax increases with increase in Na.
and the relation seems to be logarithmic ~~[illegible]~~

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- V_{bi} vs Temperature

Theoretically, V_{bi} should linearly increase with increase in temperature. However, in simulation it was found that V_{bi} is decreasing linearly with increase in temperature.

- The plot of $\frac{1}{C^2}$ vs V was as expected, i.e it decreased linearly with V. and became 0 at nearly V_{bi}.

- graded P^+N junction

the dependence of C on V is given as $C \propto (V_{bi} - V)^{-1/m+2}$

for $m = 0.5$

$$C \propto (V_{bi} - V)^{-2/5}$$

the simulated graph, as expected, showed decrease in C with increase in V.

for $m = 1$

$$C \propto (V_{bi} - V)^{-2/3}$$

and for $m = -1.5$

$$C \propto (V_{bi} - V)^{-2}$$

The graphs for above two cases decreased first with but then had peaks further on increasing voltage

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CONCLUSION

- The doping profiles, Electric and potential profile, and capacitance vs voltage graphs were obtained for all cases
- The V_{bi} values were similar to calculated values.
- The W values differed slightly which could be due to the fact that SCAPS used $\varepsilon_r = 10$.
- The theoretical values of E_{max}, C_0 agreed with simulation values to some extent.
- The temperature dependence of V_{bi} was found out to be different in simulation and theoretical case.
- The structures for graded p'n junction was successfully simulated for $m = 0.5, 1, -1.5$.

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