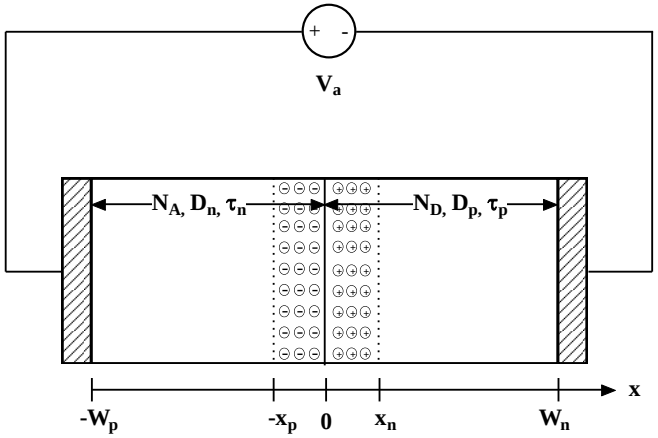
Diode Current-Voltage Characteristics: Numerical Examples

EECS 320

Introduction to Semiconductor Devices

"General Solution"

- Assumptions
  - Uniform, Abrupt Doping
  - Uniform Diffusivity, Lifetime
  - Low Level Injection
  - No Recombination in Depletion Region
  - Perfect Ohmic Contacts
  - Minority Current flow in neutral regions by diffusion only



Results

$$\left.\begin{aligned}\Delta n_p(x) &= \left[\frac{\sinh\left(\frac{W_p+x}{L_n}\right)}{\sinh\left(\frac{W_p-x_p}{L_n}\right)}\right] n_{p0}\left(\exp\left(qV_a/kT\right)-1\right)\\ J_n(x) &= \frac{qD_n}{L_n}\left[\frac{\cosh\left(\frac{W_p+x}{L_n}\right)}{\sinh\left(\frac{W_p-x_p}{L_n}\right)}\right] n_{p0}\left(\exp\left(qV_a/kT\right)-1\right)\end{aligned}\right\} -W_p \le x \le -x_p$$

$$J_n(x) = J_n(-x_p) = \frac{qD_n}{L_n}\left[\coth\left(\frac{W_p-x_p}{L_n}\right)\right] n_{p0}\left(\exp\left(qV_a/kT\right)-1\right) \qquad \left\{-x_p \le x \le x_n\right\}$$

$$\left.\begin{aligned}\Delta p_n &= \left[\frac{\sinh\left(\frac{W_n-x}{L_p}\right)}{\sinh\left(\frac{W_n-x_n}{L_p}\right)}\right] p_{n0}\left(\exp\left(qV_a/kT\right)-1\right)\\ J_p(x) &= \frac{qD_{pn}}{L_p}\left[\frac{\cosh\left(\frac{W_n-x}{L_p}\right)}{\sinh\left(\frac{W_n-x_n}{L_p}\right)}\right] p_{n0}\left(\exp\left(qV_a/kT\right)-1\right)\end{aligned}\right\} x_n \le x \le W_n$$

$$J_p(x) = J_p(x_n) = \frac{qD_{pn}}{L_p}\left[\coth\left(\frac{W_n-x_n}{L_p}\right)\right] p_{n0}\left(\exp\left(qV_a/kT\right)-1\right) \qquad \left\{-x_p \le x \le x_n\right\}$$

$$J_{sat} = \frac{qD_{pn}}{L_p}\left[\coth\left(\frac{W_n-x_n}{L_p}\right)\right] p_{n0} + \frac{qD_n}{L_n}\left[\coth\left(\frac{W_p-x_p}{L_n}\right)\right] n_{p0}$$

$$J_{total} = J_{sat}\left(\exp\left(qV_a/kT\right)-1\right)$$

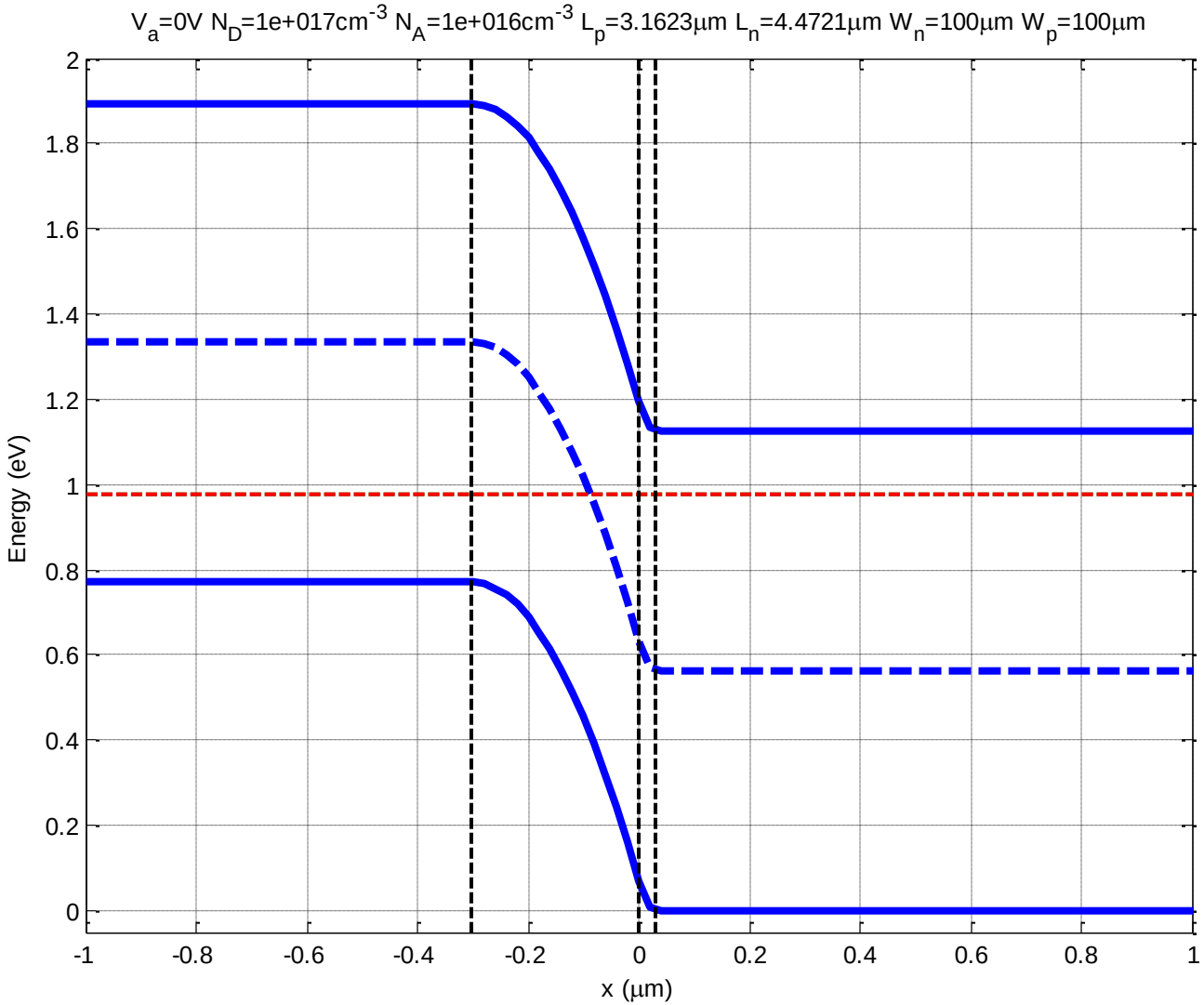
Long Diode

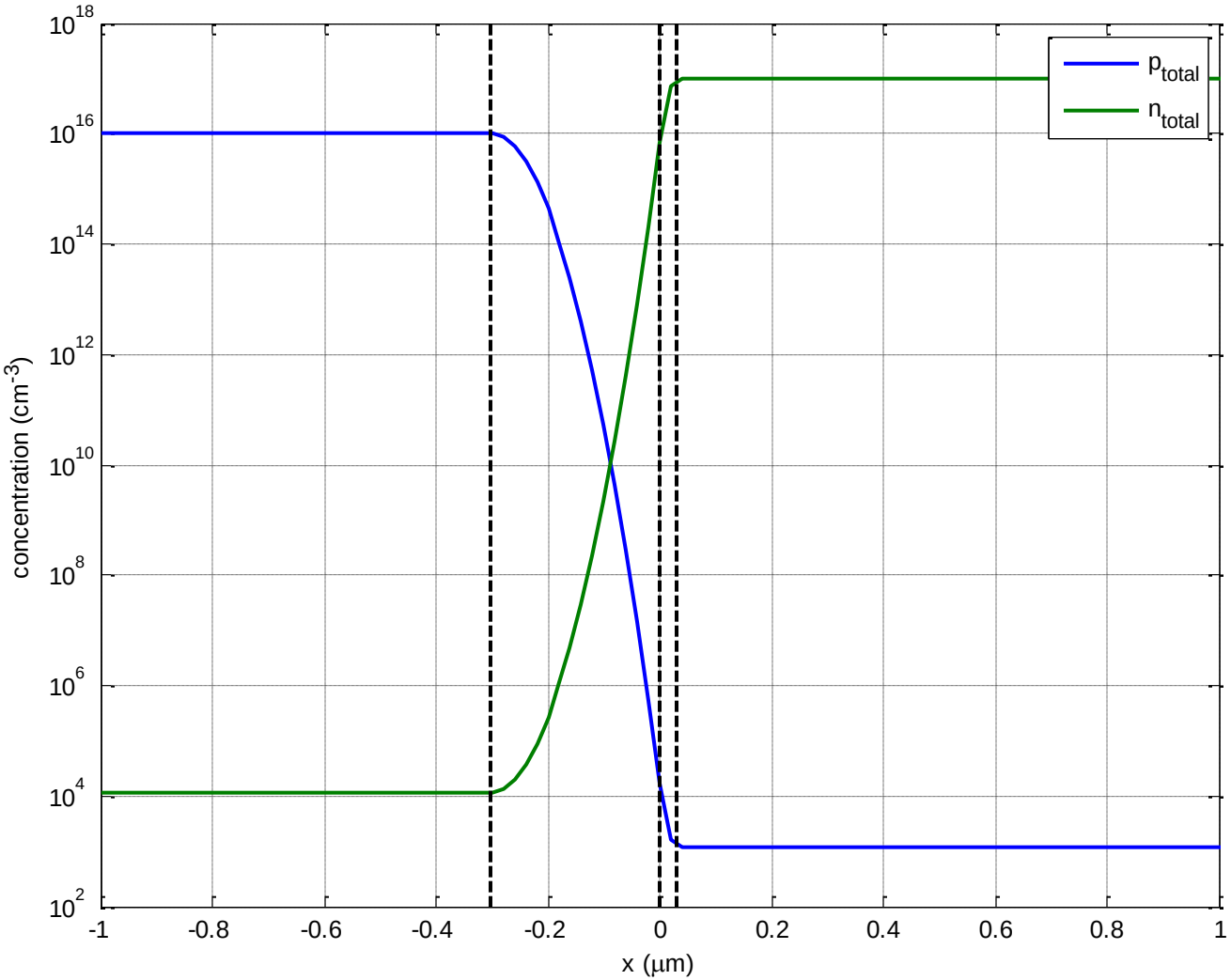
$$N_D = 1x10^{17} cm^{-3} \quad N_A = 1x10^{16} cm^{-3}$$

$$D_p = 10 cm^2 / s \qquad D_n = 20 cm^2 / s$$

$$\tau_p = 10 ns \qquad \tau_n = 10 ns$$

$$W_n = 100 \mu m \qquad W_p = 100 \mu m$$


V_a=0V N_D=1e+017cm^{-3} N_A=1e+016cm^{-3} L_p=3.1623µm L_n=4.4721µm W_n=100µm W_p=100µm
Energy (eV)
x (µm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1


10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
concentration (cm^{-3})
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
x (μm)
p_{total}
n_{total}

Long Diode

$$N_D = 1x10^{17} cm^{-3} \quad N_A = 1x10^{16} cm^{-3}$$

$$D_p = 10 cm^2 / s \qquad D_n = 20 cm^2 / s$$

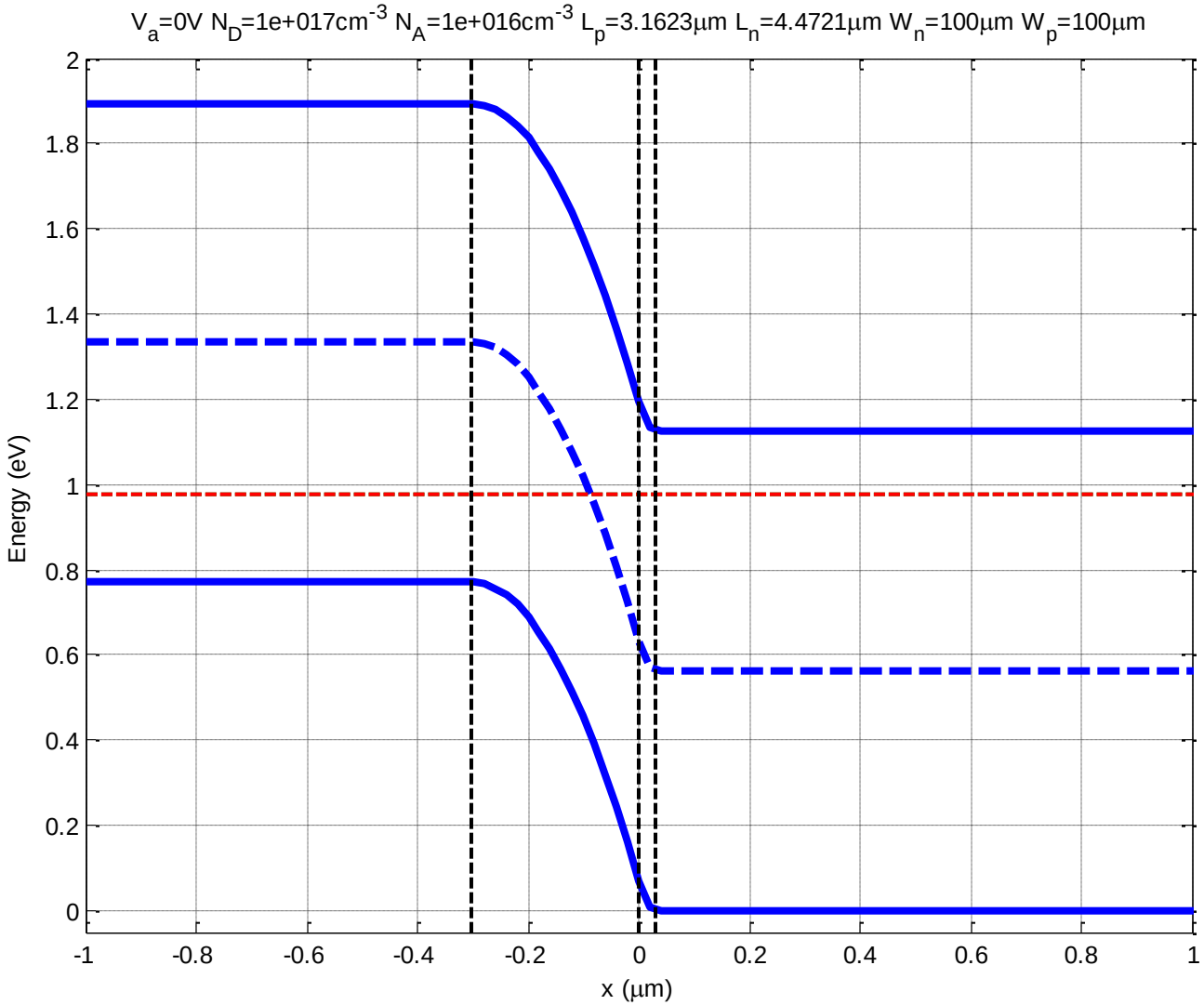
$$\tau_p = 10 ns \qquad \tau_n = 10 ns$$

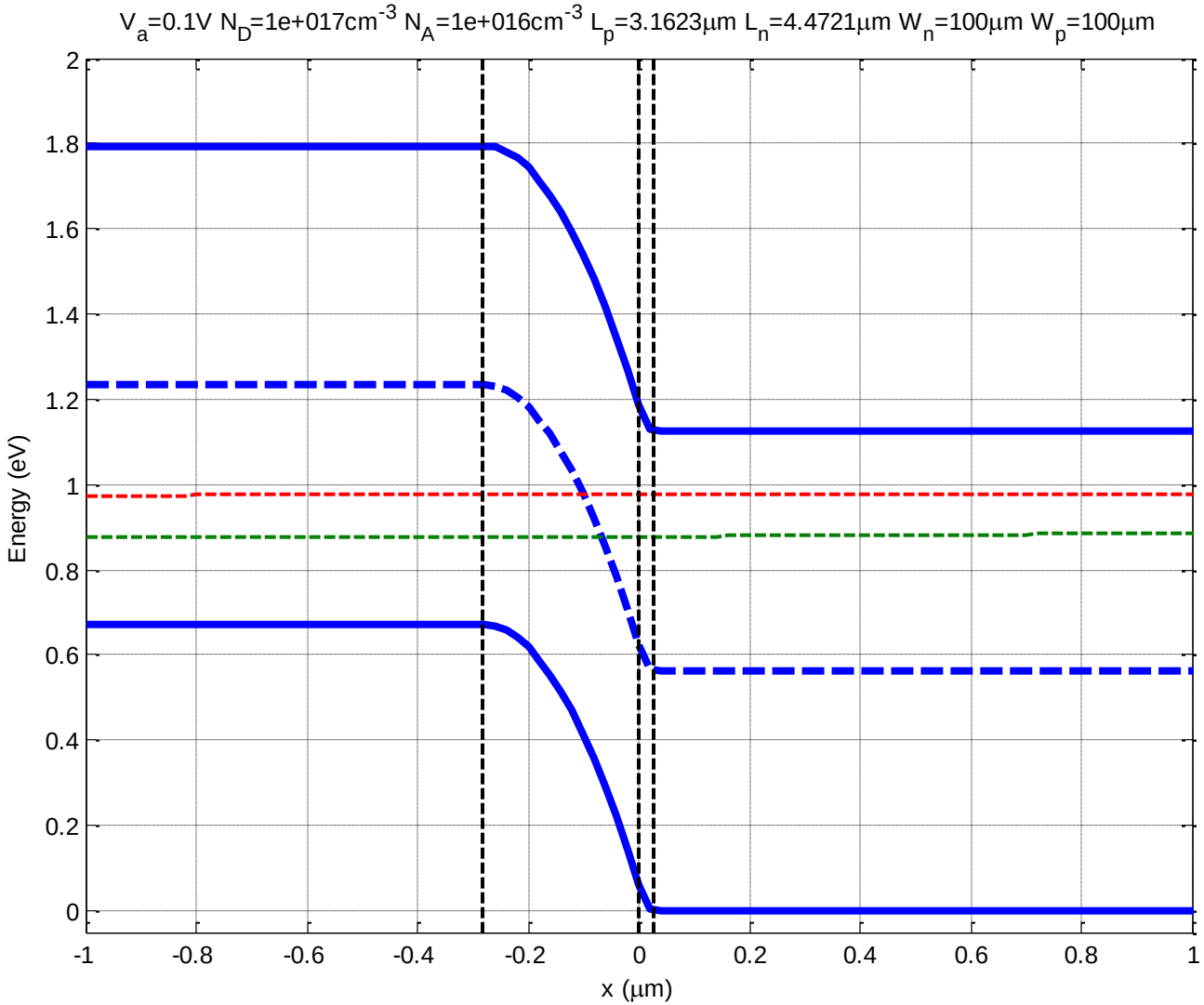
$$W_n = 100 \mu m \qquad W_p = 100 \mu m$$

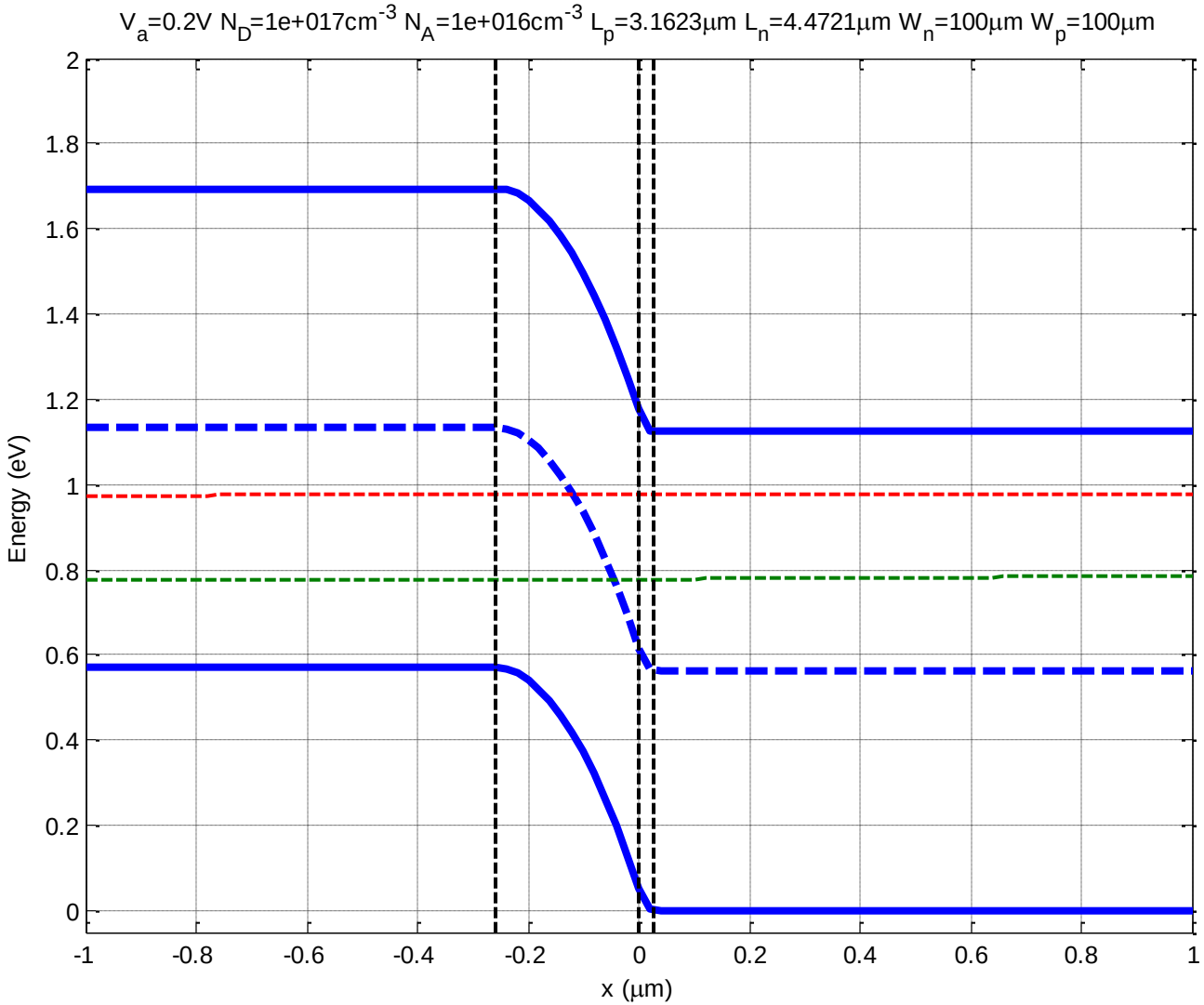
$$V_a = 0.6V \qquad J_{sat} = 88.182 pA / cm^2$$

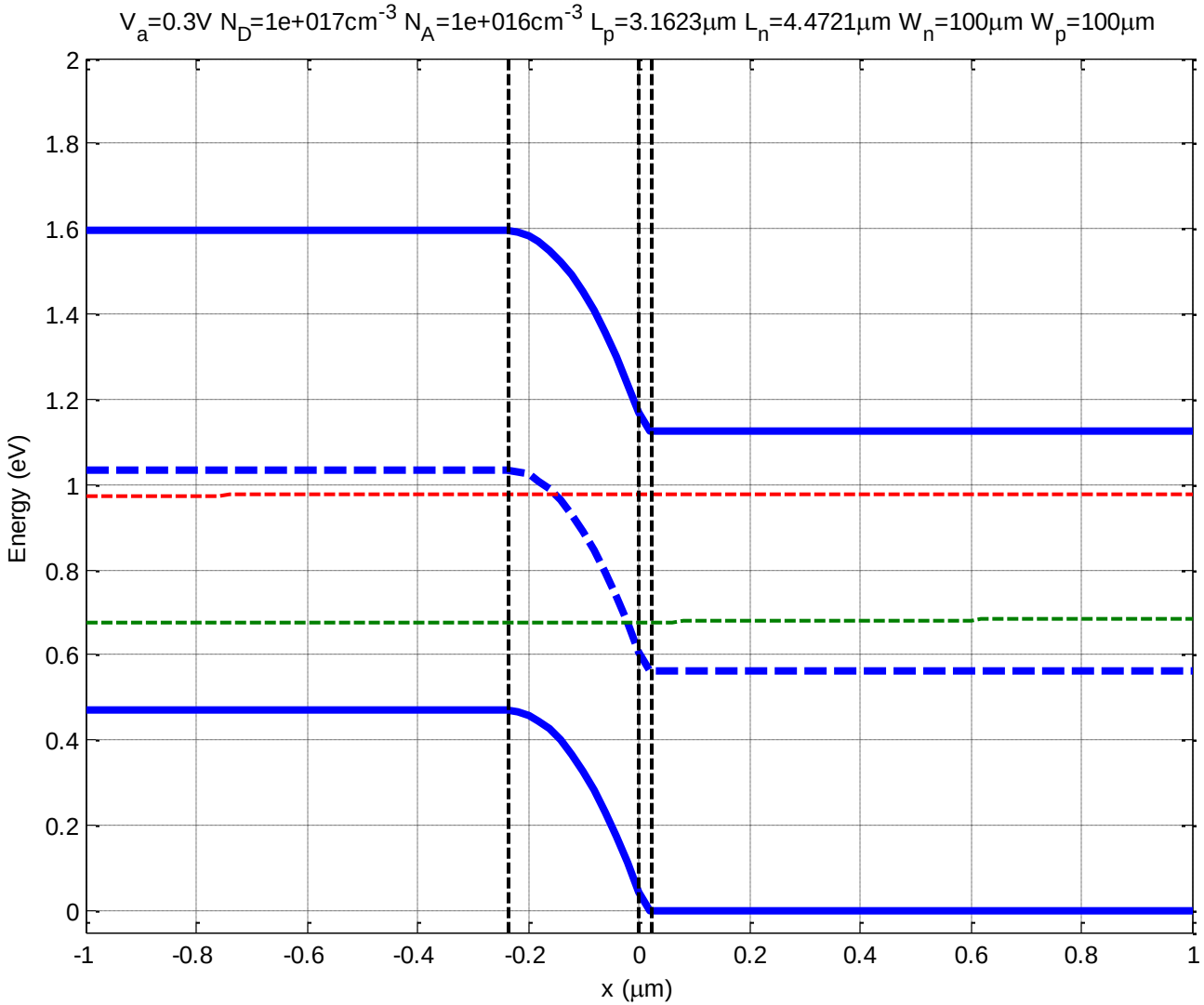
$$J = 1.0609 A / cm^2$$

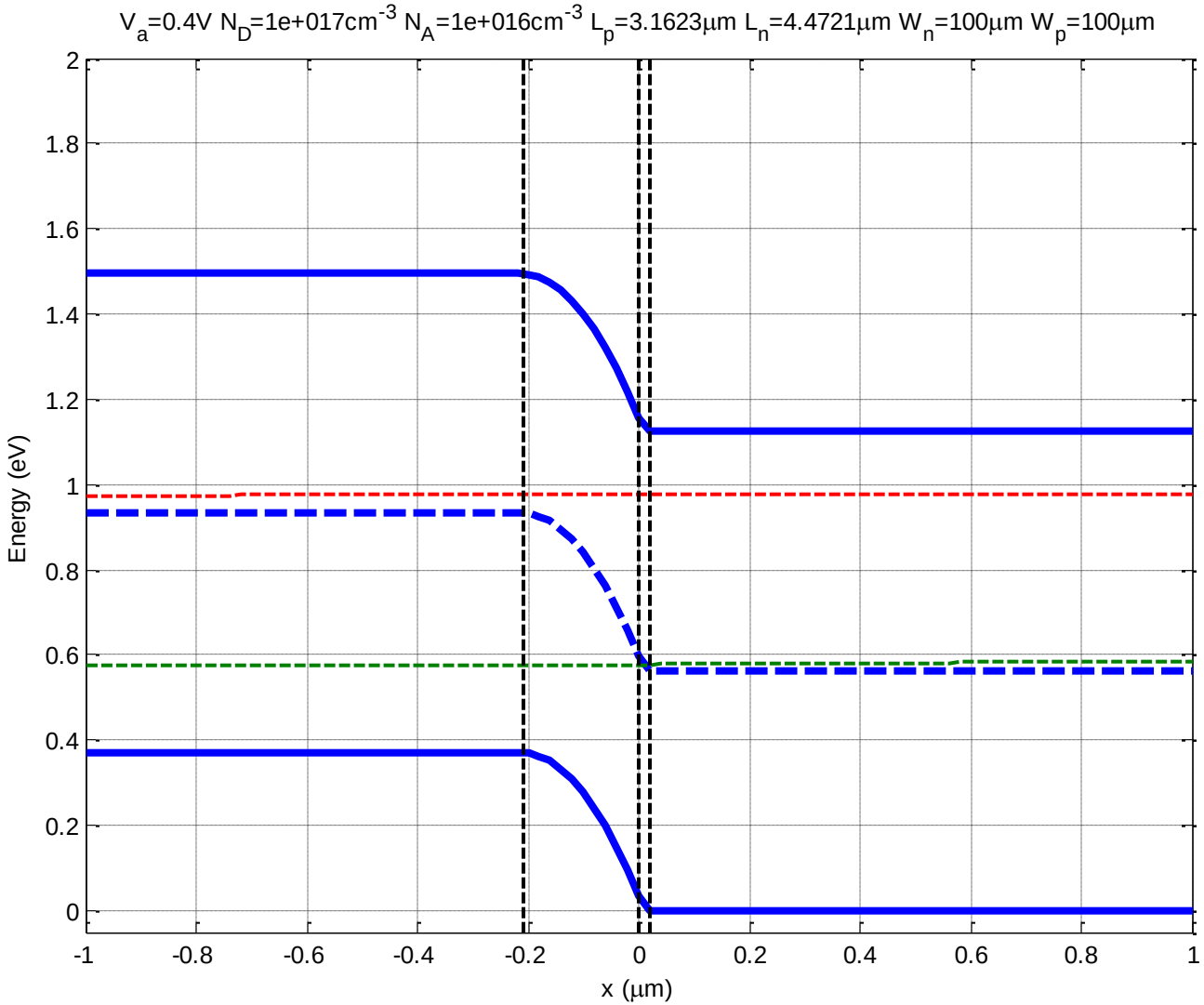
$$x_n = 14.207 nm \quad x_p = 142.07 nm$$

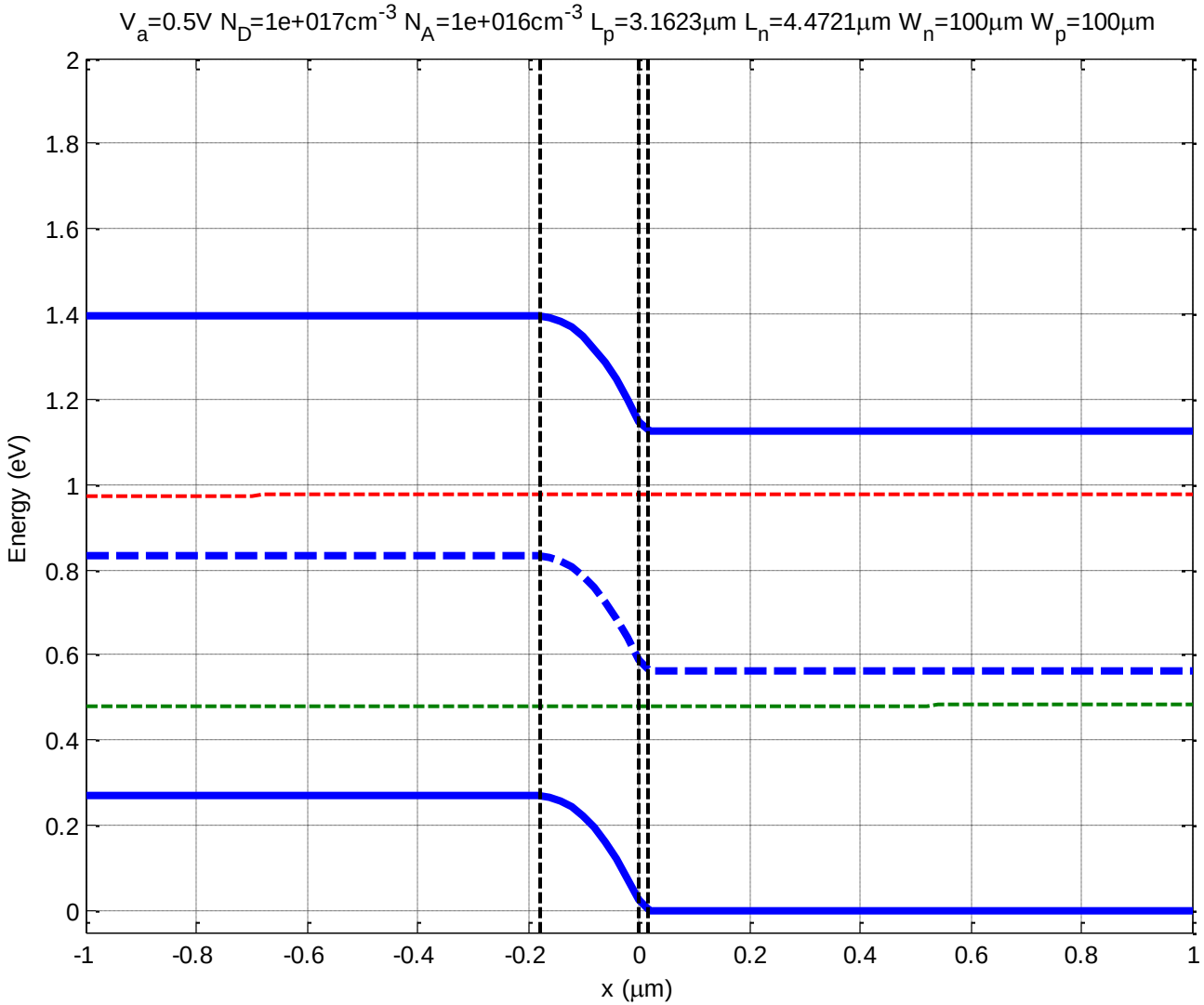

V_a=0V N_D=1e+017cm^{-3} N_A=1e+016cm^{-3} L_p=3.1623µm L_n=4.4721µm W_n=100µm W_p=100µm
Energy (eV)
x (µm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

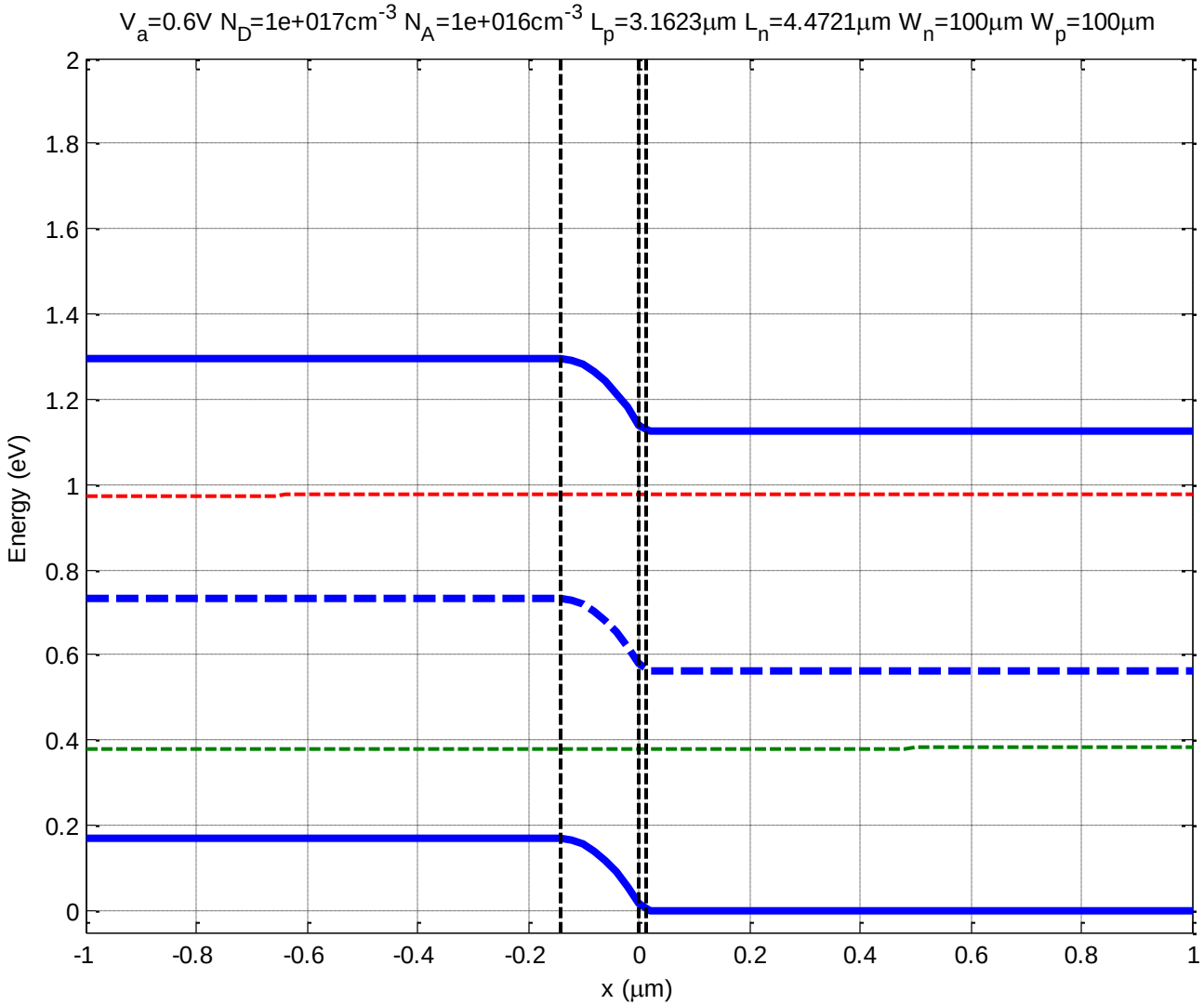

V_a=0.1V N_D=1e+017cm^{-3} N_A=1e+016cm^{-3} L_p=3.1623μm L_n=4.4721μm W_n=100μm W_p=100μm
Energy (eV)
x (μm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

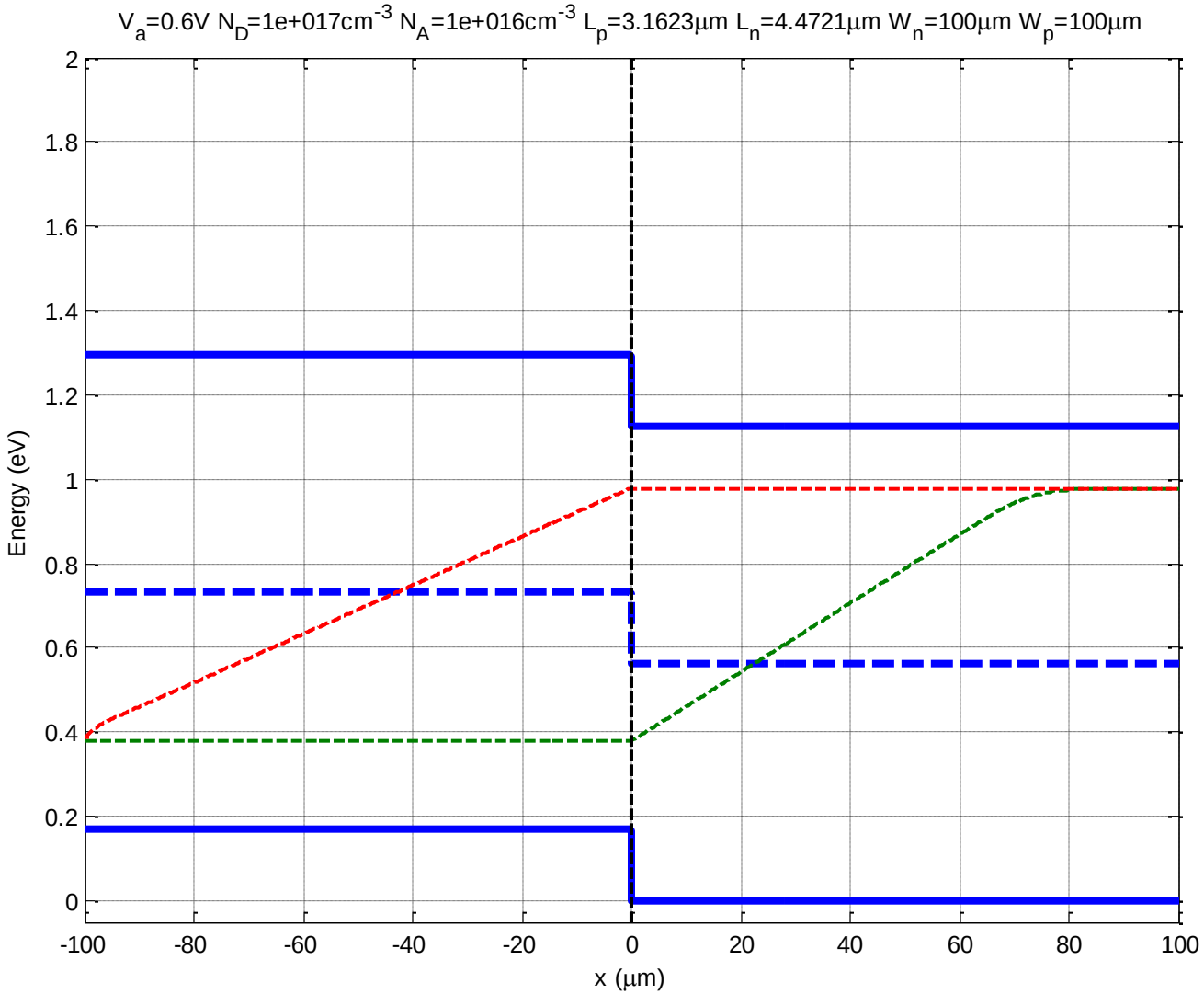

V_a=0.2V N_D=1e+017cm^{-3} N_A=1e+016cm^{-3} L_p=3.1623μm L_n=4.4721μm W_n=100μm W_p=100μm
Energy (eV)
x (μm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

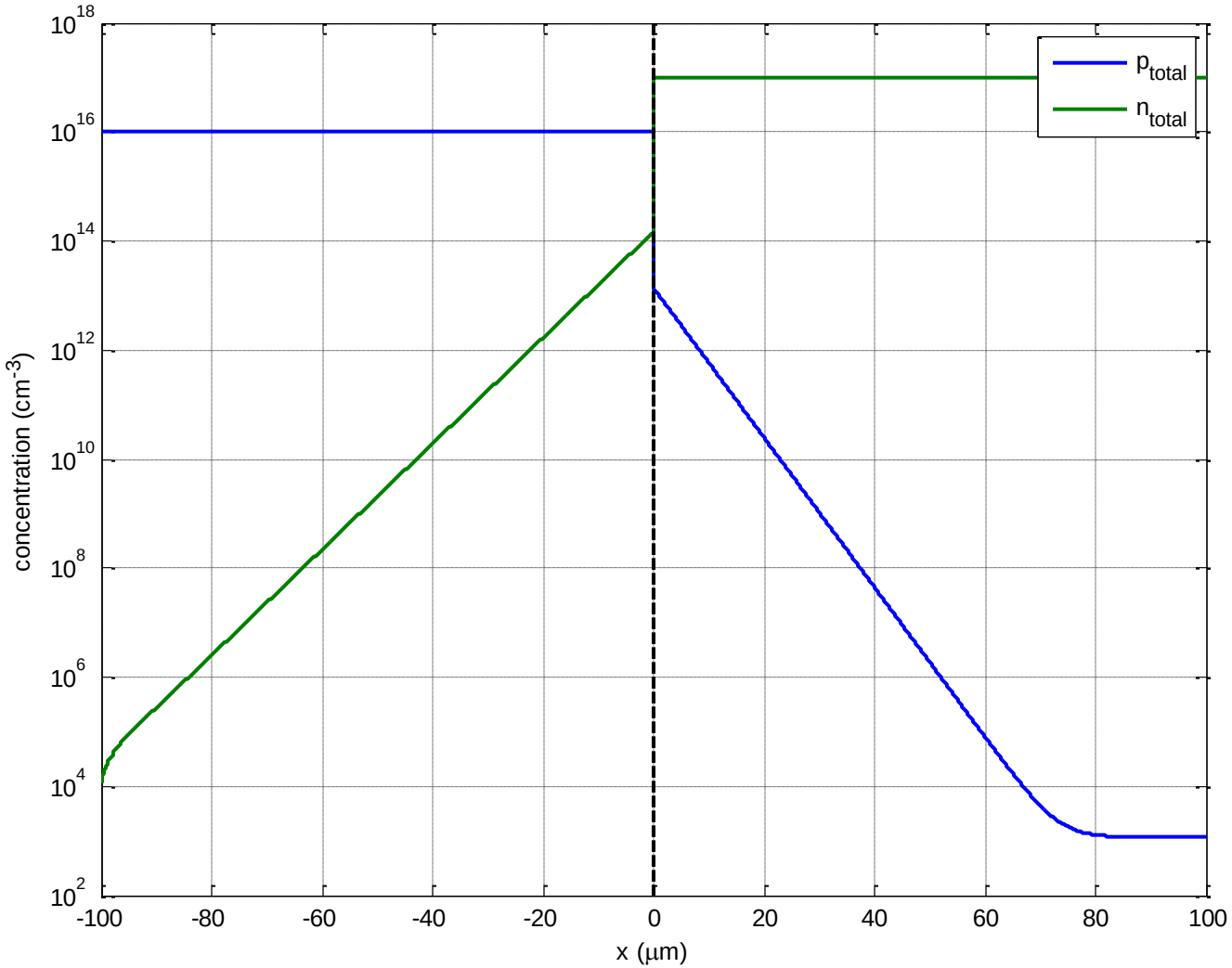

V_a=0.3V N_D=1e+017cm^{-3} N_A=1e+016cm^{-3} L_p=3.1623μm L_n=4.4721μm W_n=100μm W_p=100μm
Energy (eV)
x (μm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

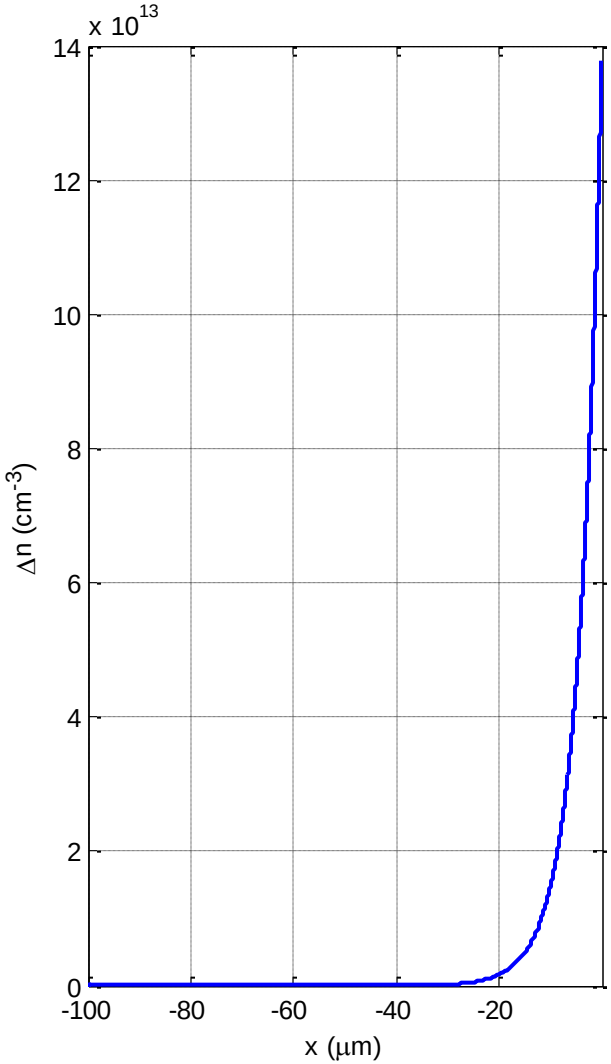

V_a=0.4V N_D=1e+017cm^{-3} N_A=1e+016cm^{-3} L_p=3.1623μm L_n=4.4721μm W_n=100μm W_p=100μm
Energy (eV)
x (μm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

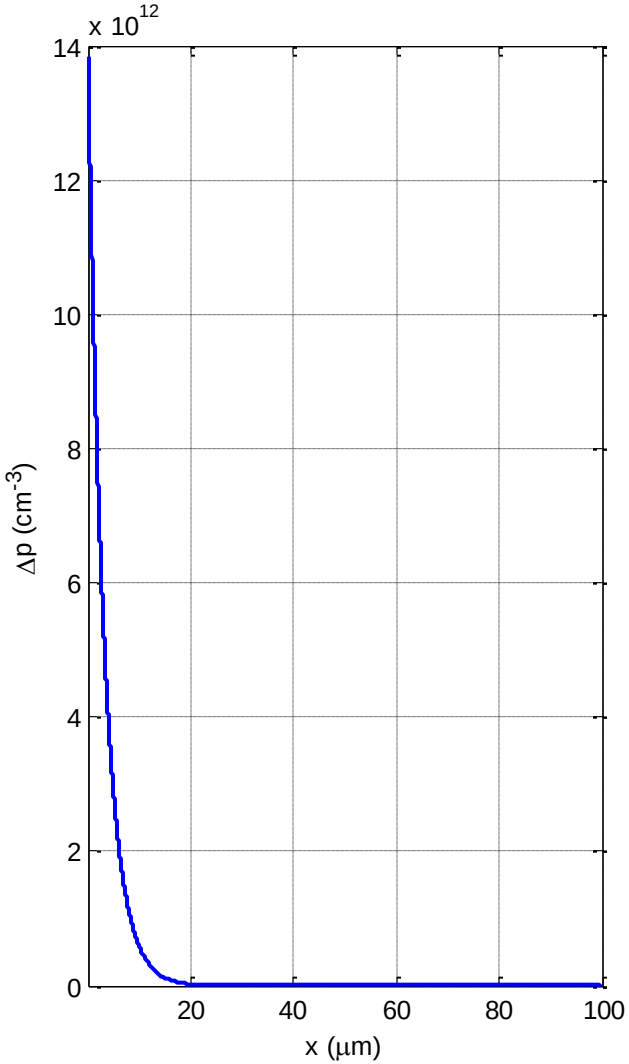

V_a=0.5V N_D=1e+017cm^{-3} N_A=1e+016cm^{-3} L_p=3.1623μm L_n=4.4721μm W_n=100μm W_p=100μm
Energy (eV)
x (μm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

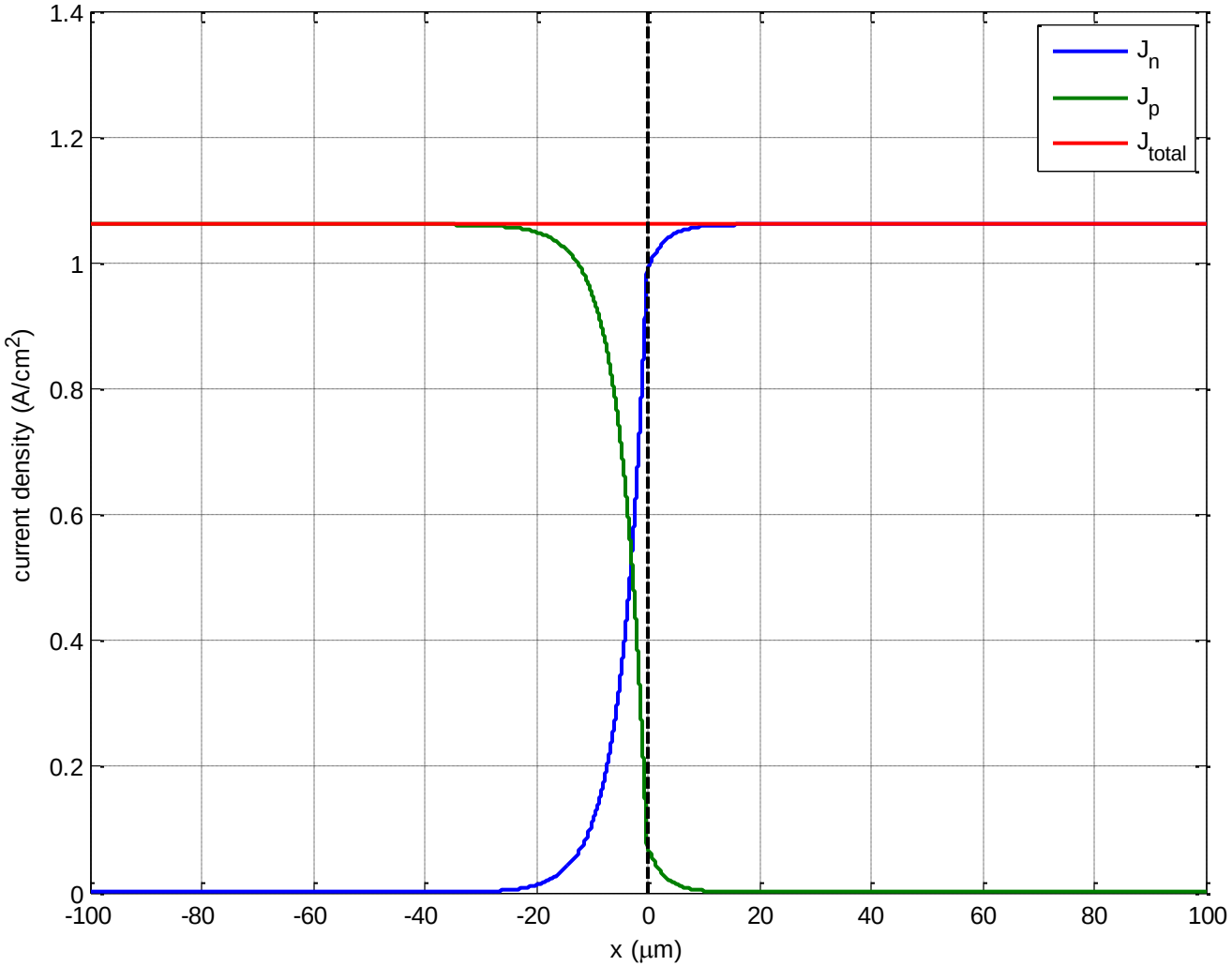

V_a=0.6V N_D=1e+017cm^{-3} N_A=1e+016cm^{-3} L_p=3.1623μm L_n=4.4721μm W_n=100μm W_p=100μm
Energy (eV)
x (μm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1


V_a=0.6V N_D=1e+017cm^{-3} N_A=1e+016cm^{-3} L_p=3.1623μm L_n=4.4721μm W_n=100μm W_p=100μm
Energy (eV)
x (μm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-100
-80
-60
-40
-20
0
20
40
60
80
100


10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
concentration (cm^{-3})
-100
-80
-60
-40
-20
0
20
40
60
80
100
x (μm)
p_{total}
n_{total}


x 10^13
14
12
10
8
6
4
2
0
Δn (cm^-3)
-100
-80
-60
-40
-20
x (μm)


x 10^12
14
12
10
8
6
4
2
0
Δp (cm^-3)
20
40
60
80
100
x (μm)


1.4
1.2
1
0.8
0.6
0.4
0.2
0
current density (A/cm2)
-100
-80
-60
-40
-20
0
20
40
60
80
100
x (μm)
Jn
Jp
Jtotal

E-field in Neutral Region

Failure of LLI

Short Diode

$$N_D = 1x10^{17} cm^{-3} \quad N_A = 1x10^{16} cm^{-3}$$

$$D_p = 10cm^2 / s \qquad D_n = 20cm^2 / s$$

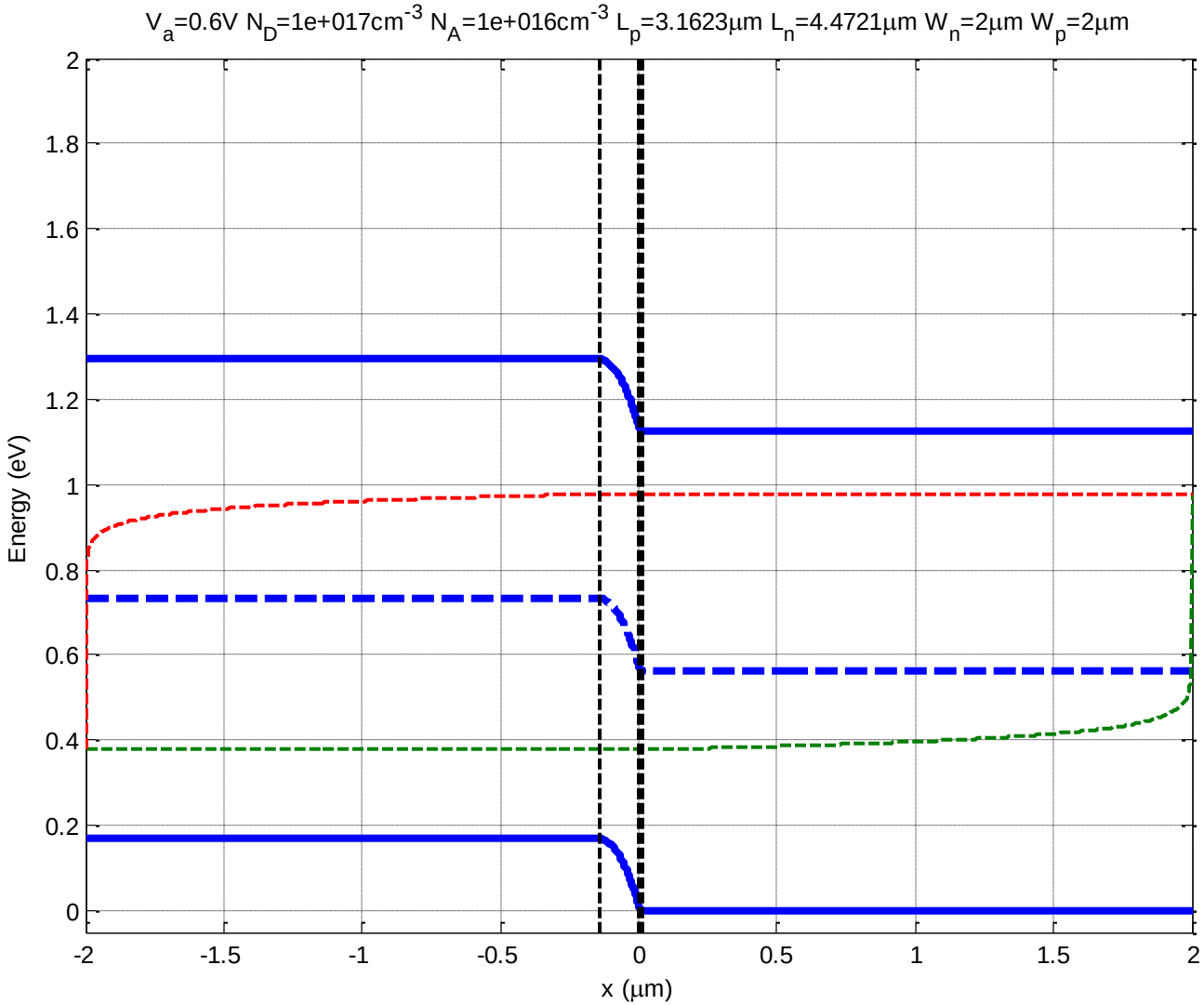
$$\tau_p = 10ns \qquad \tau_n = 10ns$$

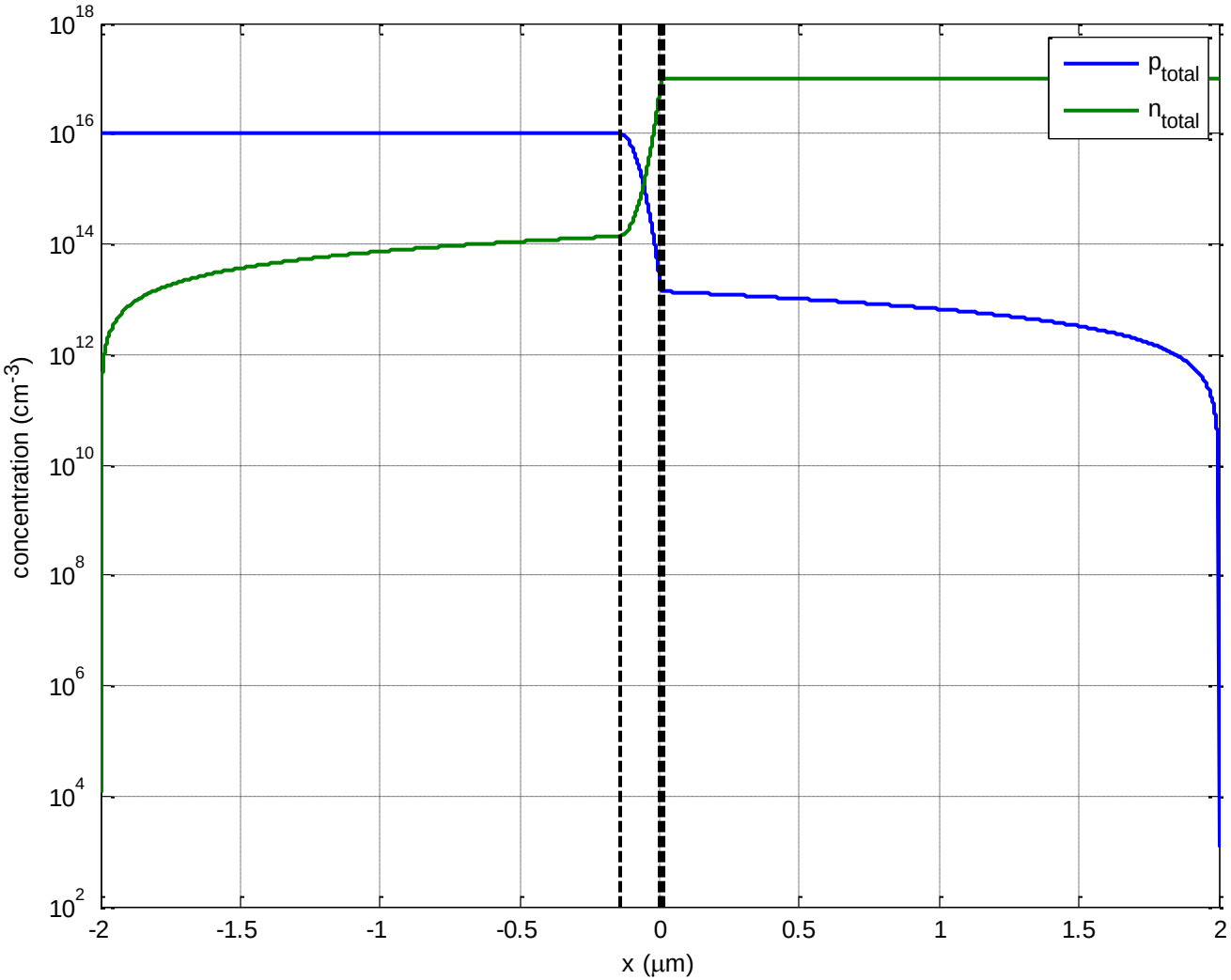
$$W_n = 2\mu m \qquad W_p = 2\mu m$$

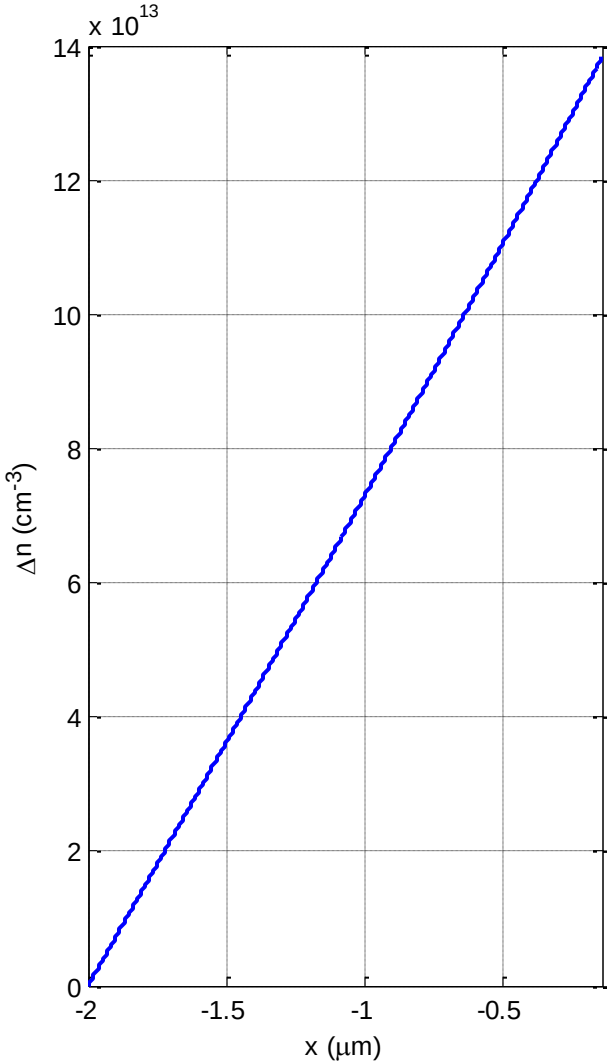
$$V_a = 0.6V \qquad J_{sat} = 88.182\, pA / cm^2$$

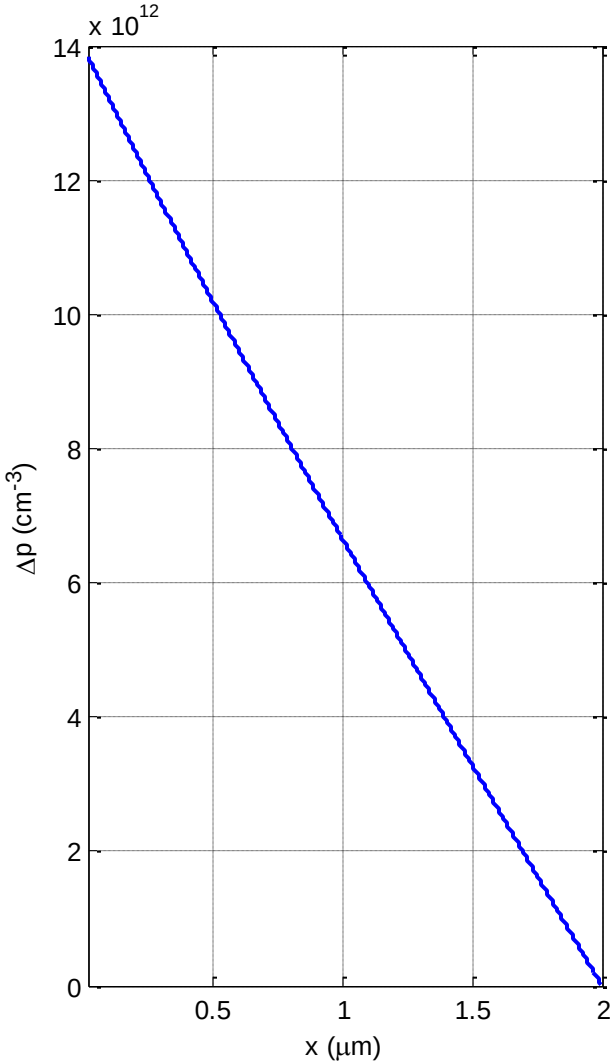
$$J = 1.0609A / cm^2$$

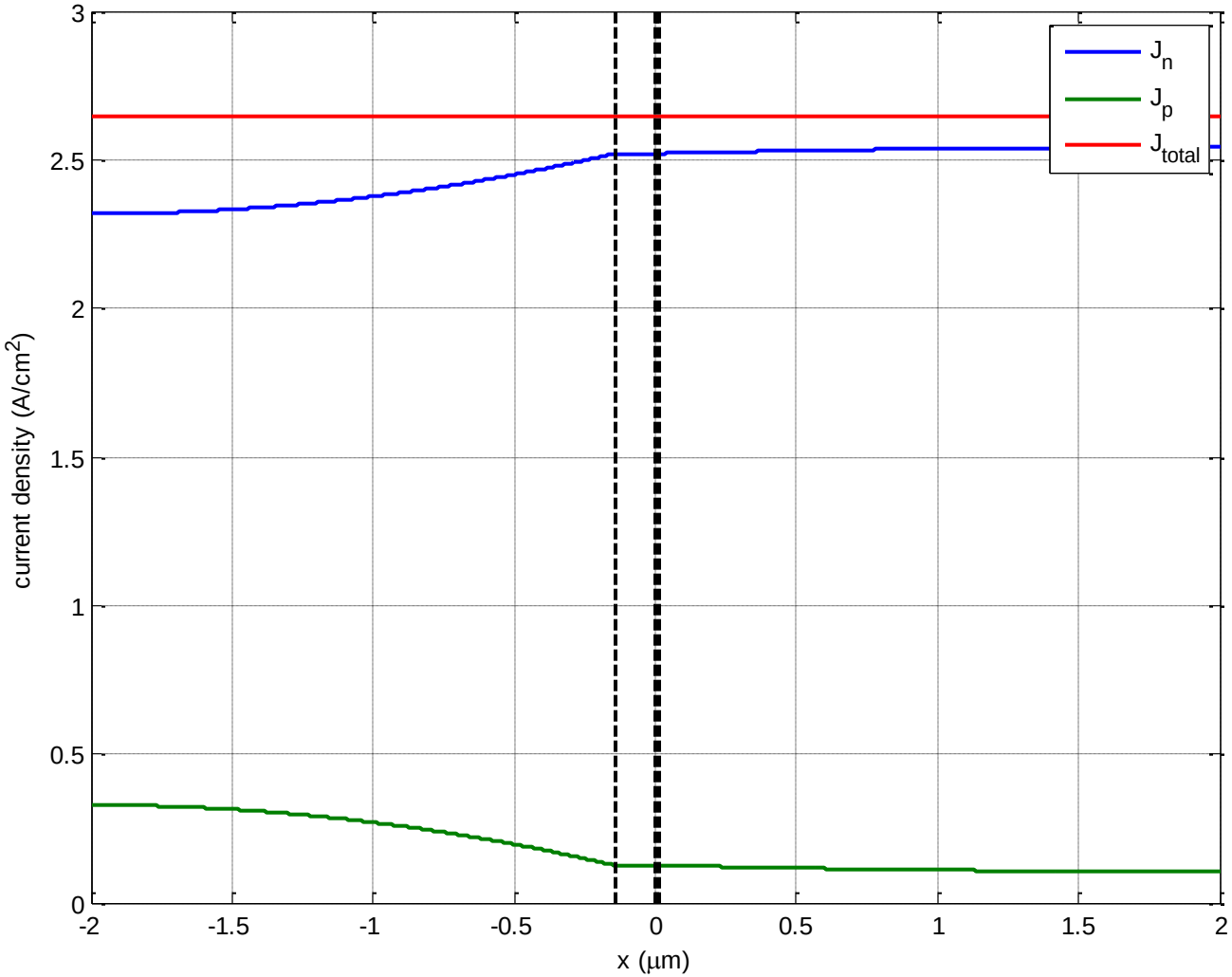
$$x_n = 14.207nm \quad x_p = 142.07nm$$


V_a=0.6V N_D=1e+017cm^{-3} N_A=1e+016cm^{-3} L_p=3.1623μm L_n=4.4721μm W_n=2μm W_p=2μm
Energy (eV)
x (μm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2


10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
concentration (cm^{-3})
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
x (μm)
p_{total}
n_{total}


x 10^13
14
12
10
8
6
4
2
0
Δn (cm^-3)
-2
-1.5
-1
-0.5
x (μm)


x 10^12
14
12
10
8
6
4
2
0
Δp (cm^-3)
0.5
1
1.5
2
x (μm)


3
2.5
2
1.5
1
0.5
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
current density (A/cm2)
x (μm)
Jn
Jp
Jtotal