**Problem:**

Consider a PN junction of length 3µm (1.5µm on each side) with an abruppt doping concentration (for Na, Nd) of $1*10^{15}cm^{-3}$ (similar to assignment 3). Consider that a voltage of 1V (across the diode terminals) in forward bias is applied for a long time and a voltage of 1V is applied in reverse bias at time, t=0. Let $ni=1.5*10^{10}\ cm^{-3}$, $\mu_p=450cm^2/s$, $\tau_p=20\ \mu s$, $J_R = 2KA/cm^2$.

Plot the decay profile of stored hole charge in the PN junction diode as a function of time from 0<t<ts from the edge of depletion region (of N-side) to the end of diode.

Also Find the value of approximate "ts" value

Where, ts is time where diode remains in the forward bias even after switching from FB to RB

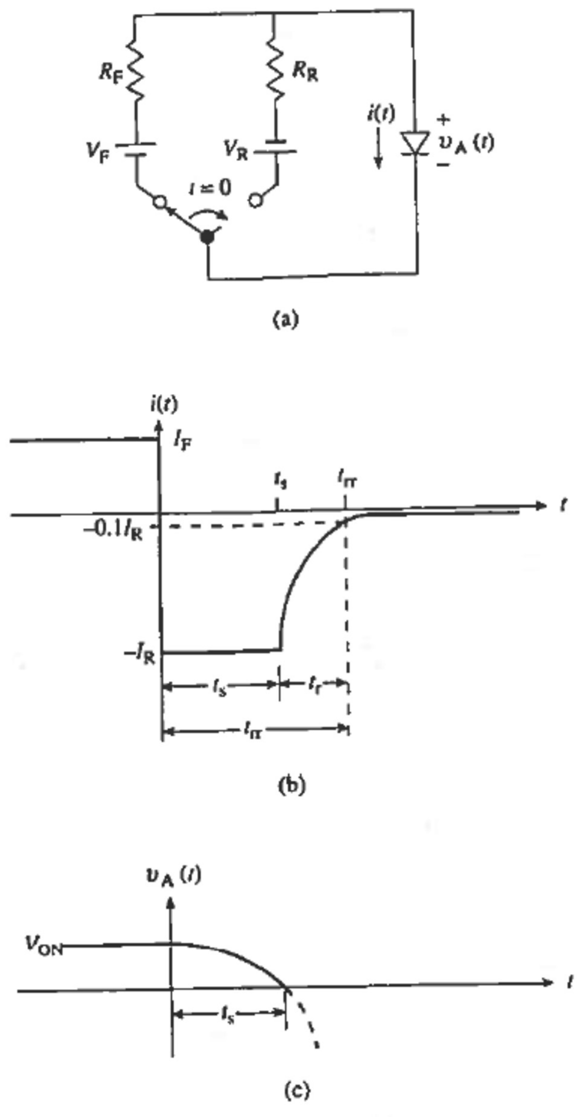



**Figure 8.1** The turn-off transient. (a) Idealized representation of the switching circuit. (b) Sketch and characterization of the current-time transient. (c) Voltage-time transient.

**Theory:**

The minority carrier diffusion equation for holes in the n-region of a PN junction diode is a partial differential equation that describes how the concentration of minority carriers (holes in this case) changes with time and position within the semiconductor. It can be written as follows:

$p(x,t) = p_o + \Delta p(x,t)$ ……………………………………………(1)

$\frac{\partial \Delta p(x,t)}{\partial t} = D_p \frac{\partial^2 \Delta p(x,t)}{\partial x^2} - \frac{\Delta p(x,t)}{\tau_p}$ ……………………………..(2)

Where

- $\Delta p(x,t)$ is the excess concentration of minority carriers (holes) as a function of position (x) and time (t)
- $p(x,t)$ is the concentration of minority carriers as a function of position (x), and time (t)
- $p_o$ is the minority carrier concentration in n-side (=$\frac{n_i^2}{N_d}$ $at\ equilibrium$)
- $D_p$ is the diffusion coefficient for holes in n-region
- $\tau_p$ is the carrier lifetime for holes

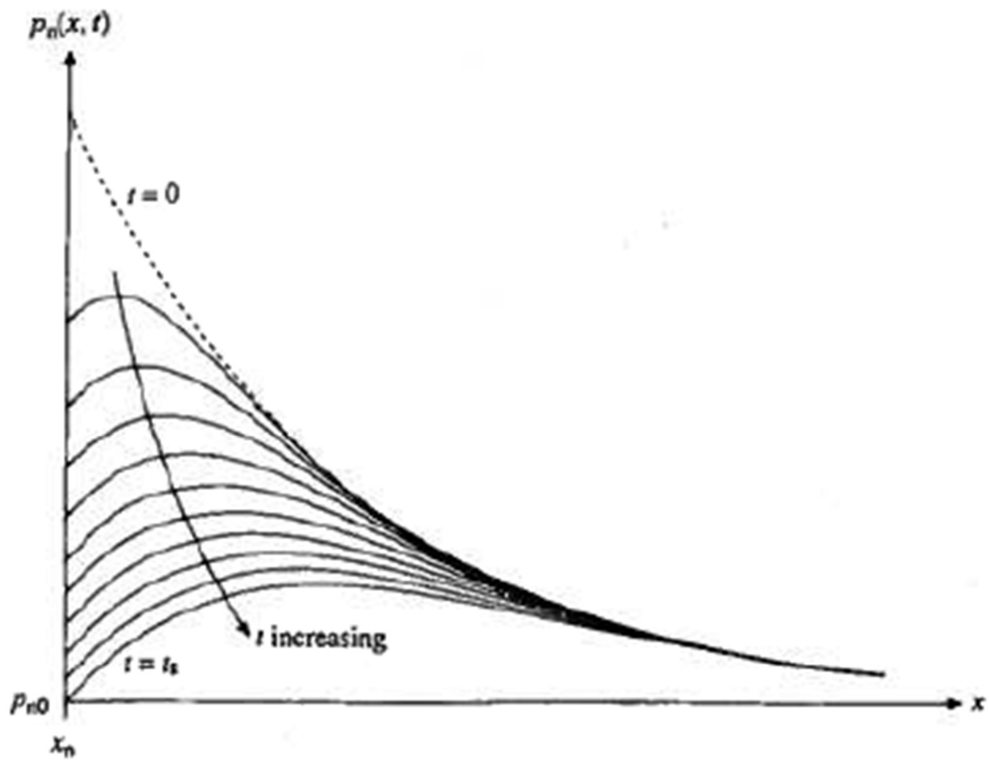



**Figure 8.3** Decay of the stored hole charge inside a $p^+$-$n$ diode as a function of time for $0 \le t \le t_s$.

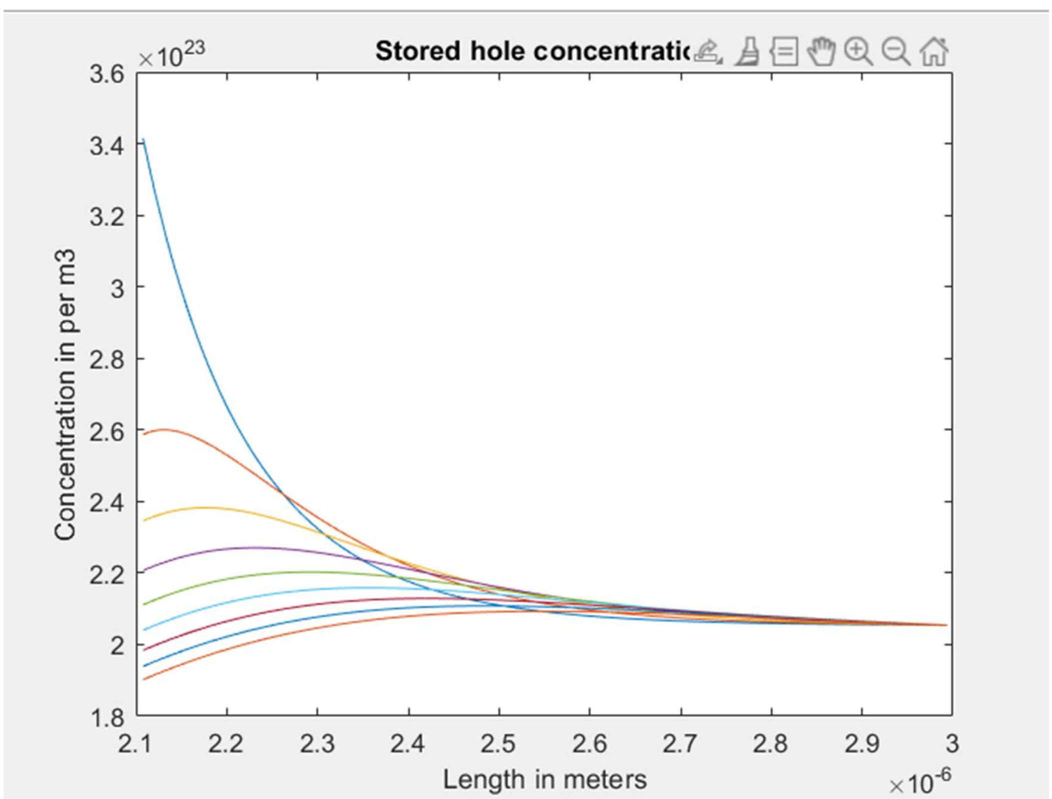
**Boundary Condition:**

Slope of $p(x,t)$ at x=$w_n$ is always constant.

$\frac{d\Delta p}{dx}\ (at\ x = w_n) = slope\ of\ p(x,t) = slope\ of\ \Delta p(x,t) = \frac{|J_R|}{qD_p}$ ……………………………………(3)

**Procedure:**

1. Determine holes concentration profiles at equilibrium for PN Diode with depletion approximation**.**
2. Determine the position of edge of Depletion region (wn) on n-side.
3. Apply variation of voltage on hole concentration profile. (p(at V=Va) = p(at equilibrium)*exp(Va/Vt)) and store these values in j=1.
4. In finite equations, equation 2, will become as follows (for i=wn+h to Ln and j=2 onwards)
$$\frac{\Delta p(i,j) - \Delta p(i,j-1)}{dt} = D_p \frac{\Delta p(i+1,j) + \Delta p(i-1,j) - 2\Delta p(i,j)}{h^2} - \frac{\Delta p(i,j)}{\tau_p}$$
5. Iteratively solve for $\Delta p(i,j)$ where, dt is the time interval, and h is step size.
6. For $\Delta p(i,j)$ at $w_n$, use boundary conditions stated in equation 3.
7. Find excess charge density (Q/A) from x= $w_n$ to $L_n$ at each interval of time. Given by Q/A (at time t) = q * (summation of excess hole concentration (at time t) from x = $w_n$ to $L_n$ )
8. At time, t=$t_s$ excess charge density will become 0. Find the approximate time taken for it.
9. Plot $p(i,j)$ from time t=$0^-$ to t= $t_s$
10. You may get a plot similar to the following figure



# EE 735 (MSL) – Additional Material

## Assignment -4 (Part-B)

**(13th Sep 2023)**

Instructor: **Prof. Saurabh Lodha**

TA : **Prabhat Prajapati**

# Question

Consider a PN junction of length 3µm (1.5µm on each side) with an abrupt doping concentration (for Na, Nd) of $1*10^{15}cm^{-3}$ (similar to assignment 3). Consider that a voltage of 1V (across the diode terminals) in forward bias is applied for a long time and a voltage of 1V is applied in reverse bias at time, t=0. Let $ni=1.5*10^{10}\ cm^{-3}$, $\mu_p=450cm^2/s$, $\tau_p=20\ \mu s$, $J_R = 2KA/cm^2$.

i. Plot the decay profile of stored hole charge in the PN junction diode as a function of time from 0<t<ts from the edge of depletion region (of N-side) to the end of diode.

ii. Also Find the value of approximate "ts" value

Where, ts is time where diode remains in the forward bias even after switching from FB to RB

# Theory

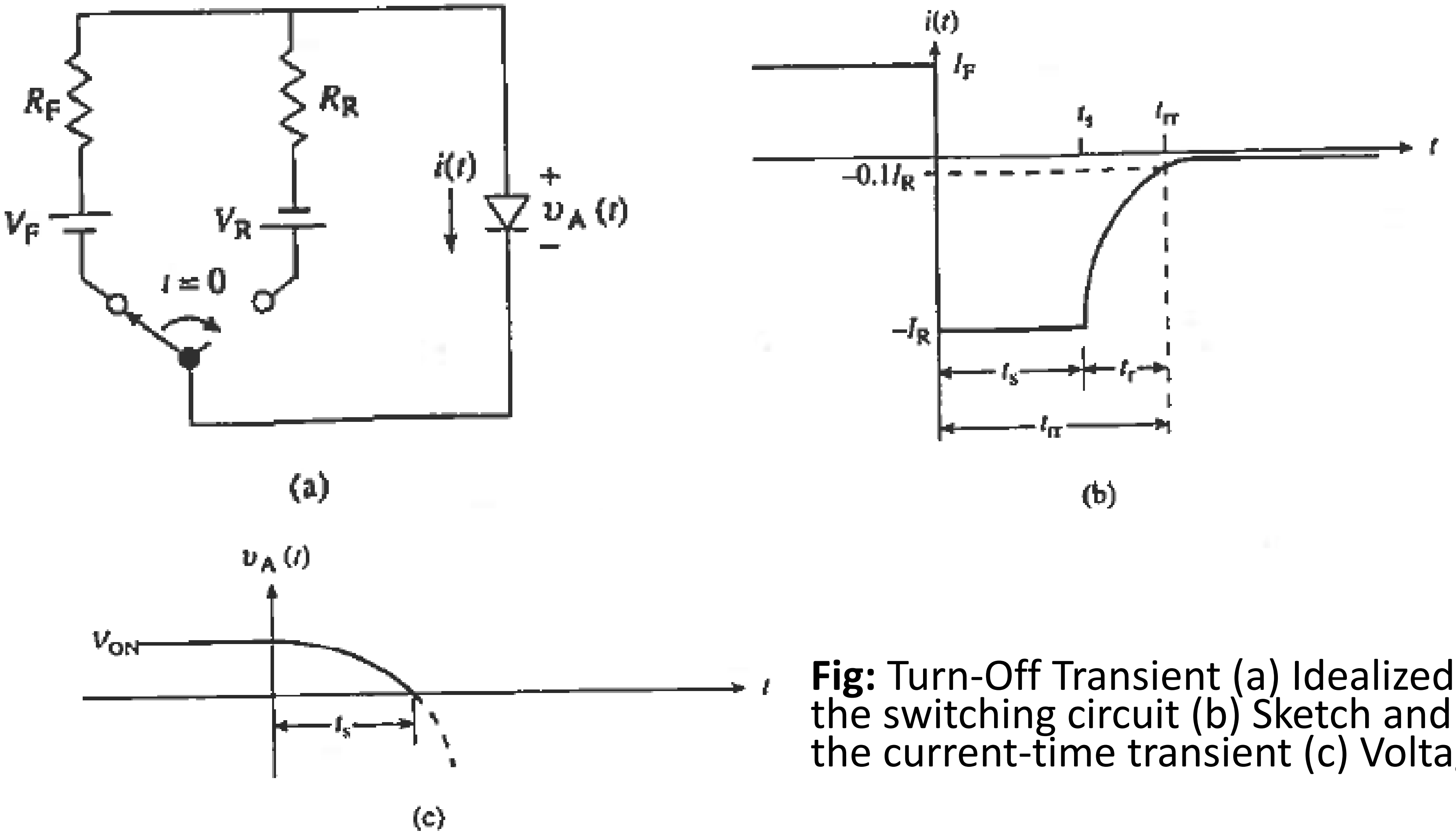



**Fig:** Turn-Off Transient (a) Idealized representation of the switching circuit (b) Sketch and Characterization of the current-time transient (c) Voltage –time transient

# Theory (cont.)

The minority carrier diffusion equation for holes in the n-region of a PN junction diode is a partial differential equation that describes how the concentration of minority carriers (holes in this case) changes with time and position within the semiconductor. It can be written as follows:

$p(x,t) = p_o + \Delta p(x,t)$ ……………………………………………(1)

$\frac{\partial \Delta p(x,t)}{\partial t} = D_p \frac{\partial^2 \Delta p(x,t)}{\partial x^2} - \frac{\Delta p(x,t)}{\tau_p}$ ……………………………………(2)

Where

- $\Delta p(x,t)$ is the excess concentration of minority carriers (holes) as a function of position (x) and time (t)
- $\mathrm{p(x,t)}$ is the concentration of minority carriers as a function of position (x), and time (t)
- $p_o$ is the minority carrier concentration in n-side (=$\frac{n_i^2}{N_d}$ *at equilibrium*)
- $\mathrm{D_p}$ is the diffusion coefficient for holes in n-region
- $\tau_p$ is the carrier lifetime for holes

# Theory (cont.)

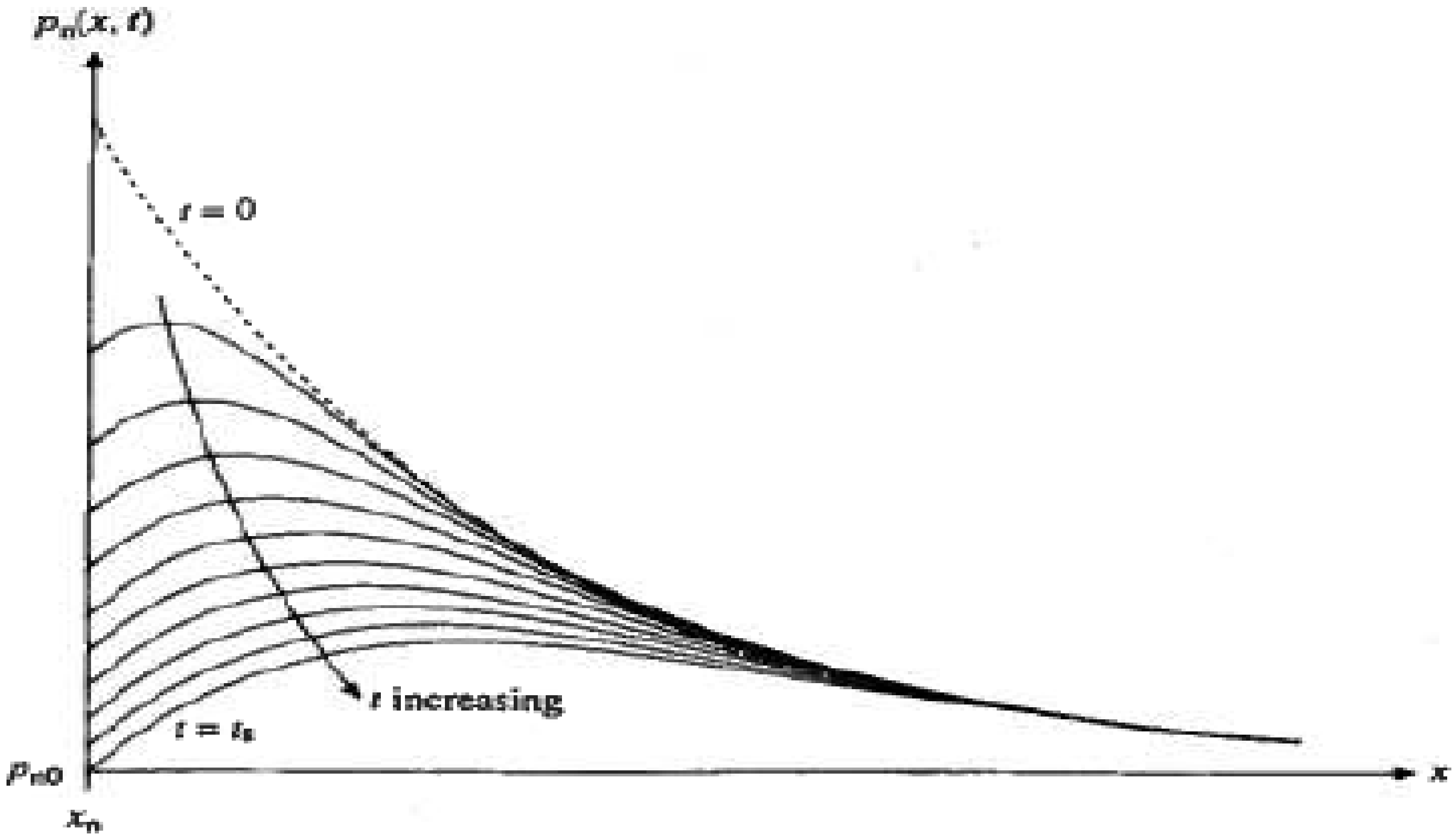



**Figure 8.3** Decay of the stored hole charge inside a $p^+$-$n$ diode as a function of time for $0 \le t \le t_s$.

# Procedure for solution

**Step** 1. Create a PN Junction Diode and compute hole concentration at in the entire PN diode region. (use without depletion approximation)

**Step** 2. Determine the position of edge of Depletion region (wn) on n-side. (you can depletion width formulas for this)

**Step 3.** Apply variation of voltage on hole concentration profile. (p(at V=Va) = p(at equilibrium)*exp(Va/Vt)) and store these values in j=1.

**NOTE:** Va is the voltage difference applied across the diode.

# Procedure for solution

**Step** 4. In finite equations, equation 2, will become as follows (for i=wn+h to Ln and j=2 onwards)

- $\frac{\Delta p(i,j)-\Delta p(i,j-1)}{dt} = D_p \frac{\Delta p(i+1,j)+\Delta p(i-1,j)-2\Delta p(i,j)}{h^2} - \frac{\Delta p(i,j)}{\tau_p}$

**Step 5.** Make an equation interms of $\Delta p(i,j)$ (from Step4) and iterate it to obtain final profile, where, dt is the time interval, and h is step size.

**Step** 6. Follow step 5 and plot the profile for all time instances.,i.e., all values of j

# Procedure for solution

**Step** 7. For $\Delta p(i,j)$ at $w_n$, use boundary conditions stated in equation 3.

**Boundary Condition:**

- Slope of $p(x,t)$ at $x=w_n$ is always constant.
- $\frac{d\Delta p}{dx}\ (at\ x = w_n) = slope\ of\ p(x,t) = slope\ of\ \Delta p(x,t) = \frac{|J_R|}{qD_p}$ …….(3)

**Step 8.** Find excess charge density (Q/A) from $x= w_n$ to $L_n$ at each interval of time. Given by Q/A (at time t) = q * (summation of excess hole concentration (at time t) from $x = w_n$ to $L_n$ )

# Procedure for solution

**Step** 9. At time, $t=t_s$ excess charge density will become 0(theortically). Find the approximate time taken for it.

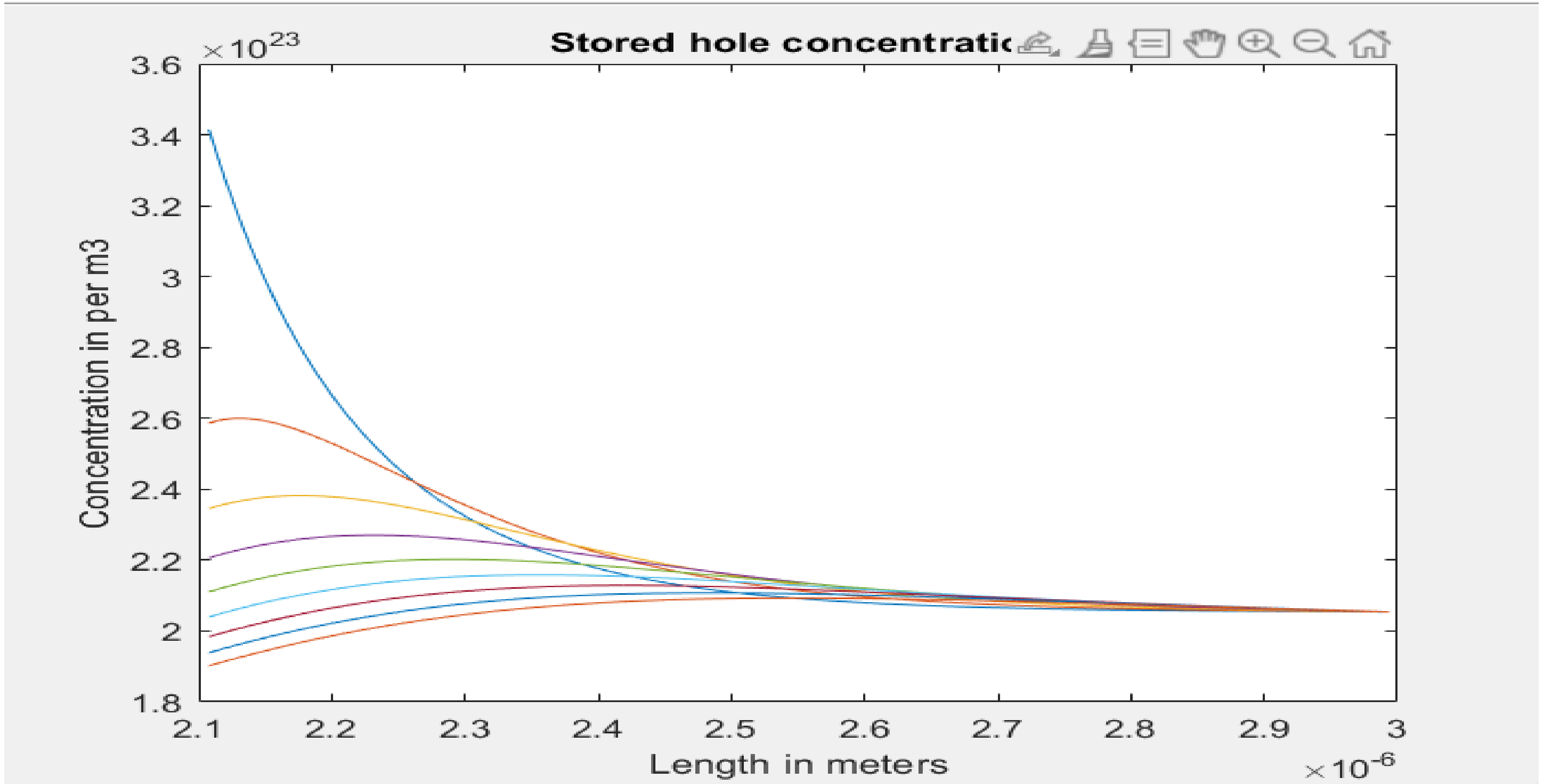
**Step 10.** Plot $p(i, j)$ from time $t=0^-$ to $t= t_s$

**Note:**

1. ts will be in order of few ns.
2. Make your "dt" small to get a non-oscillating plot

# Procedure for solution (cont.)

- Your overall profile may look something similar to this.



# Reference

- Section 8.1 from “Semiconductor Device Fundamentals” by Robert F Pierret
- https://nanohub.org/resources/6500/download/2009.03.09-ECE606-L24.pdf for more info
- Video Lectures: https://www.youtube.com/watch?v=wqb_N8sLcZQ&t=0s

Thank you..