ECE 3040 Microelectronic Circuits

Exam 1

February 5, 2004

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Print your name clearly and largely: Solutions

Instructions:
Read all the problems carefully and thoroughly before you begin working. You are allowed to use 1 new sheet of notes (1 page front and back) as well as a calculator. There are 100 total points. Observe the point value of each problem and allocate your time accordingly. SHOW ALL WORK AND CIRCLE YOUR FINAL ANSWER WITH THE PROPER UNITS INDICATED. Write legibly. If I cannot read it, it will be considered a wrong answer. Do all work on the paper provided. Turn in all scratch paper, even if it did not lead to an answer. Report any and all ethics violations to the instructor. Good luck!

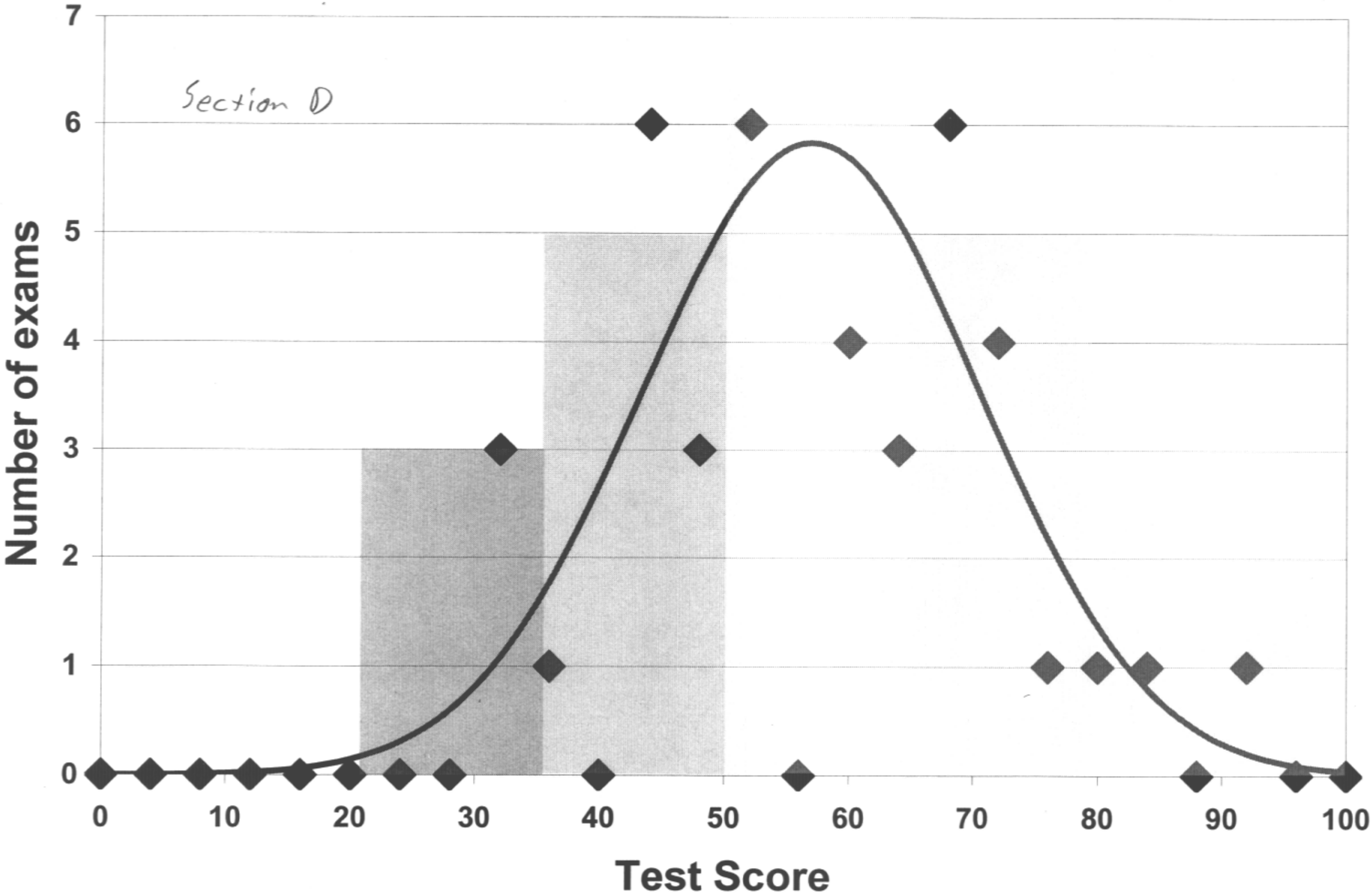
Sign your name on **ONE** of the two following cases:

I DID NOT observe any ethical violations during this exam: ______________________

I observed an ethical violation during this exam: ______________________

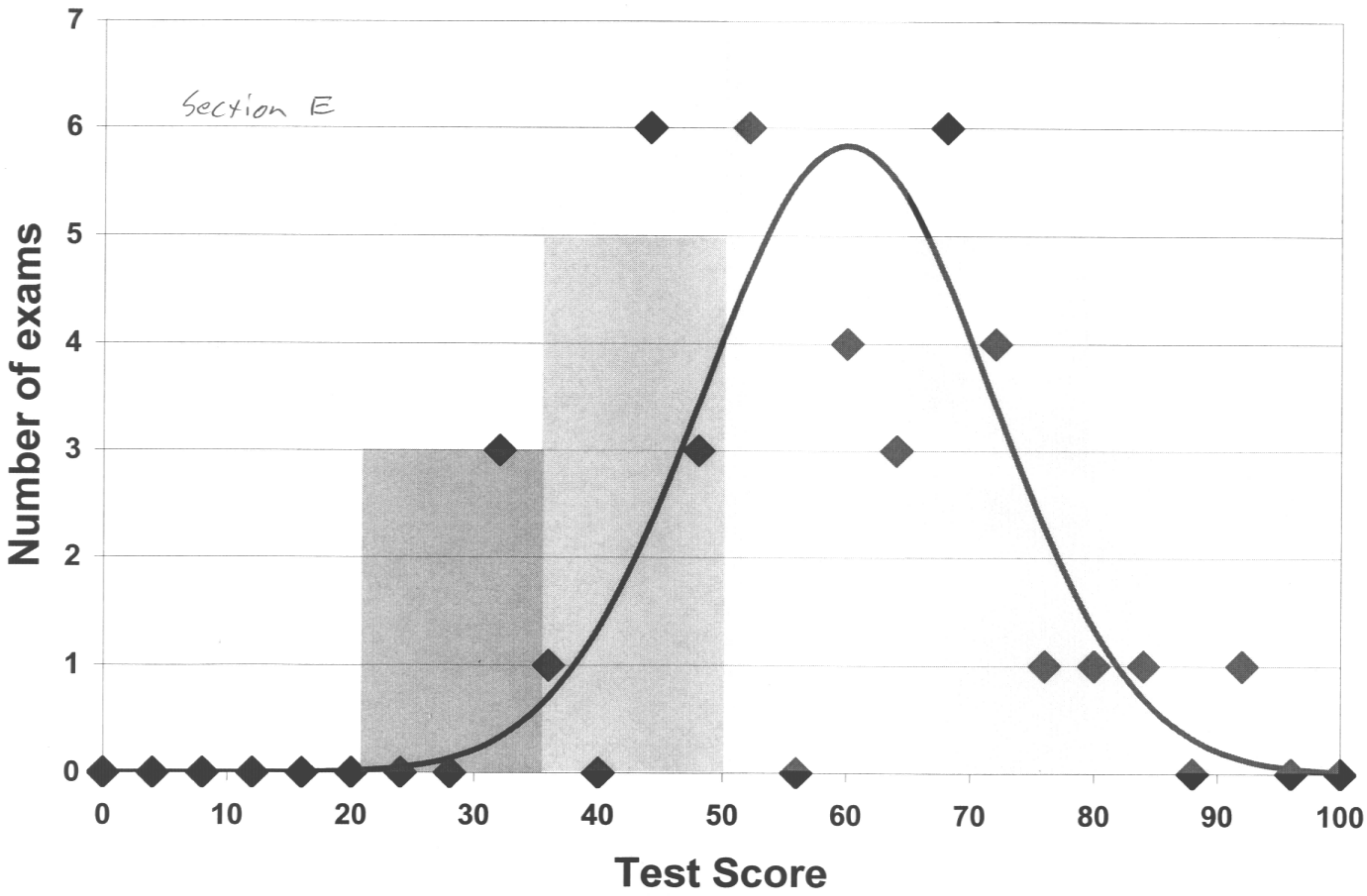
Section D

Class Totals	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13a	#13b	#14
Number of Tests=	29														
Point Value of problem=	2	2	2	2	2	3	3	3	3	3	10	15	7	18	25
Individual Problem Average=	90.9	100.0	97.0	100.0	72.7	72.7	57.6	97.0	69.7	61.6	88.8	56.8	65.4	51.3	43.9
Exam Average=	56.93														
Exam Standard Deviation=	13.58														
Exam Max=	86														
Exam Min=	30														



Section E

Class Totals	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13a	#13b	#14
Number of Tests=	30														
Point Value of problem=	2	2	2	2	2	3	3	3	3	3	10	15	7	18	25
Individual Problem Average=	90.9	100.0	97.0	97.0	60.6	72.7	60.6	97.0	75.8	68.7	96.1	55.2	68.8	58.8	40.7
Exam Average=	59.97														
Exam Standard Deviation=	11.67														
Exam Max=	82														
Exam Min=	37														



First 25% **Multiple Choice and True/False (Circle the letter of the most correct answer)**

1.) (2-points) True or False: An intrinsic material has equal concentrations of electrons and holes.
2.) (2-points) True or False: A semiconductor material has a wider bandgap than an insulator.
3.) (2-points) True or False: An intrinsic semiconductor is also a degenerate semiconductor.
4.) (2-points) True or False: Direct bandgap semiconductors are used as light emitters (LEDS and LASERS) because of their efficient conversion of electrons to photons.
5.) (2-points) True or False: A zincblende crystal structure has more atoms in the unit cell than does the diamond crystal structure.

Select the **best** answer or answers for 6-10:

6.) (3-points) A "new" semiconductor consists of fictitious group II elements Dr, Do, Is and group VI elements Go and Od in equal composition. To within 1%, what is the correct reduced semiconductor notation for this remarkable compound?

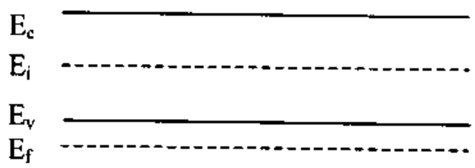
a.) DrDoIsGoOd
b.) $Dr_{0.333}Do_{0.333}Is_{0.333}Go_{0.5}Od_{0.5}$
c.) $Dr_{0.20}Do_{0.20}Is_{0.20}Go_{0.20}Od_{0.20}$
d.) Cannot be determined from the information given.
e.) You cannot have more than 4 elements making up a semiconductor.

7.) (3-points) Which of the following mathematical expressions describes the free electron concentration? Hint: G_C is the density of states function, and f(E) is the fermi distribution function

a.) $n = G_C f(E)$
b.) $n = G_C \, {}^{df(E)}\!/_{dE}$
c.) $n = \int_{E_C}^{\infty} G_C f(E) dE$
d.) $n = G_C \int_{E_C}^{\infty} f(E) dE$
e.) Looks like I will be working as a Walmart clerk!

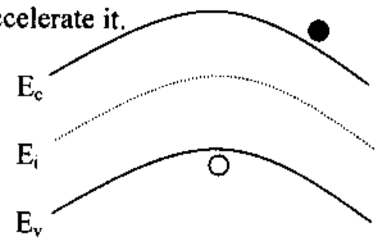
8.) (3-points) The following energy band diagram indicates the material is:

a.) Non-degenerate n-type
b.) Degenerate n-type
c.) intrinsic
d.) Non-degenerate p-type
e.) Degenerate p-type



9.) (3-points) For the electron and hole shown in the following band diagram circle **all** that are true.

a.) The electron experiences an electric field that will accelerate it.
b.) The hole experiences an electric field that will accelerate it.
c.) The hole will tend to stay where it currently is.
d.) The device is in a transient state
e.) The device has to be in equilibrium



10.) (3-points) Effective mass...

a.) ... of an electron is always smaller than for a hole.

b.) ... takes into account many different forces acting on the carrier that would otherwise not be present in free space

c.) ... is always less than the mass of an electron in vacuum

d.) ... determines (in part) how easy it is to move a carrier through the material

e.) ... is a fundamental constant that does not change from material to material.

Second 25% Short Answer ("Plug and Chug"):

For the following problems (11-12) use the following material parameters:

n_i=1e-14 cm^{-3} N_D=8e17 cm^{-3} donors N_A=6e12 cm^{-3} acceptors.

$m_n^*=0.2m_o$ $m_p^*=1.2m_o$

Electron mobility, $\mu_n = 900\ cm^2/Vsec$ Hole mobility, $\mu_p = 10\ cm^2/Vsec$

Temperature= 150 degrees C

11.)(10-points) Assuming total ionization, what is the electron and hole concentrations and is the material p or n-type?

$N_D >> N_A$, $N_D >> n_i$

$$\boxed{n \approx N_d = 8e17\ cm^{-3}}$$

$$\boxed{p = \frac{n_i^2}{n} = 1.25e-46\ cm^{-3}}$$

12.) (15-points) What is the bandgap of the semiconductor material?

$$N_v = 2\left[\frac{m_p^*(kT)}{2\pi\hbar^2}\right]^{3/2}$$

similarly

$= 5.5\ e25\ cm^{-3}$

$$N_c = 2\left[\frac{m_n^*(kT)}{2\pi\hbar^2}\right]^{3/2} \qquad n_i = \sqrt{N_c N_v}\, e^{-E_G/2kT}$$

$$= 2\left[\frac{0.2(9.11e-31)\left[(8.617e-5)(1.6e-19)(150+273)\right]}{\cancel{2\pi}\ \underbrace{(6.63\times10^{-34})^2/\cancel{(2\pi)^2}}_{\hbar = h/2\pi}}\right]^{3/2}$$

$= 3.74\ e24\ cm^{-3}$

$$E_g = -2kT \ln\left(\frac{n_i}{\sqrt{N_c N_v}}\right)$$

$$= -2(8.617e-5)(150+273) \ln\left[\frac{1e-14}{\sqrt{1.94e24(2.83e25)}}\right]$$

$$\boxed{E_g = 6.57eV}$$

Third 25% Problems (3rd 25%)

13.) (25-points total)

A 500 μm thick semiconductor at room temperature (27 degrees C) has the following parameters:

Electron mobility, μ_n=500 cm^2/Sec

Substrate intrinsic concentration, n_i=1e10 cm^{-3}

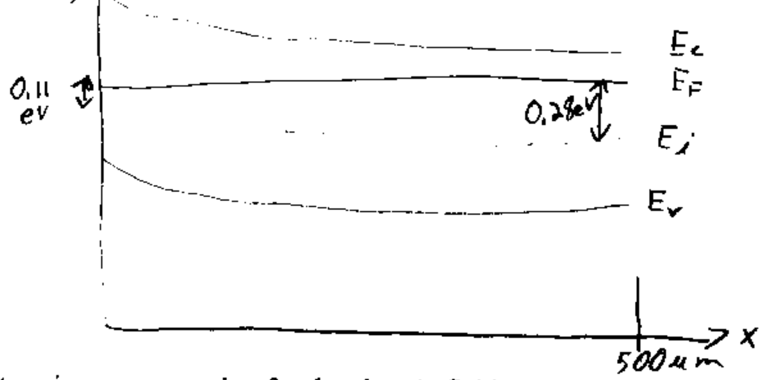
The bandgap, Eg=1.1 eV

The substrate doping is linearly graded such that $N_d=100n_i+1e16x$, where x is in cm.

$N_D \gg n_i$

a.) (7 points) Sketch ~~Draw~~ the band diagram in equilibrium and CLEARLY label Ec, Ev, Ei, and Ef

$$E_F - E_i = kT \ln\left(\frac{100n_i + 1e16x}{n_i}\right)$$



b.) (18 points) Determine an expression for the electric field verses position in the material.

$$J_n = 0 = \cancel{q}\mu_n n\vec{E} + \cancel{q}D_n \nabla n$$

$$D_n = \frac{kT}{q}\mu_n$$

$$0 = n\vec{E} + \frac{kT}{q}\nabla n$$

$$\vec{E} = -\frac{kT}{q}\frac{\frac{d}{dx}(100n_i + 1e16x)}{100n_i + 1e16x}$$

$$\vec{E} = -\frac{kT}{q}\frac{1e16 \text{ cm}^{-4}}{[100n_i + 1e16x] \text{ cm}^{-3}} \quad V/cm$$

unit [V]

$$\boxed{\vec{E} = \frac{-259}{1 + 1e4x} \quad V/cm}$$

Extra work can be done here, but clearly indicate which problem you are solving.

Alternative Solution

$$E_f - E_i = kT \ln\left(\frac{n}{n_i}\right)$$

$$E_i = E_f - kT \ln\left(\frac{100n_i + 1e16x}{n_i}\right)$$

$$\mathcal{E} = \frac{1}{q}\frac{dE_i}{dx} = \cancel{\frac{1}{q}\frac{dE_f}{dx}}^{\,0 \,=\, \text{Flat}} - \frac{kT}{q}\left(\frac{1e16}{100n_i + 1e16x}\right)$$

$$\mathcal{E} = -0.0259[V]\left(\frac{1e16}{100n_i + 1e16x}\right)$$

$$\boxed{\mathcal{E} = \frac{-259}{1 + 1e4x} \quad V/cm}$$

Pulling all the concepts together for a useful purpose: (4th 25%)

~~14.) (25 points)~~

When the dinosaurs walked the planet, a light was turned onto a 10 μm thick InP semiconductor held at room temperature (27 degrees C). InP has a problem that the surfaces are really efficient recombination centers. Thus, the excess electron concentration at the surfaces will always remain 0 cm^{-3}. The light uniformly generates 10^{18} additional holes per cm^3 per second. Determine the excess electron concentration in the InP for all positions ~~AND plot your result, labeling the graph.~~ Assume a minority carrier diffusion length of 0.1 μm and the mobility at room temperature is 3000 cm^2/V-sec.

Given: $0 = D_n \frac{d^2 \Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n}$ General Solution is: $\Delta n_p(x) = Ae^{-x/L_n} + Be^{+x/L_n}$

Given: $0 = D_n \frac{d^2 \Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} + G_L$ General Solution is: $\Delta n_p(x) = Ae^{-x/L_n} + Be^{+x/L_n} + G_L \tau_n$

Given: $0 = D_n \frac{d^2 \Delta n_p}{dx^2}$ General Solution is: $\Delta n_p(x) = A + Bx$

Given: $0 = D_n \frac{d^2 \Delta n_p}{dx^2} + G_L$ General Solution is: $\Delta n_p(x) = Ax^2 + Bx + C$

Given: $0 = D_n \frac{d^2 \Delta n_p}{dx^2} + G_{LO} f(x)$ General Solution is: $\Delta n_p(x) = \left[-\frac{G_{LO}}{D_N} \iint f(x) dx \right] + Bx + C$

Given: $\frac{d\Delta n_p}{dt} = -\frac{\Delta n_p}{\tau_n}$ General Solution is: $\Delta n_p(t) = \Delta n_p(t=0) e^{-t/\tau_n}$

Given: $0 = -\frac{\Delta n_p}{\tau_n} + G_L$ General Solution is: $\Delta n_p = G_L \tau_n$

Steady state → $\overset{0}{\cancel{\frac{\partial n_p}{\partial t}}} = D_n \frac{\partial^2 \Delta n_p}{\partial x^2} - \frac{\Delta n_p}{\tau_n} + G_L$

Light is on

given L_n so

$L_n = \sqrt{D_n \tau_n}$

$0.1\ \mu m = 0.1e\text{-}4\ cm$

$= \sqrt{\underbrace{\left(\mu_n \frac{kT}{q}\right)}_{D_n} \tau_n}$

$\tau_n = \frac{(0.1e\text{-}4)^2}{0.0259V(3000 cm^2/V\text{-}sec)}$

$= 1.287\ ps$

$G_L \tau_n = 1.287e6\ cm^{-3}$

Extra work can be done here, but clearly indicate which problem you are solving.

B.C.

$$\Delta n_p(x=0) \Rightarrow A + B + G_L\tau_n = 0$$

$$\Downarrow$$

$$* \quad B = -(G_L\tau_n + A)$$

$$\Delta n_p(x = 10um = 0.001cm) = Ae^{-100} + Be^{+100} + G_L\tau_n = 0$$

Here we see, for a reasonable result $\Delta n_p \rightsquigarrow 0$, B will be small!

$$e^{-100}A = -(G_L\tau_n) - (Be^{100})$$

$$= -(G_L\tau_n) + (G_L\tau_n + A)(e^{100})$$

$$= -G_L\tau_n + G_L\tau_n e^{100} + Ae^{100}$$

$$A(e^{-100} - e^{100}) = G_L\tau_n(-1 + e^{100})$$

$$A = \frac{G_L\tau_n(-1+e^{100})}{e^{-100}+e^{100}}$$

From $*$ above:

$$B = -G_L\tau_n - \frac{G_L\tau_n(-1+e^{100})}{e^{-100}+e^{100}}$$

$$= -G_L\tau_n\left(\frac{-1+e^{100}}{e^{-100}+e^{100}} + 1\right) \quad (\text{Note: } \sim 2G_L\tau_n)$$

$$\therefore \Delta n_p(x) = G_L\tau_n\left[1 + \left(\frac{-1+e^{100}}{e^{-100}+e^{100}}\right)e^{-x/1e\text{-}5cm} - \left(\frac{-1+e^{100}}{e^{-100}+e^{100}} + 1\right)e^{+x/1e\text{-}5cm}\right]$$

$$\boxed{\Delta n_p(x) = 1.287e6\left[1 + \left(\frac{-1+e^{100}}{e^{-100}+e^{100}}\right)e^{-x/1e\text{-}5cm} - \left(\frac{-1+e^{100}}{e^{-100}+e^{100}} + 1\right)e^{+x/1e\text{-}5cm}\right] cm^{-3}}$$

Note: As will be done for the BJT later, this can be reduced to sinh functions