EE566 Solid State Devices

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Dept of Electrical Engineering
University of Notre Dame
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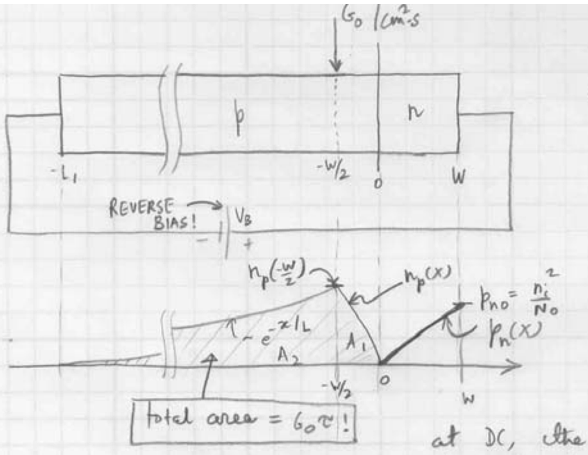
Assignment 5

SOLUTIONS

Problem 1



FIRST, note that the generation rate is in /cm² * s, & NOT in/cm³ * s !!

So $n_p(-\frac{W}{2}) \neq G_0 \tau$, UNITS ARE WRONG!

To find $n_p(-\frac{W}{2})$, we note that at DC, the total excess electrons in the p-region is given by the area

$$\frac{1}{2} n_p(-W/2) * W/2 + n_p(-W/2) \int_0^{L_1} dx\, e^{-x/L} = G_0 \tau$$

$$\Rightarrow n_p(-W/2) = \frac{G_0 \tau}{L*(1-\underbrace{e^{-L_1/L}}_{\approx 0 \text{ since } L_1 \gg L}) + W/4} \approx \frac{G_0 \tau}{L + W/4}$$

$$\therefore \boxed{n_p(-W/2) \approx \frac{G_0 \tau}{L + W/4}}$$ NOW the units are right!

(b) $\therefore$ Current with illumination is (@ $x = 0$),

$$J_{tot}^{ill} = J_n^{diff} + J_p^{diff} = q G_0 \left[\frac{2D\tau}{W(\frac{W}{4}+L)}\right] + \frac{qDn_i^2}{N_0 W}$$

$$\boxed{|J_{tot}^{ill}| = \frac{qD}{W}\left[\frac{2G_0\tau}{(\frac{W}{4}+L)} + \frac{n_i^2}{N_0}\right]}$$

(c) Steady S. Current without illumination is just revers-bias leakage

$$\therefore |J_{tot}^{noill}| = qD\left[\frac{n_i^2}{N_0 L} + \frac{n_i^2}{N_0 W}\right] = \frac{qDn_i^2}{N_0}\left[\frac{1}{L} + \frac{1}{W}\right] \approx \frac{qDn_i^2}{N_0 W}$$

$$\boxed{|J_{tot}^{noill}| \approx \frac{qDn_i^2}{N_0 W}}$$!

Problem 2

). $W=\sqrt{2\frac{\epsilon_s}{q}(V_{bi}-V_a)(\frac{1}{N_a}+\frac{1}{N_d})}$

$=\sqrt{\frac{2\times11.7\times8.85\times10}{1.6\times10^{-19}}\times(0.7382-0.589)\times10^{-16}\times(\frac{1}{1.5}+\frac{1}{3.0})}$

$\approx 0.137\,um$ $N_A\cdot x_p=N_D\cdot x_n$

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$\Rightarrow x_n=0.045$, $x_p=0.09\,um$

when $J_{majo}=J_{tot}-J_{mino}$ $\Rightarrow J_{mino}=\frac{1}{2}J_{tot}=0.247\,A/cm^2$

$\therefore J_p(x)=0.3790\cdot e^{\frac{-x-x_n}{L_p}}$

$=0.247$

$\Rightarrow x=1.4\,um$ from the x_n in the n-type region.

problem 2

a) $J_0=q(\frac{D_n}{L_n}n_{p0}+\frac{D_p}{L_p}p_{n0})=qn_i^2(\frac{D_n}{L_nN_a}+\frac{D_p}{L_pN_d})$ $D_n\approx200\,cm^2/s$ $D_p\approx10\,cm^2/s$

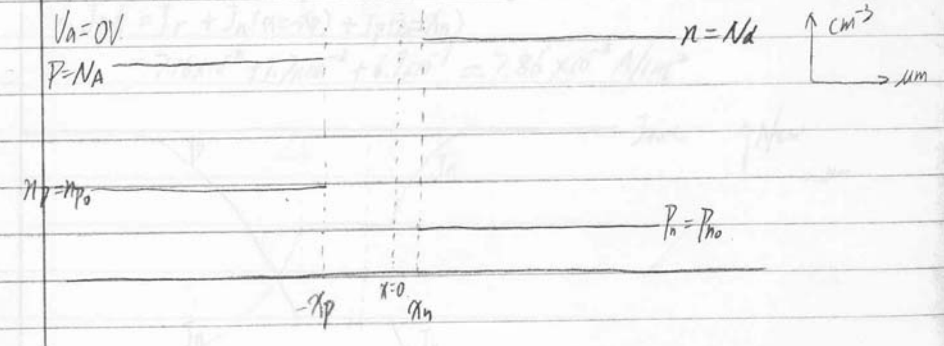
$L_n=\sqrt{D_n\tau_n}=0.0063\,cm$ $n_i\approx2.1\times10^6\,cm^{-3}$

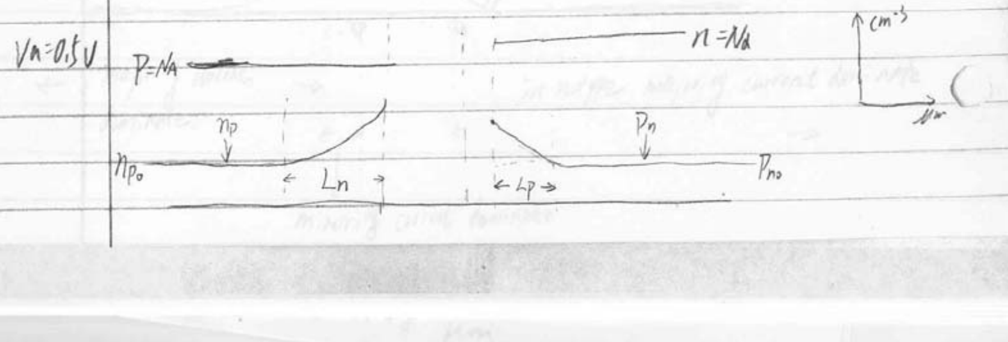
$L_p=\sqrt{D_n\tau_p}=0.0014\,cm$

$\therefore J_0=2.2365\times10^{-17}\,A/cm^2$

b) in the p-side $P=N_A$ $n_p=n_{p0}\cdot e^{\frac{qV_a}{kT}}$ $e^{-x/L_n}=\frac{n_i^2}{N_A}\cdot e^{\frac{qV_a}{kT}}\cdot e^{\frac{(x+x_p)}{L_n}}$

in the n-side $n=N_D$ $P_n=P_{n0}\cdot e^{\frac{qV_a}{kT}}\cdot e^{-x/L_p}=\frac{n_i^2}{N_D}\cdot e^{\frac{qV_a}{kT}}\cdot e^{\frac{-(x-x_n)}{L_p}}$





c). Outside depletion region in n-type

$$J_p = q n_i^2 \frac{D_p}{N_a L_p}\left(e^{qV_a/kT}-1\right) e^{-\frac{x-x_n}{L_p}} \approx 7.7\times10^{-12} e^{-\frac{x-x_n}{L_p}} \qquad x > x_n$$

Outside depletion region in p-tye

$$J_n = q n_i^2 \frac{D_p}{N_a L_n}\left(e^{qV_a/kT}-1\right) e^{\frac{x+x_p}{L_n}} = 6.9\times10^{-9} e^{\frac{x+x_p}{L_n}} \qquad x < -x_p$$

$$\begin{cases} W = \sqrt{\frac{2\varepsilon_s}{q}(V_{bi}-V_a)\left(\frac{1}{N_a}+\frac{1}{N_d}\right)} \\ V_{bi} = \frac{kT}{q}\ln\frac{N_a N_d}{n_i^2} \end{cases}$$

$\Rightarrow W = 0.81\ \mu m$.

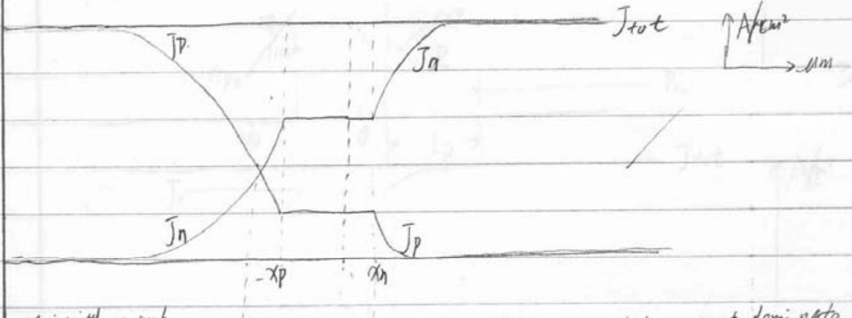
At the juction $x=0$, $E(0) = \frac{2(V_{bi}-V_a)}{W} = 16.75\ kV/cm$

$$J_{recombination} = \frac{q\pi n_i}{2\tau}\cdot\frac{kT}{qE(0)}\exp\left(\frac{qV_a}{2kT}\right) = 7.16\times10^{-8}\ A/cm^2$$

Inside the depletion region, the minority current is constant

$\therefore J_{tot} = J_r + J_n(x=-x_p) + J_p(x=x_n)$

$= 7.16\times10^{-8} + 7.7\times10^{-12} + 6.9\times10^{-9} \approx 7.86\times10^{-8}\ A/cm^2$



← majority current dominate. →

in n-type majority current dominate →

minority current dominate

d). In the p-type region. $L_n = \sqrt{D_n \tau_n} = \sqrt{200 \times 0.2 \times 10^{-6}} = 0.0063 \text{ cm} \simeq 63 \mu m \gg W_B$

$\therefore \Delta n(x) = \frac{n_i^2}{N_A}\left(\frac{x + x_p}{W_B - x_p} + 1\right)\left(e^{qV_a/kT} - 1\right)$ $n(x) = \Delta n(x) + n_{p0}$

$\because N_A x_p = N_D x_n$

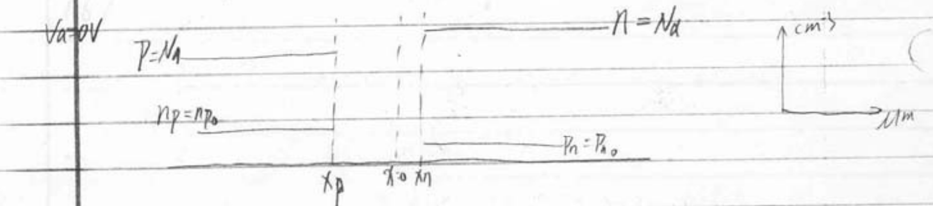
$\therefore x_p \simeq W = 0.8 \mu m$; $J_n(x = -x_p) \gg J_p(x = x_n)$

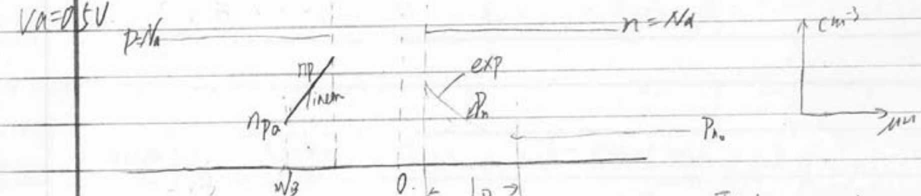
$J_n = q D_n \frac{dn(x)}{dx} = \frac{q n_i^2 D_n}{N_A (W_B - x_p)}\left(e^{\frac{qV_a}{kT}} - 1\right)$ where $x_p \simeq W = 0.8 \mu m$.

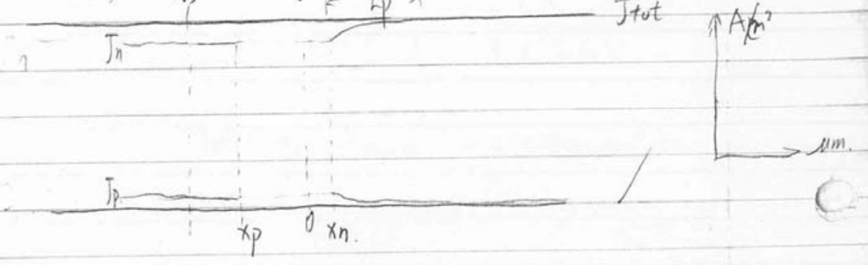
$\Rightarrow J_n(x = -x_p) \simeq 3.3 \times 10^{-7} \text{ A/cm}^2$

J_{rec} is not changed. $J_{rec} = 7.16 \times 10^{-8} \text{ A/cm}^2$

$J = J_n + J_p + J_{rec} \simeq 4.0 \times 10^{-7} \text{ A/cm}^2$







e. The current in long base diode is much smaller than the current in short base diode.

The reason is in long base diode $W_B \approx L$, therefore most minority carrier has been combined before they reach the contact. While in short diode. $W_B << L$. Therefor most minority carrier can get through the base without recombination. When they reach the contact, the current increase.

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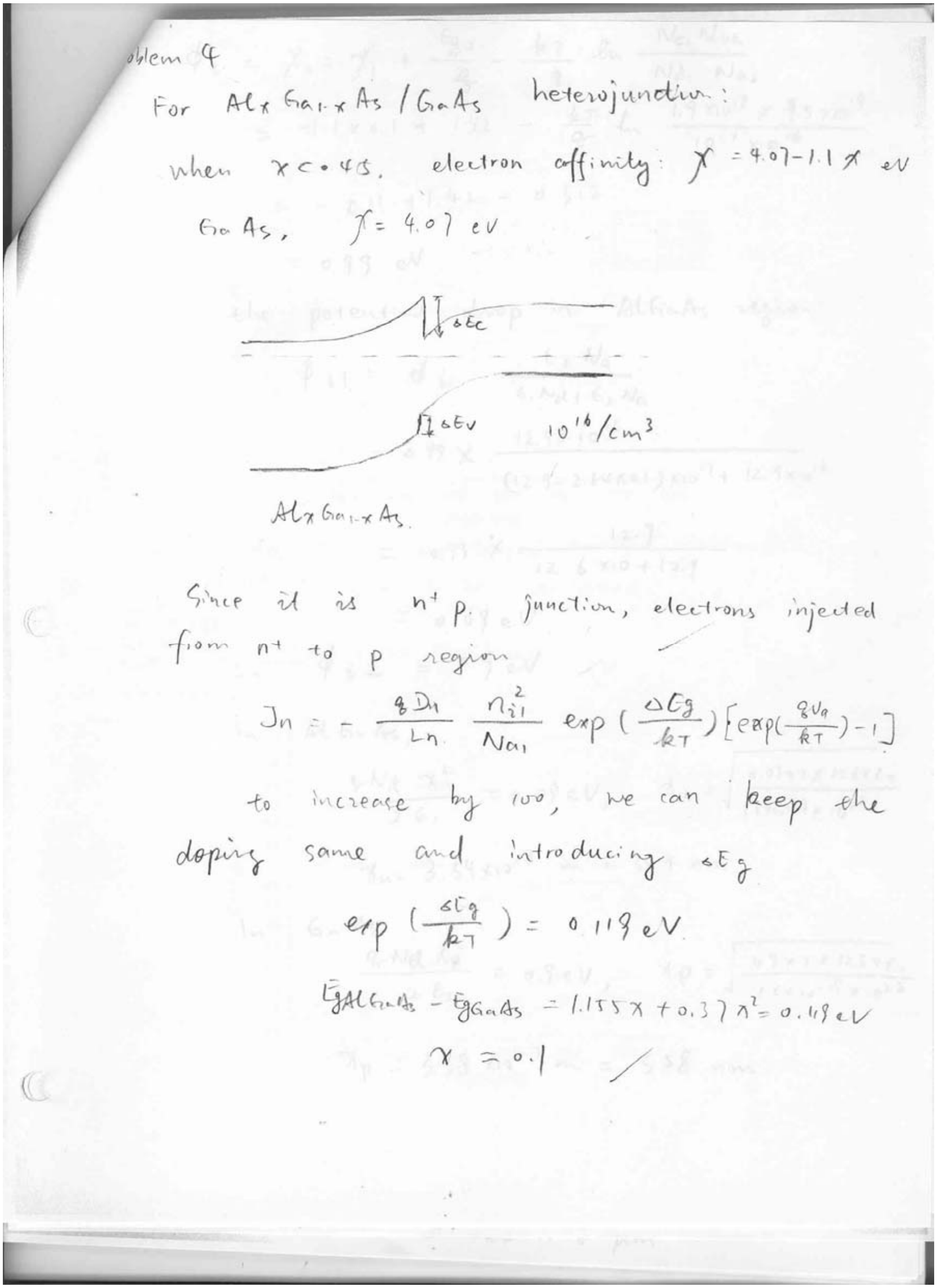
Problem 3



oblem 4

For $Al_xGa_{1-x}As$ / GaAs heterojunction:

when $x < .45$, electron affinity: $\chi = 4.07 - 1.1x$ eV

GaAs, $\chi = 4.07$ eV

Since it is n^+p junction, electrons injected from n^+ to p region

$$J_n = -\frac{qD_n}{L_n}\frac{n_{i1}^2}{N_{a1}}\exp\left(\frac{\Delta E_g}{kT}\right)\left[\exp\left(\frac{qV_a}{kT}\right)-1\right]$$

to increase by 100, we can keep the doping same and introducing ΔE_g

$$\exp\left(\frac{\Delta E_g}{kT}\right) = 0.119\ \text{eV}$$

$$E_{gAlGaAs} - E_{gGaAs} = 1.155x + 0.37x^2 = 0.119\ \text{eV}$$

$$x = 0.1$$

$$\phi_i = \chi_2 - \chi_1 + \frac{E_{g2}}{q} - \frac{kT}{q} \ln \frac{N_{c1} N_{v2}}{N_{d1} N_{a2}}$$

$$= -1.1 \times 0.1 + 1.42 - \frac{kT}{q} \ln \frac{1.9 \times 10^{19} \times 9.5 \times 10^{18}}{10^{17} \times 10^{16}}$$

$$= -0.11 + 1.42 - 0.312$$

$$= 0.99 \text{ eV}$$

the potential drop in AlGaAs region:

$$\phi_{i1} = \phi_i \frac{\epsilon_2 N_a}{\epsilon_1 N_d + \epsilon_2 N_a}$$

$$= 0.99 \times \frac{12.9 \times 10^{16}}{(12.9 - 2.84 \times 0.1) \times 10^{17} + 12.9 \times 10^{16}}$$

$$= 0.99 \times \frac{12.9}{12.6 \times 10 + 12.9}$$

$$= 0.09 \text{ eV}$$

$$\therefore \quad \phi_{i2} = 0.9 \text{ eV}$$

In AlGaAs,

$$\frac{q N_d x_n^2}{2 \epsilon_1} = 0.09 \text{ eV}, \quad x_n = \sqrt{\frac{0.09 \times 2 \times 12.6 \times \epsilon_0}{1.6 \times 10^{-19} \times 10^{23}}}$$

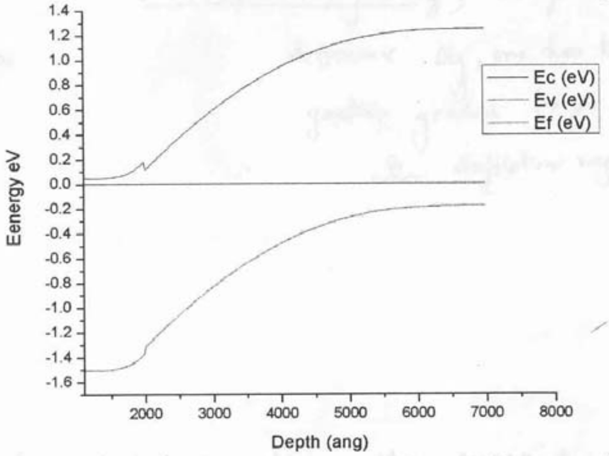
$$x_n = 3.54 \times 10^{-8} \text{ m} = 35.4 \text{ nm}$$

In GaAs

$$\frac{q N_d x_p^2}{2 \epsilon_2} = 0.9 \text{ eV}, \quad x_p = \sqrt{\frac{0.9 \times 2 \times 12.9 \times \epsilon_0}{1.6 \times 10^{-19} \times 10^{22}}}$$

$$x_p = 3.58 \times 10^{-7} \text{ m} = 358 \text{ nm}$$

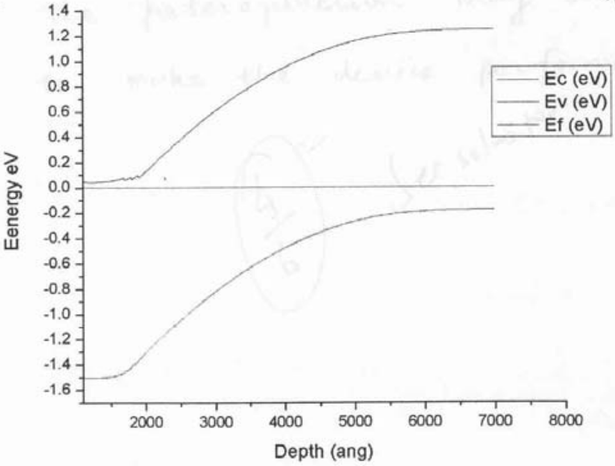
With I-V posim, for $Al_{0.1}Ga_{0.9}As$ / GaAs with doping of $1\times10^{17}/cm^3$ and 1×10^{16} cm^{-3}, we can see the ΔE_c is not very big.



If I add 3 gradient layer to the structure, the ΔE_c kink could be removed:

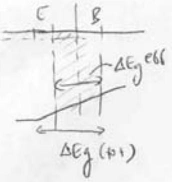
GaAs $N_a = 1\times10^{16}/cm^3$
$Al_{0.01}Ga_{0.99}As$ 30nm
$Al_{0.04}Ga_{0.96}As$ 30 nm
$Al_{0.07}Ga_{0.93}As$ 30nm
} $N_d = 1\times10^{17}/cm^3$
$Al_{0.1}Ga_{0.9}As$

try 'graded' structure too....



(c)

Since the $e^{\frac{\Delta E_g}{kT}}$ factor depends upon the ΔEg across the E-B depletion region only, to get all the bandgap difference ΔEg, one has to ensure that the ~~grating~~ graded layer lies entirely inside the depletion region.



(d). for heterojunction, the current is high

The disadvantage is: require epitaxy growth, thus increasing cost.

The heterojunction may contain defects to make the device performance worse

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