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Studies on some parameters in heavily doped $Al_xGa_{1-x}As/GaAs$ double heterostructure

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Abstract : The variation of several parameters within heavily doped $Al_xGa_{1-x}As/GaAs$ double heterostructure has been investigated theoretically taking into account band gap narrowing and carrier degeneracy as heavy doping effects. The results of the computational analyses are shown graphically.

Keywords : Heterostructure

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The minority carrier lifetime in III-V semiconductors like GaAs and $Al_xGa_{1-x}As$ is an important parameter for a number of applications. To produce electrical and optical devices like high electron mobility transistors (HEMTs) [1], double heterostructure lasers [2] and high-efficiency devices [3], $Al_xGa_{1-x}As/GaAs$ heterostructure is commonly used. Time resolved photo-luminescence [4] technique is used to measure minority carrier lifetime in some III–V semiconducting materials. Minority carrier lifetime is useful for minority-carrier devices like light emitting diodes (LEDs), photovoltaic cells, bipolar transistors. Various methods are used widely to determine the minority carrier lifetime in photovoltaic devices [5–7]. In III–V compounds, time-resolved photoluminescence decay method is useful for the measurement of the minority carrier lifetime. Carrier lifetime in silicon is measured by using pulse optical excitation and photo-conductivity decay technique. Heavy doping effects play important role in producing high emitter efficiency in bipolar transistors and high open-circuit voltage in solar cells, and have influence on lifetime in band-to-band processes. Experimentally measured lifetimes [4,8] of heavily doped GaAs and quaternary alloy are reported earlier to study Auger effects.

In this presentation, assuming uniform distribution of SRH (Shockley-Read-Hall) defects within specified region, the variation of bulk minority carrier lifetime with carrier density and photoluminescence lifetime with interface recombination velocity in heavily doped $Al_xGa_{1-x}As/GaAs$ double heterostructure have been investigated. Band gap narrowing and carrier degeneracy are considered as heavy doping effects. As band-to-band Auger recombination effect is a must, the variation of quantum efficiency and photoluminescence lifetime with nominal current density are studied for the same hetero-structure. Spatial variation of minority carrier density has been ignored owing to lower value of diffusion transit-time compared to the minority carrier lifetime. The results so obtained by computational analyses are shown graphically. For $Al_xGa_{1-x}As/GaAs$ double heterostructure, photoluminescence [9] lifetime, under low interface recombination velocity, approaches the bulk minority carrier lifetime. The photoluminescence lifetime τ_{PL} is given by [10]

$$\frac{1}{\tau_{PL}} = \frac{1}{\tau_R} + \frac{1}{\tau_{SRH}} + \frac{1}{\tau_S} \tag{1}$$

where $\frac{1}{\tau_S} = \frac{2S}{d}$.

τ_R is the radiative lifetime; τ_{SRH}, the Shockley-Read-Hall lifetime; τ_S, the surface lifetime; S, the interface recombination velocity, and d is the active layer thickness.

The relationship among minority carrier diffusivity (D), decay time (t) and mobility (μ) can be written as

$$D = \frac{d^2}{2t} \text{ and } D = \frac{KT}{q}\mu, \tag{2}$$

where K is the Boltzmann constant; q, the electronic charge, and T is the absolute temperature. For n-type semiconductor with donor concentration N_D, the electron mobility μ is given by [11]

$$\mu_e(N_D) = \frac{\mu_o}{1 + \left(N_D/N_{eff}\right)\alpha} + \mu_{min}. \tag{3}$$

μ_o is the difference between the expected maximum and minimum mobilities; μ_{min}, the expected minimum mobility value; N_{eff}, a reference concentration, and α is an exponential factor that controls the slope around $N_D = N_{eff}$. Again the radiative and SRH lifetime [12] are given by

$$\tau_R = \frac{\Delta n}{Bnp}, \quad \tau_{SRH} = \frac{\Delta n}{np}\left[\tau_p(n + n_i) + \tau_n(p + n_i)\right], \tag{4}$$

where Δn is the excess photogenerated carrier; B, the radiative recombination coefficient; n_i, the intrinsic carrier concentration and τ_p and τ_n are the hole and electron lifetimes, respectively. Under heavy doping condition, electron (n) and hole (p) concentrations can be expressed as [13]

$$n = n_i F_{1/2}(\eta_n) \exp(-\eta_n) \exp \frac{A\Delta E_g}{KT} \exp \frac{E_{fn} - E_i}{KT}, \tag{5a}$$

$$p = n_i F_{1/2}(\eta_p) \exp(-\eta_p) \exp \frac{(1-A)\Delta E_g}{KT} \exp \frac{E_i - E_{fp}}{KT}, \tag{5b}$$

where $F_{1/2}$ (η_n) is the Fermi-Dirac integral of order 1/2; η, the reduced Fermi energy; A, the asymmetry factor; ΔE_g, the bandgap narrowing; E_i, the intrinsic Fermi energy, and E_{fn} and E_{fp} are the quasi-Fermi energies of electron and hole, respectively. At equilibrium, $E_{fn} = E_{fp}$.

Moreover, the interface recombination velocity (S) is related to recombination current density (J_s) as

$$S = \frac{J_s}{q\Delta n}, \tag{6}$$

$$J_s = q\left[R_{\mathrm{SRH}} + R_{\mathrm{Aug}}\right], \tag{7}$$

where R_{SRH} is the interface recombination due to SRH process [14,15] and R_{Aug} is the net Auger recombination. These are expressed as

$$R_{\mathrm{SRH}} = \frac{np - n_i^2}{\tau_n(p+n_i) + \tau_p(n+n_i)}, \tag{8}$$

$$R_{\mathrm{Aug}} = r\left(\frac{np-n_i^2}{n_i^2}\right)(n+p), \tag{9}$$

r is the Auger recombination coefficient.

Thus, from eqs. (1) – (9), one obtains

$$\frac{1}{\tau_{PL}} = \frac{n_i}{\Delta n} \Bigl[\Bigl[F_{1/2}(\eta_n)\, F_{1/2}(\eta_p) \exp \frac{\Delta E_g}{KT} \exp\bigl\{-(\eta_n+\eta_p)\bigr\}\Bigr]$$

$$\times \Bigl[n_i B + \Bigl[\tau_n \Bigl\{F_{1/2}(\eta_p) \exp(-\eta_p) \exp \frac{(1-A)\Delta E_g}{KT}\cdot$$

$$\times \exp\left(\frac{E_i - E_{fp}}{KT}\right) + 1 \Bigr\} + \tau_p \Bigl\{F_{1/2}(\eta_n) \exp(-\eta_n)$$

$$\times \exp \frac{A\Delta E_g}{KT} \exp\left(\frac{E_{fn} - E_i}{KT}\right) + 1\Bigr\}\Bigr]^{-1}\Bigr] + \left(\frac{2q}{tKT}\right)^{1/2}$$

$$\times \left\{\frac{\mu_o}{1+(N_D/N_{\mathrm{eff}})\alpha} + \mu_{\min}\right\}^{-1/2} \Bigl[\Bigl[\tau_n \Bigl\{F_{1/2}(\eta_p)$$

$$\times \exp(-\eta_p) \exp \frac{(1-A)\Delta E_g}{KT} \exp\left(\frac{E_i - E_{fp}}{KT}\right) + 1 \Big\}$$

$$+ \tau_p \left\{ F_{1/2}(\eta_n) \exp(-\eta_n) \exp \frac{A\Delta E_g}{KT} + \exp\left(\frac{E_{fn} - E_i}{KT}\right) + 1 \right\} \Big]^{1}$$

$$+ r\Big\{ F_{1/2}(\eta_n) \exp(-\eta_n) \exp \frac{A\Delta E_g}{KT}$$

$$\times \exp\left(\frac{E_{fn} - E_i}{KT}\right) + F_{1/2}(\eta_p) \exp(-\eta_p) \exp \frac{(1-A)\Delta E_g}{KT}$$

$$\times \exp\left(\frac{E_i - E_{fp}}{KT}\right)\Big\}\Big]\Big[F_{1/2}(\eta_n) F_{1/2}(\eta_p) \exp \frac{\Delta E_g}{KT}$$

$$\times \exp\left\{-(\eta_n + \eta_p\right\} - 1\Big]\Big]. \tag{10}$$

The computational analyses of eq. (10) have been carried out for a fixed composition under different circumstances. Figure 1 represents the variation of bulk minority carrier lifetime of

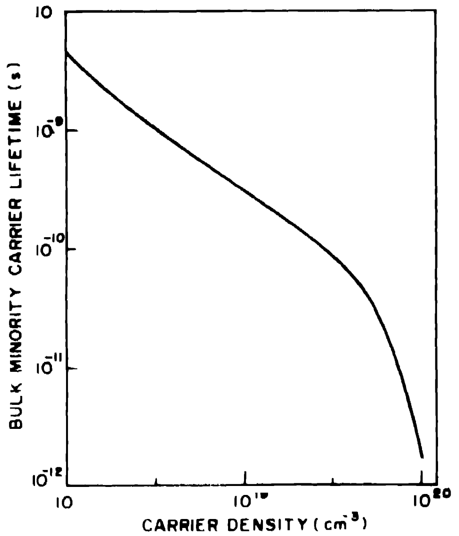

Figure 1. Bulk minority-carrier lifetime *versus* carrier density of an $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ DH device (d = 4 μm).

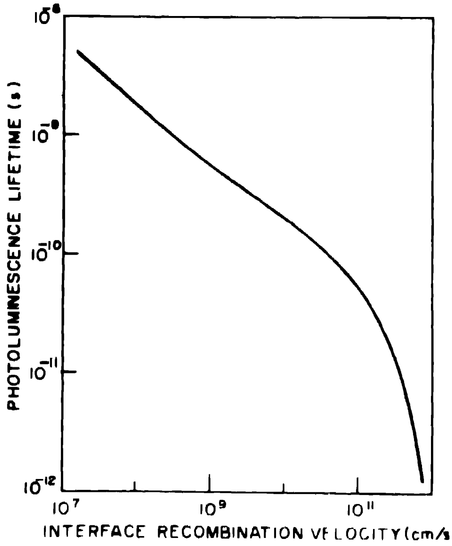

Figure 2. Photoluminescence lifetime *versus* interface recombination velocity of an $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ DH device (d = 4 μm).

heavily doped $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ DH (d = 4 μm) with carrier density under 20 mw focussed power. The nature of variation reveals that bulk minority carrier lifetime decreases in a nonuniform manner with the increase of concentrations under the focussed power for a given cross-sectional area and thickness of a double heterostructure. Numerical computations of equation (10) are worked out considering $\Delta E_g = 10.23\ (N/10^{18})^{1/3} + 13.12\ (N/10^{18})^{1/4} + 2.93\ (N/10^{18})^{1/2}$ meV [16], $T = 300$ K, $B \simeq 10^{-10}$ cm^3 s^{-1}. The values of η_p, η_n, $F_{1/2}(\eta_p)$ and $F_{1/2}(\eta_n)$ are chosen suitably [17] for the given carrier densities. In numerical analysis, change of carrier lifetime with carrier densities is considered.

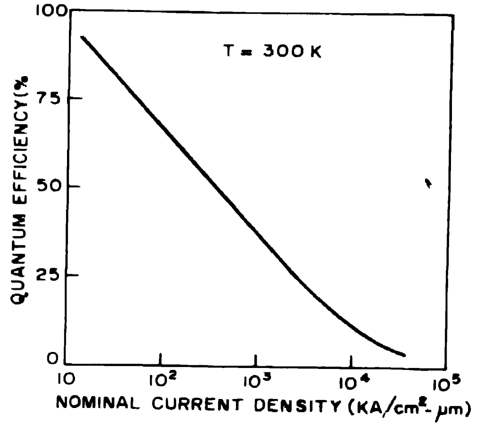

Figure 3. Variation of quantum efficiency with nominal current density of an Al$_{0.3}$Ga$_{0.7}$As/GaAs/Al$_{0.3}$-Ga$_{0.7}$As DH device (d = 2 μm).

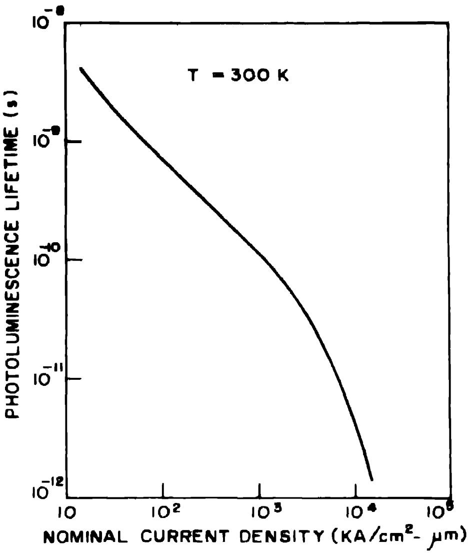

Figure 4. Variation of photoluminescence lifetir with nominal current density of an Al$_{0.3}$Ga As/GaAs/Al$_{0.3}$Ga$_{0.7}$As DH device (d = 2 μm).

The values of minority carrier lifetimes are chosen within $5 \times 10^{-7} - 10^{-7}$ s when majori carrier concentration varies in the range $10^{18} - 10^{20}$ cm^{-3}. Again, the values of majority carri lifetimes are chosen within $10^{-8} - 10^{-12}$ s when minority carrier concentration varies in tl range $(1\text{–}8) \times 10^{16}$ cm^{-3}. These data are used to study the change of photoluminescen lifetime with interface recombination velocity of an Al$_{0.3}$Ga$_{0.7}$As/GaAs/Al$_{0.3}$Ga$_{0.7}$As D (d = 4 μm), which is depicted in Figure 2. Figure 3 represents the change of quantu efficiency with nominal current density for the same semiconducting compound with the sa composition and d = 2 μm. The variation of photoluminescence lifetime with nominal curr density of the same DH (Al$_{0.3}$Ga$_{0.7}$As/GaAs/Al$_{0.3}$Ga$_{0.7}$As) with d = 2 μm is shown Figure 4.

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