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VARIATION OF PHOTOLUMINESCENCE LIFETIME IN HEAVILY DOPED $Al_xGa_{1-x}As/GaAs$ DOUBLE HETEROSTRUCTURE

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A model has been developed to study the variation of photoluminescence lifetime with concentration in heavily doped $Al_xGa_{1-x}As/GaAs$ double heterostructure (DH) taking into account bandgap narrowing and carrier degeneracy as heavy doping effects. The results so obtained by computational analysis are shown graphically.

1. Introduction

Time-resolved photoluminescence [1] is a useful technique to measure minority carrier lifetime in III-V semiconductore like GaAs and $AL_xGa_{1-x}As$. Minority carrier lifetime is an important parameter, the knowledge of which is essential for the devices, viz., light emitting diodes (LEDs), photovoltaic cells, bipolar transistors, heterojunction lasers. There are various methode to determine the minority carrier lifetime as applied to photovoltaic devices [2–6]. Time-resolved photoluminescence decay method is useful for the measurement of the minority carrier lifetime in III–V compounds. Carrier lifetime in silicon is usually found by using pulse optical excitation and photoconductivity decay technique. Actual lifetime measurements on low moderately doped silicon were reported earlier [7]. The expression of effective steady state Shockley-Read-Hall (SRH) lifetime in aritrary injection level has been derived by Blakemore [8]. Also, the illumination-effects on AlGaAs/GaAs modulation-doped-field-effect-transistor (MODFET) structure are understood [9]. It is found that absorption of optical radiation in AlGaAs can increase the number of electrons diffusing in GaAs. Recombination is an important feature in laser operation in double heterostructure diodes. Heavy doping effects produce high emitter effiviency in bipolar transistors and high open-circuit voltage in solar cells. Lifetimes for high carrier concentrations are important in band-band processes. There are several works on experimentally measured lifetimes [1,10] of heavily doped GaAs and quaternary alloy to study Auger effects.

In this presentation, assuming uniform distribution of SRH defects within specified region, an attempt has been made to develop a model to study the variation of photoluminescence lifetime with concentration in heavily doped $Al_xGa_{1-x}As/GaAs$ double heterostructure incorporating bandgap narrowing and carrier degeneracy as heavy doping effects. In the analysis, spatial variation of minority carrier density has been neglected due to the very low value of diffusion transit-time compared to the minority carrier lifetime. The results of the computational anlysis are shown graphically.

2. Mathematical formulation

For $AL_xGa_{1-x}As/GaAs$ double heterostructure, when the interface recombination velocity becomes low, photoluminescence [11] lifetime approaches the bulk minority carrier lifetime. The linearised expression [12] for the photoluminescence can be given by

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

where,

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

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

Minority carrier diffusivity (D) is related to decay time (t) and mobility (μ) as

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

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_e is given by [13]

$$\mu_e(N_D) = \frac{\mu_0}{1 + (N_D/N_{eff})^{\alpha}} + \mu_{min} \tag{3}$$

μ_{min} is the minimum mobility value expected; μ_0, the difference between the maximum and minimum mobility expected; N_{eff}, a reference concentration, and α is an exponential factor that controls the slope around $N_D = N_{eff}$. Thus, from (1)–(3), one obtains photoluminescence lifetime for n-type semiconductor as

$$\frac{1}{\tau_{PL}} = \frac{1}{\tau_R} + \frac{1}{\tau_{SRH}} + S\left(\frac{2q}{tKT}\right)^{1/2} x$$
$$x\left\{\frac{\mu_0}{1 + (N_D/N_{eff})^{\alpha}} + \mu_{min}\right\}^{-1/2} \tag{4}$$

The radiative and SRH lifetimes [14] in terms of excess photogenerated carrier ($\Delta\mu$) are given by

$$\tau_R = \frac{\Delta n}{\beta np}, \quad \mathit{and} \quad \tau_{SRH} = \frac{\Delta n}{np}[\tau_P(n + n_i) + \tau_n(p + n_i)] \tag{5}$$

where, B is the radiative recombination coefficient; n_i, the intrinsic carrier concentration, and τ_P and τ_n are the hole and electron lifetimes, respectively. n and p are the electron and hole concetrations, which under heavy doping condition can be expressed as

$$n = n_i F_{1/2}(\eta_n)\exp(-\eta_n)\exp\frac{A\Delta E_g}{KT}\exp\frac{E_{fn} - E_i}{KT} \tag{6a}$$

$$p = n_i F_{1/2}(\eta_p)\exp(-\eta_p)\exp\frac{(1-A)\Delta E_g}{KT}\exp\frac{E_i - E_{fp}}{KT} \tag{6b}$$

where, $F_{1/2}(\eta_P)$ 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, $E_{fn} = E_{fp}$. Again, the interface recombination velocity is defined as

$$S \equiv \frac{J_S}{q\Delta n} \tag{7}$$

where, J_S is the recombination current density.

Moreover,

$$J_S = q[R_{SRH} + R_{Aug}] \tag{8}$$

R_{SRH} is the interface recombination due to S.R.H. process [15,16] and R_{Aug} is the net Auger recombination.

Now,

$$R_{SRH} = \frac{np - n_i^2}{\tau_n(p + n_i) + \tau_p(n + n_i)} \tag{9}$$

and

$$R_{Aug} = \gamma\left(\frac{np - n_i^2}{n_2^i}\right)(n + p) \tag{10}$$

where, γ is the Auger recombination coefficient.

Thus, from (4)–(10), one obtains

$$\frac{1}{\tau_{PL}} = \frac{n_i}{\Delta n}\bigg[\bigg[F_{1/2}(\eta_n)F_{1/2}(\eta_p)\exp\frac{\Delta E_g}{KT}\exp\{-(\eta_n + \eta_p)\}\bigg]$$
$$\bigg[\eta_i B + \bigg[\tau_n\bigg\{F_{1/2}(\eta_p)\exp(-\eta_p)\exp\frac{(1-A)\Delta E_g}{KT}\exp\left(\frac{E_i - E_{fp}}{KT}\right) + 1\bigg\}$$
$$+\tau_p\bigg\{F_{1/2}(\eta_n)\exp(-\eta_n)\exp\frac{A\Delta E_g}{KT}\exp\left(\frac{E_{fn} - E_i}{KT}\right) + 1\bigg\}\bigg]^{-1}\bigg]$$
$$+\left(\frac{2q}{tKT}\right)^{1/2}\left\{\frac{\mu_0}{1 + (N_D/N_{eff})^{\alpha}} + \mu_{min}\right\}^{-1/2} \times$$

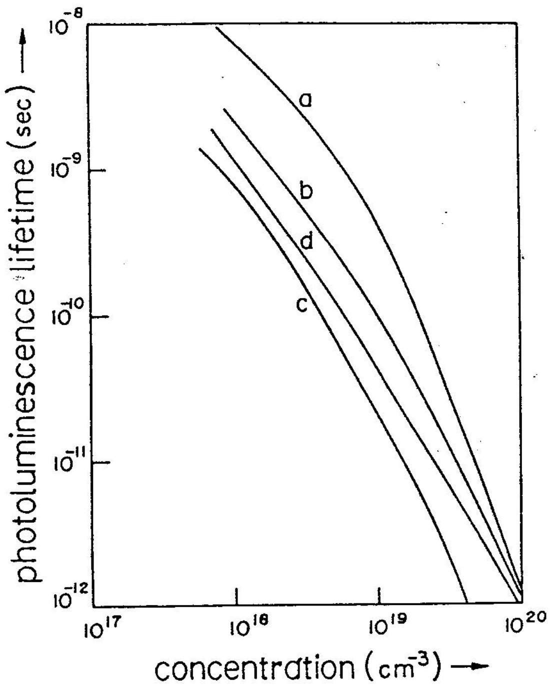

Fig.1 Variations of photolumenescence lifetime of $Al_{0.9}Ga_{0.1}As/GaAs/Al_{0.9}Ga_{0.1}As$ Dh ($d = 4\,\mu m$) with concentrations under focused powers (60 mW for curve a, 20 mW for curve b, 2 mW for curve c) and unfocused power (2 mW for curve d).

$$\times\left[\left[\tau_n\left\{F_{1/2}(\eta_p)\exp(-\eta_p)\exp\frac{(1-A)\Delta E_g}{KT}\exp\left(\frac{E_i-E_{fp}}{KT}\right)+1\right\}\right.\right.$$
$$\left.+\tau_p\left\{F_{1/2}(\eta_n)\exp(-\eta_n)\exp\frac{A\Delta E_g}{KT}+\exp\left(\frac{E_{fn}-E_i}{KT}\right)+1\right\}\right]^{-1}$$
$$+\gamma\left\{F_{1/2}(\eta_n)\exp(-\eta_n)\exp\frac{A\Delta E_g}{KT}\exp\left(\frac{E_{fn}-E_i}{KT}\right)\right.$$
$$\left.+F_{1/2}(\eta_p)\exp(-\eta_p)\exp\frac{(1-A)\Delta E_g}{KT}\exp\left(\frac{E_i-E_{fp}}{KT}\right)\right\}\Bigg]$$
$$\left.\left[F_{1/2}(\eta_n)F_{1/2}(\eta_p)\exp\frac{\Delta E_g}{KT}\exp\{-(\eta_n+\eta_p)\}-1\right]\right] \qquad (11)$$

3. Numerical analysis and discussion

The numerical analyses of (11) are presented for a fixed composition in Fig. 1 under different circumstances. It depicts the variation of photoluminescence lifetime of heavily doped $Al_{0.9}Ga_{0.1}As/GaAs/Al_{0.9}Ga_{0.1}As$ DH ($d = 4\mu m$) with different concentrations under focused powers 60 mW, 20 mW, 2 mW and unfocussed power 2 mW. These are presented by curves a, b, c and d, respectively. The nature of variation reveals that the photoluminescence lifetime decreases rapidly with the increase of concentrations and always increases with the power excitation for a given cross-sectional area and thickness of a double heterostructure. Numerical computations of (11) have been carried 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 [17], $T = 300\,K$, $B \simeq 10^{-10} cm^3 sec^{-1}$. The values of η_p, η_n, $F_{1/2}(\eta_p)$ and $F_{1/2}(\eta_n)$ are chosen suitably [18] for the specified dopant densities. Variation of carrier lifetime with different concentrations is also incorporated in the numerical analysis. The values of minority carrier lifetimes for the variation of majority carrier concentration in the range $10^{18} - 10^{20} cm^{-3}$ have been chosen within $5\times10^{17} - 10^{-7}$sec; while in the minority carrier concentration range between $(1-8)\times10^{16} cm^{-3}$, the values of majority carrier lifetimes are taken within $10^{-8} - 10^{-12}$sec. Due to unavailability of experimental data of photoluminescence material, it is not possible to make a comparative study of this present result.

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