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Carrier-Density Dependent Lifetime and Output Nonlinearity of InGaAsP LED's

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I. Introduction

Intensive studies are going on to understand the physical mechanisms of strong output nonlinearity and temperature sensitivity of InGaAsP/InP DH LED's for optical communications 1)- 2). The present report deals with the improved treatment of carrier lifetime data, showing the necessity to re-interpret the previous estimate of the injection carrier density. A reasonable estimate of radiative recombination coefficient is obtained by considering both leakage of hot carriers and Auger process.

II. Estimate of Carrier Lifetime Considering Strong Carrier Density Dependence

Extending the bimolecular recombination theory $^{3)}$, multi-particle (including Auger recombination) process is treated exactly in the analysis of both frequency and time-domain modulation characteristics. Injected carrier density of the active layer Δn and the photon-generation rate R_{spon} are expressed as

$$\frac{d\Delta n}{dt} = \frac{J}{qd} - \frac{\Delta n}{\tau(n)}, \quad \frac{1}{\tau(n)} = A(n_0 + \Delta n)^2 + B(n_0 + \Delta n), \tag{1}$$

$$R_{spon} = \eta_{in}\frac{\Delta n}{\tau(n)} = \frac{\Delta n}{\tau_r(n)}, \tag{2}$$

where J is current density, q is electronic charge, d is thickness of the active layer, and η_{in} is internal quantum efficiency. Applying the small signal approximation to eq.(1), it is shown that ac carrier lifetime defined by $\tau_{ac} = (2\pi f_c)^{-1}$ is not equal to the true lifetime τ, but has a correction factor

$$\frac{\tau}{\tau_{ac}} = \tau\frac{d}{d\Delta n}\left(\frac{\Delta n}{\tau}\right) = \frac{B(n_0 + 2\Delta n) + A(n_0^2 + 4n_0\Delta n + 3\Delta n^2)}{B(n_0 + \Delta n) + A(n_0 + \Delta n)^2}. \tag{3}$$

In Fig.1, calculated values of τ and τ_{ac} are plotted for the injection current I. Carrier lifetime evaluated from step-response waveform τ_{step} is simulated by solving eq.(1) numerically, and is plotted also in Fig.1. In both cases correction factor ranging between 1.5 and 2.5 is necessary to get true lifetime τ.

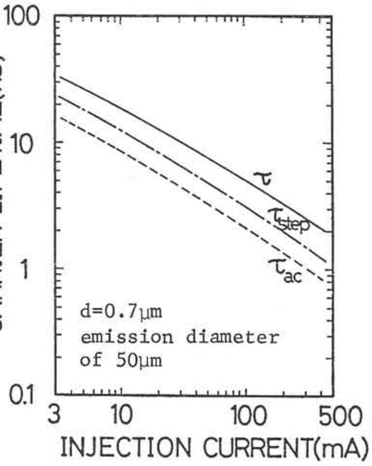

Fig.1 Difference between real lifetime τ and apparent values τ_{ac} and τ_{step}. This model assumes radiative recombination coefficient $B = 0.5 \times 10^{-10}\mathrm{cm}^3/\mathrm{s}$, Auger coefficient $A = 2 \times 10^{-29}\mathrm{cm}^6/\mathrm{s}$, and doping concentration $n_0 = 2 \times 10^{16}\mathrm{cm}^{-3}$.

III. Analysis of Output nonlinearity and Modulation Characteristics

Output nonlinearity and frequency characteristics of 1.3μm InGaAsP/InP DH LED's with 0.23μm active layer thickness are shown in Fig.2(a) and (b). We also show the result of the efficiency normalized by its derivative $D = (P_0 Im)/(PmI_0)$ (Fig.2(c)), which satisfies the relationship

$$D = \frac{\tau}{\tau_{ac}}\,\frac{n_0 + \Delta n}{n_0 + 2\Delta n}. \tag{4}$$

Therefore the injected carrier density Δn is determined from the formula

$$\Delta n = \sqrt{\left(\frac{J_0 D\tau_{ac}}{qd}\right)^2 + \left(\frac{n_0}{2}\right)^2} + \left(\frac{J_0 D\tau_{ac}}{qd}\right) - \frac{n_0}{2}. \tag{5}$$

Fig.3(a) shows the carrier density dependence of radiative and nonradiative lifetime based on the

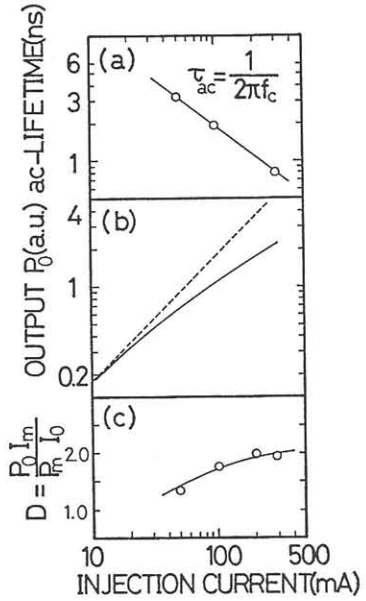

Fig.2(a) ac-carrier lifetime τ_{ac}, (b) light output P_0, (c) the efficiency normalized by its derivative $D = \frac{P_0/I_0}{P_m/I_m}$, where Im and Pm are low frequency modulation current and output, respectively, under pulsed operation (duration ranging 0.1 - 2μs).

treatments described above. Carrier density dependence of internal quantum efficiency is obtained from the output nonlinearity data. The estimated value of B is $0.2 \times 10^{-10} cm^3/s$, which is much smaller than the previous reports ranging around 1×10^{-10} and also the result of the recent direct measurement ($B=0.5 \times 10^{-10} cm^3/s$) using photoluminescence phase shift technique 4). This very small value of B may be connected with the overestimation of injected carrier density because of the neglect of carrier leakage process in our model calculation. In Fig.3(b) the results of a revised calculation is shown where carrier density is estimated by the relation $\Delta n = \frac{J - J_L}{qd} \tau (6)$. Leakage current density J_L is evaluated by using Anderson's theory 5)6) with the assumption of electron temperature $T_e = T_L + 100K$ 2). This plot gives a more reasonable estimate, $B = 0.35 \times 10^{-10} cm^3/s$.

IV. Conclusion We report the improved treatment of carrier lifetime data, by exactly taking the strong carrier density dependence into consideration. Previous treatments of output nonlinearity and carrier lifetime lead to the underestimation of carrier density. In order to get a reasonable estimate of radiative recombination coefficient, it is concluded that incorporation of hot-carrier leakage as well as Auger recombination is necessary at the injection levels around $5 \times 10^{18} cm^{-3}$.

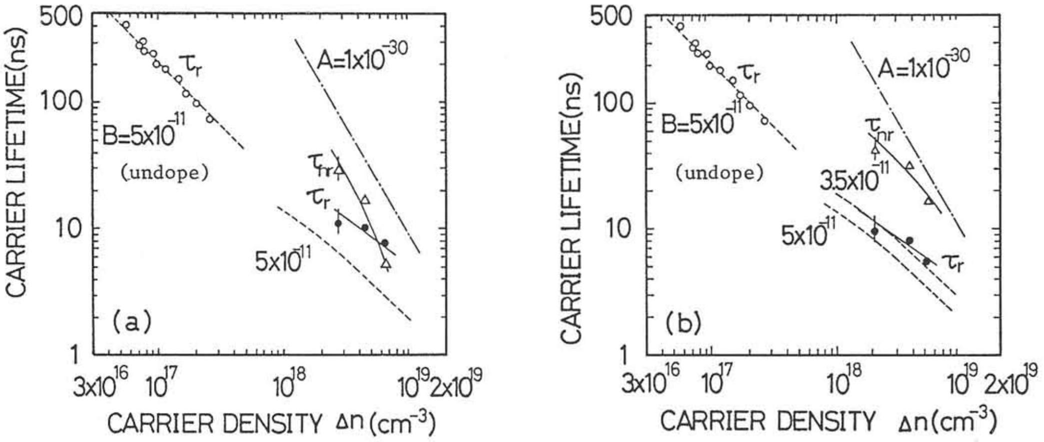

Fig.3(a) Carrier density dependence of radiative lifetime τ_r (closed circles) and non-radiative lifetime τ_{nr} (triangles). Radiative lifetime of high purity DH wafers 4) (open circles) is also shown.

(b) Revised derivation of radiative and non-radiative lifetime by considering the leakage of hot carriers.

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