$$n(I) = \eta_{int} \cdot \int_0^I \tau_d(I_1)\, dI_1 \qquad (3).$$

The very high values of carrier lifetime at low currents indicate the importance of measuring τ_d down to low bias current for accurate estimation of carrier concentration. Fig.3 shows the relationship of the carrier concentration and drive current.

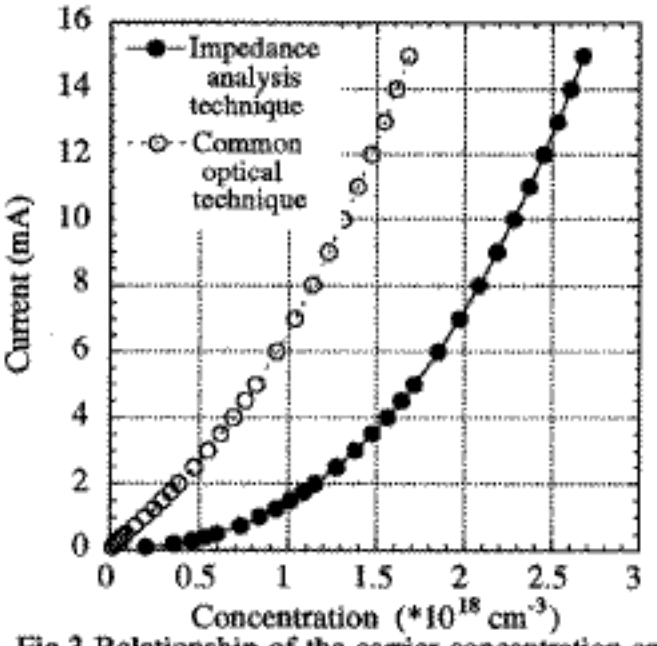

Fig.3 Relationship of the carrier concentration and current.

Using data provided by the common optical technique tends to underestimate the carrier concentration by about 1×10^{18} cm^{-3} at threshold. Another important result is that new relation between current and concentration implies considerably different recombination parameters. The usually formula relating current to carrier concentration is:

$$\frac{I}{eV} = An + Bnp + Cnp^2 \qquad (4),$$

where $p=p_o+n$ is concentration of holes and p_o is background doping level in the active layer. Coefficient A is attributed to nonradiative recombination, and B and C to radiative and Auger recombination respectively. Fractional degree terms ($Dn^{0.52}$) were introduced[3] to account for the saturation of the lifetime at low currents, but data in Fig.2 indicate this procedure is unnecessary.

In order to study recombination rates, it is convenient to analyze the dependence of the reciprocal of differential lifetime on the carrier concentration (Fig.4). Transforming eq.(4), we obtain:

$$\frac{1}{\tau_d} = a + 2nb + 3cn^2,\ a = A + Bp_o + Cp_o^2,$$

$$b = B + 2Cp_o, \text{ and } c = C \qquad (5).$$

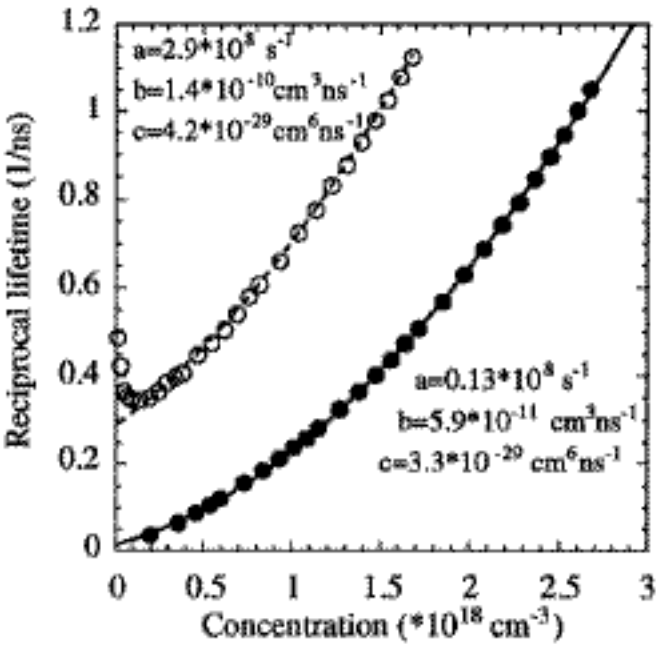

Fig.4 Dependence of the reciprocal lifetime on carrier concentration, measured using common optical (open circles) and impedance analysis (solid circles) techniques. Lines are fits to eq.(5), fitting coefficients are shown.

In cases of moderate doping $B>Cp_o$, and thus $a=A+Bp_o$. When correct values of carrier lifetime are used, the zero intercept a is very small and is well explained as Bp_o, a value determined by background doping. Evaluation of Bp_o provides a new way to analyze the background doping concentration in the active layer of a semiconductor laser. For the device studied in this work, we estimate $p_o \leq 2\times10^{17}$ cm^{-3}. This value is in a good agreement with data provided by secondary ion mass spectrometry study of original wafers. Preliminary data using highly doped active region[6] provided an intercept of $a=0.5ns^{-1}$, giving $p_o \sim 2\times10^{18}$ cm^{-3}.

In conclusion, a new technique is presented for carrier lifetime measurement, based upon the electrical measurements of laser impedance. Unlike optical measurements, this new technique can be used to very low bias currents with high accuracy. Correct carrier concentration data permits accurate analysis of recombination rates and background doping.

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