Carrier recombination rate in GaAs-AlGaAs single quantum well lasers under high levels of excitation

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The carrier recombination rate in GaAs-AlGaAs single quantum well lasers is investigated using a small-signal technique for carrier densities from 10^{17} to $10^{19}/cm^3$. For carrier densities up to mid $10^{18}/cm^3$, the inverse of the differential carrier lifetime, $1/\tau_d$, increases linearly with the carrier density. The differential rate, however, saturates at higher carrier densities and remains nearly constant for carrier densities higher than $10^{19}/cm^3$. The deviation from the bulk recombination behavior is due to a portion of the injected carriers populating the semicontinuum states where the rate for the radiative transition is much smaller. The experimental data indicate that the runaway increase of threshold current with decreasing cavity length commonly observed in the short-cavity lasers is mainly due to the loss of carrier confinement at high carrier densities rather than due to fast carrier-depleting processes, such as Auger recombination.

Single quantum well semiconductor materials have been widely used for high-power lasers which offer low threshold current and high efficiency. Due to the small volume of the gain medium, the carrier density required for lasing is on the order of $10^{19}/cm^3$, which is one order of magnitude higher than that for the conventional double-heterostructure lasers. At such high carrier densities, a number of carrier loss mechanisms, such as Auger recombination, carrier leakage over the quantum well potential barriers, and population of the indirect valleys, become strong enough to compete with the radiative recombination process.[1,2] Indeed, the phenomena of runaway threshold current increase and low characteristic temperature T_0, commonly observed in the short-cavity lasers as the cavity length decreases, is indicative of the loss of radiative efficiency and have been explained based on a model that includes all the aforementioned processes.[1,2] There have been a number of papers on the carrier recombination rates in GaAs and GaAs quantum wells for carrier densities in the 10^{17} to $10^{18}/cm^3$ regime.[3-5] The recombination rate generally follows a simple relation: $R = An + Bn^2$, where the A and B are coefficients for the band-to-impurity and band-to-band bimolecular recombination processes, and n is the injected carrier density. At higher carrier densities, the recombination rate is expected to deviate from this simple relation. For example, the rate of Auger recombination is proportional to n^3, the rate of carrier leakage is proportional to n^x with x possibly larger than 4,[3] and the rate of the stimulated emission is faster than n^2. The presence of the indirect valleys is expected to contribute a negative term due to the longer carrier lifetime in the indirect valleys although the exact values of the lifetime and intervalley scattering rate are unknown.

In this letter, we present an experimental study on the carrier recombination rate in GaAs/AlGaAs single quantum well lasers using the differential carrier lifetime technique.[3] The differential carrier lifetime, defined as $1/\tau_d = \partial R/\partial n$, is measured by the rise time of the luminescence of the laser when driven by a small step-function current pulse at various dc bias below the threshold. Using samples with antireflection (AR) coating on both mirrors, the laser action is suppressed. This allows the measurement of the differential carrier lifetime and carrier density to be made at carrier densities up to $2\times10^{19}/cm^3$ for the first time. We have found that, for carrier densities up to $10^{18}/cm^3$, the differential recombination rate $1/\tau_d$ is linearly proportional to the carrier density. The recombination rate, however, saturates and becomes independent of the injection level for carrier densities above $10^{19}/cm^3$. The experimental data suggest that fast carrier-depleting processes, such as Auger recombination and carrier leakage over the quantum well potential barrier, do not play a major rule in the loss of efficiency at very high injection levels.

The lasers used in this study are the graded-index separate-confinement (GRIN-SCH) single quantum well lasers. The structure, as shown in Fig. 1, consists of a 100-Å-thick undoped GaAs quantum well flanked by two 2000-Å-thick linearly graded $Al_xGa_{1-x}As$ layers. We have studied samples with $0.3 < x < 0.4$ and $0.3 < x < 0.6$. The materials were grown by the atmospheric pressure metalorganic chemical vapor deposition (MOVCD) technique, and processed into laser devices with 60-μm-wide and 300-μm-long stripes. ZrO_2 AR coatings ($R < 0.5\%$) are applied to both mirrors in order to suppress

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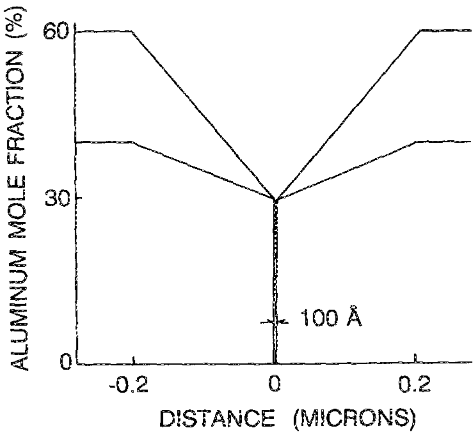

FIG. 1. Layer composition of the graded-index separate-confinement $Al_xGa_{1-x}As/GaAs$ single quantum well lasers.

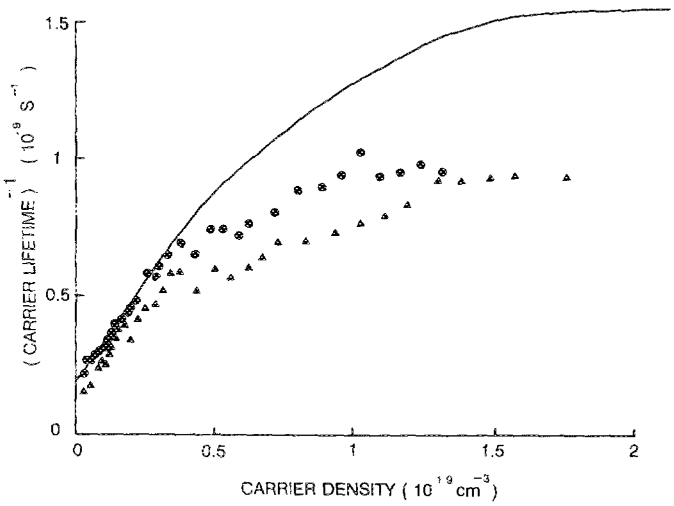

FIG. 2. Measured $1/\tau_d$ as a function of carrier density for aluminum mole fraction $0.3<x<0.6$ (dots) and $0.3<x<0.6$ (triangles) in the graded region. The solid curve is the theoretical band-to-band radiative recombination rate.

the laser action. A laser device without the AR coating has a threshold current of 100 mA. With the AR coating, the laser action is no longer observed for currents as high as 1 A. The differential carrier lifetime is measured by the rise time of the luminescence from the front mirror when the laser is driven by a small step-function-like current pulse with a rise time of <100 ps. The current pulse is superimposed on a dc bias current, ranging from 1 to 300 mA. The luminescence is detected by a silicon avalanche photodiode with a rise time of 150 ps. The intensity of the luminesence increases superlinearly with current in a complex way. However, for an incremental change in the drive current, the corresponding change in the luminescence intensity is proportional to the change in the carrier density and its rise time is the same as the differential carrier lifetime. The detected signal is amplified using a B&H model DC-7000 broadband (DC-7 GHz) microwave amplifier. The waveform is then displayed using a fast sampling oscilloscope with a Tektronix S4 sampling head. The overall response time of the system is 300 ps. The oscilloscope traces are recorded using a Tektronix DCS01 digital camera and processed using a computer. By averaging over hundreds to thousands of waveforms, the accuracy is greatly enhanced. The present experiment is carrier out at room temperature. The dc bias current is expected to increase the junction temperature by about 20 K at a laser current of 300 mA. By comparing the lifetime data taken at various temperatures, we have found that the junction temperature increase has a negligible effect on the carrier lifetime.

Once the differential carrier lifetime τ_d is measured as a function of dc bias current, I, the injected carrier density n is determined by[3]

$$n=\left(\frac{1}{eAd}\right)\int \tau_d(I)dI, \tag{1}$$

where A is the area of the stripe and d is the thickness of the quantum well. Figure 2 shows the measured $1/\tau_d$ as a function of carrier density for samples with $0.3<x<0.4$ and $0.3<x<0.6$. For low carrier densities, $1/\tau_d$ increases linearly with increasing carrier density and can be fitted by $1/\tau_d = A + Bn$ with $A = 1\times10^8$/s and $B = 1.5\times10^{-9}$/s/cm^3 for the $0.3<x<0.4$ sample, and $A = 1.8\times10^8$/s and $B = 1.5\times10^{-9}$/s/cm^3 for the $0.3<x<0.6$ sample. The B factor is about one-half the value reported in Ref. 5. The $1/\tau_d$ vs n curve becomes sublinear at higher carrier densities and $1/\tau_d$ remains approximately $(1\ \text{ns})^{-1}$, independent of n for $n>10^{19}/\text{cm}^3$. Except for the different intercepts at zero carrier density, there is no significant difference in the carrier lifetime data of these two samples. We note that a similar saturation behavior has also been observed in pseudomorphic InGaAs/GaAs single quantum well materials,[6] in which case $1/\tau_d$ saturates at a $(3\ \text{ns})^{-1}$ for $n>10^{19}/\text{cm}^3$.

The sublinear $1/\tau_d$ vs n relation indicates that the carriers are depleted at a much slower rate than predicted based on a n^2-dependent bimolecular recombination rate and that fast carrier-depleting processes, such as Auger recombination and carrier leakage, do not play a major role in determining the differential carrier lifetime in GaAs quantum wells at high carrier densities. Indeed, based on the published Auger recombination coefficient of $c = 4.22\times10^{-30}$ cm^3 s^{-1} for bulk GaAs,[3] the lifetime of carriers caused by Auger process would be $\tau_{\text{Auger}} = 1/3cn^2 = 350$ ps at a carrier density of $1.5\times10^{19}/\text{cm}^3$, which is considerably shorter than the observed lifetime. This suggests that the Auger recombination coefficient in GaAs quantum wells must be smaller than that of bulk GaAs.

In the present study, we are unable to quantify the contribution of the stimulated emission to the carrier recombination rate. However, its importance can be ruled out based on the following argument. If the stimulated emission were significant, the differential recombination rate would be faster, rather than slower, than predicted based on the n^2 process and $1/\tau_d$ would increase superlinearly, rather than sublinearly with n. The nearly constant $1/\tau_d$ under high levels of excitation reflects the absence of any fast recombination processes.

The general features of the experimental data can be understood by considering a simple band-to-band radiative transition at high levels of excitation when a considerable amount of carriers becomes unconfined due to band filling. A numerical calculation reveals that for a carrier density of $2\times10^{19}/\text{cm}^3$, the quasi-Fermi level in the conduction band is at 246 meV. Thus a considerable portion of the injected carriers populates the semicontinuum states. The n^2 recombination rate for the carriers in the semicontinuum states is much smaller because the carrier volume density is diluted by the larger volume of the confinement layers. In addition, because the minimum of the L valley is 50 meV, or less than two times the thermal energy above the Fermi energy, the radiative transition rate could be further reduced due to the population of the indirect valley. The solid curve in Fig. 2 is the calculated bimolecular recombination rate as a function of carrier density. In this calculation, we have assumed a parabolic band structure with the effective masses equal to $0.067m_e$, $0.46m_e$, and $0.082m_e$ for the electrons, heavy holes, and light holes, respectively. The radiative transition is assumed to follow the k selection rule. The tails of the Fermi–Dirac distribution above the quantum well potential barriers are ignored. Since the values of the transition matrix elements are unknown, we have adjusted the slope of the calculated (relative) $1/\tau_d$ vs n relation and shifted the intercepts to fit the experimental data in the low carrier density regime. The calculation did not include the effect of the L valley, which may cause the transition rate to saturate at lower carrier densities.

In conclusion, the differential carrier recombination rate in AlGaAs/GaAs single quantum well lasers have been investigated using a small-signal technique for carrier densities from 10^{17} to $10^{19}/\text{cm}^3$. For carrier densities up to mid $10^{18}/\text{cm}^3$, the differential carrier lifetime τ_d follows the relation: $1/\tau_d = A + Bn$, where A and B are the coefficients for the band-to-impurity and band-to-band recombination processes. The differential rate saturates at higher carrier densities and becomes independent of the injection level for carrier density above $10^{19}/\text{cm}^3$. The experimental data suggest that the loss of efficiency of single quantum well laser under high levels of injection is mainly due to loss of carrier confinement rather than due to fast carrier-depleting processes.

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