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Carrier Recombination Rates in Strained-Layer InGaAs–GaAs Quantum Wells

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Abstract—**The carrier recombination rates in semiconductor quantum wells are found to be structure dependent, and under high levels of excitation, generally do not follow the recombination rule of the bulk material. Through a differential carrier-lifetime measurement in the strained-layer InGaAs–GaAs quantum wells, we show that in quantum wells with lower potential barrier or thinner well width, the recombination rates are smaller due to a larger portion of the injected carriers populating the confinement layers where the carriers recombine more slowly owing to diluted carrier volume density. The present study indicates that the carrier recombination rate is not an intrinsic property of the material composition, and that a simple recombination rule based on the power series of carrier density is, in general, not applicable in quantum wells.**

In bulk III–V semiconductors, the carrier recombination rate R can be described by the relation

$$R = An + Bn^2 + Cn^3 \qquad (1)$$

where n is the carrier density, A is the coefficient for the recombination with impurity, at defects, or on the surface, B is the coefficient for bimolecular recombination, and C is the coefficient for Auger recombination. Other higher order processes may also become important at higher carrier densities, one of them being the carrier leakage loss having a rate proportional to n^x with $3 < x < 4$ [1]. In the regime where the higher order recombination processes are strong, the differential carrier lifetime, defined as $1/\tau_d = \partial R/\partial n$, increases superlinearly with the carrier density [1]. In semiconductor quantum wells, the bimolecular recombination process follows the n^2 rule for the carrier densities in the low $10^{18}/\text{cm}^3$ [2], [3]. It was assumed that the n^2 and n^3 recombination processes at higher carrier densities were similar to that in the bulk material [4], [5]. Possible ways to suppress Auger recombination through band-structure engineering have also been discussed [6]. However, a recent study [7] revealed that the relation described in (1) did not hold in AlGaAs–GaAs quantum wells under high levels of excitation ($n > 10^{19}/\text{cm}^3$). Typically, the inverse of the differential carrier lifetime increased sublinearly with increasing carrier density and became nearly independent of carrier density for $n > 10^{19}/\text{cm}^3$. The deviation from the recombination rule of bulk materials is attributed to the storage of a portion of carriers in the continuum states where the radiative transition rate is much smaller due to diluted carrier volume density. Faster carrier depletion processes, such as Auger recombination and carrier leakage loss [4], [5], which would result in a superlinear increase in the recombination rates, are apparently masked by this carrier storage effect.

In this paper, through a differential carrier-lifetime study in the strained-layer InGaAs–GaAs quantum wells, we provide the first experimental evidence which shows that the carrier lifetime is not an intrinsic property of the material, but is structure dependent. By reducing the height of the potential barrier or decreasing the well width, the carrier lifetime can be prolonged. Thus, the A, B, and C coefficients in (1) cannot be regarded as the characteristics of the material composition of the well. Although the present study is done using the strained-layer InGaAs–GaAs quantum wells, the structure dependency is generic to quantum wells with finite potential barriers, and it should be taken into account when the higher order recombination processes are evaluated based on the lifetime data.

The structures of the samples used in this study are shown in Fig. 1. For studying the effect of the barrier height on the carrier lifetime, a comparison is made between sample (A) with an undoped 70 Å thick strained $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ single quantum well flanked by two 2000 Å thick graded $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($0.2 < x < 0.65$) confinement layers, and sample (B) with an undoped 70 Å thick strained $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ single quantum well flanked by two 1000 Å thick GaAs confinement layers, followed by the second stage of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ confinement layers. For studying the effect of the well width, a comparison is made between two samples with an undoped strained $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ single quantum well with 120 Å

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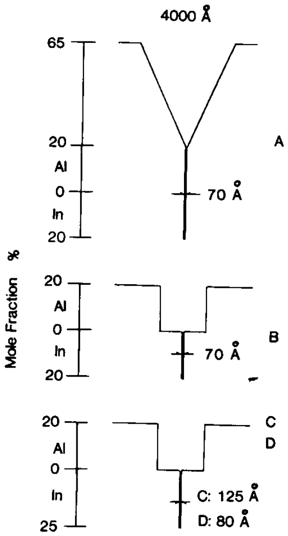

Fig. 1. Layer structure of the samples.

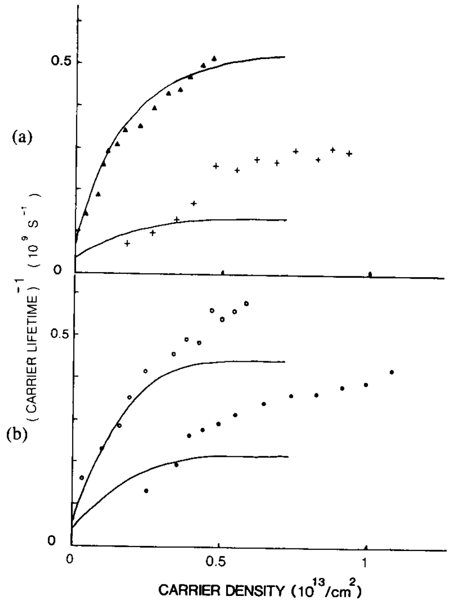

Fig. 2. Experimental data of $1/\tau_d$ versus n_s relations for (a) samples A (triangles) and B (crosses), and (b) samples C (open circles) and D (closed circles).

(sample C) and 80 Å (sample D) well widths, respectively, flanked by two 1000 Å thick GaAs barrier layers, followed by $Al_{0.2}Ga_{0.8}As$ barrier layers. The step-confinement materials were grown at the University of Illinois, and the graded confinement materials were grown at the David Sarnoff Research Center. All samples were made of efficient laser materials, as reported previously [9], [10]. The materials were prepared by metalorganic chemical vapor deposition, and were processed into 60 μm wide stripe-geometry lasers.

The method of carrier-lifetime measurement was described previously [1], [7]. Briefly, the differential carrier lifetime τ_d ($1/\tau_d = \partial R/\partial n_s$) of the injected carriers is measured by the risetime of the luminescence emitted from the front mirror when the laser is driven by a small step-function current pulse at various dc bias levels below the threshold. Once the differential carrier lifetime τ_d is measured as function of the dc bias current I, the injected sheet carrier density n_s is calculated using the formula [1]

$$n_s(I) = (1/ed) \int \tau(I)\, dI \qquad (2)$$

where d is the thickness of the quantum well. Since the injected carriers are not necessarily confined in the well, we have adopted the sheet carrier density rather than the volume carrier density.

Fig. 2(a) shows the measured data of $1/\tau_d$ as a function of n_s for samples A and B with different barrier heights. When a comparison of the carrier recombination rates is made for samples of different structure and growth condition, the role of the material quality factor needs to be evaluated. The carrier recombination rates associated with the quality factors, including the defect density, impurity concentration, and surface recombination rates, are linearly proportional to the carrier density. In the differential carrier-lifetime measurement, these factors are represented by the intercepts with the abscissa in the $1/\tau_d$ versus n_s curve, and they can be conveniently separated from other factors of interest. From the small values of intercepts in Fig. 2, we conclude that the material quality factors can be neglected in the present study.

In both samples, the $1/\tau_d$ versus n_s relations exhibit a sublinear behavior similar to those observed in the AlGaAs-GaAs single-quantum-well lasers [7]. The $1/\tau_d$ value of sample B, with lower barrier height, is significantly smaller than that of sample A, and it stays essentially constant for $n > 0.5 \times 10^{13}/\mathrm{cm}^2$. Fig. 2(b) shows the $1/\tau_d$ versus n_s data of samples C and D with different well widths. The lifetime is longer by a factor of two in sample D, which has a smaller well width.

Previously, a sublinear $1/\tau_d$ versus n_s relation had been observed in the bulk GaAs and InGaAsP materials for carrier densities from 10^{17} to $10^{18}/\mathrm{cm}^3$ at low temperatures [1] (-50°C for GaAs and -150°C for InGaAsP). In those cases, the sublinear behavior has been attributed to the carrier-density dependency of the B coefficient when a bandtail effect is taken into account [11]. However, the bandtail in the quantum-well material cannot explain why the radiative recombination rate is affected by the barrier height as shown in Fig. 2.

The observed structure dependency in the $1/\tau_d$ versus n_s relation can be understood in terms of the effective number of carriers confined in the wells participating in the radiative transition [7]. In sample B, the only confined quantum-well state (one subband) in the conduction band is located at approximately $\Delta E = 80$ meV ($\approx 3kT$ for $T = 300$ K) below the energy barrier. In the limit of the low carrier density when the Fermi level is below the band edge, the ratio of the numbers of carriers per unit energy interval in the continuum and in the confined state is exp $(-\Delta E/kT) \times \rho_{\text{bulk}}/\rho_{\text{QW}}$ where ρ_{bulk} and ρ_{QW} are the densities of the states of the continuum and of the confined state, respectively. This ratio is estimated to be on the order of 1 for a 5 meV energy interval at the bottom of the continuum. This estimate is consistent with a previous numerical calculation [12]. Hence, even at very low carrier density, a considerable fraction of the injected carriers is unconfined. The well width determines the number of the confined states, and thus also has a profound influence on the carrier distribution. In the case of sample *B*, once the carriers populate the continuum states, their volume density is reduced by a factor of 70/2000 Å, the ratio of the thickness of the quantum well and the confinement layers, and the bimolecular recombination rate, proportional to n^2, is reduced by the same ratio. When a significant portion of the carriers populates the confinement layers, the overall carrier recombination rate is reduced. The nearly constant carrier lifetime of sample *B* at high carrier densities is indicative of a large fraction of the carriers populating the confinement layers. Thus, the confinement layers serve as a carrier reservoir, and the carrier lifetime in the reservoir is primarily limited by the nonradiative recombination caused by, e.g., defects. This process effectively introduces a negative term to the total recombination rate (1). This external effect also gives rise to effective coefficients *A*, *B*, and *C* in (1) which cannot be treated solely as the material composition of the well. Based on the experimental data obtained in GaAs-AlGaAs [7] and in the strained InGaAs-GaAs quantum wells, we conclude that the structure dependency of the carrier lifetime is generic to quantum-well structures with finite potential barriers.

We note that the intensity of the confinement layers' emission at a shorter wavelength in all of our samples is rather weak, even at very high injection currents. This is consistent with the low recombination rates in the confinement layers due to the low carrier volume density.

Owing to a lack of detailed knowledge on the magnitude of the transition matrix element of the strained InGaAs-GaAs quantum well, a quantitative comparison between the theory and the experiment has not be made. However, since two samples with identical material composition in the quantum well share the same radiative-transition matrix element, the key feature of the structure dependency can be explained by simply comparing the numbers and the distribution of the carriers in the quantum well. We have adopted the following approach. Using the published data of the effective masses, the energy levels and the density of states in the quantum wells can be accurately determined. If the radiative transition is assumed to follow the *k*-selection rule, the transition rate as a function of the injected carrier density can be calculated to within a proportionally constant which is the square of the matrix element. For comparison to the experimental data, the proportionality constant is adjusted so that the calculated curve for sample *A* fits the experimental data of sample *A*. The same proportionality constant is then used in the calculation for other samples.

These calculated curves are shown in Fig. 2. The intercept, which represents the material quality factor as discussed above, for each curve has been shifted to fit the data in the low carrier-density limit. We have used the effective masses for electron and heavy hole (perpendicular to the plane of the well) of the unstrained material listed in [13]. The light-hole band (perpendicular to the plane of the well) is unconfined [13], and therefore does not need to be considered. The in-plane effective mass that determines the density of states in the valance band is 0.191 m_e from [14]. Since the carriers in the confinement layers have a much smaller radiative transition rate, the tails of the Fermi-Dirac distribution above the quantum-well potential barriers are neglected. The calculation correctly explains the general features of the experimental data.

The present study indicates that the carrier recombination rate is not an intrinsic property of the material composition, and that a simple recombination rule such as that of (1) is, in general, not applicable in quantum wells. In materials with low potential barriers, the carrier storage effect may lead to an underestimation of the recombination coefficients based on the carrier-lifetime data unless appropriate correction is made for the carrier density in the well. The study also suggests that the radiative recombination rate can be enhanced or suppressed in a tailored structure to meet the device requirement. For example, a higher potential barrier enhances the rate of the radiative transition and reduces the threshold current. A lower potential barrier suppresses the radiative and higher order nonradiative recombination processes and facilitates the energy storage for *Q* switching or pulse amplification [8].

In conclusion, we have found that the carrier recombination rates in semiconductor quantum wells are structure dependent, and under high levels of excitation, generally do not follow the recombination rule of the bulk material. Through a carrier-lifetime measurement in the strained-layer InGaAs quantum wells, we show that the inverse of the carrier lifetime typically increases sublinearly with the injection carrier density, and in the case of quantum wells with lower potential barriers, it stays nearly constant at high carrier densities. The deviation from the bulk recombination rule is due to the storage of the injected carriers in the continuum states where the radiative transition rate is much smaller due to the diluted carrier density.

REFERENCES

[1] C. B. Su and R. Olshansky, "Carrier lifetime measurement for determination of recombination rates and doping levels of III-V semiconductor light sources," *Appl. Phys. Lett.*, vol. 41, pp. 833-835, 1982; R. Olshansky, C. B. Su, J. Manning, and W. Powaznik, "Measurement of radiative and nonradiative recombination rates in InGaAsP and AlGaAs light sources," *IEEE J. Quantum Electron.*, vol. QE-20, pp. 838-854, 1984; C. B. Su, R. Olshansky, J. Manning, and W. Powaznik, "Carrier dependence of the radiative coefficient *i* III-V semiconductor light sources," *Appl. Phys. Lett.*, vol. 44, pp. 732-734, 1984.

[2] Y. Arakawa, H. Sakaki, M. Nishioka, J. Yoshino, and T. Kamiya, "Recombination lifetime of carriers in GaAs-GaAlAs quantum wells near room temperature," *Appl. Phys. Lett.*, vol. 46, p. 519, 1985.

[3] E. H. Bottcher, K. Ketterer, D. Bimberg, G. Weimann, and W. Schlapp, "Exitonic and electron-hole contribution to the spontaneous

recombination of injected charge carriers in GaAs-GaAlAs multiple quantum well lasers at room temperature," *Appl. Phys. Lett.*, vol. 50, pp. 1074-1076, 1987.

[4] A. R. Reisinger, P. S. Zory, and R. G. Waters, "Cavity length dependence of the threshold behavior in thin quantum well semiconductor lasers," *IEEE J. Quantum Electron.*, vol. QE-23, pp. 993-999, 1987.

[5] S. R. Chinn, P. S. Zory, and A. R. Reisinger, "A model for GRIN-SCH-SQW diode lasers," *IEEE J. Quantum Electron.*, vol. 24, pp. 2191-2214, 1988.

[6] E. Yablonovitch and E. O. Kane, "Reduction of lasing threshold current density by lowering of valence band effective mass," *J. Lightwave Technol.*, vol. LT-4, pp. 504-506, 1986; ——, "Band structure engineering of semiconductor lasers for optical communications," *J. Lightwave Technol.*, vol. 6, pp. 1292-1299, 1988.

[7] P. Wang, R. G. Waters, G. Yao, K. K. Lee, and Y. C. Chen, "Carrier recombination rate in GaAs-AlGaAs single quantum well lasers under high levels of excitation," *Appl. Phys. Lett.*, vol. 56, pp. 2083-2085, 1990.

[8] Y. C. Chen, P. Wang, R. G. Waters, and K. K. Lee, "Energy storage in quantum well lasers," *Opt. Lett.*, vol. 15, p. 1073, 1990.

[9] D. P. Bour, R. U. Martinelli, D. B. Gilbert, L. Elbaum, and M. G. Harvey, "Operating characteristic of InGaAs/AlGaAs strained single-quantum-well lasers," *Appl. Phys. Lett.*, vol. 56, pp. 318-320, 1990.

[10] K. J. Beernink, P. K. York, and J. J. Coleman, "Dependence of threshold current density on quantum well composition for strained-layer InGaAs-GaAs lasers by metalorganic chemical vapor deposition," *Appl. Phys. Lett.*, vol. 25, pp. 2582-2587, 1989.

[11] F. Stern, "Calculated spectral dependence of gain in excited GaAs," *J. Appl. Phys.*, vol. 47, pp. 5382-5386, 1976.

[12] J. Nagle, S. Hersee, M. Krakowski, T. Weil, and C. Weisbuch, "Threshold current of single-quantum-well lasers: The role of the confining layers," *Appl. Phys. Lett.*, vol. 49, pp. 1325-1327, 1986.

[13] S. H. Pan, H. Shen, Z. Hang, F. H. Pollak, W. Zhuang, Q. Xu, A. P. Roth, R. A. Nasut, C. Lacelle, and D. Morris, "Photorelectance study of narrow-well strained layer InGaAs/GaAs coupled quantum well structures," *Phys. Rev. B*, vol. 38, pp. 3375-3390, 1988.

[14] S. Y. Lin, C. T. Liu, D. C. Tsui, E. D. Jones, and L. R. Dawson, "Cyclotron resonance measurement of electron effective mass in strained AlGaAs/InGaAs/GaAs pseudomorphic structures," *Appl. Phys. Lett.*, vol. 55, pp. 666-668, 1989.

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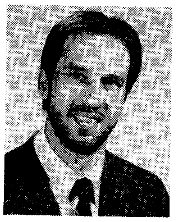

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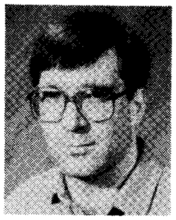

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K. K. Lee, photograph and biography not available at the time of publication.

R. G. Waters, photograph and biography not available at the time of publication.