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Switching Characteristics of Photoluminescence in AlGaAs SCH-QW Structure by Electric Field

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The dynamics of field-controlled luminescence intensity modulation on the quantum well structure have been studied with transient photoluminescence measurements. With a new technique, the field-induced radiative life time enhancement and field-induced carrier life time shortening are observed independently of each other. The intensity modulation with a constant carrier density in combination of radiative and nonradiative life times is demonstrated, suggesting a device applicability for a light emitter with a wide frequency range from DC to several GHz.

1 Introduction

Field effects on optical properties of GaAs/AlGaAs quantum well (QW) structures are of great interest in recent years because of their unique behaviour and their high speed switching capability. The device applications as well as the physics of the field effects have been investigated and reported by many authors[1-3]. Introducing the field effect, we have proposed the light emitting device in which the field-induced carrier separation instead of the change in the carrier density is made use of to modulate the light output intensity[1]. To understand the physics of the field effect and to demonstrate high speed switching capability, we have carried out the transient PL measurements on QW structures. As a result, we observed the field-induced carrier life time enhancement due to the carrier separation inside the QW[4] and high speed switching of PL by pulsed electric field[5].

In this report, we show the experimental results on transient PL measurements for an electric field at room temperature. With a new technique for evaluating the carrier life time, the field dependence of the radiative and nonradiative life times are separately observed. From the practical view point, the modulation scheme for consecutive pulse inputs is examined, demonstrating the modulation with a constant carrier density.

2 Experimental

Figure 1 shows the sample configuration used in the experiment. The undoped SCH-QW structure was sandwiched between p,n-$Al_{0.7}Ga_{0.3}As$ layers, forming a p-i-n diode. Carriers were excited in the QW by He-Ne laser beam (6328Å) focused to about 100μm in diameter on the sample surface. An electric field was applied across the QW by a pulsed voltage. The electric field was estimated to be zero with a forward voltage of 2V by

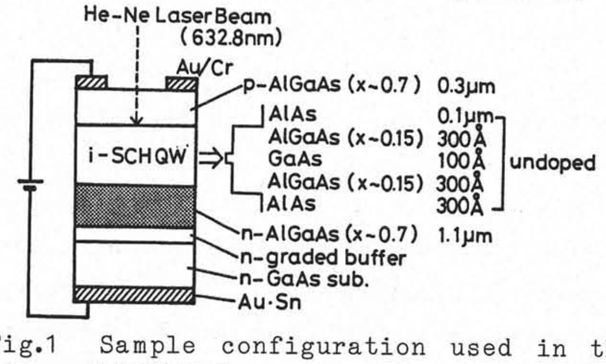

Fig.1 Sample configuration used in the experiment.

cancelling a built-in potential of a p-i-n diode and was strengthened with lower voltage or reverse voltage. The transient response of the PL intensity was detected by a high speed photomultiplier (Hamamatsu Photonics Co., Ltd. R1894 with a response time of 0.8ns), followed by amplifying with an amplifier (TOKO INC. ATH-3624) and averaged by a boxcar integrator (NF circuit block model BX-531/unit BP-10).

3 Field Dependence of Carrier Life Time

Evaluations of the field dependence of life time are based on the following simple rate equation;

$$dN/dt=G-N/\tau_r-N/\tau_{nr} \qquad (1)$$

where G is the constant carrier generation rate, N is the electron (or hole) density in the well, τ_r is the radiative life time which is a function of the electric field, and τ_{nr} is the nonradiative life time.

For the steplike increase in the electric field from E_ℓ to E_h at a time, t=0, one can expect a steplike increase in the τ_r from $\tau_{r\ell}$ to τ_{rh} due to the field-induced electron-hole separation inside the well. If the radiative processes dominate over nonradiative processes ($N/\tau_r >> N/\tau_{nr}$), the emission rate can be written as a function of time t[4],

$$N(t)/\tau_r(t)=G-G(1-\tau_{r\ell}/\tau_{rh})\exp(-t/\tau_{rh}) \quad (t\geqq 0)$$
$$=G \qquad (t\leqq 0) \qquad (2)$$

indicating a sudden decrease in the emission rate resulting from the change in the τ_r at t=0, followed by an exponential recovery resulting from increase in the carrier density and followed by an unchanged steady state emission rate G. Therefore, the radiative lifetime τ_{rh} for the applied field E_h can be determined from the recovery rate of the PL intensity. Figure 2 shows the observed transient responses for three bias conditions. The predicted responses are observed.

The field dependence of the carrier life time determined from the recovery rate is shown in Fig.3, denoted as "Overall Life Time". Obviously, the life time increase with increasing field at low field, while at higher field over $1x10^5$V/cm, it decrease with increasing field. The former increase in life time can be ascribed as the field-induced carrier separation inside the well. The latter decrease is due to the increase in nonradiative processes, since as denoted as "ΔIs", the steady state intensity at high field decreases from the level at zoro field, which must be equal if the radiative processes dominate over the nonradiative processes. Thus, the carrier life time at high field is expressed as $\tau_{overall}{}^{-1}=\tau_r{}^{-1}+\tau_{nr}{}^{-1}$. The similar result has been reported by Polland et al., who made use of the short pulse excitation method[6].

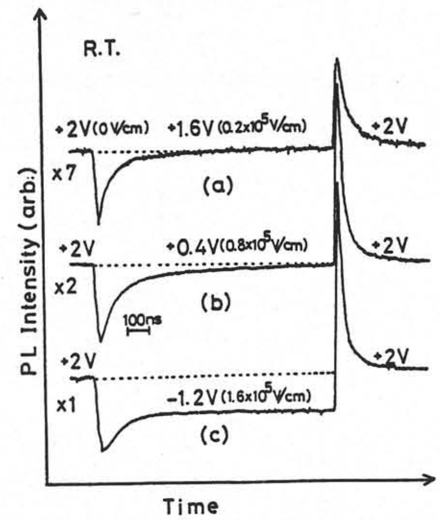

Fig.2 Transient responses of PL intensities for pulsed electric fields.

In discussing the field dependence of radiative life time, it is desirable to evaluate the radiative life time independently of the nonradiative life time. Returning to the previous rate equation, we examined the radiative life time. In eq.(2), at a time t=0, the PL intensity switches from G at low field E_ℓ to $G\tau_{r\ell}/\tau_{rh}$ at high field E_h. The ratio of these PL intensities is proportional to the ratio of the radiative life times. Thus the field dependence of radiative life time can be directly estimated from the PL intensity ratio. The resultant field dependence of radiative life time determined from the PL intencity ratio is shown denoted as "Radiative Life Time" in Fig.3. The absolute value of the radiative life time is determined with the value of the overall life time at low field, since, as discussed above concerning the steady state intensity, the nonradiative processes are negligible at low field. As is clearly shown, the two curves of life time coincide quite well with each other at low field, indicating that the radiative life time is dominant. On the other hand, at higher field over $1X10^5$V/cm, the overall life time decreases with increasing field, while the radiative life time still increases with increasing field. This difference is due to the nonradiative processes.

Figure 4 shows the field dependence of nonradiative factors; photocurrent, decrease in steady state intensity and nonradiative rate τ_{nr}^{-1} that is calculated with the obtained values as $\tau_{nr}^{-1}=\tau_{overall}^{-1}-\tau_r^{-1}$.

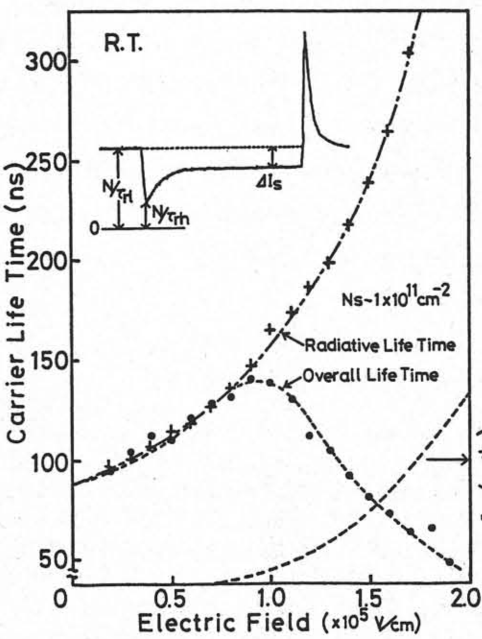

Fig.3 Observed field dependence of carrier life times. The curve denoted as "overall life time" was obtained from the recovery rate of PL intensity, and the curve denoted as "radiative life time" was obtained from the ratio of PL intensities at zero field ($N/\tau_{r\ell}$ in the inset) and at high field (N/τ_{rh}).

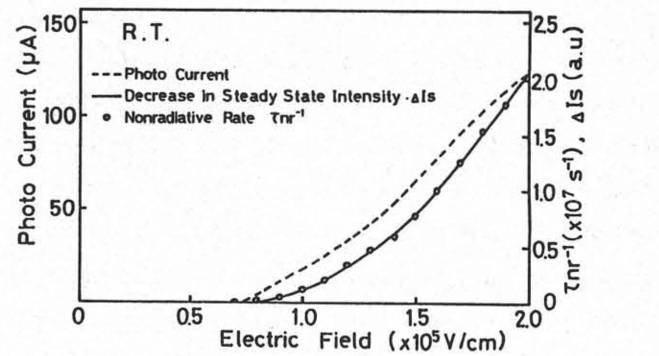

Fig.4 Field dependence of the nonradiative factors.

Since they show good agreement with each other, the field-induced life time shortening at high field can be attributed to the carrier leakage from the QW by electric field. Our results ensure that the radiative and the nonradiative can be evaluated separately and simultaneously in this measurement.

4 Modulation Scheme of PL intensity

Figure 5 shows our previous work on the PL response for a short electrical pulse on the MQW sample[5], showing the response time of about 300ps, much shorter than the carrier life time of 30ns observed in a similar experiment. This fact shows the high speed switching capability which is free from life time limitation. However, when the consecutive pulsed electric fields are applied under the condition that the radiative processes domi-

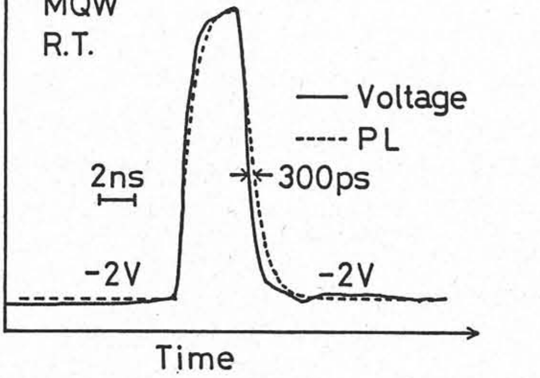

Fig.5 PL response for a short pulsed electric field on the MQW sample at room temperature. The delay of PL from the pulsed voltage was valued by subtracting the response time of the detection system from the observed PL response.

nate over nonradiative processes and the carrier generation rate is unchanged in the modulation, the response of PL intensity is degraded significantry with the influence of the change in carrier density as shown by trace(a) in Fig.6. In this case, after many input pulses are applied, the carrier density finally approaches to a value expressed as;

$$n_f = G\tau_{rh}\{1-(1-\tau_{r\ell}/\tau_{rh})\frac{1}{1+\frac{T_h}{T_\ell}\frac{\tau_{r\ell}}{\tau_{rh}}}\} \qquad (3)$$

where T_h and T_ℓ are the pulse widths of high field and low field. To maintain the PL response in the modulation, the carrier density must be unchanged. At high electric field where nonradiative processes dominate over radiative processes, the life time τ_{rh} in eq.(3) should be replaced by the overall life time $\tau_{overall}$. As shown in Fig.3, the overall life time at high field decreases to the value comparable to the life time at zero field. If the $\tau_{overall}$ at high field is equal to $\tau_{r\ell}$ in eq.(3), the carrier density is always kept unchanged so that the intensity modulation is brought about by the field-induced change in the radiative life time without changes in carrier density. Therefore, we can expect a completely life time free switching of PL intensity, independent of the width and repetition rate of the pulsed input voltages. This is an essential mind of the original proposal on field controlled light emitting devices[1]. The result of this modulation scheme is shown by trace(b) in Fig.6. A significant improvement in the PL intensity response is clearly shown.

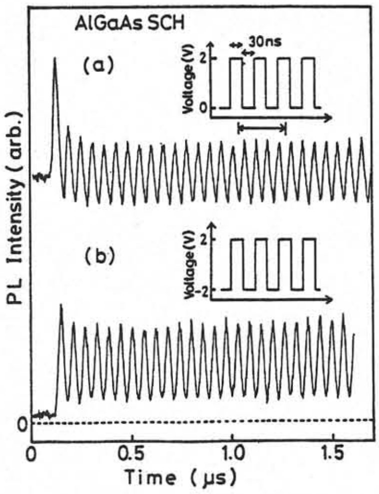

Fig.6 Transient PL responses for consecutive short electrical pulses.

5 Conclusion

In conclusion, we have carried out the transient PL measurements on the SCH-QW structure at room temperature to clarify the dynamics of intensity modulation by electric field. The field dependences of radiative life time and nonradiative life times have been separately observed with our method. And also by examining the relationship between radiative and nonradiative processes, the intensity modulation with a constant carrier density has been demonstrated. Recent development in fabrication of microstructures and new concepts on device geometry such as lateral current injection QW laser[7] convince us of the realization of the light emitter utilizing above mentioned field effect[1].

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