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Life Time-Free Switching of Luminescence from MQW Structures by Electric Fields

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Transient photoluminescence measurements for pulsed electric fields on a GaAs/AlAs multi-quantum well structure at room temperature have been carried out to demonstrate a fast switching of the luminescence intensities due to the field-induced change of the recombination life time of carriers. The very fast switching with a response of ~300ps much shorter than the life time of carriers is obtained. Moreover, field-controlled modulation schemes are discussed from the practical view points.

§1. Introduction

The switching speed of the light emitting devices is inevitably limited by the recombination life time as far as the change of carrier density is used to modulate light output intensity. A fast switching of the light intensity free from the life time limitation is attracting a great deal of practical interest in their application to integrated optics. Electric field effect on optical properties of the quantum well (QW) structure is one of the available phenomena resulting in a very high speed switching. External optical modulators using the field effect in QWs were proposed and the high speed operation of the devices were demonstrated.[1)-3)]

On the other hand, we have proposed the light emitting device[4),5)] with capability of high speed switching, making use of the field effect instead of the change in carrier density. So far, the photoluminescence (PL) measurements under the influence of the applied field were performed[6)-8)] to understand physics of the field effects. As a result of the transient responses of the PL intensities for pulsed electric fields at room temperature in the GaAs/$Al_{0.7}Ga_{0.3}As$ single-QW structures, the predicted increase in the recombination life time with increasing field was observed.[4)]

In this paper, we show experimental results on switching of luminescence intensities in GaAs/AlAs multi-QW (MQW) structures with pulsed electric field at room temperature. The transient characteristics for short pulsed voltages are observed to be free from life time limitation. Moreover, the field-controlled modulation schemes will be discussed from the practical view points. Fast modulation of light intensities with a pulse width of 5ps at a repetition frequency of 15GHz will be predicted theoretically.

§2. Sample Preparation

The PL measurements were performed using the sample configuration as shown in Fig.1. N-doped $Al_{0.7}Ga_{0.3}As$ (1.0μm), a 20 period undoped superlattice composed of alternate 100Å GaAs well and 300Å AlAs barrier, p-doped $Al_{0.7}Ga_{0.3}As$ (0.3μm) and p-doped GaAs contact layer were sequentially grown on an n-type GaAs substrate by moleqular

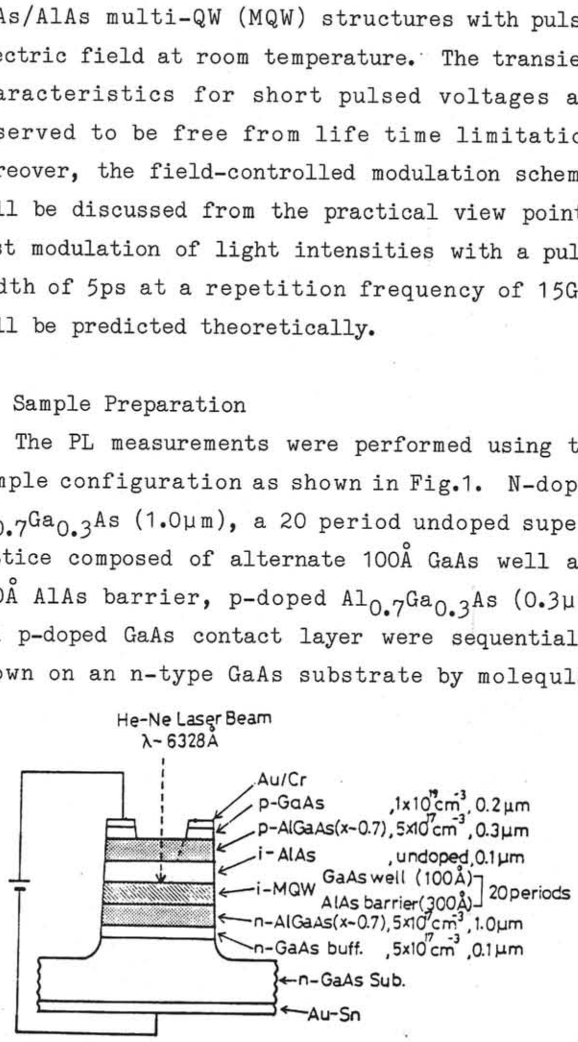

Fig.1 Sample configuration used in the experiments.

beam epitaxy technique. The couplings between the adjacent wells may be negligible in the MQW structure because of the thick AlAs barriers. The electric field across the MQW structure perpendicular to the well plane could be applied by reverse-biasing the effective p-i-n diode. The barrier height of the $Al_{0.7}Ga_{0.3}As$ or AlAs layers was enough high to prevent the carrier escaping out induced by the applied field. A $\sim$50μm diameter optical window was fabricated by selective etching of an opaque GaAs contact layer. The sample was defined by a mesa about 120μm in diameter, producing 3.0pF capacitance, which implies a CR time constant of 150ps when driven with a 50Ω source.

The GaAs wells were selectively pumped by a 6328Å He-Ne laser line through the optical window. The excitation power density was about $30W/cm^2$, giving an estimated carrier density of the order of $10^{17}cm^{-3}$.

§3. Experiments

Figure 2 shows the field-dependence of the recombination life time of carriers determined from the recovery time of the PL transient responses for long pulsed applied electric fields.[7] The life time increases with the increasing field, consistent with our previous works,[7),8] due to the field-induced reduction in the overlap between electron and hole wavefunctions inside the well.

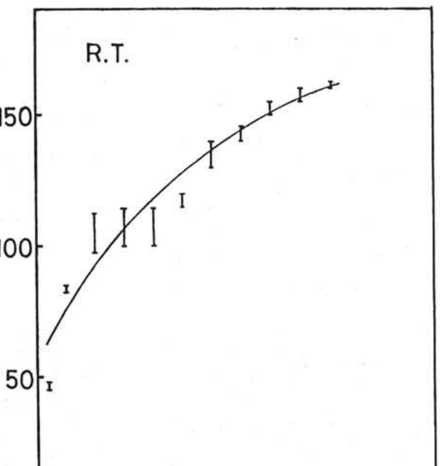

Fig.2 Field-dependence of the recombination life time of carriers.

The transient response of the PL intensity for a short electric pulse is shown in Fig.3. The luminescence intensity was detected with the photomultiplier (Hamamatsu Photonics Co. Ltd. R1894 with a response time of 0.8ns), followed by averaging with the boxcar integrator (NF Circuit Block, model BX-531/unit BP-12S) operating with a gate width of 75ps. In addition to the fast switch-on of the PL intensity with the application of a forward bias of 2V, where a built-in potential in the p-i-n structure was just canceled out, a forced quenching at the end of the short pulse (width of 3ns) was observed. The observed PL response time, including the response time of the detection system (0.9ns), was obtained to be 1.6ns. The switching time is obviously much shorter than the natural PL decay time (about 30ns) for the long pulse input, which was determined by the recombination life time.

The observed speed of the PL intensity was mainly limited by a response time of the photodetection system (0.9ns). A broken line in the figure shows the actual transient response of the PL intensity obtained with numerically subtracting off the response time of the detection system from the measured one. The response time of the PL intensity itself was deduced to be about 0.8ns, still including the rise (or fall) time of applied

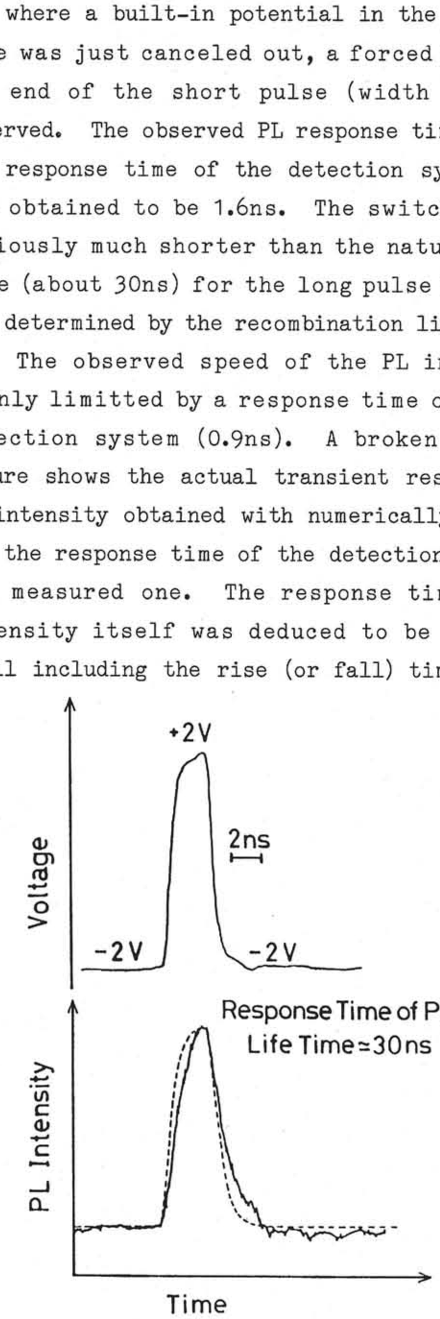

Fig.3 Transient response of the PL intensity for a short pulse voltage. Broken line shows the response of PL intensity itself, obtained by subtracting off the response of the detection system from measured one.

voltage pulse (about 0.5ns). The switching time of the PL intensity is supposed to be about 300ps which is close to a CR product of 150ps.

§4. Periodic Transient Response

The above-mentioned result means that a short input pulse of electric field can modulate luminescence intensity without life time limitation. In this section, the transient response of the luminescence intensity for consequtive pulse inputs is discussed within framework of the following rate equation ;

$$\frac{dn}{dt} = G - n/\tau_r \qquad (1)$$

where G is the generation rate for carriers which is assumed to be constant, n is the carrier density in the well and τ_r is the radiative recombination life time which is a function of the electric field. The periodic electric pulse modulating the luminescence intensity was assumed as shown in Fig.4. The lower and higher fields are alternately applied with widths of T_{rL} and T_{rH}, respectively.

Figure 5 shows an example of the calculated transient response for periodic electric pulses. The life times in low and high field states were assumed 150ns and 50ns, respectively, which are typical value in the present experiments. The decrease in light intensity for consequtive input pulses is caused by the decrease in carrier density as far as the generation rate is unchanged.

After N-times repetition of the modulation, carrier density n at $t=N(T_L+T_H)$ can be written by solving the equation (1) ;

$$n = G\tau_{rH}\,\{1-(1-\tau_{rL}/\tau_{rH})(1-e^{-T_L/\tau_{rL}}) \times \frac{e^{-T_H/\tau_{rH}}}{1-e^{-T_H/\tau_{rH}-T_L/\tau_{rL}}}\,(e^{-T_H/\tau_{rH}-T_L/\tau_{rL}})^N\} \qquad (2)$$

where τ_{rL} and τ_{rH} are the life times in the low and high field states, respectively. Assuming the sufficiently large N, $T_L/\tau_{rL} \ll 1$ and $T_H/\tau_{rH} \ll 1$, the carrier density finally approaches to the following value

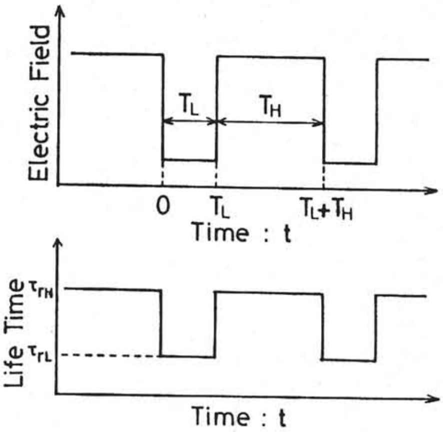

Fig.4 Schematic drawings of the periodic electrical pulses used in the calculation. The CR time constant is neglected in consideration. The lower drawing shows the postulated change of the life time due to the field effect.

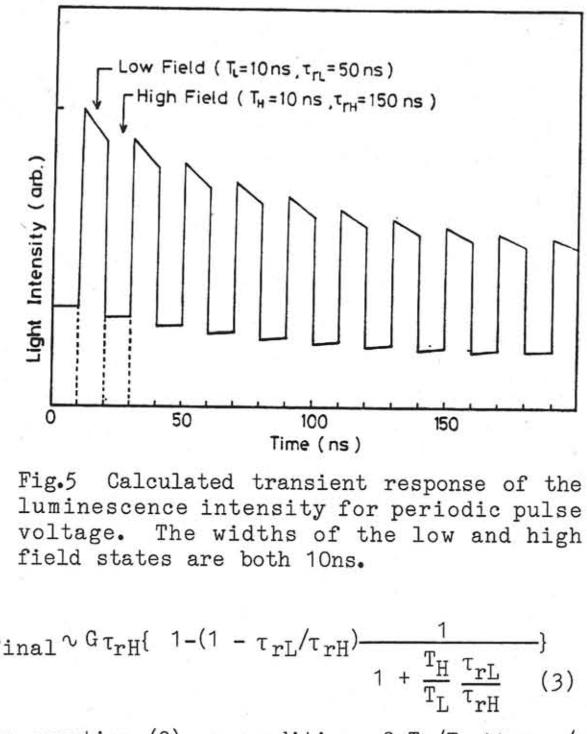

Fig.5 Calculated transient response of the luminescence intensity for periodic pulse voltage. The widths of the low and high field states are both 10ns.

$$n_{final} \sim G\tau_{rH}\{\,1-(1-\tau_{rL}/\tau_{rH})\frac{1}{1+\frac{T_H}{T_L}\frac{\tau_{rL}}{\tau_{rH}}}\} \qquad (3)$$

From equation (3), a condition of $T_H/T_L \gg \tau_{rH}/\tau_{rL}$ would minimize the reduction of the carrier density compared with the initial one ($=G\tau_{rH}$). This means that a short T_L and a long T_H is preferable as a practical modulation scheme. Figure 6 shows the calculated change of luminescence intensity for field-off time T_L of 5ps and field-on times of 25ps and 65ps, respectively. In both cases, the reductions of the luminescence intensity may be allowable as practical modulation scheme.

To test the above-mentioned scheme, we performed the preliminary measurements on transient responses of PL intensities for periodically applied electric pulses. Figure 7 shows the results. A drastic reduction of the PL intensity after a few repetitions of the optical pulse was observed in Fig.7(a). The pattern effect can be reduced by lengthening the interval of the voltage pulse as shown in Fig.7(b).

§5. Conclusion

Transient PL measurements for pulsed electric field on a GaAs/AlAs MQW structure at room temperature were carried out to demonstrate a fast switching of the luminescence intensity, free from life time limitation. The very fast switching with a response of ∿300ps much shorter than the life time of carriers was obtained. The switching time was essentially limited by a CR time constant and will be shortened more by reducing the sample capacitance. Moreover, a fast modulation scheme of the luminescence intensity with a short pulse width of 5ps at a repetition frequency of 15GHz was predicted theoretically. The results obtained here seem to promise us a realization of field controlled light emitting devices with a capability of ultra-fast switching.[4,5]

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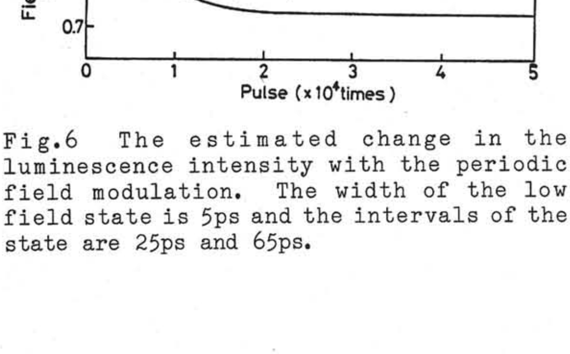

Fig.6 The estimated change in the luminescence intensity with the periodic field modulation. The width of the low field state is 5ps and the intervals of the state are 25ps and 65ps.

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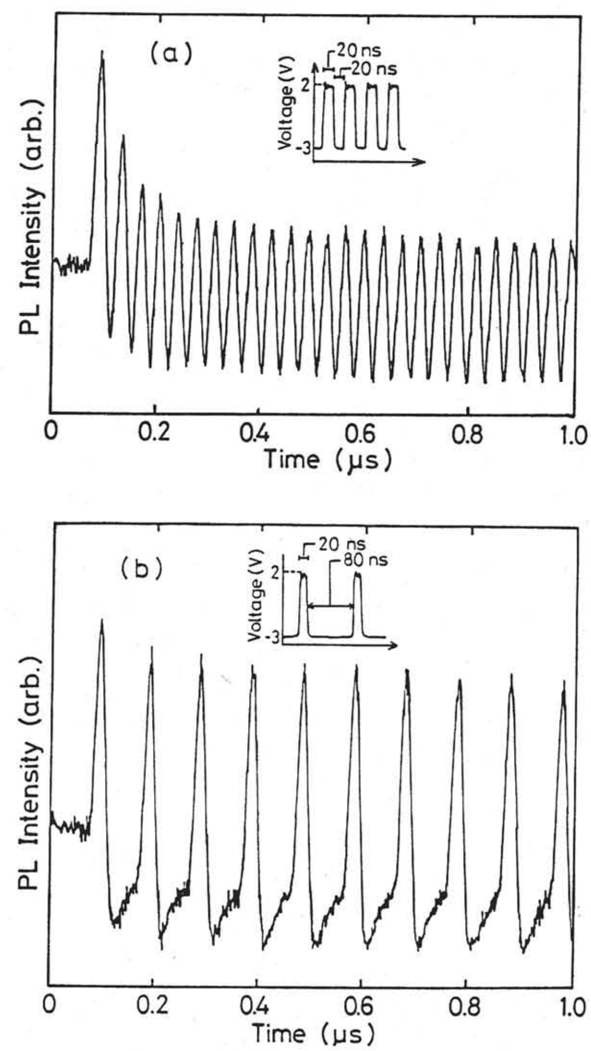

Fig.7 Observed periodic response of the PL intensity for 20ns width voltage pulse with repetition of 20ns (a) and 80ns (b). Boxcar integrator was operated with a gate width of 10ns to average the signal. Other detection system was same as that in Fig.3. The applied voltage pulses are also shown as inserts.