Improved recombination lifetime of photoexcited carriers in GaAs single quantum well heterostructures confined by GaAs/AlAs short-period superlattices

K. Fujiwara
Central Research Laboratory, Mitsubishi Electric Corporation, Amagasaki, Hyogo 661, Japan
A. Nakamura
Department of Applied Physics, Faculty of Engineering, Nagoya University, Nagoya 464, Japan
Y. Tokuda and T. Nakayama
Central Research Laboratory, Mitsubishi Electric Corporation, Amagasaki, Hyogo 661, Japan
M. Hirai
Department of Applied Physics, Faculty of Engineering, Tohoku University, Sendai 980, Japan

(Received 17 June 1986; accepted for publication 8 September 1986)

Photoluminescence (PL) decay time measurements at 77 and 300 K are reported from 6.1 nm GaAs single quantum well heterostructures (SQWH's) confined by GaAs/AlAs short-period superlattices (SPS's) or ternary AlGaAs alloys with similar Al content, prepared by molecular beam epitaxy. The SQW PL intensity exhibits a single exponential decay with a time constant of 1.6 ns for SQWH's confined by SPS's and 0.3 ns for SQWH's confined by AlGaAs alloys at 77 K. From comparison of the decay rates in both types of the sample, it is found that the radiative recombination efficiency is improved by a factor of about 6 in SPS confined SQWH's. This higher efficiency is attributed to the improved heterointerfaces in addition to the enhanced radiative recombination rate due to the increased overlap of electron and hole wave functions in the narrow SQW.

The decay time of photoluminescence (PL) in GaAs/AlGaAs quantum well (QW) heterostructures has recently received increasing attention. This is because in such a quasi-two-dimensional (2D) system, the dynamics of injected carriers are strongly altered, and attractive optical properties such as the high radiative recombination of electrons and holes due to the localization are expected for optoelectronic devices. Previous investigations,[1,2] however, have predominantly put emphasis on the studies of recombination processes at helium temperature. Only a few studies (mostly for multiple quantum wells, MQW's) are reported at room temperature and liquid-nitrogen temperature.[3–6]

In this letter, recombination lifetime measurements of photoexcited carriers in GaAs single quantum well heterostructures (SQWH's) confined by short-period superlattices (SPS's)[7] are reported at 77 and 300 K for the first time. In the present work we have investigated GaAs SQWH's with a well width of $L_Z = 6.1$ nm which are confined by all-binary GaAs/AlAs SPS layers with $L_Z = 3.4$ nm and a barrier layer thickness $L_B = 1.2$ nm and for comparison by ternary AlGaAs alloy layers with Al mole fraction of 0.24 [nearly equal to the average in the SPS, $L_B/(L_B + L_Z) = 0.26$]. By comparing both PL spectra and PL decay rates of two types of SQWH samples having the same well width, we have investigated origins of the higher efficiency of QW luminescence.

All the nominally undoped SQWH samples studied in this paper were grown on GaAs (100) substrates by molecular beam epitaxy (MBE) in a fully computer-controlled system. The growth was made in the following sequence: 0.2 μm GaAs buffer, 10 periods of 10 nm GaAs/10 nm $Al_{0.4}Ga_{0.6}As$ MQW buffer when necessary, 1.4 μm $Al_{0.4}Ga_{0.6}As$ lower cladding, 40 periods of the GaAs/AlAs SPS below and above the 6.1 nm GaAs SQW, and 0.2 μm $Al_{0.4}Ga_{0.6}As$ cap layers. Two similar SQWH samples with $Al_{0.24}Ga_{0.76}As$ confinement layers were also grown. PL decay times were measured by a time-correlated single photon counting method after about 10 ps pulse excitation by synchronously mode-locked dye laser (rhodamine 6G) at 613.4 nm. Photoexcitation was made in the weak excitation limit by defocusing the laser beam to 1–2 mm Φ at the sample surface.

Figure 1 shows PL spectra at 77 K for the two types of SQWH samples confined by (a) the GaAs/AlAs SPS layers and by (b) the AlGaAs alloy layers having the MQW buffer layer. The lowest heavy-hole related SQW transition (E_{1hh}^{SQW}) was observed at 1.612 eV in (a) and 1.574 eV in (b) while the MQW emission line (E_{1hh}^{MQW}) with a width of 3 meV was located at 1.550 eV in both spectra. Comparison of the two spectra clearly demonstrates that the SQWH confined by SPS exhibits superior emission efficiency to that confined by the ternary alloys and this is in agreement with the previous study at 2 K.[7] Furthermore, the PL intensity of the E_{1hh}^{SQW} transition in (a) was approximately four times higher than that of E_{1hh}^{SQW} in (b), while the PL intensity of the E_{1hh}^{MQW} transition was nearly the same for both samples. This proves that the observed difference between the spontaneous emission efficiencies of (a) and (b) is intrinsic to the heterostructure configurations that we designed. The observed large difference (38 meV) of the E_{1hh}^{SQW} transition energy between the two types of the SQW with $L_Z = 6.1$ nm is due to the use of different confinement layers, GaAs/AlAs SPS and AlGaAs alloy layers. A shoulder at 1.591 eV seen in Fig. 1(b) is due to the light-hole related transition (E_{1lh}^{SQW}). In

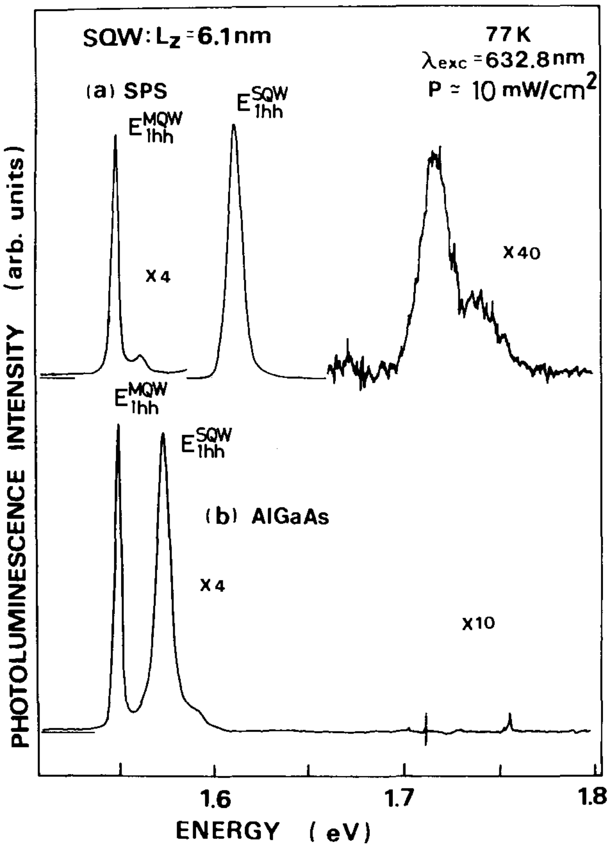

FIG. 1. 77 K photoluminescence spectra of two types of SQWH samples with (a) GaAs/AlAs SPS's and (b) $Al_{0.24}Ga_{0.76}As$ cladding layers both with MQW buffer.

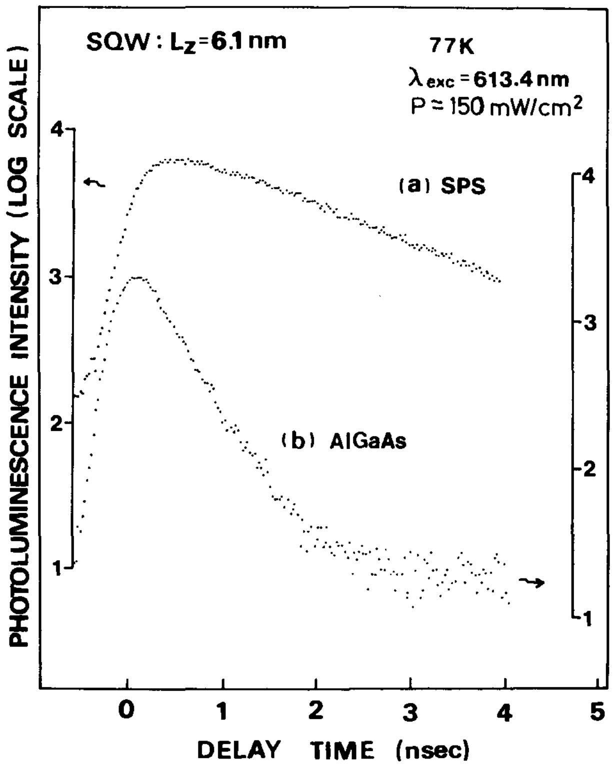

FIG. 2. Decay of the SQW photoluminescence intensity for two types of SQWH samples with (a) GaAs/AlAs SPS's and (b) $Al_{0.24}Ga_{0.76}As$ cladding layers both with MQW buffer.

the luminescence spectrum from the SPS layers, two peaks were observed at 1.717 and 1.739 eV. Measurements of the polarization dependence allowed us to assign them to the heavy-hole (E^{SPS}_{1hh}) and light-hole (E^{SPS}_{1lh}) related transitions for the SPS layers.[8] PL measurements for similar samples without MQW buffers showed the same trend between the two types of the SQWH. Therefore, $GaAs/Al_{0.4}Ga_{0.6}As$ MQW buffer layers have no effect on the improvement of SQWH epilayers in this case.

Figure 2 shows the decay of the E^{SQW}_{1hh} PL peak intensity (in log scale) for the two types of SQWH samples with the MQW buffer layer at 77 K. As shown in Fig. 2(a), the SQW PL intensity at 1.612 eV from the SPS confined SQWH exhibited a single exponential decay with a time constant of 1.6 ns. In the ternary AlGaAs confined SQWH, however, the decay time is 0.3 ns, which is much shorter than that of the SPS confined SQWH. The decay time of the E^{SQW}_{1hh} transition becomes 1.6 ns for the SPS confined SQWH sample without the MQW buffer. These experimental results directly indicate that a carrier lifetime in the SQW is significantly increased for the SPS confined SQWH with $L_Z = 6.1$ nm, suggesting the improvement in the radiative recombination efficiency if the observed decay times are determined by the nonradiative process. Decay measurements at the E^{SQW}_{1lh} transition and its high-energy tail revealed that the lifetime was constant across the spectrum. This indicates that free carriers in the heavy-hole and light-hole subbands are in thermal equilibrium. The time evolution of SQW PL intensity shows a rise time of about 0.3 ns in (a), whereas no rise time is observed in (b). This means that a majority of photoexcited carriers which recombine in the SQW are coming from the SPS layers by tunneling through the SPS layers. A detailed analysis of dynamics of the trapping processes into SQW will be reported elsewhere. The decay time of the E^{SQW}_{1hh} transition at 300 K was decreased to 1.2 ns for the SPS confined SQWH. A summary of the decay times for four SQWH samples is listed in Table I, together with the data for the MQW buffer layers. Decay times are 4–5 ns for the MQW with $L_Z = 10$ nm and independent of the types of the confinement layers. This demonstrates reproducibility of our

TABLE I. Decay times of SQW's ($L_Z = 6.1$ nm) and $GaAs/Al_{0.4}Ga_{0.6}As$ MQW's ($L_Z/L_B = 10$ nm/10 nm) photoluminescence intensity at 77 and 300 K.

			Decay times (ns)			
			SQW		MQW	
Sample	MQW	Clad	77 K	300 K	77 K	300 K
1	Yes	SPS GaAs/AlAs (3.4 nm/1.2 nm)	1.6	1.2	4	4
2	No	SPS GaAs/AlAs (3.4 nm/1.2 nm)	1.6	1.2	···	···
3	Yes	AlGaAs ($x = 0.24$)	0.3	0.3	5	4
4	No	AlGaAs ($x = 0.24$)	0.3	0.3	···	···

high quality MBE samples studied in this work, which is consistent with the time-integrated PL intensity measurements in Fig. 1.

Let us discuss the origin of the improvement in the radiative recombination efficiency from comparison of carrier lifetimes in the SQW between the two types of SQWH samples. Assuming that the carrier diffusion based phenomenological theory of the rate equation model[9] is still valid in quantum wells, we can introduce an effective interface recombination velocity S_{eff} for the heterointerfaces of the SPS confined SQWH. According to the definition of S_{eff} by Duggan *et al.*,[10] the minority-carrier lifetime τ_{mc} is written in the following equation:

$$\frac{1}{\tau_{\text{mc}}}=\frac{1}{\tau_r}+\frac{1}{\tau_{\text{nr}}}+\frac{2S_{\text{eff}}}{L_Z},$$

where τ_r is the radiative lifetime and τ_{nr} is the bulk nonradiative lifetime excluding the surface recombination process. It is reasonable to assume that the bulk nonradiative decay rate τ_{nr} in the GaAs well is negligibly small because of the high luminescence of the bulk undoped GaAs layer in the laser wafers. The quantum effect due to the localization of the electron and hole wave functions in the SQW should be almost the same for the two cases because of large conduction- and valence-band discontinuities. We further assume the SQW radiative recombination time τ_r of 6 ns at 77 for both samples.[3] Therefore, the observed decay times of 1.6 ns for the SPS confined SQWH and of 0.3 ns for the alloy confined SQWH give the values of S_{eff} of 140 and 970 cm/s, respectively. This reduced S_{eff} value resulted in the improved internal quantum efficiency η_i ($=\tau_{\text{mc}}/\tau_r$) as much as six times higher for the SPS confined SQWH. This is in agreement with the increase of the external PL efficiency observed in Fig. 1. This improvement in the internal quantum efficiency η_i does not strongly depend on the choice of the τ_r value. As shown in Table I, decay times of SQW's in the SPS confined SQWH's measured at 300 K slightly decrease (1.2 ns) while those in the alloy confined SQWH's do not change (0.3 ns). This weak temperature dependence confirms that the decay times are determined by the nonradiative process due to the interface recombination, which is larger in the alloy confined SQWH.

In summary, recombination lifetimes of carriers in 6.1 nm GaAs single quantum well heterostructures (SQWH's) confined by GaAs/AlAs short-period superlattices (SPS's) have been investigated by photoluminescence decay time measurements at 77 and 300 K. Intense QW photoluminescence at room temperature is attributed to the simultaneous realization of the reduced interface nonradiative recombination centers and the enhanced radiative recombination rate due to the increased overlap of electron and hole wave functions in the narrow SQW.

[1]E. O. Göbel, H. Jung, J. Kuhl, and K. Ploog, Phys. Rev. Lett. **51**, 1588 (1983); E. O. Göbel, J. Kuhl, and R. Hoger, J. Lumin. **30**, 541 (1985) and references therein.

[2]Y. Masumoto, S. Shionoya, and H. Kawaguchi, Phys. Rev. B **29**, 2324 (1984).

[3]P. Dawson, G. Duggan, H. I. Ralph, and K. Woodbridge, *Proceedings of International Conference on Physics of Semiconductors* (Springer, San Francisco, 1984), p. 551.

[4]B. Sermage, F. Alexandre, J. L. Lievin, R. Azoulay, M. El Kaim, H. Le Person, and J. Y. Marzin, Proceedings of the 15th International Conference on GaAs and related compounds, Biarritz, Inst. Phys. Conf. Ser. No. **74**, 345 (1984).

[5]J. E. Fouquet and A. E. Siegman, Appl. Phys. Lett. **46**, 280 (1985); J. E. Fouquet, A. E. Siegman, R. D. Burnham, and T. L. Paoli, Appl. Phys. Lett. **46**, 374 (1985).

[6]Y. Arakawa, H. Sakaki, M. Nishioka, J. Yoshino, and T. Kamiya, Appl. Phys. Lett. **46**, 519 (1985).

[7]K. Fujiwara and K. Ploog, Appl. Phys. Lett. **45**, 1222 (1984); K. Fujiwara, J. L. deMiguel, and K. Ploog, Jpn. J. Appl. Phys. **24**, L405 (1985).

[8]K. Fujiwara (unpublished).

[9]R. J. Nelson and R. G. Sobers, J. Appl. Phys. **49**, 6103 (1978).

[10]G. Duggan, H. I. Ralph, and R. J. Elliot, Solid State Commun. **56**, 17 (1985).