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Dynamical transport of photoexcited carriers between shallow and deep quantum wells embedded in a GaAs/AlAs superlattice

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Temperature dependence of the emission properties in a novel composite quantum-well-structure consisting of wide and narrow GaAs quantum wells (QWs) embedded in a GaAs/AlAs short-period superlattice (SPS) has been studied by steady-state and time-resolved photoluminescence (PL) measurements. At low temperature (~20 K), distinct PL peaks originating from the QWs and SPS are observed. When temperature is increased to 60 K, the PL intensity of the wide QW with deep confinement states significantly increases, while the ones of the narrow QW and the SPS gradually decrease. Above 100 K, however, the former PL intensity decreases and the latter ones increase. Temperature dependence of the measured PL decay behaviors directly evidences that the complex PL properties of the composite QWs are due to the interplay of the photoexcited carriers between the deep and shallow QWs by Bloch-type transport in the SPS.

Keywords: Vertical transport, Time-resolved photoluminescence, GaAs/AlAs superlattice

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1. Introduction

Transport of photoexcited carriers along the growth direction (i.e., vertical transport) has recently received considerable interest. In a short-period superlattice (SPS) with an enlarged single quantum well (SQW), photoexcited carriers are transported by Bloch conduction via extended states or by tunneling-assisted hopping conduction, being eventually trapped by the enlarged SQW. This phenomenon has been observed in steady-state and time-resolved photoluminescence (PL) experiments [1-6]. The previous experiments, however, were mostly performed at the fixed temperature (4.2 and 77 K) and the temperature dependence of the vertical carrier transport has not been investigated in detail.

In this work, we have investigated the vertical transport between two GaAs SQWs with wide and narrow well thicknesses embedded in a GaAs/AlAs SPS. The SQWs were intentionally designed so that the potential depth of confined states might be different with respect to miniband edges of the SPS barriers. We have performed steady-state and time-resolved PL measurements as a function of lattice temperature between 20 and 280 K. The PL intensities of the deep SQW, the shallow SQW and the SPS are strongly dependent on temperature. The temperature dependence of the PL intensity indicates that the tunneling efficiency strongly depends on temperature and the photoexcited carriers in the shallow SQW are transported to the deep SQW. Temperature evolution of the vertical transport between the deep and shallow SQWs embedded in the GaAs/AlAs SPS is directly evidenced by the time-resolved PL measurements.

2. Experimental

The sample studied here was grown on a GaAs (100) substrate by molecular beam epitaxy. The heterostructure consists of two GaAs SQWs with well widths of 7.8 nm (QW1) and 5.5 nm (QW2). The barriers are formed by 6 periods of a GaAs/AlAs (4.9 nm/1.0 nm) superlattice (SL1). The SQW layers are grown using 2-minutes growth interruption at the

GaAs well interfaces under arsenic beam flux. The whole system is put between a pair of another GaAs/AlAs (2.3 nm/1.0 nm) superlattice (SL2). Steady-state and time-resolved PL measurements were performed between 20 and 280 K in a closed-cycle He cryostat. The steady-state PL spectra were recorded using a cw He-Ne laser at 632.8 nm for excitation and a conventional lock-in technique for detection. The time-resolved PL measurements were performed with a streak-scope system. A laser diode with 52 ps pulses is used for excitation at 653 nm (1.90 eV). The time resolution of this system is about 200 ps.

3. Results and Discussion

Fig. 1 shows steady-state PL spectra of the sample measured at 20, 60, 140, and 200 K. The PL intensities are normalized to the maximum peak in each PL spectrum. In the top PL spectrum measured at 20 K, the PL peaks originating from QW1 (1.59 eV) and QW2 (1.64 eV) as well as from SL1 (1.66 eV) and SL2 (1.89 eV) are identified. The split PL structures with an energy separation of 8 meV are observed for QW2 due to the formation of the growth island terraces [7]. When temperature is increased, the PL peaks shift to low energy side according to Varshni empirical relation: $E(T) = E(0) - \alpha T^2 / (\beta + T)$, where $E(0)$ is the transition energy at 0 K, and α and β are Varshni thermal coefficients, whose values are close to those found in the literature for GaAs [8]. At temperatures above 140 K, the PL peaks due to the light-hole exciton also appear on the high-energy side of the respective heavy-hole exciton peaks.

The important point to note is that the PL intensity distribution shows the complicated temperature behaviors. For the temperature regime from 20 K to 60 K, the PL intensity of QW1 (I_{QW1}) increases with increasing temperature, while the ones of QW2 (I_{QW2}) and SL1 (I_{SL1}) gradually decrease. At temperatures above 100 K, QW2 and SL1 recover their PL intensity. That is, the intensity ratio of I_{QW1}/I_t ($I_t = I_{QW1} + I_{QW2} + I_{SL1}$) increases with increasing temperature below 60 K and decreases above 100 K, while I_{QW2}/I_t and I_{SL1}/I_t decease below 60 K and increase above 100 K, as is shown in the inset of Fig.1. The observations below 60 K indicate that both of transporting the carriers from QW2 (shallow SQW) to QW1 (deep SQW) and sinking the photoexcited carriers from SL1 into QW1 are occuring through the miniband transport of SL1.

In order to obtain additional information about the carrier transport dynamics, we have measured time-resolved PL spectra at several temperatures between 20 and 280 K. Figs 2 (a), (b) and (c) show the spectrally integrated PL transients recorded at 20, 60, and 140 K, respectively, which are plotted on a semi-logarithmic scale. At 20 K, the PL transients of QW1, QW2, and SL1 show the exponential time decays with two components. The fast decay in QW1 and QW2 is due to the recombination of free excitons, while the slow decay is due to that of bound excitons. The decay times of free excitons in each layer are measured to be 0.9 ns for QW1, 1.2 ns for QW2, and 0.6 ns for SL1, respectively. When temperature is increased to 60 K, the bound excitons are delocalized, so that the PL transients can show single exponential time decays. The decay time of QW1 increases to 2.4 ns, while those of QW2 and SL1 decrease to 180 ps and 160 ps, respectively. At 140 K, the decay times of QW2 and SL1 suddenly increase to 11 ns and 17 ns, respectively, while that of QW1 is further increased to 31 ns. The decay times of each layer as a function of temperature are shown in Fig. 3.

The decay time of QW1 increases with increasing temperature below 180 K. This behavior can be understood by considering the fraction of excitons within the finite energy width of radiative recombination [9, 10], which is varied by temperature. At further higher temperatures, the decay time of QW1 decreases from 36 ns at 180 K to 8.3 ns at 280 K. This reduction of the decay time is due to the enhancement of the nonradiative recombination processes. On the other hand, the decay times of QW2 and SL1 gradually decreases with increasing temperature below 80 K. As a result, the transport time in the SPS becomes faster with increasing temperature. At 140 K, however, the decay times of QW2 and SL1 suddenly become long as much as that of QW1, as shown in Fig. 2 (c), and decreases with increasing temperature above 180 K, similar to that of QW1.

The temperature evolutions of the PL transient and the PL intensity indicate the following processes as shown in Fig. 4. The photoexcited carriers in SL1 partly recombine radiatively there, but most of them vertically transport by Bloch conduction via the extended miniband states, until they relax into QW1 and QW2, where they radiatively recombine in each well. Since the transport time is faster than the radiative recombination lifetime, the PL decay time of SL1 is mainly determined by the transport processes, which strongly depend on the barrier thickness of the superlattices [6]. In the low temperature regime below 80 K [cf. Fig.4 (a)], the carriers in QW2 (shallow SQW) are thermally activated into the miniband of SL1 because of their shallower potential depth than the thermal energy. Then, they relax quickly into QW1 (deep SQW) during moving across the SL1 before the radiative recombination can occur with in SL1. In this case, the PL decay time of QW2 is determined by the combination of the radiative recombination, relaxation and detrapping processes. The detrapping process is strongly affected by the thermal activation and the transport processes. Actually, the PL intensity of QW1 increases due to the vertical transport from QW2 to QW1, which is evidenced by the reduction of the PL decay times of QW2 and SL1 with increasing temperature. In the temperature regime above 140 K [cf. Fig. 4 (b)], the carriers in QW1 can also be thermally excited into the miniband of SL1. The carrier relaxation from SL1 to QW1 is effectively restrained by the detrapping processes, so that the decay time of SL1 suddenly increased.

4. Conclusions

In summary, the dynamical transport of photoexcited carriers between shallow and deep SQWs embedded in a GaAs/AlAs SPS has been investigated by steady-state and time-resolved PL experiments for a wide lattice temperature range between 20 and 280 K. The temperature evolutions of the PL intensity and the PL decay time directly evidence that the interplay of photoexcited carriers between the shallow and the deep SQWs as a function of temperature is determined by trapping and thermal detrapping processes mediated by Bloch-type miniband conduction across the SPS.

References

[1] A. Nakamura, K. Fujiwara, Y. Tokuda, T. Nakayama, H. Hirai, Phys. Rev. B 34 (1986) 9019.

[2] A. Chomette, B. Deveaud, J. Y. Emery, A. Regreny, B. Lambert, Solid State Commun. 54 (1985) 75.

[3] B. Deveaud, A. Chomette, B. Lambert, A. Regreny, Phys. Rev. B 34 (1986) 9010.

[4] A. Chomette, B. Deveaud, A. Regreny, G. Bastard, Phys. Rev. Lett. 57 (1986) 1464.

[5] K. Fujiwara, J. L. de Miguel, K. Ploog, Jpn. J. Appl. Phys. Pt. 2 24 (1985) L405.

[6] K. Fujiwara, N. Tsukada, T. Nakayama, A. Nakamura, Phys. Rev. B 40 (1989) 1096.

[7] K. Fujiwara, U. Jahn, R. Hey, J. Kastrup, H. T. Grahn, J. Menniger, J. Cryst. Growth 150 (1995) 43.

[8] H. C. Casey, M. B. Panish, in: Heterostructure Lasers (Academic, New York, 1978), pt. A.

[9] J. Feldmann, G. Peter, E. O Gögel, P. Dawson, K. Moore, C. Foxon, Phys. Rev. Lett. 59 (1987) 2337.

[10] G. W. 't Hooft, W. A. J. van der Poel, L. W. Molenkamp, C. T. Foxon, Phys. Rev. B 35 (1987) 8281.

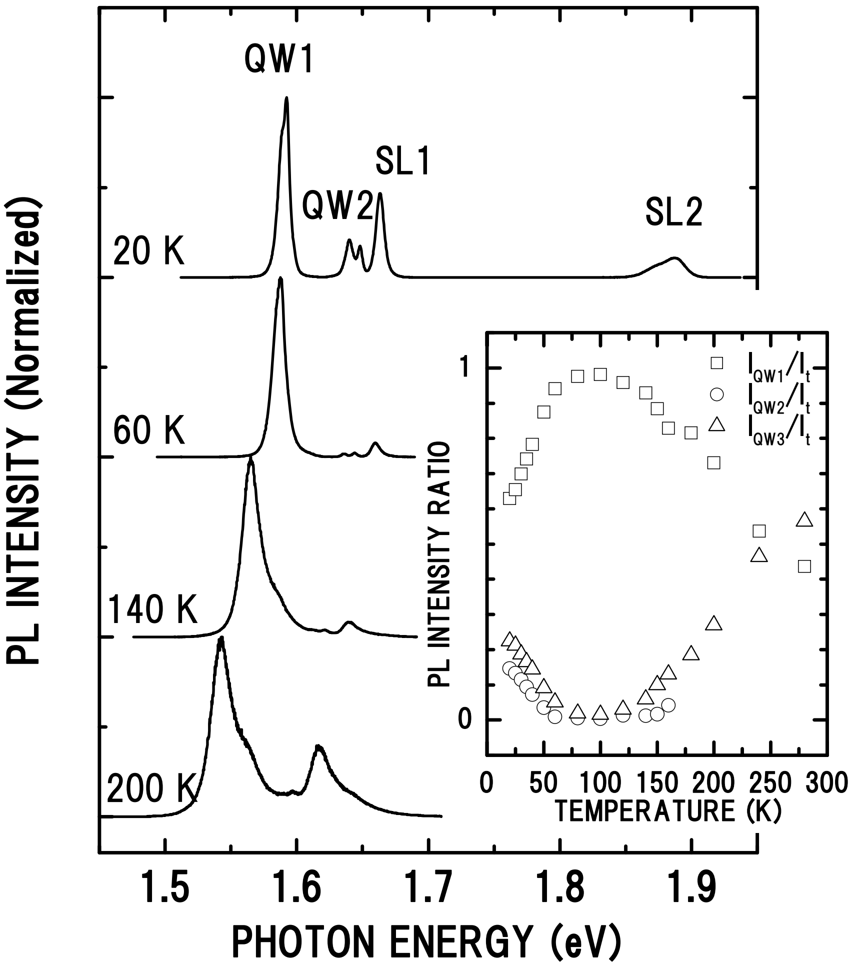
Figure captions

Fig. 1 Temperature dependence of cw PL spectra of the sample. The spectra are normalized to the maximum peak intensity in each spectrum, and are plotted to the scale with offset. The inset shows the PL intensity ratios of QW1, QW2 and SL1 to the total PL intensity as a function of temperature.

Fig. 2 PL transients for QW1, QW2 and SL1 as a function of time measured at 20 (a), 60 K (b) and 140 K (c). The time resolution of the measurements is about 200 ps.

Fig. 3 PL decay times of QW1 (open squares), QW2 (open circles) and SL1 (open triangles) as a function of temperature.

Fig. 4 Schematic diagrams for vertical transport between shallow and deep SQWs at lattice temperatures from 40 to 80 K (top), and above 140 K (bottom).



QW1
SL1
QW2
SL2
20 K
60 K
140 K
200 K
PL INTENSITY (Normalized)
1.5
1.6
1.7
1.8
1.9
PHOTON ENERGY (eV)
PL INTENSITY RATIO
TEMPERATURE (K)

Fig. 1

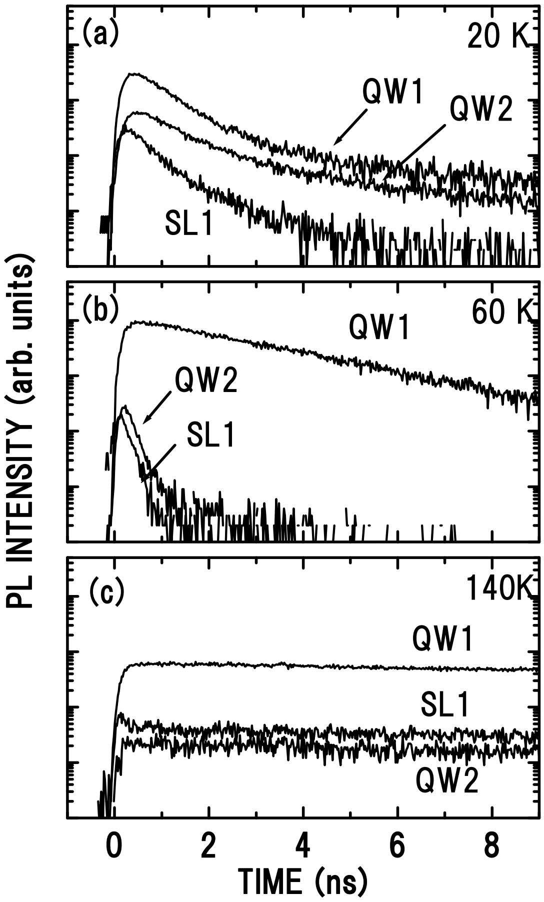
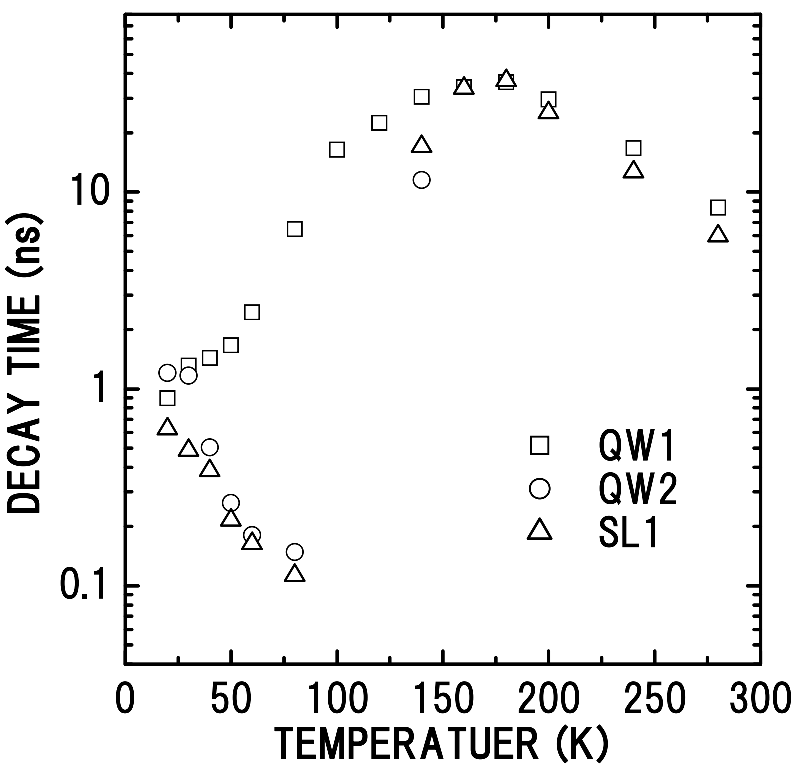

(a)
20 K
QW1
QW2
SL1
(b)
60 K
QW1
QW2
SL1
(c)
140K
QW1
SL1
QW2
PL INTENSITY (arb. units)
0
2
4
6
8
TIME (ns)

Fig. 2



DECAY TIME (ns)
10
1
0.1
0
50
100
150
200
250
300
TEMPERATUER (K)
QW1
QW2
SL1

Fig. 3

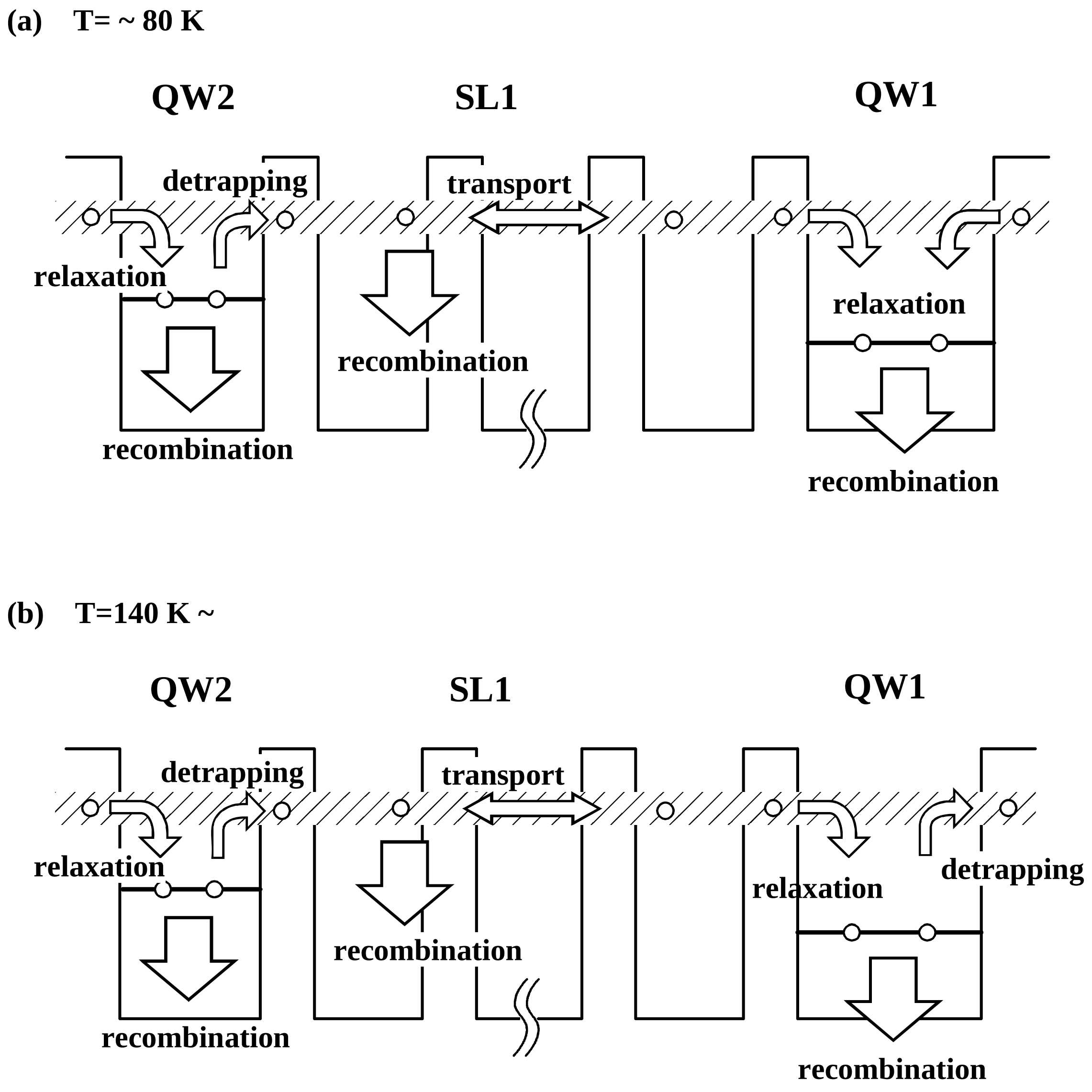

(a) T= ~ 80 K
QW2
SL1
QW1
detrapping
transport
relaxation
relaxation
recombination
recombination
recombination
(b) T=140 K ~
QW2
SL1
QW1
detrapping
transport
relaxation
relaxation
detrapping
recombination
recombination
recombination

Fig. 4