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AlAs/GaAs Disordered Superlattices

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AlAs/GaAs disordered superlattice, a kind of disordered crystalline semiconductor we have proposed, exhibits optical properties quite different from the $Al_{0.5}Ga_{0.5}As$ bulk alloy and the $(AlAs)_2(GaAs)_2$ ordered superlattice. The photoluminescence intensity of the disordered superlattice is about 10^3 times stronger than those of two other materials at 77K. The optical absorption edge of the disordered superlattice shifts to a long wavelength side, and a short decay time is observed in time-resolved photoluminescence measurement. Based on these experimental results, radiation recombination process in the disordered superlattice is suggested.

1. INTRODUCTION

Luminescence capability of the indirect-gap semiconductor is inferior to that of the direct-gap semiconductor. A shorter wavelength in a visible region is hardly radiated at room temperature from III-V semiconductors with a wide band gap, e.g., AlP and AlAs.

Amorphous semiconductors exhibit luminescence capability superior to single-crystal semiconductors.[1,2] Microparticles of a semiconducting material show a high quantum efficiency of luminescence. It has been considered possible, because the microparticle would be a kind of quantum dot in which an energy band structure is altered from a composite semiconducting material. However, epitaxial growth which is very often required for device fabrication is not possible on an amorphous substrate nor on microparticles.

In this paper, we describe AlAs/GaAs disordered superlattice (d-SL), a kind of disordered crystalline semiconductor we have proposed.[3] The d-SL exhibits a remarkable photoluminescence capability as compared with those of the $Al_{0.5}Ga_{0.5}As$ bulk alloy (b-AL) and the $(AlAs)_2(GaAs)_2$ ordered superlattice (o-SL). A single-crystal layer can be grown epitaxially on the d-SL. Experimental results of the optical absorption and the time-resolved photoluminescence are presented. Radiation recombination process is suggested based on these experiments.

2. DISORDERED CRYSTALLINE SEMICONDUCTOR

A new semiconducting material called as a disordered crystalline semiconductor is constructed either naturally or artificially so that chemical composition is disordered but physical arrangement is sufficiently ordered enough for epitaxial growth to be possible. Examples of disorder in the chemical composition are given, and their schematic energy band structures are shown in Fig.1.

(i) AlAs and GaAs layers appear alternately with an equal width in an ordinary superlattice. Disordered variations in individu-

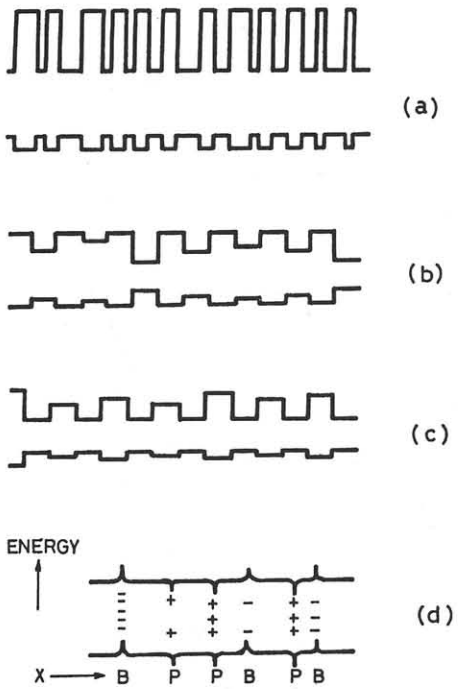

Fig.1. Disordered superlattices: examples of disordered crystalline semiconductor.

al widths can be introduced along the growth direction as shown in Fig.1(a).

(ii) The disorder in composition can be realized by changing composite composition in a conventional superlattice, e.g., the aluminum composition x either in the $AlAs/Al_xGa_{1-x}As$ superlattice or in the $Al_xGa_{1-x}As/GaAs$ superlattice, as shown in Figs.1(b) and (c).

(iii) The disorder in composition is also realized by the impurity doped with δ-doping technique. The impurity is doped with the varied intermittent periods and/or the amount of impurity doping is disorderly varied from a doped layer to the other, as shown in Fig.1(d).

(iv) Disordered variations in area, composite composition, and/or impurity doping can be made in a plane layer perpendicular to the growth direction.

(v) Disordered variations described from (i) to (iv) can be combined to fabricate a disordered crystalline material. An example of the ultimate structure is a semiconductor in which GaAs quantum dots exist in a AlAs bulk material as shown in Fig.2.

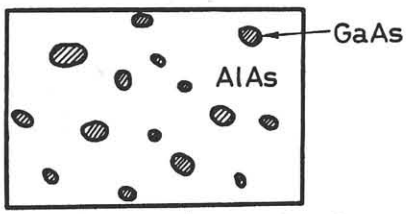

Fig.2. An example of disordered crystalline semiconductor.

3. SAMPLE PREPARATION

Three samples of different structures were prepared by molecular beam epitaxy and their specifications are summarized in Table I. GaAs buffer layer of 0.3 μm-thickness was grown on a (100)-oriented GaAs substrate and then the sample layer was grown at 600°C over the buffer layer. In the d-SL, AlAs and GaAs layers are prepared alternately with an equal probability of appearance of m,n=1,2, and 3, i.e., P(1)=P(2)=P(3)=1/3. A portion of the sample structure can be seen in Fig.1(a).

Table I. Sample specifications

SAMPLE	THICKNESS
b-AL $Al_{0.5}Ga_{0.5}As$	1.0 μm
o-SL $(AlAs)_2(GaAs)_2$	0.34 μm
d-SL $(AlAs)_m(GaAs)_n$ m,n=1,2,3	0.34 μm

All three samples prepared for the experiments have equal macroscopic composition, i.e., the aluminum composition x=0.5, but their microscopic structures are different. The micro-Raman spectra were measured.* Two phonon peaks which would be identified as the GaAs-like and the AlAs-

* The experiments were carried out by Dr. M.Ichimura, Nagoya Institute of Technology.

like LO phonons were observed. The full width at half maximum of the d-SL is about two to three times wider than those of the b-AL and the o-SL. The results suggest microscopic disordered lattice alignment in the d-SL.

4. OPTICAL PROPERTIES

Photoluminescence(PL) spectra were measured at 77K by exciting the samples with an Ar-ion laser of 0.5W and the results are shown in Fig.3. The PL intensity ratios of the d-SL to the b-AL and the o-SL are about 2×10^3 and 3×10^3, respectively. The intensity was measured at main peak, although the spectra of the b-AL and the o-SL are very broad. The main peak of the d-SL shifts to a longer wavelength side, i.e., the red shift, relative to those of the b-AL and the o-SL, as can be seen in Fig.3. The values of the intensity ratio would not be taken rigorously as they are. They are greatly dependent on the PL of the b-AL and the o-SL, since the spectra are very weak and broad. However, it is certainly stated that the luminescence capability can be remarkably improved by artificial disordering.

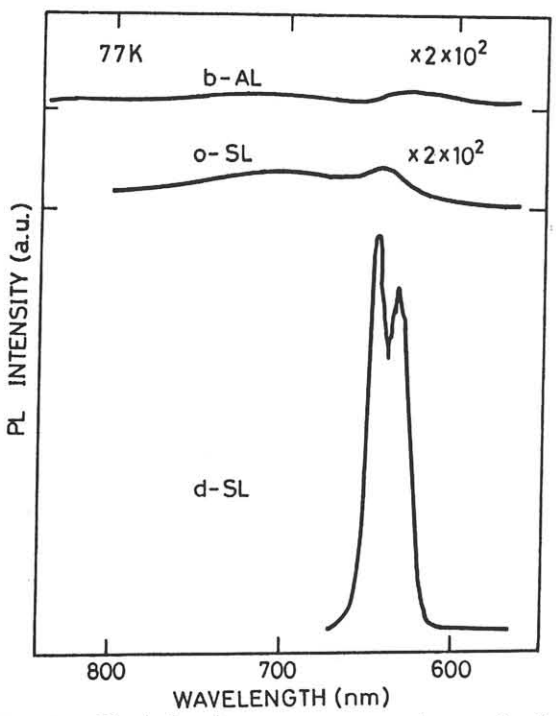

Fig.3. Photoluminescence spectra of three samples.

The optical absorption was measured at 7K. The results are shown in Fig.4[4] where the PL spectra at 4.2K are also drawn. The PL peak energies of the b-AL and the o-SL appear lower than the absorption edge. The phonon emissions occur in both processes of the photon absorption and emission, since the band gap is indirect and the number of phonons is quite small at low temperature. The energy difference is estimated to be twice as much as a phonon energy,[5,6] 72(36x2)meV for two GaAs-like LO phonons, 100(50x2)meV for two AlAs-like LO phonons, and 86(36+50)meV for the sum of each one phonon. In measurements, the energy differences are 80meV for the b-AL and 110meV for the o-SL. On the other hand, the absorption edge energy of the d-SL extends below the edges of the b-AL and the o-SL. The PL of the d-SL appears in the extended energy range: it suggests that the phonon assist is not required in the recombination process in the d-SL.

The time-resolved photoluminescence was investigated at 77K, and the results are given in Fig.5. The relaxation time constants of the b-AL with the indirect gap and the o-SL are about 10ns, and that of the b-AL with the direct gap is about 0.1ns. The d-SL exhibits the intermediate

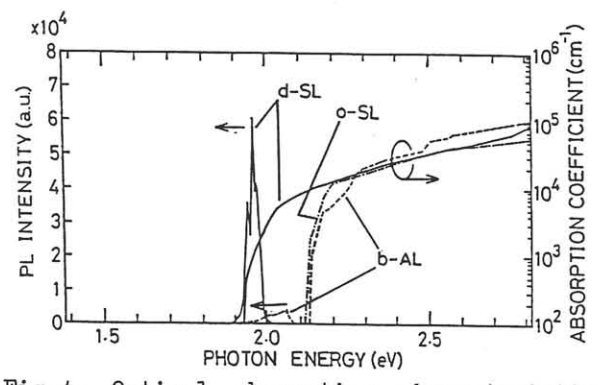

Fig.4. Optical absorption characteristics and photoluminescence spectra.

value, i.e., about 1ns, as compared with other materials. The recombination occurs very slowly in the indirect b-AL and the o-SL, because it requires the phonon assist. However, the recombination occurs very quickly in the direct b-AL, because of the direct transition.

5. RADIATION RECOMBINATION PROCESS

The investigations of the optical absorption and the time-resolved photoluminescence suggest that the radiation recombination process in the d-SL does not require the phonon assist to satisfy the momentum conservation. It can be stated that the requirement of the momentum conservation is relaxed in the d-SL.

It can be interpreted as that the artificial disordering creates localized states such as Anderson's localized state[7]. Due to the uncertainty principle $\Delta\bar{r}\cdot\Delta\bar{p} \geq \hbar/2$, the localization implies $\Delta\bar{r}$ smaller. It causes the momentum ambiguity $\Delta\bar{p}$ larger. Even if the band gap is indirect, the radiation recombination becomes possible without the phonon assist. The recombination process can be considered similar to the process through the isoelectronic trap. Further study is continued to interpret definitely the luminescence capability in the d-SL.

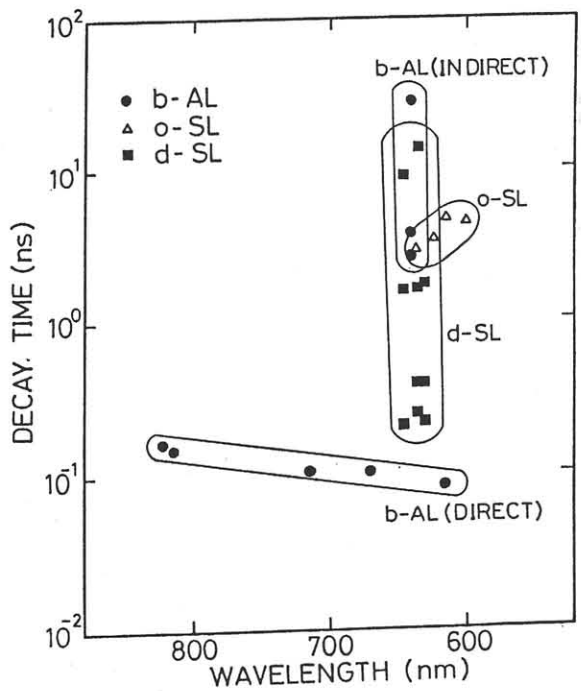

Fig.5. Decay times in time-resolved photoluminescence.

6. SUMMARY

The new concept of a disordered crystalline semiconductor has been introduced, and examples have been described. It is experimentally confirmed that AlAs/GaAs disordered superlattice, a kind of disordered crystalline semiconductor, exhibits remarkable luminescence capability. Based on the investigation of the optical absorption and the time-resolved photoluminescence, it has been understood that the improvement in luminescence capability would be due to localized states created by artificial disordering.

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