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Time-resolved photoluminescence study of InGaAs/GaAs quantum wells on (111)B GaAs substrates☆

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Abstract

The exciton dynamics in $In_{0.15}Ga_{0.85}As$/GaAs quantum wells grown on (111)B and (100) GaAs substrates are studied by the time-resolved photoluminescence (PL). We have found that the piezoelectric fields in (111)B samples affect the transient behavior of PL spectra. Compared with the reference (100) samples, we have confirmed that the piezoelectric effect induces slower exciton relaxation in (111)B strained quantum wells. © 1999 Elsevier Science Ltd. All rights reserved.

In recent years, studies of epitaxial layers on (111)B GaAs substrates increased rapidly. One of the most interesting characteristics in such layers is the piezoelectric effect caused by the strain layers on GaAs substrates of this direction [1]. A lot of works have been devoted to the growth of the strain quantum wells and the study of piezoelectric fields [2–5]. However, there are still very few studies on the carrier-dynamic of the strain quantum wells under strong piezoelectric fields. The carrier dynamics of quantum structures is important in many applications, especially in optoelectronic devices. In this work, we found some unique dynamic behaviors in (111)B InGaAs/GaAs quantum wells which might be related to the piezoelectric effect. We have measured time-resolved photoluminescence (PL) of samples with two InGaAs/GaAs quantum wells on both (111)B and (100) GaAs substrates, grown side by side.

The structures we used are two $In_{0.15}Ga_{0.85}As$/GaAs quantum wells, separated by a 150 nm GaAs space layer and capped by a 50 nm GaAs layer. The well widths are 2 nm and 3 nm. There are two kinds of arrangement: structure A is with the 3 nm quantum well above the 2 nm quantum well, and structure B is with the 2 nm quantum well above the 3 nm quantum well. We use QWA and QWB to represent these two kind of structures. Both structures were grown by molecular beam epitaxy on (111)B and (100) GaAs substrates placed side by side in the chamber. We labeled these four samples as QWA_0, QWA_1, QWB_0 and QWB_1, with index ‘‘0’’ representing (100) samples, and ‘‘1’’ for (111)B samples. The GaAs layers were grown at 590°C and the InGaAs layers were grown at 525°C. The samples were excited by an amplified mode locked Titanium Sapphire laser from Spectra Physics with the laser energy at 3.1 eV. The time-resolved PL spectra were measured by a Hamamatsu streak camera C4334 with a time resolution of 5 ps. The measurements were performed at 4.2 K.

The PL intensity versus wavelength and time both were obtained at the same time. One example of the measured results is shown in Fig. 1. We can integrate the data over the exciton lifetime to get an ordinary PL spectra, or integrate over a short range of wavelength to get the transient behavior in that wavelength range. Figs. 2 and 3 show the integrated results of the structure B samples. Fig. 2 is the time-integrated PL spectrum, while Fig. 3 is the transient behavior which is the wavelength-integrated result over the range of each peak shown in the spectra of Fig. 2. In order to distinguish the eight quantum wells of four samples more clearly, the quantum wells were labeled QWA_{0t}, QWA_{0b}, QWA_{1t}, QWA_{1b}, QWB_{0t}, QWB_{0b}, QWB_{1t} and QWB_{1b}, where the second index, ‘‘t’’ represents the top quantum wells, and ‘‘b’’ is for the bottom quantum wells. In those PL spectra, the peaks at the shorter wavelength side are from the 2 nm quantum wells, while those at longer wavelengths are from the 3 nm quantum wells. All the peaks show strong intensity with linewidth no larger than 5 meV, indicating

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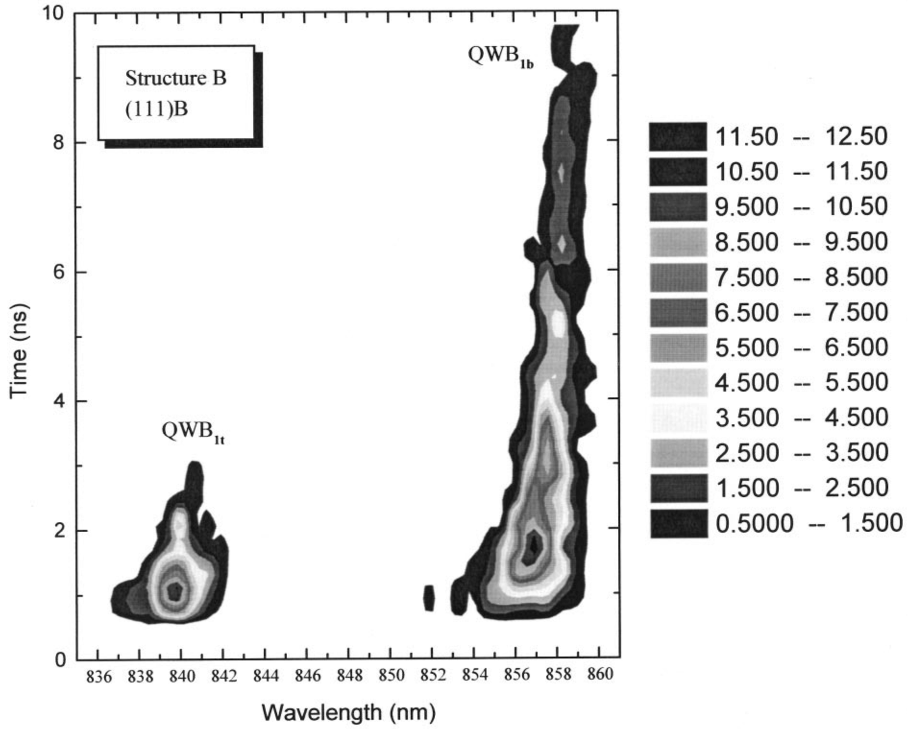

Fig. 1. One example of the measured results on the (111)B sample of structure B. The PL intensity versus wavelength and time both were shown at the same time.

good sample quality. However, in Fig. 3, the dynamic behaviors of the two quantum wells show significant differences in (111)B samples. Obviously, the rise and decay time depends on the position of the quantum well. The fitted decay time constants of peaks from all quantum wells are listed in Table 1. For the quantum wells near surface, the decay time constants are around 500 ps, while the time constants of the quantum well beneath are well above 1 ns. For the (100) samples of the same structures, which were grown at the same time, the decay time differences are much smaller.

There are several possible mechanisms could be involved in the dynamic behaviors observed. The first mechanism is carrier diffusion. The incident laser energy we used for the PL measurement is 3.1 eV. The absorption coefficient of GaAs at this energy is around 10^5 cm^{-1}. Therefore, the number of carriers excited in GaAs decreases a lot at the location more than 100 nm away from surface. Many carriers diffused toward the bottom quantum wells and were captured. This mechanism is called ‘‘vertical ambipolar transport’’ [6] and exists in both (100) and (111)B samples. We considered it as the basic mechanism that induced a longer lifetime of the peak from the quantum well located farther from surface.

The second mechanism is the wavefunction separation [7] of electrons and holes inside the quantum wells of (111)B samples, because of the high piezoelectric fields. It could be easily found in Table 1 that for both (100) and (111)B samples of the same structure, the time constant of the (111)B quantum well is larger than that of the (100) quantum well located at the same position in the sample. For the quantum wells in the same (111)B samples, the piezoelectric fields inside the quantum wells near surface (QWA_{1t} and QWB_{1t}) were compensated by the surface

Table 1
The fitted decay time constants of quantum wells

	Well width (nm)	Distance from surface (nm)	Decay time constant τ (ps)
QWA_{0t}	3	50	263
QWA_{0b}	2	200	516
QWB_{0t}	2	50	275
QWB_{0b}	3	200	393
QWA_{1t}	3	50	622
QWA_{1b}	2	200	1744
QWB_{1t}	2	50	479
QWB_{1b}	3	200	2221

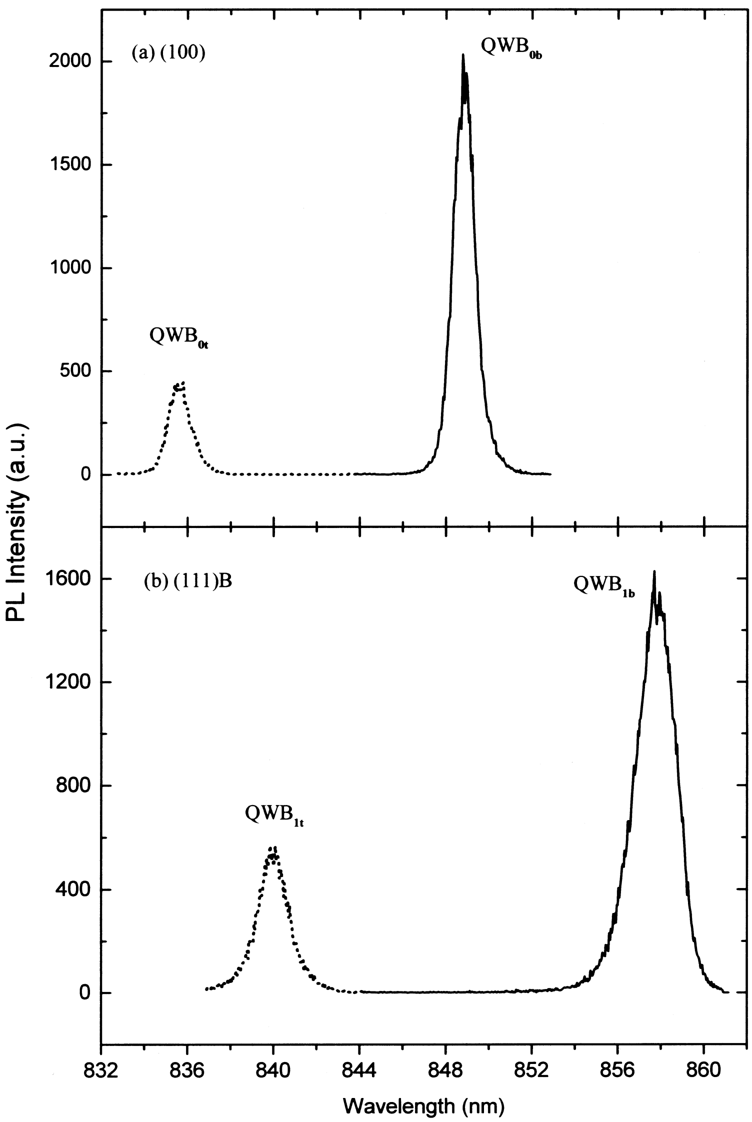

Fig. 2. The time-integrated PL spectra of structure B samples.

potential. Besides, the barrier thickness of the top quantum well is also thinner, which induces smaller strain and therefore lower piezoelectric field. As a result, the time constant of the top quantum well is smaller compared with that of the bottom quantum well. These two mechanisms combined together in the (111)B samples to make the time constant difference between the two quantum wells of the same sample much larger. In (100) samples, the quantum wells near surface are also influenced by the field from the surface potential, though there is no piezoelectric field inside. However, the effect of the surface potential seemed to be smaller than the effect of ''vertical ambipolar transport'' in (100) samples. Therefore, the time constants of the bottom quantum wells are still larger. As the two mechanisms in (100) samples were opposite to each other, the time constant difference between the quantum wells of the sample is much smaller. The wavefunction separation effect can also be found in the quantum wells located at the same depth inside the (111)B samples. The time constant of the 3 nm quantum well (QWA_{1t}, QWB_{1b}) is larger than that of the 2 nm quantum well (QWA_{1b}, QWB_{1t}). This is because of the larger wavefunction separation of electrons and holes in the (111)B quantum well of larger well width. While in the (100) samples, the situation is just opposite. The shorter decay time of the 3 nm quantum well might be contributed by the larger confinement of the quantum well.

There is another possible mechanism for longer decay time in (111)B samples. That is the hopping conduction [8,9] under piezoelectric fields. The measurements were performed at 4 K. The carriers excited in GaAs regions could be trapped easily by the shallow impurity levels. Under the strong piezoelectric field in the (111)B samples, with the help of optical phonons, the trapped carriers in GaAs regions might be able to arrive at the bottom quantum

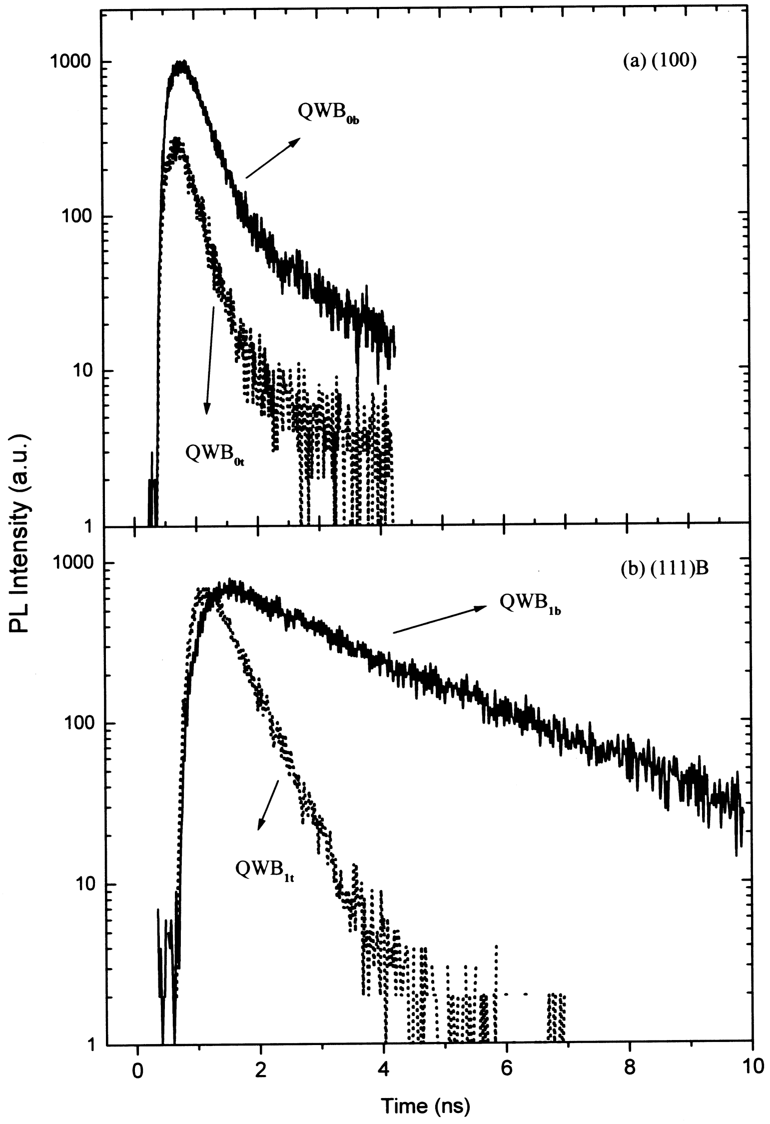

Fig. 3. The wavelength-integrated results over the range of each peak shown in the spectra of Fig. 2.

well by hopping conduction along the field. If the concentration of the impurity level is low, the hopping mobility will be low and therefore contributes to the longer time constants of the bottom quantum wells. For (100) samples, the only field is from the surface potential and should be much weaker. If the hopping mobility is low, most of the carriers in GaAs barriers are recombined before reaching the bottom quantum wells. This also can explain why the time constants of the bottom quantum wells are much longer in (111)B samples. However, further studies are needed to confirm this assumption.

Finally, we have considered the possibility of the carriers inside the top quantum wells escape out and drift into the bottom quantum wells through the piezoelectric fields. When the carriers excited by the 3.1 eV laser, a lot of phonons would be released during the cooling process and these phonons might in turn, assist the carriers inside the quantum wells to escape out. We have prepared additional samples of single quantum wells, QWC and QWD, on (100) and (111)B substrates both. The capping GaAs layers were designed to be 200 nm and 50 nm for QWC and QWD, respectively. The PL results are shown in Fig. 4. It is obvious that the time-resolved results are consistent with those of the previous samples. Therefore, the final argument should be invalid.

In conclusion, we have studied the carrier dynamic of the InGaAs/GaAs strained quantum wells located at different positions on (111)B GaAs substrates, together with the references of (100) samples grown side by side with the (111)B samples, by the measurements of the high resolution time-resolved photoluminescence. Longer lifetime of the PL peaks was found from the quantum wells deep inside the samples, as compared with that from the quantum wells near surface. This is the first time that the piezoelectric

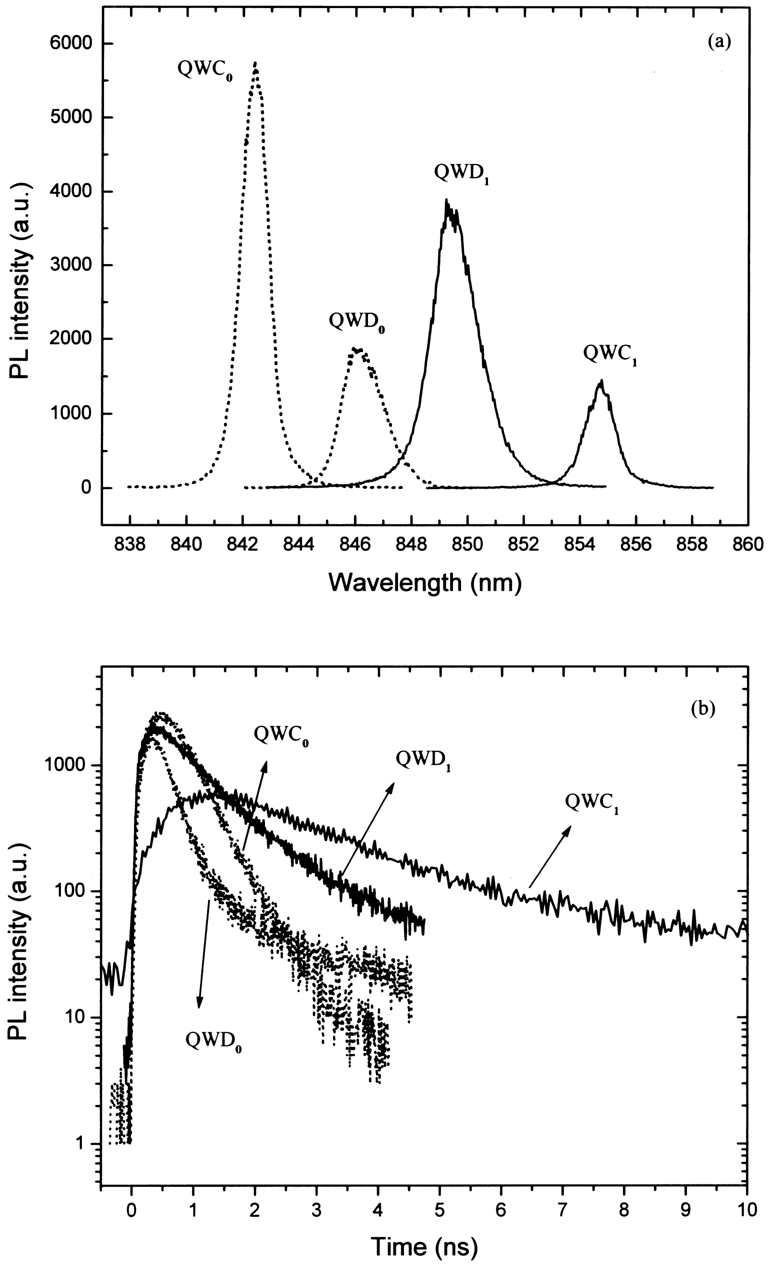

Fig. 4. The measured results of QWC and QWD: (a) the time-integrated PL spectra, (b) the wavelength-integrated results over the range of each peak shown in the spectra of part (a).

effect on the carrier dynamics of (111)B InGaAs/GaAs is studied.

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