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LETTER TO THE EDITOR

Room-temperature excitons in strained InGaAs/GaAs quantum wells

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Abstract. We report sharp and well resolved exciton peaks in the room-temperature absorption spectra of strained InGaAs/GaAs single-quantum-well (SQW) and multiple-quantum-well (MQW) structures and demonstrate for the first time that the strength of the exciton–LO-phonon coupling, determined from the linewidth analysis, is stronger in InGaAs/GaAs SQW structures than in InGaAs/GaAs MQW structures. The inhomogeneous linewidth and homogeneous broadening in InGaAs/GaAs SQW and MQW structures are discussed in detail.

Recently, considerable interest has been devoted to the lattice-mismatched InGaAs/GaAs quantum well structures (QWs) because of their potential applications in novel devices, e.g., optical modulators, high-electron-mobility transistors, and laser diodes [1]. Room-temperature excitonic effects in QWs allow very promising features such as optical bistability, four-wave mixing, and large electro-optic coefficients [2]. Furthermore, the advantage of observation of sharp, well resolved exciton peaks in the room-temperature absorption spectra, while the corresponding bulk material shows excitons at very low temperature, may allow the development of optoelectronic devices for the selected wavelength, since the band gap can be tailored via the QW parameters. Huang *et al* [3] first reported the room-temperature exciton and measured the exciton–phonon coupling in strained InGaAs/GaAs multiple-quantum-well structures (MQWs), and found the coupling strength was small, similar to that of unstrained GaAs/AlGaAs MQWs [4] ($\sim$7 meV). Up to now, the reported room-temperature excitons have been mainly in conjunction with the MQW structures [3–7], due to their strong excitonic resonances at room temperature.

However, by studying the single-quantum-well structures (SQWs), we can avoid any complexities in the linewidth arising from interwell width variations. Very recently, we reported the first observation of room-temperature excitons in strained InGaAs/GaAs SQWs in relation to the thickness of the GaAs cap layer and showed strong exciton–phonon coupling in them ($\sim$20 meV) [8]. In order to lend further support to these conclusions, which are of consequence for the use as optoelectronic devices, we study in this letter, for the first time, the room-temperature excitons in strained InGaAs/GaAs SQW and MQW structures as a function of InGaAs well width using absorption techniques. The observations presented here therefore link together the previous results.

The strained $In_xGa_{1-x}As/GaAs$ QW samples were grown on (001)-oriented semi-insulating GaAs substrates in a Varian GEN II molecular beam epitaxy (MBE) system. The growth temperature of 580 °C used for the GaAs buffer layers was reduced to 520 °C for the remaining layers. All of the samples contained a GaAs buffer layer 0.5 μm thick and a GaAs cap layer 0.2 μm thick, which can be considered fully strained [8, 9]. The SQW samples a, b, and c have InGaAs well widths of 5, 10, 25 nm, respectively, while the MQW sample d consists of alternating thin InGaAs wells (5 nm) and GaAs barriers 20 nm thick (four periods), and the MQW sample e, consisting of two InGaAs wells each 10 nm thick separated by a GaAs barrier 20 nm thick, is actually a double-quantum-well (DQW) structure. All layers are undoped. The parameters of the samples were obtained by reflection high-energy electron diffraction (RHEED) oscillation and x-ray diffraction (XRD) (table 1). In all samples, a composition between 0.135 and 0.155 was found. Absorption measurements were performed in a Nicolet 800 Fourier transform infrared spectrometer over the temperature range of 4.0 K to room temperature (295.0 K), while the absorption spectra were detected by a Si photodiode with a tungsten lamp focused onto the sample. The optical measurement was made at 4 cm^{-1} resolution.

Table 1. Summary of structural parameters, absorption, photoluminescence and calculated data (77 K), and fitted results.

Sample	RHEED+XRD QW (nm)[a]	Analysis x (±0.006)	Absorption 1e–1hh (eV)	PL 1e–1hh (eV)	Calculation 1e–1hh (eV)	x_{cal}	Γ_i (meV)	Γ_c (meV)
a	SQW(5)	0.147	1.4395	1.4380	1.4370	0.138	2.25	15.0
b	SQW(10)	0.145	1.4056	1.4044	1.4035	0.135	1.85	19.3
c	SQW(25)	0.145	1.3772	1.3770	1.3775	0.139	1.75	22.1
d	MQW(5)	0.148	1.4276	1.4261	1.4284	0.145	5.55	7.0
e	DQW(10)	0.147	1.3647	1.3640	1.3655	0.155	6.50	7.7

[a] The numbers in brackets represent the InGaAs well width.

The band gaps for the strained InGaAs/GaAs QW material were calculated from the composition dependence of the unstrained $In_xGa_{1-x}As$ given in [10] and corrected for the effects of biaxial compressive strain. More details have been given in [8–12]. The interband transition energies for SQW samples were calculated by using a standard square-well model, while for MQW samples they were calculated in the regime of the envelope function method [10].

Our five samples all show strong and well resolved exciton peaks in their room-temperature absorption spectra (figure 1). Each spectrum has an excitonic structure in the lower-energy portion, corresponding to the 1e–1hh transition, except for the spectrum of sample c, where there are two additional higher-subband excitonic transitions. (The notation ne–$m$hh indicates the transitions between the nth conduction and the mth valence heavy-hole subband). The full width at half-maximum (FWHM) of the 1e–1hh peaks in figure 1 is $\sim 8.5 \pm 0.8$ meV, comparing well with previous results [3, 8]. The sharp rise in the higher-energy portion of the spectra is due to the absorption in the GaAs substrate, which was only polished and not removed. Low-temperature (77 K) absorption spectra of the five samples are given in figure 2, together with the photoluminescence (PL) peak energies shown by vertical bars. Little Stokes shift between the PL and absorption peaks is found for all of the five samples, which shows the high quality of our samples. The identification of the excitonic transitions in the absorption spectra is confirmed by the theoretical calculation with the conduction-band offset ratio $Q_c = 0.70 \pm 0.05$ [8, 9]. The energies of the 1e–1hh transitions in the lower-energy portion of the 77 K absorption spectra are summarized in table 1.

The most striking feature which can be observed in figure 2 is the large difference between the FWHM of the 1e–1hh peaks of the MQW and SQW samples, which yields

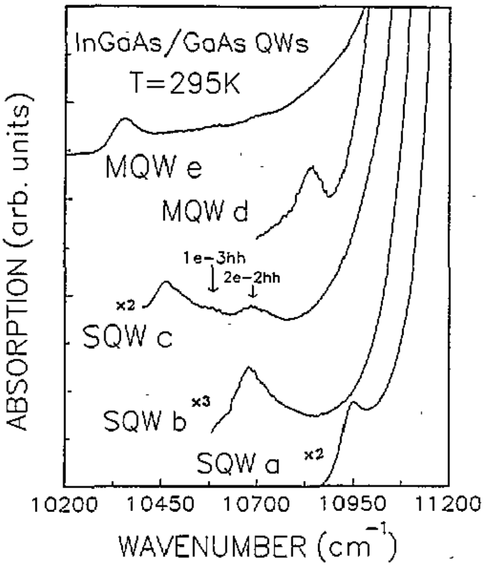

Figure 1. Room-temperature absorption spectra of InGaAs/GaAs SQW (samples a, b, and c) and MQW (samples d and e) structures. The structural parameters are given in table 1.

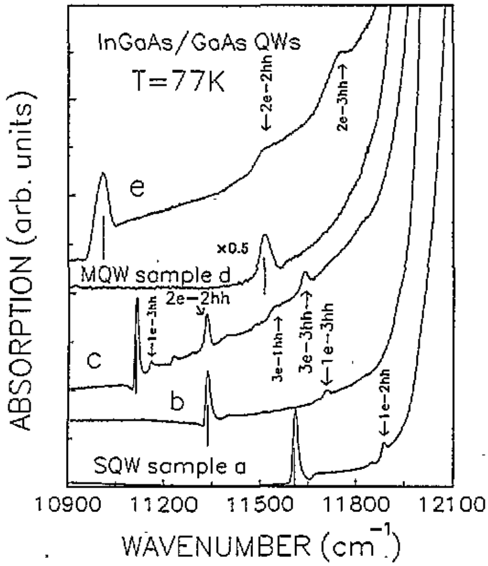

Figure 2. Absorption spectra of InGaAs/GaAs SQW (samples a, b, and c) and MQW (samples d and e) structures at 77 K. The luminescence peak energies are shown by vertical bars.

quite different exciton–phonon coupling. The FWHM of 1e–1hh peaks in SQW samples is ∼2 meV, in contrast to the value for the MQW samples of ∼6 meV. In addition, the small features observed in SQW samples are believed to be longitudinal-optical-phonon (LO-phonon) replicas of the exciton lines from their energy positions. As usual, we have used the exciton–optical-phonon coupling model in which free excitons scatter off LO phonons [3–8, 13] to describe exciton broadening by the following expression:

$$\Gamma = \Gamma_i + \Gamma_h$$

$$\Gamma_h = \Gamma_c[\exp(E_{ph}/K_B T) - 1]^{-1}$$

where Γ_i is the inhomogeneous linewidth due to interface roughness and alloy disorder for SQW structures, while for MQW structures an additional influence of well width fluctuations should be taken into account. Γ_h is the temperature-dependent homogeneous term with Γ_c being its measure of the exciton–phonon coupling, $K_B T$ is the thermal energy, and E_{ph} is the LO-phonon energy (∼35.3 meV) in $In_{0.15}Ga_{0.85}As$ [14]. The values of Γ_i and Γ_c obtained by a good fit with the experimental results are summarized in table 1. The Γ_i-value of only 2.0 ± 0.2 meV in InGaAs/GaAs SQW samples shows that the linewidth of SQW structures at low temperature is dominated by the random alloy disorder since it yields the excitonic linewidth [15, 16]

$$\Gamma_i = 2.36 \frac{dE_g}{dx} \left[\frac{3x(1-x)}{16\pi a_{ex}^3 a_0^{-3}} \right]^{1/2}$$

where dE_g/dx is the change of the energy gap with the alloy composition x, and a_0 is the lattice constant. Using an exciton Bohr radius a_{ex} of ∼11 nm, we can obtain $\Gamma_i \sim 2.0$ meV in $In_{0.15}Ga_{0.85}As$. These results are also in good agreement with the PL measurements (not shown here), where the PL signal of each SQW sample demonstrates a narrow FWHM (~2.1 meV at 77 K) and high intensity, revealing the high-quality structures in which the interface is smooth and abrupt. Furthermore, as the well width decreases, the increase of Γ_i (see table 1) is due to the decrease of the exciton Bohr radius. However, in the PL spectrum of each MQW sample, an additional shoulder appears in the low-energy side of the PL peak at low temperatures, with the energy spacing of 2.8 meV for sample d and 3.8 meV for sample e, due to the well width fluctuations of about 0.5 and 1.6 monolayers, respectively, based on the theoretical calculation. Confirmation of this assignment was obtained from a careful study of the PL with increasing sample temperature. The high-energy structure shows a more rapid decrease of the luminescence intensity due to the thermionic emission of the electrons in the relatively narrow well [17]. The total contribution to the linewidth at low temperature due to the random alloy disorder and well width fluctuations is close to the measured value of Γ_i (6.0 ± 0.5 meV) in InGaAs/GaAs MQW samples, indicating that the contribution from the interface roughness is very small, also consistent with their high-intensity PL signal. A more detailed analysis of PL results will be presented in another publication.

The measured exciton–phonon coupling strength in our InGaAs/GaAs MQW and SQW samples is ~7 meV and ~20 meV, respectively, in good agreement with the previous separate results for InGaAs/GaAs MQW [3] and SQW [8] samples, demonstrating that the strength of the exciton–phonon coupling in InGaAs/GaAs MQW structures is actually smaller than that of InGaAs/GaAs SQW structures. This can be understood as follows: in MQW structures, the existence of the periodicity in the growth direction alters the symmetric behaviour of the phonon vibration modes, e.g., the LO-phonon dipole moment can only result in a change in the exciton motion perpendicular to the layers [18], resulting in a striking reduction of the exciton–LO-phonon interaction [19]. However, this does not hold in SQW structures. Another possible factor, comparing SQW and MQW structures, is the obvious increase in exciton binding energy in SQW structures due to the fact that their wavefunctions are well confined within the wells [20], also increasing the interaction with LO phonons. In addition, the experimental fact that the exciton–phonon coupling decreases with the well width in SQW structures (see table 1) can be explained in terms of the decrease of the size of the exciton, because the LO phonons are restricted to the wells only [2, 18]. This also persists in the MQW structures. The above arguments are further consistent with the experimental facts that (i) possible phonon replicas can be seen in the absorption spectra of SQW samples at low temperatures, which shows strong exciton–phonon coupling in SQW structures, and (ii) more phonon replicas appear in the absorption spectrum of sample c with larger well width due to the stronger exciton–phonon coupling (see figure 2).

In summary, we have demonstrated for the first time that the exciton–LO-phonon coupling in InGaAs/GaAs MQW structures is smaller than that of SQW structures; this should be considered in any InGaAs/GaAs QW device design. We explain the result qualitatively as being due to the existence of the periodicity in the growth direction and the reduction in exciton binding energy in MQW structures. A fuller understanding of the mechanism will be necessary for a quantitative analysis. In addition, our results also show that the random alloy disorder dominates the inhomogeneous linewidth in SQW structures, while in MQW structures the well width fluctations have played an important role.

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