Temperature Dependence of the Quantization Energy in Self-Assembled InGaAs Quantum Dots

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The photoluminescence of electron excitations in the $In_xGa_{1-x}As$ self- assembled quantum dot system was measured at different temperatures. The temperature dependence of both the photoluminescence intensity and the electron recombination energy give an evidence of formation of quantum dots. The strong proof of the lower dimensionality of the quantum dots comparative to the reference quantum well was obtained from the temperature shift of the photoluminescence peaks.

I. Introduction

Self-assembled quantum dot (QD) systems attract much attention because of the possibility to obtain high quality low-dimensional structures, which can be grown free of any imperfections (dislocations, impurities) and thus can present more perfect quantum electron systems comparative to the low-dimensional structures obtained by lithography. Self-organized QD's obtained in different III-V heterostructures have been studied by atomic force microscopy, transmission electron microscopy and scanning tunneling microscopy[1−3]. The electron properties of such structures have been studied by photoluminescence (PL) and transport measurements[3,4]. Recently Raman results have also been reported[5,6].

In this paper we fix our attention on the dependence of the electron quantization energy on temperature. A drastic temperature dependence of the electron recombination energy was found in QD's in comparison with relatively weak temperature shift of the recombination energy in the reference quantum well. We suppose that the lower dimensionality of a QD in comparison with the dimensionality of a quantum well (QW) manifests itself in the stronger temperature dependence of the electron recombination energy found in QD's relative to those found in QW's.

The samples were grown by MBE using a Meca 2000 system, on semi-insulating (001) oriented GaAs substrates (GaAs growth rate of 1μ/h). The structure contained 20 periods of the GaAs/AlAs (2nm/2nm) superlattice, 0.5 μm of the GaAs buffer layer and 3 nm of the $In_{0.2}Ga_{0.8}As$ reference QW. The QD's were separated from the QW by a 100 nm GaAs layer. The QD's were formed by Stranski-Krastanow growth mode when the strained two-dimensional layer was transformed to the net of three-dimentional islands after the thickness of the layer was larger then the critical thickness. In our case the 6 and 15 monolayers of InAs and $In_{0.5}Ga_{0.5}As$ respectively were deposited in order to form QD's. To complete the structure a 50 nm GaAs cap layer was grown. The substrate temperature was 600°C during the superlattice growth and 500°C for other $InAs/In_{0.5}Ga_{0.5}As$ layers. The interface smoothness was introduced by growth interruptions during InAs deposition at both interfaces. The QD's nucleation was directly seen by reflection high energy electron diffraction (RHEED)[1].

The photoluminescence (PL) was excited by the 5145 Å line of an Ar^+ ion laser with an average excitation density of 150 W/cm^2.

The PL spectra of the samples with the InAs and $In_{0.5}Ga_{0.5}As$ layers formed by Stranski-Krastanow

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growth taken at T=22K are shown in Fig.1. The PL lines at 1.47 eV originate from the reference QW, while the broad lines found around 1.35 eV (for the layer with $x = 1$) and 1.27 eV ($x = 0.5$) are due to luminescence of the layers where we expect the formation of QD's. With the temperature increase both lines (those originated from the QW and those from the QD's) disappeared; however PL from the QW disappeared at $T \simeq$ 100K, while PL from the QD's was seen up to 160 K, which gives an evidence of the quantization energy increase due to an additional lateral confinement[7]. It should be mentioned that the shape of the PL lines due to the QD's did not change with temperature; thus we do not expect that the different thermalization of the dots with different size will strongly influence the temperature shift of the PL line.

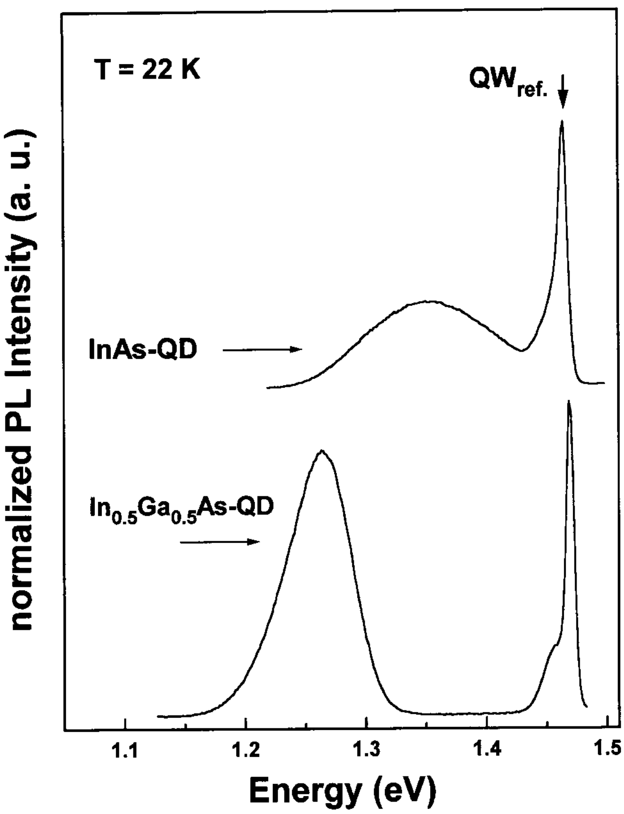

Figure 1. PL spectra of the samples grown with the InAs and $In_{O.5}Ga_{0.5}As$ quantum dots; the PL spectra of the 30Å $In_{0.2}Ga_{0.8}As$ reference quantum wells are also presented.

In addition, as it follows frorn Fig. 2 we obser red more rapid decrease of the PL peak energies with the temperature increase in the QD's in comparison with the reference QW. We suppose that this different temperature behavior of the excitation energies found in the QW and in the QD's gives an additional proof of the lower dimensionality of the structures formed in the InAs ($In_{0.5}Ga_{0.5}As$) layer grown by the Stranski-Krastanow mode. In order to support this point of view we are going to use the simple treatment of the problem when we neglect the finite barrier height and the non-parabolicity, which are actually important for the QD's under consideration. However, the main idea of this study is to explain qualitatively the different temperature behavior of PL peak positions in a QW and in a QD and these simplifications allowed us to obtain the factors which determine the temperature changes in both of them from direct comparison of the corresponding quantization energies. Then more correct calculations can be used to obtain the temperature shift of the PL peak position in QD's, which obviously will contain the contribution discussed in this paper.

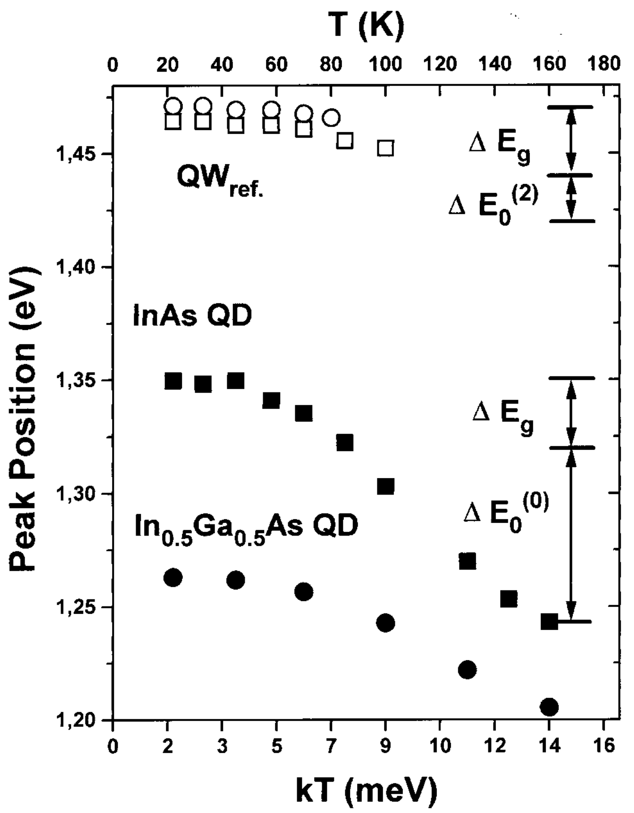

Figure 2. Temperature dependence of the PL peak positions of the 30Å $In_{0.2}Ga_{0.8}As$ reference quantum wells and the InAs and $In_{0.6}Ga_{0.5}As$ quantum dots together with the calculated temperature energy shifts ΔE_g and $\Delta E_0^{(2,0)}$ (as explained in the text).

As it is well known (see for instance [8]) the ground state energy of a single electron-hole pair in a square infinite well is defined by the formula

$$E_0^{(2)} = \frac{\hbar^2}{2m_r}\left(\frac{\pi}{L_c}\right)^2 \quad (1)$$

where $m_r = m_e m_h/(m_e + m_h)$, m_e, m_h are the electron and hole masses respectively and L_c is the QW thickness.

The lowest confined state of an electron-hole pair in the spherical potential well is given by [8]

$$E_0^{(0)} = \frac{\hbar^2}{2m_r}\left(\frac{\pi}{R}\right)^2 \qquad (2)$$

where R is the radius of the well.

Thus the quantization energy of an electron-hole pair in the QD is higher by factor 4 (because $R = L_c/2$) than those in the QW; this causes the more drastic change in the quantitation energy of the QD relative to those of the QW when the effective masses (m_e, m_h) are changed.

According to [9] the effective mass of electrons in InAs does not depend on temperature up to 80 K (when $m_e = 0.023m_0$) and then increases up to $m_e = 0.027m_0$ at $T = 300K$, while m_h remains constant in this temperature range. This increase in the electron effective mass causes the decrease of the quantization energy and as a consequence the decrease of the recombination energy revealed in PL, which is essentially different in the QW and in the QD.

We estimated the temperature shifts of the excitation energies in the QW and QD taking into account the temperature dependencies of the direct gap (E_g) and the effective masses from

$$\Delta E_{ex}^{(2,0)} = \Delta E_g + \Delta E_0^{(2,0)} + \Delta E_{eh}^{(2,0)}\ , \qquad (3)$$

Where $\Delta E_{eh}^{(2,0)}$ is the energy shift due to the Coulomb electron-hole interaction, which is small enough comparative to the $\Delta E_0^{(2,0)}$ [8]. We obtained $\Delta E_g \simeq 30$meV with an increase of temperature from 20 K to 160 K. In order to explain the temperature shift of $\Delta E_{ex}^{(2,0)}$ found in the InAs QD's, the electron effective mass should be varied from $0.023m_0$ at $T = 80$ K to $0.025m_0$ at $T = 160$ K (this variation of the effective mass gives the values of $\Delta E_0^{(0)}$ and $\Delta E_0^{(2)}$ shown in Fig.2); the obtained temperature variation of the electron effective mass is rather close to the data presented in [9].

Moreover, the temperature shift of the excitation energy measured in the QD's formed in the $In_{0.5}Ga_{0.5}As$ layer was weaker than those in the InAs QD's. This is explained by the weakening of the temperature dependence of the electron effective mass in the $In_{0.5}Ga_{0.5}As$ alloy comparative to those in InAs.

In conclusion, the different temperature behavior of the PL measured in the QW and in the self-assembled QD structures gives an evidence of the QD formation. The strong temperature shift of the recombination energy found in the QD structures can be considered as an additional proof of the lower dimensionality of the QD relative to the reference QW.

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