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Wavelength tuning in GaAs/AlGaAs quantum wells by InAs submonolayer insertion

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Abstract. Wavelength tuning of exciton emissions has been achieved simply by inserting an InAs submonolayer at the centre of GaAs quantum wells during molecular beam epitaxy growth. Photoluminescence measurements show that the emission energy can be effectively tuned from the quantum-well-determined energy down to less than the band gap of GaAs, depending on the well width as well as the InAs layer thickness. Using the effective-mass approximation, the tuning effect can be well predicted theoretically. The results reported here may provide an alternative way to tune the wavelength in optoelectronic devices.

1. Introduction

The study of highly strained InAs/GaAs heterostructures has attracted much attention in recent years due to their intriguing novel properties. Such a strained structure may provide a promising way to obtain high-quality quantum dot arrays through the spontaneous formation of three-dimensional islands during Stranski–Krastanov-like growth [1–3]. Meanwhile, monolayer (ML) and submonolayer (SML) insertion of InAs in a GaAs matrix has been proved to lead to superior optical properties [4–8], such as a greatly improved luminescence efficiency [5], very narrow linewidth (down to 0.15 meV) [6], a surprisingly high exciton oscillator strength [6, 7], and huge binding energy [8]. Photoluminescence (PL) and time-resolved PL studies revealed the 2D properties of the emission [9]. An InAs monolayer was also ingeniously used to measure the spatial dependence of the probability density of eigenstates in GaAs/GaAlAs quantum wells by means of the insertion of a one-monolayer InAs probe plane at different positions in the quantum well [10].

In this paper we report an important application of the InAs submonolayer, i.e. its ability to tune the wavelength of the exciton emission in GaAs/AlGaAs quantum wells (QWs). The tuning effect is achieved simply by inserting the InAs submonolayer at the centre of the GaAs QWs during the MBE growth. PL measurement shows that the emission energy can be effectively tuned from the QW-determined energy down to less than the band gap of GaAs. For example, when a half-ML InAs layer is inserted at the centre of a 12 nm GaAs well, the exciton energy can be tuned from 1.540 eV (805.2 nm) down to 1.504 eV (824.5 nm) at low

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temperature. Additionally, we found that the insertion of InAs did not degrade the material quality: no obvious change in the luminescence linewidth and efficiency was observed in our samples. Using the effective-mass approximation, we have calculated the exciton states in GaAs/GaAlAs QWs with insertion of an InAs submonolayer, and found that the tuning effect can be well predicted theoretically.

2. Experiment

The samples used in this study were grown by MBE on semi-insulating (100) GaAs substrates with a 0.7 μm buffer layer. The basic structure of the sample is composed of three single GaAs quantum wells of 3, 6.2, and 12 nm, separated by 40 nm $Ga_{0.8}Al_{0.2}As$ barriers. The whole QW structure was sandwiched between 0.1 μm $Ga_{0.8}Al_{0.2}As$ cladding layers. The InAs submonolayer was inserted at the centre of each GaAs well during the MBE growth with the growth rate of 0.043–0.066 ML s^{-1}. The growth temperature was 480–510 $^{\circ}$C for InAs, and 600 $^{\circ}$C for GaAs and GaAlAs. Finally, the structure was capped with a 10 nm GaAs layer to protect the surface. A reference $GaAs/Ga_{0.8}Al_{0.2}As$ QW sample without InAs insertion was grown under the same conditions. The excitation of the sample was carried out with an argon laser in the cw PL measurements. In the time-resolved PL measurement, a Ti:sapphire sub-picosecond pulse laser was used as an excitation light source, and the time-correlated signal was analysed by a 2D synchroscan streak camera with an overall resolution less than 30 ps.

3. Results and discussion

Figure 1 shows low-temperature PL spectra of three samples with or without InAs insertion. A systematic energy shift was observed in the PL spectra when the thickness of the InAs layer was increased. For the reference sample (see trace (a) in figure 1), the three PL peaks at 1.653, 1.579, and 1.540 eV are attributed to the heavy-hole exciton emissions of 3, 6.2, and 12 nm GaAs wells, respectively. It is seen that the insertion of the InAs layers into the well shifted the exciton energy towards the red. The amount of red-shift increases with the increase of the

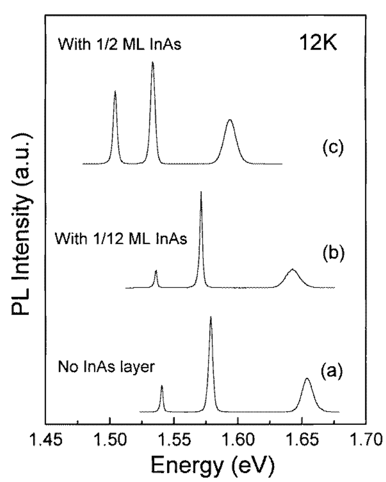

Figure 1. Photoluminescence spectra of GaAs/GaAlAs QW samples with or without InAs SML insertion, illustrating the systematic red-shift of the exciton emission with the increase of the InAs thickness.

InAs layer thickness. For the sample in which half a ML of InAs was inserted (see trace (b) in figure 1), the PL peak energies are shifted to 1.593, 1.533, and 1.505 eV, respectively, i.e., there are 60, 46, and 35 meV shifts for the 3, 6.2, and 12 nm wells, respectively. However, for the sample with one twelfth of a ML of InAs, the corresponding shifts are 10, 7 and 4 meV, respectively, as shown by trace (c) in figure 1. It is worth noting that the emission energy of 1.505 eV for the 12 nm GaAs well with half a ML of InAs inserted is already below the band gap of GaAs at 12 K. Even lower exciton energy is to be expected when thicker InAs layers are inserted.

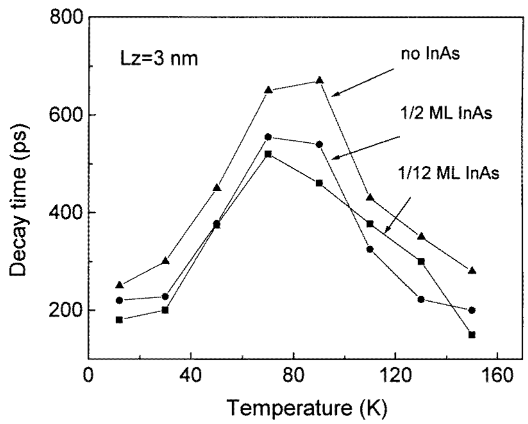

Figure 2. Comparison of the temperature dependences of the exciton decay times for the 3 nm GaAs well in the samples of figure 1.

It is important to point out that the observed linewidth and luminescence efficiency were almost unchanged for the samples with InAs insertion. This indicates that the insertion of an InAs layer did not introduce any further defects, and consequently did not affect the quality of the samples. This is very significant in applications, and was further verified by investigating the temperature dependence of the exciton lifetime using time-resolved photoluminescence. It is well known that the lifetime of photogenerated carriers is very much influenced by the nonradiative centres in the material [11, 12]. For a 2D quantum well structure, a linear temperature dependence of the exciton lifetime was expected [13]. However, for a real structure the measured decay time very often reaches its maximum when the temperature is increased to a certain value, and then falls off with further increase of temperature [11, 12]. This behaviour has been explained by the activation of nonradiative centres associated with the defects or other thermal escape channels of photo-carriers. In figure 2 the measured decay times versus temperatures are shown for the 3 nm GaAs well in the samples described as for figure 1. In the temperature range below 30 K, the decay times are almost unchanged due to exciton localization. When the temperature is increased, a linear dependence is observed, in qualitative agreement with the theoretical prediction [13]. The decay times reach their maxima at around 70–90 K for our samples. This characteristic temperature could vary from sample to sample, depending on the thermal barrier of the material defects, the potential barriers, and other nonradiative channels [11, 12]. Discussion of the physics is beyond the scope of this paper. However, it is worth emphasizing that the trends of the three curves in figure 2 are very similar. This further supports our assumption that the insertion of InAs layers in our samples did not significantly change the material quality. Note that the decay times for the reference sample are slightly longer than those for the other two samples (figure 3). This can be understood by

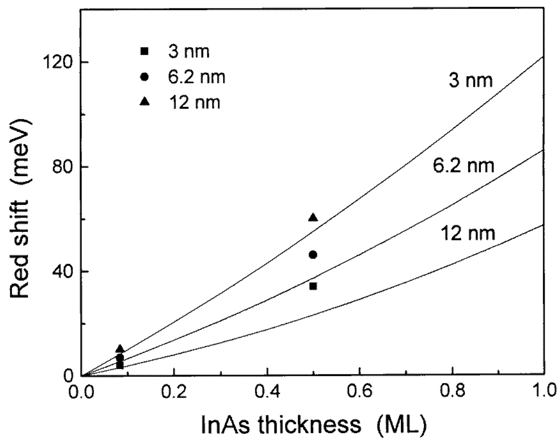

Figure 3. The calculated tuning curves for the exciton energy of GaAs/GaAlAs QWs with InAs insertion: the red-shift of the exciton emission versus the InAs layer thickness. The experimental data are denoted by symbols.

considering the effect of trapping of carriers into the InAs submonolayer and probably into the InAs/GaAs interfaces as well.

In order to compare the experimental data with the theoretical prediction, we have calculated the excitonic states in GaAs/GaAlAs QWs with InAs submonolayer insertion within the envelope function model [14, 15], taking into account the influence of strain. It is worth mentioning that we do not use any adjustable parameters to fit the experimental results. In the calculation, the InAs submonolayer in GaAs is treated as a thin finite potential located at the centre of the GaAs quantum well, and the electron and hole ground states of the structure are calculated by invoking periodic boundary conditions [15, 16]. Also, the exciton states are calculated using a variational method including the Coulomb interaction between the electrons and holes [15]. The material parameters used for the calculation are taken from reference [5]. Figure 3 shows the calculated red-shift, defined in each case as the difference of the exciton energy for the GaAs well with InAs insertion from that for the case without InAs insertion. Indeed, with the increase of the InAs layer thickness a systematic red-shift of the exciton emission is predicted. For a 3 nm well, the tuning range could be as large as 120 meV. For comparison, the experimental data are also plotted in the figure. A reasonable agreement between the experiment and calculation is obtained, despite the fundamental limitations of the envelope function model in the limit of ultrathin wells.

4. Conclusions

In summary, we have demonstrated the wavelength tuning in GaAs/GaAlAs QWs achieved simply by the insertion of InAs submonolayers in the middle of the GaAs wells. This provides an alternative way to tune the photon emission in GaAs/GaAlAs systems, and therefore may have potential application in optoelectronic devices.

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