JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 10, No. 2, February 2008, p. 323 - 326

Capacitance spectroscopy study of InGaAs/GaAs quantum dot structures

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Self assembled InGaAs/GaAs quantum dots (QD) have a great potential for high performance optoelectronic devices such as low threshold laser diodes, infrared detectors, modulators, memories. In order to characterize the behavior of the QD system, we use two p^+-n structures grown epitaxially on GaAs under similar conditions. The first structure acts as reference while in the second structure a single QD self-assembled layer is introduced in the middle of the n-GaAs matrix layer. The structure is designed such that for 0V applied bias the QD layer lies outside the depleted region. When the reverse bias is increased, the charge from the QD system is removed and the depletion layer moves further into the GaAs matrix material. The electronic structure of the QD is investigated using two methods: photoluminescence, in order to characterize the transition energies between electron and hole levels in the QD system and capacitance spectroscopy in order to study the electron levels in the conduction band only. In addition, admittance spectroscopy spectra are measured in order to characterize the carrier transport mechanism. There is no evident step in the capacitance versus frequency behavior at room temperature in the range 1 Hz-1 MHz, indicating a large carrier cross section caption and/or a low activation energy for the carrier transport between the dot system and the wetting layer and GaAs barriers. The plateau in the C-V behavior, due to charging or discharging of the QD system is modeled using the solution of a Poisson equation and the resulting energy of the electron states within the conduction band and QD size distribution are correlated with results from photoluminescence studies, which involve transitions between energy levels both from the conduction and valence bands.

(Received September 25, 2007; accepted February 7, 2008)

Keywords: Quantum dots, InGaAs, Photoluminescence, Capacitance spectroscopy

1. Introduction

Nanostructured materials are under intensive investigation at the present moment due to the additional degree of freedom for tailoring their properties not only by controlling the material composition but also by adjusting their size below the limit where the quantization effects become sizeable. Due to their 0D (zero dimensional) nature, improvements are expected for all main parameters of optoelectronic devices such as emitters (IRED's, laser diodes) or photodetectors. An important issue is the characterization of such materials before incorporating them in a fully operational device structure. The main characterization tools are photoluminescence (PL) and photocurrent (PC). In both these techniques we are probing transitions that involve both the conductance and valence bands, making the task of identifying the energetic band structures more difficult than if we could probe only one band. A technique that offers this possibility is the capacitance spectroscopy [1], which refers to measuring C-V curves under quasi-static conditions, i.e. for frequencies lower than the value for which carriers fully respond to small signal changes of bias. Under these conditions the measured C-V characteristics no longer depend on the small signal frequency. This is a very useful technique that complements the PL and PC characterization tools. Since the hole band structure is considerably more complex than its electronic counterpart, due to mixing between heavy and light hole states, the best approach is to use capacitance spectroscopy to probe electronic levels in the conduction band and then photoluminescence and/or photocurrent in order to derive the hole levels involved in optical inter-band transitions. This paper conducts such an investigation for epitaxial $In_{0.50}Ga_{0.50}As/GaAs$ quantum dots grown by MOCVD.

2. Experimental

$In_{0.50}Ga_{0.50}As/GaAs$ quantum dots are grown in the Stranski-Krastanow mode by MOCVD [2]. We use two p^+-n structures grown epitaxially on GaAs, under similar conditions.

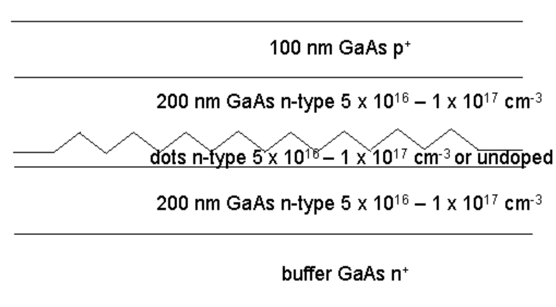

Fig. 1. Details of the layer structure used for capacitance spectroscopy characterization. A similar reference structure is grown separately without the quantum dot layer.

The first structure in which there are no QDs acts as reference while in the second structure a single quantum dot (QD) self-assembled layer is introduced in the middle of the n-GaAs matrix layer. The structure is designed such that for 0V applied bias the QD layer lies outside the depleted region and when the reverse bias is increased, the charge from the QD system is removed and the depletion layer moves further into the GaAs matrix material. The details of the layer structure are given in Fig. 1.

The PL measurements are performed at 77 K, using a green He-Ne laser (543.5 nm) and an InGaAs photodiode, after etching the top p^{++} GaAs layer, because it absorbs the PL light emitted from the quantum dot region. The temperature dependent C-V measurements were performed using a closed cycle (Ebara) He cooled Janis cryostat system at 100 Hz, 1 kHz, 10 kHz and 100 kHz using an Agilent bridge. The admittance spectra are taken using a Zahner electrochemical workstation fitted with impedance spectroscopy and noise measurement modules and software. The contact area is circular, having a diameter of 780 μm.

3. Results and discussion

The QD density measured from AFM studies on uncapped samples (figure not shown) is about $N_{dot} = 3 \times 10^{10}$ cm^{-2}.

Fig. 2 shows the PL spectra at 77K for the QD structure in comparison with the reference, for two different values of the excitation density. The PL of the wetting layer lies at 972 nm, as seen in the high intensity excitation spectrum, after filling the quantum dot states. At lower excitation densities the quantum dot states are clearly visible on the right side of the PL spectrum, for wavelengths in the range 1000-1150 nm. The PL peak of the wetting layer is of higher intensity than that corresponding to the quantum dots because its volume is larger than that of the dots. Due to the relatively large spread of the Gaussian size distribution of the dots the transitions corresponding to different energy levels in the nanodot layer are not well resolved.

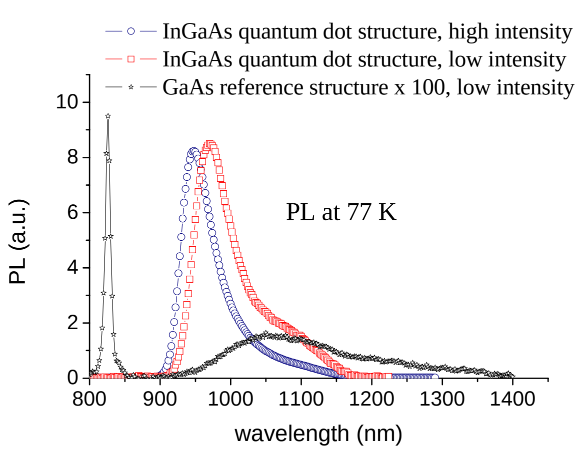

Fig. 2. PL spectra taken at 77 K from the QD and the reference structure.

It is interesting to notice that the spectra in Fig. 2 suggest the presence of an excited quantum dot transition, situated in energy close to the wetting layer transition and having a significantly higher intensity than that corresponding to the ground state. This is not typical for quantum dot samples where the intensity of the wetting layer photoluminescence is generally significantly lower than that corresponding to the quantum dots due to the fact that they are situated higher in energy and are considerably less populated, especially at lower temperatures.
Fig. 3 (a) shows the C-V characteristics for the QD and reference structures taken at 100 kHz. The QD structure clearly shows a plateau associated with the discharging of the QD levels when the space charge region is increased by applying reverse bias and it extends beyond the QD region. Fig. 3 (b) shows the modeled potential distribution over the whole quantum dot structure for 0 V external applied bias.

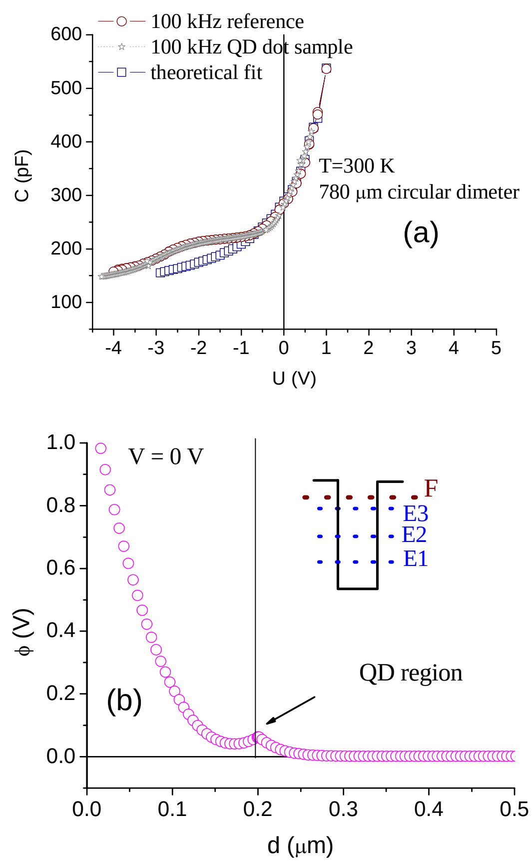

Fig. 3. (a) Experimental comparison between the C-V quasi-static characteristics of the reference and QD structures and (b) modeled potential distribution for 0 V applied bias.

For both structures there is no significant difference between the C-V curves taken at 100 Hz, 1 kHz, 10 kHz and 100 kHz. We conclude that the quantum dots are in quasi-static conditions even for 100 kHz, meaning that the carrier occupancy of the quantum dot levels is fast enough to follow the small ac signal for capacitance measurements even at 100 kHz. The absence of a frequency dispersion is quite surprising for the QD structure. E. Gombia et al. shows that the frequency dispersion of the C-V and G-V curves strongly depends on the growth conditions, being present in some structures and absent in others, but they point out that the reason behind this behavior is not fully understood. Further investigation is required to clarify this point, using different structures grown under different conditions.

Fig. 4 show the admittance spectroscopy results. The capacitance spectra (not shown) do not reveal any features in the frequency range 1 Hz – 1 MHz, in the QD as well as in the reference structure. This is again surprising and means that the QD structure is under quasi-static conditions even at 1 MHz. Fig. 4 (a) and (b) show the conductance spectra for the two structures, for different values of the applied bias.

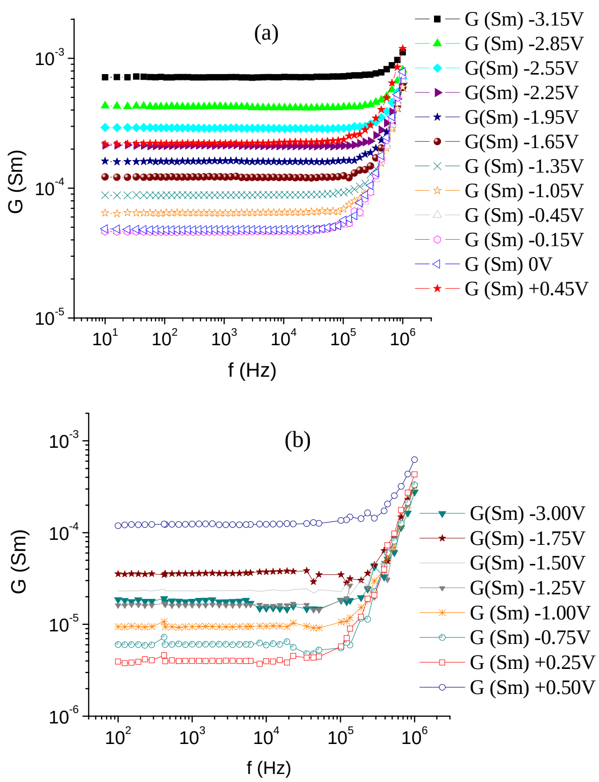

Fig. 4. Room temperature small signal conductance spectra for different values of the applied bias (a) reference structure and (b) QD structure.

These spectra reveal a similar increase of conductance for frequencies larger than 200 kHz in both cases. The increase in conductance is not associated with a change in capacitance and does not depend strongly on the applied bias. We attribute this behavior to trap-related minority carrier recombination in the GaAs layers. A similar behavior was observed for the case of silicon based MOS structures under inversion [4].

In order to extract the conductance band structure for the quantum dots region from Fig. 3, we fitted the quasi-static C-V curve using a model similar to the one used in ref. [5]. The n-type doping in the GaAs layer was found from the slope of $1/C^2$ versus V plots to be 5.9 x 10^{16} cm^{-3}. The built-in voltage Vb extracted from the intercept of the $1/C^2$ plots with the voltage axis is 1.3 V at room temperature. The model takes into consideration the incomplete donor ionization and the donor level is taken to be 6 meV below the conduction band in GaAs. The electron distribution in the dot layer is modeled as:

$$N = 2N_{dot} \cdot \sum_{i=1}^{N\,levels} \left[g_i \frac{1}{\sqrt{2\pi}\sigma_i} \int_{-\infty}^{\infty} e^{-\frac{(E-E_i)^2}{2\sigma_i^2}} \frac{1}{\left(1+e^{\frac{E-E_c}{E_t}}\right)} dE \right] \quad (1)$$

where the parameter σ_i describes the Gaussian spread in size and g_i is a degeneracy factor which accounts for the fact that the excited states have several wavefunction distributions corresponding to the same energy level. F is the Fermi level describing the carrier population in the whole structure and E_t is the thermal energy equal to 26 meV at room temperature.

We detect in this way the presence of three quantized levels having the confining energies: E_3=0.090 eV, E_2=0.180 eV and E_1=0.375 eV respectively. The Gaussian spread in energies is described by the parameters σ_3= 80 meV, σ_2= 180 meV and σ_1= 200 meV while the degeneracy factors are g_1 = 4, g_2 = 3 and g_3 = 1 respectively for the three energy levels. Fig. 3 (b) shows the modeled potential profile for 0 V applied bias. Even if the QD layer lies outside the space charge region, its presence is evidenced by the potential perturbation due to the fact that the energy levels are partially filled with carriers, the filling factor being higher for higher confinement states and lower for the excited states. The energy positions identified from theoretical modeling of the conduction band profile and the quantized energy transitions involving both electron and hole states from PL measurements are in good agreement if we take the ratio $\Delta E_c/\Delta E_g$ as 60 %. The state having the smaller confinement (0.090 eV) is associated either with the wetting layer or with an excited state in the quantum dots very close in energy to the wetting layer's confined energy level. The spread in energy for this state is smaller than for bound quantum dot states. The FWHM of the Gaussians describing the spread of deeper quantum dot energies (E_2 and E_3) due to the spread in dot sizes derived from theoretical modeling of the capacitance spectra is a factor of two larger than those derived from PL spectra. This can be explained taking into account that the quantization effects are larger for electrons, with a lower effective mass than for heavy holes. The lower the effective mass, the higher is the quantized energy level with respect to the band edge and also the larger will be the spread in energy associated with the spread in size. PL involve inter-band transitions, thus the FWHM of a PL peak will be lower than the FWHM of the conduction band density of states due to size fluctuations. Since the capacitance spectroscopy scans only conduction band states it reveals a larger spread of energies around the quantized levels than the PL spectra.

4. Conclusions

We used the method of capacitance spectroscopy as a characterization tool for the electronic band structure of the conductance band in $In_{0.50}Ga_{0.50}As$/GaAs quantum dots, complementing photoluminescence that involves inter-band transitions between both electrons and holes. In addition, admittance spectroscopy spectra are taken in order to characterize the carrier transport mechanism. A single QD self-assembled layer is introduced in the middle of the n-GaAs matrix layer. The structure is designed such that for 0 V applied bias the QD layer lies outside the depleted region and when the reverse bias is increased, the charge from the QD system is removed and the depletion layer moves further into the GaAs matrix material. A second structure is grown as a reference without inserting the QD self-assembled layer in the middle of the n-GaAs matrix layer.

The C-V characteristics are quasi-static in the whole frequency range 1 Hz - 1 MHz at room temperature, indicating a large carrier cross section caption and/or a low activation energy for the carrier transport between the dot system, the wetting layer and GaAs barriers. The plateau in the C-V behavior, due to charging or discharging of the QD system is modeled using the solution of a Poisson equation and the resulting energies of the electron states within the conduction band correlate well with results from photoluminescence spectra. The Gaussian spread in energy due to Gaussian size fluctuations of the InGaAs dots in the conduction band is a factor of two larger than the one found from PL measurements, that involve electron-hole inter-band transitions.

Acknowledgements

This work was financially supported by the Romanian Ministry of Education and Research in the frame of the nucleus project **41N/ 2006.** Australian authors gratefully acknowledge financial support from the Australian Research Council.

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