

## Deep level transient spectroscopy characterization of InAs self-assembled quantum dots

V. V. Ilchenko, S. D. Lin, C. P. Lee, and O. V. Tretyak

Citation: *Journal of Applied Physics* **89**, 1172 (2001); doi: 10.1063/1.1336519

View online: <http://dx.doi.org/10.1063/1.1336519>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/jap/89/2?ver=pdfcov>

Published by the [AIP Publishing](#)

---

### Articles you may be interested in

[Deep levels in GaAs\(001\)/InAs/InGaAs/GaAs self-assembled quantum dot structures and their effect on quantum dot devices](#)

*J. Appl. Phys.* **107**, 073111 (2010); 10.1063/1.3359704

[Combined optical and electrical studies of the effects of annealing on the intrinsic states and deep levels in a self-assembled InAs quantum-dot structure](#)

*J. Appl. Phys.* **100**, 043703 (2006); 10.1063/1.2234817

[Conduction band offset in InAs/GaAs self-organized quantum dots measured by deep level transient spectroscopy](#)

*Appl. Phys. Lett.* **76**, 2571 (2000); 10.1063/1.126411

[Tuning the energy levels of self-assembled InAs quantum dots by rapid thermal annealing](#)

*Appl. Phys. Lett.* **76**, 691 (2000); 10.1063/1.125863

[Near-field magneto-optical spectroscopy of single self-assembled InAs quantum dots](#)

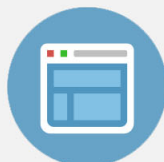
*Appl. Phys. Lett.* **73**, 517 (1998); 10.1063/1.121919

---



## Re-register for Table of Content Alerts

Create a profile.



Sign up today!



# Deep level transient spectroscopy characterization of InAs self-assembled quantum dots

V. V. Ilchenko, S. D. Lin, and C. P. Lee<sup>a)</sup>

*Department of Electronics Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu, Taiwan, Republic of China*

O. V. Tretyak

*Faculty of Radiophysics of Kiev Taras Shevchenko University, 64 Vladimirskaya Street, Kiev, Ukraine*

(Received 3 July 2000; accepted for publication 3 November 2000)

Deep level transient spectroscopy (DLTS) was used to obtain the energy level and the capture characteristics of InAs self-assembled quantum dots embedded in GaAs. A specially designed structure was used for the DLTS measurement for enhanced resolution. This structure allows us to detect capacitance relaxation signal from a single layer of quantum dots and to separate this signal from those of the DX centers inside the structure. The DLTS spectra with different filling pulses and different rate windows provide clear information on the energy level and the capture characteristics of the quantum dots. © 2001 American Institute of Physics. [DOI: 10.1063/1.1336519]

## I. INTRODUCTION

Considerable interest has recently been focused on characterization of self-organized quantum dots (QD).<sup>1–8</sup> In order to develop a new generation of devices such as QD lasers, optical memory elements, and resonant-tunneling devices based on quantum dots, it is very important to have a complete understanding of the physical properties of the QDs. To obtain information about energy levels of quantum dots, optical methods such as photoluminescence (PL)<sup>4–6</sup> are usually used. Recently, deep level transient spectroscopy (DLTS) has also been used.<sup>1–3,9,10</sup> In principal the DLTS method has some advantages over conventional optical methods. The transient capacitance techniques are able not only to detect levels of quantum dots, but also unambiguously to determine their capture parameters. However, investigation of a single layer of QDs in ordinary Schottky-diode structures by means of DLTS has been difficult because of small or not clear relaxation signals. The DLTS spectras on QDs reported in the literature usually dealt with multiple layers of QDs.<sup>2</sup> In this article we describe a structure, which contains a GaAs–Al<sub>0.35</sub>Ga<sub>0.65</sub>As heterojunction, for the DLTS investigation of a single layer of QDs. It enables us to obtain very clear and unambiguous DLTS signals of the QDs. Because of the presence of the second potential barrier, which is provided by the GaAs/Al<sub>0.35</sub>Ga<sub>0.65</sub>As heterojunction not far from the QDs, the structure allows us to easily change the extent of filling of the QDs and to obtain the signals.

## II. EXPERIMENT DATA AND DISCUSSION OF RESULTS

### A. Samples and method of study

The samples used for this study were grown by molecular beam epitaxy using a Varian GEN II system. The structure consisted of, starting from the (100)  $n^+$ -GaAs substrate, a Si-doped  $n^+$ -GaAs buffer layer, an  $n^+$ -Al<sub>0.35</sub>Ga<sub>0.65</sub>As

layer ( $2 \times 10^{18} \text{ cm}^{-3}$ , 300 nm), an  $n^+$ -Al<sub>0.35</sub>Ga<sub>0.65</sub>As layer ( $1 \times 10^{17} \text{ cm}^{-3}$ , 150 nm), a 10 nm  $n$ -type graded Al<sub>*x*</sub>Ga<sub>1–*x*</sub>As layer, an  $n$ -GaAs space layer ( $3.5 \times 10^{15} \text{ cm}^{-3}$ , 30 nm), an undoped InAs quantum dot layer (2.6 ML), and an  $n$ -GaAs layer ( $n = 3.5 \times 10^{15} \text{ cm}^{-3}$ , 270 nm). The structure and the band diagram are schematically shown in Fig. 1. The growth rate of InAs quantum dots was about 0.1 ML/s and the growth temperature was 520 °C. To improve the uniformity of the dot size, we interrupted the In flux for 6 s for every 0.2 ML. After the layers were grown, Ti/Au Schottky diodes with a size of  $1.44 \times 10^{-3} \text{ cm}^2$  were formed for DLTS measurement by standard lithographic technique. The back ohmic contact was formed by alloying In to the  $n^+$ -GaAs substrate. The quantum dot formation was confirmed by the atomic force microscope (AFM) image (see Fig. 2), which was taken after the dots were grown.

The additional GaAs/Al<sub>0.35</sub>Ga<sub>0.65</sub>As heterobarrier underneath the QDs of this specially designed structure has two purposes: (1) to create conditions under which all QD states can be completely filled at zero or small negative offset voltages, and (2) to provide a more desirable voltage distribution near the quantum dot layer to facilitate the filling and escaping processes for electrons in the quantum dots during DLTS measurement.

The DLTS measurement was carried out using a MI-401 Megabytec DLTS spectrometer. Low temperature (at 20 K) photoluminescence (PL) spectra were measured using argon laser for excitation. InGaAs detector and a Si-PMT were used for light detection.

### B. Result and discussion

All the DLTS measurements were performed by direct determination of the electron emission rate as a function of temperature from 80 to 472 K in a wide range of time window from  $10^{-6}$  to  $10^{-1}$  s under dark condition. Before each scan, the sample was cooled down under zero bias and the measurements were made during the warm up cycle. Figure 3 shows the measured DLTS spectra with different filling

<sup>a)</sup>Electronic mail: cplee@cc.nctu.edu.tw

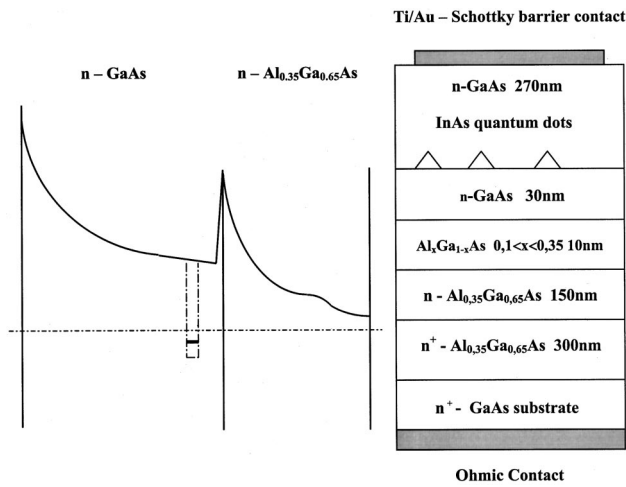


FIG. 1. Band diagram of the structure for DLTS measurements at zero offset voltage and layer structure of the quantum dot sample.

pulses. The rate window was  $3.4 \times 10^{-4}$  s and the offset voltage was  $-5.5$  V. To vary the average occupation of the dots, the amplitude and the duration of the filling pulses were varied. DLTS signals [curves (1–3) in Fig. 3] from the quantum dots were clearly observed when the positive filling pulses were more than 3 V with different duration of filling pulses. In cases when the filling pulses were smaller and long, wider and more symmetric DLTS signals (curves 4 and 5) were obtained. These signals were observed in all samples with and without QDs and they had distinctly different physical characteristics. We suppose these signals are attributed to the well-known DX centers in the  $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$  layer.<sup>11,12</sup> To separate parentage of different peaks we have also prepared a similar structure but without quantum dots. In this case, all the quantum dot peaks completely disappeared. Only the DLTS signal from those related to DX centers remained. Besides, the signal from these centers could be completely switched off by means of short filling pulses with duration less than  $5 \times 10^{-5}$  s because of the relatively small capture cross section of such kinds of defects. Figure 3 also shows that the position of the QDs DLTS peak varies with the height of the filling pulses when they are below 5 V and remains about the same when the pulse height is above 5 V. This is due to the shift in the energy level caused by the electric field from the offset voltage and the filling pulses.

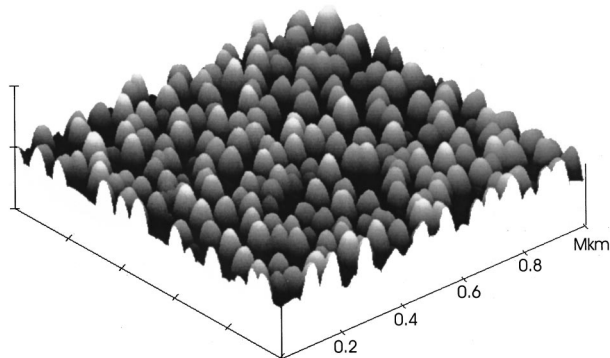


FIG. 2. AFM image of InAs islands.

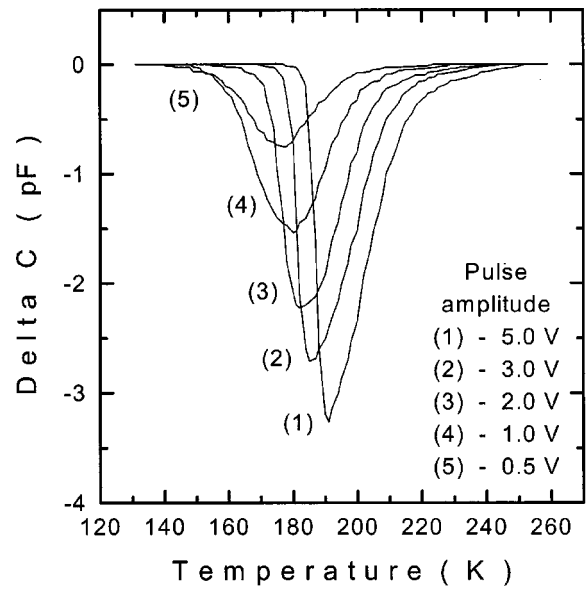


FIG. 3. DLTS spectra taken at a constant offset voltage of  $-5.5$  V and a rate window of  $3.4 \times 10^{-4}$  s with different amplitudes of filling pulses.

From activation plots of these dependencies we determine the emission energies (see Fig. 4). The saturation point corresponds to the flat band condition and the measured activation energy gives an energy difference between the quantized level in the dots and the GaAs band edge to be 0.4 eV. Because of the excellent resolution of the DLTS spectrum, we were able to measure the capture characteristics of the QDs. The electron capture cross section and the quantum dot concentration were then calculated using the ordinary procedure for DLTS analysis to be  $1.07 \times 10^{-12}$  and  $1.0 \times 10^{10}$   $\text{cm}^{-2}$ , respectively. It should be mentioned that the cross section about  $10^{-12}$   $\text{cm}^2$  is much higher than those of commonly observed defects, and it is a good indication of the existence of quantum dots.

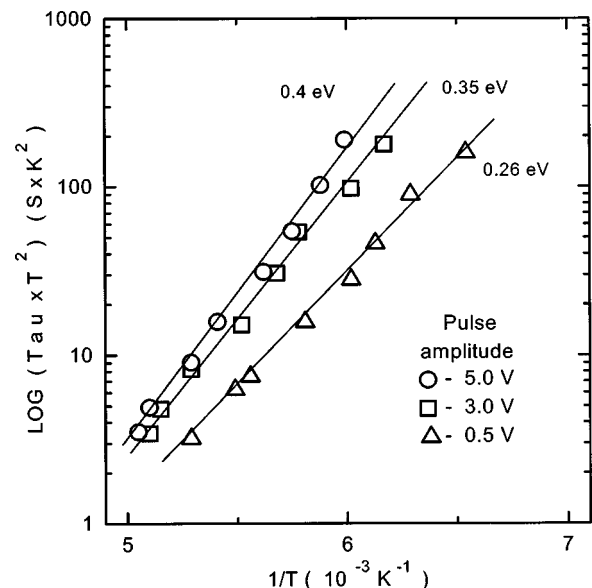


FIG. 4. Activation plot for DLTS signal from QDs with the 3.0–5.0 V pulses, and from DX centers obtained with the 0.5 V amplitude of filling pulses.

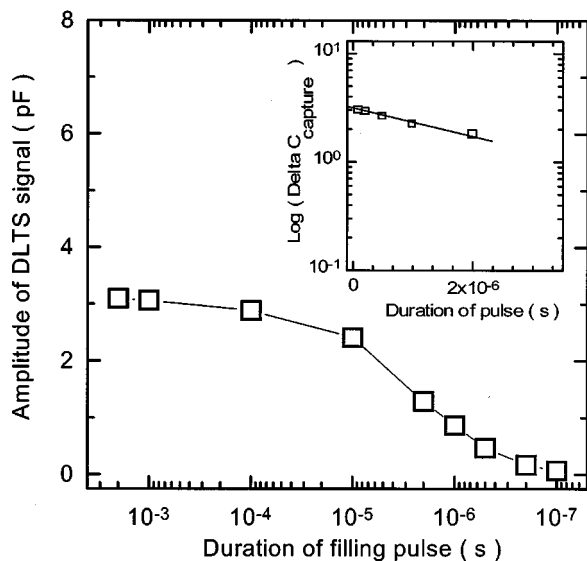


FIG. 5. Dependence of the amplitude of DLTS signal on the duration of the filling pulses. The results of measurements were taken at a constant offset voltage of  $-5.5$  V and amplitudes of filling pulses  $5.0$  V at different duration of filling pulse.

Figure 5 shows the dependence of the amplitude DLTS signal on the duration of the filling pulse. The measurement was taken at a constant offset voltage of  $-5.5$  V and a rate window of  $3.4 \times 10^{-4}$  s. The amplitude of the filling pulses was  $5.0$  V. The capture time can be obtained by fitting this dependence with the following equation<sup>13</sup>

$$C(t_p) - C(t_p = \infty) = C_0 \exp\left(-\frac{t_p}{t_c}\right), \quad (1)$$

where  $C(t_p)$  is the relaxation signal measured with a pulse width of  $t_p$ ,  $C(t_p = \infty)$  is the relaxation signal when the pulse width is infinitely long to saturate the DLTS signal.  $t_c$  is the time of capture, which can be expressed as  $t_c = (\sigma v n)^{-1}$ , where  $\sigma$  is the capture cross section,  $v$  is the electron's thermal velocity, and  $n$  is the free electron concentration. The inset of Fig. 5 shows the fitted result. We see that experimental data of short enough duration of pulses followed Eq. (1) very well. Time of capture of  $3 \times 10^{-6}$  s was calculated on the basis of this result.

We have studied the QDs using an atomic force microscope for as-grown InAs islands (Fig. 2). The average lateral size of the these islands is around  $200$  Å, and height of the islands is around  $30$  Å. Average concentration is about  $1.25 \times 10^{10}$  cm<sup>2</sup>. These numbers agree with the concentration determined by DLTS.

The samples were characterized by photoluminescence. Figure 6 shows the 20 K PL spectra of the samples. The peak related to QDs ground state transition gives an energy of  $1.08$  eV. Combining the QD emission activation energy of  $0.4$  eV from DLTS with the energy of GaAs related emission ( $1.52$  eV) we can approximately estimate a very small band offset for holes.

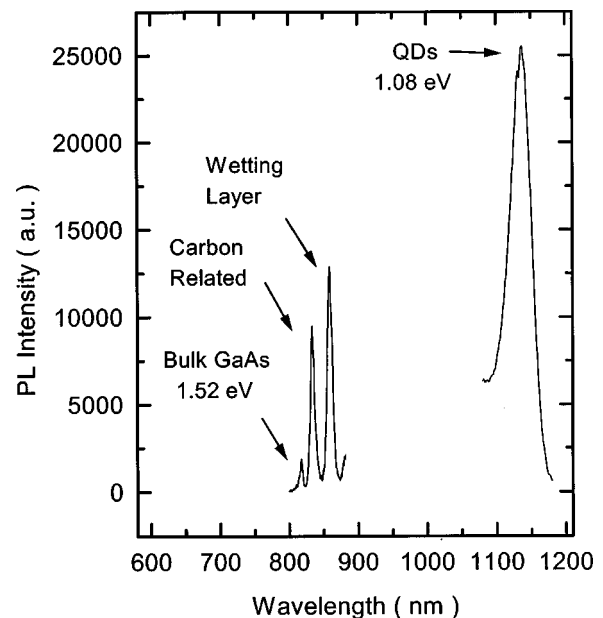


FIG. 6. PL spectra of our sample.

### III. CONCLUSIONS

In conclusion, we have used DLTS to characterize a single-layer of self-assembled InAs QDs. The excellent resolution of the DLTS signals was obtained by using a specially designed structure. The electron ground state energy of the quantum dots was unambiguously determined. The density of the QDs, the capture cross section and the capture time were also determined based on the DLTS results. The obtained results agree with those determined by other methods such as AFM and low temperature PL.

### ACKNOWLEDGMENTS

This work was supported by the National Science Council under Contract No. NSC 89-2215-E-009-013 and the Leem-TI Center of National Chiao Tung University.

- <sup>1</sup>M. M. Sobolev, A. R. Kovsh, V. M. Ustinov, A. Yu. Egorov, A. E. Zhukov, and Yu. G. Musikhin, *Fiz. Tekh. Poluprovodn.*, **33**, 184 (1998) [*Semiconductors* **33**, 157 (1999)].
- <sup>2</sup>H. L. Wang, D. Ning, H. J. Zhu, F. Chen, H. Wang, X. D. Wang, and S. L. Feng, *J. Cryst. Growth* **208**, 107 (2000).
- <sup>3</sup>S. Ghosh, B. Kochman, J. Singh, and P. Bhattacharya, *Appl. Phys. Lett.* **76**, 2571 (2000).
- <sup>4</sup>V. K. Kalevich, M. N. Tkachuk, P. Le Jeune, X. Marie, and T. Amand, *Phys. Solid State* **41**, 789 (1999).
- <sup>5</sup>Y. Toda, S. Shinomori, K. Suzuki, and Y. Arakawa, *Phys. Rev. B* **58**, R10147 (1998).
- <sup>6</sup>F. Y. Tsai and C. P. Lee, *J. Appl. Phys.* **84**, 2624 (1998).
- <sup>7</sup>F. Chen, S. L. Feng, X. Z. Yang, Q. Zhao, Z. M. Wang, and L. S. Wen, *Phys. Low-Dimens. Semicond. Struct.* **11/12**, 179 (1997).
- <sup>8</sup>P. N. Brunkov, A. A. Suvorova, N. A. Bert, A. R. Kovsh, A. E. Zhukov, A. Yu. Egorov, V. M. Ustinov, A. F. Tsatsul'nikov, N. N. Ledentsov, P. S. Kop'ev, L. Eaves, and P. S. Main, *Fiz. Tekh. Poluprovodn.* **32**, 1229 (1998) [*Semiconductors* **32**, 1096 (1998)].
- <sup>9</sup>S. Anand, N. Carlsson, M.-E. Pistol, L. Samuelson, and W. Seifert, *Appl. Phys. Lett.* **67**, 3016 (1995).
- <sup>10</sup>S. Anand, N. Carlsson, M.-E. Pistol, L. Samuelson, and W. Seifert, *J. Appl. Phys.* **84**, 3747 (1998).
- <sup>11</sup>G. Grummt, R. Piekenhain, and L. Lehmann, *Solid State Commun.* **73**, 257 (1990).
- <sup>12</sup>P. M. Mooney, *Semicond. Sci. Technol.* **6**, B1 (1991).
- <sup>13</sup>J. A. Pals, *Solid-State Electron.* **17**, 1139 (1974).