Vol. **114** (2008) *ACTA PHYSICA POLONICA A* No. 5

Proc. XXXVII International School of Semiconducting Compounds, Jaszowiec 2008

Hole-Related Electrical Activity of InAs/GaAs Quantum Dots

P. Kruszewski[a], L. Dobaczewski[a,b,*], V.P. Markevich[b],
C. Mitchell[b], M. Missous[b] and A.R. Peaker[b]

[a]Institute of Physics, Polish Academy of Sciences
al. Lotników 32/46, 02-668 Warsaw, Poland
[b]Microelectronics and Nanostructure Group, School of Electrical
and Electronic Engineering, The University of Manchester, Manchester, UK

We present the hole-related electrical activity of the InAs quantum dots embedded in the *n*-type GaAs. We performed our experiments with the use of the Laplace and conventional deep level transient spectroscopies combined with the above GaAs band-gap illumination. We observed that depending on temperature and electric field the hole emission process is an interplay between the pure thermal emission and tunnelling processes. The tunnelling was quantitatively described by a simple model of the potential barrier.

PACS numbers: 73.21.La, 79.40.+z

1. Introduction

In recent years, due to unusual electrical and optical properties self-assembled quantum dots (QDs) have become an object of intensive investigations [1]. Various experimental techniques like photoluminescence [2, 3] or photocurrent [4–6] have been successfully used to determine the QDs ground state and mechanisms of the carrier capture, redistribution and escape processes. It is well known that InAs QDs embedded in the GaAs matrix form confined quantum wells in the conduction and valence bands. The electron and hole binding energies in such a system strongly depend on the dot size [7] and also depending on size QDs can be occupied by a different number of carriers with at most two electrons and/or holes on the ground state. These carriers can be thermally activated at high temperatures or can tunnel through an energy barrier if QDs are at an electric field in a space charge region of a sample.

The major feature of the deep level transient spectroscopy (DLTS) method is that it can precisely detect changes of the total charge of a p–n or the Schottky

---

[*] corresponding author; e-mail: dobacz@ifpan.edu.pl

junction depletion region. If QDs are in the space charge region then by detecting the sign of these changes it is also possible to distinguish the QD's charge variation resulting from the majority and minority carriers trapping and emission processes. For the QDs embedded in the *n*-type material the majority carrier electrical pulses used in the conventional DLTS method allow to study the QD-related trapping potential for electrons in the conduction band. If the majority carrier pulses are replaced by the above band-gap light pulses then the hole-binding potential in the valence band can be analysed. In the literature the latter experimental procedure is called the minority carrier transient spectroscopy (MCTS) [8].

2. Samples

The samples used in this study consisted of the InAs wetting layer with quantum dots and this was sandwiched by two 400 nm thick Si-doped *n*-type GaAs layers grown by molecular beam epitaxy on (100) n^+-GaAs substrates. Two studied samples differed by the amount of InAs used to form QDs: 2.2 monolayer (ML) and 1.8 ML. Quantum dots density was around 3×10^9 cm^{-2} in both cases and was evaluated by the atomic force microscope measurements. The standard ohmic contacts were produced by evaporating of Au–Ge–Ni on the back side of the sample, and the top Schottky contacts were defined by evaporating Au–Ti through the shadow mask with the diameter of 450 μm. The $C{-}V$ measurements showed that for the zero voltage bias QDs were outside of the depletion region. For the reverse bias the depletion region could be expanded up to QDs layer which allowed to change their occupancy which was necessary for signal detection [9].

3. Results

A schematic diagram demonstrating processes leading to the QDs charging and emptying is presented in Fig. 1. The incident light creates a certain concentration of minority carriers which diffuse near the space charge region and then are dragged into it by the electric field. This allows QDs to trap holes with the binding energy E_{a}. The ground-state electronic level can be occupied by one or two holes. However, for the two-hole occupancy the holes repeal each other which shifts the total energy of QD by the so-called "Coulomb blockade" energy.

At low temperatures, when thermal emission is slow, the tunnelling process can take place if the electric field is high enough. This process is showed in Fig. 1 by a black horizontal arrow. The probability (rate) of the tunnelling process strongly depends on the electric field at QD. At higher temperatures thermal emission becomes faster than tunnelling thus depending on temperature and electric field contributions of these two processes into the hole emission vary. In the present study the competition between these processes has been analysed and the fact that both of them could be observed helped to conclude about the hole binding potential character.

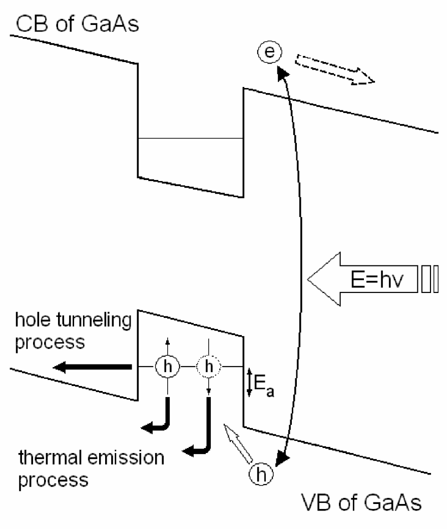

Fig. 1. Schematic diagram of the emission processes from the ground state of a quantum dot. Incoming over GaAs band-gap light creates an exciton from which a hole can be trapped by the dot if it is in the sample space charge region. Black arrows indicate the tunnel and thermal hole emission processes.

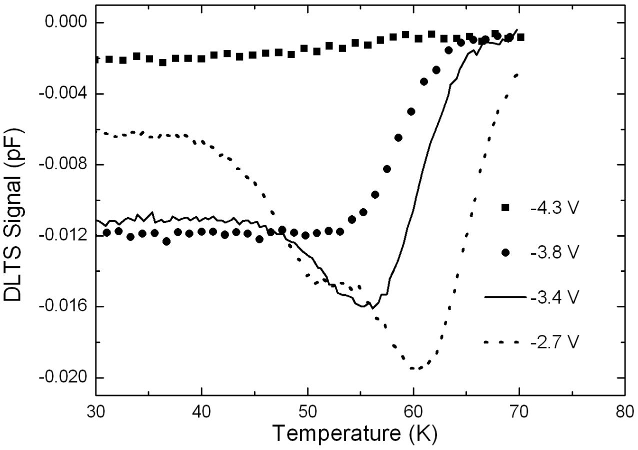

Fig. 2. Conventional DLTS spectra obtained for four different sample biases. Spectra were taken in for the minority carrier (hole) filling pulses and at a rate window of 20 s^{-1}. See text for details.

Figure 2 shows four conventional DLTS curves measured with the same rate window (RW = 20 s^{-1}) and for the same light pulsing procedure and different sample reverse biases. Here larger sample reverse bias means that the QDs experience stronger electric field. All curves are below zero base line which is an indication that the measured DLTS signal comes from the minority carriers. It is seen that for the highest electric field (square points in Fig. 2), the signal is rather small and does not change much with the temperature. In the conventional DLTS-type emission process analysis this means that the emission is very fast and temperature independent. For a smaller bias the signal is still constant but the amplitude is higher (circle points in Fig. 2) which can indicate that the emission is still temperature independent but slower than in the previous case. For the bias of –3.4 V more features appeared (solid line in Fig. 2). In this case at lower temperatures the signal is still constant but small, then increases and at 55 K reaches the maximum. This is a typical behaviour observed on the conventional DLTS curve when a temperature independent defect ionisation process (the tunnelling in this case) observed predominately at low temperatures competes with the temperature activated thermal emission observed at higher temperatures [10]. The curve obtained for the –2.7 V (dotted line in Fig. 2) shows a similar character as the one for –3.4 V. The peak associated with the thermal activation process shifts to higher temperature. Moreover, at 50 K a new peak appears which is well separated from the main one. In previous works [9, 11] it has been reported that it is possible to observe the emission of one or two electrons from the ground state. We expect that this is an analogous situation observed for the binding potential in the valence band. As it has been mentioned above, the binding energy for both holes should be the same. However, the capture process of the second hole should be prevented by the Coulombic repulsion which should form a capture barrier for the second carrier [2]. This makes that on the DLTS spectra the emission processes of both carriers are observed at different temperatures.

This general picture of the hole emission process has been qualitatively analysed in the following way. At high temperature range and for the lowest electric fields possible a series of the isothermal Laplace DLTS [12, 13] spectra have been taken at different temperatures in order to construct the Arrhenius plot for the thermally activated hole emission process. This allowed to obtain the hole binding energy for both samples analysed. Then at low temperature range, where the emission is not thermally activated, again a series of the Laplace DLTS spectra have been measured at different sample biases and, as a result, electric fields, and this gave the electric field dependence of the hole emission at temperatures where the thermal emission process is not contributing to the overall emission. For the tunnelling emission a simple triangle energy barrier model has been applied [14]. In this model the logarithm of the emission rate should linearly depend on the inverse of the electric field according to the formula

$$e(F) = \frac{qF}{4\sqrt{2m^{*}E_{\mathrm{a}}}} \exp\left(-\frac{4}{3}\frac{\sqrt{2m^{*}}E_{\mathrm{a}}^{3/2}}{q\hbar F}\right), \qquad (1)$$

where q — elementary charge of the hole, F — electric field, E_{a} — energy depth of the hole level (see Fig. 1), m^{*} — hole effective mass, $\hbar$ — the Planck constant.

TABLE

Comparison of the calculated and experimental values of the emission rate logarithm versus reciprocal electric field dependence (see formula (1)).

Sample	Calculated value	Experimental value
2.2 ML, $E_\mathrm{a} = 56$ meV	-2.39×10^7	-5.0×10^7
1.8 ML, $E_\mathrm{a} = 46$ meV	-1.90×10^7	-3.0×10^7

The experimental values when plotted in the logarithm of the emission rate versus reciprocal electric field followed straight lines for both samples and the slopes of these lines are given in Table. These slopes could be calculated according to formula (1) when the activation energies for the thermal emission process measured at higher temperatures have been taken as the thermal depths of the hole levels. The obtained values are given in Table as well. Keeping in mind simplicity of the model used the agreement between measured and calculated values is very satisfactory. The experimental values are larger than the calculated ones and this could be explained by rather unknown value of the carrier mass which tunnel through the barrier. We took the valence band effective mass, however it could be that in the tunnelling process the mass should be closer to the free electron mass and this could be seen as a larger experimental than calculated value of the slope.

4. Summary

In our work the hole related electrical activity of the InAs/GaAs quantum dots has been analysed. It is presented that the conventional DLTS measurements realised in the MCTS mode show two regimes where the trapped holes are released from the dots. At low temperatures it is the pure tunnelling process, which can be described by a simple triangle energy barrier model, while at higher temperatures the holes are emitted in the thermal process.

Acknowledgments

The work has been financially supported in the UK by the Engineering and Physical Research Council (EPSRC) and Oxford Instruments Plasma Technology and in Poland by the Ministry of Science and Higher Education project No. N N202 0911 33.

References

[1] I.N. Stranski, L. Von Krastanow, *Abhandlungen der Mathematisch-Naturwissenschaftlichen Klasse*, Akademie der Wissenschaften und der Literatur in Mainz, Vol. 146, 1939, p. 797.

[2] K.H. Schmidt, G. Medeiros-Ribeiro, M. Oestreich, P.M. Petroff, *Phys. Rev. B* **54**, 11346 (1996).

[3] S.W. Lin, A.M. Song, N. Rigopolis, B. Hamilton, A.R. Peaker, M. Missous, *J. Appl. Phys.* **100**, 043703 (2006).

[4] P.W. Fry, I.E. Itskevich, S.R. Parnell, J.J. Finley, L.R. Wilson, K.L. Schumacher, D.J. Mowbray, M.S. Skolnick, M. Al-Khafaji, A.G. Cullis, M. Hopkinson, J.C. Clark, G. Hill, *Phys. Rev. B* **62**, 16784 (2000).

[5] P.N. Brounkov, A. Patane, A. Levin, L. Eaves, P.C. Main, *Phys. Rev. B* **65**, 085326 (2002).

[6] W.-H. Chang, T.M. Hsu, C.C. Huang, S.L. Hsu, C.Y. Lai, N.T. Yeh, T.E. Nee, J.I. Chyi, *Phys. Rev. B* **62**, 6959 (2000).

[7] P. Hawrylak, A. Wojs, *Semicond. Sci. Technol.* **11**, 1516 (1996).

[8] R. Brunwin, B. Hamilton, P. Jordan, A.R. Peaker, *Electron. Lett.* **15**, 349 (1979).

[9] S. Schulz, S. Schnull, Ch. Heyn, W. Hansen, *Phys. Rev. B* **69**, 195317 (2004).

[10] K. Bonde Nielsen, E. Andersen, *J. Appl. Phys.* **79**, 9385 (1996).

[11] O. Engstrom, M. Malmkvist, Y. Fu, H.O. Olafsson, E.O. Sveinbjornsson, *Appl. Phys. Lett.* **83**, 3578 (2003).

[12] L. Dobaczewski, A.R. Peaker, K. Bonde Nielsen, *J. Appl. Phys.* **96**, 4689 (2004).

[13] See: http://www.laplacedlts.eu.

[14] M. Geller, E. Stock, C. Kapteyn, R.L. Sellin, D. Bimberg, *Phys. Rev. B* **73**, 205331 (2006).