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Solid State Communications 126 (2003) 563–566

solid state communications

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Deep level transient spectroscopy of vertically stacked $InAs/Al_{0.5}Ga_{0.5}As$ self-assembled quantum dots

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Received 5 March 2002; received in revised form 14 March 2003; accepted 4 April 2003 by H. Akai

Abstract

Quantum dots (QDs), which capture and emit carriers like a giant trap, are studied using deep level transient spectroscopy (DLTS). The electrons and holes in the QDs are emitted from the relevant energy levels to the conduction and valence bands, respectively, of the barrier layers with increasing temperature. The thermal emission energies from the QDs are related to their initial energy levels. In this paper, five-period vertically stacked InAs QDs in the barrier layers of a field-effect type structure are measured. The results agree well with capacitance–voltage and photoluminescence measurements. In addition, the dependence of DLTS signal on the pulse voltage and light illumination is presented. The results prove that DLTS is a powerful tool for the study of the electronic structure of QDs.

PACS: 73.20.Dx; 68.65. + g; 71.55.Eg; 61.82.Fk

Keywords: A. Semiconductors; B. Epitaxy; D. Recombination and trapping

Deep levels often behave as carrier traps or as generation and recombination centers. For this reason, the deep level transient spectroscopy (DLTS) established by Lang has been widely used to investigate the properties of deep levels [1,2]. Quantum dots (QDs) acting as giant traps can capture and emit carriers from the barrier regions in the same way as deep levels. In this paper, the self-assembled QDs with large confinement potentials, which are used to store charges as memory devices [3], are studied by DLTS. Capacitance–voltage (C–V) measurement for QSs is also performed to clarify the electronic structure [4,5]. The thermal emission from the QDs with large confinement potentials might be able to mask the emission from the deep levels in the DLTS data since the latter has exponential dependence on the binding energy with increasing temperature [6]. To know the position of the QD energy levels, particularly of the ground state, is of primary importance. These discrete energy levels are described by use of the DLTS data and are compared with the C–V and photoluminescence (PL) results.

The sample is first cooled down below 90 K using liquid nitrogen and then heated until 400 K. In the PL measurement the sample is in a closed-cycle He cryostat (20–300 K) and excited by a 514.5 nm line of Ar^+ ion laser as an excitation source. The sample in this study is 5-period vertically stacked InAs QDs in an $Al_{0.5}Ga_{0.5}As$ barrier layer grown by molecular beam epitaxy using solid sources of Al, Ga, In, and As in non-cracking K-cells [6,7]. The structure of the QD sample consists of a 500 nm Si-doped GaAs buffer layer on Si-doped GaAs substrate, a 500 nm GaAs

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0038-1098/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0038-1098(03)00299-0

layer, a 15 nm $Al_{0.5}Ga_{0.5}As$ barrier layer, 5-periods of vertically stacked InAs QDs after depositing 2 monolayers of GaAs smoothing layer, a 50 nm $Al_{0.5}Ga_{0.5}As$ barrier layer, and a 15 nm GaAs cap layer. The QDs at respective period are about 3 nm high and about 30 nm wide in size, and about $1 \times 10^{10}\ cm^{-2}$ in density, which are vertically separated by 5 nm thick spacer layers each other.

In Fig. 1, the surface morphology of the first and fifth sheets are shown together with the histograms of width and height of the dots. The atomic force microscopy data show no big difference between the first and fifth QD layer as is seen in the histograms. This indicates that the vertically stacked QDs are homogeneously distributed, which enables the strong confinement in the vertical stacking of InAs QDs.

The DLTS and C–V measurements were carried out using standard technique in New Materials Research Center, Osaka Institute of Technology and performed using a HP 4280A 1 MHz capacitance meter, a pulse generator, and a temperature controller. The measurement process is controlled by a computer: the different rate window signals of the capacitance meter, which are regulated by the computer controlled generator, are applied to Au metal electrode (about 1 mm^2) of the sample surface and In metal electrode on the sample rear, the sample temperature is varied within 90–400 K range.

C–V measurement is known to be a very powerful technique to obtain the concentration and distribution of carriers, band offsets, density of states and other parameters of the semiconductors [8]. The signals related to wetting layer (WL) and QDs might be obtained by the C–V measurement at 77 K using a back contact geometry [9,10]. The capacitance spectrum in Fig. 2 is obtained under the illumination by a fluorescent lamp and dc bias which is used to move the Fermi level in the $Al_{0.5}Ga_{0.5}As$ band gap. At $U < -1.3$ V, both the ground states of QDs and WL are above the Fermi level. At $U \sim -1.2$ V, the ground state of

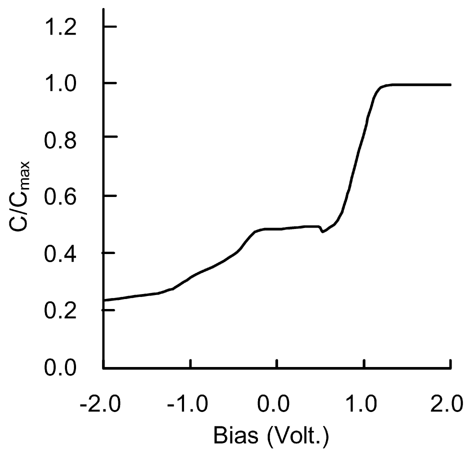

Fig. 1. The surface morphology of first sheet and fifth sheet QDs by AFM and histograms of width and height of QDs, to which the good-distribution is shown.

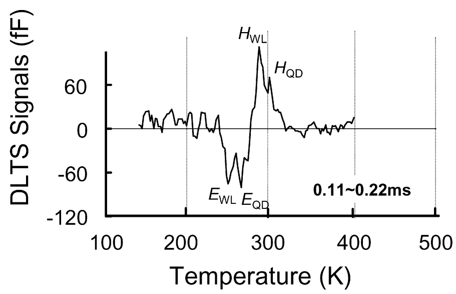

Fig. 2. C–V spectrum for a stacked QD sample.

QDs is shifted below the Fermi level, and electrons become to tunnel from the back contact into each QD. With increasing the bias voltage, the QD ground state continues to be charged, and the tunneling into the QDs is shown by the broad shoulder between $-1.2\ V < U < -0.4$ V. At U about -0.2 V, the ground state of WL is shifted below the Fermi level. Therefore, more electrons start to tunnel from the back contact into the two-dimensional (2D) WL, and then a plateau is observed in the C–V curve due to the successive electron tunneling through the high potential barrier of $Al_{0.5}Ga_{0.5}As$, which is one of characteristics of the QD structure under the illumination.

QDs may be characterized by three parameters: an activation energy which is the position of the energy level in the band gap, the concentration, and the capture cross section which provides a measure of the ability of QDs to trap carriers. The signal of DLTS is the difference between capacitances measured at times $t_1 - t_2$, namely $C(t_1) - C(t_2)$, and the overall signal amplitude from the QD samples over the entire range of scanned temperature is found to be higher than that without QDs. The sign of the peaks indicates the type of trapped carriers (i.e. the positive signal corresponds to a hole energy level, and the negative one to an electron trapping energy level), the height of the peaks is proportional to the concentration, and the position, in the scanned temperature, of the peaks is uniquely determined by the degree of carrier confinement [11]. Some papers have reported that DLTS peaks of InAs/GaAs self-assembled QDs locate at low temperature regions (typically below 100 K) due to the small activation energy [4,11]. In the case of $InAs/Al_{0.5}Ga_{0.5}As$ QDs with high potential barrier, however, it is reasonable to expect the QD DLTS signals to appear at around room-temperature.

Fig. 3 shows the DLTS spectra in the dark. The rate window is $t_1 - t_2$, mean voltage, pulse voltage and pulse hold time are $0.11 - 0.22$ ms, -2, 2 V, and 10 ms, respectively. While increasing temperature, the energy levels corresponding to the different thermal ionization energy gradually become visible in the DLTS spectrum, which is a consequence of the increased thermal escape of carriers from the dots. The electron thermal emission peaks from WL ground state (E_w) and QD ground state (E_q) and the hole thermal emission peaks from WL ground state (H_w) and QD ground state (H_q) are all observed. In contrast to the

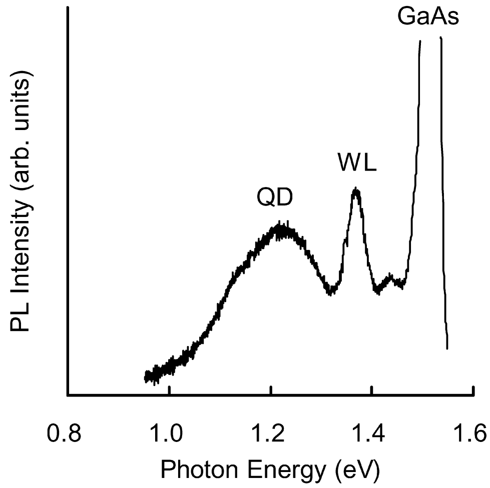

Fig. 3. DLTS spectrum observed from a stacked QD sample. The QD and WL thermal emission peaks of electrons and holes are observed. The electron thermal activation energies of QD ground state and WL layer are about 0.51 and 0.39 eV, and the hole thermal activation energies of QD ground state and WL layer are about 0.32 and 0.24 eV.

spectra shown in Fig. 3, in the HEMT type structure without QDs, the major peak is due to the EL_2 antisite donor deep level, which is the most common trap in GaAs [12].

The PL spectrum at 20 K is shown in Fig. 4, where the transition (1.37 eV) between two WL ground states as well as the transition (1.23 eV) between two QD ground states is observed. The emission peak from the QDs is very weak compared to the emission from the GaAs band edge, because a part of the excited carriers escape from the QDs due to the strong built-in bias in the $Al_{0.5}Ga_{0.5}As$ barrier layer. Phonon bottleneck mechanism also dominates the intrinsically poor luminescence efficiency from the QDs at 20 K [13,14]. The carrier relaxation into the QD discrete levels would be significantly slowed due to a lack of phonons to satisfy the energy conservation rule, and the long relaxation lifetime is thought to significantly degrade the efficiency of radiative recombination [15]. On the other hand, the thermal emissions of electrons and holes from the QD ground states to the barrier layer are expected to occur much slower than those from the WL ground states. In fact, only the radiative recombination at the QDs is observed in the PL spectra at room-temperature.

Fig. 5 shows the result of the DLTS measurement in the dark. The mean voltage is -2 V, the pulse voltage being 1 V, the pulse hold time being 10 ms, and the rate window $t_1 - t_2$ being $0.2 - 0.6$ ms. Since pulse voltage becomes small, the efficiency of electron tunneling to the QDs is obviously small; however, the efficiency of hole tunneling keeps nearly equal to the former case shown in Fig. 3 because the quantum confinement of holes is smaller than that of electrons (i.e. the barrier potential for holes is smaller than that for electrons).

In Fig. 6, the parameters for measurement are the same to Fig. 5 except the illumination by the fluorescent lamp and the rate window. In the figure, the enhancement of peak height is observed probably due to the increased thermal emission by the illumination. Note that the height of respective peaks is about six times stronger compared to those in Figs. 3 and 5. Under the illumination, electrons are ionized from the valence to conduction bands of the barrier layer to produce excess carriers which might be excessively trapped by the QDs [16]. These trapped carriers apt to stay in the ground state due to the lowest-kinetic-energy and rapid relaxation from other discrete levels, which explains the selective enhancement of H_{qd} and E_{qd} peaks compared to E_{wl} and H_{wl}.

In conclusion, the energy levels of electron and hole emissions from vertically stacked InAs QDs embedded in $Al_{0.5}Ga_{0.5}As$ barrier are studied by C–V, DLTS, and PL spectroscopy. Due to a strong quantum confinement by the deep $Al_{0.5}Ga_{0.5}As$ barrier, the retarded carrier relaxation at the WL and QD ground state levels makes a sizable contribution to the DLTS spectra, the peaks of which appear at around room-temperature. The DLTS measurement shows the spectra of electron and hole levels as negative and positive peaks, respectively, which indicates the importance of this technique to study electronic properties of QDs.

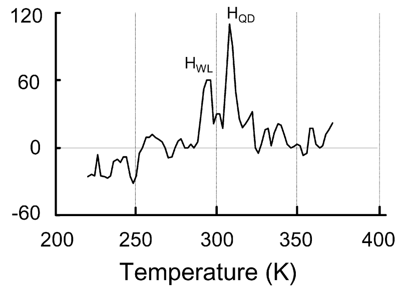

Fig. 4. PL spectrum observed from the same sample to Fig. 1. QD and WL transition peaks corresponding to the C–V and DLTS spectra are observed.

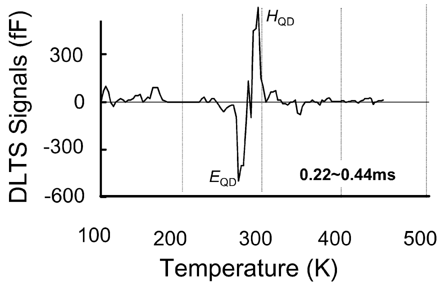

Fig. 5. DLTS spectrum with a decreased pulse voltage. Only the hole peaks of QD and WL are observed since the barrier potential for holes is smaller than that for electrons.

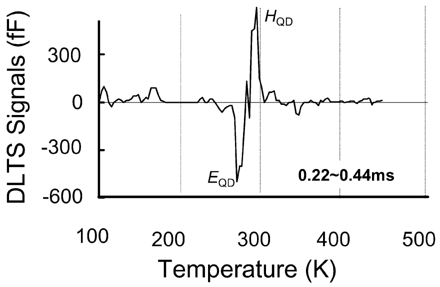

Fig. 6. DLTS spectrum under an illumination. The signals of the electron and hole ground state peaks are six times larger than former results.

Acknowledgements

The author was supported by the Monbusho's Grant-in-Aid for JSPS Fellows relating to the JSPS Postdoctoral Fellowship for Foreign Reseachers.

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