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Comparison of hole and electron emission from InAs quantum dots

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Abstract. Carrier escape processes from self-organized InAs quantum dots (QDs) embedded in GaAs are investigated by time-resolved capacitance spectroscopy. Electron emission is found to be dominated by tunneling processes. In addition to tunneling from the ground state, we find thermally activated tunneling involving excited QD states with an activation energy of 82 meV. For holes, the tunnel contribution is negligible and thermal activation from the QD ground state to the GaAs valence band with an activation energy of 164 meV dominates. Extrapolation to room temperature yields an emission time constant of 5 ps for holes, which is an order of magnitude larger than for electrons. The measured activation energies agree well with theoretically predicted QD levels.

Introduction

The peculiar properties of self-organized quantum dots (QDs) have stimulated rapidly growing research interest during the last few years [1]. Capacitance spectroscopy of self-organized QDs has been used to investigate the electronic level structure and Coulomb charging effects [1–3]. In this paper, we report on study of carrier emission from single-layer InAs QDs in GaAs matrix by means of deep level transient spectroscopy (DLTS). Using very similar QDs in n- and p-doped matrices, it is possible to investigate electron and hole escape separately and to compare the emission mechanisms. We clarify fundamental differences in the emission processes for electrons and holes.

1. Experimental details

Two types of samples were investigated: The first, referred to as 'P', is a n^+p diode structure with InAs QDs (nominally 3.3 ML, grown at 480 °C) embedded in a Be-doped GaAs matrix ($p = 2.0 \times 10^{16}\,\mathrm{cm}^{-3}$) at a distance of 500 nm from the n^+p interface. The QDs are sandwiched between two 10 nm thick undoped GaAs buffers. To form devices, processing based on standard optical lithography was applied. Circular mesas with 200 μm diameter were created by wet chemical etching and ohmic contacts to the p^+ substrate and the n^+ top layer were formed by evaporation and alloying of AuZn and AuGe, respectively. The second sample, referred to as 'N', contains InAs QDs grown under very similar conditions (nominally 4 ML InAs, grown at 485°C) in Si-doped GaAs ($n = 2.0 \times 10^{16}\,\mathrm{cm}^{-3}$) at a distance of 400 nm from AuCr Schottky contacts, also with 10 nm thick undoped buffers. The circular Schottky contacts have a diameter of 350 μm. From photoluminescence experiments (not shown here) we conclude that the structural properties of both sets of QDs are very similar. The ground state transition of the QDs in sample 'P' at 1.113 eV at 10 K is only 33 meV lower than the one of the QDs in sample 'N'. Furthermore the excited state splitting observed in PL under high excitation density of 75 meV as well as the linewidths are almost identical for both samples.

2. Results and discussion

The capacitance–voltage characteristics (CV) of both samples (Fig. 1) show pronounced steps. This behavior is directly related to the QDs [2, 3]. When the reverse bias is increased, the depletion region of the n^+p or Schottky interface reaches the QD layer and is pinned there. As a consequence the capacitance remains roughly constant until all charge from the QD layer is removed and the depletion region starts to extend further into the matrix material. This happens for a reverse bias of about −3 V in sample 'N'(Fig. 1(a)) and a reverse bias of about 0.5 V in sample 'P' (Fig. 1(b)). For higher biases the device capacitance C follows the bulk dependence on external bias U for constant doping concentration: $C \sim U^{-1/2}$. From such steps it is possible to estimate the QD energy levels by comparison with simulations [2]. If the depletion region is sufficiently larger than the distance of the QDs from the interface, the QD ground states are lifted above the Fermi level. Consequently the QDs are releasing their carriers (see inserts of Fig. 1).

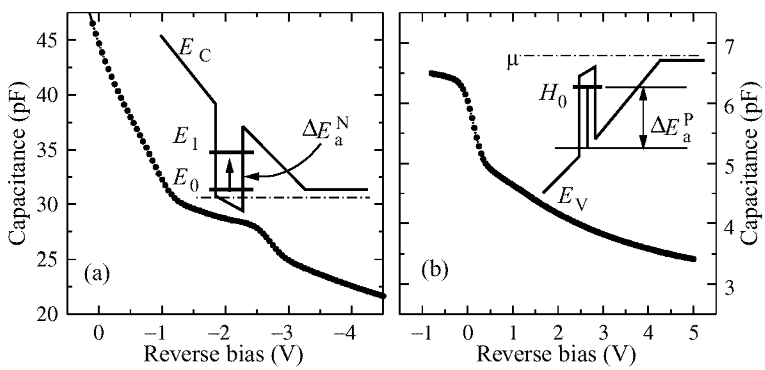

Fig. 1. Capacitance–voltage characteristics of samples 'P' (a) and 'N' (b) at $T = 160$ K for a measurement frequency of 1 MHz. The schematic valence band for a QD in the depletion region of p-GaAs at finite reverse bias is depicted in the inset of panel (a), the schematic conduction band for a QD in the depletion region of n-GaAs at finite reverse bias is depicted in the inset of panel (b).The QD ground state levels, H_0 and E_0 respectively, are lifted above the Fermi level μ of the undepleted GaAs, therefore carriers are emitted.

In order to investigate the carrier emission processes, we used a standard DLTS technique. First, the diodes were biased with a detection bias U_{low} for which the QDs are empty. Then during a forward bias pulse U_{high} the QDs are filled with carriers. After the pulse, carrier emission can be directly monitored via the transient capacitance of the space charge region of the diode. The data is finally converted into DLTS plots using a double-boxcar correlator with a reference time constant t_{ref}. The width of the space charge region depends on the amount of charge inside, and thus on the amount of carriers in the QDs.

The DLTS signal of sample 'N' (open circles in Fig. 2(a)) is due to electron escape. It exhibits a peak at about 40 K and a constant contribution towards lower temperatures. Similar behavior has previously been observed for electron emission from vertically coupled QDs [3]. The constant low-temperature signal is due to tunnel emission from the QD ground state to the matrix conduction band and the peak is attributed to thermally activated

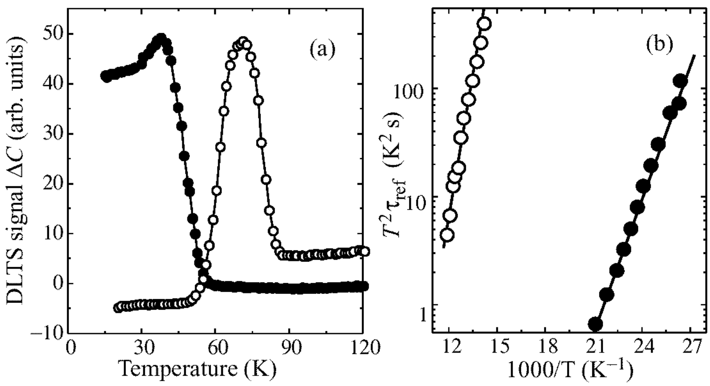

Fig. 2. (a) DLTS signal of hole emission from the QDs in sample 'P' (open circles) for detection/pulse biases of 2.0 V/ −0.4 V, a filling pulse width of 20 ms, and a reference time constant of $t_{\mathrm{ref}} = 62.5$ ms. For comparison, the DLTS signal from electron emission in sample 'N' (filled circles) is displayed for detection/pulse biases of −2.8 V/ −0.2 V and identical filling pulse width. (b) Arrhenius plot of the QD-related DLTS peaks of samples 'P' and 'N' (open and filled circles, respectively).

tunneling. The thermal emission rate is usually written:

$$e_{\mathrm{a}} = \gamma T^2 \sigma_\infty \exp\left(-\frac{\Delta E_{\mathrm{a}}}{kT}\right) \tag{1}$$

where ΔE_{a} is the activation energy, σ_∞ the capture cross section for $T = \infty$, and γ a temperature-independent constant. From an Arrhenius plot of the DLTS peak position for varying reference time constants t_{ref} (Fig. 2(b)) we obtain $\Delta E_{\mathrm{a}}^N = (82 \pm 10)$ meV and $\sigma_\infty^N \simeq 3 \times 10^{-12}$ cm^2. We attribute the high-temperature escape to a two stage process: thermal activation from the QD ground state to the first excited state and subsequent tunnel emission, see inset of Fig. 1(a). The activation energy ΔE_{a}^N can thus be taken as a measure for the ground state/excited state level spacing. This interpretation is in very good agreement with theoretical predictions (see below) and previously reported experimental results for the QD ground and excited state localization energies of the same sample, 140 meV and 60 meV below the GaAs conduction band, respectively [2]. Comparison with the excited state splitting of 75 meV observed in PL under high excitation conditions [2] suggests the hole state splitting to be much smaller.

Sample 'P', showing DLTS signal from hole escape, exhibits a fundamentally different behavior. No constant low-temperature signal related to tunneling processes is visible and the thermally activated peak appears at a significantly higher temperature of about 75 K. At higher temperature, a slowly increasing background signal becomes visible, which belongs to a peak related to defects in the GaAs barrier grown at low temperatures. From an Arrhenius plot, Fig. 2(b), one obtains $\Delta E_{\mathrm{a}}^P = (164 \pm 10)$ meV and $\sigma_\infty^P \simeq 5 \times 10^{-12}$ cm^2. These values depend somewhat on the detection- and pulse-biasing conditions, which reflects the fact, that it is possible to only partly fill or empty the QD ensemble, depending on the position of the Fermi level during the filling pulse and detection, respectively. Also barrier lowering effects due to the vertical electric field, as described previously for electrons [3], may play a role. For the biases applied here, this effect is estimated to lie in the order of 5 meV and is therefore not taken into account. In contrast to the case of electrons, however, the hole emission is purely thermally activated on the time-scale accessible by DLTS.

The measured activation energy $\Delta E_{\mathrm{a}}^{P}$ is attributed to thermal activation from the QD hole ground state to the GaAs matrix valence band, i.e. the emission in the case of holes is taken to be a single step process, see inset of Fig. 1(a). This interpretation is supported by predictions for the hole localization based on 8-band $\mathbf{k} \cdot \mathbf{p}$ calculations for pyramidal InAs/GaAs QDs with {101} side facets, see Ref. [4].

The fundamental difference in the emission processes observed for electrons and holes can be explained by the larger effective mass of the latter, which has a twofold effect. First, tunneling is suppressed for holes, since the tunneling current depends exponentially on the square root of the effective mass. And second, the level spacing in a QD is predicted to be much smaller for holes than for electrons [4], which is also supported by the present data. The effectively higher density of hole states in the QD and provides more effective carrier relaxation. An increasing relaxation rate decreases the efficiency of multi stage escape processes and conclusively increases the effective barrier height. The extrapolated hole confinement time of 5 ps at room temperature in our experiment, is much larger than for electrons with about 0.4 ps.

In conclusion, we have investigated hole and electron escape from a single layer InAs QDs in a GaAs matrix by time-resolved capacitance spectroscopy and found fundamentally different behavior. In the case of electrons, besides direct tunnel emission a thermally activated tunneling process involving excited QD states dominates for high temperatures. For holes, however, only thermal activation from the QD ground state directly to the GaAs valence band contributes and tunneling is not observed. Therefore the hole localization time in the QDs is significantly larger than the one of electrons. This effect can be explained by the larger effective mass having two consequences: a reduced tunneling probability and more effective carrier relaxation mechanisms.

Acknowledgements

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