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Electron escape from self-assembled InAs/GaAs quantum dot stacks

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Abstract

Capacitance–voltage characteristics have been measured at various frequencies and temperatures for a Schottky barrier structure containing three sheets of self-assembled InAs quantum dots in an n-GaAs matrix. By changing the frequency of the measuring signal at fixed temperature, it is possible to control the ratio between the thermionic and the tunnel contributions to the electron escape from the quantum dots. An applied magnetic field reduces the thermionic emission rate and increases the importance of the tunnel part of escape of electrons from the dots due to the deepening of electron level in the dots by Landau quantization in the GaAs conduction band. © 1998 Elsevier Science B.V. All rights reserved.

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In recent years there has been great interest in the properties of heterostructures containing quantum dots (QDs) formed by the transformation of inherently unstable two-dimensional coverages [1–8]. In this paper we report a capacitance–voltage ($C(V)$) study of a structure with a Schottky barrier on an n-type layer containing an array of vertically coupled quantum dots (VECQDs).

The samples are based on a type I InAs–GaAs heterostructure and were grown by MBE on a n^+-GaAs substrate. The array of VECQDs consists of three sheets of InAs QDs with a 50 Å thick GaAs spacer inserted between the InAs islanding layers. The QDs were formed in situ as the result of the transformation of an elastically strained InAs layer with effective thickness 1.7 ML on a lattice mismatched GaAs layer. The QDs may be used as stressors to form the next layer of QDs, provided the thickness of the spacer is less than 100 Å [3,4]. In this case the QDs are vertically aligned (stacked) and electronically coupled in the growth direction. Therefore, each stack of QDs may be

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considered as one large QD (like a pillar). The VECQDs were sandwiched between a 0.5 μm-thick GaAs cap and 1 μm-thick GaAs buffer layers. The cap and buffer layers were uniformly doped with Si at a level of about 2×10^{16} cm^{-3} except for 100 Å thick undoped spacers on each side of the VECQDs layer. Schottky barriers were made by deposition of Au through a shadow mask (350 μm diameter).

The $C(V)$ characteristics of the devices were measured over a frequency range of 10 kHz to 1 MHz using an HP4275A LCR meter. The amplitude of the measuring signal (V_{osc}) was 10 mV.

There is a step in the $C(V)$ characteristic related to the discharging of the QDs (Fig. 1a) [5–7]. Applying the depletion-layer approximation [9] to the $C(V)$ characteristic, we calculate the *apparent* concentration profile $N_{CV}(W)$ (Fig. 1b) using the relations

$$N_{CV}(W) = C^3\left(q\varepsilon\varepsilon_0\frac{dC}{dV}\right)^{-1} \quad \text{and} \quad W = A\frac{\varepsilon\varepsilon_0}{C}, \quad (1)$$

where W is the depth, q is the electron charge, ε is the dielectric constant, and A is the area of the Schottky barrier.

For $T > 50$ K, there is a peak at $W = 0.52$ μm corresponding to the depth of the QD plane (Fig. 1b). According to the model presented in Refs. [5–7], the width of a plateau in the $C(V)$ characteristic depends on the steady-state occupation of the electron levels in the QDs. This, in turn, is determined at a given temperature by the sheet concentration N_{qd} of QDs and the Fermi–Dirac function depending on the relative positions of the electron level in the QDs (E_{qd}) and the bulk Fermi level (E_F) in the GaAs matrix [5–7]. The sheet concentration of QDs was found to be $N_{qd} = 5\times10^{10}$ cm^{-2} from a plan-view transmission electron microscopy image. The density of electron states in the QD sheet may be approximated by a Gaussian function, which describes the spread of energies associated with the distribution of QD sizes [3]. By fitting measured $C(V)$ characteristics to the model [5–7] we find that the density of electron states in VECQDs corresponds to a Gaussian distribution with centre at $E_{qd} = 70$ meV from the bottom of the GaAs conduction band and standard deviation of $\Delta E_{qd} = 80$ meV.

Our model describes fairly accurately the experimental $C(V)$ and $N_{CV}(W)$ characteristics at temperatures higher than 70 K (Fig. 2a and b). However, discrepancies between the model and experimental data are observed at $T < 70$ K (Fig. 2c), when the step in the $C(V)$ characteristic is suppressed and a second peak appears in the $N_{CV}(W)$ profile at $W = 0.62$ μm (Fig. 1a and b). This is not due to the charge appearing at this point in the structure, but it is probably due to the fact that the calculated capacitance of the QD structure is derived from the equation $C = \Delta Q/\Delta V$, based on "quasi-static" conditions, i.e., the temporal change in the charge variation ΔQ caused by the increment of the reverse bias ΔV is neglected. However, in practice, the capacitance is measured by superimposing a small oscillation signal V_{osc} at a frequency f on the applied DC reverse bias V_{rev}. Note that V_{osc} modulates the charge both at the edge of the space charge

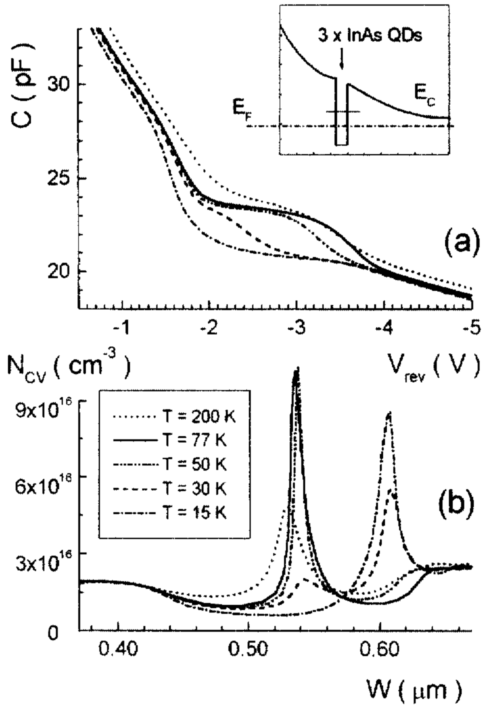

Fig. 1. (a) $C(V)$ and (b) calculated apparent $N_{CV}(W)$ characteristics of QD structure at $f = 1$ MHz. The inset shows the conduction band diagram of the structure.

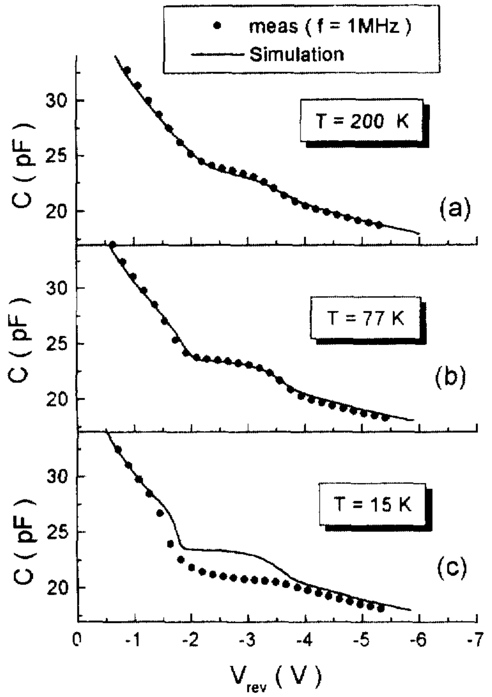

Fig. 2. (a–c) $C(V)$ characteristics of the QD structure at different temperatures: experimental data at $f = 1$ MHz (●) and model simulations (——).

region (dQ_{3D}) and at the point where the Fermi-level crosses the electron level in the QDs (dQ_{qd}).

A theoretical treatment of the $C(V)$ characteristics of QD structures [5–7] indicates that in the region of the capacitance plateau from -2.0 to -3.5 V (Fig. 1a) the change in the space-charge-region width dW due to the increment of the reverse bias dV becomes so small that dQ_{qd} is larger than dQ_{3D}, i.e. C_{qd} is higher than C_{3D} (Fig. 1a). As the temperature is lowered from 70 to 15 K, the quantum part of capacitance C_{qd} decreases (Fig. 1a), despite the fact that the occupation of QDs tends to be saturated [5,6]. At $T = 15$ K, C_{qd} disappears entirely (Fig. 1a). Considering that escape of electrons from the QDs is a slower process than capture [3], at $T = 15$ K the thermionic emission rate of electrons (e_n) from the QDs is much lower than the angular measurement frequency $2\pi f$ ($f = 1$ MHz in Fig. 1a), i.e. freezing out of electrons on QD levels takes place [7]. This freezing-out of the carriers in the QDs sheet at low temperatures is a distinctive property of zero-dimensional systems and is not observed in quantum-well structures possessing in-plane conductivity [10].

To remove electrons from QDs at $T = 15$ K, a higher electric field is required so that the electrons leave the QDs by tunneling through a narrow triangular potential (insert on the Fig. 1a). This process gives rise to the second peak in the $N_{CV}(W)$ profile at $W = 0.62$ μm (Fig. 1b), which corresponds to the small second plateau in the $C(V)$ characteristic at higher reverse bias -3 to -3.5 V (Fig. 1a). In the presence of an electric field, a potential of constant slope along the direction of the field vector is superimposed on the QD potential. For a high electric field ($\approx 4\times10^5$ V/cm) we estimate that a narrow triangular potential (≈ 25 Å) is formed, allowing the electrons to tunnel out of the QDs.

The thermionic emission rate depends exponentially both on the temperature and the energy of the QD electron levels. Since the array of self-assembled QDs has a Gaussian density of states, there are two ways for electrons to leave the QDs: by thermionic emission (when $e_n \gg 2\pi f$) and by tunneling through the triangular barrier (when $e_n \ll 2\pi f$). At a given temperature, decreasing the measurement frequency tends to increase the number of QDs from which electrons can escape thermally (Fig. 3a and b). A magnetic field of 12 T has little effect on the electron levels in the QDs [8], but forms a Landau ladder in the GaAs conduction band so that the lowest-energy state is higher than in zero field ($\Delta E_c = \hbar\omega_c/2 \approx 10$ meV, where $\hbar\omega_c$ is the cyclotron energy). This results in an effective deepening of the QD electron level and, consequently, a reduction of the thermionic emission rate of electrons from QDs. This manifests itself in a decrease of the width of the capacitance plateau (Fig. 4a) and an increase of the peak in the $N_{CV}(W)$ profile at $W = 0.62$ μm due to the tunneling escape of electrons from QDs (Fig. 4b). This phenomena does not depend on the orientation of the magnetic field and disappears at $T > 70$ K, when $kT \geqslant \Delta E_c$, where k is the Boltzmann constant.

In conclusion, we have investigated the frequency-dependent $C(V)$ characteristics of an n-GaAs structure containing self-assembled InAs QDs. It was found that the reference voltage

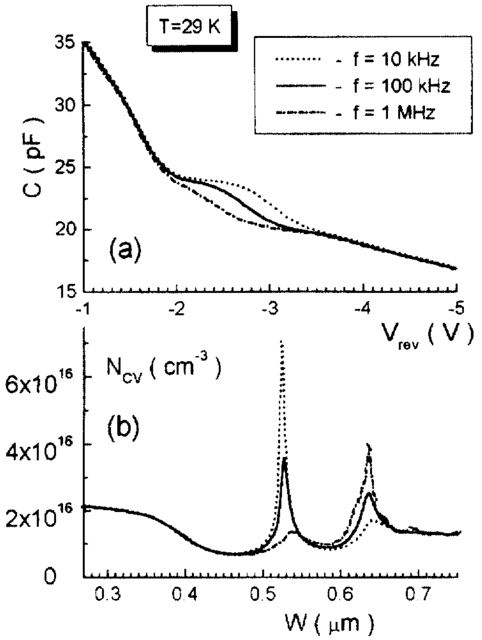

Fig. 3. $C(V)$ (a) and $N_{CV}(W)$ (b) characteristics of the structure with QDs measured at $T = 29$ K.

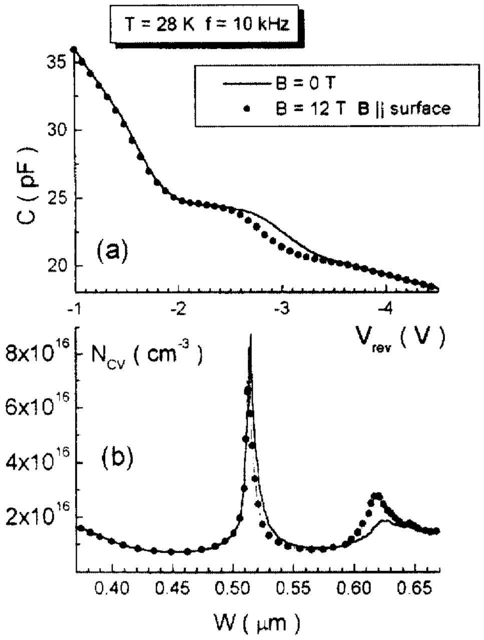

Fig. 4. $C(V)$ (a) and $N_{CV}(W)$ characteristics of the structure with QDs measured at $f = 10$ kHz and $T = 28$ K.

modulates charge in the QDs, and there are two routes for electrons to leave the QDs under decreasing reverse bias: (i) thermionic emission over the barrier and (ii) tunneling escape through a triangular barrier. The relationship between these two components depends on the relation between the thermionic emission rate e_n and the angular measurement frequency $2\pi f$.

Acknowledgements

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