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Admittance spectroscopy of Schottky barrier structures with self-assembled InAs/GaAs quantum dots

P. N. Brounkov†‡, A. A. Suvorova† A. E. Zhukov† A. Yu. Egorov† A. R. Kovsh† V. M. Ustinov† S. G. Konnikov† S. T. Stoddart‡ L. Eaves‡ and P. C. Main‡

† Ioffe Physico-Technical Institute, 194021, St. Petersburg, Russia
‡ Department of Physics, University of Nottingham, NG7 2RD Nottingham, UK

Abstract. Capacitance- and conductance-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 temperature and the frequency of the measuring signal, it is possible to control quantum dot part of capacitance of the structure. It was shown that analysis of the admittance spectra allows us to obtain information about dynamic parameters of quantum dots.

Introduction

In recent years there has been great interest in the properties of heterostructures containing self-assemled quantum dots (QDs) [1-8]. It has been shown that capacitance-voltage ($C(V)$) spectroscopy may be used to investigate the electronic structure of QDs [5-8]. In this paper we report an admittance spectroscopy study of a structure with a Schottky barrier on a n-type layer containing an array of vertically-coupled quantum dots (VECQDs). This technique allows us to study dynamic properties of QDs.

1 Experimental details

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 considered as a one large QD (like a pillar). The VECQDs were sandwiched between a 0.5 μm-thick GaAs cap and a 1 μm-thick GaAs buffer layer. Both 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 sides of the VECQDs layer. Schottky barriers were made by deposition of Au through a shadow mask (350 μm diameter).

The capacitance (C) and conductance (G) 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.

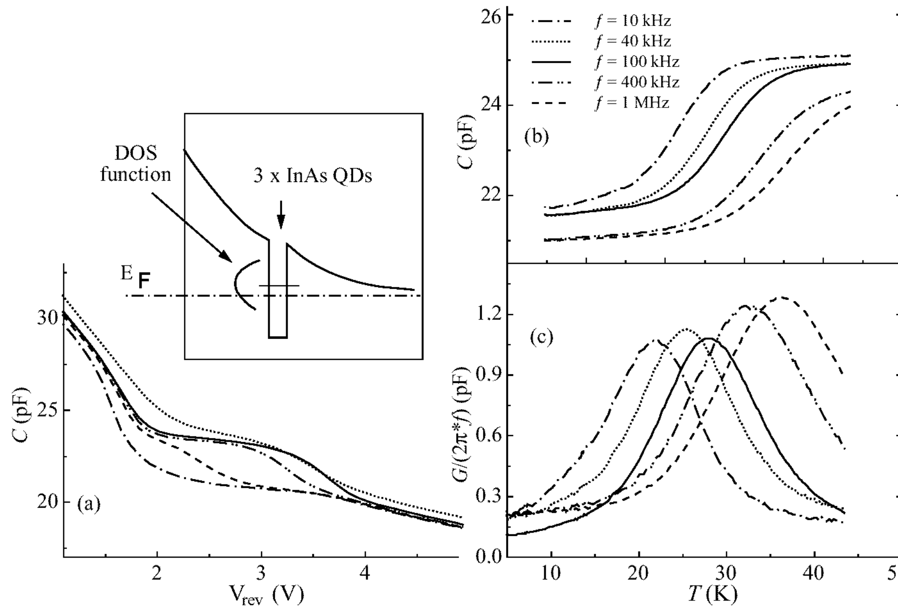

Fig 1. (a) $C(V)$ characteristics of QD structure at $f = 1$ MHz measured at digfferent temperatures: ·— 15 K, – – 30 K, —··— 50 K, — 77 K, ··· 200 K. The insert shows the conduction band diagram of the structure. (b) $C(T)$ and (c) $G(T)$ characteristics of QD structure at $V_{rev} = -2.75$ V.

2 Results and discussion

There is a step in the $C(V)$ characteristic related to the discharging of the QDs (Fig. 1a) [6-8]. According to the model presented in Refs. [6-8], 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 (insert on Fig. 1a) [6-8]. The sheet concentration of QDs was found to be $N_{qd} = 5 \times 10^{10}$ 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 [7, 8] 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. However, discrepancies between the model and experimental data are observed at $T < 70$ K, when the step in the $C(V)$ characteristic is suppressed. It is 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

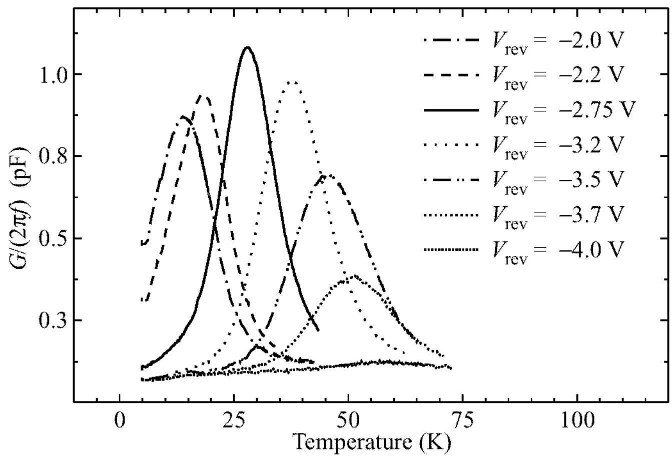

Fig 2. $G(T)$ characteristics of the QD structure, measured at $f = 100$ kHz for different values of the V_{rev}.

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 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 V to -3.5 V (Fig. 1a) the change in the space-charge-region width ΔW due to the increment of the reverse bias ΔV 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 K 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 [6, 7]. 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 $2\pi f$, i.e. freezing-out of electrons on QD levels takes place [8]. 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 [9].

The thermionic emission rate depends exponentially both on the temperature and the energy of the QD electron levels, therefore through the change of the measurement frequency and the temperature we can control the quantum part of capacitance C_{qd}. In Fig. 1b,c $C(T)$ and $G(T)$ characteristics of QD structure measured at $V_{rev} = -2.75$ V are depicted. Temperature of the recovery of the C_{qd} depends on the measurement frequency. Each steps in capacitance corresponds to the peak in conductance. Since the array of self-assembled QDs has a Gaussian density-of-states, we can study different part the QD energy spectra through the change of the reverse bias (insert on Fig. 1a). As the V_{rev} is increased the position of the conductance peak goes to higher temperature (Fig. 2). It means the more deaper states contributes to the quantum part of capacitance C_{qd}. Note, that there is no signal in $G(T)$ spectrum if $V_{rev} > -4$ V, because in this case QDs are practically empty (Fig. 1a, Fig. 2).

3 Conclusions

We have investigated the frequency-dependent admittance spectra of an n-GaAs structure containing self-assembled InAs QDs. It was found that the $C(T)$ and $G(T)$ characteristics of the quantum part of capacitance $C_{\rm qd}$ depend on the relation between the thermionic emission rate e_n of electrons from QDs and the angular measurement frequency $2\pi f$. Analysis of the admittance spectra can give us information about dynamic parameters of the QDs.

Acknowledgments

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