Vol. 94 (1998) *ACTA PHYSICA POLONICA A* No. 2

Proc. of the XXVII Intern. School on Physics of Semiconducting Compounds, Jaszowiec 1998

CAPACITANCE SPECTROSCOPY OF SINGLE-BARRIER GaAs/AlAs/GaAs STRUCTURES CONTAINING InAs QUANTUM DOTS

A.E. BELYAEV

Institute of Semiconductor Physics, NASU, Kiev 252028, Ukraine

L. EAVES, P.C. MAIN, A. POLIMENI, S.T. STODDART AND M. HENINI

Department of Physics, University of Nottingham, Nottingham, NG7 2RD, U.K.

An electrostatic profile of single-barrier heterostructures with InAs quantum dots encased into barrier has been studied. The role of growth conditions and structure's design is investigated. The charging state and position of energy levels for InAs quantum dots embedded in AlAs matrix are discussed.

PACS numbers: 73.40.Gk, 85.30.Mn

In this paper we investigate the capacitance–voltage, $C(V)$, and magneto–capacitance, $C(B)$, characteristics of a series of single-barrier n-i-n GaAs/AlAs/GaAs heterostructures incorporating a layer of self-assembled InAs quantum dots (QDs) in the AlAs barrier. Thicknesses of the layers of AlAs deposited before and after the InAs QD growth are varied. The $C(V)$ and $C(B)$ results are compared with those from a control sample that has no InAs and a sample in which the InAs thickness is such that a continuous wetting layer (WL) of InAs is grown.

The samples presented in this study were grown on a (100) n^+-GaAs substrate using MBE and all consist of n-type GaAs devices with an AlAs tunnel barrier region surrounded by 100 nm not intentionally doped spacers to minimise the effect of dopant diffusion into the central barrier region. These spacers are then enclosed by 100 nm of n-type GaAs doped to a density of 10^{16} cm^{-3} lightly doped region, followed by 100 nm doped to 10^{17} cm^{-3}, and then a heavily doped contact layer, at 10^{18} cm^{-3}. The control sample consists of a 10 nm AlAs single barrier, while the WL sample consists of an AlAs double barrier structure enclosing 1.4 ML of InAs. The QD samples consist of a InAs QD layer enclosed in AlAs layers grown previously and subsequently to the QD growth. The QDs are produced by deposition of 1.8 ML of InAs at a growth temperature of 520°C. The detailed layer make-up of the samples presented in this work are shown in Table.

The band diagram of the samples at zero voltage and under applied bias is drawn schematically in Fig. 1. Electrical contacts were formed on the doped GaAs

TABLE

The layer composition of InAs QD samples and the control sample.

Sample	Underlayer [nm]	InAs layer [ML]	Overlayer [nm]
A	5.1	1.8	5.1
B	3.4	1.8	6.4
C	5.1	1.8	7.2
D	5.1	1.8	3.8
WL	5.1	1.4	5.1
Control	10 nm AlAs single barrier	no QDs	

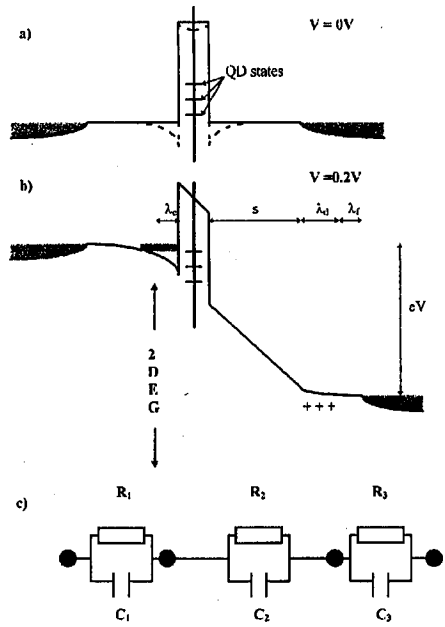

Fig. 1. Schematic band diagrams of the device at zero bias (a) and 0.2 V (b), and equivalent electric circuit of the device (c).

layer by AuGe alloying, and devices were fabricated into mesas of 200 μm diameter. In this paper the convention of negative substrate for forward bias is used. The measurements of capacitance were all made using a HP 4275A Multi-Frequency LCR Meter, in a variable temperature cryostat. The $C(V)$ analyser is capable of measuring in the frequency range of 10 kHz–10 MHz.

Figure 2 shows the capacitance–voltage curves of the samples nominated in Table. The values of the WL and QD sample curves have each been displaced by 4 pF for clarity. This measurement treats the sample as if it were a parallel

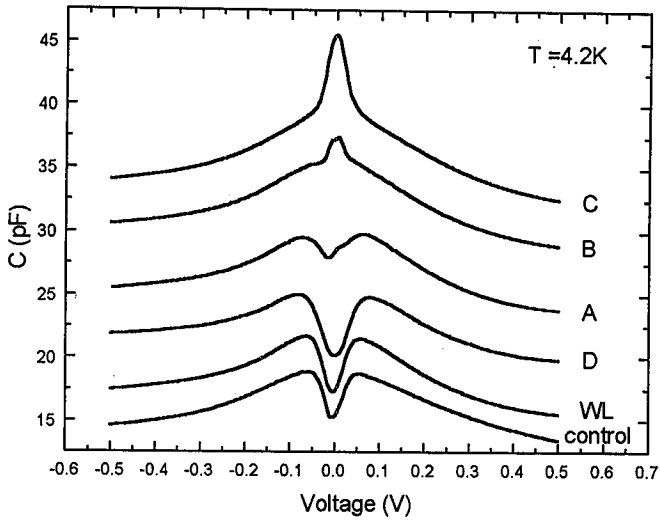

Fig. 2. Capacitance–voltage curves for the various devices taken at 4.2 K and zero magnetic field. Top five curves are displaced vertically by values of $\Delta C = 4$ pF each for clarity.

combination of impedance, R, and single capacitance, C. It can be seen that there is no clear partition between QD and non-QD samples apparent from the $C(V)$. All the $C(V)$ characteristics share a common form for biases above *ca.* 200 mV, characterised by a declining capacitance. This is to be expected as the capacitance is simply dominated by that of the depleted contact region for all the samples. The most variance seen in the samples is in the form of $C(V)$ around zero voltage. There are four samples that exhibit a pronounced dip in $C(V)$, while two of QD samples show a pronounced peak at zero bias. To understand the origin of the form of the $C(V)$ we will follow the arguments described below. If there is no net charge in the barrier (or there is a small negative charge) at zero bias, then at low bias voltages we have accumulation on the left hand side and depletion on the right hand side. In this case resistances R_1, R_3 more or less short circuit C_1, C_3. Also $R_2 \approx \infty$ since AlAs barrier is thick and high. So we are mainly concerned with behaviour of C_2. The areal capacitance C_2 equals to $\varepsilon_r \varepsilon_0 / d$. Here $d = \lambda_e + b + s + \lambda_d$, where λ_e is the quantum stand-off distance of the electrons in the 2DEG, s is the undoped spacer layer thickness, λ_d is the depletion layer width and λ_f is the width of the lightly doped contact layer, see Fig. 1b. Thus, C_2 will strongly depend on variation of λ_e and λ_d. The Fang–Howard theory [1] gives $\lambda_e \sim n_s^{-1/3}$ and $\lambda_d \sim n_s$, where $n_s e$ is areal charge in the left hand side of 2DEG. So, at low n_s $1/C_2$ is proportional to $n_s^{-1/3}$, but at high n_s $1/C_2$ gradually increases with n_s. This shows qualitatively that there is a maximum in C_2, and consequently in measured capacitance, at finite n_s (non-zero voltage) and minimum at zero voltage. The control sample has a clear minimum in capacitance at 0 V, a feature that is shared by the wetting layer sample, and QD samples A and D. Therefore the similarity in the capacitance

values of the low bias $C(V)$ leads to the conclusion that samples A and D, and the control sample as well as the WL sample are very similar electrostatically, and that the QD-containing barrier in samples A and D is almost electrically neutral. If we assume that samples have a small positive charge in the barrier (associated with QDs), then at zero bias both contacts are accumulated. Under these conditions middle capacitance C_2 is given by the expression: $1/C_2 \sim \lambda_{e1} + b + \lambda_{e2}$, where λ_{e1} and λ_{e2} are the quantum stand-off distances of the electrons in the 2DEG formed in front and at rear of the barrier. Both λ_{e1} and λ_{e2} will be determined by sheet density of the 2DEG, i.e., $\lambda_{e1} \sim n_{s1}^{-1/3}$ and $\lambda_{e2} \sim n_{s2}^{-1/3}$, and $n_{s1} + n_{s2} = N_0$, where N_0 is the net positive charge density concentrated in the barrier. A simple algebra shows that in the case of $n_{s1} = n_{s2}$ capacitance C_2 has a maximum at zero bias. The behaviour of $C(V)$ characteristics around zero voltage for samples B and C is consistent with this interpretation, thus confirming the presence of a net positive charge in the QD-containing barrier.

In order to probe the structures further, magneto-capacitance measurements were performed at 4 K upon the samples. These entailed sweeping a magnetic field B, applied parallel to the growth direction, up to $\approx$ 10 T for a given bias voltage. This results in familiar Shubnikov–de Haas-like magneto-oscillations in the capacitance with a periodicity in $1/B$, due to the Landau levels in the accumulation layer passing through the Fermi energy [2]. The charge modulation arising in this case affects the distribution of electric potential and screening length, and hence modulates the capacitance of the device. The frequency of the oscillations of fundamental field, $B_f = [\Delta(1/B)]^{-1}$, is thus related to the Fermi energy E_F by $B_f = 2\pi m^* E_F/eh$, where m^* and h are the effective mass and the Plank constant, respectively. The B_f therefore measures the electronic sheet density of 2DEG in the accumulation layer $n_s = 2eB_f/h$. Sheet density at zero voltage determined by such a manner for all samples is shown in Fig. 3, where the extracted Δn_s values are plotted versus $C(0)$. The result confirms our explanation of the zero-field $C(V)$ at low temperatures.

In conclusion, we investigate the $C(V)$ and $C(B)$ characteristics of a series of single-barrier n–i–n GaAs/AlAs/GaAs heterostructures incorporating a layer of self-assembled InAs quantum dots in the AlAs barrier. Some of the samples show minima and some maxima in the zero-field $C(V)$ at low temperatures. This provides information about the degree of accumulation in the GaAs layers adjacent to the barrier at zero bias. We have shown that the control sample exhibits the same behaviour as some QD samples, implying electrical neutrality in the QD-containing barrier of these samples. Other samples are seen to have a slight surfeit of positive charge, leading to electron accumulation at zero bias. There are two interesting consequences of this arrangement. The first is that there are electrons brought into intimate contact with the QDs at zero applied bias. The coupling of the electrons to the QDs may be enhanced by this at low biases, and may even lead to interesting zero-bias tunneling effects. Another consequence is that the positive charge in the QD-containing barrier radically alters the picture of the band bending in the devices coming from a model consideration of only the charging QD states with electrons.

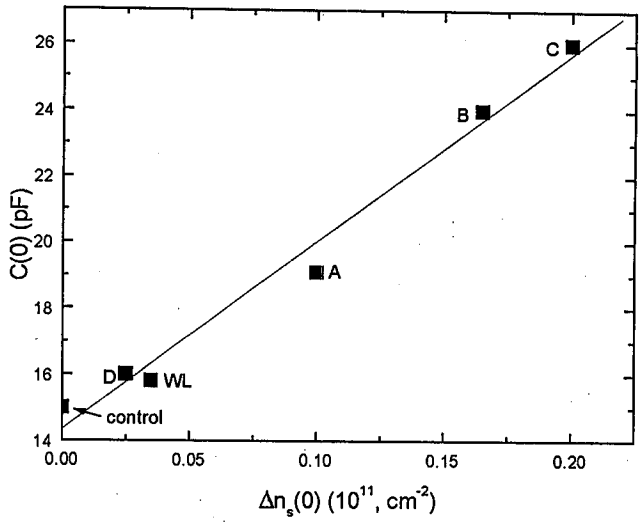

Fig. 3. The values of capacitance at zero voltage versus Δn_s. Solid line presents least-squares fit.

This work is supported by EPSRC (U.K.). A.E. Belyaev and L. Eaves acknowledge the Royal Society and EPSRC for financial support respectively.

References

[1] F.F. Fang, W.E. Howard, *Phys. Rev. Lett.* **16**, 797 (1966).

[2] M.L.L. Leadbeater, E.AS. Alves, F.W. Sheard, L. Eaves, M. Henini, O.H. Hughes, G.A. Toombs, *J. Phys., Condens. Matter* **1**, 10605 (1989).