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Defect related current instabilities in InAs/GaAs and AlGaAs/GaAs structures?

Zs. J. Horváth[1], S. Franchi[2], A.Bosacchi[2], P. Frigeri[2], E. Gombia[2], R. Mosca[2], and Vo Van Tuyen[1]

[1]Hungarian Academy of Sciences,
Research Institute for Technical Physics and Materials Science
Budapest 114, P. O. Box 49, H-1525 Hungary

[2]MASPEC Institute - C.N.R.
Parco Area delle Scienze 37a, 43010 Fontanini-Parma, Italy,

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Abstract. Unexpected excess current was obtained in GaAs/InAs quantum dot structures at low temperatures and low current levels. This excess current exhibited instabilities with changing the bias, and over the time. It has been concluded that the excess current is a minority injection current connected with recombination through defects originated from the formation of QDs. The instabilities are connected with unstable occupation of energy levels induced by the above defects, which depend on temperature and on the current level. Excess currents have also been obtained in annealed AlGaAs/GaAs structures. These excess currents exhibited memory effect, which was probably connected with formatin of defects during annealing.

Introduction

Recently the electrical characteristics of InAs quantum dot (QD) and quantum well (QW) structures embedded in GaAs confining layers were studied [1,2]. Unexpected excess current was obtained in the QD structures at low temperatures and low current levels. This excess current exhibited instabilities with changing the bias, and over the time. Excess currents exhibiting memory effect, were also obtained in annealed AlGaAs/GaAs structures. In this paper these results are presented and discussed.

Experimental

The InAs QD and QW structures embedded in GaAs confining layers were grown by MBE and Atomic Layer MBE (ALMBE); as the coverages of the highly mismatched InAs layers increase beyond a critical value Θ_{tr} (1.6 ML for InAs on GaAs) the growth of continuous two-dimensional InAs layers evolves in the formation of self-aggregated three-dimensional QDs, according to the Stranski-Krastanov growth mode. The structures consist: (i) of GaAs buffer layers with electron concentration of $2x10^{16}$ cm^{-3} and thickness of 1 μm (ii) of QDs or QWs obtained using InAs coverages of 3.0 ML and 1.0 ML, respectively, and (iii) of GaAs upper confining layers, with electron concentration of $2x10^{16}$ cm^{-3}. The buffer layers were grown by MBE at 580 °C; then the growth was interrupted for 210 s to lower the growth temperature to that used for the deposition of InAs QWs or QDsby ALMBE (at 460 °C). The upper confining layers were grown after interruptions of 210 s by ALMBE (at 400 °C) for 0.4 micrometers and by MBE (at 580 °C) for the subsequent 0.6 μm. This growth procedure was determined so as to optimise the photoluminescence properties of the InAs/GaAs QDs. As_4/Ga and As_4/In beam equivalent pressure ratios of ~16 and ~ 28 were used; the In and Ga fluxes were adjusted for InAs and GaAs growth rates of 0.16 ML/s and 1.0 ML/s, respectively; during ALMBE, the growth rate was set at 0.2 ML/cycle and the As supply time was chosen so as to give a sharp (2x4) surface reconstruction at the end of the As cycle. The substrates were radiatively heated at growth temperatures Tg, which was measured by a suitable optical pyrometer for Tg of 450 °C and by a thermocouple (TC) not in direct contact with the substrate for Tg < 450 °C. For Tg < 450 °C, the TC readings were corrected by the difference (~200 °C) between the TC and the optical pyrometer values measured at Tg > 450 °C. The InAs coverages were determined by using the growth rate measured by observing the 2D-3D growth transition on a calibration substrate just before the preparation of the QDs or of the QWs, and by assuming that the transition takes place at the generally accepted value Θ_{tr} of 1.6 ML. This value is very close to that (1.57 ML)

determined by very careful experiments described in Ref. 10, under slightly different conditions; it should be recalled, however, that the values of Θ_{tr} are not very sensitive to growth conditions. The QD density was about 10^{11} cm^{-2}. A similar reference wafer was also grown without any InAs growth.

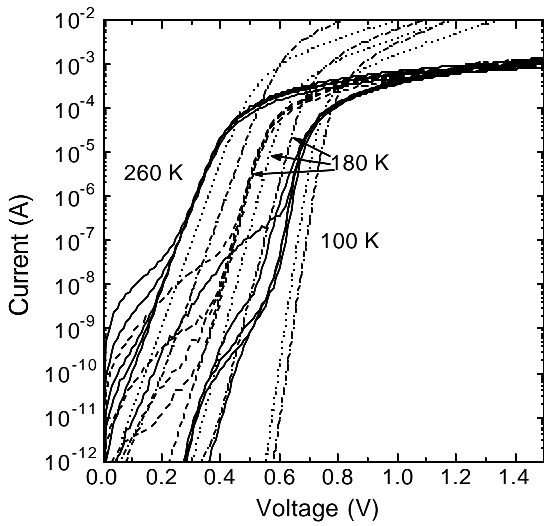

Fig. 1: I-V characteristics of five different GaAs/InAs QD (solid and dashed lines), one QW (dotted lines) and one reference Schottky structures (dashed-dotted lines) measured at 100, 180 and 260 K, and with voltage steps of 10 mV

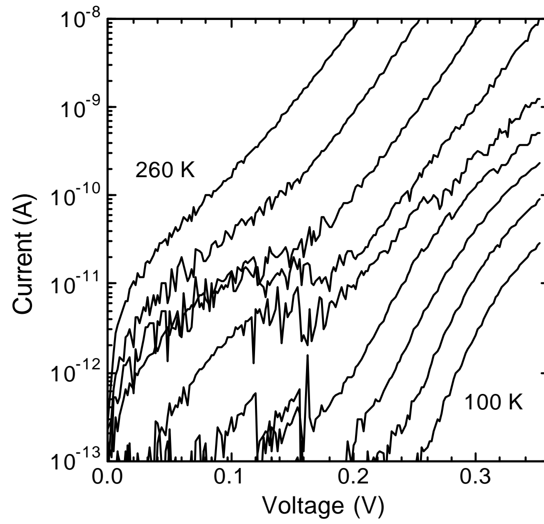

Fig. 2: Excess currents in a GaAs/InAs QD structure measured in the temperature range of 100-260 K with temperature steps of 20 K and voltage steps of 2 mV.

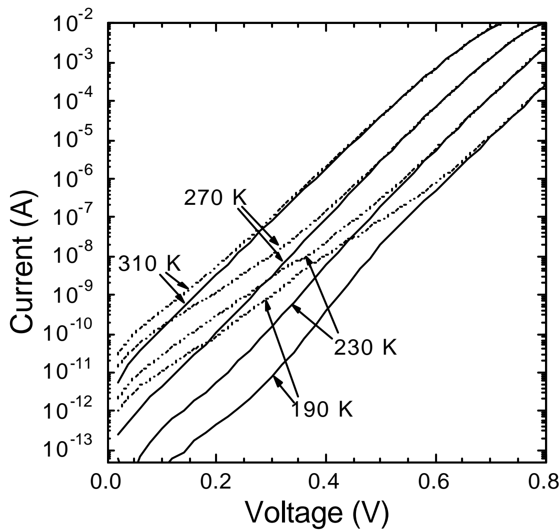

Fig. 3: I-V characteristics of a GaAs/AlGaAs/AlAs structure measured at 190, 230, 270 and 310 K, after forward (solid lines) and reverse (dotted lines) bias stresses of 10 mA and 5 V, respectively.

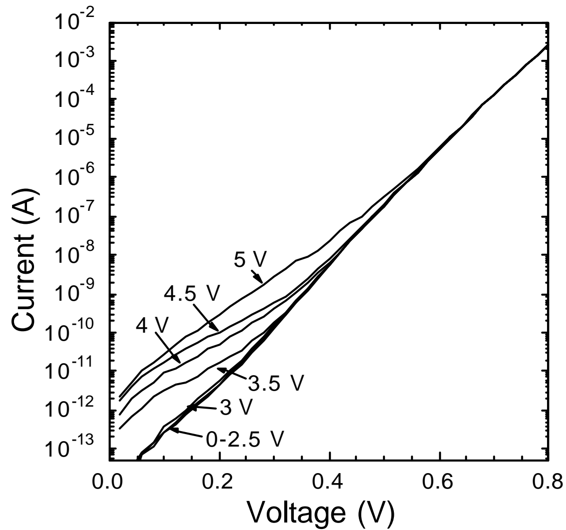

Fig. 4: Excess currents in the same GaAs/AlGaAs/AlAs structure measured at 230 K after reverse bias stresses in the range of 0 - 5 V.

Back ohmic contacts were prepared by evaporation and annealing of AuGeNi alloy. Au Schottky contacts with a diameter of 400 μm were then formed by evaporation and conventional photolitographic techniques. The current-voltage (I-V) measurements were performed in the temperature range of 80-300 K in dark.

Concerning the AlGaAs/GaAs structures, 2 μm thick Si-doped $Al_{0.25}Ga_{0.75}As$ active epitaxial layers were grown on an n^+ GaAs buffer layers and n^+ GaAs substrates by MBE. Then an undoped AlAs cap layer was grown with a thickness of 4 nm. Finally an epitaxial Al layer was grown with a thickness of 250-300 nm. The final circular dots with a diameter of 0.3 mm were patterned by photolithography. The In that bonded the sample to the holder during the epitaxial

growth, provided the backside ohmic contact. The structures got a cumulative heat treatment from 176 K up to 400 K by steps of 32 K. The duration of annealing was 2 hours for each step.

The current-voltage measurements were performed in the temperature range of 80-360 K in dark.

Table 1. The parameters obtained from the current-voltage measurements at 300 K: apparent barrier height, ideality factor, and series resistance

Sample	Φ_{bI}, eV	n	R_S, Ω
Reference	0.86±0.01	1.03±0.01	50±10
QW	0.81±0.01	1.03±0.01	<100
QD	0.75±0.01	1.03±0.01	950±5

Results and discussion

Although QW and QD layers were relatively far from the Au/GaAs interface out of the equilibrium depletion depth of the Schottky junction, it has been observed that QDs affect the electrical behaviour of the structures much more, than QWs [1,2]. Concerning the I-V characteristics, the structures with QDs showed lower apparent Schottky barrier height and much larger series resistance, than the reference structure and the structures with QW (see Table 1 and Fig. 1). Further on, an excess current was observed in all the studied QD structures at low temperatures and low current levels, while no excess current was present for QW structures, as can be seen in Fig. 1. The excess current in the QD structures was different for each individual diodes and unstable exhibiting instabilities with changing the bias, as it is presented in Fig. 2, and over the time [3].

We propose the following model for the explanation of these peculiarities. The current is limited mainly by the Schottky junction. However, QW and QDs act as effective recombination centers in the vicinity of the edge of the depletion layer. This results in an additional minority injection current in these structures. The depletion depth near the QD layer is wider, than that near the QW, yielding higher concentration gradient of the minority carriers injected from the metal, in the non-depleted part of GaAs between the Schottky junction and QDs. This yields higher minority injection current and lower apparent barrier height. The minority injection current in this case is limited by the concentration gradient of minority carriers. However, in QD structures there is a third parallel current mechanism due to recombination probably via defect levels which can be connected with mechanical stresses originated from the formation of QDs. These defects are located closer to the metal/semiconductor interface yielding additional minority injection current paths. This current component is limited by the recombination velocity through the defect levels which is much lower than that via QW and QDs. So, it exhibits a considerable contribution at low currents only. The accupation of these levels is unstable, therefore the depletion depth around these defects and the recombination velocity through them change with changing the bias and over the time, yielding instability of this current component.

In AlGaAs/GaAs structures excess currents have also been obtained. However, in these structures the excess current exhibited memory effect. It was present after negative bias stress only (see Figs. 3 and 4), and its value was proportional with the applied reverse bias voltage, as shown in Fig. 4. Similar to the InAs/GaAs QD structures, The excess current was different for each individual diodes on AlGaAs/GaAs structures as well. This indicates that it is not characteristic for the layer srtructure, but it was connected also with defects, formed probably during annealing. Similar excess currents were observed for annealed GaAs Schottky junctions, but without memory effect [4].

Conclusions

Unexpected excess current has been obtained in GaAs/InAs quantum dot structures at low temperatures and low current levels. This excess current exhibited instabilities with changing the bias, and over the time. It has been concluded that the excess current is a minority injection current connected with recombination through defects originated from the formation of QDs. The instabilities are connected with unstable accupation of energy levels in defects depending on temperature and on the current level.

Excess currents have also been obtained in annealed AlGaAs/GaAs structures. The excess currents that exhibited memory effect, were probably connected also with defects, formed during annealing.

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