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Resonant tunneling through GaAs quantum well with embedded InAs quantum dots

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In recent years there has been great interest in the properties of heterostructures containing self assembled InAs quantum dots (QD) [1–8]. To identify their electronic states, photoluminescence (PL) and PL excitation spectroscopies [1–3], capacitance spectroscopy [4], far-infrared spectroscopy [5], and resonant tunneling via InAs QD [6, 7] have been performed.

InAs QD in semiconductor nanostructures can be used to monitor their physical properties. For example, Main *et al.* [8] have used InAs QD to probe the local density of states of a two-dimensional electron system at all energies from the sub-band edge to the Fermi energy. On the other hand, double-barrier heterostructures (DBHS) have been studied extensively due to the resonant tunneling phenomenon exhibited in these systems, leading to numerous potential applications in ultra high-speed electronic devices. In the present work we are concerned with a study of the tunneling current through a GaAs-$Al_{0.4}Ga_{0.6}As$ double-barrier heterostructure with InAs QD embedded in the well region.

The samples were grown by molecular-beam epitaxy on a n^+(100) GaAs substrate. The structure consisted (in the order of growth) of a lightly Si-doped, 300-nm-thick GaAs layer ($N_d = 3 \cdot 10^{18}\,cm^{-3}$), a 50.4-nm-thick GaAs layer ($N_d = 2 \cdot 10^{17}\,cm^{-3}$), a 50.4-nm-thick undoped GaAs layer; a 8.3-nm-thick $Al_{0.4}Ga_{0.6}As$ barrier layer; a 5.6 nm undoped GaAs layer, 1.8 monolayers (ML), or 2.3 ML InAs with growth rate 0.13 ML/s to form InAs QD, a 5.6-nm-thick undoped GaAs layer, a 8.3-nm-thick $Al_{0.4}Ga_{0.6}As$ barrier layer, a 50.4 nm undoped GaAs layer, a 50.4-nm-thick GaAs layer ($N_d = 2 \cdot 10^{17}\,cm^{-3}$), a 300-nm-thick GaAs layer ($N_d = 3 \cdot 10^{18}\,cm^{-3}$) cap-layer. A control sample, lacking the InAs layer but identical otherwise, was also grown.

Ohmic contacts were obtained by successive deposition of AuGe/Ni/Au layers and subsequent annealing. Mesa-structures were fabricated by conventional chemical etching.

The current-voltage ($I-V$) characteristics at 4.2 K of the samples with 200 μm mesa diameter are shown in Fig. 1. Curve 1 corresponds to the sample without QD, and curves 2 and 3 to the samples with 1.8 ML and 2.3 ML of InAs in the centre of the QW respectively. The sample without QD has three resonant peaks due to tunneling via quantum-well quasi-bound states. The second and the third resonances exhibit bistability in the form of strong hysteresis in the $I-V$ curves arising from the electrostatic effects of a buildup of negative space charge in the quantum well when biased at resonance [9]. In the $I-V$ curves of the samples with QD the first resonance is suppressed and only wide shoulders are left in the appropriate voltage bias region. The second resonance is roughly at the same bias for the 1.8 ML sample as for the one without QD, and apparently weaker for the 2.3 ML sample.

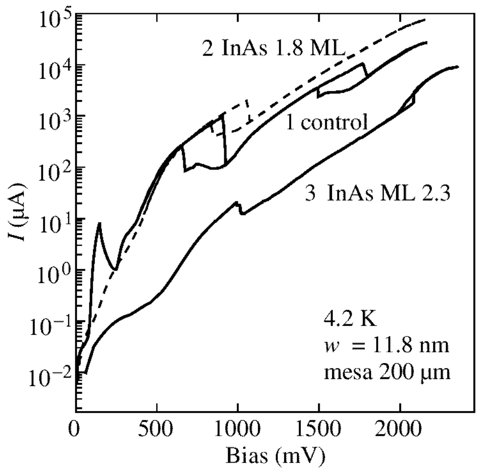

Fig. 1. $I-V$ characteristics of the experimental devices at 4.2 K.

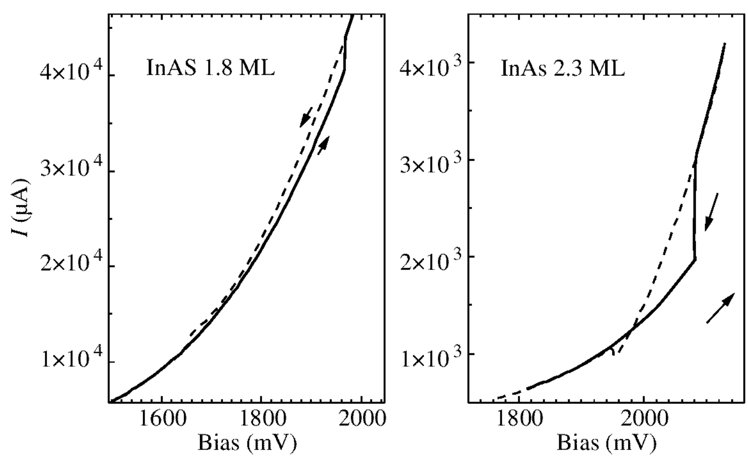

Fig. 2. $I-V$ characteristics in the region of the "inverted bistability" of the samples with different QD embedded in the well.

The third resonances of both QD samples display an unusual shape and are shown in more detail in Fig. 2.

To explain the difference between hows the first and second resonances appear in the $I-V$ curves of the different samples it is enough to take into account the influence of the localised perturbation generated by the InAs QD. It is strong for the first resonance associated with the first quasibound state when the wave function has the amplitude maximum coincident with the QD location in the well. It is weaker for the second resonance since the density maximum of the electronic wave function for the second subband is located far from the centre of the QW.

The distinguishing feature of the third resonances of the samples with QD is that the off-resonant current is greater then the on-resonant one when the bias is swept from low to higher voltage. Similar behaviour of the current near the second resonance was observed previously [10] on asymmetric double barrier structures when the bias was swept in the reverse direction and was termed “inverted bistability”. The effect arose from the additional charge buildup in the lowest subband in the well on resonance originating from inelastic, intersubband electron transfer in the well. In contrast, in the off-resonant condition, the energy of the top of the second barrier is lowered so that off-resonant electrons have only to pass one barrier, while on-resonant electrons must pass two barriers. We argue that the interplay of the intersubband scattering rates is strongly increased by the presence of the perturbation potential from the QD and relative positions of the subband levels in the wells could create the “inverted bistability” with the shapes found in the present work.

Thus we have investigated the electron resonant tunneling through the GaAs quantum wells with embedded InAs quantum dots. It was found that the localised perturbation generated by the InAs quantum dots strongly influences the wave functions of the subband states in the quantum wells. The “inverted bistability” of the third resonance was observed for the samples with quantum dots. The shape of the resonances on the $I-V$ curves under “inverted bistability” differs from that previously observed adding to the collection of the butterfly-like resonances on the double barrier structures.

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