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Multiple Gated InAs Dot Ensembles

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1. Introduction

We have recently introduced a new hybrid technology for fabricating sub-μm vertical resonant tunneling structures with separate gates in order to study single-electron phenomena in deformable *artificial atoms* [1, 2]. We now adapt this technology to characterize a dense ensemble of InAs dots embedded in a thin layer within an AlGaAs tunneling barrier. So called "self-assembled" InAs quantum dots have recently attracted considerable attention. Two terminal current- voltage [3, 4, 5], and capacitance-voltage [6] measurements of mostly μm-sized devices have already been reported. Here we describe our initial attempt to gate a layer of InAs dots. We hope this will lead to a better understanding of the electrical properties of such dots, and help answer controversial questions about the actual composition of the dots, and the influence of the surrounding matrix material. This technology has the potential to allow us to probe spectroscopically a single dot in new ways.

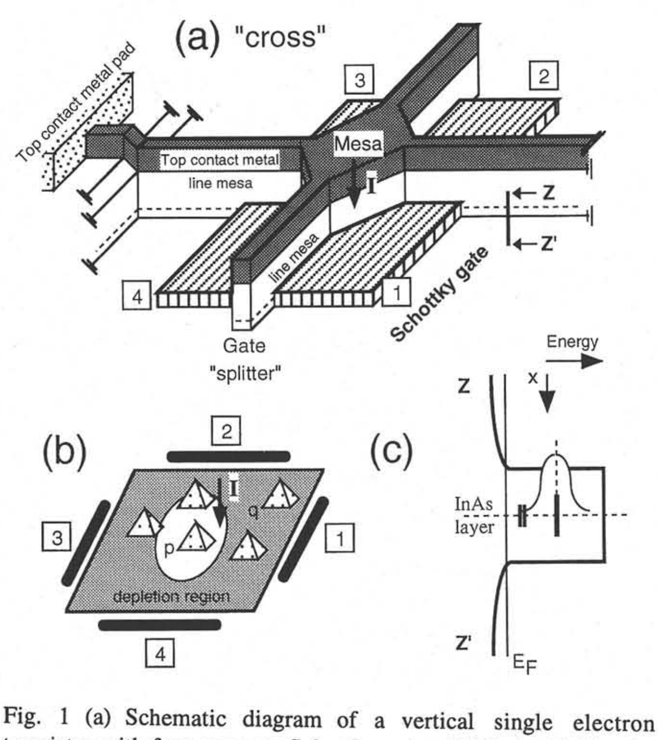

Fig. 1 (a) Schematic diagram of a vertical single electron transistor with four separate Schottky gates. (b) Embedded in the square mesa at the center of the "cross" in the plane of the gates is a layer with a dense ensemble of dots. The depletion region associated with the gates spreads inwards towards the center of the mesa and the current flows through this plane. (c) Simple conduction band energy profile along the vertical section ZZ'. The distribution of energy levels due to the ensemble of dots is above the Fermi energy, E_F.

2. Experimental details

The fabrication steps are described elsewhere [1]. Fig. 1(a) shows a schematic diagram of the transistor. Current can only flow through the square mesa at the center of the "cross" from a large top contact metal pad to the substrate because the top contact metal is resting on thin line mesas which are always "pinched-off". Such line mesas can also "split" the gate metal so each side of the mesa has a separate Schottky gate (numbered 1 to 4).

For compatibility, the starting material is almost identical to that of an *artificial atom* **except** the wide InGaAs (5% In) quantum well is replaced by a 5 Å layer of InAs at the center of a 140 Å AlGaAs (20% Al) tunneling barrier. Growth is on a (311)B GaAs substrate. It is well known that the Stranski-Krastonov growth mode for lattice mismatched semiconductors can lead to the spontaneous formation of "self-assembled" quantum dots. The starting material discussed here has not been structurally or optically characterized but based on studies of related materials we expect the dot density, average dot height, and average lateral size to be about 500 μm^{-2}, 3 nm, and 20 nm respectively [7, 8]. We can picture the dots as a collection of "black boxes", and try to learn something about their electronic properties.

Measurements were performed in a ^3He 0.3K cryostat. Current-voltage (I-V) characteristics were obtained with a Hewlett-Packard 4142B. The top contact metal is grounded so in forward bias electrons flow to the substrate.

3. Principle of Operation

Embedded in the mesa at the center of the "cross" in the plane of the gates is a layer with a dense ensemble of dots (several hundred). Fig 1(b) pictorially shows only a few of these dots. The depletion region associated with the gates spreads inwards towards the center of the mesa as the voltage on the gates is made more negative. Dot p at the center of the mesa, when it eventually enters the depletion region should be acted on equally by all four gates. On the other hand, dot q, which is closer to the edge is already in the depletion region, but being closer to gates 1 and 2, it should only be strongly affected by the voltages on gates 1 and 2, and not by the more remote gates 3 and 4.

A simple conduction band energy profile along the vertical section ZZ' is given in Fig. 1(c). The distribution of energy levels due to the ensemble of dots is placed above the Fermi energy, E_F. *For this particular case*, a finite bias is required for electrons in the emitter to tunnel through quasi-discrete states in the low energy tail of this distribution. A more negative gate voltage would also be expected to push this distribution up, so current resonances due to tunneling through the low energy quasi-discrete states should also move **away** from zero bias.

4. Results

The bold trace in Fig. 2 is an I-V characteristic for a 0.7 μm square mesa with all four gates fixed at +0.3 V. The faint trace is the same trace but expanded vertically by a factor of 20. Many sharp resonance peaks are evident close to threshold in both (a) forward bias and (b) reverse bias. We attribute these features to the tunneling of electrons from emitter states (the emitter may behave like a disordered conductor exhibiting local structure [9]) through a few dots whose lowest energy states are in the low energy tail of the distribution. The absence of current in the -100 to 100 mV range strongly suggests that at zero bias the dots are empty and that the distribution is well above E_F. Another key observation is that the sharp peaks look similar so we can not tell if the peaks belong to different dots. To distinguish the origin of the peaks, we must vary the gate voltage.

Fig. 3 shows (a) low contrast and (b) high contrast grey scale plots of dI/dV for the same mesa (positive dI/dV is "black", and negative dI/dV is "white"). The voltage on all four gates is varied from +0.5 V to -0.5 V. At least four families of peaks with different gate voltage dependences can be identified (in order of increasing strength: W, M2, M1, S). We attribute each family to tunneling through a different "active" dot. Peaks in a given family have the same gate voltage dependence and may give information about density of state fluctuations in the emitter [9], or the states of a certain dot. As the gate voltage is made more negative, the resonances move away from zero bias, and no new peaks appear. This supports the picture in Fig. 1(c). We note that for tunneling into extended Coulombic (hydrogenic) donor states, the peaks only shift a little with gate voltage before fading away probably due to a field ionization process [10]. In contrast, the resonant peaks in Fig. 3 remain well defined with gate voltage, which is consistent with states confined by a hard-wall potential rather than a soft-wall potential. We have also measured the response of the resonances to the action of the gates operating separately so in principle spatial information about the "active" dots can be deduced .

5. Conclusions

For our first attempt we have learnt some useful information about an ensemble of InAs dots located in a plane within a gated mesa. In particular, *for our particular starting material*, the distribution of energy levels seems to be well above E_F at zero bias, and is pushed up further when the gate voltage is made more negative. With more material and device optimization we hope to track the effect of each gate on states in the tail of the energy distribution which initially contribute to the current close to threshold.

References

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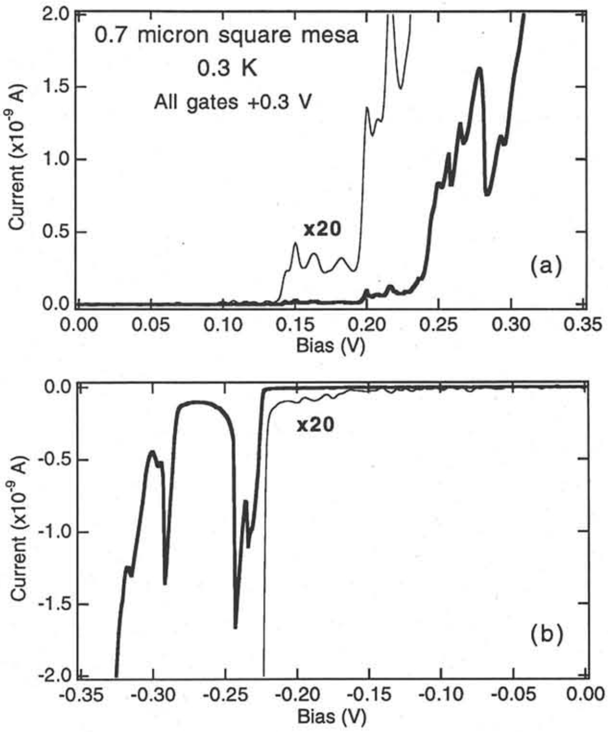

Fig. 2 Bold trace: I-V characteristic for a 0.7 μm square mesa. All four gates are fixed at +0.3 V. Faint trace: bold trace expanded vertically (x20). Many sharp resonances are evident close to threshold in both (a) forward bias and (b) reverse bias.

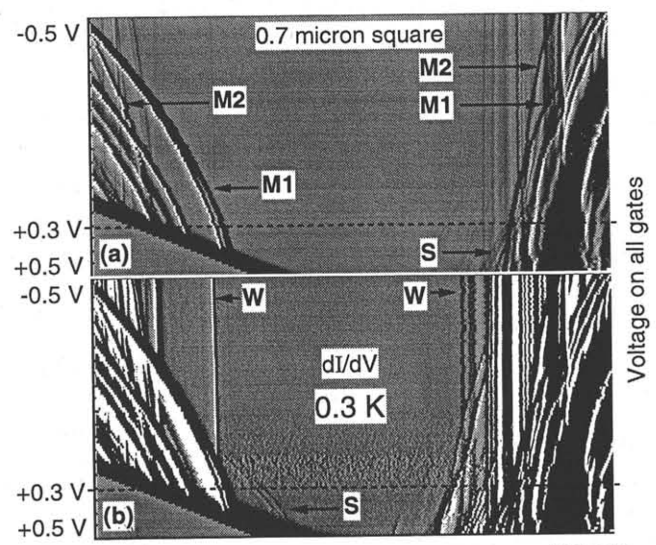

Fig. 3 (a) Low contrast, and (b) high contrast grey scale plots of dI/dV for the 0.7 μm square mesa. The voltage on all four gates is varied from +0.5 V to -0.5 V. Families of peaks with different gate voltage dependences can be identified (in order of increasing strength W, M2, M1, and S).