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Tuning the electron density in structures for vertical quantum dot artificial atom applications

G Yu, J A Gupta, G C Aers and D G Austing

Institute for Microstructural Sciences, National Research Council of Canada, Montreal Road, Ottawa, Ontario K1A 0R6, Canada

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Abstract
We report on the systematic variation with well composition of the electron density in the quantum well of GaAs/AlGaAs/InGaAs double barrier resonant tunnelling structures designed for vertical quantum dot applications. By increasing the indium content in the quantum well from 4.0 to 5.5% we tune the electron density, n, from $\sim$6 to $\sim$13 $\times$ 10^{10} cm^{-2}. Current–voltage traces for large mesas made from these structures display the desired characteristics, i.e. a finite differential conductance at zero bias showing that electrons occupy the quantum well without application of a bias, and the current resonances exhibiting negative differential resistance are close to zero bias. The electron density is determined from (Shubnikov–de Haas) oscillations in the differential conductance at zero bias by applying a magnetic field parallel to the tunnelling current.

1. Introduction

For nearly ten years vertical quantum dot artificial atoms have proved excellent vehicles for studying single-particle and many-body properties of confined electrons in a well-controlled environment [1, 2]. The properties include shell filling and spin effects related to Hund's first rule for zero or weak magnetic fields [1], two-electron spin singlet–triplet transitions and the formation of the spin-polarized maximum density droplet at high magnetic fields [3, 4], and novel Kondo physics effects [5]. Before fabricating sub-micrometre gated quantum dot mesas it is necessary to carefully test the starting structures and fine-tune some of the key layer parameters of the designed structure. Much iteration is required, and invariably nominally identical structures are slightly different depending on the source of the grown material and when the structure is grown.

In this paper, we focus on the properties of a sequence of GaAs/AlGaAs/InGaAs double barrier resonant tunnelling structures (DBRTSs) and show that we can systematically tune the zero bias electron density in the quantum well, an important parameter, by changing the composition of the quantum well. The full details of these important structures for quantum dot applications and their basic characterization have not been previously reported.

2. Experimental details

The nominal layer parameters of these structures are shown in table 1. The materials were grown by molecular beam epitaxy (MBE) on Si-doped GaAs (100) substrates. The In content of the InGaAs quantum wells was varied from 4.0 to 5.5% to alter the zero bias electron concentration, n, in the quantum well. The upper and lower AlGaAs barriers intentionally have different thickness so we should expect asymmetric current–voltage traces. Above and below the quantum well and the two barriers, the contacts are formed of GaAs, initially undoped but then Si-doped in steps from 1 $\times$ 10^{17} cm^{-3} to 2 $\times$ 10^{18} cm^{-3} on moving away from the quantum well region. Details of all the layer parameters, in particular the n-doped GaAs regions, have not been previously published [1, 6]. The Si delta-doping near the surface is used to facilitate non-alloyed ohmic contacts as discussed below. Other useful information related to the growth includes: (i) all epilayers were grown at 600 °C except for the quantum well, barriers and undoped GaAs spacer layers adjacent to the barriers which were grown at 520 °C to minimize In segregation in the quantum well region; (ii) growth interrupts were performed whenever the doping concentration was changed in the GaAs contact regions to allow for the adjustment of the Si-dopant cell temperature; and (iii) the Al concentration in the barriers was chosen to

Table 1. Nominal layer parameters of the grown structures. These parameters are only partly shown in figure 1 of [6].

Layer	Thickness (nm)	Doping concentration
n^+-GaAs	7.0	2.0×10^{18} cm^{-3}
Si delta doping } × 10	–	1.5×10^{13} cm^{-2}
n^+-GaAs } × 10	2.5	2.0×10^{18} cm^{-3}
n^+-GaAs	17.5	2.0×10^{18} cm^{-3}
n-GaAs	180.0	2.0×10^{17} cm^{-3}
n-GaAs	150.0	1.4×10^{17} cm^{-3}
n-GaAs	70.0	1.0×10^{17} cm^{-3}
GaAs	3.0	–
$Al_{0.22}Ga_{0.78}As$	9.0	–
$In_xGa_{1-x}As$	12.0	–
$Al_{0.22}Ga_{0.78}As$	7.5	–
GaAs	3.0	–
n-GaAs	70.0	1.0×10^{17} cm^{-3}
n-GaAs	150.0	1.4×10^{17} cm^{-3}
n-GaAs	180.0	2.0×10^{17} cm^{-3}
n^+-GaAs	500.0	2.0×10^{18} cm^{-3}
n^+-GaAs substrate		Si-doped GaAs

Table 2. Nominal quantum well In content and measured electron density, n, for a sequence of five structures.

Structure	Quantum well In content (%)	Electron density, n (10^{10} cm^{-2})
V0063	5.5	12.6
V0046	5.0	11.7
V0168	5.0	8.8
V0062	4.5	8.5
V0169	4.0	5.6

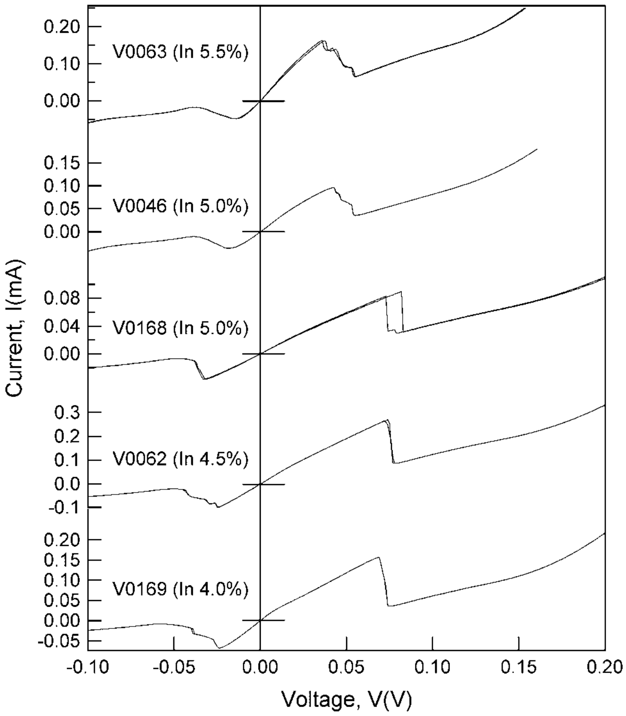

Figure 1. Current–voltage traces for a sequence of mesas made from the five structures arranged in order of decreasing quantum well In content from top to bottom. The mesas are all 75 μm in diameter and the measurement temperature is ~1.4 K. The differential conductance at zero bias for all the mesas is non-zero, and current resonances exhibiting negative differential resistance are located within ±100 mV of zero bias.

be comfortably below the concentration (~30%) above which X-related bandstructure effects could play a role.

Table 2 gives the nominal quantum well indium content for five structures grown in three batches over a time scale of approximately one year. V0046 came from the first batch, V0062 and V0063 from the second batch, and V00168 and V00169 from the third batch. The MBE chamber is used to grow other III–V materials including dilute nitrides and antimonides, but this did not appear to affect the quality of the GaAs/AlGaAs/InGaAs DBRTSs discussed in this paper. Prior to the growth of V0046, the Ga, In and Al fluxes were calibrated using In(0.05)Ga(0.95)As/GaAs and In(0.157)Al(0.843)As/AlAs multiple quantum well test structures. The growth rates for the test structures were found from dynamical diffraction analysis of high-resolution x-ray rocking curves. Any slight changes in composition of the other structures grown later were due to changes in the effusion cell flux calibration as the source material was depleted.

After growth, large mesas with diameter, D, between 50 and 150 μm were made by standard fabrication procedures. The ohmic contact on the backside of the conducting GaAs substrate is formed of Ni/Au/Ge (25 nm, 55 nm, 80 nm) subsequently annealed to 415 °C for 15 s in N_2/H_2 forming gas. After patterning by photolithography, the top contact is made by evaporating Ti/Au (20 nm, 200 nm) metal. These top metal contacts acted as a mask, allowing the mesas to be formed by wet etching with H_2SO_4:H_2O_2:H_2O (1:8:160) at room temperature to a depth well below the lower 7.5 nm AlGaAs barrier. We note that for both large mesas and small quantum dot mesas [1, 2], non-alloyed Ti/Au top contacts are rugged and reliable. Had the Si delta-doping layers near the surface been omitted, these contacts would, however, be more Schottky-like than ohmic-like. For some specialized measurements on vertical quantum dots, e.g. in the study of the Kondo effect [5], both non-alloyed Ti/Au and annealed AuGeNi are used together although two separate metal evaporation steps are required.

3. Results and discussions

Figure 1 shows current–voltage (I–V) traces for a sequence of mesas made from the five structures arranged in the order of decreasing quantum well In content from top to bottom (table 2). All mesas are 75 μm in diameter and the measurement temperature is ~1.4 K. The I–V traces were recorded with an Agilent E5270A unit with the substrate contact grounded, so that in forward bias the electron flow is from the substrate to the top contact. The differential conductance, σ ($=\mathrm{d}I/\mathrm{d}V$), for all mesas at zero bias is clearly non-zero, and current resonances exhibiting negative differential resistance are located within ±100 mV of zero bias. The asymmetry, i.e. the systematically higher peak voltage of the resonance in forward bias compared to that of the resonance in reverse bias, is consistent with the lower 7.5 nm AlGaAs barrier being thinner than the upper 9.0 nm AlGaAs barrier for all the structures. We note that the trace for each of the mesas shown in figure 1 is actually composed of two traces superimposed: one for sweeping from reverse bias to forward bias ('up-going'), and one for sweeping from forward bias to reverse bias ('down-going'). Apart from some expected difference, i.e. hysteresis, in the region of negative differential resistance, there is practically no difference between the up-going and down-going traces.

A non-zero value for σ at zero bias, as observed, is essential for studying the linear conductance properties of vertical quantum dots [1, 2], since it indicates that electrons are accumulated in the quantum well at zero bias. This is why prior to the fabrication of small vertical quantum dot single-electron transistors, large mesas should be made to check the suitability of the structures, as we report in this paper. We note that the actual values for the positions, as well as the peak current densities, of the resonances in figure 1 are not particularly relevant for vertical quantum dot applications. Far more important is that by scaling the typical currents passed by the 75 μm mesas, the current level at a bias voltage $\sim$1 mV for sub-micrometre mesas made from the same structures is expected to be hundreds of pA which is ideal [1, 2].

In addition to observing a non-zero σ at zero bias, simple magneto-transport measurements allow us to evaluate the density of electrons accumulated in the InGaAs quantum well. The differential conductance versus magnetic field (σ–B) for a sequence of mesas made from the five structures arranged in the order of decreasing quantum well In content from top to bottom are shown in figure 2(*a*). The mesas here are either 100 or 150 μm in diameter, and the measurement temperature is $\sim$1.4 K. The magnetic field is applied parallel to the current flowing through the mesas. Although we could have measured the current at a small fixed bias, we choose to monitor the zero-bias resistance directly with an AVS-47 resistance bridge for a fixed excitation current of $\sim$300 nA, and then invert to get σ. The $\nu = 2$ minimum is identified from the magneto-oscillations (Shubnikov–de Haas oscillations) for each trace by inspection. At weak field, several even-integer filling factor ($\nu \geqslant 2$) minima are clear. The inverse of the B-field positions of the minima scale linearly with index ν and the extrapolated line (the gradient of which allows an estimation of n) passes through zero. On the other hand, at higher B, the $\nu = 1$ minimum is broad, and occurs at a B-field $\sim$20% above that obtained by simply doubling the B-field of the $\nu = 2$ minimum (see also [4]). We therefore use the $\nu = 2$ minimum directly to estimate the value of n in table 2. Specifically, we calculate $n = (2e/h)\,B(\nu = 2)$, where e is the charge of an electron and h is Plank's constant. Figure 2(*a*) clearly shows that as the In content in the quantum well is lowered, n is systematically reduced since the $\nu = 2$ minimum tracks towards zero field. Note that the difference in the value of n extracted for nominally identical structures V0046 and V0168 is not unsurprising since they were grown a year apart and conditions of the growth system invariably change with time. The properties of DBRTSs are well known to be very sensitive to the precise details of the layer parameters so we find it remarkable that the variation is as good as $\sim$25%.

Figure 2 also shows calculated zero bias conduction band profiles along the growth direction (z-axis) in the vicinity of a quantum well with 5% In content. Two situations are modelled: (*b*) when band bending is completely neglected, and (*c*) when band bending calculated self-consistently is included. Standard values are taken for the conduction band offsets, and the effective mass varies with material composition. The Fermi energy, E_F, in the contacts is $\sim$11.7 meV. The ground (E_0), first excited (E_1), and second excited (E_2) energy levels, in the z-direction, are indicated. In (*b*) E_F is $\sim$20.5 meV above E_0, i.e., electrons are present in the quantum well at zero bias as desired. The effect of properly including band bending in the central region is to push up systematically and strongly all the energy levels relative to E_F, although E_0 is not depleted. (All other parameters unchanged, E_0 is not depleted provided the In content of the quantum well is not less than about $\sim$2% according to our self-consistent model). In (*c*)

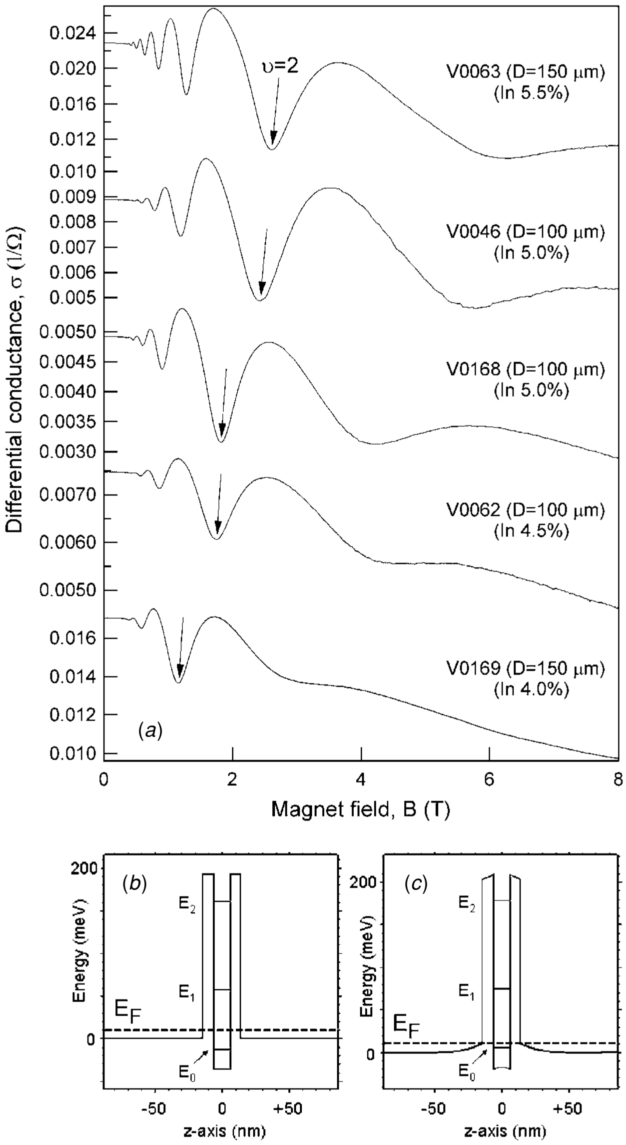

Figure 2. (*a*) Differential conductance at zero bias versus magnet field for a sequence of mesas made from the five structures arranged in the order of decreasing quantum well In content from top to bottom. The mesas are either 100 or 150 μm in diameter. The measurement temperature is $\sim$1.4 K, and the magnetic field is applied parallel to the current. The excitation current is $\sim$300 nA. The distinctive $\nu = 2$ minima are identified for each trace by an arrow. Also shown are the zero bias conduction band profiles along the growth direction (z-axis) in the vicinity of the quantum well for the situations (*b*) when band bending is completely neglected, and (*c*) when band bending calculated self-consistently is included. The profiles here are for a quantum well with 5% In content.

E_F is $\sim$6.2 meV above E_0. This translates into a quantum well electron density, n, of $\sim 17 \times 10^{10}$ cm^{-2}. This value is larger than the measured values for V0046 and V0168 (table 2). However, this is not unexpected since we have assumed that all the layer parameters of the grown structures are exactly those of the nominal layer parameters (table 1). Furthermore, any influence of, for example, interface traps is neglected in our simple model. The presence of traps would cause the value of n measured to be less than predicted. Thus while the actual value of the electron density can be 30–50% less than that calculated, and is unsurprisingly sensitive to the particular growth system and the details of the growth (for example, calibration procedures and interface traps), nonetheless, figure 2(a) does show that the electron density can be systematically tuned, as desired. The experiments and calculations are in good agreement regarding the following very useful design parameter. For an In content of around 5%, assuming a rough linear fit to the numbers in table 2, as a rule-of-thumb n changes by $\sim 2.3 \times 10^{10}$ cm^{-2} per 0.5% change in the quantum well In content. The corresponding value for the self-consistent calculations is $\sim 2.0 \times 10^{10}$ cm^{-2} per 0.5% change in the quantum well In content.

Finally, given the properties displayed in figures 1 and 2 of the GaAs/AlGaAs/InGaAs DBRTSs designed for vertical quantum dot applications, we give some historical context. Prior to the use of these structures for successfully measuring the linear conductance characteristics of vertical quantum dot artificial atoms [1, 2], a number of research efforts in this direction were reported [8–14]. Micrometre and sub-micrometre mesas, some gated and others not gated, were fabricated mostly from GaAs/AlGaAs/GaAs DBRTSs [9–14], and in one instance from GaAs/AlGaAs/InGaAs DBRTSs [8]. However, none of these structures exhibited a finite differential conductance at zero bias, i.e., no electrons were accumulated in the quantum well without application of a bias, and so none were suitable for measuring the linear conductance characteristics. The use of suitably engineered GaAs/AlGaAs/InGaAs DBRTSs for vertical quantum dot artificial atoms to overcome this limitation was partly motivated by a few reports on closely related structures for quite different applications [15, 16].

4. Conclusions

We have grown several GaAs/AlGaAs/InGaAs DBRTSs in order to systematically vary the quantum well electron density. From simple electrical characterization, we find that by increasing the indium content in the quantum well from 4.0 to 5.5% we can tune the zero bias electron density from $\sim$6 to 13×10^{10} cm^{-2}. This capability is important for vertical quantum dot applications. For example, a low (high) electron density is a good starting point to study in detail the fractional quantum Hall regime (regular quantum Hall regime) beyond (below) the formation of the maximum density droplet at filling factor one in a single-gated quantum dot disc [4], and is a useful handle to optimize the next generation of multiple laterally gated vertical quantum dots [7].

Finally, single-gated quantum dot mesas have been recently fabricated from the grown structures discussed in this paper. At 0 T clear Coulomb diamonds are observed, and on sweeping the magnetic field up to $\sim$7 T a clear shell filling is identified from the Coulomb oscillations [1, 2]. These observations demonstrate the quality of the grown structures [17].

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References

[1] Tarucha S, Austing D G, Honda T, van der Hage R J and Kouwenhoven L P 1996 *Phys. Rev. Lett.* **77** 3613
[2] Kouwenhoven L P, Austing D G and Tarucha S 2001 *Rep. Prog. Phys.* **64** 701
[3] Kouwenhoven L P, Oosterkamp T H, Danoesastro M W S, Eto M, Austing D G, Honda T and Tarucha S 1997 *Science* **278** 1788
[4] Oosterkamp T H, Janssen J W, Kouwenhoven L P, Austing D G, Honda T and Tarucha S 1999 *Phys. Rev. Lett.* **82** 2931
[5] Sasaki S, De Franceschi S, Elzerman J M, van der Wiel W G, Eto M, Tarucha S and Kouwenhoven L P *Nature* **405** 764
[6] Bednarek S, Szafran B and Adamowski J 2001 *Phys. Rev.* B **64** 195303
[7] Hatano T, Stopa M, Yamaguchi T, Ota T, Yamada K and Tarucha S 2004 *Phys. Rev. Lett.* **93** 066806
[8] Reed M A, Randall J N, Aggarwal R J, Matyi R J, Moore T M and Wetsel A E 1988 *Phys. Rev. Lett.* **60** 535
[9] Tarucha S, Tokura Y and Hirayama Y 1991 *Phys. Rev.* B **44** 13815
[10] Tewordt M, Ritchie D A, Syme R T, Kelly M J, Law V J, Newbury R, Pepper M, Frost J E F, Jones G A C and Stobbs W M 1991 *Appl. Phys. Lett.* **59** 1966
[11] Dellow M W, Beton P H, Langerak C J G M, Foster T J, Main P C, Eaves L, Henini M, Beaumont S P and Wilkinson C D W 1992 *Phys. Rev. Lett.* **68** 1754
[12] Guéret P, Blanc N, Germann R and Rothuzien H 1992 *Phys. Rev. Lett.* **68** 1896
[13] Goodings C J, Mizuta H, Cleaver J R A and Ahmed H 1994 *J. Appl. Phys.* **76** 1276
[14] Schmidt T, Tewordt M, Blick R H, Haug R J, Pfannkuche D, von Klitzing K, Förster A and Lüth H 1995 *Phys. Rev.* B **51** 5570
[15] Tagg W I E, Skolnick M S, Emeny M T, Higgs A W and Whitehouse C R 1992 *Phys. Rev.* B **46** 1505
[16] Tagg W I E, White C R H, Skolnick M S, Eaves L, Emeny M T and Whitehouse C R 1992 *Phys. Rev.* B **48** 4487
[17] Nishi Y and Tarucha S, private communication