Resonant Tunneling through the Bound States of a Single Donor Atom in a Quantum Well

M. W. Dellow,[1] P. H. Beton,[1] C. J. G. M. Langerak,[1] T. J. Foster,[1] P. C. Main,[1] L. Eaves,[1] M. Henini,[1] S. P. Beaumont,[2] and C. D. W. Wilkinson[2]

[1]Department of Physics, University of Nottingham, Nottingham NG7 2RD, United Kingdom
[2]Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom
(Received 12 June 1991)

We have observed a series of sharp peaks in the low-temperature $I(V)$ characteristics of a gated 1 μm×1 μm GaAs/(AlGa)As resonant tunneling diode, in which the gate is used to reduce the effective cross-sectional area from 0.7 to $<0.1\ \mu m^2$. These peaks, which occur at voltages well below the calculated resonant threshold, show a weak dependence on temperature, magnetic field, and cross-sectional area. We argue that this subthreshold structure is due to an inhomogeneity which gives rise to a localized preferential current path, and we deduce that the spatial extent of the inhomogeneity is approximately 25 nm. The likely origin of the inhomogeneity is a donor impurity in the quantum well.

PACS numbers: 73.40.Gk, 71.55.Eq, 85.30.Tv

The strongly nonlinear $I(V)$ characteristics of resonant tunneling diodes (RTDs) are a direct manifestation of the quantum confinement of electrons in a potential well formed between two barriers [1]. This leads to quantization of motion perpendicular to the barriers, but electrons remain free to move in the plane of the well. By further quantizing this planar motion it should be possible to form laterally confined *zero-dimensional states.* This aim has been pursued by fabricating RTDs with dimensions small enough ($<1\ \mu$m) to produce lateral confinement [2-4]. New features appearing in the $I(V)$ of such devices have been attributed to lateral confinement [2-4] and/or Coulomb blockade [5]. However, it is difficult to show experimentally that these features are directly related to the lateral dimension of the device, since two-terminal devices with fixed dimensions have been used.

We have recently fabricated [6] a three-terminal RTD in which the effective lateral dimension may be varied using a gate electrode. In this Letter we report the variation of $I(V)$ of such a device with gate voltage, temperature, and magnetic field. In particular, we observe peaks below the predicted resonant threshold voltage which have a weak dependence on the lateral dimension of the device, and so cannot be explained simply by either Coulomb blockade or laterally quantized states. We propose that the peaks are due to resonant tunneling through zero-dimensional bound states formed by a shallow donor impurity in the quantum well of the device.

The device, shown schematically in the inset of Fig. 1, is similar to one described by Kinard *et al.* [7]. It is fabricated from a semiconductor layer grown by molecular-beam epitaxy (MBE) with $Al_{0.4}Ga_{0.6}As$ barriers, of thickness $b=5.7$ nm, separated by a GaAs quantum well of thickness $w=12$ nm, in which the lowest quasi-bound-state energy E_1 is calculated to be 24 meV. The barriers are separated from the doped n-type GaAs contact regions by an undoped GaAs spacer layer 3.4 nm thick and the doping varies from a low value, 2×10^{16} cm^{-3}, close to the barriers, to a high value, 2×10^{18}

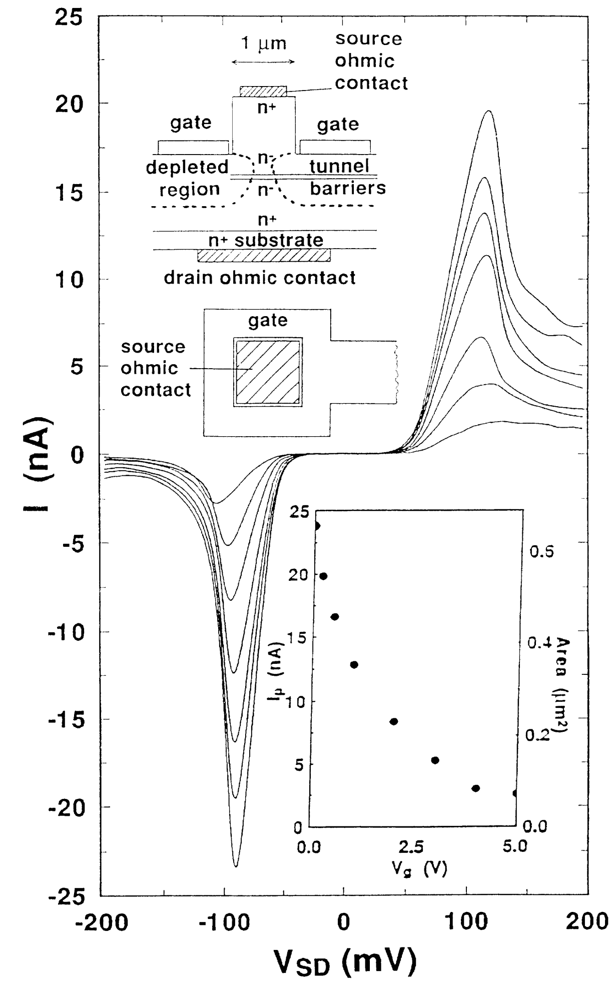

FIG. 1. The source-drain $I(V)$ characteristic measured at 4.2 K for various gate voltages: $V_g=0$, 0.2, 0.5, 1.0, 2.0, 3.0, and 5.0 V in order of decreasing peak current. Top inset: A schematic diagram of the device. The extent of the depleted region, enclosed by the dotted line, may be varied by varying the gate voltage. Bottom inset: A plot of peak current, together with the cross-sectional area, vs gate voltage.

cm^{-3}, over a thickness of order 1 μm (for more details see Ref. [6]). By increasing the (negative) gate voltage V_g, the extent of the depletion region may be increased thereby reducing the effective conducting area of the device. Figure 1 shows current versus source-drain voltage V_{SD}, for various V_g, measured at low temperature ($T=4.2$ K) on a typical device. The gate voltage is applied with respect to the earthed substrate (drain) and the current is measured from the voltage across a 100-kΩ series resistor. Peaks are observed in each polarity due to resonant tunneling of electrons through the quasibound well state. As V_g is increased, the peak current is reduced. Thus the current, and therefore the effective cross-sectional area of the device, may be varied by applying a voltage to the gate. In the inset to Fig. 1 we plot I_p, the peak current in reverse bias, versus V_g. We deduce a value for the effective cross-sectional area of the device, A, from the relation $A=I_p/j_p$, where $j_p=3.6\times10^4$ A/m^2 is the peak current density in reverse bias. The value of j_p is found by comparing $I_p(V_g=0)$ for devices with different mesa dimensions. Thus we may determine the variation of A with V_g (values of A are marked on the right-hand axis of the lower inset to Fig. 1).

We now focus on $I(V)$ close to the threshold for conduction (plotted for $V_g=0$ in Fig. 2) in which a series of peaks are clearly seen. A peak to valley ratio of $\simeq 3$ is observed for the first peak in reverse bias. We have observed similar, although not identical, structure in several devices. The top inset of Fig. 2 plots $I(V)$ at temperatures from 2 to 20 K at $V_g=0$. The structure clearly persists up to $\simeq 10$ K. The peaks in reverse bias occur at -26, -36, and -43 mV, and those in forward bias at voltages 31, 40, and 50 mV. We have calculated the voltage threshold for resonant tunneling, V_{th}, from electrostatic considerations (see Eaves *et al.* [8] for details), and find $V_{th}\simeq 50$ mV. The structure shown in Fig. 2 therefore occurs at subthreshold values of voltage. To elucidate the origin of these subthreshold resonances we have studied their variation with V_g.

In Fig. 3 we plot $I(V)$ in reverse bias measured at $T=39$ mK for various gate voltages. For clarity of presentation we have only plotted selected traces, together with the dependence of the positions of the peaks on gate voltage (see inset to Fig. 3). Over this range of V_g the shift in the voltage positions of the peaks is small compared with their separation in voltage. In particular, the position in voltage of the lowest peak changes by less than 1 mV, and its amplitude remains approximately constant over the gate voltage range 1.7 V $> V_g >$ 0 V. However, for 2.1 V $> V_g >$ 1.7 V the amplitude of the lowest peak is reduced to zero, and its position in voltage increases by $\simeq 1.5$ meV. The peak at $V_{SD}\simeq -43$ mV shows a very weak dependence on gate voltage—its position in voltage

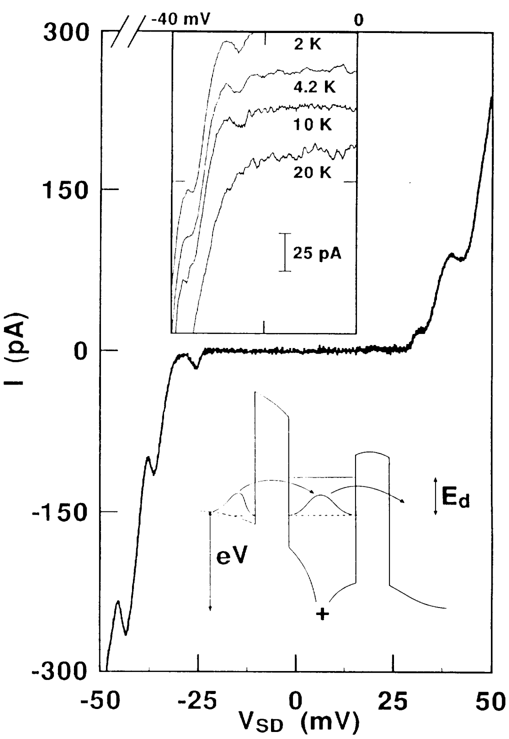

FIG. 2. $I(V)$ close to threshold at zero gate voltage measured at 39 mK. Bottom inset: The conduction-band profile close to an ionized donor for an applied voltage V. Top inset: $I(V)$ in reverse bias close to the threshold at zero gate voltage for temperatures $T=2$, 4.2, 10, and 20 K from top to bottom, respectively.

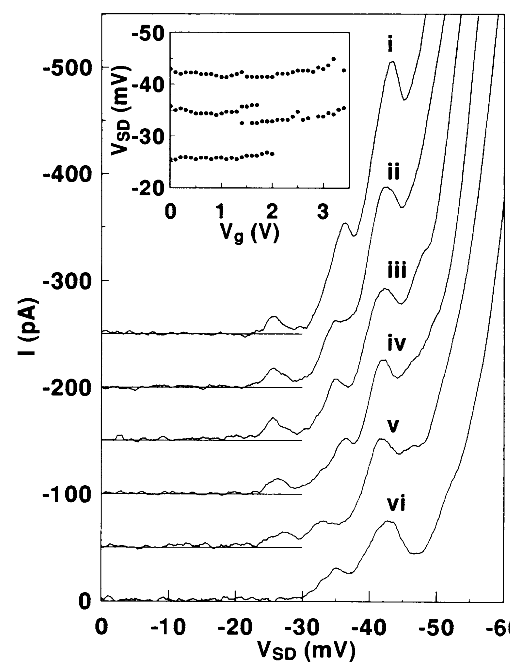

FIG. 3. Reverse-bias $I(V)$ for various gate voltages: (i) $V_g=0$ V, (ii) 0.6 V, (iii) 1.1 V, (iv) 1.5 V, (v) 1.9 V, and (vi) 2.5 V from top to bottom, respectively. Inset: A plot of peak position vs gate voltage.

varies by less than 2 mV for 1.7 V > V_g > 0 V, and its amplitude remains approximately constant, although it is superimposed on a background current which is progressively reduced as V_g is increased. The behavior of the peak at $V_{SD} \simeq -35$ mV is more complex—although its voltage position remains approximately constant it appears to split into two peaks over a narrow range of gate voltage 1.8 V > V_g > 1.4 V. The corresponding set of peaks in forward bias have a similar dependence on V_g. In particular, the lowest peak is unaffected over a wide range of gate voltage and then suppressed above a critical gate voltage ($V_g \simeq 1.8$ V).

Our data cannot be explained by either lateral quantization or Coulomb blockade resulting from the electrostatic confining potential of the gate since the positions in voltage of any structure related to either effect would be strongly dependent on the device area [2-5] A (in particular, the peak positions should vary on a scale comparable to their separation in voltage). However, as A varies by a factor of 3 (as V_g is varied from 0 to 1.5 V), the position in voltage of the subthreshold structure is unaffected. Furthermore, neither Coulomb blockade nor lateral quantization can explain why the structure appears *below* the threshold voltage, and the values of the energy scales for these effects are < 0.1 meV which correspond to a temperature of 1 K, whereas the peaks persist up to 10 K.

Our explanation of these effects is that current flows through a locally favorable path associated with an inhomogeneity in the active region of the device. We propose that the microscopic origin of the inhomogeneity is a donor impurity atom unintentionally situated in the quantum well of the RTD. A local minimum in the potential is formed due to this donor with associated bound states in the well. The binding energy E_d of the lowest-energy bound state depends on the position of the donor in the quantum well. For a well width $w = 12$ nm, E_d has been calculated [9] to be 12 meV for a donor at the center of the well and 8 meV for a donor at the well/barrier interface. The presence of a single donor also gives rise to weakly bound states at the interface between the undoped GaAs spacer regions and the (AlGa)As barriers as shown schematically in Fig. 2. The binding energy of these states E_I is < 1.5 meV, which is estimated from the binding energy of a donor at the interface between a semi-infinite GaAs region and an infinite barrier [10]. Current flows when sufficient voltage is applied for an electron in the weakly bound interface state to tunnel through the donor bound well states. Taking $E_d \simeq 10$ meV and $E_I = 1$ meV, the energy difference between the interface state and the lowest bound state in the well, $\Delta E = E_1 - E_d + E_I$, is $\simeq 15$ meV. We have calculated the corresponding voltage threshold for current to flow to be $V_{\text{th}} \simeq 28$ mV, in good agreement with our data. In effect, we propose that full lateral quantum confinement does occur, but that it is due to a single ionized donor which forms bound states through which electrons may resonantly tunnel.

We can use the gate to probe the spatial extent of the states associated with the inhomogeneity as follows. A peak in $I(V)$ is unaffected until the depletion edge impinges on the region of the corresponding localized state through which electrons tunnel. However, as the depletion encroaches on this region the structure in $I(V)$ will be modified, since the energy of the state will be perturbed. When it extends throughout the region the amplitude will be strongly affected, since the lateral overlap of states in the emitter and donor bound well states will be reduced. This corresponds qualitatively to what is observed. For example, the lowest peak is unaffected until $V_g \simeq 1.7$ V. As V_g is further increased by a small amount to a value $V_g = 2.1$ V the peak is strongly affected. The effective sample dimension d for a given gate voltage may be obtained from Fig. 1, and we estimate the spatial extent of the lowest state as $\Delta x = [d(V_{g1}) - d(V_{g2})]/2$, where V_{g1} ($=1.7$ V) is the highest gate voltage for which the peak is unaffected and V_{g2} ($=2.1$ V) is the lowest gate voltage at which the peak is suppressed. For the state corresponding to the lowest peak in each bias direction this gives a spatial extent $\simeq 25$ nm. The spatial extent of the lowest bound state of a donor in bulk GaAs is $\simeq 3a_0$ (since the expectation value of the radial position of the electron is $3a_0/2$), where a_0, the effective Bohr radius, $\simeq 10$ nm for GaAs. In bulk GaAs we therefore expect the lowest state to be localized over a region of width $\simeq 30$ nm. However, electrons in a quantum well are more tightly bound so this value represents an upper limit for their spatial extent, but it is unlikely to be in error by more than 20%. Our experimental value for the spatial extent of the state is therefore close to the value expected for a single donor bound state. We have also measured $I(V)$ in various magnetic fields and find that for a field $B < 5$ T the lowest peak position and amplitude is weakly affected. According to our model we would expect that a magnetic field would have little effect if $2l_B > \Delta x$, where $l_B = (\hbar/eB)^{1/2}$, and Δx is defined above. This implies that a magnetic field would have little effect for $B < 4$ T, which is consistent with our data.

The slight asymmetry in the positions of the peaks shown in Fig. 2 probably arises since the donor is not exactly at the center of the well. This means that (i) the binding energies E_I of the two barrier/spacer-layer interface states are different, and (ii) the effective barrier heights will be slightly different. Both these effects would lead to asymmetry in $I(V)$. For example, the energies of the interface states could differ by 1-2 meV, resulting in a difference in peak positions in forward and reverse bias in the range 2-4 meV. The observed difference in the lowest peak position in the two polarities is $\simeq 5$ meV, which is slightly above the expected range.

The origin of the donor in the quantum well could be either (i) unintentional background impurities or (ii) related to Si segregation in the doped contact layers. The latter effect causes an exponential decay (in the MBE growth direction) of the doping density with position from an interface between doped and unintentionally doped material. The doping density decay length λ has been measured [11] and is found to be $\lambda = 5.6$ nm for the growth temperature used (630 °C), which means that the doping density at the barrier/well interface is $n \simeq 4\times10^{21}$ m^{-3}. The background doping density for material grown in our MBE machine has been measured [12] and is found to be n type with a concentration in the range $5\times10^{19}-10^{20}$ m^{-3}. Si segregation is therefore the dominant source of donors and would be expected to give rise to $N_d \simeq nA\lambda$ donors in the well. For $V_g = 0$ we find $N_d = 15$, and for $V_g = 4$ V, $N_d = 1-2$. Therefore it is plausible for one or a small number of donors to control the subthreshold characteristics of the device.

We now discuss the origin of the peaks at $V_{SD} \simeq -35$ mV and $V_{SD} \simeq -43$ mV. Three possibilities are considered: (i) The peaks are due to tunneling through the excited states of the same donor which gives rise to the lowest peak. The separation in energy of these states is [9] $\simeq$5–8 meV, which would give rise to a separation of corresponding peaks in $I(V)$ of 10–16 meV. This is slightly higher than the observed value of 9 meV. (ii) They are due to tunneling through the bound states of other donors, which are situated at a different position in the quantum well. Since the bound-state energy of a donor depends on its position relative to the barriers (a centrally placed donor has the largest binding energy), the peaks from different donors occur at different voltages. (iii) They arise from a combination of these effects. A possible explanation of the apparent splitting and subsequent lowering in voltage position of the peak which occurs at $V_{SD} \simeq -35$ mV when $V_g = 0$ is that it is composed of two closely spaced peaks, one at $V_{SD} \simeq -33$ mV and one at $V_{SD} \simeq -36$ mV, which arise from separate donors. The peak at -36 mV has the larger amplitude and at low gate voltage the peak at -33 mV overlaps and merges into the stronger peak. For 1.8 V $> V_g >$ 1.4 V the amplitude of the higher peak is reduced, presumably since the donor-assisted conduction path corresponding to this peak is switched off, allowing us to resolve the separate peaks. A further increase in gate voltage reduces the amplitude of the higher peak to zero and only the weaker peak at $V_{SD} \simeq -33$ mV remains. The peaks at $V_{SD} \simeq -35$ mV and $V_{SD} \simeq -43$ mV are weakly affected by a magnetic field, but nevertheless show a stronger dependence than the lowest peak. This implies that not all peaks arise from tunneling through the lowest bound state of a donor. On the basis of the evidence available it is likely that some of the peaks at higher voltage arise from tunneling through excited states, and some from tunneling through states associated with other donors.

To summarize, we have been able to rule out lateral confinement and Coulomb blockade as causes for the subthreshold structure which we observe in small-area RTDs. We propose that this structure is instead due to the presence of a locally favorable current path due to an ionized donor in the well region of the RTD. This is qualitatively and, where it is possible to make detailed predictions, quantitatively consistent with the dependence of the subthreshold structure on gate voltage, temperature, and magnetic field.

We would like to thank M. J. Kelly, M. Tewordt, and C. T. Foxon for interesting discussions. P.H.B. thanks the Royal Society for financial support. This work was funded by the Science and Engineering Research Council, United Kingdom.

[1] L. L. Chang, L. Esaki, and R. Tsu, Appl. Phys. Lett. **24**, 593 (1974).

[2] M. A. Reed, J. N. Randall, R. J. Aggarwal, R. J. Matyi, T. M. Moore, and A. E. Wetsel, Phys. Rev. Lett. **60**, 535 (1988).

[3] M. Tewordt, V. J. Law, M. J. Kelly, R. Newbury, M. Pepper, D. C. Peacock, J. E. F. Frost, D. A. Ritchie, and G. A. C. Jones, J. Phys. Condens. Matter **2**, 8969 (1990).

[4] B. Su, V. J. Goldman, M. Santos, and J. E. Cunningham, Appl. Phys. Lett. **58**, 747 (1991).

[5] A. Groshev, Phys. Rev. B **42**, 5895 (1990); V. J. Goldman, B. Su, and J. E. Cunningham, in Proceedings of the International Symposium on Nanostructures and Mesoscopic Systems, Sante Fe, New Mexico, 1991 (to be published).

[6] M. W. Dellow, P. H. Beton, M. Henini, P. C. Main, L. Eaves, S. P. Beaumont, and C. D. W. Wilkinson, Electron. Lett. **27**, 134 (1991).

[7] W. B. Kinard, M. H. Weichold, G. F. Spencer, and W. P. Kirk, J. Vac. Sci. Technol. B **8**, 393 (1990).

[8] V. J. Goldman, D. C. Tsui, and J. E. Cunningham, Phys. Rev. Lett. **58**, 1256 (1987); see also L. Eaves, G. A. Toombs, F. W. Sheard, C. A. Payling, M. L. Leadbeater, E. S. Alves, T. J. Foster, P. E. Simmonds, M. Henini, O. H. Hughes, J. C. Portal, G. Hill, and M. A. Pate, Appl. Phys. Lett. **52**, 212 (1988).

[9] R. L. Greene and K. K. Bajaj, Solid State Commun. **45**, 825 (1983); see also N. Jarosik, B. D. McCombe, B. V. Shanabrook, J. Comas, J. Ralston, and G. Wicks, Phys. Rev. Lett. **54**, 1283 (1985), for measured values of the binding energies of donors in quantum wells.

[10] G. Bastard, Phys. Rev. B **24**, 4714 (1981).

[11] J. J. Harris, J. B. Clegg, R. B. Beall, J. Castagne, K. Woodbridge, and C. Roberts, J. Cryst. Growth **111**, 239 (1991).

[12] M. B. Stanaway, R. T. Grimes, D. P. Halliday, J. M. Chamberlain, M. Henini, O. H. Hughes, M. Davies, and G. Hill, in *Proceedings of the International Conference on Shallow Impurities in Semiconductors*, edited by B. Monemar, IOP Conf. Proc. No. 95 (Hilger, Bristol, England, 1989), p. 295.