Resonant tunneling in an $Al_xGa_{1-x}As$/GaAs quantum dot as a function of magnetic field

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We report magnetotunneling through a quantum dot realized in a 200-nm-diameter $Al_xGa_{1-x}As$-GaAs double-barrier diode. Steplike current-voltage characteristics are observed at low temperatures in the low-bias regime and are assigned to tunneling though zero-dimensional states. With increasing magnetic field parallel to the current direction, the first six resonances shift to higher bias by the same amount. The data are discussed in terms of a simple model of electrostatic quantum confinement in a magnetic field, allowing for Coulomb-charging effects. We conclude that a more detailed theory is needed to obtain a clear explanation of the mechanism leading to the current steps.

Submicrometer-diameter resonant tunneling diodes (RTD's) are excellent devices to study zero-dimensional (0D) electronic states in semiconductors.[1–14] The 0D states are formed in the quantum well (quantum dot) of the RTD due to size quantization and were observed by Reed *et al.*[1] Subsequent theoretical and experimental studies included subband mixing in tunneling through quantum dots,[2,3] Coulomb-charging effects,[6,12] and the steplike nature of the current-voltage characteristics in these devices.[4,5,9,11–14] The latter work makes accessible the physics of the linewidths of the quantum-dot states (and therefore the transmission probability), electron-transfer times, and scattering contributions in transport through submicrometer RTD's. Magnetotunneling has been reported previously, but the shifts in bias of the current steps were not analyzed.[9] This problem is addressed in the present paper, in which we study magnetotunneling through a 200-nm-diameter $Al_xGa_{1-x}As$-GaAs RTD with the magnetic field (B) parallel to the current direction. The analysis is based on a model of electrostatic quantum confinement in a magnetic field, and allows for Coulomb-charging effects. We will conclude that an improved theory is in demand to account for the magnetotunneling data.

A steplike fine structure in the low-temperature I-V characteristics of quantum-dot RTD's may arise either from size quantization or from single-electron charging. If size quantization between the diode sidewalls is present, quasi-one-dimensional (1D) subbands are formed in the emitter and collector contacts, and 0D states are formed in the quantum dot. When under bias the 0D states fall below the occupied 1D subband states in the emitter, electrons can tunnel into the 0D states and from there into the collector. At zero temperature the total tunneling current at bias V can be written as

$$I(V)=e\sum_n\int_{E_F-eV}^{E_F}N_n(E)v_n(E)T_n(E,V)dE\ , \qquad (1)$$

where the sum is over all 1D subbands n below the Fermi energy E_F in the emitter, $N_n(E)$ ($\propto E^{-1/2}$) is the 1D density of states of the nth subband in the emitter, $v_n(E)$ ($\propto E^{1/2}$) is the velocity of electrons at the energy E in subband n, and $T_n(E,V)$ is the transmission probability through the double-barrier structure. In 1D subbands, the product $N_n(E)v_n(E)=1/h$ is constant, independently of the band structure. If the transmission $T_n(E,V)$ near resonance is approximated by a Lorentzian line shape with the linewidth Γ_e and peak transmission $T_{0,n}(V)$, a current contribution of

$$\Delta I_n=e\pi T_{0,n}(V)\Gamma_e/h \qquad (2)$$

is obtained for each spin state in every occupied emitter subband. When with increasing bias a 0D state falls below the Fermi energy in the emitter contact, a new channel for tunneling through the quantum dot is opened and a current step ΔI_n occurs in the I-V characteristics. For several 1D subbands and 0D states a steplike I-V is obtained, if $T_{0,n}(V)$ is only weakly dependent on V. The plateau width in bias of the steps reflects the energy spacing of the 0D states in the dot. A steplike I-V in submicrometer RTD's has been observed previously.[4,5,9]

The simple picture of a steplike I-V fine structure resulting from size quantization could be altered for the following reasons: (i) The peak transmission $T_{0,n}(V)$ can be strongly dependent on the bias V, thus producing steps with an upwards or downwards slope;[5,14] (ii) it has been shown theoretically that if the contacts are three dimensional (3D), the I-V for 3D-0D tunneling exhibits a peaklike fine structure.[15] This results from the fact that the density of states in Eq. (1) is then 3D and therefore $N(E)_n\propto E^{+1/2}$. Tunneling from 3D states into 0D states has been reported recently.[16] If, however, the undoped central layer with the double-barrier structure is very thin (i.e., less than the sidewall depletion width), the quantum dot and the contact regions have nearly the same lateral confinement width. Thus if size quantization is present in the dot it is also present in the contacts. The system is then 1D-0D and a steplike I-V is expected. The latter case applies to the experiments described here.

Current steps in the I-V of ultrasmall RTD's may also arise from single-electron charging of the dot, if the temperature broadening k_BT is smaller than the elementary charging energy e^2/C of the dot, where C is the effective capacitance of the double-barrier structure.[6,12] In submicrometer RTD's the effective capacitance can be of the order $C \approx 10^{-17}$ F, and therefore $e^2/C \approx 16$ meV, which is much larger than $k_BT \approx 0.35$ meV at $T=4$ K. The current step height is then the same as in Eq. (2), and thus the flatness of the steps depends on $T_{0,n}(V)$. It is difficult to distinguish between size-quantization and Coulomb-charging effects and in fact both effects may coexist.[6,12] An assignment to size quantization or single-electron charging is only possible with proper modeling.[17]

We have observed a steplike I-V fine structure in a RTD fabricated from an $Al_xGa_{1-x}As$-GaAs double-barrier heterostructure grown by molecular-beam epitaxy (MBE) on n^+-type (Si-doped) GaAs substrate. The layer sequence as grown on top consisted of (i) 1 μm of GaAs, Si doped to 10^{18} cm^{-3}, (ii) 5.0 nm GaAs (spacer), (iii) 5.25 nm AlGaAs (32% Al, bottom barrier), (iv) 5.5 nm GaAs (well), (v) 5.0 nm AlGaAs (32% Al, top barrier), (vi) 5.0 nm GaAs (spacer), and (vii) 1 μm of GaAs, Si doped to 10^{18} cm^{-3} (top contact layer). Layers (ii)–(vi) inclusive are undoped. While this structure provides the vertical quantization, the lateral quantization was achieved by plasma etching[18] a 200-nm-diameter column under a top Ohmic contact of the same size, providing a narrow vertical electron channel through the double barrier to the n^+-type substrate. The latter forms the back electrode via an Ohmic back contact. The details of the fabrication process have been reported previously.[4]

Figure 1 shows the current-voltage (I-V) characteristics of the 200-nm-diameter single RTD at $T \approx 4.2$ K and at zero magnetic field. Negative differential conductance peaks are clearly observed in both bias polarities and exhibit a peak-to-valley ratio of $P/V \approx 2.3$. The peak current in forward bias is $I_p \approx 1.25$ μA. Using the current density of $j \approx 2.2 \times 10^4$ A/cm^2 obtained from larger diameter diodes from the same MBE structure, we can estimate the conducting diameter of the diode by extrapolation and find $d_{cond} \approx 83$ nm. The interesting features of the data are the small current steps (marked by the arrows) at the current thresholds in both bias polarities.

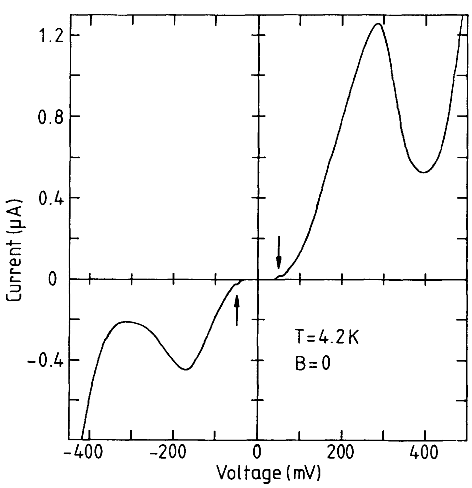

FIG. 1. Current-voltage characteristic of a 200-nm-diameter resonant tunneling diode at $T \approx 4.2$ K. The arrows mark the steps arising at the current threshold.

The expanded low-bias I-V characteristics for zero magnetic field are shown in the top trace of Fig. 2. Here, the temperature is lower (dilution refrigerator mixing chamber temperature $T \approx 30$ mK) and the much sharper fine structure clearly produces an I-V staircase. The experimental step height $\Delta I \approx 12$ nA of the first step in forward bias is in good agreement with calculations of $T_{0,n}(V)\Gamma_e \approx 0.1$ meV, using a transfer-matrix calculation for the transmission probability with the barrier heights and thicknesses specified above as input parameters, and the relation Eq. (1). The value $T_{0,n}(V)\Gamma_e$ is only weakly dependent on the bias V,[5] in good agreement with the experimental observation. Up to the bias where the first step appears, the current is zero in both bias polarities. At $V=44$ mV forward bias a sharp current step occurs, followed by a second step at $V=56$ mV, and so forth.

In Fig. 2 the magnetotunneling data for magnetic fields B parallel to the current direction are also shown. The steplike character of the I-V is retained, but the voltages at which the steps occur shift to higher biases with increasing B. This effect is more clearly seen in Fig. 3, where the differential conductance-voltage (G-V) characteristics are plotted for magnetic fields varying between $B=0$ and 13 T. For $B=0$ a series of resonances appears with spacings in bias between 4 and 11.5 mV. The peak amplitudes are between 2 and 3 μS, and the linewidths are $\Delta V \approx 3$ mV. The details of the line shapes in these spectra have been discussed previously.[4,5] As a function of magnetic field, we find that generally the peak amplitudes decrease by a few tens of percent between $B=0$ and 13 T. Some peaks oscillate in amplitude with B, and

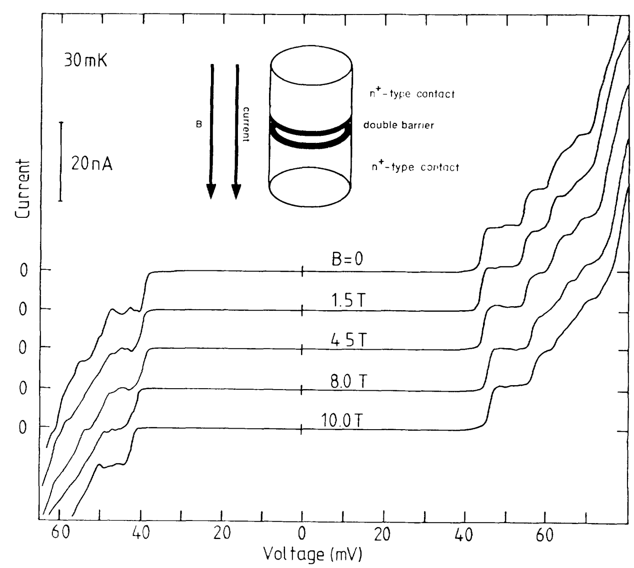

FIG. 2. Detailed I-V characteristics of the diode in Fig. 1 in the low voltage regime for different magnetic fields B parallel to the current flow, showing the I-V staircase at $T \approx 30$ mK. The inset shows the experimental geometries.

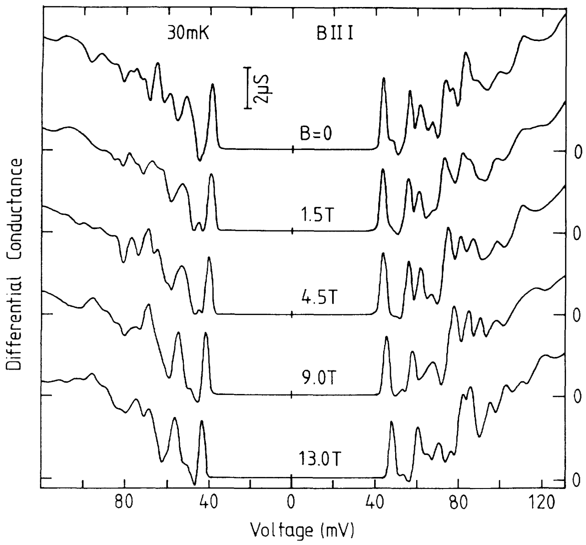

FIG. 3. Differential conductance-voltage (G-V) plot of the same device as in Fig. 2 in the low-bias regime, and for different magnetic fields parallel to the current direction, showing resonances which can be assigned to the 0D box states.

13 T. Some peaks oscillate in amplitude with B, and most of the peaks shift to higher biases, as has already been noted. Some resonances oscillate in bias by a few millivolts.

Figure 4 shows the resonance positions in forward bias as a function of the magnetic field B. The first (lowest) resonance shifts from $V=44$ to 48 mV (i.e., $\Delta V_B=+4$ mV). All resonances shift by the same amount of $\Delta V_B \approx 4-8$ mV to higher bias (expect only for the oscillating resonance at $V\approx 82$ mV). This is in contrast to single-electron theories for two-dimensionally and three-dimensionally confined, nearly cylindrical quantum boxes in magnetic fields,[19] where some states increase their energy with B, while others decrease. In particular, the first state always shifts upwards in energy, while the second shifts downwards (without regarding the spin).

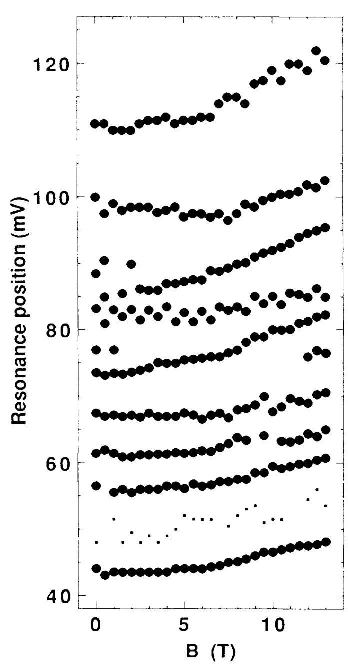

FIG. 4. Plot of the peak positions in forward bias of the G-V resonances vs magnetic field B parallel to the current direction. The small dots represent a very weak resonance structure.

Before proceeding to model our data we note the qualitative difference between the magnetotunneling in 1D-0D diodes[1,4,9] and in 2D-1D diodes.[8] Tarucha and Hirayama[8] investigated resonant tunneling in a RTD with 2D contacts and a 1D well, where a *peak* (rather than a step) appears in the I-V, whenever the energy of a 2D subband in the emitter matches the energy of a 1D subband in the well. Since both the 2D and the 1D subbands shift up in energy with B by an equal amount, there is no shift with B observable in the resonance bias. A shift in bias with B may in this case only arise when the confinement widths in emitter and quantum well are different. In our 1D-0D system, steps in the I-V (and peaks in the G-V) appear when the 0D states in the quantum dot match the Fermi energy in the emitter. Since the Fermi energy is only weakly dependent on B (for $\mathbf{B}\|\mathbf{z}$) for the doping levels considered,[20] the shift in bias of the resonance peaks reflects the magnetic field dependence of the 0D states.

To discuss the magnetic field dependence of the resonance states in Fig. 4, we consider a single-electron model for a quantum dot in a magnetic field B. We account for the Coulomb-charging energy in terms of a single effective capacitance C. This is the usual approach in studies of resonant tunneling in quantum dots,[6,22] although recently it has been noted that electron-electron interactions within the dot can be important.[12,23,24] The resonant energies of the quantum-dot states can be written as

$$E(n,m,B,N)_{\text{box}}=(e^2/C)(N-\tfrac{1}{2})+E_z+E(B)_{n,m} \; . \tag{3}$$

The Coulomb-charging energy of the quantum dot filled with N electrons gives the term $(e^2/C)(N-\frac{1}{2})$.[21] The term E_z ($=68.5$ meV for our system) is the energy from the confinement between the barriers. We consider for E_z only the ground state, because the confinement in z direction is much stronger than in the (lateral) x-y plane. $E(B)_{n,m}$ is the eigenenergy of the two-dimensional lateral confinement potential in a magnetic field B with the quantum numbers n and m. The data in Fig. 4 were modeled using several different geometries for the lateral confinement potential, such as square-shaped, rectangular, and circular, with either the hard-wall potential or the parabolic potential shape. Since we have arrived at the same conclusions for all the confinement potentials considered, we shall discuss here the simplest model of a cylindrical potential box with parabolic confinement. In the circular symmetric, two-dimensional harmonic oscillator model the eigenenergies are[19]

$$E(B)_{n,m}=(2n+|m|+1)\{(\hbar\omega_c/2)^2+(\hbar\omega_0)^2\}^{1/2}+m(\hbar\omega_c/2) \tag{4}$$

with the radial $n=0,1,\ldots$ and the azimuthal

$m=0,\pm1,\pm2,\ldots$ quantum numbers. Here, $\hbar\omega_c=\hbar eB/m^*$ is the cyclotron energy, with the magnetic field B perpendicular to the barriers ($\mathbf{B}\|\mathbf{z}$). To estimate the lateral quantization energy $\hbar\omega_0$ in our experiment, we assume the two-dimensional parabolic potential to be occupied with electrons up to the Fermi energy E_F. The eigenenergies $\hbar\omega_0$ are then related to E_F and the conducting diameter d_{cond} by

$$\hbar\omega_0=(2\hbar/d_{\text{cond}})(2E_F/m^*)^{1/2} . \quad (5)$$

Using $d_{\text{cond}}=83$ nm, $E_F=50$ meV, and $m^*=0.067m_e$, we obtain $\hbar\omega_0=8.1$ meV. The Coulomb-charging energy can be estimated from the effective capacitance C of the quantum dot:[25,26,12]

$$C=C_e+C_c\approx(\epsilon\epsilon_0 d_{\text{cond}}^2/4\pi)(d_e^{-1}+d_c^{-1}) . \quad (6)$$

Here, C_e (C_c) is the effective capacitance between the emitter (collector) reservoir and the well. The dielectric constant is $\epsilon_{\text{AlGaAs}}\approx13.2$, and $d_e\approx5$ nm and $d_c\approx5$ nm are the effective emitter and collector barrier thicknesses, respectively. The charging energy can then be estimated to be $e^2/C\approx6.25$ meV.

The resonances in G-V arise when $E(n,m,B,N)_{\text{box}}=E_F'$ in Eq. (3). Peaks occur then at voltages given by

$$V_{\text{res}}(n,m,B,N)\approx(1/\eta e)\{E_z+E_{n,m}(B)+[e^2/C(N-\tfrac{1}{2})] -(E_F+\Delta)\} , \quad (7)$$

where Δ accounts for the charge accumulation in the emitter contact,[27] and e is the electron charge. The factor η represents the fraction of the voltage drop between emitter and the quantum dot and can be approximated by $\eta=(d_e+w/2)/(d_e+w+d_c+d_s)$, with the thicknesses of the emitter barrier d_e, the well w, the collector barrier d_c, and the collector spacer d_s. Note, however, that the potential drop over the double-barrier structure may be considerably altered by electron charging and thus η may be bias dependent. Typical estimated spacings of the 0D states $\Delta V_{0D}\approx\hbar\omega_0/e\eta\approx8.1$ mV/0.3855$\approx$21 mV and $\Delta Vc\approx e/C\eta\approx7$ mV/0.3855$\approx$18 mV are larger than the observed spacings in Fig. 4 of 5–12 meV. They are, however, acceptable considering that the confinement potential and the charge distributions have been modeled with the simplest assumptions.

There are two possibilities to fit the parameters η, $\hbar\omega_0$, C, and Δ in Eq. (7) to the experimental data in Fig. 4. (i) The resonance positions for $B=0$ can be related to the energy states in Eq. (5). The spacings between the first two resonances correspond to the charging energy e^2/C (because the first two states are spin degenerate), and the second spacing corresponds to an energy $[(e^2/C)+\hbar\omega_0]$, which is larger than the first. Equation (7) reproduces then all the resonance positions for $B>0$, since the cyclotron energy $\hbar\omega_c=\hbar eB/m^*$ is known. This approach fails to explain our data for constant η, because the second spacing in Fig. 4 is larger than the first. (ii) The above parameters can be fitted using only the two lowest resonances in Fig. 4. In this case $\hbar\omega_0$ is fitted by the curvature of the resonances with B in Fig. 4. From this we obtain $\hbar\omega_0\approx36$ meV, and the corresponding spacing in bias $\Delta V=\hbar\omega_0/e\eta$ is about an order of magnitude larger than any spacing of adjacent resonances in Fig. 4. This discrepancy becomes greater, if the Coulomb-charging energy is included, because the spacing of adjacent states increases while the curvature with B remains the same (note that the Coulomb term is in first order independent of B).

We conclude that the simple model based on lateral confinement from surface depletion is unsatisfactory. A possible explanation for this deficiency is that η may be strongly bias dependent due to charging effects or that the Fermi energy E_F may increase with B. Another explanation relies on the existence of several conducting filaments in the box, that may result from potential fluctuations or impurities. Such a model has been proposed recently to explain experiments on the diameter dependence[10] in quantum dots.

The conducting filaments could be due to potential fluctuations in the central region, such as might arise from single impurities sitting in the well or from randomly distributed donors in the contacts (i.e., beyond the spacer layers, in a similar way as has been described for high mobility heterojunctions[28]). These fluctuations will exhibit lateral quantum confinement. One of several potential minima will have an (absolute) minimum energy with corresponding energy state E_{min1}. When at one bias E_{min1} matches the Fermi energy in the emitter, the first electron will tunnel in this channel. The shift in forward bias with B of the first resonance implies that the first state has a lateral spatial extension of $d_G\approx11$ nm (for $\hbar\omega_0\approx36$ meV).[29] A further increase in bias will align the next minimum state in the well (E_{min2}) with the Fermi energy in the contracts, and thus will allow a second electron to tunnel. The parallel shift of the resonances with magnetic field suggest that the lateral extensions of the wave functions in all the states are about the same. Thus a model of several 1D current filaments in parallel carry-

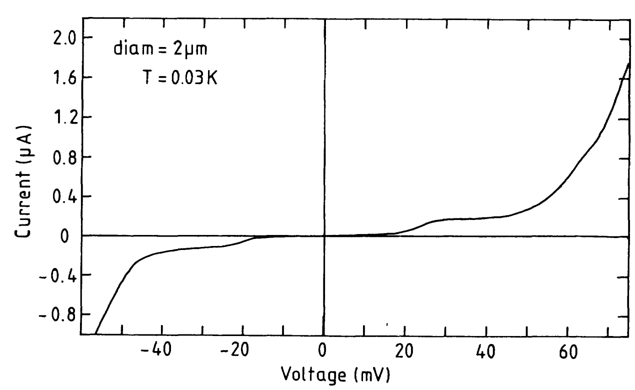

FIG. 5. Current-voltage characteristics of a 2-μm-diameter double-barrier diode, showing current steps in the low-bias regime at $B=0$ and $T\approx20$ mK. The diode exhibited 2D resonance peaks at higher biases. The MBE structure is identical to the one discussed in the text, except for the barrier thicknesses being reduced to 4 nm. The thinner barriers led to an increased step height as compared to the steps in Fig. 3.

ing the current in the low-bias regime is obtained. Such a model would explain our observation of current steps in the I-V of a double-barrier diode with 2-μm diameter as shown in Fig. 5. The observed step width in bias is $\Delta V \approx 20$ mV, i.e., it is substantially larger than either size quantization or single-electron charging may predict. However, the model of 1D filaments in parallel is only one possible explanation to account for our experiment. An improved theory for size quantization from surface depletion which includes electron-electron interactions self-consistently and thus a bias-dependent potential drop may explain our data.

In conclusion, we have reported magnetotunneling experiments in a double-barrier RTD with a conducting diameter of $d_{\text{cond}} \approx 83$ nm. A steplike fine structure was observed in the low-bias regime, which could be assigned to single-electron tunneling by estimating the tunneling rates. The fine structure exhibits an upward shift in bias with increasing magnetic field B parallel to the current. The data were discussed using a model of lateral electrostatic quantum confinement in a magnetic field and including Coulomb-charging effects. While the measured plateau widths in bias of the steps have the same order of magnitude as the estimated Coulomb-charging and single-electron quantization energies, their dependence on magnetic fields cannot be explained with the simple approximations used up to now. An improved theory is needed before an assignment of the mechanism responsible for the steplike I-V characteristics of resonant tunneling through quantum dots can be made.

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