Confinement and Single-Electron Tunneling in Schottky-Gated, Laterally Squeezed Double-Barrier Quantum-Well Heterostructures

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The conductance of laterally confined double-barrier quantum-well resonant-tunneling heterostructures is investigated. The confinement is provided by a Schottky gate and can be varied in a continuous way, giving *direct* proof of the quantum size effect. Data for dots with nominal diameters in the submicron range are reported. Possible evidence for a modulation of the Coulomb blockade by quantum confinement is presented.

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The subject of vertical transport through confined heterostructures is of great interest in view of the continuous trend towards miniaturized devices. It is also an important area of research into quantization effects, electron-electron interactions, single-electron tunneling, and the interplay between them. To our knowledge, Reed and co-workers [1] were the first to study resonant tunneling through quantum pillars fabricated by etching, and to present evidence for mode confinement. It has been argued elsewhere, however, that Reed's data can be better described when Coulomb charging effects are also taken into account [2]. Recently, Goldman, Su, and Cunningham reported the observation of single-electron tunneling and Coulomb interactions in similar, but asymmetric quantum pillars [3]. In order to gain further understanding of transport phenomena in vertical structures, we have adopted a somewhat more elaborate approach that allows *variable* control of the lateral confinement. The structure we use, shown in Fig. 1, has cylindrical symmetry. The lateral confinement is provided in part by etching a submicron dot in the semiconductor, and then adding a separately biased Schottky gate which surrounds the dot completely. The heterostructure under study is located in the bulk of the semiconductor but is fairly close ($\simeq 100$ nm) to the surface such that it can easily be depleted by the Schottky gate as indicated by the dashed lines. The depletion thus leaves a cylindrical channel whose boundaries are fairly smooth. This type of structure can be regarded as the vertical analog of the planar quantum point contact on a two-dimensional electron gas [4], and allows the study of confined vertical transport through various heterostructures in a controllable way. As a three-terminal, transistorlike device, the structure is also potentially of interest for logic applications.

The heterostructure that is the subject of this paper is a double-barrier quantum-well (DBQW) resonant-tunneling structure, which provides a quantum dot of squeezable diameter with the applied gate voltage. The devices have been designed to operate in a regime where the energy level spacing and the charging energy in the dot are comparable. They are thus expected to exhibit the interplay between quantum confinement and Coulomb interactions, with a fairly rich and hybrid conductance spectrum [2,3,5,6].

The DBQW heterostructure is described in Fig. 1 with the help of the inset. It consists of two $Al_{0.13}Ga_{0.87}As$ barriers separated by a GaAs quantum well [7], and is sandwiched between two n-doped GaAs electrodes ($n = 10^{17}$ cm^{-3}). Undoped spacers 1 nm thick (not shown) are placed symmetrically between barriers and electrodes. The fabrication steps are fairly standard and have been described elsewhere [8]. With the n doping shown, the Fermi level in the GaAs electrodes is about 12 meV above the conduction band edge. Without lateral confinement, the resonant energy in the well is about 42

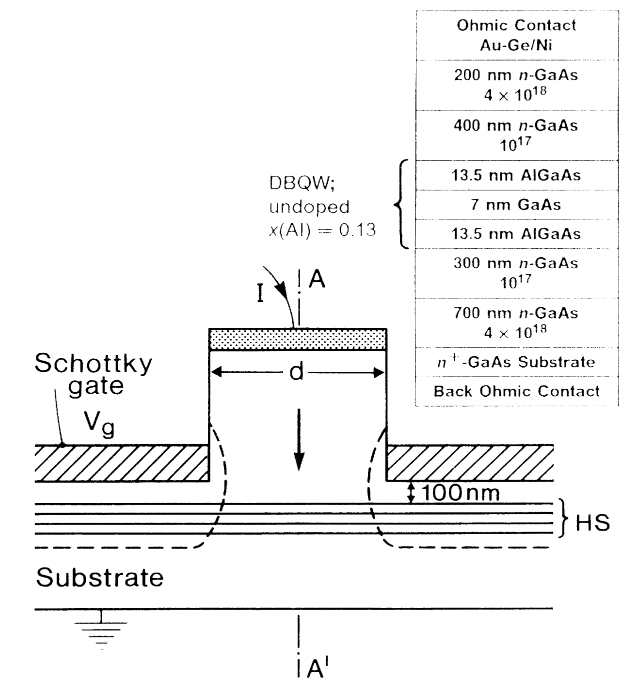

FIG. 1. Vertical transport through heterostructure (HS) laterally confined by voltage V_g on Schottky gate. Structure has cylindrical symmetry around axis AA'. Inset: Successive layers in molecular-beam-epitaxy–grown structure. From [8].

meV [7]. Owing to the unavoidable asymmetries resulting from the fabrication process (epitaxial growth, doping, etc.), the transport characteristics of our devices exhibit the usual asymmetries also observed in large-area devices. The differences observed for opposite voltage polarities are, however, not overly significant and indicate the same overall device behavior with reasonably symmetric and qualitatively similar conductance peaks. With the exception of Fig. 2, the $I(V)$ and $G(V)=dI/dV$ data reported in this paper refer to positive sample voltages, which means that electrons are injected from the substrate into the dot.

Figure 2 shows the experimental $I(V)$ characteristics of a sample with nominal dot diameter $d=0.5$ μm, with the gate voltage V_g as a parameter. The observed characteristics are as expected. The gradual decrease of the current level with increasing gate voltage proves that lateral confinement by the gate does indeed occur [8]. These data are qualitatively similar to those reported by another group [9]. Quantitatively, however, the small dot diameters we use (submicron versus 1 μm in [9]) yield larger current reduction factors at smaller gate voltages and with negligible gate currents (the peak current of the 0.4-μm dot studied below is reduced by a factor of 10 at $V_g=-2.5$ V). Note that, owing to the insensitivity of the dc measurement technique used, Fig. 2 hardly exhibits the fine structure present in the conductance. Figures 3–5 instead are data obtained with a sensitive, low-noise ac technique.

Data from a set of samples of different nominal dot diameters d yield [8] that the effective dot diameter d_0 ($V_g=0$) is about 150 nm smaller than its nominal value, consistent with the doping density and a Fermi-level pinning at -0.8 V at the etched surface of the dot. The dependence of the effective dot diameter $d_e(V_g)$ on gate voltage has also been determined [8] and follows approximately a linear law $d_e \simeq d_0(1-\alpha|V_g|)$ with $d_0 \simeq d-150$ nm. The coefficient α is largest for the smaller dots, and is $\alpha \simeq 0.26$ V^{-1} for dots of nominal diameter $d=0.4$ μm. A dot of nominal diameter $d=0.4$ μm has thus a conducting channel of about 100 nm diam at a gate voltage of -2.3 V. For such channel dimensions, the calculated level spacings in the quantum dot are already fairly large, of the order of a few millielectronvolts so that mode confinement should be observable at sufficiently low temperature. We expect, however, that the simple quantum confinement picture will be modified by both the Coulomb blockade and electron-electron interactions within the dot. In particular, quantum-dot level peaks and peaks due to charging effects are both expected to coexist, as predicted by various authors [2,5].

Briefly stated, we find that our data, although not free from the influence of sample nonuniformities, support the confinement picture quite well: The conductance peaks of a given sample evolve overall according to a $1/d_e^2$ law with the confinement voltage, and the average peak spacings in samples having different nominal dot diameters (0.5, 0.4, and 0.3 μm) are found to be larger for the smaller dots.

Figure 3 shows a set of experimental conductance curves for a sample with a nominal dot diameter of $d=0.4$ μm at different gate voltages. The spectrum is fairly rich, as expected (vertical bars in the figure are to guide the eye to some of the peaks and kinks at $V_g=0$, -1.9, and -2.1 V). Since the voltage scale in Fig. 3 is, to a good approximation, twice the voltage between the emitter electrode and the quantum dot, the spacing between the first two arrows at $V_g=0$ corresponds to a level spacing in the dot of about 0.4 meV and is of the expected magnitude for a dot of this size. Although the temperature here is $T=40$ mK, we find that the characteristics show no significant change up to about 1 K. The conduc-

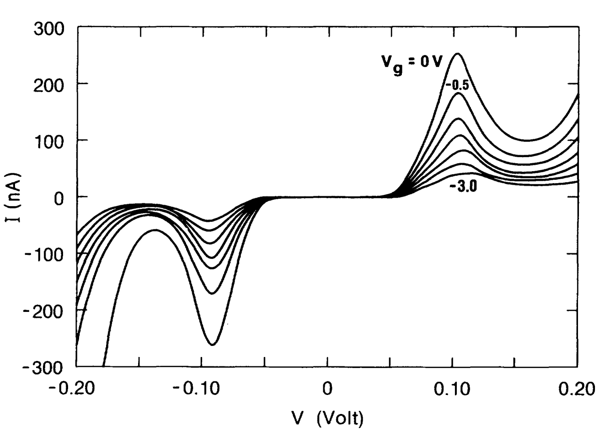

FIG. 2. Current-voltage characteristics of structure as in Fig. 1 for a nominal dot diameter of $d=0.5$ μm, gate voltage steps of -0.5 V, and $T=4.2$ K.

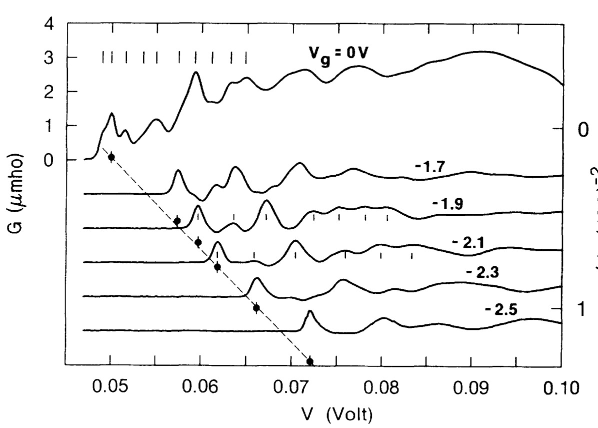

FIG. 3. Conductance data $G(V)$ at 40 mK, for increasing gate voltage (curves translated vertically for clarity, curve $V_g=0$ as measured). Structure has nominal dot diameter of 0.4 μm. Dots show displacement of first peak position vs $1/(d_e/100)^2$ (d_e in nm, right scale).

tance peaks are then nearly washed out above 10 K [10].

We also often observe that the variable lateral confinement provided by the gate does not affect the positions, spacings, and amplitudes of all the conductance extrema in exactly the same way. It is thus not always possible to follow a given extremum over the entire range of V_g. This is possibly due to sample nonuniformities, but likely also to the complex interplay between quantum confinement and Coulomb interactions. We find nevertheless that most of the peaks move approximately according to a $1/d_e^2$ law with gate voltage, as one expects for a confinement effect (preliminary calculations by Stern, Kumar, and Laux [11] show that the lateral confining potential in our structure is fairly sharp and that the potential rise at the center of the dot does not exceed 2 meV throughout the entire range of gate voltages). The displacement of the first peak versus $1/d_e^2$ is shown in Fig. 3 (dashed line) and gives *direct* evidence for the quantum size effect. One thus deduces a level dependence on confinement given by $\Delta E = 9.5/(d_e/100)^2$ meV (d_e in nm) over the entire gate voltage range. Since a satisfactory model taking Coulomb interactions and the exact potential shape into account is not yet available, an attempt at unequivocal mode identification would be somewhat premature at this point. Nevertheless, preliminary calculations [12] of quantum-dot levels in a circular dot with two electrons including Coulomb and exchange interactions yield results which are consistent with the observed peak spacings and overall dependence of the peak positions on gate voltage (or dot diameter d_e).

As mentioned above, the situation described here is further complicated by the fact that the charging energy of the dot is not negligible. For the barrier thickness of 13.5 nm shown in Fig. 1, the capacitance of a dot of effective diameter $d_e = 100$ nm (obtained for $V_g \simeq -2.3$ V) is $C = (\varepsilon\pi d_e^2/4)/b \simeq 0.6\times10^{-16}$ F. Assuming that the lateral distribution of the charge in the dot is uniform, this yields a charging energy of $E_c = q/2C \simeq 1.35$ meV, which is of the same order as the level spacing in the dot (the actual charging energy is probably larger since the radial charge distribution in the dot is not uniform, the wave function of the ground state being approximately the Bessel function J_0). As predicted by several groups [2,5], this leads to transport properties which exhibit both quantum confinement and charging effect features, provided the transmission coefficients of the two barriers are not too different (which is the case in the low-bias region of the measured characteristics). To see this, we have thus integrated the conductance curves in Fig. 3 to obtain the current-voltage characteristics $I(V) = \int G(V)dV$. The result, shown in Fig. 4 for a set of gate voltages (curves offset for clarity), exhibits remarkable plateaus. Similar plateaus have also been reported recently by other groups [3,13]. Since the plateaus reported in Ref. [13] occur at device biases which are lower than the theoretical zero-temperature threshold for resonance, they have been attributed to tunneling through an isolated impurity

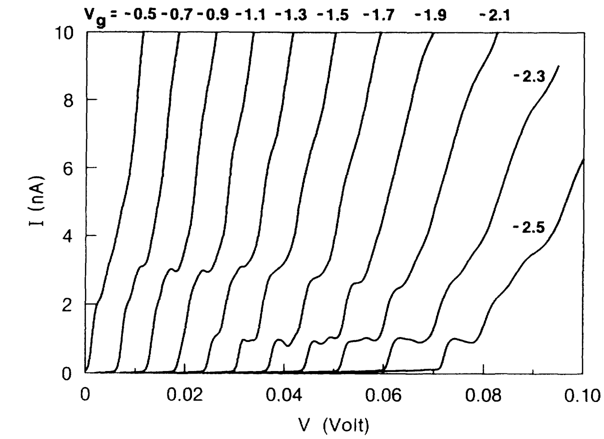

FIG. 4. Current-voltage characteristics of same device as in Fig. 3, with gate voltage as a parameter (curve for $V_g = -2.5$ V as measured, other curves translated horizontally by 5-mV steps for clarity). Characteristics obtained by numerical integration of measured conductance data.

in the well, consistent with the observed insensitivity of the steps to both the temperature and the gate voltage. Although we have occasionally also observed low-voltage features with a behavior similar to that described in [13], the data (and dot sizes) reported here indicate that we are not dealing with such a case, but rather with a confinement effect (the $1/d_e^2$ dependence implies that the entire active area of the dot is involved). The fact that the lowest observed feature at $V_g = 0$ is slightly (~ 5 meV) below the *theoretical* resonance of an *ideal* quantum well is not unusual nor typical of small-area diodes [7], and can be traced to the known uncertainties of the fabrication process (barrier composition [14], layer widths [14], doping, etc.).

Referring now to Fig. 4 (characteristics offset as explained in the caption), we observe that the plateaulike features occur at near multiples of 1 nA (2 nA for $V_g = -0.5$ V, 3 nA for $0.7 < -V_g < 1.5$ V, and 1 nA for $1.3 < -V_g < 2.5$ V). The 1-nA plateau in particular is fairly robust, although the conductance in the linearly increasing part of the $I(V)$ changes by a factor of about 3.5 in this range. This strongly suggests that resonant tunneling in the plateau region is inhibited by Coulomb interactions, a hypothesis which is further supported by the observed increase of the width of the plateau with the confinement voltage. For a barrier capacitance $C \simeq 0.6\times10^{-16}$ F (at $V_g = -2.3$ V) and a conductance $G \simeq 0.5\times10^{-6}$ Ω^{-1} (the first peak in Fig. 3 for $V_g = -2.3$ V), one obtains according to this hypothesis a current step value [15] of the order of $\Delta I = q/(2C/G) \simeq 0.7$ nA, close to the value observed at the plateau. We therefore suggest that the 1-nA current step observed at the larger gate voltages is the signature of the *first* electron tunneling through the dot. The slight modulation of the plateau, accompanied by negative conductance within

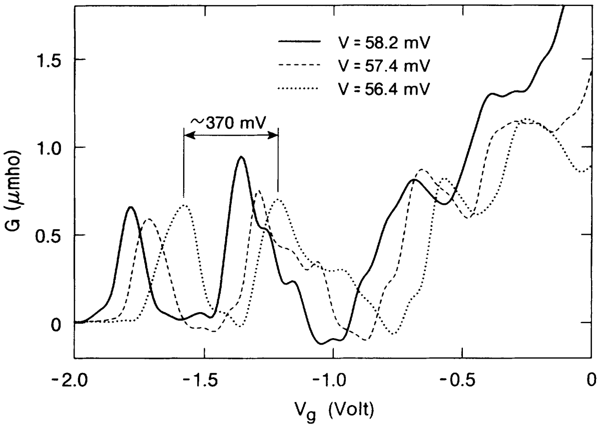

FIG. 5. Dependence of conductance G on gate voltage V_g with bias V as a parameter (same device as in Figs. 3 and 4).

it, suggests a modulation of the Coulomb interaction by level quantization, as predicted by Averin, Korotkov, and Likharev [5].

Further evidence for the above picture is provided in Fig. 5, which shows the oscillations of the conductance versus gate voltage with the bias voltage V as a parameter. With the $1/d_e^2$ dependence established in Fig. 3, the 370-mV spacing translates into a level change in the dot by about 1.3 meV, and is of the right magnitude to be attributed to a superposition of Coulomb blockade and two-electron repulsion within the dot [3]. The slight modulation superimposed on the oscillations has a smaller period and is tentatively attributed to a modulation of the Coulomb interaction by the quantum size effect [5]. The overall displacement of the characteristics with the device bias V is consistent with this description.

In summary, we have provided direct experimental evidence for quantum confinement in a resonant-tunneling dot of squeezable diameter for which the energies associated with confinement and Coulomb interactions are of comparable magnitude. Our observation of slightly modulated current steps of stable magnitude has suggested the occurrence of a Coulomb blockade of the resonant tunneling modified by level quantization. Finally, we believe to have observed the first electron tunneling through the dot.

Further measurements as a function of temperature and magnetic field [10] confirm the confinement picture described here and will be published elsewhere.

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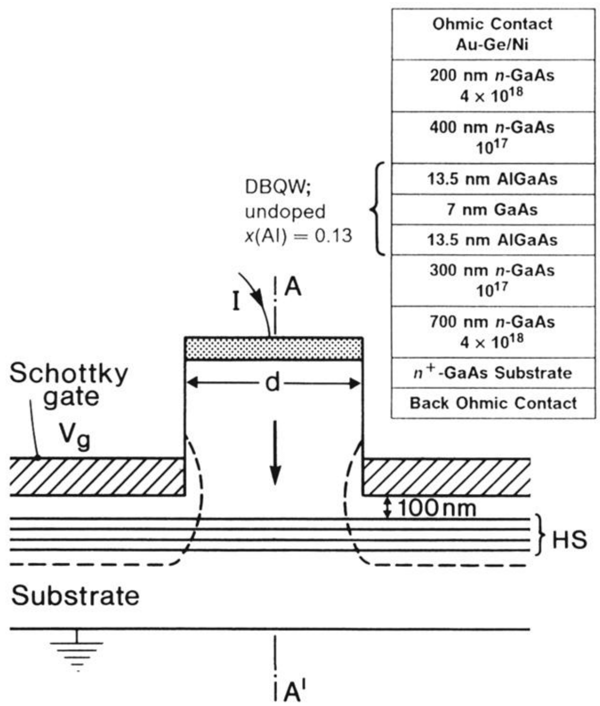

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