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## Transport through a Finite One-Dimensional Crystal

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We have studied the magnetotransport properties of an artificial one-dimensional crystal. The crystal consists of a sequence of fifteen quantum dots, defined in the two-dimensional electron gas of a GaAs/AlGaAs heterostructure by means of a split-gate technique. At a fixed magnetic field of 2 T, two types of oscillations with different amplitude and period are observed in the conductance as a function of gate voltage. A simple model demonstrates that the oscillations arise from the formation of a miniband structure in the periodic crystal, including energy gaps and minibands which contain fifteen discrete states.

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One of the basic principles of solid-state theory is the formation of an energy-band structure in a regular crystal. The coupling between atomic states in a perfect crystal results in a collective state which is characterized by energy bands separated by energy gaps. The conductivity properties of a solid strongly depend on the location of the Fermi energy in the band structure. The solid is an electrical insulator (at 0 K) if the Fermi energy is within an energy gap or an electrical conductor if the Fermi energy is within an energy band.

The advances in material technology over the last two decades have suggested the possibility of making artificial superlattices in which one could study these basic solid-state properties.<sup>1</sup> The first experimental evidence for the formation of a band structure in a vertically grown superlattice was reported in the seventies by Esaki and Chang,<sup>2</sup> who found a negative differential conductance in the nonlinear transport properties. The linear transport in terms of resonant transmission in a finite superlattice has been studied theoretically by Tsu and Esaki<sup>3</sup> and more recently by others.<sup>4-6</sup> It was shown that when the Fermi energy of the system is varied, the transmission through a finite superlattice reflects the energy gap as well as the discrete states forming the so-called minibands. In a normal crystal, the discrete states in the energy bands are usually unnoticeable due to the large number of participating atoms.

In this Letter we study the transport properties of an artificial one-dimensional (1D) crystal. The crystal consists of a sequence of fifteen quantum dots, which are electrostatically defined in a two-dimensional electron gas (2DEG) by means of two metallic gates on top of a GaAs/AlGaAs heterostructure. The inset of Fig. 2 shows a schematic layout of the device. The ungated 2DEG has an electron density of  $2.7 \times 10^{15} \text{ m}^{-2}$  and a

transport mean free path of  $10 \mu\text{m}$ . A negative voltage of  $-0.44 \text{ V}$  on the gates depletes the electron gas underneath the gates and forms a corrugated ballistic channel in the 2DEG of  $3 \mu\text{m}$  length and a width alternating between 250 and 400 nm. The voltage  $V_{g1}$  on the first gate defines the depletion region around the "fingers" (in total, sixteen fingers or, correspondingly, fifteen quantum dots) at a period of 200 nm. The effect of lowering (making more negative) the voltage  $V_{g2}$  on the second gate is threefold. The increasing depletion area around the second gate reduces the coupling between adjacent dots, reduces the area of each dot, and lowers the Fermi energy in the conducting regions. The detailed shape of the depletion region in the 2DEG is unknown, but presumably resembles a periodic (asymmetric) saddle-shaped electrostatic potential with the maxima in the narrow regions.

In this 1D crystal device the spatial quantization is realized in all three directions, which differs from earlier studied superlattices in which only one<sup>2,7</sup> or two<sup>8</sup> directions were quantized. The transport properties of single quantum dots, fabricated with the same split-gate technique, have been studied earlier in zero magnetic field<sup>9</sup> as well as in a high magnetic field.<sup>10</sup> The observed oscillating conductance demonstrated the formation of zero-dimensional (0D) states in a single quantum dot. In a sequence of equal quantum dots with equal coupling to nearest neighbors, the 0D states develop into minibands.<sup>3-6</sup> The number of states within a miniband is equal to the number of dots and the energy gap between consecutive bands is determined by the coupling between the dots. Weak coupling yields a narrow band and a large gap, while strong coupling will result in a wide band and a small gap.

We have performed conductance measurements as a

function of gate voltage  $V_{g2}$  on the second gate, for several fixed values  $V_{g1}$  on the first gate, and for several fixed magnetic fields. The measurements are performed at a temperature of 10 mK with a standard lock-in technique using ac current biasing of 0.2 nA rms. At zero magnetic field, no evidence has been found for the formation of a band structure. Nor did we find quantized plateaus in the conductance resulting from the transverse confinement in the corrugated channel. The quantization, which would indicate adiabatic transport, is destroyed due to intersubband scattering either by the fingers or by impurities in the 3- $\mu\text{m}$ -long channel.<sup>11</sup> At a constant magnetic field of 2 T we find quantum Hall plateaus at multiples of  $e^2/h$  in the conductance  $G$  as a function of gate voltage  $V_{g2}$ . The effect of a magnetic field is to establish adiabatic transport through the corrugated channel, as is known from theoretical<sup>12</sup> and experimental<sup>13</sup> work on two quantum point contacts in series. In the case of adiabatic transport, the subbands can be treated as independent 1D current channels. The only scattering now takes place within a single subband at the potential maxima defined by the fingers. In Fig. 1 the first (spin-resolved) conductance plateau is shown for several fixed values of  $V_{g1}$  (which defines the potential around the fingers). Below the first plateau (i.e.,  $G < e^2/h$ ), large oscillations are seen, while in the plateau region, deep downward peaks enclose smaller oscillations. Above the plateau, only downward peaks are seen, which are clearly separated. Some of the deeper peaks in Fig. 1 are marked to indicate their shift when the voltage  $V_{g1}$  is varied.

The plateau region of the curve with  $V_{g1} = -0.45$  V is measured and shown enlarged in Fig. 2. As can be seen, the two deeper peaks enclose fifteen oscillations, which

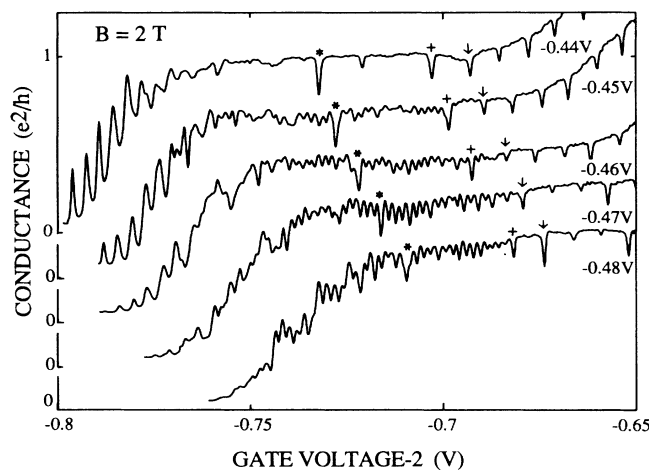


FIG. 1. Conductance as a function of gate voltage 2  $V_{g2}$  on the second gate at a fixed magnetic field of 2 T and for different values of gate voltage 1  $V_{g1}$  on the first gate. Corresponding peaks are marked. The curves have been offset for clarity.

corresponds exactly with the number of quantum dots in the 1D crystal. The deeper peaks can be associated with energy gaps (the decrease of the conductance is then due to the location of the Fermi energy within a gap), and the smaller oscillations with the discrete states in the miniband. This interpretation will be substantiated below by a numerical calculation. The formation of energy gaps is also indicated by the downward peaks above the plateau region in Fig. 1. The spacing between these downward peaks differs from those in the plateau region, which may be related to additional peaks originating from the second subband. In the plateau region the average conductance is nearly constant (here the transmission probability of the lowest subband through a single barrier is nearly equal to 1) indicating that the coupling is approximately constant, which yields approximately constant energy gaps. The effect of lowering the gate voltage  $V_{g2}$  here is mainly the decrease in Fermi energy and the reduction in dot area. Note that the reduction in area results in larger energy separations which increases the bandwidth. Both effects move the Fermi energy through the miniband structure.

The large oscillations below the plateau occur while the average conductance changes relatively fast from pinchoff to the first plateau. Here the transmission through each barrier changes from 0 (large band gap) to nearly 1 (small band gap). In this case the reduction of the band gap moves the Fermi energy through a miniband. A maximum in the conductance occurs when the Fermi energy coincides with the energy of a discrete state within the miniband.

The finite crystal allows a simple counting comparison

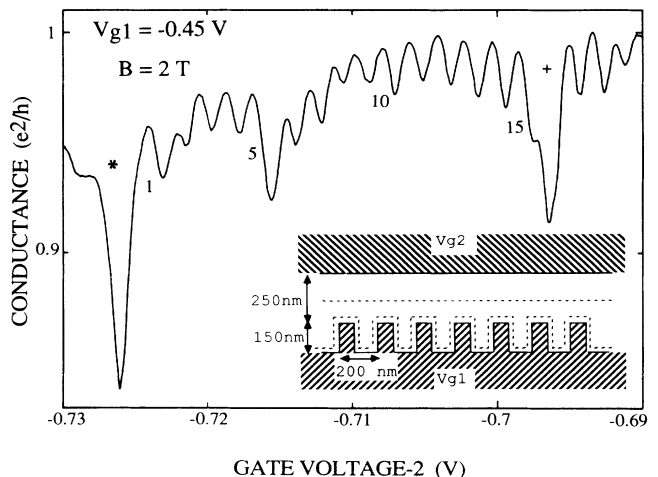


FIG. 2. Conductance as a function of gate voltage 2  $V_{g2}$  on the second gate at 2 T and  $V_{g1} = -0.45$  V on the first gate. The inset schematically shows the gate geometry; the dashed lines indicate the depletion regions in the 2DEG. The upper depletion region is moved towards the fingers when  $V_{g2}$  is made more negative.

between the number of oscillations in a band and the number of quantum dots. For the curves of  $V_{g1} = -0.45$  and  $-0.48$  V the number of oscillations is fifteen, in accordance with the number of dots. However, the curve of  $V_{g1} = -0.46$  V shows sixteen (reproducible) oscillations and in the curve of  $V_{g1} = -0.47$  V the gap marked by the plus sign is not seen. The disappearance of the gap is presumably caused by irregularities, which introduces mixing between minibands. The sixteen oscillations in  $V_{g1} = -0.46$  V cannot be understood from the number of quantum dots, not even when the dots are considered to be unequal. An additional scatterer somewhere in the channel may be the cause for this extra oscillation. The smaller oscillations on the left of the asterisk in Fig. 1 indicate another discrete miniband, although less regular. The influence of irregularities on the miniband structure will be discussed further below. The oscillations reproduce if the sample is kept cold ( $< 4$  K), but not after warming up to room temperature. So far the oscillations have only been studied in one sixteen-finger sample. In a one-finger sample of identical design, we found that the conductance versus  $V_{g2}$  shows quantized plateaus at zero magnetic field, which shows that a single finger acts as a quantum point contact.<sup>11</sup> In a two-finger sample we have observed structure at 2 T with a period of  $\Delta V_{g2} \approx 25$  mV. This period corresponds to the energy difference between consecutive OD states in the single quantum dot and is approximately the same, as one would expect, as the gate-voltage difference between the two downward peaks in Fig. 2. From these different finger samples we can conclude that the additional smaller oscillations in Figs. 1 and 2 indeed originate from the coupling between the quantum dots.

To substantiate the interpretation of minibands we have calculated the transmission probability  $T_N = t_N t_N^*$  through a 1D chain of  $N$  symmetric barriers. The calculation is a numerical solution of a recursive formula for the complex transmission amplitude  $t_N$ , expressed in the complex amplitudes  $t$  for transmission and  $r$  for reflection through a single barrier and the phase  $\theta$  acquired by an electron after one revolution in a single quantum dot:

$$t_N = \frac{t_{N-1}}{1 - r r_{N-1} e^{i\theta}}. \quad (1)$$

Current conservation yields the additional relations  $t_N/t_N^* = -r_N/r_N^*$  and  $t_N t_N^* + r_N r_N^* = 1$ . For  $N=2$ , Eq. (1) describes the transmission through OD states in a single quantum dot.<sup>10,14</sup> A OD state in a single quantum dot is defined by the condition that the phase  $\theta$  equals an integer times  $2\pi$ . At zero magnetic field this condition is fulfilled when an integer times half the Fermi wavelength exactly fits between the two barriers.<sup>9</sup> At a high magnetic field when the cyclotron radius is small compared to the dot dimensions, the current-carrying electrons are confined in an edge channel located at the

boundary of the dot. Here the phase  $\theta$  is given by  $2\pi$  times the number of flux quanta  $\phi/\phi_0$  enclosed by this edge channel.<sup>10,14</sup> At intermediate values for the magnetic field, the phase will depend in a complicated way on the electron trajectories within the confining potential, which in our case is not exactly known. Therefore we have calculated the transmission  $T_N$  as a function of a generalized phase  $\theta$ . Some results of this model for  $N=16$  barriers are shown in Fig. 3; an extensive description will be published elsewhere.<sup>15</sup> To simulate our conductance measurements, with  $G = T_N e^2/h$ , we simultaneously varied the phase  $\theta$  and the transmission amplitude  $t$ . In this way the effect of the gate voltage on the confining potential and on the coupling between adjacent dots is simulated. The transmission  $T_N$  is plotted as a function of phase, and the simultaneously varying transmission probability  $t t^*$  of a single barrier is the lowest curve shown in Fig. 3. The two calculated transmissions illustrate the effect of one deviating barrier. For the middle curve in Fig. 3 all amplitudes  $t$  and phases  $\theta$  are taken equal for the fifteen quantum dots, while for the upper curve one barrier transmission amplitude in the middle of the crystal deviates by a factor of 0.97.

The calculation illustrates the effect of the formation of a band structure on the conductance, with the deeper downward peaks associated with the gaps and the fifteen smaller oscillations with the discrete minibands. With one deviating barrier in the middle of the crystal, the calculated smaller oscillations group together in pairs of two, very similar to the pattern seen in the experimental curves of  $V_{g1} = -0.46$  and  $-0.47$  V in Fig. 1. Further calculations show that if the amount of disorder is in-

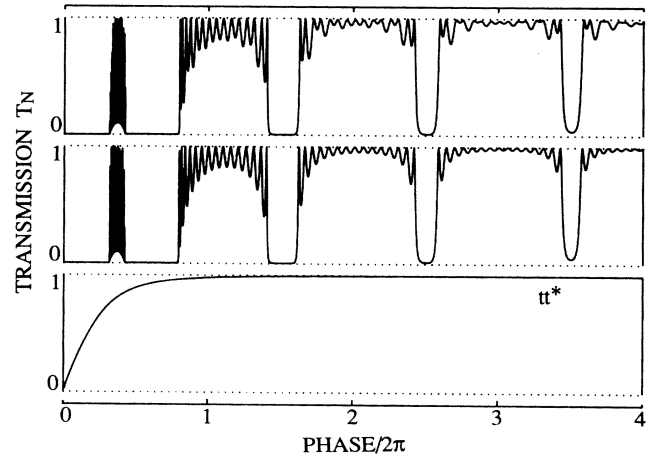


FIG. 3. Calculations from Eq. (1) of the transmission  $T_N$  as a function of phase  $\theta$  of a 1D chain of  $N=16$  barriers. The lowest curve shows the simultaneously varying transmission probability  $t t^*$  through a single barrier. In the middle curve all barriers are taken equal, while in the upper curve a small amount of disorder is included by one deviating barrier.

creased (accomplished by variations in the individual  $t$ 's and  $\theta$ 's), the oscillations become more irregular and eventually the gaps disappear.<sup>15</sup> From the above simulations we can conclude that the recursive Eq. (1) demonstrates the origin of the experimental results in the formation of a miniband structure in our 1D crystal.

A striking difference with the experiment is the deep gaps appearing in the calculations. We note, however, that for an asymmetric barrier in a magnetic field, both amplitudes  $t$  and  $r$  are unequal to the amplitudes  $t'$  and  $r'$  for a wave in the opposite direction. Incorporating this in the calculation we found that the gaps become less deep compared to the amplitude of the smaller oscillations. Another reason for the difference in experimental and theoretical gaps may be related to screening effects in the real device. Because of the absence of states in the gaps, it may be possible that the Fermi energy does not change continuously with the gate voltage, but jumps from the top of a miniband to the bottom of the next one. This may result in observing smaller gaps. However, screening effects are difficult to estimate in small low-electron-density samples, and are not taken into account in our simple model.

In summary, the transport properties of the 1D crystal reflect the formation of a miniband structure of which the discreteness is clearly observable. In contrast to the vertically grown superlattices, the electrostatic definition of the crystal by means of a split gate allowed us to tune the Fermi energy through the miniband structure. In this way some basic solid-state properties are exhibited in the conductance, for instance, electrical insulation or conduction of the 1D crystal depending on the location of the Fermi energy in a gap or a band, respectively. A simple 1D model can account for the observed features in the conductance and illustrates the formation of a band structure in the solid state in terms of resonant transmission.

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