

One-dimensional electron transport in semiconductor nanostructures*

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In this short article, a summary is presented of recent progress in understanding the behaviour of electrons in semiconductor nanostructures. The method of shaping the electron gas is by electrostatic confinement with split gates. Whereas a rigid one-dimensional system shows the canonical conductance quantization, the relaxation of confinement, towards two-dimensionality results in strong electron–electron repulsion, splitting the line of electrons into two separate rows. This situation is the precursor to the formation of a Wigner lattice and is an example of how the topology of the electron gas is determined by electron correlation.

Keywords: Conductance quantization, electron gas, nanostructures, semiconductor.

One of the benefits of the advances in electronics technology developed to produce integrated circuits of higher packing density has been its use in the fabrication of structures and devices for basic physics research.

Early pioneering experiments at IBM showed that the inversion layer of the Silicon MOS device was a two-dimensional (2D) electron gas. Ando *et al.*¹ reviewed this work. Subsequent work at Bell Laboratories developed the 2D electron gas at the interface of GaAs and AlGaAs, which has a higher carrier mobility due to the decreased scattering compared to that at the Si–SiO₂ interface².

Studies of 2D conduction have been fruitful, leading to such developments as the integer and fractional quantum hall effects and a range of localization and interaction effects. In the 1980s work in the author's laboratory started to explore the possibilities of further reducing the dimensionality of transport from two to one. The first attempt was using silicon accumulation layers with an *n*-type substrate. At low temperatures this froze out and the properties of the accumulation layer could be measured. Implanted *p*-type layers were used to 'electrostatically squeeze' the accumulation layer by reverse biasing the *p*–*n* junction formed by the implanted layer and the substrate. The electron gas could be narrowed until it was pinched-off and then the properties were measured. The results showed that as the temperature was decreased, localization set in and increased in strength as the channel was narrowed³. Phase coherence lengths were subsequently measured and found to be characteristic of one dimension⁴. However, there was no evidence of a spatial

quantization of the energy levels in the channel when it was narrowed, as would be expected on the basis of a 'particle in the box' type of picture.

Greater success was achieved with the use of the GaAs–AlGaAs heterostructure with split gates fabricated on the AlGaAs surface to confine the 2D electron gas and convert it to 1D (Figure 1). Results on channels of approximately 15 μm in length showed that the quantum corrections due to weak localization and interaction effects had the appropriate 1D form⁵. However, it was energy level determination as a transverse magnetic field was applied, which confirmed that there was a spatial quantization⁶. Application of the magnetic field resulted in the quantized energy levels increasing in energy and passing through the Fermi energy to depopulate. Analysis showed that the behaviour of the levels as a function of field did not follow the 2D behaviour, but showed a

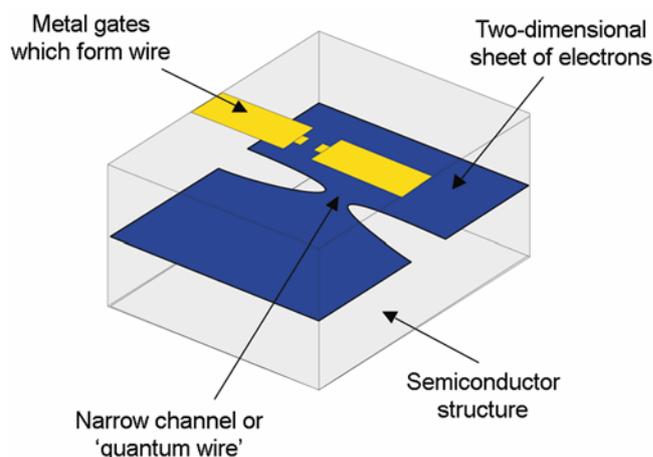


Figure 1. Formation of a narrow channel in a two-dimensional electron gas by means of split gates.

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pronounced deviation indicative of the spatial quantization caused by the confinement. In the absence of the field the quantized levels did not show in the conductance, the cause of which was attributed to scattering in the long channel. Following this breakthrough, the quantization was clearly demonstrated by the use of short devices (1 μm or less) by our group⁷, and Van Wees *et al.*⁸ using the same split gate technique, where the quantization of the ballistic resistance (often discussed as conductance quantization), was clearly demonstrated. The short length of the channel results in the elimination of scattering and ballistic transport. Under these circumstances each quantized level has a conductance given by $2e^2/h$, where the quantum of conductance is e^2/h and the factor of 2 is due to spin degeneracy. As all the levels behave as independent resistors in parallel, the total conductance is given by $2ne^2/h$, where n is the number of levels which reduces by one each time a level is pushed above the Fermi energy. Hence, as shown in Figure 2, a series of steps are observed separated by $2e^2/h$. Applying a parallel magnetic field lifts the spin degeneracy and then steps appear, which are separated by e^2/h .

A feature of the conductance quantization which does not fit into a simple one-dimensional model is structure, often a plateau, near the value of $(0.7) 2e^2/h$ (Figure 3)^{9,10}. Application of a magnetic field progressively reduces the 0.7 value down to the fully spin-polarized level of 0.5, indicating that the anomalous feature is related to a spin polarization in the absence of a magnetic field. The origin of this spin polarization is not fully clear as of now and many theories have been proposed. A zero bias anomaly (ZBA) occurs in the current versus voltage relationship as the temperature is lowered and this causes the 0.7 feature to disappear, which has given rise to suggestions that it

arises from a Kondo effect in the channel in an analogous manner to that which is observed in a quantum dot¹¹. However, the behaviour of ZBA as a function of carrier concentration and temperature does not fit with predictions of a Kondo model¹². The overall behaviour of the resistance indicates that the exchange drives a spontaneous spin polarization. Experiments have been performed in which a parallel magnetic field causes the highest energy spin level from the ground sub-band to cross the lowest energy spin level derived from the first sub-band. An anti-crossing behaviour was found, which is repeated every time two opposing spin levels cross. Analysis of the level behaviour indicates that in the absence of the field there is a strong repulsion between the opposing spin levels, which causes one to hover at the source potential and only partially contribute to the conductance until the carrier concentration increases and the carriers become spin degenerate¹³. In Figure 3, 0.7 is the first in a series of instabilities which causes a lifting of the spin degeneracy.

More recently, devices have been developed in which the channel potential narrows at the entrance and exit regions, such that by applying an offset voltage to the split gates it is possible to induce strong reflections and create a bound state in the channel. This then gives rise to a strong resonance located at $(0.5) 2e^2/h$, which is precisely where it should be located; decreasing temperature results in Kondo screening and the resonance becomes broadened and moves up in conductance value. The resonant feature at 0.5 is so unlike the 0.7 and hence it appears very likely and hence this does not arise from Kondo behaviour¹⁴.

Apart from the 0.7, the basic quantization can be explained on the basis of one-electron theory. However, more recently, it has been suggested that when the con-

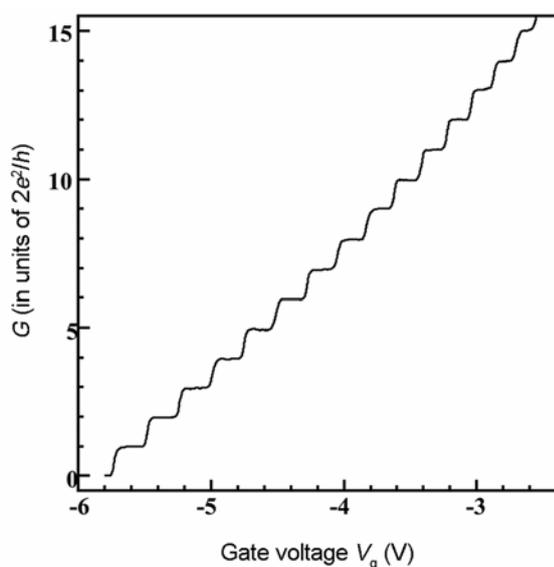


Figure 2. Quantized conductance as the split gate voltage is changed. An increasingly negative voltage narrows the channel.

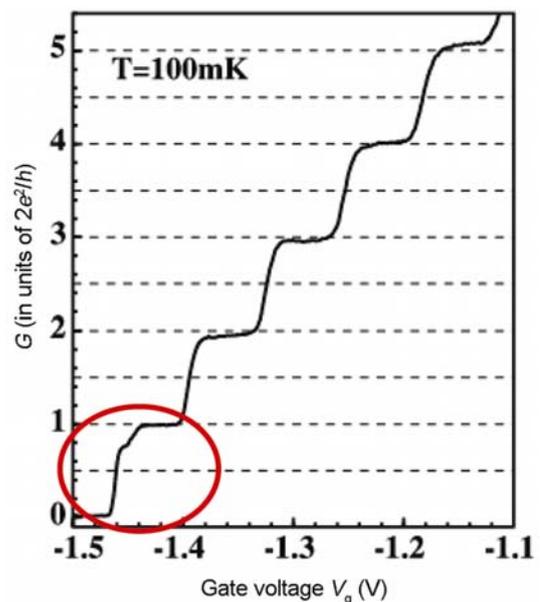


Figure 3. The 0.7 feature which appears below the first quantized plateau.

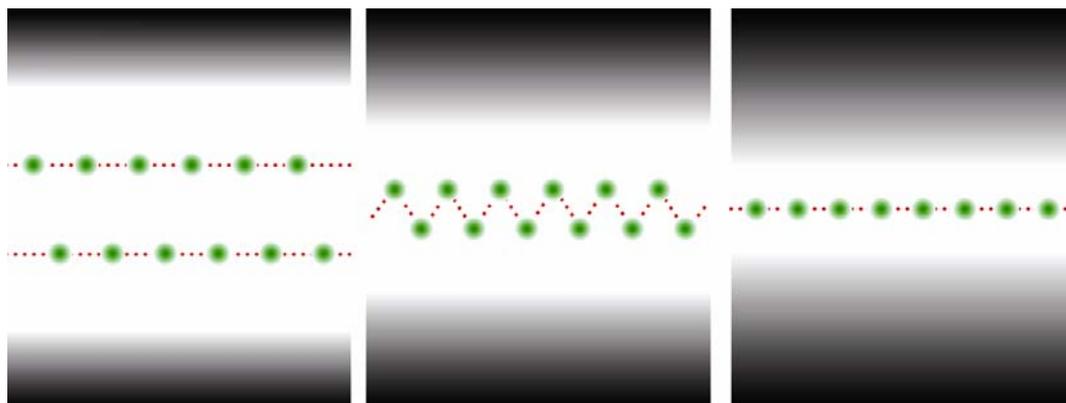


Figure 4. Splitting of a line of electrons into two separate rows¹⁶.

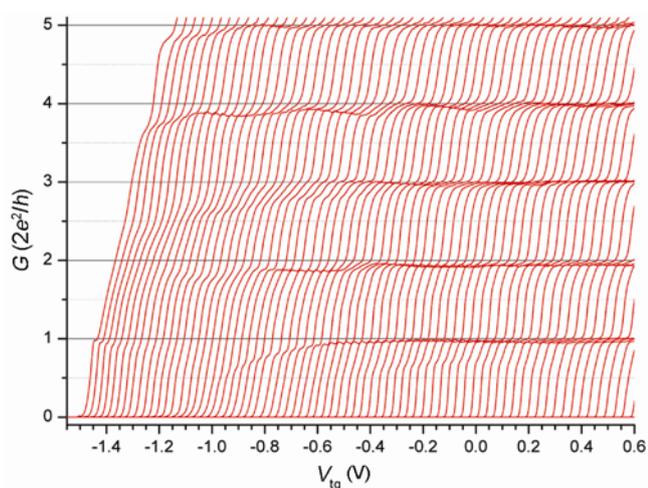


Figure 5. Quantized conductance as a function of carrier concentration as a function of the top gate voltage. The confinement progressively decreases from right to left; the first plateau disappears with weak confinement.

finement potential is weak, then in order to minimize their mutual repulsion, electrons will move sideways and increase their separation. Classical calculations have pursued this topic to study the formation of a 2D Wigner lattice in which distinct rows of electrons develop as the carrier concentration is increased¹⁵. More realistic quantum treatments have also shown that as the confinement (interaction) is reduced (increased), a line of electrons becomes progressively more zigzag and then splits into two distinct rows (Figure 4)^{16,17}. As the number of rows increases, the lattice becomes difficult to distinguish from the conventional picture with n significantly greater than one.

Experiments have been performed on reducing carrier concentration as the confinement is reduced, which bear out the prediction of a transition to two rows. As seen in Figure 5, as the confinement is reduced, the first plateau at $2e^2/h$ disappears and the system exhibits a first plateau at $4e^2/h$; as the first observed plateau corresponds to the

ground state, this value cannot be explained on the basis of a single row or line of electrons. It must correspond to two rows which are degenerate and spontaneously form a ground state^{18,19}. This was the first indication that the electron–electron interaction could dominate the behaviour of electrons in a confined environment. Experiments on wider devices have revealed the stages of formation of the incipient lattice. As the ratio of interaction to confinement is increased, electrons start to move sideways and then form a ‘bonding’ state in which they hybridize. Further increase in the ratio results in two distinct rows forming corresponding to the ‘non-bonding’ states. It was also found that increasing the source-drain voltage could break the ‘bonding’ states to form two separate rows. The weakly confined 1D system shows behaviour completely different from that found in the strongly confined case. For example, when the spin degeneracy is lifted by a strong magnetic field of 8 T, as the carrier concentration is increased the system switches between two configurations producing a pattern in the conductance which resembles beating. As seen in Figure 6, a stable configuration is not reached until n is 4 or 5.

One interesting phenomenon which has been studied using such devices has been the spin incoherent regime. This occurs when the exchange energy J between neighbouring electrons becomes less than the thermal energy kT . Under these circumstances the spin becomes indeterminate and due to the exclusion principle the factor of 2 in the quantum of conductance is lost which then becomes e^2/h . By lowering the temperature so that $kT < J$, it is possible to regain the spin coherence and then the factor of 2 in the conductance is regained. Application of a magnetic field also results in the reestablishment of the spin degeneracy²⁰.

Other systems have been developed which illustrate the principles of conductance quantization and its relation to the one-dimensionality. For example, when a wire is stretched, the resistance shows quantized steps just before it breaks due to the narrowest part being reduced successively to 3, 2, 1 atoms in width²¹.

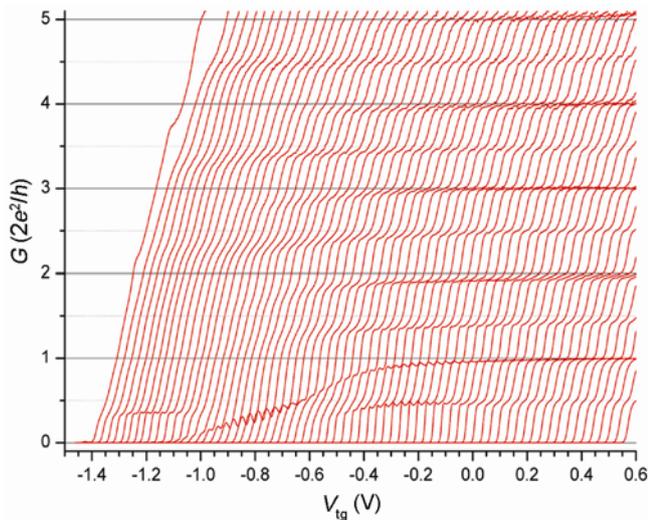


Figure 6. Similar to Figure 5, but in the presence of a magnetic field of 8 T.

Many experiments have been performed with split-gate type of devices since the introduction of the concept and it is proving to be a remarkable laboratory of quantum physics. The resistance of a one-dimensional channel is extremely sensitive to the presence of nearby charge, which has resulted in the device being used as a minimally invasive detector of single electrons in a nearby quantum dot²². Even when the current through the dot is too small to measure, corresponding to a single electron tunnelling into and out of the dot at an extremely slow rate, its presence can still be detected. This has allowed many studies of single spin behaviour and is under active study as a read-out mechanism for quantum computation.

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