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Viewpoint

Early work on semiconductor quantum nanoelectronics in the Cavendish Laboratory

Guest Editors

M Pepper
London Centre for Nanotechnology and Department of Electronic and Electrical Engineering, University College London, Torrington Place, London, WC1E 7JE, UK
E-mail: michael.pepper@ucl.ac.uk

T J Thornton
School of Electrical, Computer, and Energy Engineering, Arizona State University, PO Box 875706, Tempe, AZ 85287-5706, USA
E-mail: t.thornton@asu.edu

D A Wharam
Eberhard-Karls-University Tübingen, Institute of Applied Physics, Auf der Morgenstelle 10, D-72076 Tübingen, Germany
E-mail: david.wharam@uni-tuebingen.de

This Viewpoint relates to an article by Wharam *et al* (1988 *J. Phys. C: Solid State Phys.* **21** L209) and was published as part of a series of Viewpoints celebrating 50 of the most influential papers published in the *Journal of Physics* series, which is celebrating its 50th anniversary.

This article is not intended as a review of the field, which would require vastly more space and a long bibliography. It is more of a personal narrative on the background to work that came out of the Semiconductor Physics group in the Cavendish Laboratory. It is a contribution to the celebration of the 50th anniversary of the *Journal of Physics* series, which is appropriate as much of the work appeared in the Institute's *Journal of Physics C* and then *Journal of Physics of Condensed Matter*. At that time we were all working in the Cavendish. We have now dispersed but maintain our interest and research in this and related fields.

The first semiconductor device studied by the group utilised the two dimensional, 2D, inversion layer of the silicon MOS device for investigations of electron localisation due to disorder. The results were regarded as being complementary to those obtained from studies of conduction in the 3D semiconductor impurity band. Reference [1] contains a summary of the early work, describing the results on variable range hopping, excitation to extended states, and minimum metallic conductivity[1]. It was later with the development of theories of quantum corrections and weak localisation that the absence of true metallic behaviour was studied [2].

As predicted behaviour in two dimensions is very different to three we investigated how to control the dimensionality of transport. For this purpose a gallium arsenide Schottky gated FET device was developed, based on a thin film of doped, epitaxial GaAs. The application of a negative gate voltage created a depletion region which narrowed the conducting region, leading to a transition between three and two dimensional electron transport with related changes in the localisation [3]. Over the next few years this device structure was used for numerous experiments in the study of electron interactions, quantum interference and phase coherence lengths as the dimensionality was varied [4].

The success of defining a conducting channel by gate induced 'electrostatic squeezing' led to the question as to how to achieve a similar transition between 2D and 1D transport. The answer was a silicon device with a 2D conducting channel formed by an electron accumulation layer at the interface of lightly doped n-type silicon and thermally grown silicon dioxide [5, 6]. In order to 'electrostatically squeeze' the electrons, two p-type regions were formed running along the channel so that reverse biasing these p–n junctions would narrow the channel until a transition to 1D transport occurred. Our device design was then shared with the IBM group, with whom we had excellent contact, and they observed a change in the temperature dependence of the hopping conductance as the channel width was reduced [7]. In the Cavendish an interesting, possible, power-law localised behaviour was observed [6, 8], but device fabrication was problematic, and it was not clear if there was a mixed 2D and 1D behaviour. In particular, as the p-type regions had to be highly doped the confining potential would not be smooth. Subsequent device fabrication showed the 1D behaviour in greater detail and also the dimensionality transition in the phase coherence [9].

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[1] For localisation in Landau levels Pepper [2].

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The development of molecular beam epitaxy (MBE) technology had increased the scope of experimentation in low dimensional physics and the Semiconductor Physics group put in a grant application in 1983 for an MBE system and a work programme which included 1D ballistic electron transport. This was based on a combination of our previous 1D silicon work and experiments on phonon, and plasmon, emission by hot, ballistic, electrons injected into a semiconductor from a 3D point contact [10]. The grant was funded but, as the MBE equipment was taking a long time to arrive, we managed to obtain high mobility material from other sources. Thornton and colleagues fabricated devices where metal split gates were used to vary the confinement of the 2D electrons. The 15 micron length devices worked remarkably well, there was clearly a variable electron confinement and localisation and interaction effects showed one-dimensionality [11]. Subsequent analysis of conductance fluctuations demonstrated that the electron–electron scattering was of Nyquist type [12]. The information on quantum correction length scales was important for establishing the size of the device necessary for obtaining phase coherence and confirmed the absence of elastic scattering. Electron transport across a short, depleted, region was found to be ballistic as optic phonon emission by hot electrons was observed [13].

We discussed this demonstration of a 1D ‘particle in a box’ with Professor Karl Berggren from Linkoping, who proposed studying the role of a magnetic field on electron transport in the regime where the electron energy would reflect the combined electrical and magnetic quantisation [14]. The results clearly showed that the electrostatic potential was smooth, as we had hoped, and so the confinement produced clear quantum confined levels which could be varied by the controlling split gate voltages. The split gate technique was then adopted by other groups.

In the 1980s the theory of electron transport in mesoscopic devices advanced considerably and we were interested in suggestions that if the number of impurities in a short channel was reduced by one, then, due to the elimination of interference loops, the channel conductance would fluctuate by $2e^2/h$ [15]. Our idea was to change the split gate bias applied to a very short device by a small value and see if we could reduce the number of loops by one, this should result in the conductance changing in the predicted way. Hence a gradual change in the channel size or location could reduce the number of impurities successively until we reached the zero scattering limit, this would be the transition to ballistic transport. By analogy with our earlier work on ballistic transport through 3D point contacts [10], we knew how to calculate the quantum ballistic resistance, which was more rigorously treated by Landauer and co-workers [16]. Wharam *et al* made a range of samples, whose lengths varied from 5 μm down to a few thousand Angstroms, with different degrees of disorder and found conductance structure as the size reduced. It proved difficult to control the diffusive regime so the ballistic regime was investigated and results showed the conductance quantisation in units of $2e^2/h$ [17]. Similar results were published by a Delft/Philips group who also used the split gate technique [18]. We found that the application of a parallel magnetic field removed the spin degeneracy and the quantisation was then observed in units of e^2/h, while a small transverse field depopulated the quantised levels in the same way as in the earlier work on longer devices [14]. (Much later Smith *et al* found the single impurity modification of the quantised conductance [19].) Wharam *et al* studied ballistic resistors in series [20], and showed that they didn’t add as when Ohmic but took the value of the highest resistance. The simple ballistic split gate device was described by van Wees *et al* [18], as a quantum point contact, by analogy with the classical type.

Smith *et al* investigated 1D channels in a parallel configuration [21], and showed that the Fermi energies tended to equalise, followed by the first demonstration of a lateral, 0D quantum dot with, as was subsequently pointed out, Coulomb Blockade [22]. It was followed by the fabrication and measurement of a Fabry–Perot interferometer [23]. Wharam *et al* also showed that electrons could be reflected back into the channel flowing along edges in a magnetic field giving rise to Aharonov–Bohm oscillations. Analysis of the oscillations allowed the geometry of the channel to be found as the split gate voltages were changed [24].

The ability to control the energy levels led to many groups developing a range of structures showing phase coherence and single electron effects. Single and double quantum dots were studied both for fundamental information, being termed ‘artificial atoms’ by Kastner [25]. This technique has been widely adopted for application in quantum information schemes as discussed in [27]. One of the issues encountered was that when a dot was strongly confined the current through it was too small to be measured; in his PhD work Mark Field solved this problem by showing that if a small 1D region was in close proximity to a dot then the presence of an electron in the dot altered the conductance of the 1D region [26]. This meant that it was now possible to measure the presence and transmission of individual electrons even though the current was too small to be measured directly. This technique has been widely adopted as discussed in [27].

The conductance quantisation itself is essentially a waveguide effect and the observation of up to 30 quantised levels owed nothing to electron–electron interactions. However, there was an intriguing feature which always appeared just below the first $2e^2/h$ plateau. This became known as the 0.7 feature because it tended to be present near $0.7(2e^2/h)$ [28, 29]. Application of a strong magnetic field, parallel to the electron gas, lowered the value of this plateau until it saturated at the fully spin polarised value of e^2/h. This observation provoked a very lively literature with many different explanations, the most favoured being a spontaneous spin polarisation or a Kondo effect arising from a trapped charge [30]. Subsequently Francois Sfigakis *et al* showed that by curving the ends of the split gates it was possible to control and produce a transition between unperturbed electron transport and transport in the presence of a trapped electron. This system was able to produce a remarkably clear Kondo effect which was superimposed on the 0.7 feature, showing that the two effects had different origins [31].

Shortly after the development of split gate devices the Philips group showed that the technology could be used to study the focussing of electrons [32]. Recently this technique has been used to study the spin populations induced by interactions within a 1D channel. This was stimulated by the surprising result that as a channel turns on there is a spin polarisation which is enhanced by lifting the momentum degeneracy with a source–drain voltage [33]. Focussing can be sensitive to a spin polarisation, and the results showed that increasing the source–drain voltage did alter the focussing signal by producing a transition from spin degeneracy to polarisation [34].

An intriguing effect can occur when the carrier concentration is sufficiently low that the exchange energy, J, between neighbouring electrons is less than the thermal energy kT, a situation which occurs at very low electron concentrations. The spin then rapidly fluctuates and becomes indeterminate. In this indeterminate, or incoherent, regime the factor of 2 for spin degeneracy in the value of the first quantised plateau disappears, and it drops to e^2/h [35]. If the temperature is further lowered, so that kT is now less than J, the exchange can dominate and restore the spin degeneracy with the plateau returning to the value of $2e^2/h$.

In a further manifestation of the electron–electron interaction there were theoretical predictions that if the confinement potential was weak then the electrons would attempt to form a zig-zag array in which they would maximise their mutual separation [36]. Eventually the zig-zag would split into two separate rows. This was investigated and the splitting was found to occur, the evidence being that the first plateau was no longer at $2e^2/h$ but $4e^2/h$ indicating a ground state comprising two separate rows. Such a configuration is the first stage towards creation of a Wigner lattice in two dimensions and has been described as an 'Incipient Wigner Lattice' [37]. In this respect the 1D channel offers a model system for the investigation of strong interaction effects.

Use of materials such as InGaAs and InAs which show an appreciable spin–orbit coupling, have opened up new areas of research in spintronics. Here application of a lateral voltage to the split gates produces spin polarised ballistic transport, via a Rashba effect, and the electron path length determines the spin phase [38].

From the early beginnings in the 1970s, the ability to electrostatically modulate the shape of an electron gas at the nano level has given rise to a number of novel and unexpected effects. The new understanding of ballistic electron transport that resulted has impacted the modern treatment of current flow in highly scaled MOS transistors [39–41] while conductance quantisation will likely play a role in next-generation random access memory chips [42, 43]. In the area which combines metrology and fundamental quantum transport, split gate defined 1D channels have been used as a tool to demonstrate shot noise due to fractional charges [44, 45]. There is no sign as of yet that this process of discovery is coming to an end as new materials are being developed and more complex structures devised for investigation.

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