QUANTUM POINT CONTACTS

Pinning down the last spin

When a tiny constriction is introduced into the path of electrons, the conductance becomes quantized. In many experiments an unexpected additional feature is observed. An explanation might now be available.

KLAUS ENSSLIN
is at the Solid State Physics Laboratory, ETH Zurich, CH-8093 Zurich, Switzerland.
e-mail: ensslin@phys.ethz.ch

One of the characteristics of ballistic — as opposed to diffusive — charge transport through a clean one-dimensional system is conductance quantization. Experimentally, this can be studied in semiconductor quantum point contacts (QPCs), which can be modelled as a waveguide for electrons where each spin-degenerate mode carries one conductance quantum, $2e^2/h$, with e being the electron charge and h the Planck constant. However, for more than a decade now, an additional feature in the conductance has been reported in many experiments. But the nature of this anomaly, dubbed the '0.7 feature', has remained elusive. Writing in *Nature*, Tomaž Rejec and Yigal Meir[1] argue, based on spin-density functional calculations, that when pinching off the waveguide, a regime emerges where a single localized spin can exist in the QPC constriction. This solid prediction puts recent experiments into a new light, and gives strong support for the existence of such a single localized electron spin in QPCs.

QPCs are typically fabricated by so-called split-gate electrodes on n-type AlGaAs–GaAs heterostructures. In 1988, it was reported that the conductance of such devices is quantized in units of $2e^2/h$ (refs 2,3). An experimental example of such observations is shown in Fig.1. The QPC is formed by the white lines in the inset. As the current flows from the source to the drain contact, the electrons have to pass the constriction whose width can be controlled by a voltage applied to the upper contact, the 'plunger gate'; the voltage tunes the number of one-dimensional electronic modes passing the QPC one by one. In a single-particle picture, each mode carries the conductance $2e^2/h$, and this explains the plateaus in the conductance, marked by the horizontal blue arrows in Fig. 1. An additional plateau-like feature in the conductance is observed[4] when the voltages are tuned such that less than one mode is occupied (marked in Fig. 1 by a red arrow). This unexpected step is called the '0.7 feature', as it occurs around conductance values of $0.7 \times 2e^2/h$. It has been seen in many laboratories and studied for different QPC geometries[5] and a range of experimental parameters. Although several scenarios — mostly based on electron–electron interactions — have been put forward, no clear explanation of these observations has emerged yet.

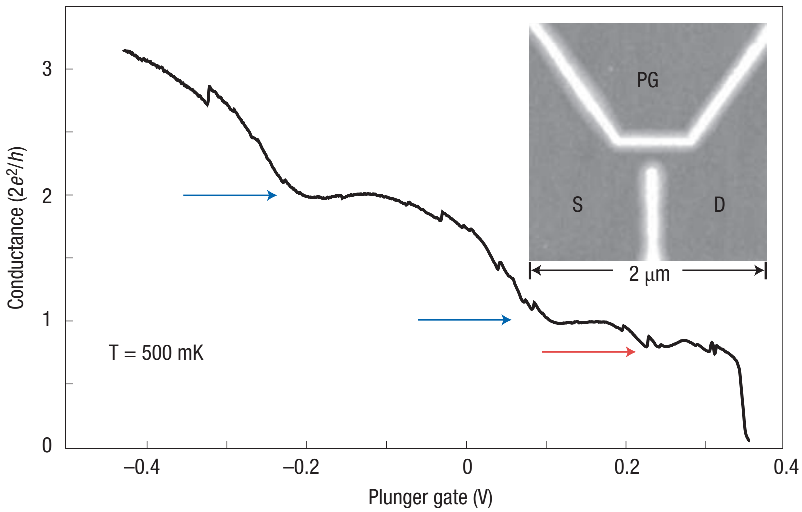

Figure 1 Conductance through a quantum point contact. In addition to the plateaux at $1 \times$ and $2 \times 2e^2/h$ (blue arrows), a plateau-like feature at $0.7 \times 2e^2/h$ (red arrow) appears. The device (shown in the inset, where S is the source contact, D is the drain contact and PG is the plunger gate) is fabricated on p-type AlGaAs heterostructures by AFM nanolithography. (Unpublished data courtesy of Boris Grbic, ETH Zürich.)

Recent experimental[6] and theoretical[7] contributions invoked the existence of a localized spin in the QPC constriction as a possible explanation of the puzzle. Rejec and Meir[1] take this idea further and present, for the first time, explicit numerical self-consistent spin-resolved calculations of the potential in a QPC. For gate voltages corresponding to standard conductance plateaux, the solutions of their equations indicate no spin polarization. Between plateaux, however, additional lower-energy solutions appear that do exhibit spin polarization. Below the first conductance plateau, a situation arises where the effective potential for the lowest spin mode — corresponding to a spin-up electron — has a double barrier shape near the centre of the QPC, and this configuration supports a quasi-bound state, which, for a typical set of parameters, forms 0.5 meV below the Fermi energy. But for spin-down electrons there is no such quasi-bound state, so there is a net single spin localized at the QPC. This finding could provide the necessary key to an understanding of QPCs close to pinch-off and explain the long-standing puzzle in mesoscopic electron transport. Several properties of the 0.7 feature, such as its temperature and magnetic field dependence, can now also be explained within this framework.

What happens for QPCs realized in different material systems, where interactions are different — be they weaker or stronger — from those in n-type GaAs? How generic are the results of the calculations by Rejec and Meir? Recently, it has become possible to fabricate QPCs on p-type AlGaAs heterostructures. In this case, holes rather than electrons carry the current. Compared with their n-type siblings, interactions between carriers are expected to be much stronger. Furthermore, the effects of spin–orbit interactions are expected to play a dominant role. In general, it is difficult to fabricate high-quality QPCs on p-type material by split-gate technology[8] because of hysteresis and stability issues. But the 0.7 feature has been investigated in different device structures[9,10] as well as in local-oxidation-defined QPCs[11]. A device similar to the latter is shown in Fig. 1; whether its conductance characteristics can be understood in the general framework of the calculations by Rejec and Meir[1] remains to be seen.

Many spintronics devices, where spin control is a central issue, rely on the tuneable tunnel coupling of a QPC. A localized spin in the tunnel barrier between a quantum dot and source/drain contact might have detrimental effects on the spin-coherence times of the dot electrons. If properly tuned, however, and with a better understanding now at hand, the properties of QPCs could become a useful tool to manipulate and control localized magnetic moments in spin-based nanoelectronics.

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