Studying electron flow through a quantum point contact

G. Metalidis and P. Bruno

Quantum coherence effects play a prominent role in the electronic transport properties of mesoscopic systems. Up to now, most people have been concentrating on global transport properties by passing a current through the sample and measuring the voltage drop between leads connected to it. Doing so, the conductance of a narrow constriction in a 2-dimensional electron gas (2DEG), called a quantum point contact (QPC), was shown to be quantized in steps of the conductance quantum \(2e^2/h\) as a function of its width [1].

However, local information about transport through mesoscopic samples, e.g. in the form of a current density distribution, was experimentally unattainable for a long time. Only quite recently it became possible to probe the electron flow in a 2DEG locally with a STM [2].

Fig. 1: Experimental setup. Conductance between ohmic contacts is measured as a function of tip position.

In these experiments, the negatively charged tip of the STM tip is used as a local scatterer (see Fig. 1); when the tip is placed over a region in the 2DEG where a lot of electrons are flowing, the electrostatic potential created by the tip will be able to backscatter electrons and thereby decrease the conductance of the sample, whereas the conductance will not decrease considerably when the tip is placed over a region where no electrons are flowing. As such, by mapping the conductance decrease of the sample as a function of the tip position, it is possible to obtain a spatial map of electron flow.

This method was used originally to study electron flow through a QPC. The results of the experiment [2] are shown in Fig. 2. The characteristic feature in this figure is that the electron flow shows a branching and channelling behavior with the branches decorated by small interference fringes. The branches result from the disorder in the system and the interference fringes spaced at half the Fermi wavelength come around from back and forth scattering between the STM tip and the QPC [2].

Fig. 2: Experimental image of electron flow from one side of a quantum point contact. The QPC (not shown) is situated on the right side of the picture.

These results were interpreted mainly with the help of electron and flux density calculations. However, the relation between the measured quantity, a conductance difference as a function of tip position, and these densities is not clear a priori. E.g. there are no interference fringes in a plot of the flux density because a STM tip is not present in this calculation. Therefore, we have developed a numerical tight-binding Green’s function method that allows to calculate both the current density distribution as well as a simulation of the
Fig. 3: Maps of electron flow through a quantum point contact. Current density distribution (a) in units of $2e^2V/(ha)$, STM conductance map (b) (conductance is measured in units of $2e^2/h$) and STM volt probe map (c). Left lead voltage $V_L = 0$, STM voltage measured in units of $V_R$. The QPC is depicted as a dotted white line.

visualization obtained with a STM tip [3]. Our method scales as $M^3N$ in the number of numerical operations, where $M$ is the width and $N$ is the length of the sample, which is a factor $MN$ better than existing methods. Therefore, we are able to treat sufficiently large systems.

The system we studied is the same as the one experimentally considered, namely a QPC in a 2DEG. The wavelength of the electrons was chosen to be $\lambda_F = 6a$, where $a$ is the lattice parameter of the tight-binding model. Our lattice counts 1001 by 351 sites. Disorder comes from a plane of point impurities above the 2DEG, where the potential from a single impurity varies as $1/r^3$, characteristic for the screened potential from a point charge. The mean free path for the potential used was estimated to be $4 \cdot 10^3a$.

In Fig. 3a, the calculated current density distribution shows the branching behavior that was also observed experimentally. The same behavior is apparent in the map of the conductance decrease as a function of STM tip position in Fig. 3b. There is a clear correspondence between the position of the branches in the current density distribution and the simulation of the STM experiment, from which we can conclude that the experimental method indeed probes directly the current density distribution of the sample. The correspondence of our numerical results with the experiment is quite clear; even the interference fringes are reproduced in our calculations (see the inset of Fig. 3b).

We also see that the branches are reflected on the upper and lower border of the sample (ballistic regime), and at crossings between branches interference patterns form because the branches are coherent. These two effects were not yet observed experimentally.

In a strong magnetic field, the STM method proposed in Ref. [2] fails because backscattering of electrons from the tip is almost completely reduced in this regime. To obtain a visualization of electron flow in high magnetic fields, we propose to allow tunnelling between STM tip and sample, and to measure the voltage on the tip. A picture of such a voltage map (without magnetic field) is shown in Fig. 3c. A clear correspondence between current density, conductance and voltage map is visible. For pictures including a magnetic field, we refer to our paper [3].

Finally, our numerical method is able to treat also the spin degrees of freedom, and take into account spin-orbit coupling. It is therefore sufficiently general to study a large range of interesting phenomena.

References