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LETTER TO THE EDITOR

e^2/h quantization of the conduction in Cu nanowires

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Abstract
We have investigated the quantum transport behaviour of Cu nanowires created by moving two macroscopic Cu wires into and out of contact. We have observed quantum conductance with steps of both e^2/h and $2e^2/h$. We conclude that the spin degeneracy can be broken in non-magnetic Cu nanowires.

In the past couple of decades the subjects of nanowires and point contacts have been investigated [1]. Quantum conduction has been seen in metallic nanowires [2] and in two-dimensional electron gas devices [3]. The study of metallic nanowires has received more attention recently because of the technological potential for creating nanoscale electronic devices. There are a variety of methods which can be used to make nanowires; for example: retracting a STM tip after it has hit a metallic surface [4], growth via an electrochemical process [5] and tapping plain wires together [6].

The general structure of a nanowire can be seen in figure 1: that is, a narrow constriction between two reservoirs. Most studies have reported that the conductance is quantized in units of $2e^2/h$ as expected from the Landauer formula [7–9] for non-magnetic materials:

$$G = G_0 \sum_i T_i \qquad (1)$$

where G is the conductance, $G_0 = 2e^2/h$ and T_i is the transmission coefficient for the ith conduction channel which will be either open or closed (1 or 0). So if there are n conduction channels open, $G = 2ne^2/h$. The factor of 2 appears due to the spin degeneracy expected for non-magnetic materials. Recent studies however [5, 10–12] have reported that in ferromagnetic Fe and Ni nanocontacts this spin degeneracy is lifted, as expected.

In a low-dimensional structure such as a nanowire the spin-polarized electronic structure and spin order can be different from the corresponding bulk quantities, depending on the physical structure of the contact. It is therefore of interest to search for possible spin-dependent effects in non-magnetic nanocontacts. In the present work we carried out an investigation into quantum transport in Cu nanowires. The nanowires were made by tapping Cu wires together in air at room temperature. The Cu wires were vibrated by mounting the wires in a light metallic

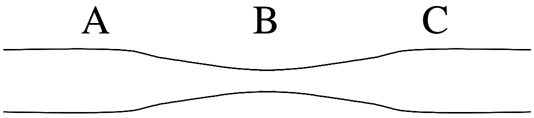

Figure 1. An outline of the nanowire: a narrow metallic constriction (B) between two metallic reservoirs (A and C). In the case of this experiment, all of these are made of Cu.

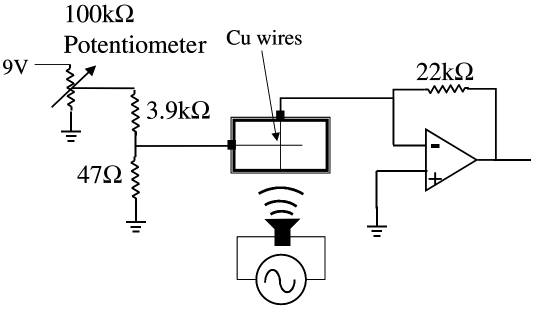

Figure 2. An outline of the set-up for the experiment. The nanowires are made by vibrating the macroscopic Cu wires by a speaker driven at about 10 Hz; the current is measured by a transimpedance amplifier and an oscilloscope.

box on top of a speaker driven by a sinusoidal signal at about 10 Hz. The circuit used can be seen in figure 2. A voltage source supplying in the region of 10 mV was connected to the wires and the current flowing through the wires was measured via a current-to-voltage converter. Both the current and the voltage were measured by a Tektronix TDS430A digital oscilloscope. Nanowires were not created every time a contact was broken, so the data sets had to be filtered to separate out those which demonstrated quantum conduction.

How the nanowires are formed is important in this case. Thin filaments extend from each Cu wire because the wire is not smooth on an atomic scale. When the wires separate, these filaments can remain in contact with the other wire and be stretched [13]. As the wires are being stretched the filaments get thinner and quantum conductance can arise. As the wire gets still thinner the various conduction channels will become closed, so the conductance will fall in the familiar staircase curve. Towards the end of the process we will have a very small number of atoms remaining in contact with the wires.

Figure 3 shows conductance against time curves; these are representative of the data that we have obtained. The nanowires are made and broken on the millisecond timescale. Quantum conduction is seen in making (e.g. figure 3(a)) and breaking contacts (e.g. figure 3(b)). Figure 3(a) shows the G_0 quantization of the conduction; this is as expected from equation (1). Figure 3(b) reveals a different story: it also shows quantization, but in this case in units of $G_0/2$. Both behaviours of the quantization can be seen in making and breaking contacts. Usually the contacts are quantized in steps of G_0, but in 5–10% of the contacts which show quantization the $G_0/2$ quantization are seen. The quantization in units of $G_0/2$ can also be seen in figure 4; this is a conduction histogram built up from many different conduction curves. Above $2G_0$ the peaks are shifted away from integer and half-integer values of G_0, due to changes in the topography of the nanowire [14, 15].

The importance of these measurements is that the observation of $G_0/2$ steps is not consistent with equation (1) for a non-magnetic material. This is because in the derivation of equation (1) we have assumed spin degeneracy which gives rise to the factor of 2 in G_0.

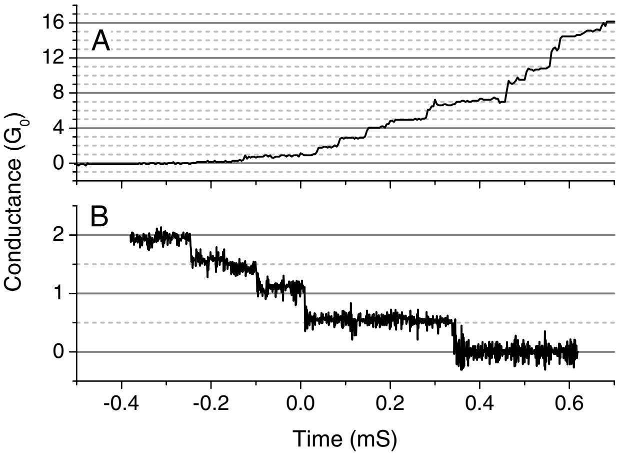

Figure 3. These are two representative curves. A shows the expected G_0 step size. B shows half the expected step size. The $G_0/2$ steps are evidence of breaking of the spin degeneracy.

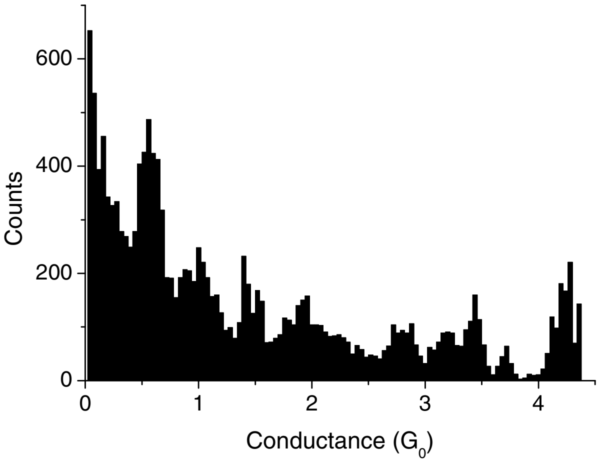

Figure 4. A typical conductance histogram, showing the $G_0/2$ steps.

Our experiments suggest that in this case this spin degeneracy has been lifted. A possible explanation of the mechanism is that while Cu in the bulk state is paramagnetic and has no overall spin, atomic Cu has a ground state of $^2S_{1/2}$, i.e. atomic Cu has a net spin. In the nanofilaments it is possible that the nearly isolated Cu atoms at the thinnest part of the nanowire revert to the spin-polarized atomic state, acting therefore as 'loose spins' giving rise to the $G_0/2$ quantization observed. Such nearly isolated atoms can occur due to the low atomic coordination of the Cu atoms at the thinnest part of the nanowire (area B in figure 1).

To summarize, we have observed quantum conduction in non-magnetic Cu nanowires with both G_0 and $G_0/2$ steps. We interpret this as evidence for breaking of the spin degeneracy in Cu nanowires from nearly isolated Cu atoms, which may revert to the spin-polarized atomic state and act as 'loose spins'. We hope that our finding of spin polarization effects in non-magnetic nanowires will stimulate further theoretical and experimental work on spin-polarized quantum transport.

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