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LETTER TO THE EDITOR

Defect switching in a mesoscopic sample induced by a scanning tunnelling microscope

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Abstract. A new method is introduced to study electron transport on the mesoscopic scale. A scanning tunnelling microscope (STM) tip is used both to form a point-contact potential probe to a thin film and to affect scattering centres in its vicinity. We detect abrupt changes in the voltage with this probe as a function of both tip position and tip–sample voltage. These changes could be interpreted as due to spatial shifts of scattering centres in the film surface.

Quantum interference effects are important in electron transport through metallic samples with dimensions less than the phase breaking length of electrons (the mesoscopic regime) [1–3]. These interference effects result in non-uniform current density and potential distributions even in a sample of homogeneous material [4]. The conductance of such a mesoscopic sample reflects fine changes in this interference pattern, changing by a finite amount of the 'universal' conductance e^2/h with any particular change of the disordered scattering potential.

A number of experiments has been carried out in this area, concerning random resistance variations of mesoscopic samples. One type of experiment concerns discrete changes of sample resistance as a function of time, caused by thermally activated changes in the sample scattering potential [5]. Such a switching can also be caused by an external influence, such as an electromigration due to a high current density in narrow bridges [6]. The other kind of experiment examines random sample resistance variations as a function of uniform magnetic field [7] or as a function of voltage of the sample [8]. In this case the electron interference pattern is changed by magnetic or electric fields, while the scattering potential remains unchanged. In some experiments these two approaches were combined, inducing switching between two states stable enough for magnetoresistance curves to be taken in both of them [9, 10].

Experiments of this kind made it possible to detect the effect of single scatters on the resistance of mesoscopic samples, and they have confirmed the theory for universal conductance fluctuations. However, these experiments can provide very limited knowledge about the location or the nature of two-state defects.

In this paper we present another approach, where we use an STM tip as a tool to locally influence a mesoscopic object. We use the electric field from the tip to alter the scattering centres and monitor the sample behaviour under such an influence. Because of the high resolution of STM and the possibilities of single-atom manipulation [11], such an approach seems to be promising for a detailed study of single-defect motion in a mesoscopic sample.

Due to thermal drift, it is difficult to keep the STM tip above a micrometre-sized sample during cooling from room temperature to liquid-helium temperature. However, it is not necessary to use a micrometre-sized sample. As shown both theoretically [12] and experimentally [13], it is possible to study quantum interference in a wide film containing a point-contact potential probe. The voltage measured on this point contact, when the film is carrying a current, depends upon the electron interference pattern near the contact. Like the resistance of a small sample, this voltage is very sensitive to changes of the scattering potential around the contact in an area with a radius of about the phase breaking length.

We produced such a point contact at liquid helium temperature by mechanically puncturing the insulating layer between two metallic films with the aid of the STM tip. Thus, we obtained a mesoscopic object just under the tip, which could be scanned near the point contact. The voltage on the contact was measured through the bottom film while the top film was carrying a current (figure 1(a)). Since this voltage in many respects is similar to the resistance of mesoscopic samples, we shall call the variations of this voltage the mesoscopic response (we also use the term AC signal).

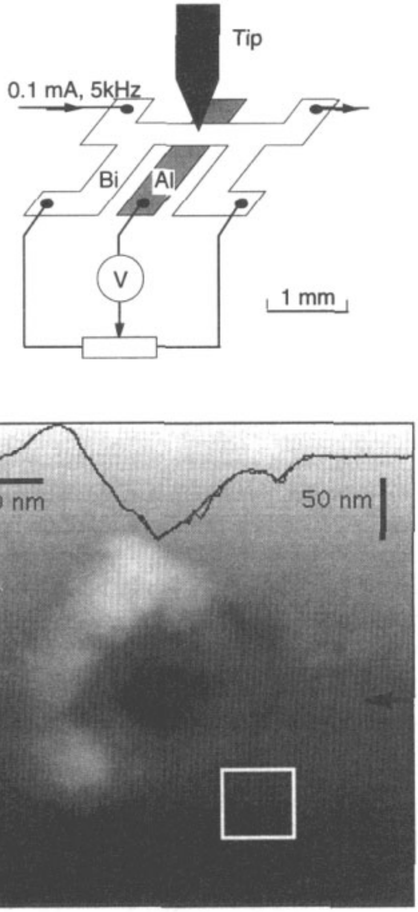

Figure 1. (a) The experimental set-up. The point-contact potential probe between the Bi film and an oxidized Al film is made by the STM tip. The AC signal from this contact is then measured as a function of the STM tip position or tip–sample bias voltage. (b) A grey-scale STM image of the point-contact area. The cross-section of the image shows the vertical scale. The small square indicates the region where mesoscopic measurements were performed.

We used oxidized aluminium for the bottom film (100 nm thick) and this film served only as a link to our point contact. Bismuth was chosen for the top film due to its low electron density and, as a result, improved mesoscopic effects at moderately low temperatures. The thickness of the Bi film was 40 nm and its sheet resistance was about 400 Ω.

The point contact was produced by gently (10 nm min^{-1}) pressing the electropolished tungsten tip into the junction area and breaking the oxide layer. During this procedure the point-contact resistance was controlled by a separate circuit (not shown in figure 1(a)). In this way we were able to produce the desired point-contact resistance of some kiloohms, corresponding to a point-contact size of several nanometres.

We used a 5 kHz AC current for the circuit excitation and a lock-in voltmeter (V in figure 1(a)) for the signal detection from the point-contact potential probe. This frequency was chosen to avoid interference of mesoscopic measurements with the STM feedback system that had a 1 kHz cut-off frequency. The background signal was eliminated by using a bridge technique. All measurements were performed at 1.3 K.

The usual measurement procedure started from the topographic STM scans of the point-contact area in order to find a proper scanning field for taking mesoscopic measurements (figure 1(b)). The fact that fairly sharp images could be obtained indicates that the tip was not damaged during the point-contact fabrication. Usually we scan in a flat region close to the point contact to be within the phase breaking length.

We operated the STM in a constant-current mode with a tunnelling current of 0.1–10 nA and with a bias voltage in the range 50–3000 mV. The STM used in this investigation is similar to one that has been described in detail elsewhere [14, 15]. The point-contact signal and the STM height signal were monitored simultaneously. Such a precaution gives us an assurance that we had no mechanical friction between the sample surface and the STM tip. Were this the case, the STM surface image should show a corresponding distortion and hysteresis, but this was not the case.

We discuss in this paper results that were obtained in two different kinds of experiment. During the first one the mesoscopic response was measured as a function of tip position near the point contact, and in the second kind the same signal was measured as a function of tip–sample voltage.

A typical example of a one-dimensional scan is shown in figure 2(a). Two important features should be noticed: the switch-like character of the AC signal, and the hysteresis. The behaviour was reproducible where we were scanning along the same line. The hysteresis is too large to be attributed to piezoceramics and it was not observed on topographic images. We performed a few experiments with different films and different point contacts. In some of them we could find a region near the contact where we observed the same kind of signal variation, although the amplitude of the signal switching varied depending on the particular point contact. We did not notice a systematic amplitude variation with the tip–point-contact distance, probably due to insufficient statistics.

We suggest that the observed changes in the AC voltage of the point-contact potential probe are due to a sudden shift of a scattering centre (such as an atom or a group of atoms) under the influence of the electric field between the tunnelling tip and the Bi film. In this model the two levels of the AC signal correspond to two metastable positions of the defect. The hysteresis observed is quite natural if the defect has to overcome a potential barrier between two metastable states (figure 2(b)). For longer scans we observed that the signal switched 'off' also. The distance between switching 'on' and 'off' was about 100 nm (figure 2(c)). This is a reasonable value for a strong-field region around the tip. Since the electric field penetrates only a few ångströms inside the metallic Bi film, all defects, which are sensitive to the electric field, are located very close to the film surface.

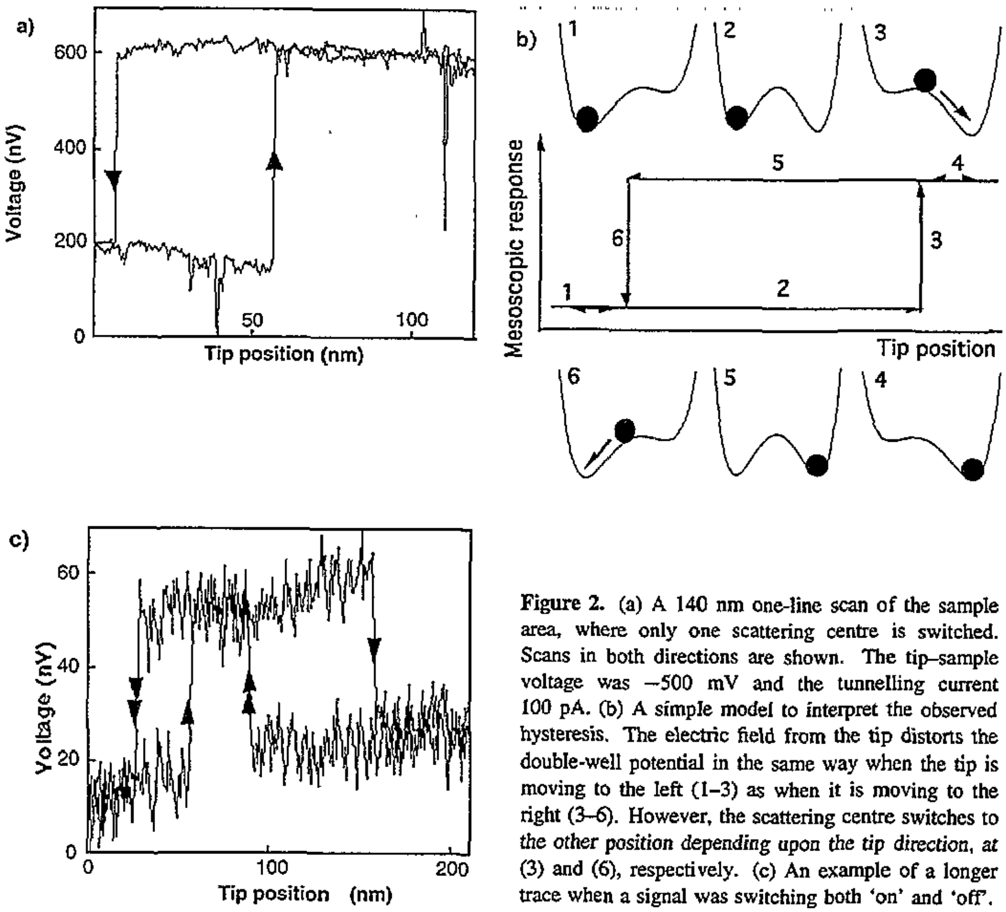

Figure 2. (a) A 140 nm one-line scan of the sample area, where only one scattering centre is switched. Scans in both directions are shown. The tip–sample voltage was −500 mV and the tunnelling current 100 pA. (b) A simple model to interpret the observed hysteresis. The electric field from the tip distorts the double-well potential in the same way when the tip is moving to the left (1–3) as when it is moving to the right (3–6). However, the scattering centre switches to the other position depending upon the tip direction, at (3) and (6), respectively. (c) An example of a longer trace when a signal was switching both 'on' and 'off'.

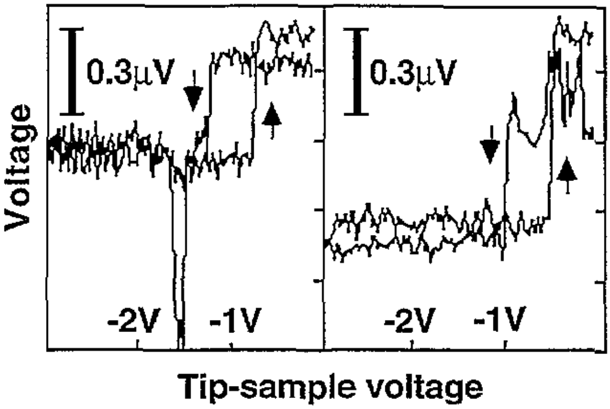

Figure 3. The point-contact signal as a function of tip–sample voltage when the feedback system of the STM keeps the tunnelling current at 100 pA. Two different scans are shown. $T = 1.3$ K.

The model shown in figure 2(b) is valid also for the case when the tip does not move, but the double-well potential is distorted due to the change of the tip–sample voltage. We

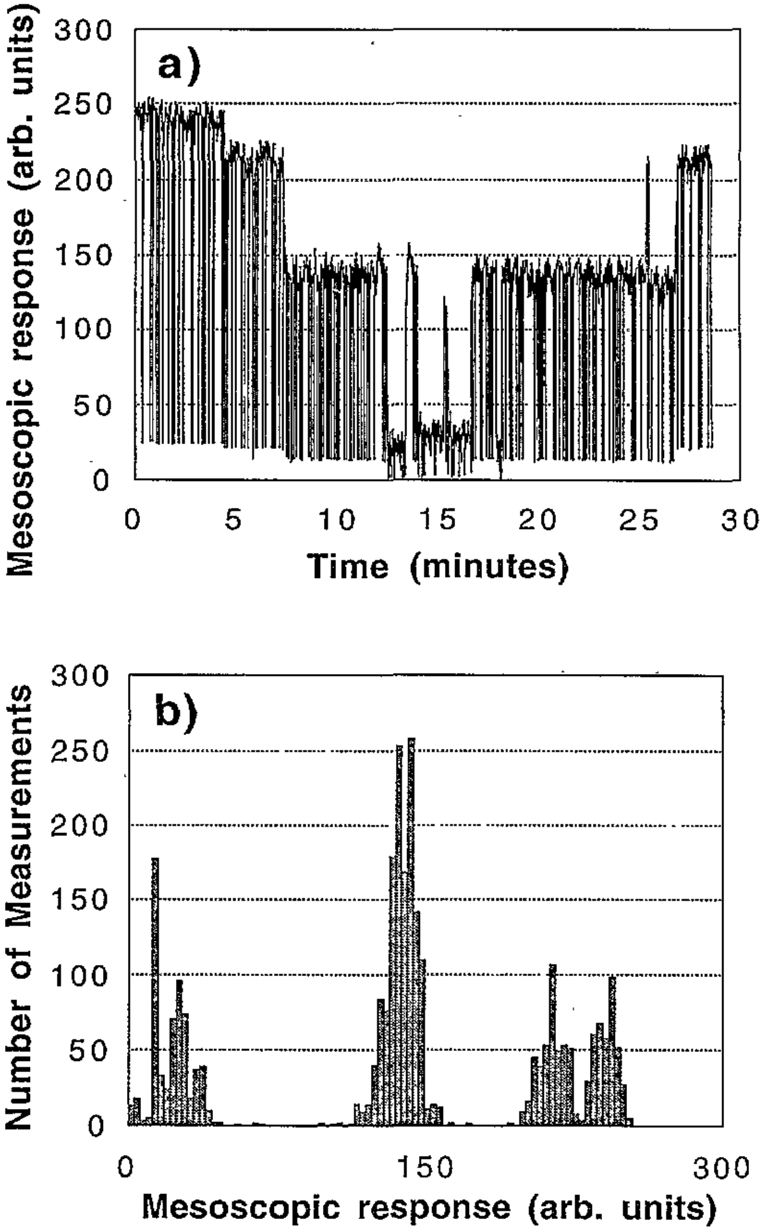

Figure 4. (a) The time dependence of the point-contact voltage showing the characteristic thermally activated multilevel noise of a mesoscopic sample. (b) A histogram of the same signal.

checked this point in the second kind of experiment.

First we located a region with a mesoscopic response by raster scanning an area near the point contact. In a small region 40 nm × 40 nm, with high enough tip-voltage bias, all traces showed the same type of reversible AC signal switch as in figure 2(a). We placed the tip just above this region of signal switching and swept the voltage of the tip in a constant-current mode, detecting [16] the same step-like behaviour of the mesoscopic signal (figure 3(b)).

We also observed a switch-like, time-dependent noise. Such a telegraph noise is conventionally attributed to thermally activated motion of scattering centres in small samples [5]. The 'intensity' of this noise was more or less related to the time that had passed from the moment of point-contact formation. Many defects were produced when the contact was made. Each of them could give its own two-level noise if appropriate metastable positions were present. The amplitude of the noise depends upon the defect location, being larger if the defect is situated closer to the point contact. At the beginning, after the contact formation, we observed an almost 'continuous' noise due to the time overlaping of these two-level signals from a large number of defects. If the sample was kept at liquid-helium temperature for several days, almost all defects found their equilibrium positions and the noise diminished. As a result, only a few defects were switching their positions and we could observe the characteristic multilevel noise of mesoscopic samples (figure 4). The histogram (figure 4(b)) shows that in this particular case we had two independently switching defects near the point contact. Signs of this noise can be seen in all traces as a background noise (see figures 2 and 3). We consider this time-dependent noise as additional proof for the mesoscopic nature of the voltage measured with the point contact.

To summarize, switching of single defects has been induced by STM and detected using a point-contact potential probe. All the data obtained in these experiments support the idea that the electric field near the tip is causing a defect to switch and this is the reason for the detected abrupt changes of the AC signal. We believe that this technique can be improved to allow studies of electron transport on a mesoscopic scale under a particular atom movement. We would like to point out that the tunnelling current also can be considered as a tool for the study of mesoscopic phenomena: locally injected electrons (if the tunnelling current is high enough) may cause phase breaking under the tip and one should be able to study its influence on the mesoscopic response.

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