Maxwell and Sharvin conductance in gold point contacts investigated using TEM-STM

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We have investigated the conductance of gold point contacts using a scanning tunneling microscope (STM) inside a transmission electron microscope (TEM). Measuring the conductance of these point contacts as a function of radius, we could directly compare it with theories both in the ballistic regime (Sharvin) as well as in the diffusive regime (Maxwell). The width of the contacts were between a single atom and 20 nm. Using an interpolation formula (Wexler) between the two limits, we obtain a mean free path of 4 nm, which is about ten times shorter than the room-temperature bulk value. The low value indicates an enhanced scattering, which is not due to high temperature in the point contact, instead a large number of scattering centers is created during the point contact formation process.

Conductivity of point contacts has been studied for many years (see, for example, Ref. 1). One relevant parameter is the resistance and its relation to the radius a of the contact and the electron mean free path l. Maxwell[2] studied the diffusive regime and later Sharvin[3] gave an expression for the ballistic case. More recently, the scanning tunneling microscope (STM) and mechanically controllable break junctions have been used to study point contacts of atomic dimensions. By pressing, for example, a gold STM tip into a gold surface, and subsequently retracting the tip, a short and narrow wire will be formed. Conductance measurements show clear signs of quantized conductance for these point contacts (see for example Ref. 4). Mechanical properties and their correlation with the conductance have been studied experimentally.[5] Theoretically,[6,7] different approaches have been done, ranging from free-electron models to molecular dynamics simulations, to understand the relation between the geometry and the conductance of these point contacts.

Despite this effort, little is known about the actual geometry of the point contacts. For a direct comparison of the conductance and the radius of the contacts, one could use the technique of TEM-STM, which is an STM placed inside a transmission electron microscope (TEM).[8–10] Ohnishi, Kondo, and Takayanagi recently used TEM-STM for the correlation of quantized conductance measurements with images of atomic sized wires.[11]

In this Brief Report, we present a TEM-STM study of point contacts where we also include contacts with larger radius, bridging the gap between the ballistic and the diffusive electron transport regimes. If we consider electron transport in point contacts, we can distinguish between two different types. In the diffusive limit, the electron mean free path l is considerably smaller than the radius a of the contact $(l \ll a)$. The conductance, G, is given by Maxwell,[2]

$$G_{\mathrm{M}}=\frac{2a}{\rho}, \tag{1}$$

where ρ is the resistivity of the metal which is given by

$$\rho=\frac{m\nu_{\mathrm{F}}}{ne^2 l}, \tag{2}$$

where m is the electron mass, ν_{F} the Fermi velocity, n the electron density, and e the electron charge. For point contacts with $(l \gg a)$, we are in the ballistic regime of electron transport. Sharvin[3] calculated the conductance:

$$G_{\mathrm{S}}=\frac{3\pi a^2}{4\rho l}. \tag{3}$$

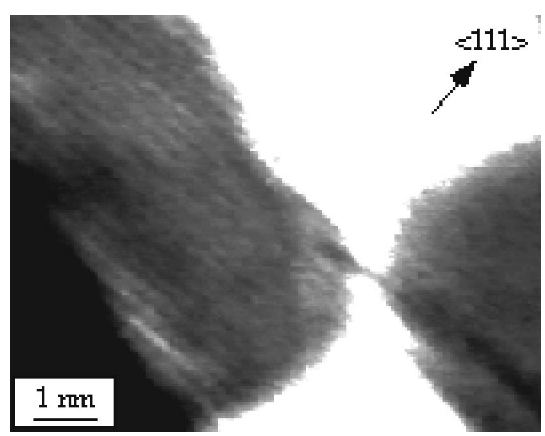

FIG. 1. TEM image of atomic-sized wide Au contact.

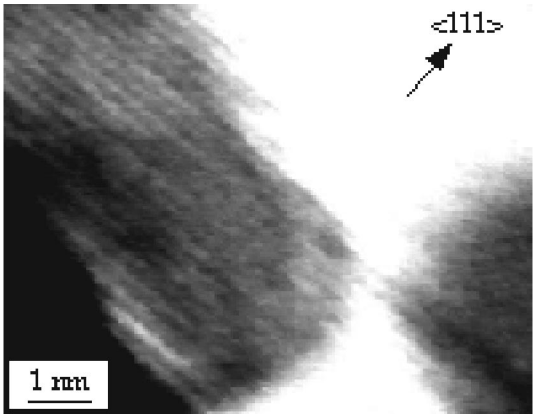

FIG. 2. TEM image of two atomic-sized wide Au contact.

Since ρ is inversely proportional to l, the Sharvin conductance does not depend on the mean free path l, in contrast to G_{M}. Between the two limits, Wexler[12] gave the expression

$$G_{\mathrm{W}}=G_{\mathrm{S}}\left[1+\frac{3\pi}{8}\Gamma(K)\frac{a}{l}\right]^{-1}, \tag{4}$$

where $\Gamma(K)$ is a slowly varying function of order unity and $K=l/a$ is the Knudsen number. One may note that Torres, Pascual, and Sáenz[7] made a correction to the Sharvin formula but the correction is small for larger contacts (5% for a radius of 2 nm) and is neglected in the present study.

Our TEM-STM consists, in short, of a 25-mm-long piezo tube (3 mm diameter) that is used for fine motion and of a geared stepping motor for coarse z motion. The TEM-STM was inserted into a Philips CM200 field emission gun TEM with attached video camera. The vacuum inside the microscope is 10^{-5} mBar. The electron irradiation density during the observation was 2.8×10^{5} A/m^2. The wires were 0.25-mm 99.99% pure gold, which had prior to insertion been mechanically thinned in the middle to a diameter less than 0.1 mm. By pulling the wires apart inside the TEM, two rough tips were produced with clean areas. The point contacts were formed by pressing the two tips together with the piezo and then pulling. Resistance measurements were performed at a constant bias voltage of 10 mV. I(V) characteristics of point contacts were obtained with voltages up to 140 mV at a frequency of 1.4 Hz. The signal was monitored on a digital oscilloscope simultaneously with the video TEM recordings. Video speed was 25 frames per second.

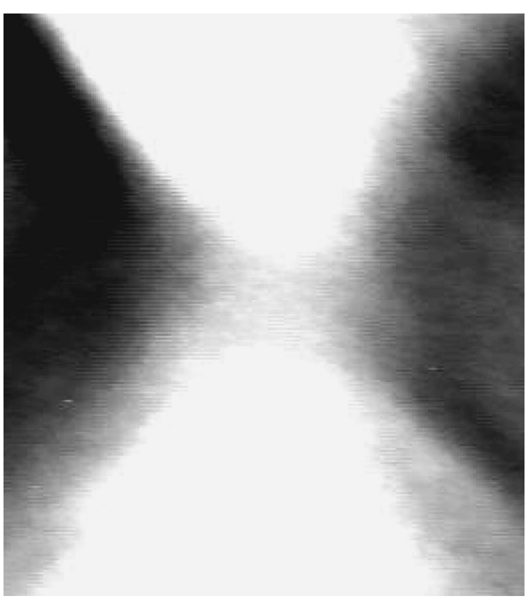

FIG. 3. TEM image of a 0.9-nm-wide Au contact.

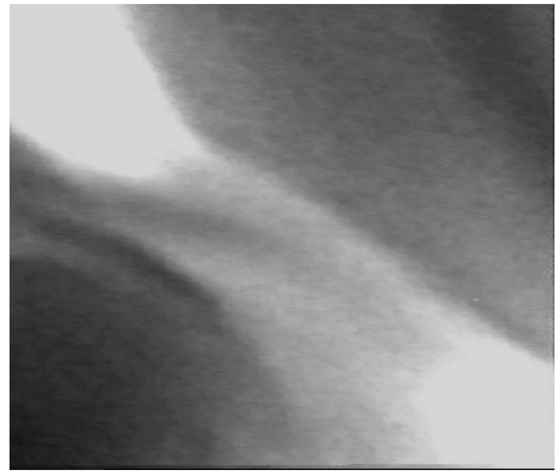

FIG. 4. TEM image of a 7-nm-wide Au contact.

Figures 1, 2 show TEM images of contacts with atomic-size widths. The resistance of point contacts with radius less than 0.4 nm showed the usual steplike behavior of earlier quantized conductance experiments.[4,5,11] In Figs. 3, 4 typical TEM images of thicker contacts are shown. In real time, these contacts looked semiliquid, and changed shape on a time scale of seconds.

Figure 5 shows the point contacts conductance versus ra-

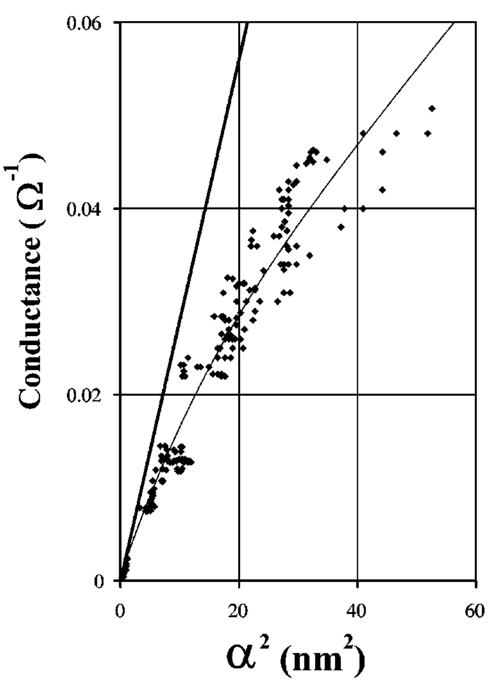

FIG. 5. Measured point contact conductance (Ω^{-1}) vs radius squared (a^2), at a bias voltage 10 mV. The Wexler interpolation formula is plotted using a mean free path value of $l=3.8$ nm and $\Gamma=0.7$. Sharvin conductance (straight thick line) is added for comparison.

dius squared (a^2). It is only for the smallest radius of about 1 nm that a good fit to Eq. (3) is obtained. These data fit well with the Wexler interpolation formula using a mean free path value $l=3.8$ nm. This is much lower than the bulk room-temperature value of 37 nm (for melting gold $l=2.7$ nm and at 1300 K, $l=6.7$ nm). The low value that we found could be reasonable when considering that a high density of scattering centers should be created during the point contact formation process. Two other recent studies of gold point contacts using other methods (one on conductance fluctuations in atomic-sized point contacts,[13] and another one on thermopower[14]) gave consistent mean free path values of about 5 nm.

One obvious question concerns the temperature in the point contacts. Heating by the TEM electron beam is negligible for a metal such as gold.[16,17] However, the current flowing through the contact may heat it considerably.[1,15,18] Holm[15] has given a simple relation about Joule heating in point contacts, assuming that the electronic heat conductivity k and the electrical resistivity ρ is related by the Wiedemann-Franz law

$$k\rho = TL, \tag{5}$$

where L is the Lorenz number. In the Maxwell limit the maximum temperature T_{m} at the contact, with surrounding temperature T_{b} is given by

$$T_{\mathrm{m}}^2 = T_{\mathrm{b}}^2 + \frac{V^2}{4L}. \tag{6}$$

For our applied voltages of 10 mV, a temperature increase of only 2 K would result, and should not be the main reason for the decreased electron mean free path. To test the heating effect on scattering we made current-voltage (I/V) measurements with a bias voltage up to 140 mV, which corresponds to a temperature of 540 K. If the thermally induced scattering was a significant part, one should expect nonlinear I/V curves. However, all our I/V curves were linear. This means that the scattering is mainly due to fixed scattering centers.

To summarize, we have investigated the conductance of nanometer-sized Au wires as a function of radius, using a scanning tunneling microscope inside a transmission electron microscope. Using this technique we could make a direct comparison with the predictions by Maxwell, Sharvin, and Wexler.

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