Quantization of the conductance of metal nanocontacts at room temperature

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The differential conductance of metal nanocontacts at room temperature exhibits properties of a ballistic quantum transport in 1D systems. The quantum of conductance of nanocontacts based on a tungsten tip $\simeq 1$ nm in diameter is e^2/h, not $2e^2/h$. © *1995 American Institute of Physics.*

A scanning tunneling microscope can be used to fabricate point metal contacts of atomic size and to make fine adjustments of their dimensions. It was mentioned in Refs. 1–4, as in Ref. 5, where current flow in thin wires upon rupture was studied, that the conductance ($G = I/V$) varies in a stepped fashion as the geometry of the contacts is varied continuously. A change in the area of the contact due to an abrupt change in the positions of surface atoms as a result of interatomic forces is regarded as the most likely cause of this behavior of the conductance. The size of the abrupt changes in the conductance was approximately equal to, or a multiple of, $2e^2/h$ for all the metals studied. This result suggests that the electron transport in nanocontacts is of a quantum nature. It has been suggested that a 1D motion of electrons, confined near the contact itself by the boundaries of the metals forming the contact, can occur in these contacts.[6] In contrast with the 1D conduction channels which form in a 2D electron gas, quantization of the conductance in metal contacts which satisfy the conditions for 1D transport should be observed at room temperature. The reasoning here is that quantization of the conductance requires that the transverse dimension (d) of the channel be on the order of the Fermi wavelength of an electron, i.e., ~ 1 nm for metals. A quantum system bounded by such dimensions has structural features in its energy spectrum which are separated by a distance on the order of $\Delta E \simeq h^2/md^2$, which is larger than the energy kT at room temperature. We have accordingly studied the behavior of the conductance of metal nanocontacts as their dimensions were varied. We also studied the behavior of the conductance as a function of the voltage applied to the contact at room temperature in air.

In this letter we show that abrupt changes in the conductance which are half as large, multiples of e^2/h, can occur in a metal nanocontact as its size is varied. We also show that the behavior of the differential conductance as a function of the applied voltage, $g(V)$, corresponds qualitatively to a theoretical model for 1D ballistic motion of electrons.[7]

We studied the transport properties of a contact formed by the tungsten tip of a tunneling microscope and the surface of a gold film on a silicon substrate. We measured the conductance as a function of the position of the tip along the normal to the surface of the sample and also as a function of the applied voltage at fixed positions of the tip and

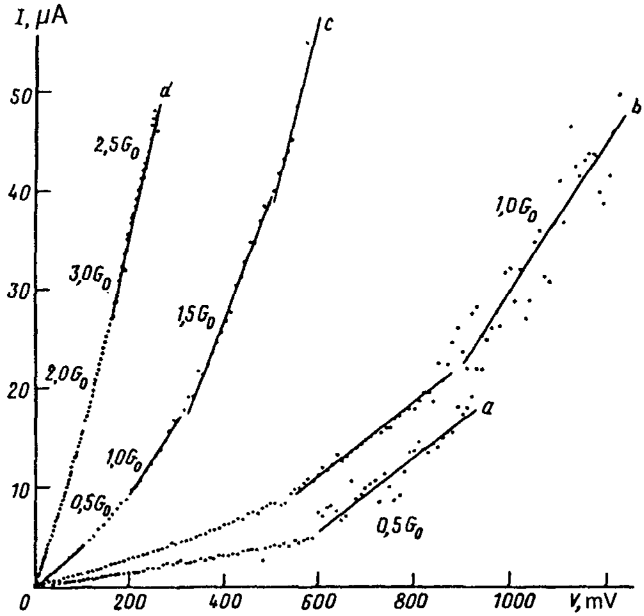

FIG. 1. Current–voltage characteristics of stable W–Au contacts for various values of the initial conductance. The slopes of the linear regions (the values of the differential conductance g) are given in units of $G_0 = 2e^2/h$. The lines are least-squares fits.

the sample. The tungsten tips were fabricated by the technique proposed in Ref. 8; the diameter of their ends was $\simeq 1$ nm. With such tips it is possible to fabricate stable nanocontacts, which exhibit a clearly defined, stepped dependence of the current on the tip position.[4]

To check whether the conductance was of a quantum nature, we measured current–voltage characteristics of the nanocontacts. Wishing to avoid destruction due to the energy dissipation near the contact, we applied the voltage to the sample in short square pulses ($t \simeq 100$ μs) with a duty factor of $1:10^3$. To monitor for possible changes in the size of the contact, we measured the current i through the contact at a low voltage ($V = 65$ mV) during the time intervals between pulses. If this current remained constant, we concluded that the contact was stable during the measurements.

If the initial conductance, i.e., the conductance at voltages up to $\simeq 100$ mV, is a multiple of e^2/h, then the function $I(V)$ is continuous and piecewise-linear with a differential conductance which is a multiple of e^2/h (Fig. 1). If the initial conductance is greater than e^2/h but not a multiple of it, the contact is unstable, and the current i varies rapidly over time, stabilizing in such a way that G becomes a multiple of e^2/h.

Particularly interesting are contacts for which the initial conductance is smaller than e^2/h. At the accuracy of our method, it is not possible to draw unambiguous conclusions about the behavior of G before the value e^2/h is reached. On the other hand, it can be asserted that the function $I(V)$ becomes piecewise-linear above 0.5–0.6 V with a differential conductance which is a multiple of e^2/h.

Figure 1 shows some typical $I(V)$ curves for stable contacts between a tungsten tip and a gold surface. In cases in which the current i changed during an experiment, the function $I(V)$ had discontinuities at the points of the changes in i.

To check for an effect of the power dissipation in the circuit of the contact on the properties of the contact, we measured current–voltage characteristics of nanocontacts as the voltage was varied continuously. The behavior was found to be the same as that found in the pulsed measurements. The measurement time was $\simeq 10$ s, and the current through the contact rose to 1 mA.

The observed features of the flow of electron current through a metal nanocontact are in qualitative agreement with the theoretical model of Ref. 7. The $I(V)$ dependence is more complex than that predicted by the theory; we attribute the difference to the circumstance that the theory was derived for the case of a single transport channel. It has been pointed out previously[4] that the existence of a single conduction channel over the area of a nanocontact seemed dubious, in view of electron scattering by atoms. The same paper proposed a model in which one conduction channel corresponds to each pair of atoms forming the contact. In this case, the differential conductance of the nanocontact is the sum of the differential conductances of the channels and of that part of the contact in which a tunneling barrier still exists:

$$g=\sum^{N} g_i+g_x, \tag{1}$$

where g_i is the differential conductance of the channel, N is the number of channels in the nanocontact, and g_x is the differential conductance of the tunneling part of the contact.

If the conductance of one channel can be described at low voltages by the Landauer formula

$$G=(2e^2/h)n, \tag{2}$$

where n is the number of subbands whose bottoms ϵ_d lie below the Fermi level ϵ_f, then the differential conductance of the channel at a voltage V is, as was shown in Ref. 7,

$$g_i(V)=(2e^2/h)k+(e^2/h)l, \tag{3}$$

where k is the number of subbands for which the relation $\epsilon_d<(\epsilon_f-eV/2)$ holds, and l is the number of subbands for which the relations $(\epsilon_f-eV/2)<\epsilon_d<(\epsilon_f+eV/2)$ hold. In that model, the behavior of the differential conductance as a function of the applied voltage is obviously much more complicated.

Curve c in Fig. 1 and Eq. (2) tell us that the conductance G of one channel at low values of V, in the case of a W–Au contact, is a multiple of e^2/h, i.e., that the quantum of conductance for this system is e^2/h, not $2e^2/h$. If this inference is correct, then steps of size e^2/h should arise in measurements of the conductance of a nanocontact as a function of the transverse dimension of the contact. Indeed, in many cases in which the sample and the tip were brought close together, i.e., in cases in which the conditions required for an increase in the transverse dimension of the contact were satisfied, we observed a step of size e^2/h on the curve of the conductance (of the current at a constant voltage) as a function of the tip position. One such plot is shown in Fig. 2.

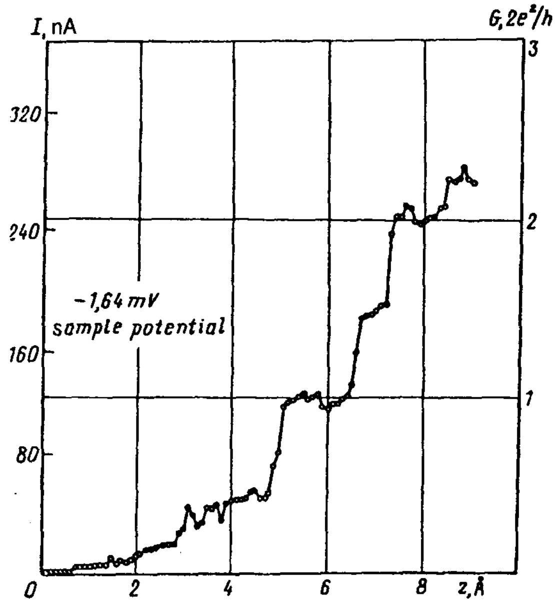

FIG. 2. Conductance of a contact between a tungsten filament and a gold surface versus the distance from the tip to the sample.

It is possible that this is a manifestation of yet another size effect: a lifting of degeneracy in terms of electron spin in the tungsten tip.

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