# Giant Peaks of the Conductance in Polycrystalline Bi Nanobridges

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Giant oscillations (up to 100%) in the conductance of Bi nanobridges were observed at liquid helium temperatures. Experimental results are discussed in terms of a model in which a polycrystalline Bi nanobridge is represented as a chain of coupled quantum dots.

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Electron transport in disordered quantum wires has been extensively studied in the past few years [1–12]. Giant oscillations, both aperiodic [1,2] and periodic [3–6], of the wire conductance were detected. The period and amplitude of giant oscillations in the experiments [1–6,9] varied in different samples and did not correlate with the wire length. Three theoretical approaches based on the models of a charge density wave or "Wigner crystal" [7,8], Coulomb blockade [9], and resonant tunneling of noninteracting electrons [10,11] have been proposed to explain the oscillations observed. However, theoretical predictions either diverge from experimental results [12] or do not allow one to interpret experimental results unequivocally [9]. It is apparent that further investigations are required in order to understand the oscillating character of the wire conductance.

Up to now, giant oscillations in conductance were observed exclusively in semiconducting quantum wires [1–12]. Only small fluctuations (<1%) in conductance of metallic nanowires were observed in [13,14] where highly disordered quantum wires with a great number of defects were studied. Electron transport in such structures is within the diffusion regime, in contrast to the quasiballistic one in semiconducting nanostructures. The small fluctuations in [13,14] were explained as due to lattice defect migration. It was speculated [15] that fluctuations in conductance of metallic nanostructures can be caused also by the specific quantum properties of the electron transport.

In this paper, we report on the first observation of giant peaks in the conductance of metallic (Bi) quantum wires of a finite length. We have developed an original technique that allows us to decrease radically the introduction of defects into metallic nanostructures during their fabrication. A sample, fabricated for electrical measurements, is shown schematically in Fig. 1. Nanostructures were fabricated according to one of the following procedures. In the first procedure, a through slit 500 nm wide and about 0.1 mm long was cut in the geometric center of a $Si_3N_4$ membrane with a focused Ga ion beam. Then four $1 \times 1$ mm$^2$ Ag contact pads 500 nm thick (the size of the specimen was $2.5 \times 2.5$ mm$^2$) were deposited onto the surface of the specimen through a mask, so that a $1 \times 1$ mm$^2$ area in the center around the slit was not covered with silver. The first Bi film 300 nm thick was deposited by the partially ionized beam technique [16], and then it was cut with a laser to the left and the right from the ends of the slit in order to have two electrically insulated parts of the Bi film. The edges of the slit were connected by a carbon bridge that was grown in the scanning transmission electron microscope via electron-beam-stimulated decomposition of hydrocarbon molecules diffused into the reaction zone along the membrane surface [17]. These bridges were ordinarily from 10 to 40 nm wide. The second Bi layer 30–50 nm thick was deposited onto both the bridges and the whole surface of the specimen. Then this film was cut with a laser again.

In the second procedure, a carbon strip was first grown on the back side of a $Si_3N_4$ membrane and served as a mask. After the membrane was cut through with an ion beam from the side of the carbon strip, a $Si_3N_4$ bridge was formed [Fig. 2(a)], onto which a Bi film was deposited [Fig. 2(b)]. In the third procedure, a carbon mask in the form of a strip was first grown too, but the membrane

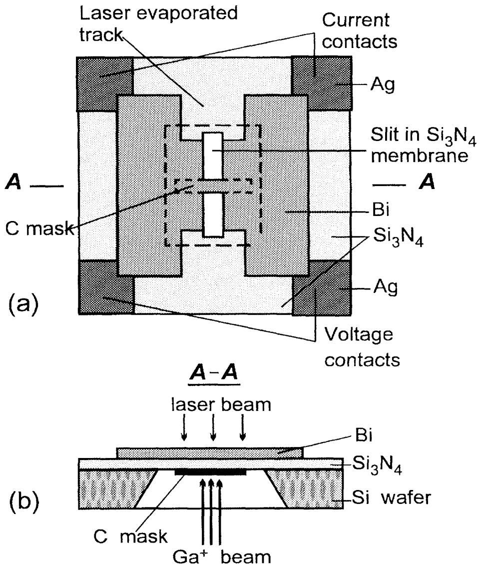

FIG. 1. Scheme of the specimen for the electrical measurements: (a) the plane view and (b) the cross section along the line *AA*.

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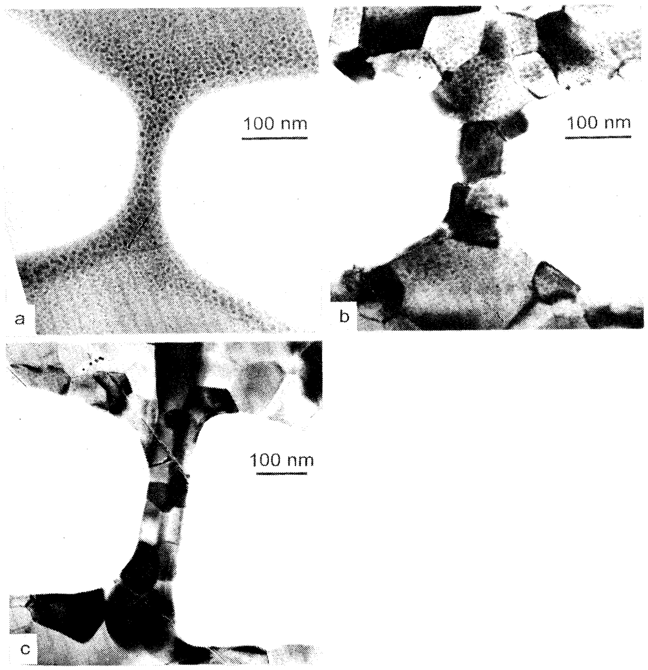

FIG. 2. TEM images of Bi nanobridges: (a) a bridge composed from $Si_3N_4$ with Ga inclusions (dark spots) formed by ion etching before Bi deposition; (b) a "short" bridge prepared according to the second procedure—dark spots on the image are Ga inclusions in $Si_3N_4$ formed as a result of the ion beam irradiation; (c) a "long" bridge formed according to the third procedure—a dark stripe along the bridge is the remaining part of the carbon mask after ion etching.

was cut through after a Bi film had been deposited on the "face" side of the membrane. The *I-V* characteristics of the nanobridges were measured at 4.2 K. The voltage was supplied to the sample through Be bronze springy contacts plated with indium.

The first procedure allowed us to fabricate nanobridges with the smallest width possible, about 10 nm; the second procedure guaranteed the best smoothness of the Bi bridge surface; and the third one made it possible to fabricate nanobridges with the most even edges [Fig. 2(c)]. However, the disadvantage of the third procedure is that the Bi bridge may be contaminated by the impurity atoms from the ion beam. Although these three procedures produce samples with different surface roughness and (possibly) contamination, we believe the important results are related only to grain size in the Bi films and geometrical sizes (width, length) of the bridge, as we shall discuss.

The resistance of the samples was checked at several stages of their fabrication. After silver contact pads were deposited, the resistance was about $10^9$ Ω. After the second Bi layer was deposited and cut into two parts with the laser beam, the resistance was within the range 100–1000 kΩ (the shunting resistance). The dimensions of the samples, their resistance, and the fabrication procedures are presented in Table I. It is seen that the resistance of samples with Bi nanobridges about 20 nm wide was not less than the shunting one; therefore we will not discuss their *I-V* characteristics here.

TABLE I. Dimensions and resistances of Bi nanobridges. Bridges (*a*), (*b*), (*c*) were produced according to the first, second, and third procedures, respectively.

| Number of bridges | Thickness (nm) | Width (nm) | Length (nm) | Resistane (kΩ) | Peaks |
|---|---|---|---|---|---|
| 1(*a*) | 30 | 15 | 200 | 480[a] | |
| 2(*a*) | 30 | 20 | 250 | 260[a] | |
| 3(*a*) | 30 | 15 | 150 | 1500[a] | |
| 4(*b*) | 50 | 75 | 130 | 0.35 | No |
| 5(*b*) | 50 | 50 | 120 | 0.80 | No |
| 6(*a*) | 50 | 90 | 450 | 13 | Aperiodic |
| 7(*a*) | 50 | 100 | 450 | 27 | Nearly periodic |
| 8(*a*) | 50 | 80 | 400 | 28 | Nearly periodic |

[a] The resistance is about equal to the shunting one of samples without bridges. A real resistance of the bridge can be much greater than this value.

Nanobridges with the cross dimensions of 50–100 nm displayed drastically different characteristics depending on bridge length. The three longest bridges (~400 nm long) had the resistance almost equal to $h/e^2$ (26 kΩ) and $h/2e^2$ and exhibited sharp peaks in the *I-V* curve [Figs. 3(a) and 3(b)]. The peaks were reproduced during repeated measurements of the *I-V* characteristics in the direction of both an increase of the current and its decrease. The amplitude of the conductance peaks was about 100%. The first peak appeared at a voltage ~10 mV; its half-width was ~0.5 mV, which approximately corresponded to temperature smearing equal to ~0.4 meV [the inset in Fig. 3(a)]. The observed peaks were either nearly periodic [the first four peaks in Fig. 3(a)] or randomly spaced [Fig. 3(b)]. The resistances of the bridges, which were about 100 nm long, were $\ll h/e^2$, and their *I-V* curves followed Ohm's law without any features [Fig. 3(c)].

After the bridge was destroyed by an electric current [Fig. 4(a)] or by an electron beam during the study in the microscope [Fig. 4(b)], the samples had linear *I-V* characteristic with resistances of 100–1000 kΩ, similar to those samples before the Bi bridge was fabricated. This provides convincing evidence that the observed effects are related to the Bi nanobridges, and current leakage through the substrate (for example, via Ga inclusions in $Si_3N_4$) is insignificant.

We believe that the observed specific features in the conductance of Bi nanobridges can be attributed to the effect of grain boundaries. It is known that grain boundaries in semiconductors and semimetals act as potential barriers about 0.1 eV high for charge carriers, whereas the grains act as potential wells [18]. At small voltages ($\ll 1$ V) the resistance of a tunnel junction can be approximately expressed by the relation $R \sim \exp[-2d(\varphi m^*)/h]$ [19], where $\varphi$ is the barrier height, $d$ is the barrier width, $h$ is the Planck constant, and $m^*$ is the effective electron mass.

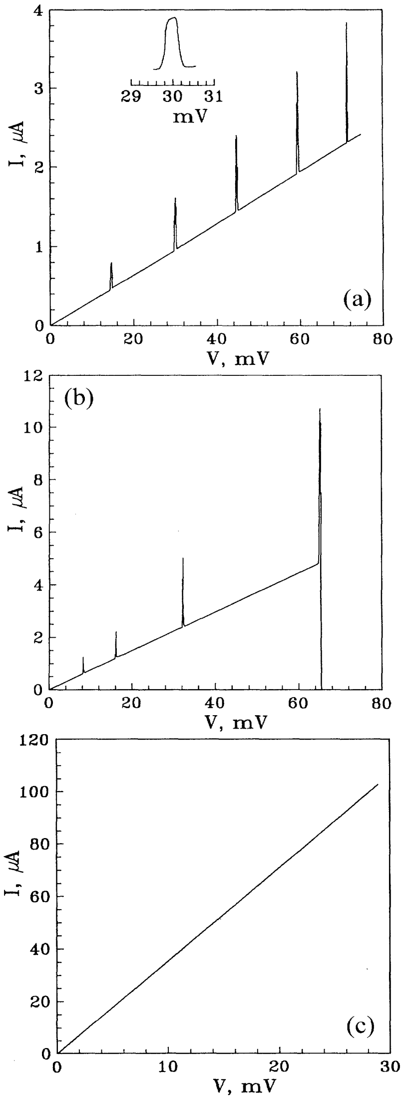

FIG. 3. *I-V* characteristic of the "long" (*a,b*) and "short" (*c*) Bi nanobridges: (a) the nearly periodic and (b) the aperiodic locations of conductance peaks. The form of the peaks is seen in the inset in (a).

The effective masses of charge carriers in Bi differ considerably: $m^* = 10^{-2}m_0$ for light electrons, $m^* = 10^{-1}m_0$ for holes, and $m^* = m_0$ for heavy electrons [20], where $m_0$ is the mass of a free electron. As the probabilities of tunneling for the three types of charge carriers differ by many orders of magnitude, the conductance of a tunnel junction is determined primarily by the lightest carriers. Since the value of wavelength $\lambda$ for light electrons in bismuth is abnormally large ($\lambda = 100$ nm), grains with sizes smaller than $\lambda$ become quantum dots for these electrons. Grains in the nanobridges fabricated in this work were just of that size.

When the cross dimensions of a bridge become less than the wave half-length for light electrons, the latter cannot travel through the bridge. In this case the conductance is determined by heavy electrons and holes, which have a lesser probability of tunneling, and this results in a very small value of conductance observed in the experiment (Table I).

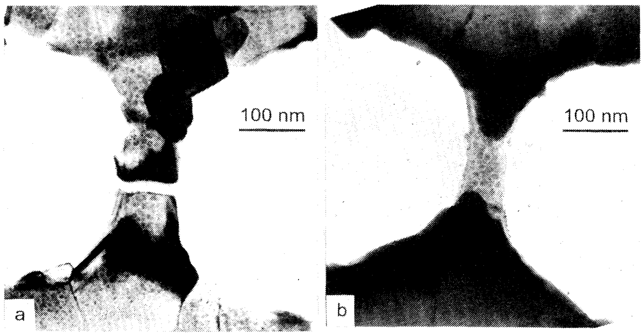

FIG. 4. Nanobridges destroyed by electrical current (a) and electron beam (b).

If the electron transport in the bridges is considered to be resonant tunneling through a chain of coupled quantum dots, a peak in the conductivity of the bridge should occur each time the electron energy, varied with the applied voltage, coincides with the intrinsic energy levels $E_i$ of the system of coupled quantum dots. These values are expected to be the order of $h^2/m^*a^2$, where $a$ is the size of a quantum dot. For $a = 50$ nm (typical grain size) and $m^* = 10^{-2}\ m_0\ E_i \sim 15$ meV, which is in good agreement with the experimental values corresponding to the first conductance peak.

Theoretically, the spectrum of energy levels in a quantum dot should be strongly dependent on the number of electrons in it. The spectrum is essentially aperiodic when the quantum dot is filled with no more than ten electrons, whereas it is almost periodic with a number of electrons greater than 30 [21]. The grain sizes in our bridges (Fig. 2) are such that the number of electrons in individual grains should be about a few tens, taking a typical electron concentration in Bi of about $10^{17}$ cm$^{-3}$ [20]. Thus both nearly periodic and aperiodic oscillations of conductivity can occur in the fabricated nanobridges, as was observed in the experiments [Figs. 3(a) and 3(b)]. The difference in oscillation periods in nanobridges Nos. 7 and 8 with an almost periodic spectrum reaches 10–15 %; the theory predicts it to be 10% for a quantum dot with a large number of electrons ($\geq 30$) [21]. According to the calculations [21], the peak width for such a quantum dot amounts to about 1 meV, which is close to our experimental value; the peak height achieves the value $e^2/h$. We have observed such values of conductance peaks on samples Nos. 7 and 8 [Fig. 3(a)]. The height and width of the peaks increased slightly with voltage; the maximal increase comprised 10% and 20%, respectively. The shape of the peaks could be approximated roughly by a Lorentzian line. These experimental results are well accounted for by the theory [21].

No explanation has yet been found for the absence of oscillations in "short" bridges, whose lengths are approximately equal to the electron wavelength. It is noteworthy that oscillations were observed neither in Bi single crystal point contacts [22] nor in semiconductor quantum wires of the shortest lengths [9]. It can be assumed that a short chain of strongly coupled quantum dots may not make a substantial barrier for electrons. This assumption is prompted by the relatively low resistance (less than 1 k$\Omega$) of "short" bridges, which is substantially less than the resistance of "long" nanobridges, by a factor exceeding 10 in our work.

In the phenomenological model [9] describing a disordered quantum wire as a chain of coupled quantum dots, two cases were considered: (1) The wire conductance is determined by one of the quantum dots, loosely bound to the rest, and (2) the conductance is determined by several dots. It was concluded that regular conductance oscillations are due to the first case, whereas the second case is responsible for irregular oscillations. The shortest quantum wires were presumed to be free of any quantum dots at all.

We could not infer whether our bridges contained only one grain loosely bound to its neighbors, which determined the conductance in the bridges, or they consisted of a chain of similarly bound grains. The electron microscope study revealed that the majority of the grains in a bridge have a similarly oriented $c$ axis. A loosely bound grain may be the one whose growth axis deviates strongly from the predominant direction. We are inclined to believe that this is the case (at least for specimens with a nearly equidistant spectrum), because otherwise it would be difficult to explain how a system consisting of inhomogeneous potential barriers and wells can produce a nearly equidistant spectrum of peaks of such a small width. Nevertheless, the second case is possible in theory [23]. The situation could be elucidated by a more detailed electron microscopic study of the grain boundary structure. However, all our attempts to do this in our microscope lacking a *TV* system have failed because a long exposure of a sample to the electron beam is needed for such study. Long exposures caused destruction of the Bi film along the grain boundary under observation [Fig. 4(b)].

Finally, we would like to discuss the effect of Coulomb blockade on the conductance of Bi nanobridges. Because a nanobridge is a chain of tunnel junctions of very small dimensions, this effect cannot be excluded. Theory predicts that the conductance of such samples can show evidence of periodic oscillations [9]. Aperiodic oscillations can be caused by the so-called stochastic Coulomb blockade [24]. However, the *I-V* characteristics of the specimens where the Coulomb blockade seems to be observed were always of stairlike character ("the Coulomb staircase") [25]. Therefore we think that the conductance peaks in our case are due to resonant tunneling. Nevertheless, it remains unclear why the bridge conductance is rather high at nonresonant voltages. Perhaps this can be associated with the so-called cotunneling processes [12,26] observed in short sized tunnel contacts at temperatures >1 K, when the effects of the Coulomb blockade were suppressed [26]. The physical cause of these processes is quantum charge fluctuations that give rise to a sufficiently large value of the Ohmic conductance of the order of $e^2/h$ at $T > 1$ K.

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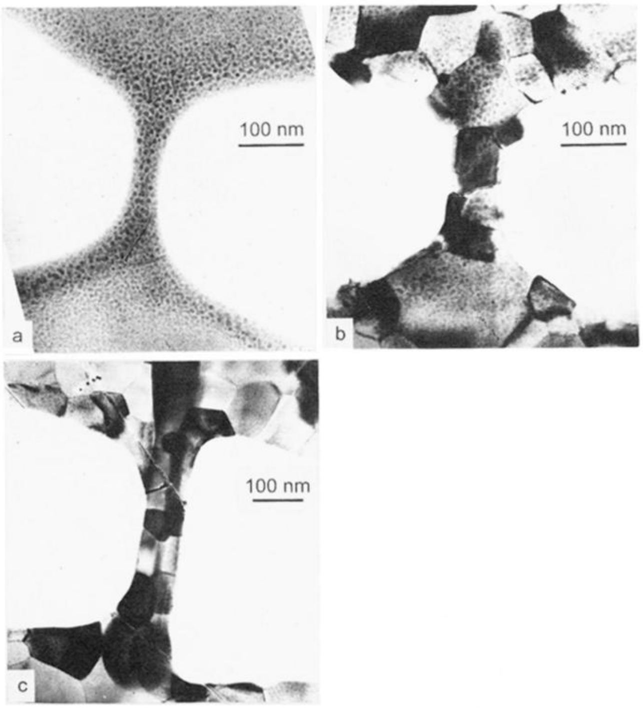

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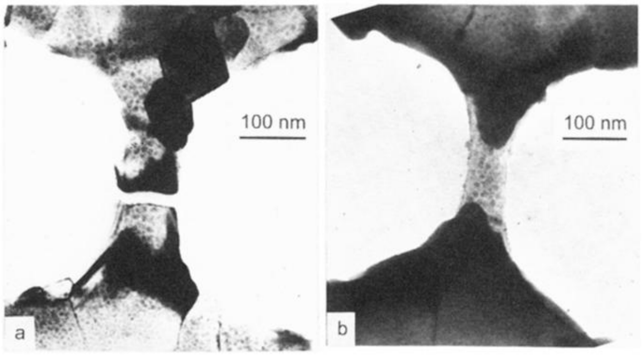

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