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Conductance Quantization in Nb-Ti/Cu Alloys and BiSrCaCuO/PbAg Superconducting Tapes

Streszczenie. *Kwantowanie przewodności elektrycznej w nanodrutach NbTi/Cu oraz w związkach BiSrCaCuO/PbAg zostało zaobserwowane w nanozłączach formowanych dynamicznie. Pomiary kwantowania przewodności wykonano w temperaturze pokojowej oraz pod ciśnieniem atmosferycznym. Analizę przewodności jednowymiarowych drutów przeprowadzono stosując teorię Landauera.(**Kwantowanie przewodności elektrycznej w stopach NbTi/Cu oraz w taśmach nadprzewodzących BiSrCaCuO/PbAg**)*

Abstract*. We present experimental results on the single – atom conductance in point contact at room temperature and in air. Quantum steps of NbTi/Cu – NbTi/Cu filament or BiSrCaCuO/PbAg–BiSrCaCuO/PbAg tapes were observed in nanocontacts formed dynamically. The striking features of these nanocontacts are presented in term of the Landauer theory.*

Słowa kluczowe: Kwantowanie przewodności elektrycznej, transport balistyczny, nanokontakt, materiały nadprzewodzące.
Key words: Single-atom conductance, ballistic electron transport, nanocontact, superconducting materials.

Introduction

The first microscopic model of electric conduction was proposed by P. Drude in 1900 and developed by H. A. Lorentz about 1909. This model successfully predicts Ohm's law and relates the resistivity of conductors to the mean speed v and the mean free path λ of the ideal electron gas within the conductor. However, when v (calculated from Maxwell-Boltzmann distribution) and λ are interpreted classically, there is a disagreement between the calculated and measured values of the resistivity, and a similar disagreement between the predicted and observed temperature dependence. Thus, the classical theory fails to adequately describe the resistivity of metals. Furthermore, the classical theory says nothing about the most striking property of solids, namely that some materials are conductors, others are insulators, and still others are semiconductors. When v and λ are interpreted using quantum theory, the magnitude and temperature dependence of the resistivity are correctly predicted. In addition, quantum theory allows us to determine if a material will be a conductor, insulator, or semiconductor. For the sake of completeness, it should also be mentioned that magnetic defects can cause a quite special kind of scattering in metals that results from spin interactions.

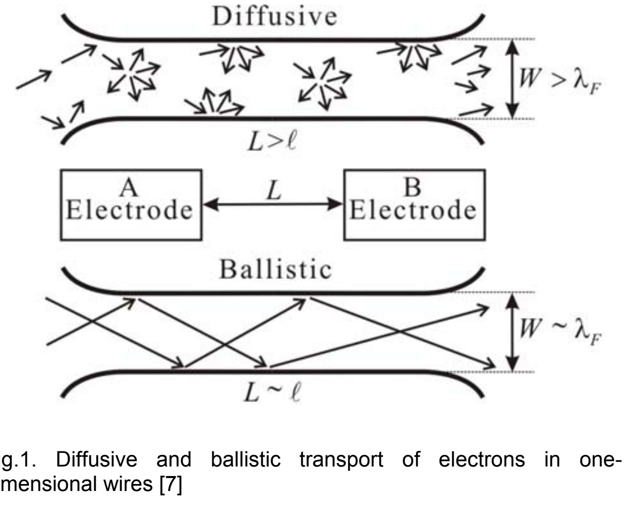

Fig.1. Diffusive and ballistic transport of electrons in one-dimensional wires [7]

Over two decades ago it was discovered [1, 2], that the conductance of a ballistic point contact is quantized in units of the conductance quantum, $G_o=2e^2/h = (12.9\ k\Omega)^{-1}$. The origin of this phenomenon is the quantization of transverse momentum in the constriction. Each of the n opened channels degenerates transverse modes at the Fermi energy E_F in such quantum point contact and contributes $2e^2/h$ to the conductance. The appearance of these interesting and potentially useful effects in practical devices is related to the size scale. With smaller devices the effect will be important at higher temperature. When the wire width is reduced to the nanometer size or the Fermi wavelength (λ_F) scale, the conductance between electrodes is quantized. Electronic transport changes from diffusive to ballistic, that is, without scattering, as shown schematically in figure 1. Quantum point contacts have been used in a wide variety of investigations [3-5], including transport through quantum dots, the quantum Hall effect, magnetic focusing and the Aharonov-Bohm effect [6].

Experiment

The experimental setup is presented in figure 2.

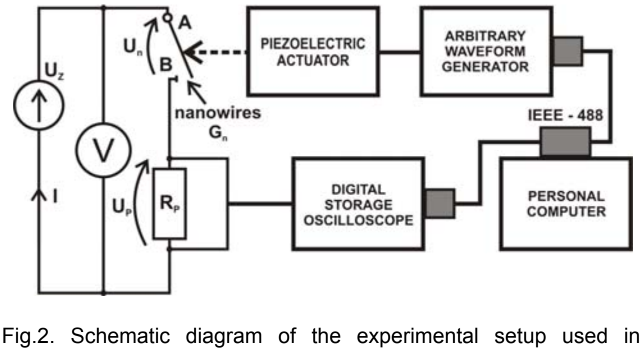

Fig.2. Schematic diagram of the experimental setup used in investigations of conductance quantization

Nanowires are formed between electrodes A and B of the studied materials. The experiments are performed at room temperature and in air.

We present experimental results on the conductance quantization of heterojunction between NbTi/Cu tip and a NbTi/Cu wires and also between BiSrCaCuO/PbAg tip and BiSrCaCuO/PbAg tapes. The conductance stepwise behavior of the nanowires was directly observed with a storage oscilloscope. Our data have been statistically analyzed by plotting histograms for more than three thousand conductance curves.

Results and discussion

In this work the histograms built using all consecutive curves at room temperature are presented for gold, copper, NbTi/Cu alloy and BiSrCaCuO/PbAg alloy. The conductance histogram for Au shows clear peaks (Fig. 4). The corresponding conductance traces clearly show the conductance quantization steps (Fig. 3).

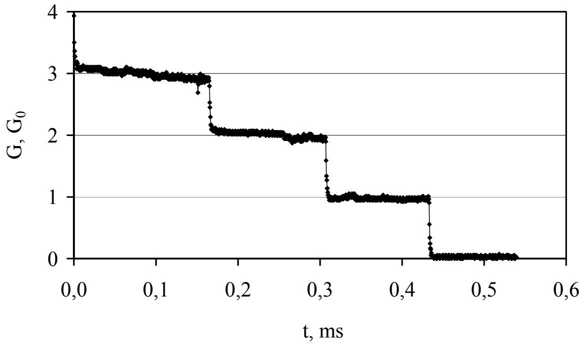

Fig.3. Conductance traces for a gold nanowire during elongation at room temperature and in air [8]

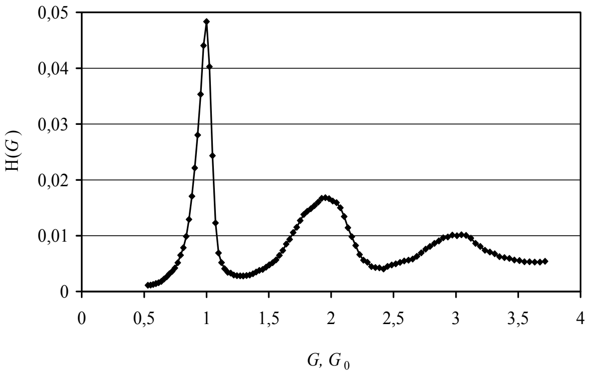

Fig.4. Conductance histogram for gold nanowires built from 5000 consecutive traces [8]

In figure 5 we can clearly see conductance steps, the last conductance step G_0 is very distinct.

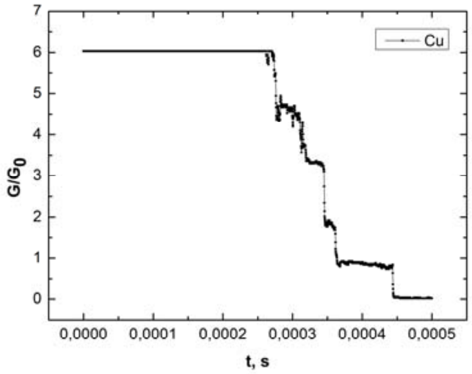

Fig. 5. Conductance traces for a copper nanowire during elongation at room temperature and in air

Little experimental and theoretical information is available about the conductance of alloy nanocontacts. Hansen et. al. [5] measured the conductance of Au-Co nanocontact and observed the same nG_0 peaks as those in pure Au. We measured the conductance of NbTi/Cu alloy nanocontact and compared the conductance histograms changes with pure Cu. Figures 6 and 8 show observed conductance histograms of Cu and NbTi/Cu nanocontacts, respectively. Histogram was constructed from 3000 conductance traces. The conductance histograms presented in figures 6 and 8 exhibit one well defined peak $1G_0$. A clear peak $1G_0$ is observed on all histograms for pure Cu and NbTi/Cu alloy. Conductance peaks nG_0 between $1,5G_0$ to $5G_0$ have a broad structure which is different as t

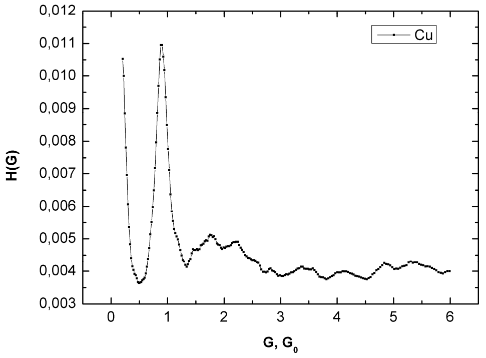

Fig.6. Conductance histogram for copper nanowires built from 3000 consecutive traces

For the NbTi/Cu wire (Fig. 7) visible conductance steps appears from $2G_0$ value, what means that ballistic transport of electrons is not possible for the very thick wires.

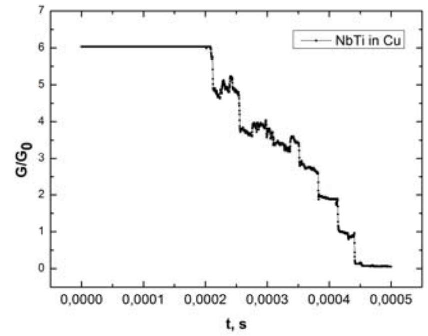

Fig.7. Conductance traces for a NbTi alloy in copper sheath nanowire during elongation at room temperature and in air

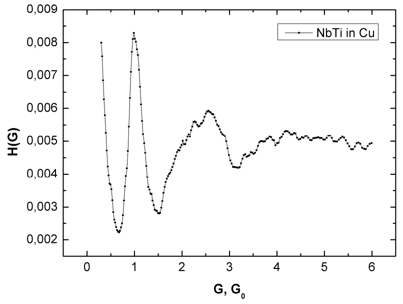

Fig.8. Conductance histogram for NbTi alloy in copper sheath nanowires built from 3000 consecutive traces

The conductance traces for BiSrCaCuO/PbAg alloy differ from those observed in figures 3, 5 and 7. There are not present wide plateaus in conductance curves (Fig. 9). It is shown on histogram (Fig. 10). Where only small peak for G_0 is visible. There are no other conductance channels during elongation and wire breaking process. It is probably related with physical properties of BiSrCaCuO/PbAg alloy. It is very fragile, brittle material which is not ductile, what prevents from forming thin nanowires. It may be also related with complex electronic structure of high temperature superconductors (BiSrCaCuO).

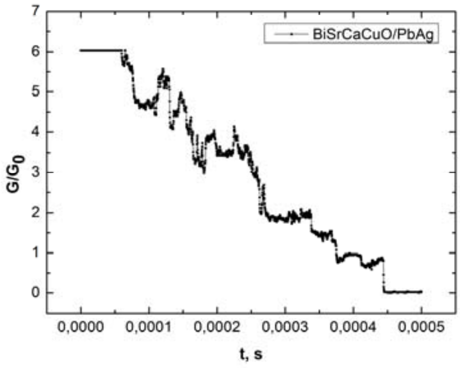

Fig.9. Conductance traces for a BiSrCaCuO/PbAg alloy nanowire during elongation at room temperature and in air

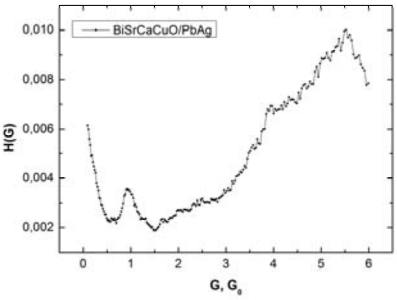

Fig.10. Conductance histogram for BiSrCaCuO/PbAg alloy nanowires built from 3000 consecutive traces

Summary

We have demonstrated striking features of atomic scale nanocontact formation dynamics. The conductance quantum or the single–atom conductance can be estimated based on the theory of Landauer [9]. Using an ideal free-electron metal model, Landauer showed that the conductance of a single tunneling channel at a zero tunneling gap is a universal constant $G_o=77.48\ \mu S$. Most experiments were conducted with gold [2, 10]. Very thin gold bridges down to a few atoms can be easily made. Gold is inert and malleable. Figure 3 shows a stepwise behavior with step sizes of the conductance quantum nG_o (where $n=1, 2, 3...$). Experiment on our samples showed slightly different values G_o. The typical histogram of NbTi, figure 8 exhibits two peaks at $G=1G_o$ and $G=2,5G_o$. Measurement on NbTi showed a typical step size of $2,5G_o$, because NbTi alloy is not typical free–electron metal.

We show that conductance quantization phenomena can be observed at room temperature in materials used commercially in superconducting magnets. The important is that this kind of behavior happens in all cases on small enough size scale, and this kind of striking features is not governed by diffusion. This means that the devices, whose operation is based on diffusion models, will work differently.

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