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Investigation of atomic-sized conductors with the mechanically controllable break junction technique

Summary of the Ph.D. thesis

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Introduction

In the recent decades the development of nanotechnology has opened the possibility of exploring the matter on a previously unaccessible length-scale. Since the invention of the scanning tunneling microscope (STM) the atomic structure of metallic surfaces can be studied, or the surface can be even modified with the STM tip. For instance, a nanowire can be pulled out of the sample if the tip is intentionally pushed into the surface and thereafter retracted back. This nanowire becomes narrower and narrower during its elongation, and before the complete break a single atom connects the two sides. The investigation of the conduction properties of such atomic-sized junctions has recently became an interesting topic of nanoscience.

A monoatomic junction can also be created during the break of a macroscopic metallic wire: in the final stage of the rupture usually a single atom forms the contact. This principle is applied in the mechanically controllable break junction (MCBJ) technique, where the sample wire is broken by bending a flexible beam on which the two sides of the sample wire are fixed. A single atom contact created with this technique can survive for several hours due to the special mechanical design. This method can be used to study the evolution of the conductance during the break of the nanojunction, or to investigate the conduction properties of a fixed contact as the function of bias voltage. As the junction is pulled the conductance shows step-like changes reflecting the atomic rearrangements in the contact. At atomic sizes the wavelength of the electrons is comparable to the contact diameter, so coherent quantum phenomena can also be observed in the conduction properties. Though the precise atomic structure of the contact remains unknown during the experiments, conductance measurements solely can tell a lot about the behavior of matter on atomic scale.

The objective of my Ph.D. work was to investigate the mechanical and electrical properties of atomic-sized metallic contacts. For this aim I have

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O. P. Balkashin, I. K. Yanson, A. Halbritter, and G. Mihály. *High frequency behavior of metallic glass Ni_xNb_{1-x} point contacts.*
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G. Mihály, A. Halbritter, L. Mihály, and L. Forró. *Search for magnetic field induced gap in a high-T_c superconductor.*
Solid State Commun., **116**, 197 (2000).

A. Halbritter, A. Yu. Kolesnychenko, G. Mihály, O. I. Shklyarevskii, and H. van Kempen. *Transport properties and point contact spectra of Ni_xNb_{1-x} metallic glasses.*
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Further publications:

J. Balogh, L. F. Kiss, A. Halbritter, I. Kézsmárki, and G. Mihály. *Giant magnetoresistance at the interface of iron thin films.*
Solid State Commun., **122**, 59 (2002).

J. Balogh, I. Vincze, D. Kaptás, T. Kemény, T. Pusztai, L. F. Kiss, E. Szilágyi, Z. Zolnai, I. Kézsmárki, A. Halbritter, and G. Mihály. *Interface magnetoresistance of Fe/Ag multilayers.*
Physica Status Solidi A, **183**, 621 (2002).

G. Mihály, A. Halbritter, L. Mihály, and L. Forró. *Crossovers in the out-of-plane resistivity of superconducting $Tl_2Ba_2CaCu_2O_8$ single crystals.*
Europhysics Letters, **52**, 584 (2000).

List of publications

Publications related to my Ph.D. work:

A. Halbritter, Sz. Csonka, G. Mihály, E. Jurdik, O. Yu. Kolesnychenko, O. I. Shklyarevskii, S. Speller, and H. van Kempen. *Transition from tunneling to direct contact in tungsten nanojunctions.*
Phys. Rev. B, submitted (2003).

Sz. Csonka, A. Halbritter, G. Mihály, E. Jurdik, O. I. Shklyarevskii, S. Speller, and H. van Kempen *Fractional conductance in hydrogen-embedded gold nanowires.*
Phys. Rev. Lett., **90**, 116803 (2003).

A. Halbritter, Sz. Csonka, O. Yu. Kolesnychenko, G. Mihály, O. I. Shklyarevskii, and H. van Kempen. *Connective neck evolution and conductance steps in "hot" point-contacts.*
Phys. Rev. B, **65**, 45413 (2002).

L. Borda, A. Halbritter, and A. Zawadowski. *Slow two-level systems in metallic point contacts.*
Advances in Physics, submitted (2003), cond-mat/0107590

O. P. Balkashin, I. K. Yanson, A. Halbritter, and G. Mihály. *Point-contact spectroscopy of the relaxation dynamics of two-level systems upon structural changes in NiNb metallic glasses.*
Low Temperature Physics, **29**, 123 (2003).

O. P. Balkashin, I. K. Yanson, A. Halbritter, and G. Mihály. *Microwave second-harmonic generation and point-contact spectroscopy of Ni-Nb metal-*

built a point-contact measurement system applying the MCBJ technique. The thesis presents the design of a new MCBJ sample holder, and the measurements performed by the setup. The experimental studies are divided into four parts. First the special mechanical behavior of tungsten nanocontacts is studied. The next part investigates the dynamical motion of atoms in locally overheated lead and aluminum nanojunctions. The third group of measurements examines the origin of nonlinear conductance in various sample material. Finally, the last part reports about the hydrogen assisted distortion of gold nanowires. The major scientific results of my Ph.D. work are summarized in five items as follows.

New scientific results

1. I have built a point contact measurement system in the low-temperature solid state physics laboratory of the Budapest University of Technology and Economics. This work included the planning of a point-contact sample holder and the arrangement of the instrumental environment required for the various types of point contact experiments. A mechanical stability of 0.02 Å/hour was achieved as demonstrated by quantum tunneling measurements. The setup is applied in a wide range of experiments, including the measurement of conductance traces and conductance histograms, and the investigation of nonlinear features in the $I-V$ characteristics. Furthermore, utilizing the high stability of the device I have developed a new method to detect quantum interference effects in nanocontacts, which is based on the modulation of the length of the interference paths.

2. I have shown that the evolution of conductance during the break of tungsten nanojunctions essentially differs from the usual behavior of metallic contacts. In the metals studied so far the conductance traces

always showed a similar pattern including a jump-like transition from direct contact to tunneling. In contrast, I found that tungsten junctions exhibit various types of conductance traces, which frequently show a smooth transition to tunneling. This unique property of tungsten can be attributed to the extremely large elastic modulus of the material. Due to the occasional absence of the adhesive jump I could continuously monitor the decay of the conductance channels during the disconnection of the electrodes. I have found that the conductance traces frequently show plateaus around 1 and $2\,\mathrm{G}_0$, which is explained by the sequential closing of conductance channels due to their different spatial distribution. The plateau at $2\,\mathrm{G}_0$ is attributed to the conductance of a monoatomic contact, while the plateau at $1\,\mathrm{G}_0$ might be interpreted by the conductance through a long-protruding surface state.

3. I have studied the influence of local Joule heating on the behavior of nanojunctions. I have shown that at elevated bias voltage the conductance traces exhibit a strong deviation from the standard low-bias behavior. During the approach of the electrodes the conductance curves saturate showing strong fluctuations around a constant level. These observations are attributed to a feedback effect due to the enhanced surface diffusion and electromigration of atoms in the hot junction. I have found that in atomic-sized junctions the thermal excitation of the contact leads to repeated jumps between metastable atomic configurations.

4. I have studied the origin of non-linear features in the conductance of atomic-sized junctions. The measurement of $\partial G/\partial z$ curves as a function of bias voltage has shown that quantum interference has a strong influence on the slope of the conductance plateaus in gold junctions. I have also investigated the voltage dependence of the bare transmission in Au, Al, Pt, W, and Ni junctions. This study has shown that in the transition metal contacts the voltage dependence of the bare transmission gives a significant contribution to the nonlinearity of the $I-V$ curve, while in gold and aluminum junctions this feature is not resolved beside the quantum interference phenomenon.

5. I have studied the influence of adsorbed hydrogen on the conductance of gold nanowires. The hydrogen environment has a strong effect on atomic-sized gold junctions, which is markedly reflected by the growth of a new peak in the conductance histogram at the half of the quantum conductance unit, $\mathrm{G}_0 = 2e^2/h$. This new peak is attributed to the repeated establishment of a special atomic configuration during the break, which arises from the interaction of the gold nanoconstriction with hydrogen. Analyzing the plateau length histograms I have shown that the new peak in the histogram is related to an atomic gold chain which is distorted due to the adsorption of hydrogen.