B. SUSŁA[1], M. WAWRZYNIAK[2], J. BARNAŚ[3,4], W. NAWROCKI[2]

[1]Poznań University of Technology, Institute of Physics, Poland, e-mail: Susla@phys.put.poznan.pl
[2]Poznań University of Technology, Institute of Electronics and Telecommunications, Poland
[3]Adam Mickiewicz University, Department of Physics, 61-614 Poznań, Poland
[4]Polish Academy of Sciences, Institute of Molecular Physics, 60-179 Poznań, Poland

CONDUCTANCE QUANTIZATION IN FERROMAGNETIC CO NANOWIRES

Room temperature electronic transport properties of ferromagnetic quantum wires have not been yet fully understood, and the role of electronic structure of magnetic atoms in the conductance quantization is still under discussion. We present experimental results on conductance quantization in point contacts between ferromagnetic (Co) or nonmagnetic (Au) wires and semiconductor (Ge) samples. The main features of the conductance histograms are consistent with the conductance quantization in the units of quantum conductance G_0 for the nonmagnetic wires and nG_0 for the ferromagnetic Co nanowires. Such behavior of the conductance of ferromagnetic wires is a consequence of the complex electronic structure of magnetic *3d* transition-metal atoms. A description of the quantization phenomena is presented in terms of the Landauer formalism.

Keywords: quantized conductance, magnetic nanowires, ballistic electron transport, quantum point contacts

1. INTRODUCTION

Crystalline nanostructures, such as magnetic nanowires, offer unique access to low dimension condensed-matter physics. Quantum wires could also be an alternative to carbon nanotubes as nanotechnology building blocks to reach device integration densities higher than in conventional fabrication methods. Rapid development of the nanostructure fabrication techniques in the past few years has made it possible to produce low-dimensional quantum wires of very high structural quality. Nanowires have been very attractive as promising candidates for the next generation electronic and photonic devices because of low power consumption. Understanding electron conduction through magnetic (Co, Ni) and semiconductor nanowires connecting two macroscopic electrodes is particularly attractive from the point of view of the fundamental physical properties of such structures as well as from the point of view of potential applications in spintronic devices.

Quantum conductance measurements for metallic nanocontacts display flat plateaus and abrupt drops during their elongation, even at room temperature, which can be attributed to atomic rearrangements. In noble metals (Ag, Au) and alkali metals (Li, Na) the last conductance step before wire breaking, most likely corresponding to a monoatomic nanocontact, has the value of G_0 [1] ($G_0 = 2e^2/h$ is the conductance quantum per double spin), which can be associated with the free propagation of valence s-electrons in two quantum channels (one per each spin orientation). For magnetic transitions metals such as Co and Ni the experimental data are less consistent. Oshima *et al*., [2] found the conductance steps in Ni nanocontacts preferentially near G_0 and $2G_0$ at room temperature (RT) and zero magnetic field, near $2G_0$ at 770K and zero field , and near $1.5G_0$ (occasionally near $0.5G_0$) at RT in a magnetic field. Ono *et al.* [3] reported again G_0 for Ni at zero field and $0.5G_0$ for Ni in a field. Recently Rodrigues *et al.* [4] observed one conductance quantum in a Co atomic chain at RT and zero fields. Untiedt *et al.* [5] obtained low temperature zero-field data for several magnetic (Fe, Co and Ni) and nonmagnetic (Pt) quantum wires, and reported a dominance of the conductance steps between G_0 and $1.5G_0$ in Co and Ni.

In this paper we investigate the conductance of atomic-sized contacts in air and at room temperature, formed between magnetic (Co) or nonmagnetic (Au) metals and semiconductor (Ge) samples. We present clear evidence of conductance quantization in ferromagnetic Co nanowires. Electronic transport properties of the metallic nanowires were measured with an oscilloscope, using the quantum point contact configuration.

2. ELECTRONIC CONDUCTION IN METALS

The electric current density j in a solid is given by the constitutive equation

$$j = g\,E, \tag{1}$$

where E is the electric field and g is the electrical conductivity of the solid. The corresponding electrical resistivity ρ is defined via the relation

$$E = \rho j, \tag{2}$$

and is related to the conductivity, $\rho = 1/g$.

The first attempt to explain the metallic conductivity was made by Drude in 1900, only three years after the discovery of the electron. Drude assumed that the metal is composed of atoms which are stationary and valence electrons which are free to move and form an ideal electron gas. On this assumption, the electrical conductivity g is given by the formula (known as the Drude formula)

$$g = \frac{ne^2\tau}{m}, \tag{3}$$

where m is the free electron mass, e is the electron charge, n is the electron concentration, and τ is the average time (mean lifetime or relaxation time) between electron collisions with impurities, electrons and other defects or quasiparticles. The relevant formula for the resistivity ρ is

$$\rho = \frac{m}{ne^2}\tau^{-1}. \tag{4}$$

From Eq. (3) once can conclude that the electrical conductivity depends on temperature mainly via different scattering processes which enter into the relaxation time τ. In a typical metal there are three dominant scattering processes; scattering by impurities, by electron – electron collisions, and by electron–phonon interactions. These are independent processes, so one should add the corresponding partial scattering rates in order to obtain the total effective scattering rate (Mathiessen rule).

The Drude model of electrical conduction is consistent with Ohm's law. However, there are many other features of electronic transport in metallic systems which cannot be accounted for using such a simple description. For instance, scattering by surface and/or interface roughness needs another quasi-classical approach. Apart from this, some of transport features need quantum-mechanical approaches. Typical examples of such features are weak localization due to enhanced back scattering and Kondo anomaly due to scattering on magnetic impurities.

Although the nature of quantum-mechanical approaches is very different from that of the Drude description, there are some noticeable similarities and many concepts developed in the classical model – such as mean free path λ, mobility and drift velocity – are also relevant in quantum models. However, values of these parameters in quantum models can be quite different from the classical ones. For example, electrical conductivity g and mobility μ are formally equivalent to those of the Drude model. The relaxation time τ, which was not exactly specified in the Drude model, is that for electrons at the Fermi level. The effective mass m^* replaces the free electron mass m. The total concentration of electrons in the conductance band appears in both models. This similarity explains why the Drude model yields satisfactory results in many situations.

3. CONDUCTANCE QUANTIZATION OF A ONE - DIMENSIONAL METAL

Electronic conductance of a macroscopic wire is inversely proportional to its length L. When the wire dimensions scale down, so the wire length becomes smaller than the phase coherence length l_φ, the macroscopic description is no longer applicable and Ohm's low breaks down (this is the so-called mesoscopic regime). Electronic transport changes then from diffusive to quasi-ballistic or ballistic, as shown schematically in Fig.1.

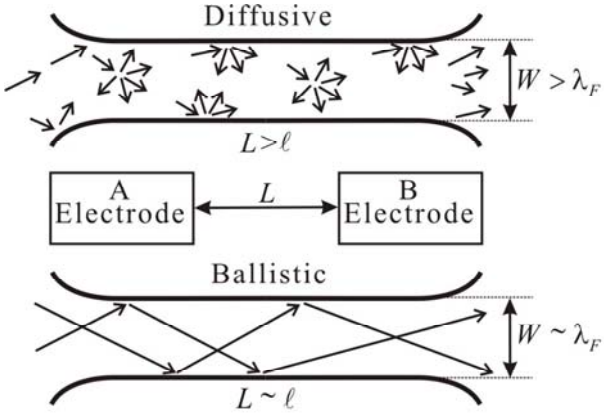

Fig. 1. Diffusive (a) and ballistic (b) electron transport in a one-dimensional wire.

When the wire width is reduced to the nanometer size or to the Fermi wavelength scale, the conductance between electrodes connected by the nanowires is quantized in steps, with the values close to nG_0, where n is an integer and $G_0 = 2e^2/h = 1/12.9\ \mathrm{k\Omega}$ ($7.75\ 10^{-5} S$) is the conductance quantum. Moreover, the conductance is no longer dependent on the length of the wire. Using the Landauer formula [6], the conductance G can be expressed as

$$G = \frac{e^2}{h}\left(\sum_{i=1}^{N_\uparrow} T_{i\uparrow} + \sum_{i=1}^{N_\downarrow} T_{i\downarrow}\right), \tag{5}$$

where the sums run over all $N_\uparrow$ and $N_\downarrow$ occupied conductance channels (subbands) for up and down spin orientations, respectively, and $T_{i\uparrow}$ and $T_{i\downarrow}$ are the corresponding electron transmission probabilities. The Fermi wavelength λ_F in metals is of the order of 0.5 nm, and the level separation is ~ 1eV, which means that conductance quantization can be observed at room temperature if W and L are smaller than the electron mean free path l ~ 10nm.
For diamagnetic nanovires the quantum channels are spin degenerate and $T_{i\uparrow} = T_{i\downarrow} = T_i$. Equation (5) then becomes

$$G = \frac{2e^2}{h}\sum_{i=1}^{N} T_i\ . \tag{6}$$

This function has a staircase behavior but the height of the quantum conductance step is $2e^2/hT_i$ instead of $2e^2/h$.

The quantum channels arise from quantization of the momentum p_x and p_y of the electron waves confined in the wire when the constriction width W is sufficiently small (see Fig. 1). Assuming a simple quantum wire based on a two-dimensional electron gas only quantization of one, say p_x, is relevant. The momentum p_x is then given by $hn/2W$ for integer values of n. The largest value of n defines the number of conduction channels N. This number depends on the wire width and is determined by the condition that the maximum value of p_x cannot exceed h/λ_F.

Of course, only electrons with energy in the window E_f to $E_f + eV$ can contribute to the conduction current, where E_f is the Fermi energy and V is the applied bias voltage. Assuming ballistic transport ($T_i = 1$), and taking into account the spin degeneracy of quantum channels in nonmagnetic wires, one finds the conductance $G_0 = 2e^2/h$ for each conducting channel. Thus, the conductance decreases stepwise as the nanowire width becomes smaller and smaller. It is worth noting that according to the classical Drude theory the conductance of a macroscopic wire depends on the wire length, its cross-section area, and type of the material. For ballistic transport, however, the conductance depends only on the wire's width.

The conductance quantization has been discussed theoretically more rigorously for simple atomic nanowires. However, the transmission properties of nanoconstrictions with electron–electron interactions, spin dependent electronic structure, and magnetic domain walls taken into account are still not fully described and understood, and are of current interest [8].

4. EXPERIMENT

The electrical conductance of a Co ferromagnetic or nonmagnetic Au nanowire at the break-junction between Co or Au wire and a Ge sample was measured by using the mechanically controllable break-junction technique. The experiments are performed at room temperature and in air.

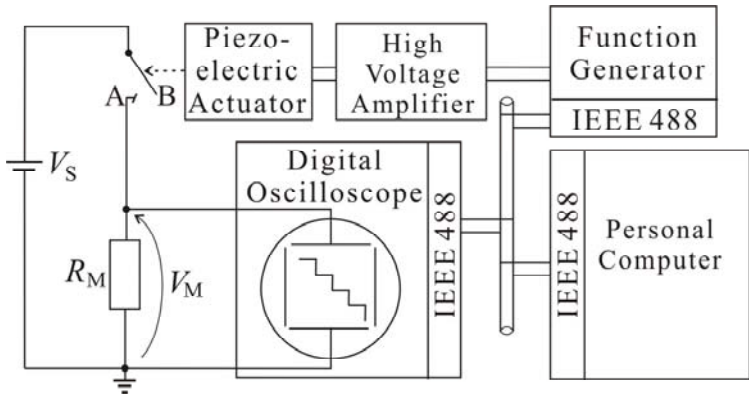

Fig. 2 Schematic diagram of the experimental setup.

The experimental setup for break-junction measurements is presented in Fig. 2. The nanowires are formed between magnetic or nonmagnetic metallic tips and a semiconductor Ge sample: A (a sample) and B (a tip). The function generator (Hewlett Packard 33120A) is used to control the movement of the piezoelectric actuator head on which the B tip is mounted. A voltage source V_S supplies a bias voltage to the nanowire. A resistor R_M is used to convert the resulting current I into a voltage signal V_M, which is measured by a digital storage oscilloscope (LeCroy 9310 CM). A digital oscilloscope is set to trigger when the nanowire breaks, and the voltage trace is transferred to the PC using an IEEE-488 interface bus and stored for later analysis. An electronic circuit for measuring the conductance of a nanowire allowed the observation of the time-dependent process and precise registration of the elongation velocity of the nanowire in a wide range.

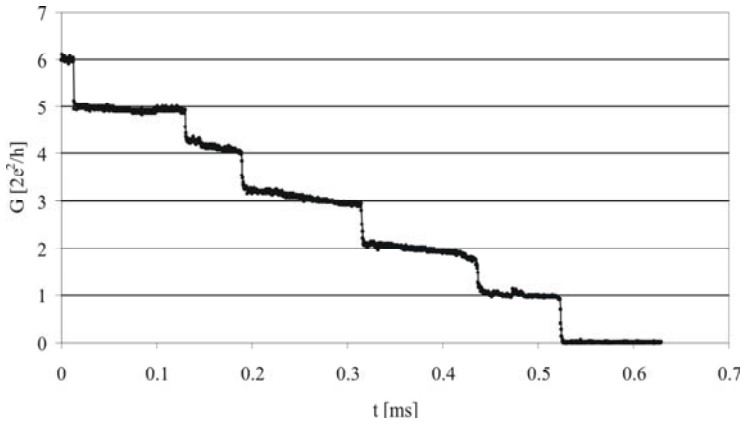

Fig. 3. Conductance traces for a gold nanowire during elongation at room temperature and in air for the electrode separation speed of 160 nm/s. The applied potential difference between the separating electrodes is 400 mV.

Similar experiments for a diamagnetic Au tip and Au sample as well as for a Co tip and Co sample have also been performed for comparison reasons.

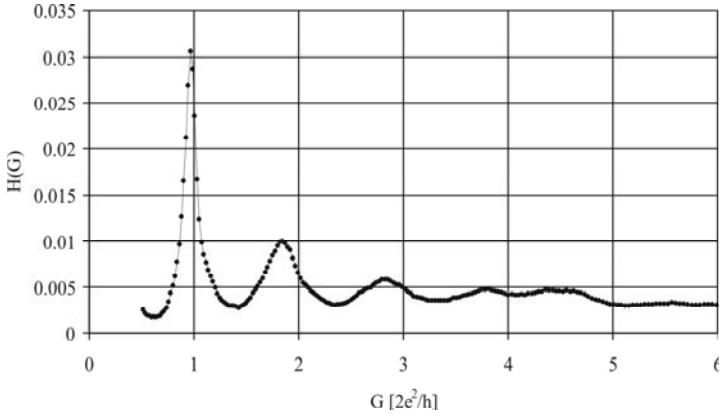

Fig. 4. Conductance histogram for gold nanowires built with 5000 consecutive traces.

5. RESULTS AND DISCUSSION

In this work the histograms built using all consecutive conductance curves at room temperature are presented for gold and cobalt nanowires and Ge samples. The conductance histogram for Au at room temperature and in air shows clear peaks (see Fig. 4). The corresponding conductance traces clearly show the conductance quantization steps (Fig. 3).

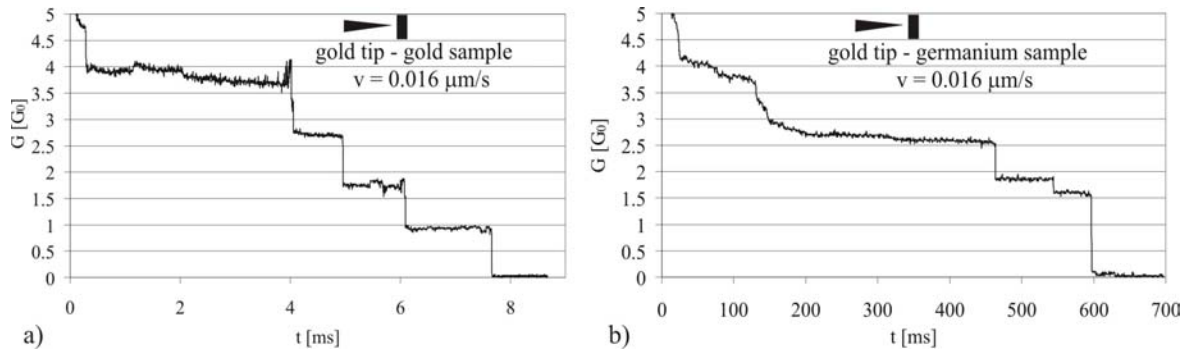

Fig. 5. Conductance traces for gold nanowires during elongation with an electrode separation speed v = 0.016 μm/s. Nanowires formed between: a gold tip and a gold surface (a) and a gold tip and a germanium surface (b).

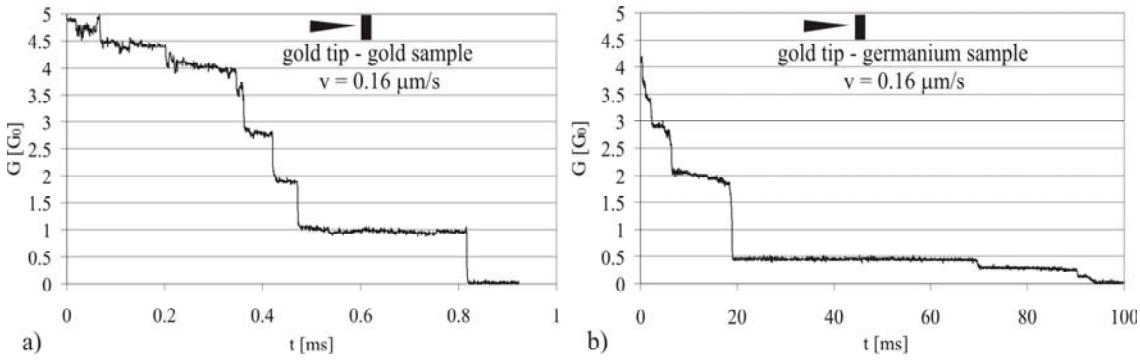

Fig. 6. Conductance traces for gold nanowires during elongation with an electrode separation speed v = 0.16 μm/s. Nanowires formed between: a gold tip and a gold surface (a) and a gold tip and a germanium surface (b).

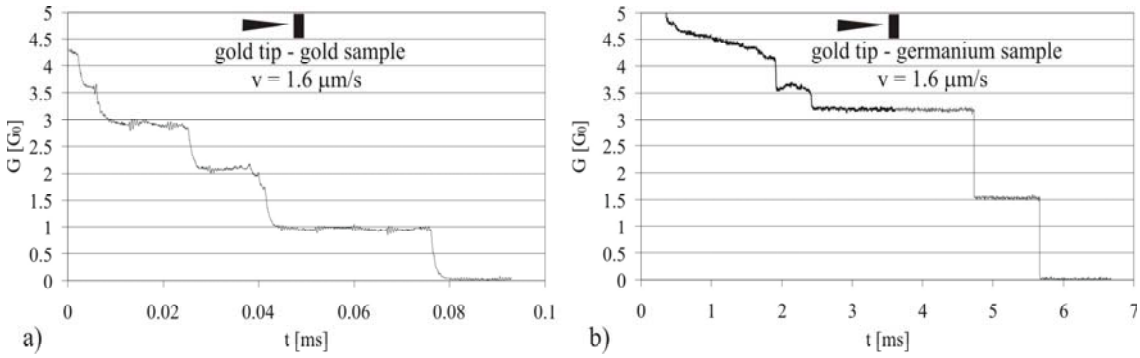

Fig. 7. Conductance traces for gold nanowires during elongation with an electrode separation speed v = 1.6 μm/s. Nanowires formed between: a gold tip and a gold surface (a) and a gold tip and a germanium surface (b).

Figures 5 (a, b), 6 (a, b) and 7 (a, b) present conductance curves for Au-Au and Au-Ge with different separation speed during the nanowire elongation. As can be seen in these figures, the conductance plateaus are different for the same electrode separation speed. The time scale of these plateaus for Au–Ge it is two orders of magnitude longer than that for Au–Au. This is due to the fact that hardness of Ge is much higher than that of Au and the gold wire during the electrode separation is elongated. The gold nanowire for the gold tip–Ge sample is a few atomic diameters wide. If the quantum point contacts with atomic necks are relatively large, the scattering of electrons may become important in the transport process and the conductivity plateaus often occur for nG_0 with n deviating from an integer.

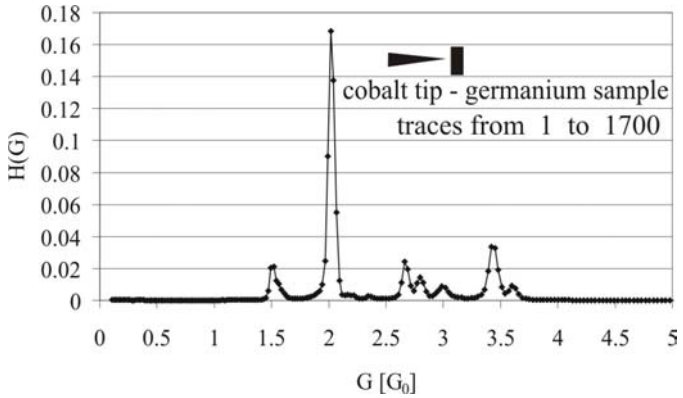

Fig. 8. Conductance histogram for cobalt nanowires built with traces from 1 to 1700. Nanowires formed between: a cobalt tip and a germanium surface at RT in air.

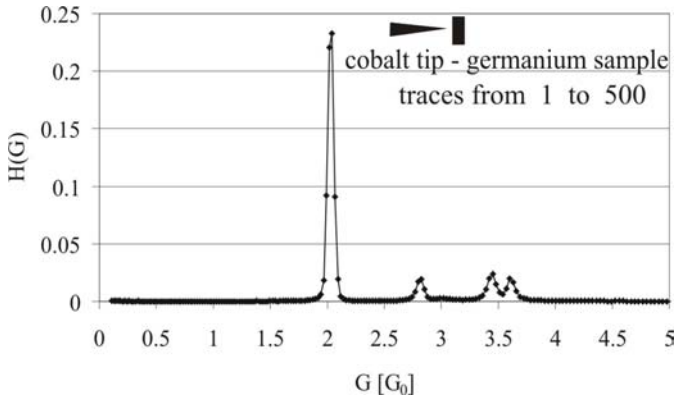

Fig. 9. Conductance histogram for cobalt nanowires built with traces from 1 to 500. Nanowires formed between: a cobalt tip and a germanium surface at RT in air.

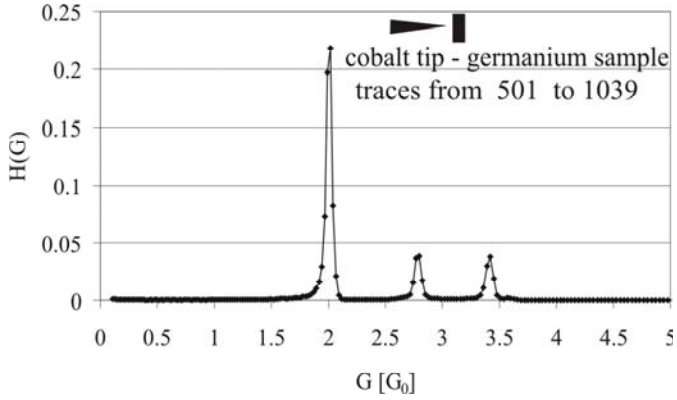

Fig. 10. Conductance histogram for cobalt nanowires built with traces from 501 to 1039. Nanowires formed between: a cobalt tip and a germanium surface at RT in air.

We find interesting electronic conductance properties of junctions formed at the contact between the Co wire and Ge sample. The corresponding conductance histogram shown in Fig. 8 is built of a series of 1700 time dependent processes. The conductance histograms presented in Fig. 9 and Fig. 10 for a magnetic nanowire are built with traces from 1 to 500 and 501 to 1039, respectively. The histograms exhibit one well-defined peak at approximately $2G_0$ and also peaks corresponding to the conductance plateaus at nG_0 ($1.51G_0$, $2.66G_0$, and $3.45G_0$). The quantization of the conductance is not merely a statistical fluctuation but it appears as an average phenomenon and can be considered as an intrinsic feature of the magnetic nanowire and semiconductor sample.

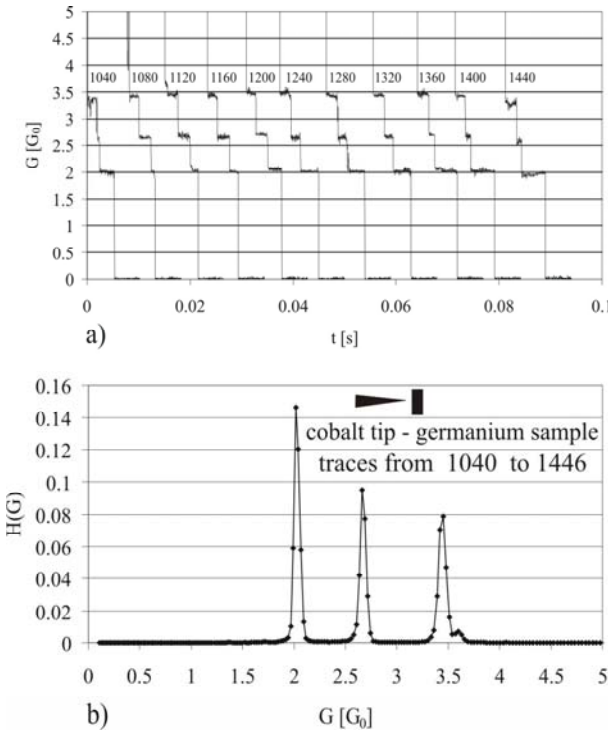

Fig. 11. a) Conductance traces from 1040 to 1440 with step 40. b) Conductance histogram for cobalt nanowires built with traces from 1040 to 1446. Nanowires formed between: a cobalt tip and a germanium surface at RT in air.

Measurements performed at room temperature in air, showing the conductance plateaus and global histogram exhibiting the statistical conductance for Co tip, are given in Fig. 11. Note that the lowest plateau in (a) and the lowest peak in (b) are located at $2.01G_0$, which corresponds to the thinnest Co wire. Such behavior of the conductance is a consequence of the complex electronic structure of ferromagnetic Co metal.

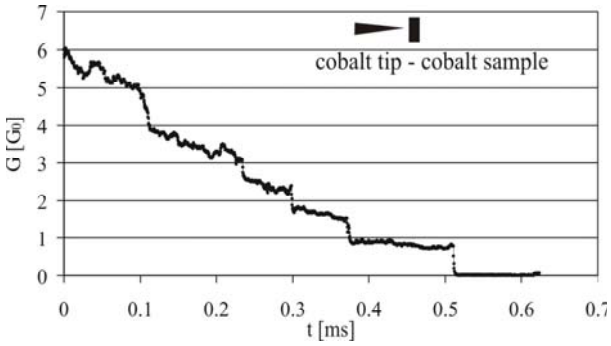

Fig. 12. Conductance traces for a cobalt nanowire during elongation at RT in air. The applied potential difference between the separating electrodes is 400 mV.

Finally we would like to mention that conductance curves in Co-Co nanowires at room temperature show staircase-quantized behavior (Fig. 12), but the histogram (Fig. 13) does not show the quantized peaks, most probably due the lifting of the spin degeneracy [4, 7].

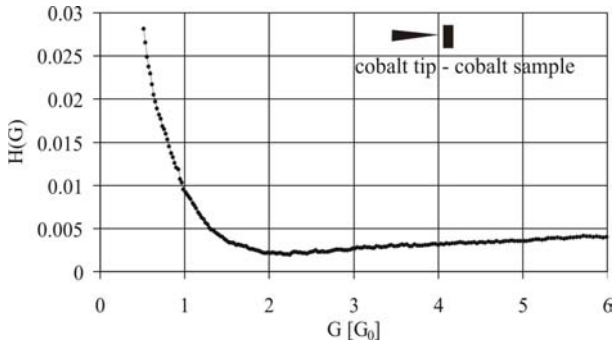

Fig. 13. Conductance histogram for cobalt nanowires built with 5000 consecutive traces.

6. SUMMARY

Our data have been statistically analyzed by plotting histograms for more than thousand measured conductance values. Figures 11a and 11b show typical features of the conductance measured in the units of G_0, and the measurements clearly demonstrate that the room-temperature conductance of Co-Ge break-junctions is quantized with the corresponding conductance plateaus at nG$_0$ ($2.01G_0$, $2.66G_0$ and $3.45G_0$). Such behavior of the conductance is a consequence of the complex electronic structure of magnetic 3d transition-metal atoms. These results create new opportunities for a deeper understanding of the spin dependent electronic structure of the ferromagnetic quantum wires and may have important implications for the development of future spintronic devices based on magnetoresistance phenomena in ferromagnetic quantum wires and point contacts.

This work is partly supported by PB 62-208/06.

REFERENCES

1. Brandbyge M., Schiotz J., Sorensen M. R., Stoltze P., Jacobsen K. W., Norskov K., Olesen L., Laegsgaard E., Stensgaard I., Besenbacher F.: *Quantized conductance in atom-sized wires between two metals*, Phys. Rev. B, 1995, vol. 52, pp. 8499-8514.
2. Oshoma H., Miyano K.: *Spin-dependent conductance quantization in nickel point contacts*, Appl. Phys. Lett., 1998, vol. 73, pp. 2203-2205.
3. Ono T., Ooka Yu., Miyajima H.: *$2e^2/h$ to e^2/h switching of quantum conductance associated with a change in nanoscale ferromagnetic domain structure*, Appl. Phys. Lett., 1999, vol. 75, pp. 1622-1624.
4. Rodrigues V., Bettini J., Silva P. C., Ugrate D.: *Evidence for Spontaneous Spin-Polarized Transport in Magnetic Nanowires*, Phys. Rev. Lett., 2003, vol. 91, pp. 96801-96801.
5. Untiedt C., Dekker D. M. T., Djukic D., van Ruitenbeek J. M.: *Absence of magnetically induced fractional quantization in atomic contacts*, Phys. Rev. B, 2004, vol. 69**,** pp. 81401-81404.
6. Landauer R.: *Spatial variation of currents and fields due to localized scatterers in metallic conduction*, IBM J. Rev. Dev., 1957, vol. 1, pp. 223-232 and vol. 44, 2000, pp. 251-259.
7. Costa - Cramer J. L.: *Conductance quantization at room temperature in magnetic and nonmagnetic metallic nanowires*, Phys. Rev. B, 1997, vol. 55, pp. R4875 – R4878.
8. Dugaev V. K., Berakdar J., Barnas J.: *Tunable conductance of magnetic nanowires with structured domain walls*, Phys. Rev. Lett. 94, 47208 (2006); Araujo M.A.N., Dugaev V.K, Vieira V.R., Berakdar J., Barnas J., *The role of electron correlations in transport through domain walls in magnetic nanowires*, cond-mat/0602399.

KWANTOWANIE PRZEWODNOŚCI W NANODRUTACH Z KOBALTU

Streszczenie

W pracy opisano kwantowanie przewodności elektrycznej w nanostrukturach typu magnetyczny kobalt (Co) lub niemagnetyczne ostrze Au oraz półprzewodnikowa (Ge) próbka. Balistyczny transport elektronów występujący w kwantowych magnetycznych drutach nie jest w pełni wyjaśniony a rola struktury elektronowej ferromagnetycznych

metali $3d^n$ w kwantowaniu przewodności elektrycznej jest aktualnie przedmiotem dyskusji. Właściwości badanego przewodnictwa w nanozłączach z elektrodą magnetyczną są konsekwencją złożonej struktury pasmowej i gęstości stanów elektronowych metali przejściowych, a tym samym właściwości funkcji falowych elektronów przewodnictwa oraz ich właściwości spinowych. Dlatego dla nanodrutów magnetycznych przewodność przybiera wartości mniejsze od pojedynczego kwantu G_0 jak również zarejestrowano wartości nG_0 znajdującymi się pomiędzy kolejnymi schodkami. Analizę przewodności jednowymiarowych drutów połączonych dwoma elektrodami przeprowadzono stosując teorię Landauera z uwzględnieniem jednoelektronowego tunelowania elektronów o zmiennym współczynniku transmisji.