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Conductance quantization in magnetic and nonmagnetic metallic nanowires

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Transport properties of ferromagnetic quantum wires at room temperature are not 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 the conductance quantization in point contacts between ferromagnetic (Co) or nonmagnetic (Au) wires and semiconductor (Ge) samples. The main features of the conductance histograms for the nonmagnetic wires are consistent with the conductance quantization in the units of quantum conductance $G_0 = 2e^2/h$. For the ferromagnetic Co nanowires, the conductance shows plateaus at nG_0, generally with non-integer n. Such behaviour 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 for the current flowing through a small nanoconstriction.

Key words: *quantized conductance, magnetic nanowire, ballistic transport, quantum point contact*

1. Introduction

Crystalline nanostructures, such as magnetic nanowires, offer unique access to low dimensional condensed-matter physics. Because of the low power consumption, nanowires are very attractive and promising candidates for the next generation electronic and photonic devices. 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.

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Since 1988, when the conductance quantization was measured in a two-dimensional electron gas quantum point contact [1, 2], charge transport has been the object of revived scientific interest. In 1993, electrical conductance quantization was found in gold nanowires made with the scanning tunnelling microscope technique at room temperatures [3] as well as at low temperatures [4]. Further studies showed that nanowires could form also in less sophisticated setups; for instance between two vibrating wires [5], or between relay contacts [6]. However, fabrication of stable nanowires of the width comparable with the corresponding Fermi wavelength turned out to be a very difficult task [7–9].

In noble (Ag, Au) and alkali (Li, Na) metals, the last conductance step before wire breaking, most likely corresponding to a monoatomic nanocontact, corresponds to the conductance quantum (per double spin) $G_0 = 2e^2/h$, which can be associated with free propagation of the valence s electrons in two quantum channels (one per each spin orientation). For magnetic transition metals such as Co and Ni, the experimental data are less consistent. Oshima et al. [10] found the conductance steps in Ni nanocontacts near G_0 and $2G_0$ at room temperatures and zero magnetic field, near $2G_0$ at 770K and zero field, and near $1.5G_0$ (occasionally near $0.5G_0$) at room temperatures in a magnetic field. Ono et al. [11] reported again G_0 for Ni at zero field and $0.5G_0$ for Ni in a field. Recently Rodrigues et al. [12] observed one conductance quantum in a Co atomic chain at room temperature and zero magnetic field. Apart from this, Untiedt et al. [13] 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.

Although the conductance quantization has been analyzed theoretically within more or less rigorous methods, some features of the electronic transport through point contacts are not well understood yet. For instance, the influence of electron–electron interactions, spin dependent electronic structure of the materials forming the nanocontacts, and magnetic domain walls at the constrictions is still unexplored and is of current interest [14–17].

In this paper, we report on the investigation of the conductance of atomic sized contacts in air and at room temperature which are formed between magnetic (Co) or nonmagnetic (Au) metals and a semiconductor (Ge) samples. We present a clear evidence of the conductance quantization in ferromagnetic Co nanowires.

2. Experimental

Figure 1 shows a schematic diagram of the experimental setup used for measurements of the conductance quantization. The nanowires are formed between the electrodes A and B of the studied material. Measured during the electrode separation, i.e., during the nanowire stretching, the electrical conductance G corresponds to the conductance of the nanowire under investigation. The digital storage oscilloscope, used for signal sampling and recording, must be triggered at a right moment for the measurements to cover the process of stretching and breaking of the last remaining nanowire. The arbitrary waveform generator is used to control movement of the A electrode. The digital storage oscilloscope and arbitrary waveform generator is controlled by a PC through the IEEE-488 interface.

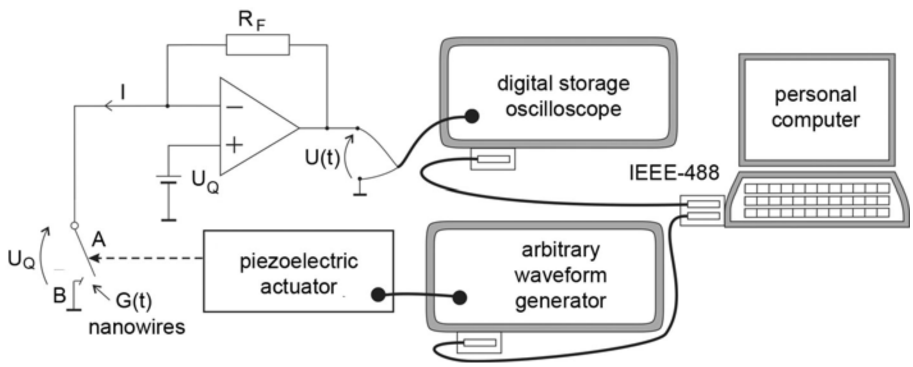

Fig. 1. Schematic diagram of the experimental setup

With an appropriate measurement software, a required number of the conductance curves can be obtained to provide the basis for building the conductance histograms. The nanowire current *I* is converted into voltage by an operational amplifier in the current amplifier circuit.

3. Results and discussion

The conductance histograms were built up using all consecutive conductance curves at room temperature. In all cases, the individual conductance traces clearly showed more or less pronounced conductance plateaus. In the case of Au–Ge and Co–Ge brake junctions, the corresponding conductance histograms obtained at room temperature and in air showed clear peaks corresponding to the conductance steps. We found no clear peaks in the conductance histograms of Co–Co nanocontacts.

Figure 2 shows one of the individual conductance traces for Au, and clearly demonstrates the conductance quantization, $G = nG_0$ with n roughly integer ($n = 1, 2, 3$). This behaviour corresponds to an almost ideal case of ballistic (scattering-free) electron transport through a nanowire with spin degenerate s-like transport channels. If, however, electron scattering occurs in the nanowire, the conductance steps may occur at lower positions (non-integer n). Therefore, the conductance histograms [1, 6] are built up from a large number of conductance traces. Our data have been statistically analyzed by plotting histograms for more than thousand measured conductance values Such a histogram for Au nanowires is shown in Fig. 3. The positions of peaks (local maxima) in the histogram provide information on the quantization phenomena. In the case of Au, these maxima occur exactly at nG_0 with integer n.

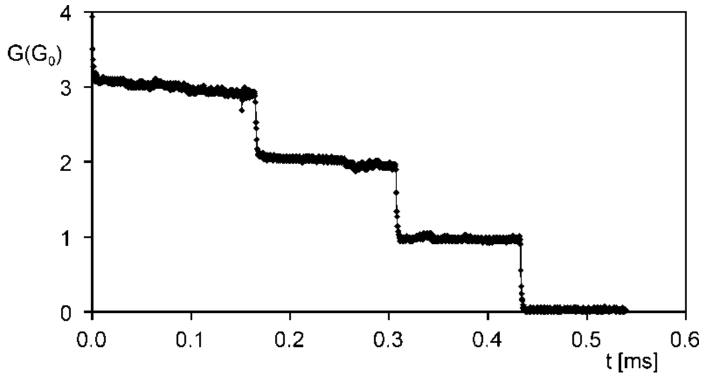

Fig. 2. Electrical conductance in an Au nanowire during elongation

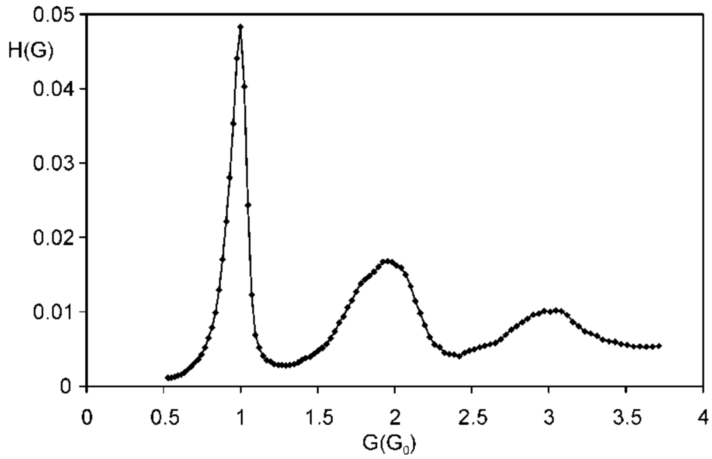

Fig. 3. Conductance histograms for gold nanowires built from 6000 curves

The situation in nanocontacts involving one or two magnetic transition metals becomes much more complex. The conductance then depends on the exact atomic and crystallographic structure of the apexes on both sides of a nanocontact, as well as on the exact electronic structure of the whole nanocontact. Moreover, even assuming the nanocontact is of single-atomic size, one still can have more transport channels as both 4s and 3d electrons can contribute to transport (2s and 7d electrons in Co). All this makes the available experimental data for Co nanowires inconsistent which additionally indicates that the Co nanocontacts in different experiments have different atomic as well as crystallographic structure. To get a qualitative interpretation of the experimental results one would need to investigate the exact atomic structures of the point contacts (including also the effects of contamination, oxidation, etc.) which is not an easy task. Then, a quantitative interpretation could be reached by ab-initio numerical calculations.

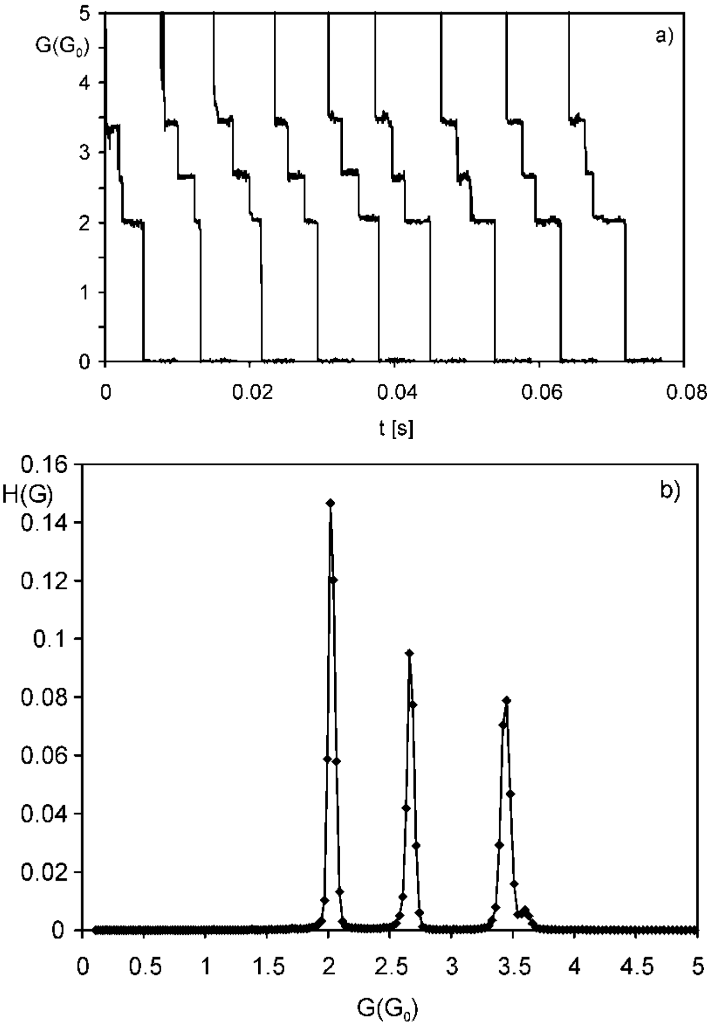

Fig. 4. Room-temperature conductance of Co nanowires and a Ge sample:
a) typical electronic transport curves showing the conductance plateaus, b) global histogram exhibiting the statistical conductance for Co. Note that the lowest plateau in (a) and the lowest -conductance peak in (b) are located at $2.01G_0$, which corresponds to the thinnest Co wire

In our case we found the conductance plateaus at $G = 2.01G_0$, $G = 2.66G_0$, and $G = 3.45G_0$ in the room-temperature conductance traces of the Co–Ge break-junctions. The corresponding experimental data are shown in Fig. 4a. The relevant conductance histogram also has pronounced peaks at these conductance values, as shown in Fig.4b. We found no signature of the $0.5G_0$ conductance plateau, observed by others [10, 11]. The lowest plateau in our case occurs at $2.1G_0$ which may indicate that either the corresponding apex is not of one-atomic shape or the atomic structure of the apex is such that it allows contribution from both s and d electrons. One may expect that s electrons would contribute to plateaus at nG_0 with roughly integer n, whereas d electrons may give contributions differing from that corresponding to perfect transmission as the d electrons of Co atoms must couple to Ge atoms which have different electronic structure. In turn, the higher conductance plateaus, $G = 2.66G_0$ and $G = 3.45G_0$, may indicate the role of d electrons and the presence of spin polarized conductance channels. However, as we have already mentioned above, a detailed investigation of the apex structure and stability would be necessary for a unique interpretation of the quantization plateaus.

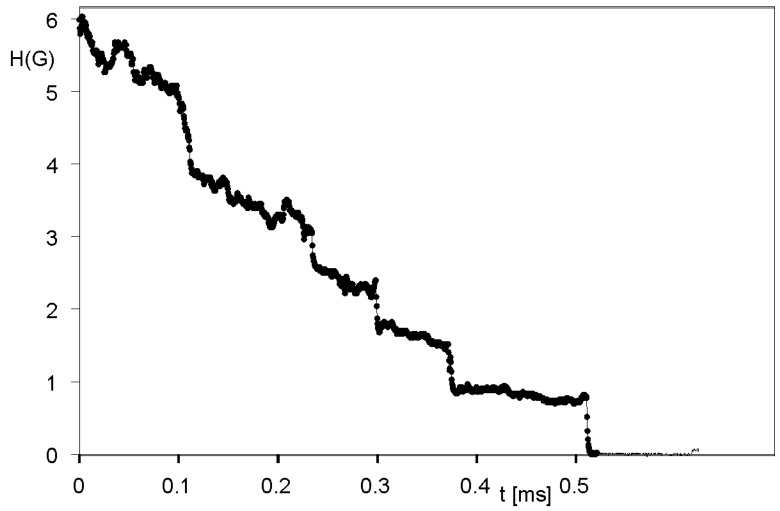

Fig. 5. Conductance traces for a cobalt nanowire during elongation at RT in air

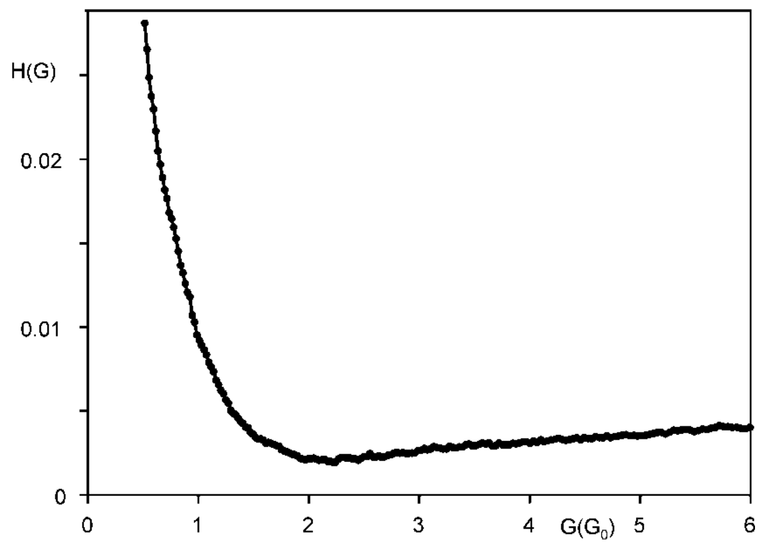

Fig. 6. Conductance histogram for cobalt nanowires built with 5000 consecutive traces

Finally, we would like to mention that the obtained conductance curves in Co–Co nanojunctions at room temperature show conductance quantization plateaus, as presented in Fig. 5, but the corresponding conductance histogram (Fig. 6) does not show clear quantized peaks. In Figure 5, the first plateau occurs roughly at G_0, most likely originating from s-like (spin degenerate) channel. The next plateau occurs roughly at $1.5G_0$ and may originate from the above mentioned s channel and one (spin polarized) d channel. Stretching the wire may then break bounds via the d states and remove the contribution from the d channel. The origin of the absence of distinct peaks in the conductance histogram is not clear. A reason for this may be a strong variation of the apexes' shape in consecutive runs. The difference in conductance traces and conductance histograms for Co–Ge and Co–Co point contacts also indicates that the apex shape strongly depends on the materials and atomic bonds in the nanocontacts.

4. Summary

We have investigated conductance quantization in Au–Ge, Co–Ge and Co–Co nanocontacts. The corresponding conductance traces clearly show the conductance quantization in all investigated nanocontacts. The data have been statistically analyzed by plotting histograms built from a large number of conductance curves. Our measurements show that the lowest conductance plateau in the room-temperature conductance of the Co–Ge break-junctions occurs at $2.1G_0$. We found no signature of the conductance plateau at $0.5G_0$. The higher conductance plateaus indicate the role of spin polarized d channels. However, to interpret properly the results, both qualitatively and quantitatively, a detailed information on the atomic structure of the nanocontacts and their electronic properties would be necessary. The results create new opportunities for a deeper understanding of the spin dependent electronic structure and electronic transport in ferromagnetic quantum wires.

Acknowledgements

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