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Conductance Quantization in the Melt-Spun Cubic RCu_5 (R = Gd, Ho, Lu) Nanowires

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Conductance quantization of heterocontacts between tungsten (W) tip and cubic RCu_5 (R = Gd, Ho, Lu) binary compounds prepared by melt-spinning was observed in nanowires produced dynamically using piezoelectric actuator. The conductance stepwise behaviour of the nanowires was directly observed with a storage oscilloscope. Quantum units of the nanowires conductance measured in their paramagnetic states are presented and discussed in terms of the Landauer formalism.

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1. Introduction

The interest in experimental data on physical properties, in particular the electron transport, of the intermetallic compounds of the RCu_5 (R = heavy rare earth) series with cubic unit cell stems from the fact that their different magnetic behaviour depending on the R element could influence resistance dependence as a function of temperature or external magnetic field. Up to the present only very few experimental data on the transport properties of this series of compounds have been available. The light RCu_5 compounds (La, Ce, Pr, Nd, Sm, Eu) crystallize in the simple hexagonal structure, while the heavy rare earth (Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) compounds exhibit the hexagonal β $CaCu_5$-type structure ($P6/mmm$ space group) or regular α $AuBe_5$-type structure ($F43m$ space group) [1]. These cubic structures are metastable and at the temperatures over 700°C transform into more stable hexagonal phases.

The electrical conductance of nanowire in quantum point contact (QPC) is quantized in units of $G_0 = 2e^2/h$ [2]. The conductance quantization phenomena are usually presented in terms of the Landauer formalism. Using the Landauer formula, the conductance G of nanowire is given by

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

where $T_{i\uparrow}$ and $T_{i\downarrow}$ are the transmittance for the i-th channel for the up-spin and the j-th channel for the down-spin, respectively, and the sums run over occupied states. For diamagnetic nanowires $T_{i\uparrow} = T_{i\downarrow}$ and then Eq. (1) can be expressed as

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

In this paper we show that conductance quantization phenomena can be observed at room temperature (RT) in RCu_5 materials in their paramagnetic state and the results are compared with the data obtained for Cu sample (without rare-earth elements).

2. Experimental

All RCu_5 samples used for measurements were prepared by arc-melting of high purity elements and subsequent melt-spinning. Melt-spun cubic phase samples in the form of ribbons were obtained in an inert atmosphere by rapid solidification of the starting ingots on the rotating copper wheel surface. The crystalline structure of the ribbons was examined by X-ray diffraction (XRD) using Co K_α radiation. Before electric measurements, the surfaces of the samples studied were cleaned by grinding. Next, the surface regions with most suitable cleanliness were selected for conductance tests.

The scheme of the experimental setup used for measurements of the conductance quantization is presented in Fig. 1 [3]. Nanowires of the materials investigated are formed between the surface of the sample (electrode B) and the tip of the tungsten probe (electrode A). In or-

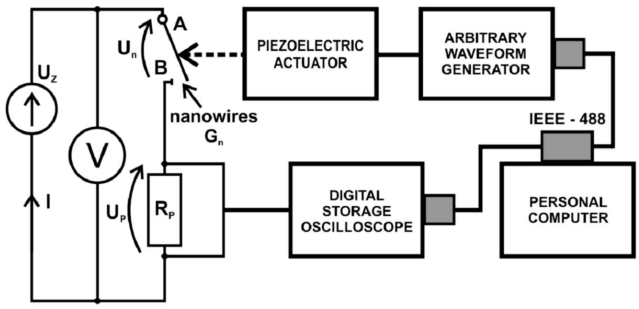

Fig. 1. Schematic diagram of the experimental setup.

der to form a nanowire, a triangular control signal is applied to the actuator. The tip moves towards the sample surface and eventually crashes against it. Next, the tip moves in the opposite direction, i.e. away from the sample surface. It is in the first phase of this tip retracting that nanowires are formed. As tungsten is much harder than the sample investigated, the sample's surface regions involved in the collision will be drawn by the retracting tungsten tip. The position of electrode A is moved with a piezoelectric actuator which is controlled by the arbitrary wave-form generator with a triangular wave. The position of electrode B is fixed. The digital storage oscilloscope is triggered at a right moment for the measurements to record the process of stretching and breaking of the last remaining nanowire. Personal computer controls the digital storage oscilloscope and the arbitrary wave-form generator through the IEEE-488 interface. The experiments are carried out at RT in air. The potential difference between the separated electrodes is 400 mV. Conductance histograms are obtained on the basis of a large number of the conductance traces with correction of the differential nonlinearity error of the analog-to-digital converter.

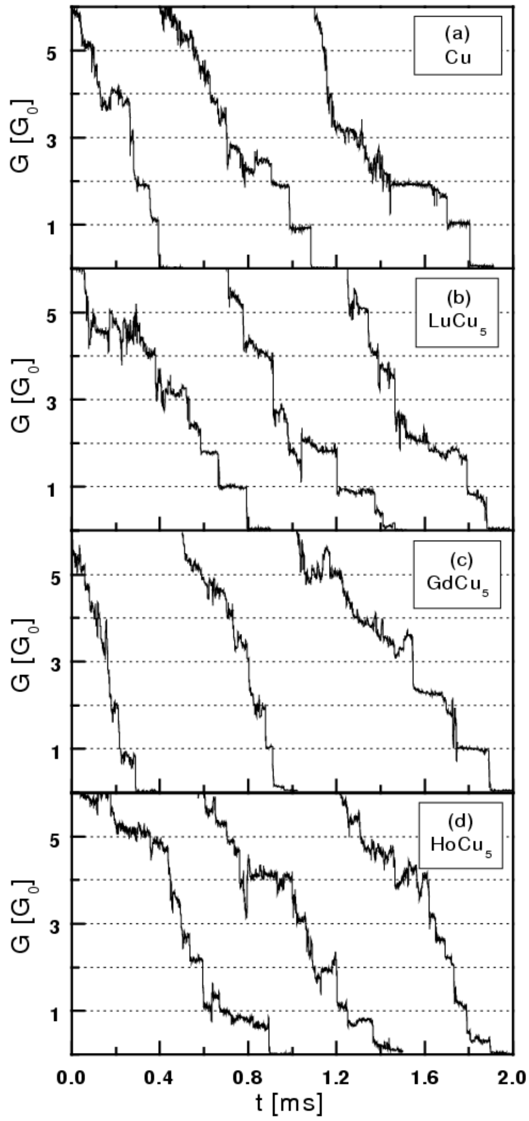

Fig. 2. Conductance traces for Cu (a), $LuCu_5$ (b), $GdCu_5$ (c) and $HoCu_5$ (d) nanowires. The applied potential difference between the separating electrodes is 400 mV.

3. Results and discussion

Figure 2 shows conductance traces for Cu, $LuCu_5$, $GdCu_5$ and $HoCu_5$ nanowires in which the stepped behavior of the conductance is quite apparent.

The conductance histograms shown in Fig. 3 are made on the basis of 2600 conductance curves recorded for every sample. Conductance peaks provide the information on the conductance quantization phenomena. The values of the conductance maxima for $LuCu_5$, $GdCu_5$ and $HoCu_5$ are much higher than those recorded for the Cu nanowire (Fig. 3a), whose maximum of the first peak occurs at $0.99G_0$. For the other nanowires the situation is more complicated. For the nanowires of $LuCu_5$, $GdCu_5$ and $HoCu_5$ we found the first conductance peaks at nG_0 with no integer n (Fig. 3b–d) at $0.92G_0$, $0.92G_0$ and $0.9G_0$, respectively. The shift towards lower conductance values G of the peaks depends on cleanliness of the system, and the latter seems to be correlated with the residual resistance [4]. Rare-earth ions can be recognized as impurities in the Cu matrix (both crystallographic structures are cubic). In the Cu nanowire the residual resistance is quite low (about 180 Ω) whereas for $LuCu_5$, $GdCu_5$ and $HoCu_5$ this parameter is equal to the 1060 Ω, 1060 Ω and 1390 Ω, respectively.

The transport properties in the intermetallic systems considered are determined by $4s{-}6s$ electron channels ($4s$ Cu electrons and $6s$ from R atoms). The possible indirect role of $5d$ or $4f$ electrons from the rare earth atoms inducing small polarization of conduction band or local crystal field perturbation in deformed nanowires is believed to be negligible because a similar transport characteristics have been observed for systems with unfilled f-shell (Gd, Ho) and for Lu, whose f-shell is completely

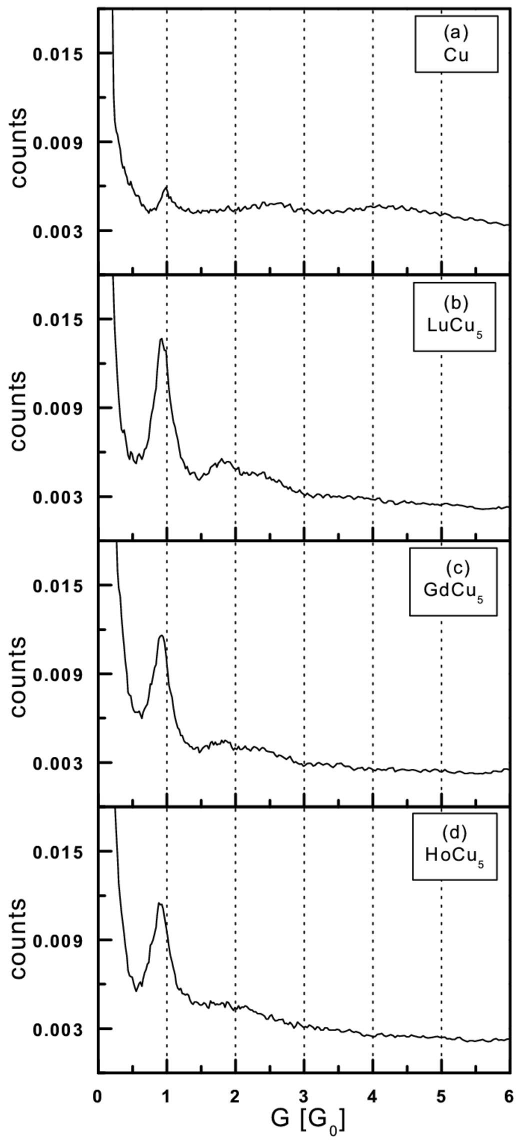

Fig. 3. Conductance histograms made on the basis of 2600 conductance traces for Cu nanowire (a) and LuCu$_5$ (b), GdCu$_5$ (c), HoCu$_5$ (d) nanowires.

filled. The process of nanowire formation described suggests that the necking is highly non-uniform along the longitudinal direction especially in the regime close to the breaking point of the nanowire, where there are only a few atoms in the cross-section. If the change in the width of the nanowire is considerable on the scale of Fermi wavelength, the simple picture of propagation along the parallel direction (specified by $k_{||}$) and formation of discrete states along perpendicular direction is not valid any more. The states of different $k_{||}$ become also mixed. This mixing certainly increases if there are atoms of different types in the cross-section. One can expect the enhancement of backscattering in this case, which would suppresses the transmission and result in the observed shift of conductance quantization steps. The earlier mentioned significant differences in the residual resistances suggest however that the impurities play the dominant role in backscattering in the investigated R–Cu nanowires. In the conductance histograms a remarkable higher intensity around a quantum of conductance is observed for nanowires with R atoms than for pure copper. One of the reasons might be higher hardness on breaking of the former wires, leading to the population of the single channel RCu$_5$ nanowires larger than that of copper wires. This suggestion requires however a separate examination. Of importance for the transport phenomena in the regime, just before the contact breaks, might be also locally introduced larger extension of s states by R atoms, which helps preserve the transmission path–nanowire–tungsten tip.

4. Conclusion

We have investigated conductance quantization in Cu, GdCu$_5$, HoCu$_5$ and LuCu$_5$ nanowires. Conductance histograms made of 2600 conductance traces clearly show the conductance quantization for all samples. The conductance peaks at nG_0 with non-integer n are connected with the presence of the large in diameter ions in the system. It is not necessary to take into account paramagnetic state of the rare-earth elements (Gd and Ho) used.

Acknowledgments

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