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High magnetic field dependence of the edge and bulk state electron transport in single-crystalline tungsten nanostructures

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Abstract. Electron conductivity of single crystalline nanostructures both of bridge- and cross-type has been investigated at 4.2 K. It shows strong dependence in magnetic field and also exhibits anisotropy against magnetic field direction. It was found new reentrance effect in ballistic properties of multi-terminal cross-type nanostructure, where ballistic properties are suppressed in moderate magnetic field and restored again at higher field.

Introduction

In magnetic field, one should consider both skipping orbits (edge states) and spiral orbits(bulk states) electron transport in solid state nanostructures. Electron interactions with surface scatters depend also on magnetic field direction against the current and the film surface. Developing of fabrication of single-crystalline planar nanostructures with large bulk mean free path, that capable of ballistic electron transport, open an opportunity to investigate new geometric effects in magnetoresistance. Here we present the results of investigation of single-crystalline tungsten nanostructures in high magnetic field, which is parallel to the sample surface (in-plane B-field), but may be along or perpendicular to the current. Multi-terminal and geometrical effects are also investigated.

1. Experimental results and consideration

Single-crystalline (001) tungsten planar nanostructures were fabricated on r-plane sapphire. Film thickness was of $d = 170$ nm, 290 and 340 nm, the width of the bridge was of $W = 7d$ and the length of $L = 2W$. Cross-type nanostructure arms were of $7d$ width. Magnetoresistance of the samples has been measured at 4.2 K by four terminal method, applying conventional AC lock-in system.

1.1. Magnetoresistance of the bridge

As found, magnetoresistance shows giant effect at B-field to be perpendicular to the current, resistance increasing mostly 10 times (Fig. 1., 1p-3p). It goes through the inflection point near $d/r_L = 0.3{-}0.5$ from quasi-linear to linear dependence and has a tendency to quadratic dependence at d/r_L coming to 2. For B-field being parallel to the current it goes through the maximum at near $d/r_L = 0.3{-}0.5$ and then decreases more than 5 times at $d/r_L = 2$ (Fig. 1, 1a-3a). When B-field is perpendicular to the current angular dependence of resistance is weak in all B-field range. When it is along the current it may show strong effect at B-declination within few degrees (Fig. 2). However, angular dependence at d smaller than $0.5r_L$ is weak, but may come stronger at higher magnetic field. Sharp anisotropy of the bridge resistance at high magnetic field is presented in the inserting in

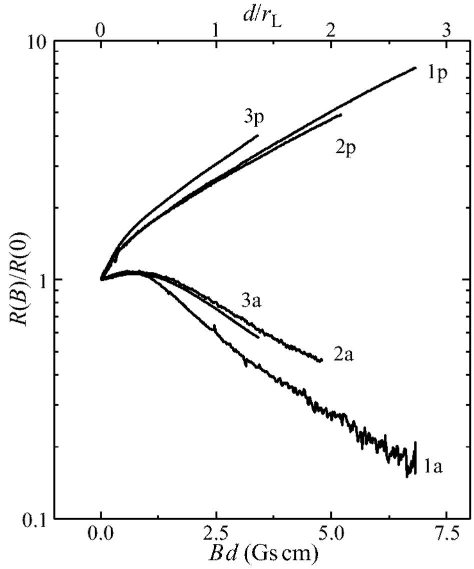

Fig. 1. Experimental data for bridge-type structures. B-field is perpendicular (1p-3p) or parallel to the current (1a-3a), thickness $d = 340$ nm (1), 290 (2) and 170 (3), respectively, r_L is cyclotron radios.

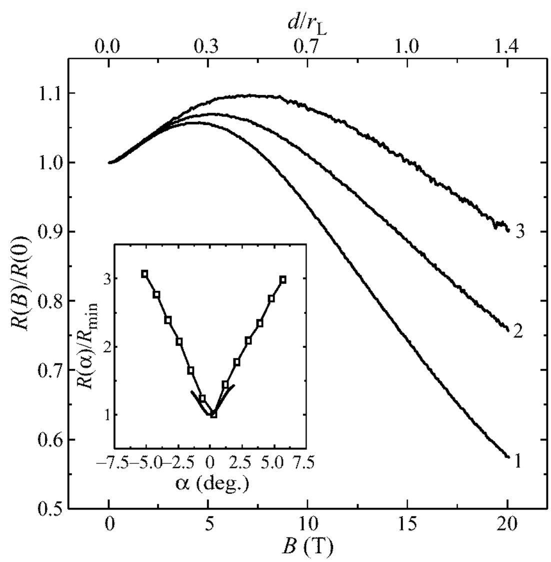

Fig. 2. Magnetoresistance data for the bridge with $d = 170$ nm. 1—B-field is along the current, 2—$\Delta\alpha = 1.43°$, 3—$\Delta\alpha = 2.25°$, where α is angle between the surface normal and the B-field direction. Rotation axis of the sample is perpendicular to the surface normal and the current. In the inserting an angular dependence of $R(B)/R(0)$ for the bridge with $d = 290$ nm (squares, $B = 16.5$ T) and $d = 170$ nm (solid line, $B = 20$ T) is shown.

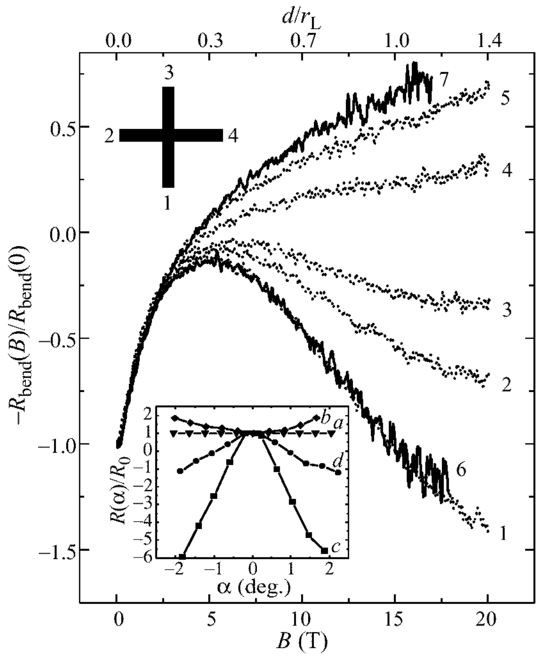

Fig. 3. Bend resistance (U4,3/I1,2) of the cross versus the B-field, $d = 170$ nm, $\Delta\alpha = 0°$ (1), 0.82 (2), 1.23 (3), 1.85 (4), 2.25 (5). For comparison, the data for the B-field being along the other cross arms are presented, $\Delta\alpha = 0°$ (6), 2.25 (7). In the inserting (bottom), angular dependence of $R_{\text{bend}}(\alpha)/R_{\text{bend}}(0)$ is shown for $B = 2$ (a), 5 (b), 10 (c) and 20 T (d). Inserting in the top is the cross-scheme with leads numbers.

Fig. 2. Declination of the B-field from the direction of the current causes transformation of $R(B)$ (1-3 in Fig. 2) from 3a to 3p type as in Fig. 1. It may be explained by an interplay between skipping orbits (edge states) and spiral orbits (bulk states) transport, controlled by magnetic field, as well as by spiral orbit scattering on the interfaces. More pronounce effect of the B-field is found for spiral orbits at high magnetic field, where magnetic focusing may suppress electron surface scattering. Estimation of electron bulk mean free path gives tens of microns for the investigated bridge-type structures.

1.2. Magnetoresistance of the cross

Geometrical and multi-terminal effects have been investigated for the cross-type nanostructures. At low magnetic field (d/r_L lower than 0.3) the bend resistance is negative, as a consequence of ballistic properties of the cross-type nanostructure, for all angles of B-declinations. At the B-field come stronger the bend resistance increases with its absolute value approaching zero. For the d/r_L more than 0.3–0.5 it may cross zero or goes down at higher field depending on declination angles (Fig. 3). Ballistic properties of the cross are restored at high field, the bend resistance coming to be negative again. At low magnetic field, angular dependence is weak (see also inserting in Fig. 3). Due to symmetry of the cross magnetoresistance shows mostly the same dependence upon the B-field at its direction being both along one pair of the arms and the other ones (compare 1 and 6 or 5 and 7 in Fig. 3).

Conclusion

Cross-over from low field to higher field range changes the skipping orbit (edge state) transport to the spiral orbit (bulk state) one. As a consequence, it leads to giant effect in magnetoresistance in bridge-type nanostructures both upon magnetic field and its angle declination in the case when B-field is parallel to the current. New reentrance effect in ballistic properties of multi-terminal cross-type nanostructures has been found, where ballistic properties of the structure are depressed at moderate B-field and restored again at its higher magnitude.

Acknowledgements

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