Abstract

Four-point electronic transport measurements have proven to be the best choice for determining the resistance of a sample and thus the resistivity properties, because the contact resistances are negligibly small. Various techniques using the 4-point method have been explored, whereby the 4-probe scanning tunneling microscope is a powerful experimental tool to measure the sample resistance on small length scales including the possibility to vary probe spacings.

Nowadays, layered materials are in the focus of interest due to their intriguing fundamental properties and their high potential in a variety of applications. In addition, they are also possible parenting materials for so-called 2D materials due to a typically weaker chemical bonding along one crystalline axis. Beside the famous parent-materials such as graphite, hexagonal boron nitride, and transition metal dichalcogenides, there is a further class of layered materials, namely the so-called MAX phases comprising both metal as well as ceramic properties. This unique combination stems from a complex, anisotropic bonding scheme that leads to an anisotropic conductivity. Growing those layered materials as thin-film samples, they comprise usually a bonding anisotropy perpendicular to the surface. Thus, an anisotropy between the in-plane and out-of-plane conductivities is expected. Such anisotropic electronic transport properties are characterized by introducing the resistivity as a second rank tensor. The resistivity is then expressed by a symmetry-dependent number of independent components that can be determined from resistance measurements along different directions of the sample. The in-plane resistivity components can be easily characterized using several well-known methods, while up to now the out-of-plane resistivity cannot be determined without any additional sample treatment or modification, if a material can only be prepared in thin-film form.

Therefore, a novel direct and parameter-free method is developed in this thesis for the accurate determination of the out-of-plane resistivity without any further treatment of the sample. A multi-probe scanning tunneling microscope is used to carry out 4-probe transport measurements with variable probe spacings. The observation of the crossover from the 3D electronic transport regime for small spacings between the probes to the 2D regime for large spacings enables the determination of both in-plane and perpendicular-to-plane resistivities. After working out the analytical description of the method, the experimental procedures for measuring electronic transport properties with a multi-probe scanning tunneling microscope are described, in particular the influences of sample size and shape, surface morphology and grain size, probe-sample contact size and as well as the main experimental error sources.

Using this method, a first direct and parameter-free measurement of anisotropic electrical resistivity of a magnetic $(Cr_{0.5}Mn_{0.5})_2GaC$ MAX phase film is presented. The observation of the crossover between the 3D and 2D transport case enables the simultaneous determination of in-plane and out-of-plane resistivities from a single sample and yields a large anisotropy. The out-of-plane resistivity exceeds the in-plane resistivity by a factor of about 500, which is a consequence of the complex bonding scheme of MAX phases. The determined resistivity ratio gives a better and quantitative insight into the interplay of crystalline structure, bonding structure, and electronic transport.

Additionally, $(Cr_{2/3}Ho_{1/3})_2AlC$ crystallites, which belong the i-MAX phases with in-plane chemical ordering, are investigated. The results give clear evidence for both out-of-plane and in-plane anisotropic resistivity. The in-plane anisotropy is a consequence of the chemical ordering of the transition and rare-earth atoms. The weaker out-of-plane anisotropy compared to conventional

MAX phases corroborates predictions of less anisotropic band structures for i-MAX phases. These measurements represent the first characterization of anisotropic resistivity in an i-MAX phase and furthermore give proof-of-principle for the determination of the entire resistivity tensor of a material with orthorhombic or higher symmetry through 4-probe electronic transport measurements of a single thin or crystalline sample.