Angle-Dependent Magnetoresistance Studies on the Spin-Triplet Superconductor UTe_2

The spin-triplet superconductor UTe_2 has attracted significant attention recently as a host of various superconducting phases that emerge depending on temperature, pressure, magnetic field strength and orientation. In this project, we explored electric-magnetotransport response of high-quality UTe_2 single-crystals in magnetic fields up to 25 T at the magnet laboratory of the Institute of Material Research at Tohoku University. We discovered so-called angle-dependent magnetoresistance oscillations originating from a coherent two-dimensional Fermi surface and Shubnikov-de Haas oscillations in the c-axis resistivity that provide deep insights into the electronic properties of UTe_2.

Recently found high-field superconducting phases of the heavy-fermion spin-triplet superconductor, UTe_2, have been attracting much attention [1-3]. Various distinct field-induced phases, i.e., the field re-entrant superconducting (FRSC) phase for $B \| b$-axis, and spin-polarized superconducting phase (SPSC) above the metamagnetic transition (B_m ~ 35 T) with ~30˚ tilted magnetic field from *b* to *c*, are confirmed. We recently revealed a correlation between the emergence of the SPSC and its upper critical field H_{c2} and a vanishing anomalous Hall effect (AHE) signal in the angle dependence of UTe_2 (see Fig. 1a) pointing at a potential compensation mechanism for this exciting high-field phase [4]. To reveal the origin of these field-induced superconducting phases, investigation of electronic properties and their changes induced by magnetic field the field orientation is essential. Especially magnetic quantum oscillations may help to understand the Fermi surface and its relation to the various ground states [5]

High-quality single crystals grown by the molten-flux-flow method are available with superconducting T_c of 2.1 K. In order to measure electrical transport precisely, we were provided with high quality-single single crystals from Prof. D. Aoki (IMR-Oarai, Tohoku University) optimized for c-axis resistivity measurements. Spot-welding gold leads to the samples achieved low-ohmic contacts.

As can be seen in the right panel, we have recently established to fabricate micron-scale transport structures from high-quality single-crystals with ohmic contacts by the help of FIB suitable for magnetotransport experiments.

We ran transport experiments in three different magnet systems, in the all-superconducting 20 T and 15 T magnets as well as in the 25 T hybrid magnet, all equipped with Helium-3 inserts and a 2-axis rotator probe.

As presented in Fig. 1a we recorded the angle-dependent magnetoresistance (AMR)

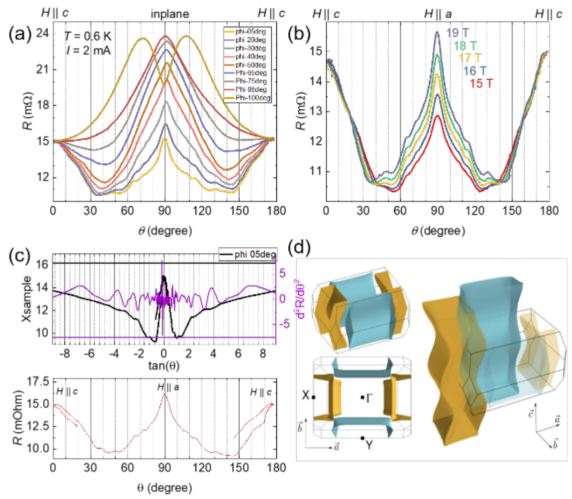

Fig.1 Angle-dependent magnetoresistance oscillations (AMROs) recorded in the 20 T superconducting magnet with continuously varying θ between 0 and 180° (θ = 90° = $B \| c$), (a) at 19 T fixed field for various fixed inplane angles ϕ, (b) at ϕ = 0° (i.e. within the a,c plane) for various magnetic fields between 15 and 19 T. (c) Comparison of AMROs at ϕ = 5°: (lower panel) Resistance *R* versus θ, (upper panel) R and $d^2R/d\theta$ plotted against tan(θ). (d) Sketch of the warped 2D Fermi-surface cylinders according to ref. [5].

of the inter-layer (i.e. *c*-axis) resistance versus the polar rotation angle, θ, recorded at fixed field and various fixed inplane angles, ϕ. For ϕ=0° clear oscillation-like features are discernible on top of a slowly varying AMR background with a local minimum around $30 < \theta < 60°$. A first weak maximum can be spotted at 50° followed by a few more for higher angles. Above 90° a mirrored AMR is found (expected from the orthorhombic crystal symmetry). We were able to check these AMROs for different angles and fields (Fig. 1b). The semi-classical AMROs are expected to be periodic in tanθ. This is confirmed by the comparison in Fig. 1c. The observed AMRO confirm the presence of warped 2D Fermi-surface cylinders in the band structure of UTe_2. We are currently analyzing these data and a publication is underway.

As can be seen in Fig. 2a slow Shubnikov-de Haas (SdH) oscillations with a frequency of approximately 90 T in the *c*-axis magnetoresistance were observed for the field oriented along the *a*-axis. This direction is perpendicular to the orientation of the 2D Fermi surface cylinders responsible for the AMROs shown above. We were able to trace these oscillations for different angles within the *a*,*b*- and the *a*,*c*-planes (see Fig.2a, b and d, respectively). The low frequency indicates a very small cyclotron orbits associated with a small Fermi surface. The value is incompatible with the large cylinders reported previously reported from de Haas-van Alphen oscillation measurements [6]. Such a small oscillation frequency may originate from a small 3D Fermi surface suggested from previous photo-emission experiments [7] and high-field tunnel-diode-oscillator experiments [8]. From the temperature dependence of the oscillation amplitude (shown in Fig. 2b and c) we extracted a rather light effective mass of about 1.5 times the free electron mass, me. This low value matches previous reports in ref. [5], where such a small cyclotron orbit was associated with quantum interference oscillations between electron- and hole-like 2D-Fermi-surface cylinders. We were able to trace the oscillations up to inplane angles of about 45°. In the *a*,*c*-plane the oscillations disappeared rather quickly already within only a few degrees away from the *B*||*a* direction. We are currently analyzing the observed data and are trying to compare them to band-structure calculations. An additional publication is underway. Therefore, our observations provide extremely valuable insights into the electronic properties of UTe_2.

In summary, we were able to observe angle-dependent magnetoresistance oscillations and the Shubnikov de Haas effect in the *c*-axis resistivity of single crystalline UTe_2. The comprehensive studies of the effects depending on field, field orientation, and temperature has resulted in a profound understanding of the electronic ground state in UTe_2. Experiments at even higher fields are highly desirable in order to learn more about the evolution of the Fermi surface, potentially also once the system transitions into the high-field spin-polarized phase above the metamagnetic transition field $B_m \sim 35$ T. I the future we would also like to study Hall effect and quantum oscillations at dilution temperatures in order to learn more about UTe_2.

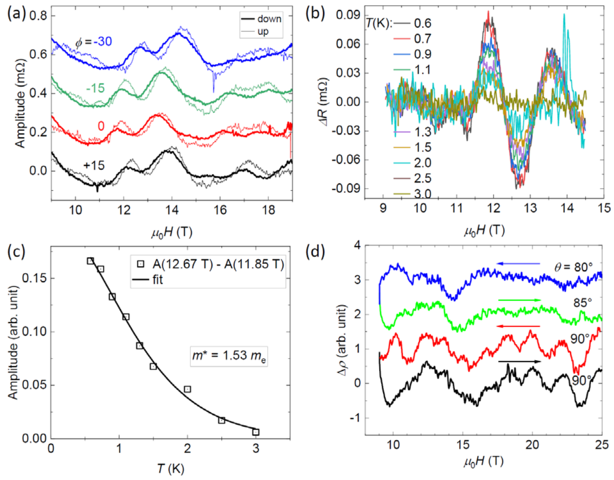

Fig.2 SdH oscillations after subtraction of an O(2) polynomial fit (a) for different inplane angles ϕ (within the *a*,*b* plane), recorded in the 20 T superconducting magnet (b) for different temperature, recorded in the 15 T superconducting magnet. (c) Effective-mass plot: Oscillation amplitude at 12.26 T for various temperatures ranging from 0.6 to 3 K. (d) SdH oscillations recorded in the 25 T hybrid magnet for three different polar angles θ (within the *a*,*c* plane).

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