Quantum transport evidence of Weyl fermions in a high-quality ferromagnetic perovskite oxide $SrRuO_3$ thin film

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Recently, Weyl fermions in ferromagnetic materials attract much attention because of their potential use in high-performance electronics, spintronics and quantum computing. $SrRuO_3$, a 4*d* ferromagnetic metal with the perovskite structure, provides a promising opportunity to seek the existence of Weyl fermions in magnetic materials.[1] However, there is no experimental evidence of the Weyl fermions in $SrRuO_3$ due to difficulties in preparing high-quality specimens,[2] and such specimens are required to reveal intrinsic transport properties of the purported Weyl fermions.

In this presentation, we report the quantum transport evidence of the Weyl fermions in an epitaxial $SrRuO_3$ film with the best crystal quality ever reported. We grew 63-nm thick $SrRuO_3$ films on $SrTiO_3$ substrates by our recently developed machine-learning-assisted molecular beam epitaxy (ML-MBE) method,[3] and the residual resistivity ratio (RRR) [ρ(300 K)/ρ(T→0 K)] of the films reached the world's best value of 84.3,[4] which allowed us to probe the intrinsic quantum transport properties of $SrRuO_3$. The films were fabricated into Hall-bar devices.

We observed direct quantum transport evidence of Weyl fermions[5]: (i) unsaturated linear positive magnetoresistance (MR), (ii) chiral-anomaly-induced negative MR, (iii) π Berry phase accumulated along cyclotron orbits, (iv) light cyclotron masses, and (v) high quantum mobility of about 10000 cm^2/Vs. Figures 1(a) and (b) show the Shubnikov-de Haas (SdH) oscillations and their Fourier transform spectra, respectively. The SdH oscillations above 2 K consist of two orbitals with frequencies of F_1 (26 T) and F_2 (44 T). In addition to signatures (i) and (ii) by independent MR measurements, we confirmed (iii)-(v) by detailed analyses of the SdH oscillation data using the Lifshitz-Kosevich (LK) theory.[6] Also, our first principles calculations found the Weyl nodes near the Fermi level which can reproduce our experimental results well.[4] Therefore, our experimental data and calculations establish $SrRuO_3$ as a magnetic Weyl semimetal.

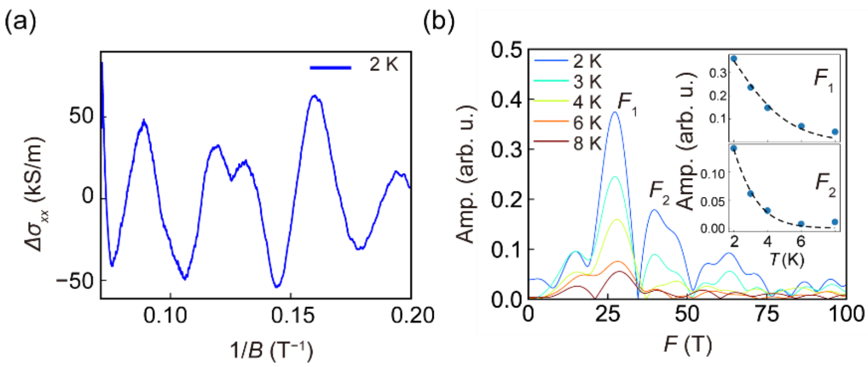

Figure 1 (a) Oscillating component of the conductivity (SdH oscillation) of $SrRuO_3$ at 2 K. (b) Fourier transform spectra of SdH oscillations at 2 - 8 K. F_1 (= 26 T) and F_2 (= 44 T) are frequency peaks of Weyl fermions with 0.35m_0 and 0.58m_0, respectively (m_0 : free electron rest mass). Insets: temp. dependences of F_1 and F_2 peak amplitudes for the mass estimation using the LK theory.

References [1] Y. Chen *et al., Phys. Rev. B* **88**, 125110 (2013). [2] G. Koster *et al., Rev. Mod. Phys.* **84**, 253 (2012). [3] Y. K. Wakabayashi, *et al., APL Mater.* **7**, 101114 (2019). [4] K. Takiguchi, Y. K. Wakabayashi, *et al.*, arXiv:2004.00810. [5] X. Huang *et al., Phys. Rev. X* **5** 031023 (2015). [6] I. M. Lifshitz & A. M. Kosevich, Sov. Phys. JETP **2**, 636 (1956).