Smart device, Clean energy

Exploration of innovative functional quantum materials by high-pressure synthesis

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Abstract

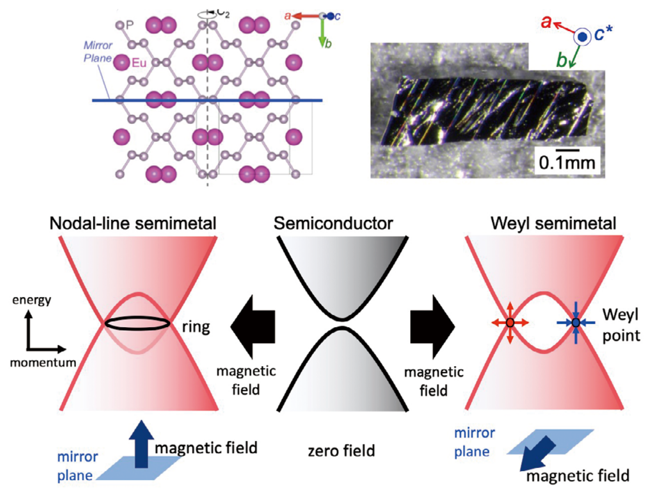
We are exploring functional quantum materials such as high-temperature superconductors, spintronics materials, and thermoelectric materials under extreme environments such as high pressure of several GPa and strong oxidation atmospheres. One group of materials that we are currently focusing on is a system called topological semimetals, which are expected to become high-speed and energy-saving electronic materials that outperform existing semiconductor materials because they contain conduction electrons with ultra-high mobility. The discovery of magnetic materials with such properties as topological semimetals could lead to the development of novel spintronics materials, but there have been very limited examples of such studies. Recently, we have succeeded in synthesizing single crystals of a new type of topological semimetal α-EuP_3 with magnetic properties under high pressures. Furthermore, by measuring various physical properties under magnetic fields and performing first-principles calculations, we have revealed that this material is a system that gives rise to multiple topological semimetallic phases with different properties depending on the magnetic field orientation with respect to the mirror symmetry plane of the crystal structure.

Background & Results

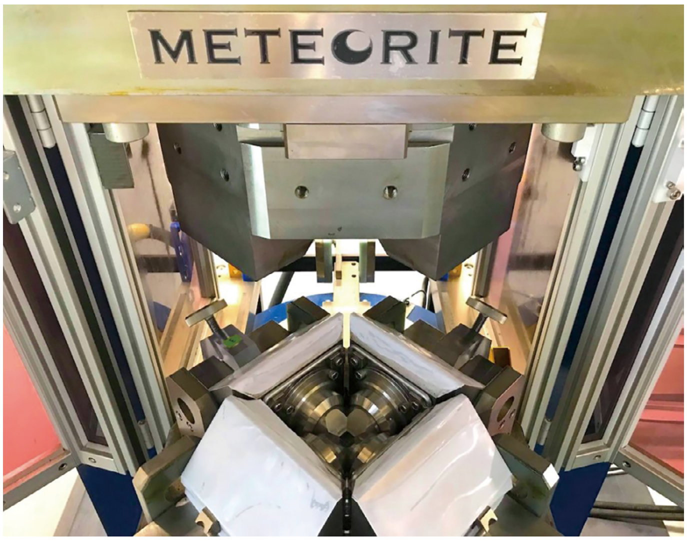
Recently, a group of materials called topological semimetals, typified by graphene, have attracted much attention. These materials contain unique electrons that behave much like massless neutrinos. If these electrons can be generated and controlled by a magnetic field, it could lead to new spintronics and super energy-saving electronic devices. However, the relationship between topological quantum phases and magnetism is not simple, and its realization has been difficult. Recently, we have succeeded in growing single crystals of a new layered magnetic semimetal α-EuP_3 under high pressure of several GPa, and by controlling the direction of the large magnetic moment of europium in the magnetic field, we have selectively generated a nodal-line semimetal phase showing a giant anomalous Hall effect and a Weyl semimetal phase showing a negative magnetoresistance effect. Furthermore, a close examination of the band structure under a magnetic field obtained by first-principles calculations reveals that the selective generation of the topological quantum phase by a magnetic field found in α-EuP_3 is due to the subtle coupling between the magnetic field controllable magnetism of europium and the conducting electrons in the phosphorus layer, and that the nontrivial topology of the band structure is protected by the mirror symmetry of the system.

Significance of the research and Future perspective

This study proposes a realistic solution for the generation and manipulation of nontrivial band topology by magnetic fields, which is expected to accelerate the development of materials for new information technology applications such as ultra energy-saving and high-speed electronic devices. In the future, by actively utilizing first-principles calculations and informatics, we aim to strategically develop functional quantum materials using high-pressure synthesis methods.



Crystal structure of magnetic phosphorus compound α-EuP3 (left upper) and its single crystal (right upper).
Selective generation of topological quantum phases by magnetic fields.



Multi-anvil-type high-pressure apparatus.

Patent

Treatise Alex Hiro Mayo; Takahashi, Hidefumi; Mohammad Saeed Bahramy et al. Magnetic Generation and Switching of Topological Quantum Phases in a Trivial Semimetal α−EuP_3. Phys. Rev. X, 2022, 12, 011033, doi: 10.1103/PhysRevX.12.011033

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