PHYSICS

Magnetic modification of electrical resistance

A switching mechanism enables finely tuned magnetoresistance for electronic devices

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Electronic devices such as data storage media or sensors need electronic properties that can switch between "on" and "off" states. One example is the giant magnetoresistance effect, which is used in sensors to detect the direction of a magnetic field (*1*). Such a sensor contains a heterostructure of two magnetic layers. The electrical resistance across the layers switches between low, when the two magnetizations are parallel, and high, when they are opposite. The direction of a surrounding magnetic field can then be detected because the field flips the magnetization of one of the layers. These sensors are the basic building blocks for high-density data storage devices and were therefore fundamental for developments in big data science (*2*). On page 377 of this issue, Suzuki *et al.* (*3*) report on a switching mechanism that flips the electrical resistance of CeAlGe for certain field orientations.

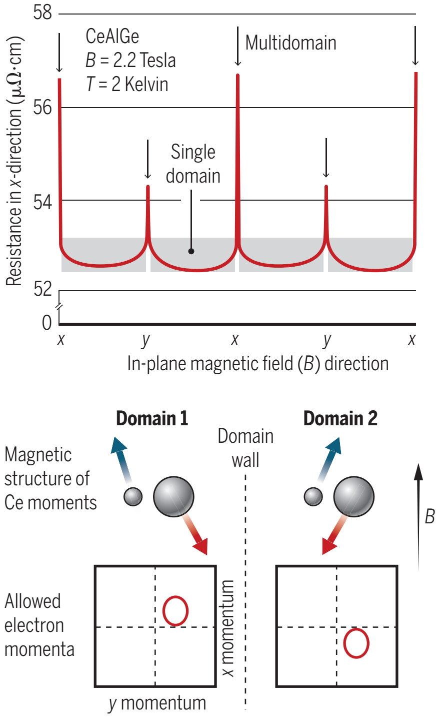
CeAlGe is a semimetal that crystallizes in a tetragonal structure in which the Ce atoms carry a magnetic moment. The resistance of CeAlGe depends on the angle of an applied magnetic field (see the figure). This dependence appears to be rooted in domains with different magnetic textures. Because the domains form only for specific field directions, the resistance has sharp spikes for these field orientations.

Understanding this unusual angular magnetoresistance of CeAlGe requires detailed theoretical modeling of how the energy of electrons in the material depends on their momentum (the band structure). Topological band theory reveals that CeAlGe has a topological semimetal band structure, which puts it in a class of materials where the very few electrons have very limited allowed momenta (*4*, *5*). Precisely which momenta are allowed is intimately connected to material properties such as magnetism.

In CeAlGe, magnetism develops in the form of antiferromagnetic order below T = 5.6 K at zero magnetic field, with moments lying in the tetragonal plane. Suzuki *et al.* found that CeAlGe undergoes a series of magnetic transitions when the magnetic field is applied along the tetragonal in-plane axes. Their findings are based on neutron scattering, magnetic, and transport measurements that are supported by extensive calculations. In between a low-field phase ($B < B_1$) with antiferromagnetic order and a high-field phase ($B > B_2$) with field-polarized collinear spins, the material enters a "canted" phase in which the spins acquire a polarization perpendicular to the direction of the magnetic field.

Singular angular switching

Sharp peaks in the electrical resistance of the semimetal CeAlGe depend on the orientation of the magnetic field.



Changes in resistance The resistance is low when the magnetic field is not oriented along the crystallographic axes because the crystal has only one magnetic domain. The resistance markedly increases when the field is aligned because of the formation of multiple domains of two types.

Multidomain state Electrons cannot cross the domain wall because their momenta do not match as a result of differences in magnetic moments (blue and red arrows). This mismatch prevents electron transport, creating a high electrical resistance.

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In the canted phase, the magnetic field, in combination with local symmetry and anisotropy around the magnetic Ce atoms, usually dictates the direction in which the spins tilt. Two distinct spin cantings are allowed when the field aligns with the crystallographic in-plane axes. For a magnetic field applied along these special directions, CeAlGe forms domains of the two types of magnetic states.

Strong coupling between magnetic and electronic properties in topological semimetals allows the magnetic state to shift the allowed electron momenta in each domain. When electrons try to move from one domain to the other, the momenta between the two domains do not match. This hinders electrons from traveling across the domain walls, which increases electrical resistance. The extreme angular dependence of the resistance arises because even a small rotation of 1° away from the crystallographic axis results in one of the magnetic orders being favored. The resistance of the material drops as domains of the other order disappear.

The singular dependence of the resistance of CeAlGe on the angle of an applied magnetic field is a striking example of how magnetic textures in real space can modify electric transport. In the giant magnetoresistance effect, an artificially built heterostructure formed by the two magnetic layers in the sensor is needed for a large change in resistance. In the topological semimetal CeAlGe, the intrinsic crystal properties are sufficient to create the magnetic texture required for the switching mechanism that results in the large change in resistance. Many recent studies have investigated the interplay of magnetism and topology (*6*, *7*), but in CeAlGe, the nodal band structure and small carrier density, not the topology itself, cause the size of the response. By showing how control over magnetism can lead to singular electronic responses, Suzuki *et al.* point the way toward technological applications of topological semimetals. ■

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