New State of Topological Insulators Offers New Opportunities

Three dimensional topological insulators are a new state of quantum matter with a bulk gap and odd number of relativistic Dirac fermions on the surface. In the presence of the time reversal symmetry, these Dirac fermions are massless with a continuous Dirac point (Fig. 1a), immune to perturbations as long as the disorder potential does not violate the time reversal symmetry.

A natural question is what will happen if the protection of the time reversal symmetry is lifted. Recent theoretical studies point out that in this case, the massless surface Dirac fermions will become massive due to the opening of an energy gap at the Dirac point (Fig. 1b). If the Fermi-level of the system resides inside this Dirac gap (and also the bulk gap), the topological insulator enters the insulating masive Dirac fermion state, a state that harbors striking topological phenomena, such as an image magnetic monopole induced by a point charge, a topological contribution to Faraday and Kerr effects and a half quantum Hall effect on the surface with Hall conductance of $e^2/2h$. Also remarkably, this state is a concrete realization of the "θ vacuum" state in a condensed matter system that is analogous to the axion phyiscs - a deep mystery in particle physics for decades. The study of this state in topological insulators can directly shed light on this intriguing mystery in particle physics and cosmology.

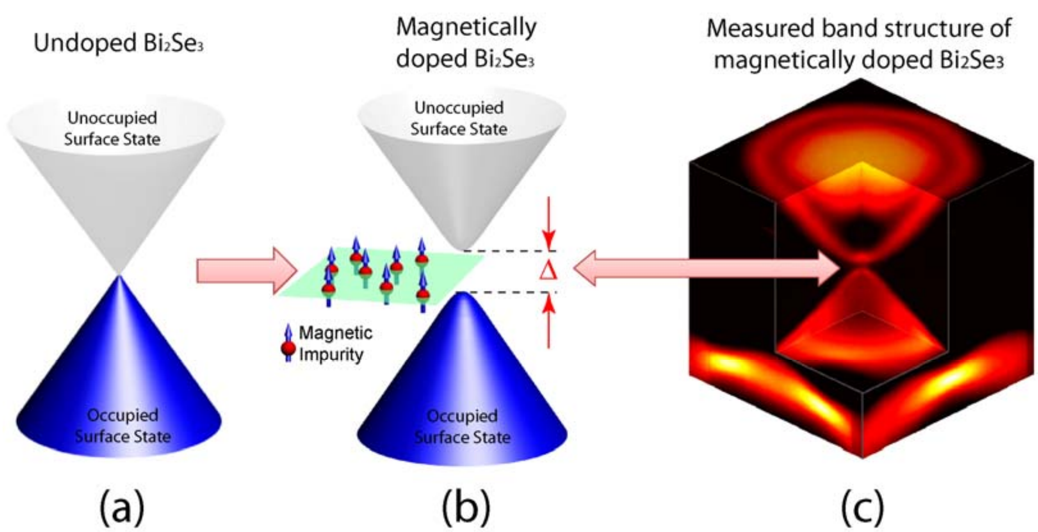

Fig. 1. (a) Illustration of the massless Dirac fermion state in undoped Bi_2Se_3 topological insulator, with the Dirac point connects the upper and lower Dirac cones. (b) A gap at the Dirac point caused by magnetic doping breaks the continuity of the Dirac cones, making the Dirac fermion massive. (c) Measured electronic band structure of a magnetically doped Bi_2Se_3 sample shows the Dirac gap that separates the upper and lower Dirac cones.

We chose the single Dirac cone topological insulator Bi_2Se_3 to realize the insulating massive Dirac fermion state. By introducing the magnetic dopants to break the time reversal symmetry, we successfully observed the formation of the massive Dirac fermion associated with the opening of an energy gap at the Dirac point, with the gap magnitude tunable by the concentration of magnetic dopants. Furthermore, the systematic study of the magnetic and charge dopings allowed us to find the exact point in two dimensional parameter space to simultaneously satisfy both stringent conditions for realizing this novel state — opening of a Dirac gap and positioning the Fermi-level into the gap. All the characteristic electronic structures of the insulating massive Dirac fermion state were confirmed by our angle resolved photoemission spectroscopy (ARPES) measurements (Fig. 1c).

This discovery not only paves the way to realize many exciting novel topological effects discussed above, but also provides a realistic method to control the topological surface state, which is immune to other perturbations that preserve the time reversal symmetry. This is crucial for turning this new state into applications, such as spintronics devices. In addition, the ability to continuously tune the material into both p- and n-type further enable the fabrication of functional devices such as topological p-n junctions. Furthermore, the use of the surface of the three dimensional topological insulator is much more attractive than realizing the 2D Dirac physics for novel devices, which have attracted a lot of enthusiasm recently due to the discovery of graphene. The difficulty encountered by working with the single atomic layer graphene is eliminated in 3D topological insulators and the mature technology used by current semiconductor industry can be adapted for developing functional devices.

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