論文の内容の要旨

論文題目 Electron scatterings and dynamics of Dirac surface state in a three-dimensional topological insulator
（三次元トポロジカル絶縁体のディラック表面状態における電子散乱及びダイナミクス）

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A continuous interest in condensed matter physics has made it possible to discover and classify distinctive phases of materials. A discovery of the quantum Hall state, one of the novel phases in condensed matter physics, has led a new classification paradigm of topological invariant. Recently, further studies with this concept of topological parameter eventually discovered quantum spin Hall state, a new phase based on the strong spin-orbit coupling, as well as led the advent of a topological insulator, a novel matter with the quantum spin Hall effect.

The most remarkable point of the topological insulator is a metallic spin-polarized boundary state. An existence of such a state in the bulk energy gap gives a clue to distinguish the peculiar matter from an ordinary insulator. Particularly, interestingly, the edge state is described by massless Dirac equation, and a large Fermi velocity is given to electrons of the edge state. Furthermore, the edge state of the topological insulator is theoretically promised to be robust. Because of those properties, the topological insulator is highly expected to be a good material for the spintronics devices with high performance.

In case of three-dimensional (3D) topological insulator, the edge state is appeared at surface, so-called Dirac surface state. After discovery of 3D topological insulator materials, such as $Bi_{1-x}Sb_x$, Bi_2Te_3, and Bi_2Se_3, many theoretical and experimental approaches have been applied for understanding such a Dirac surface state. Consequently, the electronic property of the peculiar surface state has been clarified intensively in the last few years. In spite of those efforts, a dynamics of the novel surface state electrons in the intrinsic insulating bulk energy gap has not yet been studied in detail, contrary to the electronic structures.

In the present study, the electron dynamics of 3D topological insulator $Bi_{2-x}Sb_xTe_{3-y}Se_y$, is investigated using scanning tunneling microscopy (STM) and spectroscopy (STS), as well as time- and angle-resolved photoelectron spectroscopy (TrARPES). Fermi energy of $Bi_{2-x}Sb_xTe_{3-y}Se_y$ can be tuned by controlling a composition of x, y between the bulk energy gap that the only single Dirac cone like surface state exist at the Fermi level. In particular, $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ has bulk-insulating resistance and the Dirac point in the bulk band gap lies very close to the Fermi energy. Thus, this is expected to be an intrinsic topological insulator. The present thesis mainly consists two parts.

In the first part, the angle-dependent elastic backscattering of the electrons in the Dirac surface state is clarified. The Dirac surface state with helical spin structure is expected to be robust from the backscattering due to time-reversal symmetry and the present work has discovered the suppression of backscattering in a wide angle range by a quantitative analysis of the quasi-particle interference (QPI) and the surface band structure. From the observed differential conductance (*dI/dV*) images

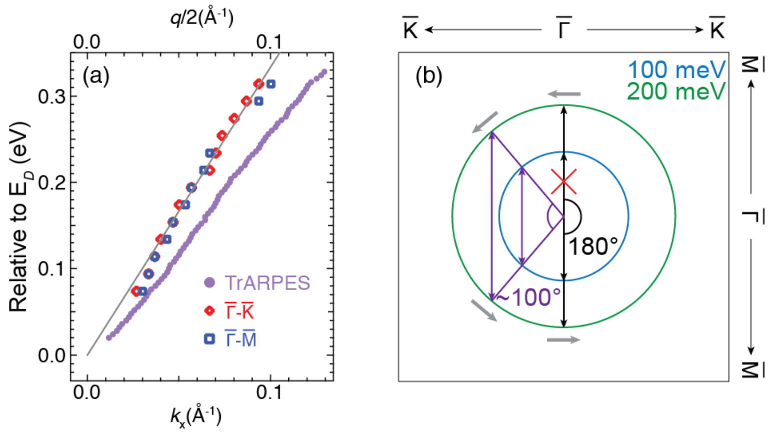

Figure 1: (a) The comparison of the critical scattering vector along Γ-K(red diamond) and Γ-M (blue square) with the diameter of the Dirac surface state constant energy contour measured by TrARPES. The critical scattering vector length is limited to only 75 % of the diameter. (b) A schematic drawn of circular constant energy contour and the maximum scattering angle.

using STM, the spatial modulation, considered to a result of QPI of surface electrons, are found even in the energy range with circular constant energy contour of band dispersion. The amplitude of Fourier-transformed *dI/dV* images rapidly decreases with the increasing the scattering vector length at a certain length. We call this a critical scattering vector length l_c. In order to compare l_c with the diameter of constant energy contour of the surface band, the dispersion was observed directly using TrARPES. In $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$, since the most part of upper Dirac cone exists in unoccupied state that it is hardly to observe the band structure with an ordinary angle-resolved photoelectron spectroscopy. The TrARPES based on pump-and-probe method makes it possible and the band dispersion including bulk conduction band is clearly observed. The comparison with diameter of circular Dirac cone at the same energy found that l_c is limited to only 75 % of the diameter as shown in Fig. 1(a). Fig. 1(b) shows the maximum scattering angle is calculated to be 100° from the result. This indicates that not only the 180° backscattering, but also a rather wide range of the scattering angle between 100° and 180° are well prohibited due to the spin mismatch. In other words, the electron backscattering is suppressed angle dependency.

The second part of the present thesis focuses on the electron scattering of the topological surface electrons in a non-equilibrium state. A decay process of photoexcited electrons in the same material of $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ is clarified from directly observed transient characteristic by TrARPES. The time evolution of the energy dependent photoelectron intensity is measured on both topological surface state and bulk conduction band. The lifetimes are found to be longer than 10 ps near the Fermi level in both states. Even a longer lifetime is measured on the bulk conduction band than on

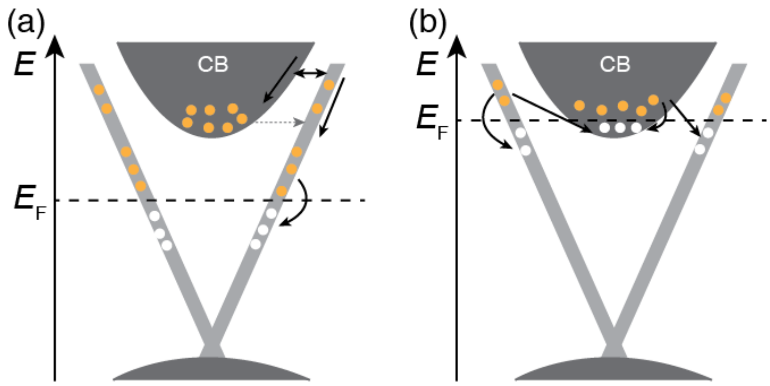

Figure 2: (a) A schematically drawn band diagram of a bulk-insulating topological insulator. Photoexcited electrons are accumulated to the bottom of the bulk conduction band because there exists no scattering channel only except the surface band. (b) A band diagram with the bulk conduction band crossing Fermi level, which increases electron – hole recombination channels.

the surface band near the energy of the bulk conduction bottom. At the bulk conduction bottom, no scattering channel found only except the surface band, and lower density of the surface band and far distance between two states in the momentum space affect to such accumulation. (Fig. 2(a)). A simple simulation with rate equation considering above scattering process, led to the own decay parameter of the surface state as $\tau \sim 4$ ps. This result is the first evidence about the τ of the metallic surface state between the real bulk-insulating band gap.

Because of a band bending, the electron dynamics is measured for various samples with different Fermi levels. The decay times of surface electrons from those samples are calculated from time evolution of the TrARPES intensity. The result shows that the lifetime depends on whether the bulk conduction band crosses the Fermi level or not. Holes in the bulk conduction band by the photoexcitation increase electron – hole recombination channels, so that the lifetime becomes short in this case as schematically shown in Fig. 2(b). On the other hand, when the sample is keeping the bulk-insulating property, the lifetime does not change at all. It means the band bending hardly affect holes in surface to combine with electrons inside of the sample.

In summary, the present work in this thesis constitutes the first experimental study about the Dirac electrons dynamics defined from both elastic and inelastic scattering. The quantitative analysis for surface state elastic scattering suggests the backscattering is significantly suppressed within a wide angle range due to helical spin texture. Furthermore, a long lifetime of the topological surface state's own and even longer lifetime of the bulk conduction band were clarified by the transient characteristic of photoexcited electrons. Such a long lifetime is kept in the "bulk-insulating" topological insulator. In particular, the latter result still needs the further theoretical understand about electron scattering on the metallic surface state between the bulk-insulating energy gap, it suggests the first experimental proof of the decay parameter, though the "spin-polarized" property is not considered.