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Akari Takayama

High-Resolution Spin-Resolved Photoemission Spectrometer and the Rashba Effect in Bismuth Thin Films

Doctoral Thesis accepted by
Tohoku University, Sendai, Japan

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[2] "Giant out-of-plane spin component and the asymmetry of spin-polarization in surface Rashba states of bismuth thin film"
A. Takayama, T. Sato, S. Souma, and T. Takahashi
Phys. Rev. Lett. **106**, 166401 (2011)

[3] "Ultrahigh-resolution spin-resolved photoemission spectrometer with a mini Mott detector"
S. Souma, A. Takayama, K. Sugawara, T. Sato, T. Takahashi
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Supervisor's Foreword

The physical and chemical properties of materials are dominated by the nature of valance electrons included therein. A complete description of the electronic state of solids is formulated by a set of three basic parameters of electrons: energy (E), momentum (k), and spin. Among various experimental methods to study the electronic states of matter, angle-resolved photoemission spectroscopy (ARPES) is regarded as a unique and powerful experimental technique, which provides direct information on the relationship between the energy and momentum of electrons, namely the band structure. Recent remarkable progress of the energy resolution in ARPES has made it possible to study the detailed electronic structure in the vicinity of the Fermi level (E_F) responsible for observed novel properties such as superconductivity. Spin-resolved measurement in ARPES has been long pursued because it completes the determination of all the three key parameters of electrons, and is expected to serve as a powerful method to investigate the exotic quantum properties originating from the electron spin. However, spin-resolved ARPES has an inherent difficulty in achieving a high energy resolution because the efficiency of detecting the electron spin polarization is typically three to four orders of magnitude lower than that in the non-spin-resolved measurement.

The present thesis describes the development and construction of a high-resolution spin-resolved photoemission spectrometer by overcoming the above-mentioned difficulty. The newly constructed spectrometer achieves the energy resolution of 8 meV, which is ten times better than that of the previous spectrometers (typically 100 meV) and is the world-best record at present. An important development to achieve this high resolution is a highly efficient mini Mott detector with a remarkably low noise level by overcoming the accidental discharge between electrodes at high voltage. Another noticeable aspect of the new spectrometer is a parallel-detection system with the multichannel plate and the Mott detector. This allows us to specify the energy and momentum of electrons with high accuracy during spin detection, enabling us to determine the momentum dependence of spin polarization with a high reliability that the previous single-Mott-type spectrometer never achieved.

By using the newly constructed spectrometer, the surface electronic state of Bi(111) has been investigated in great detail. Previous theoretical and experimental studies reported the spin-split surface band on Bi(111) originating from the Bi 6*p* orbital. This spin-split band is ascribed to the surface Rashba band, where the spin degeneracy is lifted by a combination of the strong spin-orbit coupling and the lack of the space inversion symmetry (SIS) at surface. The standard model of the Rashba effect supposes a purely two-dimensional (2D) SIS, so that the spin of the electron is laid on the surface plane and, at the same time, directed perpendicularly to the electron momentum. This results in a 2D vortex spin texture of the Fermi surface in the momentum space. In contrast to this simple picture, the present work has revealed the anomalous spin texture deviated from the standard Rashba model. The spin polarization shows strong anisotropy even in the plane, and, more surprisingly, shows a sizable out-of-plane component. This result requests further sophistication of theory in describing the anomalous behavior of spin at the surface.

The present study also provides a useful hint for application to spintronic devices. This study reports the systematic change in spin polarization as a function of film thickness in a high-quality Bi thin film grown on Si crystal. The spin polarization at surface is reduced by decreasing the film thickness. This indicates the existence of a spin-polarized state at the interface between Bi film and Si surface in a manner similar to the surface, but with the opposite spin polarization. This finding of the Rashba effect at the interface would open a way for fabricating stable and highly efficient heavy-element-based spintronic devices, because the interface is much more stable than the surface and the magnitude of spin-splitting is far larger than that of semiconductor-based devices, both of which are favorable to advanced spintronic devices.

In this book, readers will see the recent remarkable progress and the present status of spin-resolved ARPES. The book also shows how spin-resolved ARPES unravels the anomalous spin-resolved electronic structure responsible for the novel properties of materials. I believe that this book will be useful for not only photoemission specialists but also for students and general materials science researchers, because in the near future spin-resolved ARPES will be widely utilized in various research fields as one of the most essential tools to study the electronic states of materials.

Sendai, March 2014 Prof. Takashi Takahashi

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