Ryuichi Masutomi
Tohru Okamoto, Youichi Yanase
Department of Physics, University of Tokyo, 7-3-1 Hongo Bunkyo-ku, Tokyo, Japan
Department of Physics, Kyoto University, Kyoto, Japan

masutomi@phys.s.u-tokyo.ac.jp

Observation of Crossover from a Complex Stripe Phase to a Helical Phase in Multiple One-Atomic-Layer Films

The Larkin-Ovchinnikov state (generally known as the Fulde-Ferrell-Larkin-Ovchinnikov state) is a novel superconducting state in which the magnitude of the superconducting order parameter modulates in the real space due to the formation of Cooper pairs with a finite center-of-mass momentum in a strong magnetic field. It has been observed in heavy fermion superconductors and organic superconductors. However, the direct evidence of the helical state (also referred to as the Fulde-Ferrell state), which is characterized by the phase modulation of the superconducting order parameter, has not yet been observed. In this study, we report the first observation of both the helical phase and the complex stripe phase, characterized by both magnitude and phase modulations of the superconducting order parameter, in multiple one-atomic-layer Pb films with a layer-dependent strong Rashba spin-orbit interaction. To observe these exotic superconducting states, we fabricated bilayer and trilayer films on the cleaved surface of a non-doped insulating GaAs substrate, which comprise one-atomic-layer Pb films with a strong Rashba spin-orbit interaction caused by the breaking of the space inversion symmetry, as depicted in the insets of Fig. 1. The detailed sample preparation and experimental procedure are shown in Ref. [1-3]. In these multilayer films, each of the one-atomic-layer Pb film is weakly coupled with a spacer layer of Sb, and it has a layer-dependent Rashba spin-orbit interaction due to an opposite potential gradient along the normal direction of the two-dimensional plane. After the sample preparation, we performed *in situ* magneto-transport measurements to obtain the temperature dependence of the parallel upper critical magnetic field $B_{c2}^{parallel}$ for the multilayer films. The data are depicted in Fig. 1. As expected in two-dimensional systems, the temperature dependence of $B_{c2}^{parallel}$ for the bilayer film varies as a negative square-root. In contrast, for the trilayer film, a steep upturn is observed in the measurement of the temperature dependence of $B_{c2}^{parallel}$. From the numerical calculations performed using the Bogoliubov-de Gennes equations, we find that this upturn corresponds to the crossover from the complex stripe phase to the helical phase in the multiple one-atomic-layer films. In this study, we also present the phase diagram of the multiple one-atomic layer Pb films; it was determined from both experimental observations of the crossover from the complex stripe phase to the helical phase and from the numerical results obtained by the Bogoliubov-de Gennes equations. Our findings pave the way for the elucidation of non-trivial superconducting states in multilayer systems composed of two-dimensional Rashba superconductors.

References

[1] T. Sekihara, R. Masutomi, and T. Okamoto, Phys. Rev. Lett., 111 (2013) 057005
[2] R. Masutomi and T. Okamoto, Appl. Phys. Lett., 106 (2015) 251602
[3] M. Niwata, R. Masutomi, and T. Okamoto, Phys. Rev. Lett., 119 (2017) 257001

Figures

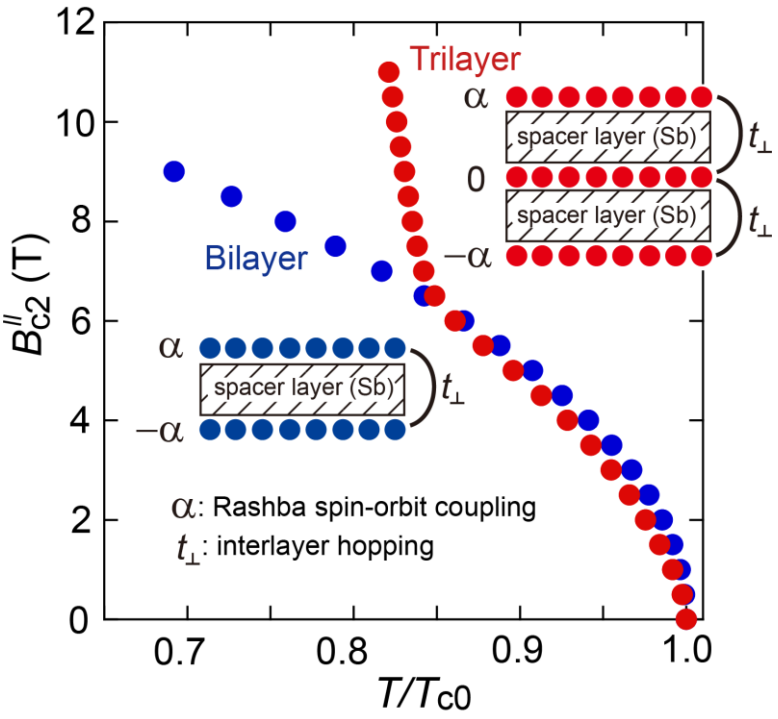

Figure 1: Temperature dependence of the parallel upper critical magnetic field $B_{c2}^{parallel}$ for bilayer and trilayer films. The red (blue) closed circles denote the data for the trilayer (bilayer) film. The film thickness of the Sb spacer layer is 2.0 nm.