Direct spectroscopic evidence of spin-dependent hybridization between Rashba-split surface states and quantum-well states

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In nanometer- or atomic-scale structures, size reduction implies an increase of the surface/volume ratio and the emergence of various quantum phenomena, intimately linked to the formation of electronic states different from those of the corresponding bulk materials. Recently, there have been vigorous investigations on nanometer-thick metal films, showing the quantum size effect, and on two-dimensional surfaces with large spin-orbit interactions, exhibiting the Rashba effect. In the present study, we prepared a quantum metal Ag(111) film, covered with a Rashba-type surface alloy of $\sqrt{3} \times \sqrt{3}$-Bi/Ag[1], to examine a mixture of these two effects, especially their spin characters.

Spin-polarized band structure of the system was investigated by high-resolution spin- and angle-resolved photoemission spectroscopy (SARPES) at KEK-PF BL-19A.

Figure 1 shows a series of the spin-up and spin-down SARPES spectra. The spin-up bands show free electron dispersion curves of the quantum-well states (QWS), while the spin-down ones show complicated band features. The former indicates that there is little interaction for the spin-up QWS with the surface state (SS) and the latter means that there is strong QWS-SS interaction. From these results it is found that the SS bands, spin-split by the Rashba effect, make spin-dependent hybridization with QWS in the nanofilm. The QWS subbands of the same spin orientation with the SS bands formed energy gap-opening, while those of the opposite orientation kept the free-electron band dispersion. Figure 2 shows a summary of the spin-dependent band diagram of the Ag(111) quantum film covered with the $\sqrt{3} \times \sqrt{3}$-Bi/Ag surface. The results also indicate that the amount of the hybridization gap depends on the SS band and the wave vectors. The difference may be understood in terms of the symmetry-matching of wave functions between the QWS and SS bands [2].

The present results give the direct evidence of the spin-dependent hybridization between the Rashba-type SS and the QWS, demonstrating that in a non-magnetic metal film the spin-degeneracy of the valence levels can be lifted by hybridization with Rashba-type SS bands.

References:
Fig. 1 SARPES spectra and band diagrams of (left) spin-up, $I^\uparrow$, and (right) spin-down, $I^\downarrow$, orientations. Dispersion of the SS and QWS bands are traced with symbols.

Fig. 2 Summary of the spin-resolved dispersion plots of Fig.1. Up- (red) and down-pointing (blue) triangles identify the peak positions in the up- and down-spin spectra, respectively. The size of the symbols is proportional to the intensity of the corresponding feature in the photoemission spectra. Thick lines between symbols guide the eye through the dispersion of bands with SS, QWS or hybrid character. The dashed lines labeled SS$_1$, SS$_2$, SS$_3$, and SS$_4$ represent the surface states. Dotted boxes highlight a portion of the energy-momentum space where the spin-selective hybridization between SS and QWS bands occurs.