Spin-resolved photoelectron spectroscopy of Ni/Cu(001)

Sunghun Kim, Koichiro Yaji, Yasuo Takeichi, Ayumi Harasawa, Takushi Iimori,

Akito Kakizaki, and Fumio Komori

Institute for Solid State Physics, The University of Tokyo

Ultrathin magnetic films grown on metal substrates have been studied for remarkable magnetic properties and electronic structures. Among them nickel (Ni) film on Cu(001) is one of the most famous systems which represents peculiar magnetic property as perpendicular magnetic anisotropy (PMA). Ni films show PMA between the thickness range of 10 and 40 atomic monolayers (ML), while the easy axis of magnetization becomes in-plane direction with respect to the film surface below and above this range [1, 2]. In order to clarify the physical origin of this magnetic anisotropy transition (MAT) the electronic structure of Ni/Cu(001) has been investigated. Several experimental studies have been performed with angle-resolved photoelectron spectroscopy (ARPES). In the former study, the Fermi surface of even a single ML Ni was observed to be very similar to that of bulk Ni [3]. However, recently, clearly different electronic structure from the bulk Ni was found below the 2-3 ML films [4, 5]. They have measured the only spin integrated electronic structure with ARPES. This motivates to clarify spin dependent electronic structure to understand further in magnetic materials. Spin- and angle-resolved photoelectron spectroscopy (SARPES) would be very powerful method to clarify the electronic structure with spin information.

A Cu single crystal (t = 1 mm) with [001] direction normal to the surface has been used for growing the Ni films. The mechanically and electrochemically polished Cu(001) crystal was cleaned by several cycles of Ar^+ ion sputtering at 1 keV and annealing up to 820 K in ultra-high vacuum (UHV) chamber. The clean surface of Cu(001) was confirmed by low-energy electron diffraction, Auger electron spectroscopy and ARPES. Ni was deposited onto Cu(001) *in situ* at room temperature. The pressure in the UHV chamber was kept below 8×10^{-10} mbar during the deposition. The thickness of the film was controlled with observing the intensity oscillation of reflection high-energy electron diffraction.

The SARPES measurement was performed at BL-19A of Photon Factory, KEK. An electron energy analyzer (Phoibos-150, SPECS) with very low energy electron diffraction type spin detector was used. Temperature was set to 100 K during both of sample magnetization and the SARPES measurements. The sample was magnetized along [110] direction.

Figure 1 (a) shows spin-resolved photoelectron spectra of 3 ~ 6 ML Ni films taken with normal emission. The photon energy ($h\nu$) was set to 43 eV. Ni d-bands (B1, B2) and surface state (S1), similar to the

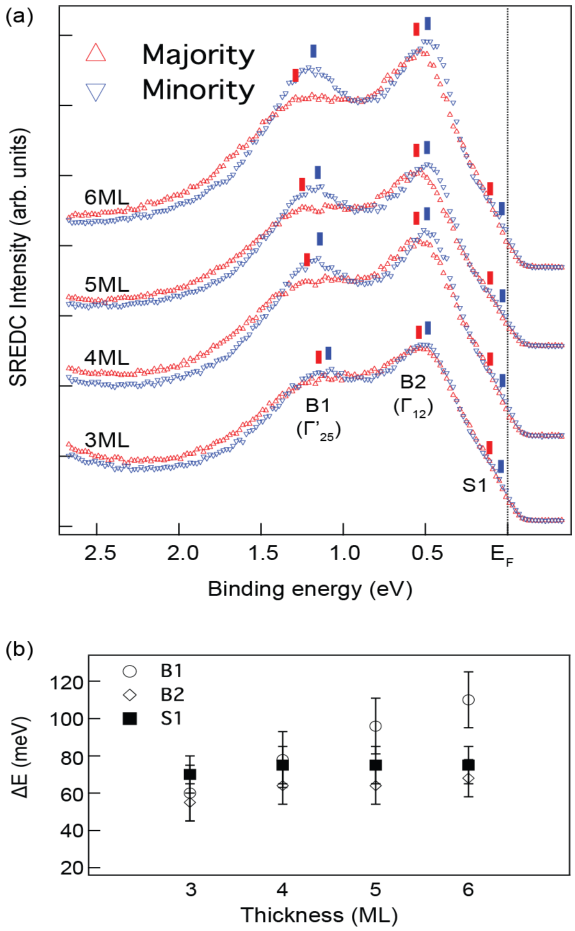

Fig. 1 (a) Spin-resolved photoemission spectra of 3 ~ 6 ML Ni/Cu(001) (b) Values of exchange split with the function of thickness recent report [5], were observed and these states are clearly spin-polarized. Binding energy of B2 and S1 do not show any difference with each film thickness, whereas B1 shows obvious shift of binding energy. The values for exchange split of each state are plotted with the function of thickness as shown in figure 1 (b). This graph also shows the only value of B1 becomes larger with increasing thickness of films, even the others show no flagrant change.

This result can be explained by our spin-integrated ARPES result. Figure 2 shows in-plane band structure of 2.5 ML Ni along $\bar{\Gamma}\bar{X}$ direction. Two solid lines show Ni *d*-band and dashed line shows a Cu *sp*-band. Focusing on the $\bar{X}$ point, we can find the crossing of the Cu *sp*-band and a Ni *d*-band, B1. The hybridization of these two bands is considerable to be an origin that B1 shows thickness dependence for spin polarization and the energy position, even the other bands have no remarkable changes [6].

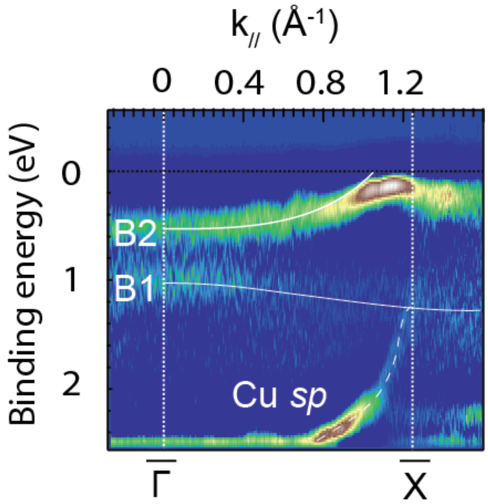

Fig. 2 Band structure of 2.5 ML Ni along Γ – X direction

In general, magneto-elastic anisotropy caused by lattice mismatch is considered for the reason that PMA appears at lower thickness of films. However, in case of the Ni/Cu(001) system, in-plane magnetic anisotropy has been appearing again below 8 ~ 10 ML Ni. Our present result from SARPES measurement shows the Ni *d*-bands are not isolated perfectly because of the hybridization with a Cu *sp*-band and this can reduce exchange interaction of Ni. This means that magneto-crystalline anisotropy should be also considered for the reason to cause MAT, because this is a consequence of spin-orbit coupling directly affecting exchange interaction in magnetic materials.

In summary, we have investigated spin dependent electronic structures of ultrathin Ni films on Cu(001) with SARPES. We have found difference of the spin polarizations between two Ni *d*-bands caused by the hybridization with the Cu *sp*-band. Suppressed exchange interaction of Ni can affect MAT in Ni/Cu(001) system and not only magneto-elastic anisotropy but also magneto-crystalline anisotropy should be considered to cause MAT at lower thickness of films.

Reference

[1] W. L. O'Brien and B. P. Tonner, Phys. Rev. B **49** 15370 (1994).
[2] B. Schulz and K. Baberschke, Phys. Rev. B **50** 13467 (1994).
[3] G. J. Mankey *et al*., Phys. Rev. Lett. **78** 1146 (1997).
[4] M. Hoesch *et al*., Phys. Rev. B **79** 155404 (2009).
[5] O. Rader *et al*., Phys. Rev. B **79** 145104 (2009).
[6] S. Kim *et al*., in preparation.