SOFT X-RAY MAGNETIC CIRCULAR DICHROISM OF c(2×2) CuMn ORDERED SURFACE ALLOY

Crystalline Mn is known as an antiferromagnetic or a paramagnetic material with quite a small magnetic moment. However, once Mn atoms crystallize with non-magnetic elements, such as Sb and even an oxygen atom, ferromagnetism appears as is found in MnSb or in $La_{1-x}Sr_xMnO_3$ [1]. Very small amounts of Mn in a semiconductor can also derive a degree of ferromagnetism, as discovered in (Ga, Mn)As [2]. One may extend this idea to a low dimensional case. An example is an Mn-based alloy fabricated on noble metal surfaces.

Wuttig *et al*. discovered that Mn based two-dimensional (2-D) ordered alloy can be formed on a clean Cu(001) surface at a coverage of 0.5 ML, where Mn and substrate atoms are alternatively placed forming a c(2×2) "checkerboard" structure, as shown in Fig. 1 [3]. A low energy electron diffraction (LEED) *I-V* measurement shows that the c(2×2) CuMn surface alloy has a pronounced corrugation in which Mn atoms in the first layer are displaced outwards by $\delta_z = 0.30 \pm 0.02$ Å, which is 17% with respect to the atomic distance in the bulk [3]. Such a remarkable atomic displacement is surprising because the other c(2×2) ordered surface alloy systems with non-magnetic elements, namely c(2×2) CuAu/Cu(001) and c(2×2) CuPd/Cu(001) show only small relaxations of 6% and 1%, respectively, instead of the larger atomic radii of Au (1.442 Å) and Pd (1.375 Å) compared to that of Mn (1.365 Å) as listed in Table I.

A theoretical band structure calculation predicts that the most stable magnetic state for c(2×2) CuMn ordered surface alloy is a ferromagnetic structure in the ground state [3]. The theory also explains that the observed large relaxation of the Mn atoms are derived from the magnetism [3]. However, no experimental evidence of the ferromagnetic state of this surface alloy has been obtained so far. The lack of the experimental evidence possibly comes from the lower ferromagnetic transition temperature (Curie temperature) as usually found in ultra-thin films with

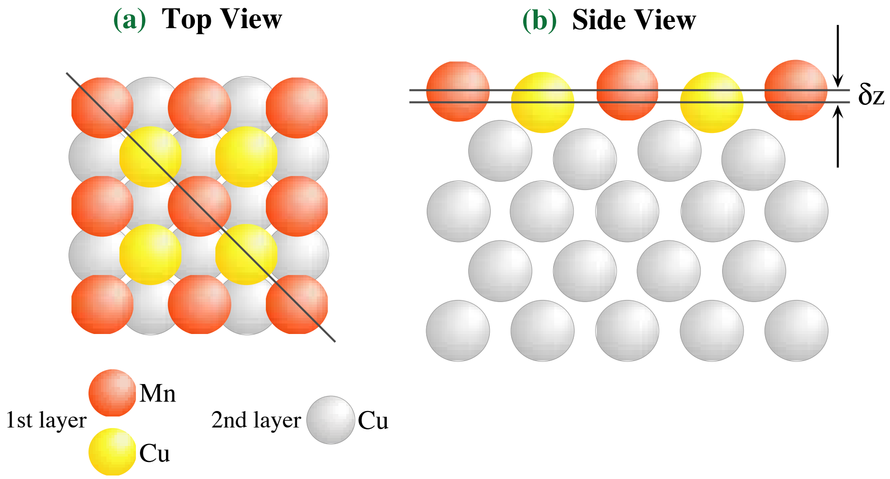

Fig. 1. Surface structure viewed from the top ***(a)*** *and from the side* ***(b)*** *of c(2×2) CuMn/Cu(001) 2-D ordered surface alloy as determined by LEED I-V analysis [3].*

Table I. *Atomic relaxation values determined by the LEED I-V analysis for several c(2×2) 2-D surface alloys [3].*

Structure	δz (Å)	Relaxation	Atomic radius (Å)
c(2×2) CuAu/Cu(001)	0.1	6 %	1.442
c(2×2) CuPd/Cu(001)	0.02 ±0.03	1 %	1.375
c(2×2) CuMn/Cu(001)	0.30 ±0.03	16.6 %	1.365
c(2×2) NiMn/Ni(001)	0.25 ±0.03	14.2 %	1.365

a couple of 3*d* transition metal monolayers. For this reason, we have tried to observe the soft X-ray magnetic circular dichroism (XMCD) spectra in the Mn 2*p* core absorption region at low temperature at beamline **BL25SU**.

Soft X-ray magnetic circular dichroism (XMCD) in core level absorption spectrum provides us with useful information related to electronic states of magnetic materials. It is noted that the XMCD not only gives us element specific magnetic moments, but also tells us how much an orbital (a spin) magnetic moment contributes to their total magnetic moments. Figure 2 shows an example of a submonolayer Mn grown on Ni(110) substrate [4]. One finds a clear XMCD of Mn and Ni 2*p* edges, and the polarities of the XMCD signals are the same for both Mn and Ni, meaning the directions of the magnetic moments are parallel between the Mn and the substrate Ni [4]. Thus one can surely obtain the element-specific information of the magnetic moments by conducting core-excited XMCD experiments.

The Mn 2*p* XAS and XMCD spectra of the c(2×2) CuMn/Cu(001) are shown in Fig. 3 [5]. We have observed several fine structures on all spin-orbit split components of the Mn 2*p* XAS spectrum.

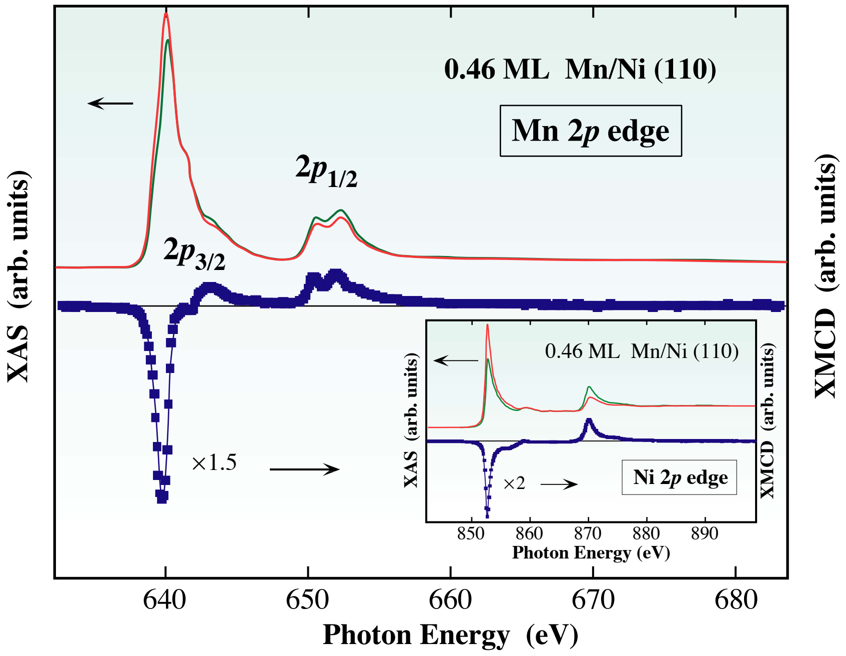

Fig. 2. Mn 2p XAS (upper) and XMCD (lower) spectra of 0.46 ML Mn ultrathin film on Ni(110). The inset shows the Ni 2p XAS (upper) and XMCD (lower) spectra of the same system. The ferromagnetic coupling between the Mn layer and the Ni substrate is clear. (see text)

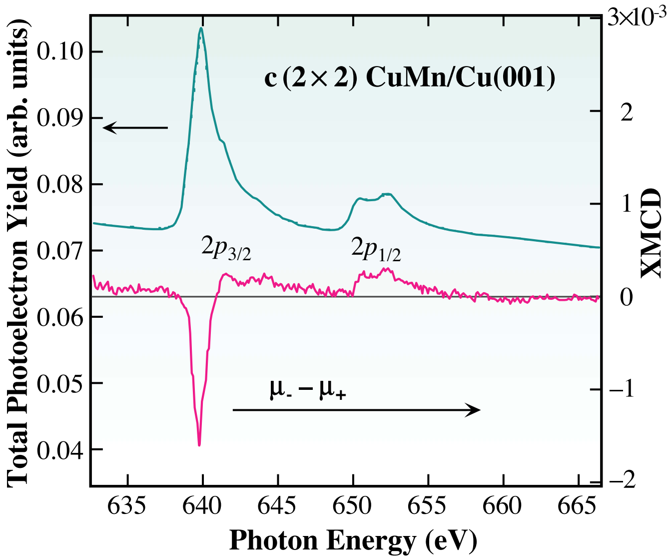

Fig. 3. Mn 2p XAS (upper) and XMCD (lower) spectra of c(2×2)CuMn/Cu(001) 2-D ordered surface alloy measured at T = 25 K. The XAS spectra are normalized by the incident photon flux. The XAS (XMCD) intensity scale is indicated at the left (right) axis.

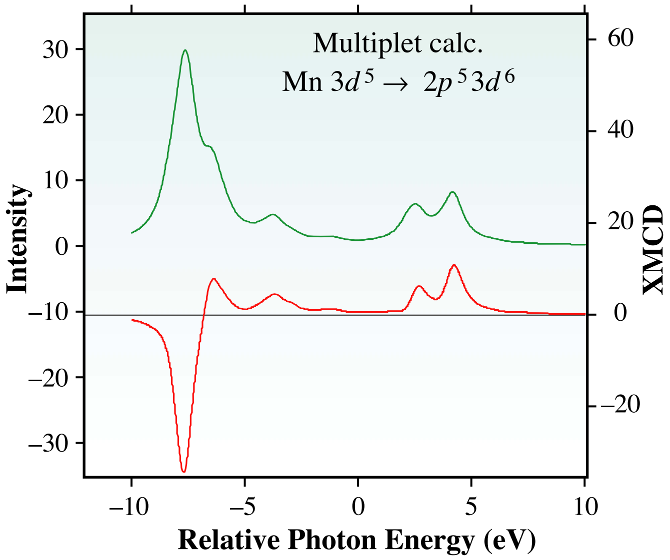

Fig. 4. Calculated Mn 2p XAS (upper) and XMCD (lower) spectra with Mn $2p^5 3d^6$ final state multiplets.

We found two shoulder states at energies ~1 and ~2 eV higher than that of the $2p_{3/2}$ main peak. Furthermore, a doublet peak structure was found for the $2p_{1/2}$ component. However, we have clearly observed the XMCD signal at T = 25 K as shown in the lower part of Fig. 3, which indicates the existence of the long-range ferromagnetic order under the external magnetic field (~1.4 T). The present XMCD spectrum shows the negative structure followed by the weaker positive structure with increasing hν in the $2p_{3/2}$ core excitation region, whereas the double peak structure with the positive sign exits in the $2p_{1/2}$ region.

We now compare the experimental Mn $2p$ XAS and XMCD spectra with the calculated Mn $2p^5 3d^6$ final state multiplets with assuming the $3d^5$ as the ground state configuration [5]. As shown in Fig. 4, we find excellent correspondence with the experimental XMCD spectrum as well as the XAS one, which shows that the observed several fine structures are derived from the multiplet effects. This result clearly indicates an almost half-filled electron nature leading to the high spin magnetic moment of the Mn atom.

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