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A direct two-dimensional comparison of magnetic circular dichroism and magnetic linear dichroism in ultraviolet photoemission spectroscopy

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The angular dependence of magnetic dichroism in photoemission (MDAD) from valence bands is more complicated than that from core levels. It gives access to spin-resolved information about the bands involved in the photoexcitation process. By using a unique ellipsoidal-mirror analyzer, we are able to observe MDAD from valence bands as a two-dimensional image, which gives a direct view of their angular dependence over a large slice through the Brillouin zone. In this work we have investigated Co films grown on a Cu(001) substrate. By using either circularly polarized light or linearly polarized light at a photon energy of 21 eV, magnetic circular dichroism and magnetic linear dichroism (MLD) from the Fermi edge shows different angular dependencies. This is due to the different excitation processes involved with the different light polarizations and it reflects the symmetry of the 3*d* bands of the Co. Furthermore, we also find that the sign of the MLD can change if differing initial states are involved. First principles calculations of Co bands and their photoelectron angular distributions with the different light polarizations will be presented. This shows that dichroism in valence band photoemission can provide valuable additional information on the electronic and magnetic properties of ultrathin films. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1456425]

I. INTRODUCTION

Further applications of giant magnetic resistance into magnetic tunneling junctions and other devices would be enhanced with additional information on the spin-resolved electronic structures of the Fermi surface at the interface of magnetic and nonmagnetic layers. Ultraviolet photoemission spectroscopy (UPS) is a well-known tool that is often used to study the electronic structures in *k* space. By studying UPS data as a function of the emission angle and the photon energy, one can evaluate the *k* dependence of the electronic structure. If a spin detector is used, one can obtain all of the relevant quantum numbers throughout the Brillouin zone. Thus even a three-dimensional reconstruction of a spin-resolved Fermi surface can be realized. However, it is normally very time consuming to measure these angular distributions over all relevant angles at even one photon energy, and it takes even longer to do this in a spin-resolved manner. An ellipsoidal-mirror analyzer is a very unique analyzer, that allows one to measure the spin-integrated angular dependence over a large angular range and the observed contours of intensity give a direct two-dimensional image of a slice through the electronic structure in *k* space.[1] When combined with polarized light, dichroism in the angular distribution can be observed from magnetic surfaces. In many cases, these magnetic dichroism measurements may yield similar information as spin-resolved experiments.[2] Magnetic dichroism experiments using such a display analyzer will be ideal to give quick and direct access to spin-resolved electronic structures of magnetic systems. In this work, we will show different angular dependencies of magnetic dichroism observed by such a display analyzer. We use first principles calculations to show that they are related to different bands with different spin character and symmetry.

II. EXPERIMENT

We have chosen fcc Co films grown on an fcc Cu(001) substrate as our sample, as this system has well-known structure and magnetic properties.[3,4] The Cu(100) substrate has been prepared by cycles of Ar^+ sputtering at 1 keV and annealing to about 700 K. Co films were then grown by electron bombardment of cobalt wire of high purity. All films were grown at room temperature with a base pressure of the deposition chamber below 2×10^{-8} Pa. No impurities could be detected on the sample by UPS before and after the film deposition.

The photoemission experiments were performed at Louisiana State University's Center for Advanced Microstructures and Devices (CAMD) synchrotron source on the plane grating monochromator beamline.[5] More details about the display-type ellipsoidal mirror analyzer can be found in Ref. 6. A schematic of the present experimental geometry for magnetic linear dichroism (MLD) is shown in Fig. 1: *p*-polarized light was incident at 45° with in-plane remanent magnetization reversed along the *y* direction and the analyzer collects electrons in a 32° half-angle cone about the sample normal. For magnetic circular dichroism (MCD), the geometry is almost identical to Fig. 1 except that the magnetization was along the *x* direction and the light was circularly polarized. Before taking MD images, angle-*integrated* energy distribution curves are collected at each photon energy.

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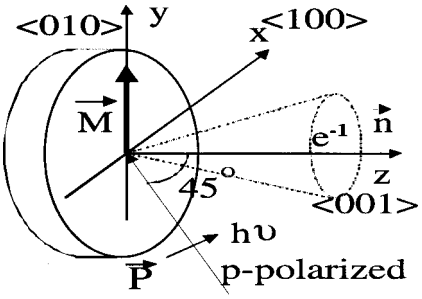

FIG. 1. The schematic of the experimental geometry for MLD. *p*-polarized light and the sample **n** is in the *x* horizontal plane, the electrons were collected in a 32° half-angle cone, and magnetization **M** was along the *y* direction.

Then the two-dimensional images of the photoelectron angular distributions for different magnetizations were collected at a constant binding energy. The dichroic images are then obtained by the subtraction of two images taken with opposite magnetization.

III. RESULTS AND DISCUSSION

With a photon energy of 21 eV, Fig. 2 shows MCD images of 10 ML Co/Cu(001) at a binding energy $E_b = -0.4$ eV in (a), MLD from 8 ML Co/Cu(001) at $E_b = -0.5$ eV in (b), and MLD at $E_b = -0.7$ eV in (c), respectively. In each panel of Fig. 2, the first two images show the photoemission angular distributions for the two opposite magnetizations, while the third is the image that results from their difference. From the results, it is clear that MCD and MLD have different angular distributions and they are also different from the original photoemission angular distributions. In MCD, the dichroic signal is more intense in the center, while the MLD images are clearly brighter along the

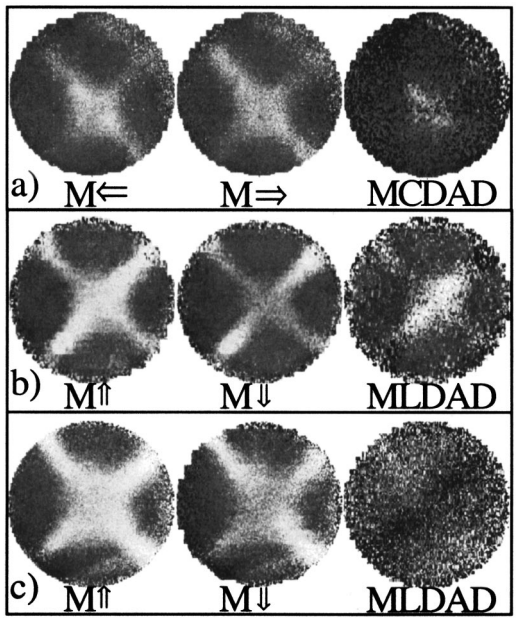

FIG. 2. (a) MCDAD from 10 ML Co/Cu(001), $h\nu = 21$ eV. Binding energy $E_b = -0.4$ eV. (b) MLDAD from 8 ML Co/Cu(001), $h\nu = 21$ eV. $E_b = -0.5$ eV. (c) The same as (b), but $E_b = 0.7$ eV.

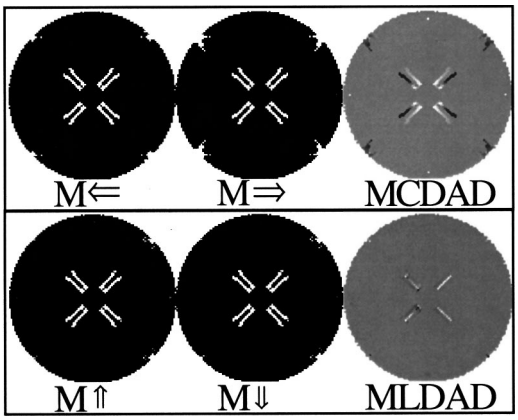

FIG. 3. (a) MCDAD calculated for fcc Co, $h\nu = 21$ eV at the Fermi surface. (b) The same as (a) but for MLDAD.

⟨110⟩ azimuth. This is due to the different excitation processes involved with the different light polarizations and it reflects the symmetry of the 3*d* bands of the Co. Moreover Fig. 2 shows that the sign of dichroism is reversed for different binding energies even with a binding energy difference of 0.2 eV. This can only be explained by the differing initial states involved and it is due to the flat closely spaced valence bands of Co near the Fermi level.

In order to better understand the origin of the observed MCDAD and MLDAD, we used the WIEN97.9 package[7] to perform a spin-polarized first-principles calculations including the spin-orbit interaction. The photoemission angular distribution patterns were obtained from the momentum matrix elements using the bulk band structure of both the initial and final states. Figure 3(a) shows photoemission intensity for reversing magnetizations by using circular polarized light with a incidence angle of 45° in the *xz* plane and with the magnetization along the *x* direction in the present geometry. The calculation gives angular distributions very similar to those obtained in the experiment shown in Fig. 2. The cross structure is due to Co 3*d* t_{2g} orbitals along the ⟨110⟩ and $\langle \bar{1}10 \rangle$ directions. Moreover the calculation reveals more information, as each arm of the cross consists of two different features from different neighboring bands. The spin-resolved calculation further shows that the center of the cross and the outside arms cut off by the perimeter of 32°, have different spin characters. The break point along each arm of the cross must be due to the exchange coupling. By including spin-orbit coupling, electronic hybridization brings opposite spin character to the two separate parts. The third image in Fig. 3(a) is the predicted dichroism resulting from the subtraction of the first two images. The calculated MCD agrees with the observation of Fig. 2(c), which gives an average bright center. However, the two lines of the each arm in most parts have opposite dichroic signal. The upper two lines and the lower two lines have the same dichroic signal, while the lines close to the horizontal plane have opposite but smaller dichroic signal except near the center, where they are also bright. This shows they belong to two different symmetry groups and the coexistence of magnetization and spin-orbit coupling breaks many symmetry operations including the inversion symmetry. For the MLD calculation in Fig. 3(b), the

angular distributions for both magnetizations gives a cross structure very similar to those in Fig. 3(a). The only difference is that the features cut by the perimeter are much weaker on the left side. The calculated MLD gives a more complicated structure than observed in the experiment. The dichroism has a cross structure, but in MLDAD the region between the two features of each arm is much enhanced in intensity. This could be related to the origin of the MLD, which is basically an interference effect in the matrix elements that occurs at hybridization points between bands of different symmetry.[2] This also shows again the different lines of each arm of the cross could have different symmetry. The difference between experiment and calculation for MLD could be due to the relatively large (0.5 eV) energy width used in the initial and final state to calculate the photoemission. Recall from Fig. 2, the dichroism changes sign with a binding energy difference of only 0.2 eV. However, this energy width was necessary to accommodate the limited number of k points used in the calculation. As a general comparison, one can see from the calculations that the MCD is stronger and more symmetric than the MLD. Although the calculations basically predict the distribution of intensity, the slight asymmetric distribution of MCD along $\langle \bar{1}10 \rangle$ and the asymmetric distribution of MLD along $\langle 110 \rangle$ are not present in Fig. 3. First, this could be due to the more simple and symmetric fcc structure used in the calculations than the true structure of Co/Cu(001) films.[3] Second, the bulk band structure used here does not take the surface effect into account. As the photoelectrons observed in the present energy range are mainly from the first several monolayers, surface effects will modify the details of the polarization of the light, which can be crucial to the details in MDAD.

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[1] R. L. Kurtz, S. W. Robey, L. T. Hudson, R. V. Smilgys, and R. L. Stockbauer, Nucl. Instrum. Methods Phys. Res. A **319**, 257 (1992).
[2] W. Kuch and C. M. Schneider, Rep. Prog. Phys. **64**, 147 (2001).
[3] A. Clarke, G. Jennings, R. F. Willis, and J. B. Pendry, Surf. Sci. **187**, 327 (1987); C. M. Schneider, J. J. de Miguel, P. Bressler, J. Garbe, S. Ferrer, R. Miranda, and J. Kirschner, J. Phys. C **8**, 1657 (1988); Hong Li and B. P. Tonner, Surf. Sci. **237**, 141 (1990).
[4] C. M. Schneider, P. Bressler, P. Schuster, J. Kirschner, J. J. de Miguel, and R. Miranda, Phys. Rev. Lett. **64**, 1059 (1990); P. Krams, F. Lauks, R. L. Stamps, B. Hillebrands, and G. Güenterrodt, *ibid.* **69**, 3647 (1992).
[5] R. L. Stockbauer, P. Ajmera, E. D. Poliakoff, B. C. Craft, and V. Saile, Nucl. Instrum. Methods Phys. Res. A **291**, 505 (1990).
[6] R. L. Stockbauer and A. Pararas, Nucl. Instrum. Methods Phys. Res. A **266**, 560 (1988).
[7] P. Blaha, K. Schwarz, and J. Luitz, *WIEN97, A Full Potential Linearized Augmented Plane Wave Package for Calculating Crystal Properties* (Karlheinz Schwarz, Vienna, 1999); P. Blaha, K. Schwarz, and S. T. Trickey, Comput. Phys. Commun. **59**, 399 (1990).