Synchrotron Radiation and Polarized Neutron Reflectivity Study the Enhanced Orbital Moment of Fe in the Epitaxial $Fe_{20}Ni_{80}/Ru/Fe_{20}Ni_{80}$ Multilayer

Chih-Hao Lee[a], Ming-Zhe Lin[a] and J.C.A.Huang[b]

[a] *Nuclear Science and Technology Development Center, National Tsing Hua University, also Department of Engineering and System Science, National Tsing Hua Univ., Hsinchu, Taiwan.*
[b] *Department of Physics, National Cheng-Kung University, Tainan, Taiwan.*

A 400% enhancement of orbital moment of Fe in the $Fe_{20}Ni_{80}/Ru/Fe_{20}Ni_{80}$ mulitlayer was found at the thickness of Ru spacer layers of anti-ferromagnetic coupling between $Ni_{20}Fe_{80}$ (permalloy, Py) layers. The enhanced orbiotal moment creates a magnetic anisotropy in the Py thin film which might induce a biquadratic coupling between the magnetic layers.

1. Introduction

Layered structures consisting of ferromagnetic and non-ferromagnetic metals are an area of intense research today partly due to the application potentials of magnetic properties such as the GMR (giant magnetoresistance) which was first observed in 1986 [1]. The indirect exchange interaction between two separated ferromagnetic layers, known as the Ruderman-Kittel-Kasyua-Yosida (RKKY) interaction, exhibits an oscillatory behaviour with respect to the spacer thickness. It is well known that orbital and spin magnetic moments are determined by the interplay of hybridization, exchange, Coulomb interactions, crystal-field and spin-orbit coupling. In contrast to the spin magnetism, the orbital magnetism in solids has its origin in the spin-orbit interaction and is closely connected with magneto-optical effects and x-ray magnetic dichroism. In this work, we prepared a Py/Ru/Py trilayer system consisting of two interfaces to compare the magnetic moment change with that of a single interface Py/Ru thin film. Usually, in transition metal solids, electron delocalization and band formation result in an almost complete "quenched" orbital moment (0.049 μ_B for bulk bcc Fe) [2], i.e., strongly suppressed by the crystal field splitting. However, the enhanced orbital moment has been found in some mechanism like capping layer effect [3], interface hybridization [4] or atomic arrangement [5]. The band narrowing and increased DOS at the Fermi energy at surface and interface in reduced dimension systems, such as thin films and multilayers, would increase the magnetic orbital moment significantly. Most of the studies, found the enhancement only at the interfaces. To our knowledge, the enhancement of orbital moment due to the interaction of two interfaces of a trilayer system is not observed before.

In this study, we apply to X-ray magnetic circular dichroism (XMCD) method to study the magnetic orbital moment. XMCD at the $L_{2,3}$ edge of transition elements has become an important tool in the study of the magnetic properties of thin film and surfaces. X-ray diffraction, X-ray Bragg rod measurement, X-ray and polarized neutron reflectivity to verify the structure of this multilayer .

2. Sample preparation

Molecular beam epitaxial Py/Ru/Py trilayers were grown on Al_2O_3(11-20) substrate with Pt buffer layer under ultra-high vacuum condition. 5 nm of Py layers and several different thicknesses of Ru spacer layers (t_{Ru}) were prepared and all samples were covered with an additional 1.5-nm-thick Pt layer to prevent the samples from oxidation. The magnetic coupling of the separated Py films was studied using longitudinal magneto-optical Kerr effect

(LMOKE). The electronic and magnetic properties of the thin films were investigated using 85% circular polarized light at the dragon beamline of Taiwan Light Source. The $L_{2,3}$ absorption spectra were recorded in total electron yield mode by reversing the applied field with fixed helicity of the incident light after magnetization of the films parallel to the surface. The grazing incidence X-ray diffraction and Bragg rod measurement showed that the Ru structure is still in hcp structure and no detectable strain developed in the permalloy layers. X-ray reflectivity measurement showed a 0.4 nm interface roughness at interfaces.

3. Results and Discussion

The result of m_{orb}/m_{spin} ratio as a function of Ru thickness is shown in the Fig. 1. For comparison, Table 1 lists also the m_{orb}/m_{spin} ratio at different conditions. A giant enhanced m_{orb}/m_{spin} ratio is observed which indicates the enhancement of the orbital moment is much stronger than the spin moment. Contribution from charge transfer and hybridization effects of Fe and Ru *d*-shells in the interface region may be present. In order to clarify the interface effect, we also perform the same procedure for a Py/Ru bilayer system. However, this 400% enhancement was not found for Py/Ru bilayer system at the same Ru layer thickness. This result implies the enhancement of the orbital moment did not come from one interface alone. It needs an interplay between two interfaces. In other words, it implies that there might be other mechanisms in addition to the hybridization effect in the trilayer system. Niklasson *et al.* [6] predicted that when two interfaces were brought closer to form a trilayer, the quasi-localized interface states may split and interact as a function of magnetic alignment and the spacer thickness. It also affects the magnetic anisotropy. Most theoretical studies of interlayer exchange coupling limit to the exchange interaction being bilinear in spin or intralayer magnetization. However, if spins of conduction electrons precesses due to the spin-orbit coupling, it could be possible to produce a noncollinear coupling of localized spin by interface spin-orbit interaction and the biquadratic coupling need to be considered. From our polarized neutron reflectivity [7], the magnetic moments between two Py neighbouring layers show a biquadratic coupling effect at the Ru thickness of anti-ferromagnetic coupling with a double unit cell at low applied fields. Thus, it is postulated that more localization of the *d* states at the interface enhances the atomic-like properties, such as the orbital polarization and the spin-orbit interaction. For a trilayer system, the interface states of the two interfaces interact via the spin-polarized states of the Ru spacer layers and couple biquadratically. This quantum interference between two interfaces might cause the enhancement of the orbital moment.

Table 1 The orbital/spin moment ratio of Fe (bcc, bulk), Py/Ru bilayer and Py/Ru/Py trilayer (ferromagnetic coupling at 1.4 nm and antiferromagnetic coupling at 0.7 nm in 4th column)

Fe (bcc)	Py/Ru bilayer (0.7 nm)	Py/Ru/Py trilayer (1.4 nm)	Py/Ru/Py trilayer (0.7 nm)
0.043	0.08	0.093	0.4

In conclusion, we have demonstrated the elemental magnetic moment property of the Py/Ru bilayer and Py/Ru/Py trilayer systems. The measurement reveals an anomalous enhancement in the orbital moment was observed as the Py-Py coupling is in anti-ferromagnetic coupling in the trilayer system. The orbital moment enhancement might be due to more localized electron at the interface and interact each other and hence may produce stronger spin-orbit coupling.

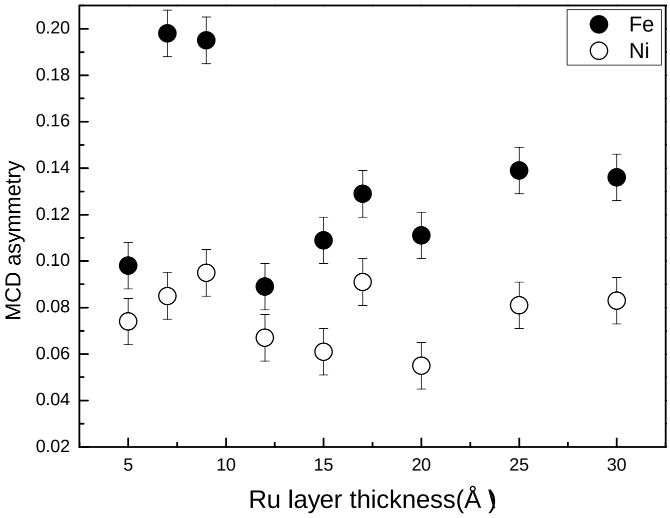

Fig. 1 The ratios of orbital/spin magnetic moment of Ni and Fe atoms in the permalloy/Ru/permalloy trilayers as a function of Ru layer thickness.

Acknowledgments

The authors would like to thank the hospitality of National Synchrotron Radiation Research Center, Taiwan. The financial support from National Science Council, Taiwan under the Contract No. of NSC93-2112-M007-017 is acknowledged.

References

[1] P. Grünberg, R. Schreiber, Y. Pang, M. B. Brodsky, H. Sowers, *Phys. Rev. Lett.* **57**, 2442 (1986).

[2] O. Hjortstam, J. Trygg, J. M. Wills, B. Johansson, and O. Eriksson, *Phys. Rev. B* **53**, 9204 (1996).

[3] J. Langer, J. Hunter Dunn, A. Hahlin, O. Karis, R. Sellmann, D. Arvanitis, and H. Maletta, *Phys. Rev. B* **66**, 172401 (2002).

[4] N. Nakajima, T. Koide, T. Shidara, H. Miyauchi, H. Fukutani, A. Fujimori, K. Iio, T.Katayama, M. Nýylt, and Y. Suzuki, *Phys. Rev. Lett*. **81**, 5229 (1999).

[5] M. Björck, G. Andersson, B. Lindgren, R. Wäppling, V. Stanciu and P. Nordblad, *J. Magn. Magn. Mater.* **284,** 273 (2004)

[6] A. M. N. Niklasson, L. Nordström, S Mirbt, B. Johansson and H. L. Skriver, *J. Phys.: Condens. Matter* **11,** 975 (1999)

[7] H. C. Su, J. J. Peir, C. H. Lee, M.Z. Lin, P. T. Wu, J. C. A. Huang and Z. Tun, *Physica B* **357**, 80-83 (2005)