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Spin and orbital magnetic moments of ultrathin Fe films on GaAs(1 0 0) studied by X-ray magnetic circular dichroism

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Abstract

The spin and orbital magnetic moments of 33 and 8 ML epitaxial BCC Fe films grown on GaAs(1 0 0)-4 × 6 have been measured using X-ray magnetic circular dichroism. Both samples have approximately the same spin moments of about 2.0 μ_B close to that of the bulk value, which confirms that there are no magnetic dead layers at the interface. A giant orbital moment enhancement of about 300% was observed in the 8 ML film, which may be partially due to an increased degree of localization of electronic states at the Fe/GaAs interface. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Interface magnetism; Orbital moment; Iron films; Semiconductors III–V

Interface magnetism in ferromagnetic metal (FM)/semiconductor (SC) heterostructures continues to be an important topic for the study of fundamental magnetic properties of ultrathin films and for the development of next generation magneto-electronic devices [1]. There are two issues of current interest concerning Fe/GaAs [2–5], a model system of the FM/III–V SC heterostructures, namely, the origin of the in-plane uniaxial magnetic anisotropy and the possible existence of magnetic dead layers at the interface. We have shown in a previous study that it is the growth morphology rather than the FM–SC intermixing which plays a dominant role in determining the evolution of the ferromagnetic phases with thickness and that there is no evidence of any significant dead layers forming at the interface in Fe/GaAs(1 0 0)-4 × 6 grown at room temperature [3]. In this paper, we report a further study of this system using X-ray magnetic circular dichroism (XMCD). The XMCD technique has been demonstrated experimentally [6–10] and theoretically [11,12] to be capable of determining both the spin and orbital magnetic moments down to submonolayer sensitivity. We shall show that the Fe/GaAs interface has a full spin moment and that the ultrathin Fe films exhibit a giant orbital moment enhancement.

Fe films were grown on GaAs substrates at ambient temperature (35°C) in a MBE chamber using an e-beam evaporator. A buffer layer (~ 0.5 μm) of homoepitaxial GaAs was grown on the commercial wafer to provide the smoothest possible GaAs surface. The substrate was then annealed to 550°C for one hour to obtain a clean and ordered Ga-rich 4 × 6 surface. Detailed growth and structure information can be found in Ref. [3]. The XMCD experiment was performed at beam line 1.1, CLRC Daresbury Laboratory, with 80% circularly polarized X-rays. The Fe $L_{2,3}$ absorption spectra were collected at room temperature in total-electron-yield mode, where the sample current was recorded as a function of photon energy. An external magnetic field of 3 T was applied perpendicular to the sample surface using a superconducting magnet. During the XMCD measurements, the circular polarization of the photon beam was fixed and the magnetization direction was alternately aligned parallel/anti-parallel to the propagation vector of the photon.

The evolution of the ferromagnetic phase was found to proceed via three phases according to our in-situ

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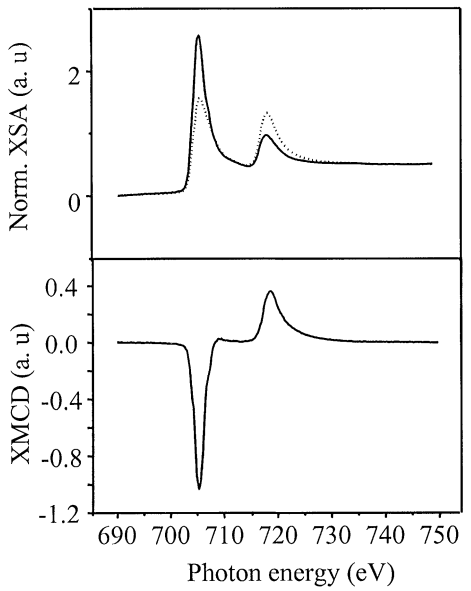

Fig. 1. (a) Normalized XAS and (b) XMCD spectra of a 33 ML film with both the external magnetic field and the photon beam applied perpendicular to the film plane.

magneto-optical Kerr effect (MOKE) measurements [3]; a non-magnetic phase for the first 3.5 ML, a short-range-ordered superparamagnetic phase, and a ferromagnetic phase above about 5 ML. The thickness dependencies of the coercivity and MOKE intensity further suggested that the films have different magnetic properties in the thickness ranges of about 5–12 ML and above 12 ML. We thus chose two typical samples of 8 and 33 ML representing a thin film and a thick film, respectively, for this XMCD study.

Fig. 1(a) shows the normalized X-ray absorption spectra (XAS) for the thick Fe film (33 ML) with two opposite magnetizations. By subtracting the XAS spectra, the XMCD spectrum is obtained and shown in Fig. 1(b). The spin and orbital moment are determined by applying the XMCD sum rule [6] with $n_h = 6.61$ [6,10] and by subtracting a simple two-step background from the XAS spectra. As included in Table 1, the spin moment is $2.07 \pm 0.12\,\mu_B$, and the orbital moment is $0.12 \pm 0.02\,\mu_B$. The spin moment is almost the same as that of the bulk BCC Fe [6], and the orbital moment is enhanced by about 40%.

Fig. 2 shows (a) the normalized XAS with two opposite magnetizations and (b) the XMCD spectrum for the thin Fe film (8 ML). One can see immediately that the ratio of the XMCD to the XAS is comparable to that in the thick 33 ML film, indicating no reduction of the magnetic moment in this thin film. To compare the XMCD spectra of two samples, both the spectra are scaled to 1 at the peak of the L_3 edge and are plotted in Fig. 3. This shows

Table 1
Spin and orbital magnetic moments of two epitaxial Fe films on GaAs(1 0 0)-4 × 6 in units of μ_B/atom

	m_{spin}	m_{orb}	m_{orb}/m_{spin}
33 ML	2.07 ± 0.12	0.12 ± 0.02	0.058
8 ML	2.03 ± 0.14	0.26 ± 0.03	0.128
Bulk BCC Fe[6]	1.98	0.085	0.043

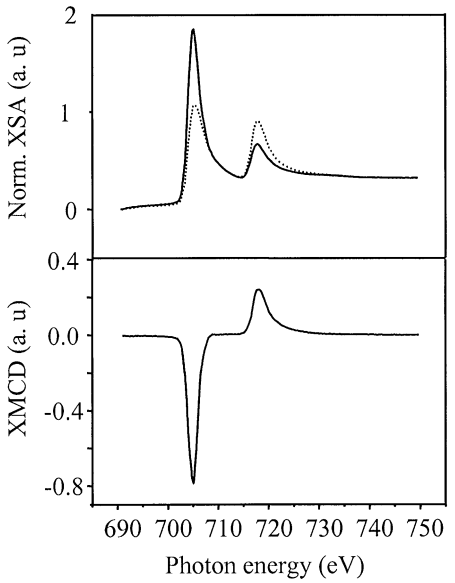

Fig. 2. (a) Normalized XAS and (b) the XMCD spectra of a 8 ML film with both the external magnetic field and the photon beam applied perpendicular to the film plane.

clearly that the dichroic area under the L_2 peak is smaller in the 8 ML film than that in the 33 ML film. Based on the XMCD sum rules [6,8] that link the dichroic areas to the orbital and spin moments, this result suggests an orbital moment enhancement in the thin 8 ML film as compared with that of the 33 ML film. As shown in Table 1, the spin and orbital moments of the 8 ML film are $2.03 \pm 0.14\,\mu_B$ and $0.26 \pm 0.03\,\mu_B$, respectively. The orbital moment is thus enhanced by about 300% as compared with that of the bulk value [6]. The bulk-like spin moment of the 33 and 8 ML films confirms that the interface is magnetic in the Fe/GaAs(1 0 0)-4 × 6, which is important for the fabrication of any spin-sensitive magneto-electronic devices.

In contrast with the bulk crystals where the orbital moment is nearly completely quenched, an enhancement of the orbital moment is expected at surfaces and interfaces due to a reduction of the symmetry, which can change the orbital degeneracy. First-principle calculations on BCC Fe surfaces have predicted a 100% enhancement of

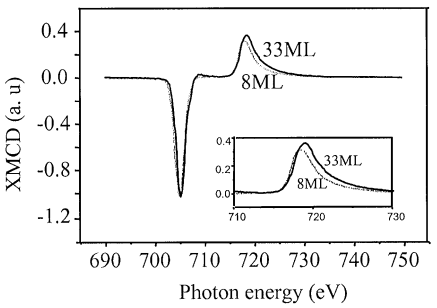

Fig. 3. XMCD spectra of the 33 and 8 ML films scaled to 1 at the peak of the L_3 edge. The difference between the L_2 peaks is shown clearly in the inset.

orbital moment as compared to the bulk value [13], which should be partially responsible for the observed orbital moment enhancement in 8 ML film. However, the observed giant enhancement of about 300% suggests an additional mechanism. As pointed out by van der Laan et al. [12], the presence of surface roughness, inter-diffusion, steps, or terraces will lead to more localized atomic-like 3d wave functions and an enhanced orbital moment. One of the distinct features of a reconstructed semiconductor surface is the formation of regular atomic scale structures, such as the Ga dimer row along the [0 1 1] direction in the GaAs(1 0 0)-4×6 surface [14]. We thus propose that this atomic scale structure leads to more localized wave functions for the Fe atoms close to the interface and a corresponding giant orbital moment enhancement in the ultrathin film.

In summary, the spin and orbital magnetic moments of the ultrathin epitaxial Fe films grown on GaAs(1 0 0)-4×6 have been studied using XMCD. We find that (1) the Fe films have a full spin moment, which confirms that there is no magnetic dead layer at the Fe/GaAs interface; and (2) the orbital moment in the ultrathin films is enhanced by up to 300%, which may be due to an increased electron localization of the 3d wave functions of the Fe atoms close to the reconstructed GaAs surface along with the reduction of the coordination number in ultrathin films.

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