# Comparison of surface spin wave modes at $Fe/MnF_2$ and Fe/Mn interfaces

I. L. Siu,[a] M. N. Islam, and J. C. Walker
*Henry A. Rowland Department of Physics and Astronomy, The Johns Hopkins University, 3701 San Martin Dr., Baltimore, Maryland 21218*

(Received 24 January 2000; accepted for publication 4 August 2000)

We have studied the thermal demagnetization in semi-infinite ferromagnets in $Fe/MnF_2$ and Fe/Mn bilayers using Mössbauer spectroscopy. We find that the hyperfine field at the $Fe/MnF_2$ interface follows a quasilinear temperature dependence, which reverts to a $T^{3/2}$ dependence further into the bulk. The region in which linear temperature dependence was observed also showed significantly higher spin canting than in the film's bulk layers. The interface in the Fe/Mn system immediately showed a $T^{3/2}$ dependence which persisted deeper into the bulk. We attribute the linear temperature behavior to surface spin wave modes created by a perpendicular surface anisotropy at the interface. This behavior diminishes farther away from the interface, until the hyperfine field goes like $T^{3/2}$ as expected for bulk, 3D spin waves. We conclude that the perpendicular surface anisotropy is much stronger at the $Fe/MnF_2$ than the Fe/Mn interface.  [S0021-8979(00)01322-0]

## INTRODUCTION

The magnetic behavior of semi-infinite ferromagnets in ferromagnetic (FM)/antiferromagnetic (AFM) bilayers have recently drawn considerable interest. Spin wave modes at the surface of ferromagnets have been the subject of theoretical investigations but they have been difficult to observe experimentally.[1–3] Surface spin wave excitations exhibit different behavior than in bulk systems due to differences in exchange interactions and anisotropy energies at the surface.[4] Early experiments have shown linear temperature dependence of the hyperfine field, attributed to two-dimensional surface spin wave modes, in 3 ML thick Fe(110) films on the Ag(111) substrate.[5] Initial calculations of the surface mode contribution to the magnetization of a semi-infinite ferromagnetic predict a quasilinear temperature dependence.[6,7] These modes are typically weak compared to the much stronger excitations and can only be detected near the surface.

Calculations performed by Mills *et al.* explicitly show that the surface of a semi-infinite ferromagnet, absent of any perpendicular surface anisotropy, introduces a hole in the bulk magnon band that exactly cancels contributions made by the surface modes.[2] He refers to this process as the cancellation theorem. Earlier work done by this group confirmed this finding by observing a $T^{3/2}$ dependence of the hyperfine field at the surface of Fe films covered by MgO and Ag.[8] However, this group also found that in Fe covered with $MnF_2$ films the surface hyperfine field decreased linearly with temperature.[8] In a semiclassical model proposed by Rado, two terms determine the surface anisotropy energy density, $K_s$ and $K_{ss}$,[7]

$$E_{\mathrm{surf}}=K_s u_x u_y+K_{ss}u_z^2,$$

where $u_x$, $u_y$, and $u_z$ are unit vector components along the cubic cell edges. $K_s$ and $K_{ss}$ represent the in-plane and out-of-plane surface anisotropies, respectively. Assuming $K_s \gg K_{ss}$, i.e., the spins lie in the film plane, Rado showed that with this new energy density the spin deviation, $\langle S-S_z\rangle$, near the surface has a quasilinear temperature dependence. However, Mills performed a quantum mechanical calculation on the same spin system also taking into account a weak perpendicular surface anisotropy.[9] In that analysis, Mills concluded that the cancellation theorem still applied in such a system, thus the temperature dependence of the magnetization remains $T^{3/2}$.

In this paper we examined two different interface systems, $Fe/MnF_2$ and Fe/Mn, to determine the thermal demagnetization temperature dependence in ferromagnetic films bounded by different cover materials. We used transmission Mössbauer spectroscopy to probe the temperature dependence of the hyperfine field at different depths in the Fe layer in $Fe/MnF_2$ and Fe/Mn bilayers. The hyperfine field is a measure of the local magnetization and therefore the hyperfine temperature behavior is proportional to that of the magnetization of the films. By doping the Fe layer with a few monolayers of $^{57}Fe$ at selected depths, a depth profile of the magnetization can be ascertained. Careful analysis of the peak intensities of the Mössbauer spectra reveal the degree of spin canting out of the film plane in the probe layer.

## EXPERIMENT

$Fe/MnF_2$ and Fe/Mn films were grown on Ag(111) substrates as described in an earlier paper.[10] The films were grown by molecular beam epitaxy (MBE) using Knudsen cells operating at a base pressure of $\sim 1\times 10^{-10}$ Torr. A thick (~1200 Å) Ag base was grown on a mica substrate. Substrates were annealed at 400 °C for 60 min prior to deposition and the substrate temperature, $T_s$, was lowered for Ag growth, $180<T_s<200$ °C. *In situ* RHEED patterns indicated epitaxial growth along the fcc (111) orientation. An ~80 Å

[a]Present address: National Institute of Standards and Technology, Gaithersburg, MD 20899; electronic mail: ilsiu@nist.gov

 

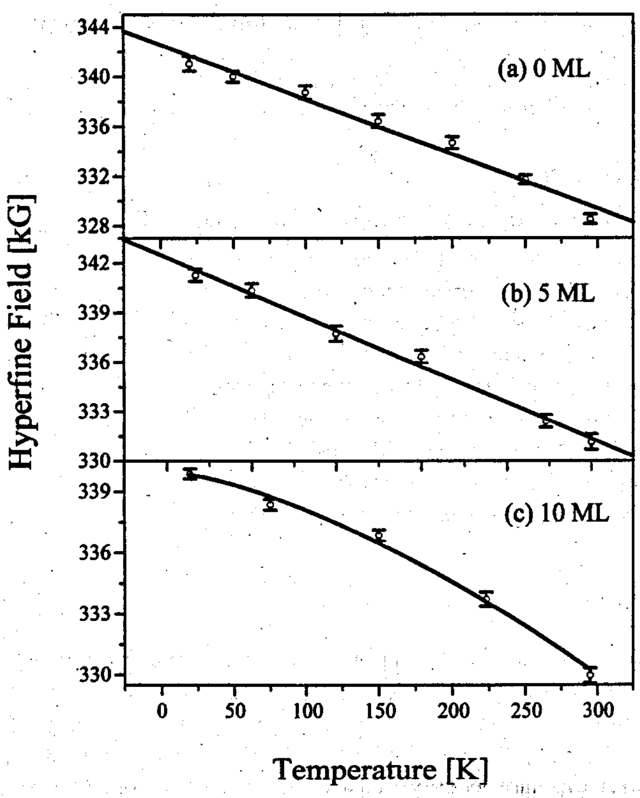


FIG. 1. Plots of hyperfine field $H$ vs temperature $T$ of probe layer in $Fe/MnF_2$ bilayers for different probe layer depths: (a) 0 ML; (b) 5 ML; and (c) 10 ML. Solid lines represent the least squares fit. Plots of (a) and (b) show linear fits while (c) is fit to $T^{3/2}$.

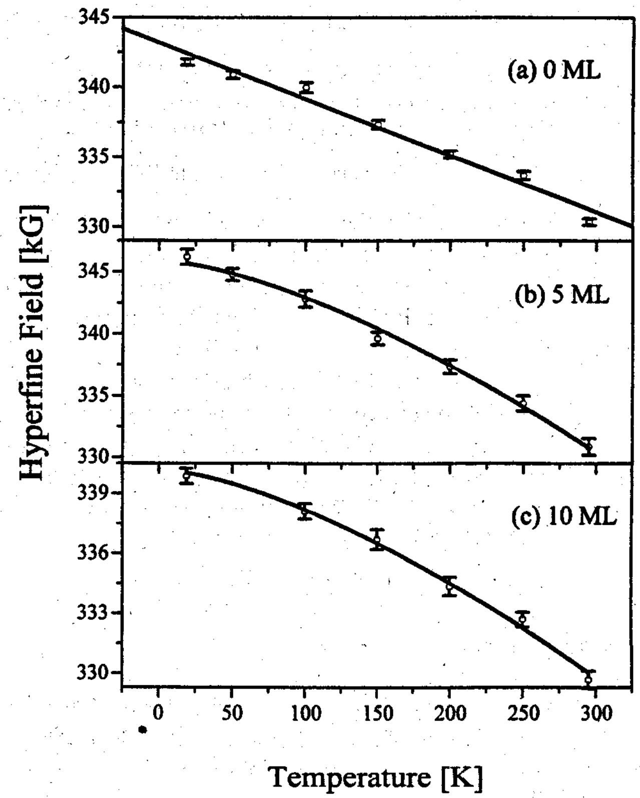


FIG. 2. Plots of hyperfine field $H$ vs temperature $T$ of probe layer in Fe/Mn bilayers for different probe layer depths: (a) 0 ML; (b) 5 ML; and (c) 10 ML. Solid lines represent the least squares fit. Plot (a) show a linear fit while (b) and (c) are fit to $T^{3/2}$.

thick Fe layer was deposited on top of the Ag base, growing in the bcc (110) orientation. This was verified by both RHEED and *ex situ* x-ray diffraction. A 2 monolayer (ML) $^{57}Fe$ layer was grown on top, followed by another $^{56}Fe$ layer of thickness varying from 0 to 20 ML. $T_s$ was lowered to room temperature during $^{57}Fe$ deposition to minimize interdiffusion of $^{57}Fe$ into the $^{56}Fe$ layers. Roughly 100 Å of either $MnF_2$ or Mn was then deposited. RHEED did not show clear streaks or spots, indicating the growth was not epitaxial, but instead polycrystalline. Three repetitions of Ag/Fe/($MnF_2$ or Mn) were grown to enhance the Mössbauer signal. Attempts at deposition of additional reps resulted in sharp degradation in the RHEED pattern, indicating poor epitaxial growth. Finally, films were capped with approximately 100 Å of Ag to prevent contamination.

## RESULTS

Mössbauer spectra were obtained at five to seven temperatures ranging from 19 K to 300 K. The spectra show a single sextet corresponding to a single hyperfine site in bcc Fe, suggesting high sample quality. Plots of the hyperfine field of the probe $^{57}Fe$ layer, at various positions in the Fe layer, versus temperature were made for the $Fe/MnF_2$ (Fig. 1) and Fe/Mn (Fig. 2) bilayers. The probe layer depths varied from 0 to 20 ML from the interface. A least squares fit shows linear temperature dependence of the magnetization at depths of 0 [Fig. 1(a)] and 5 ML [Fig. 1(b)] in the $Fe/MnF_2$ films. This is interpreted as evidence of surface spin wave modes responsible for linear temperature dependence in 2D magnetic systems. At 10 ML, bulk spin wave modes begin to compete with the surface modes, resulting in a more $T^{3/2}$-like temperature dependence [Fig. 1(c)]. At depths of 15 ML and beyond, the temperature dependence is clearly $T^{3/2}$. Bulk spin wave modes completely dominate.

Line intensity ratios of the spectra at all depths reveal out of plane spin canting ranging from 18° to 26° (Fig. 3). In contrast, spectra of Fe/Mn bilayers show mixed $T$ and $T^{3/2}$

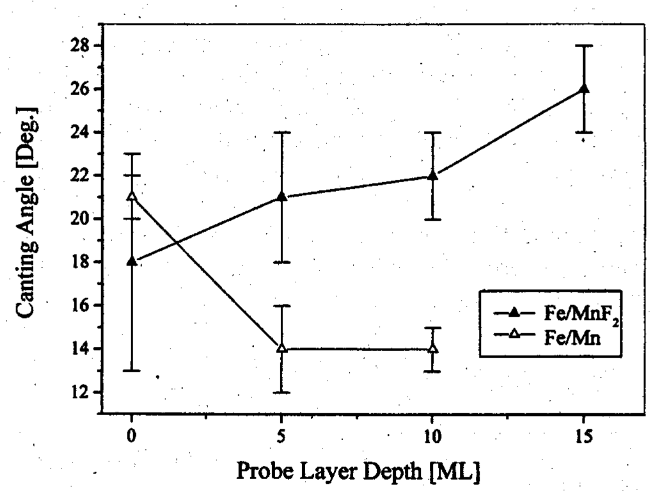


FIG. 3. Out-of-plane spin canting angle in the $^{57}Fe$ probe layer vs probe layer depth in the $Fe/MnF_2$ and Fe/Mn bilayers.

dependence immediately at the interface [Fig. 2(a)]. By a depth of 5 ML, the linear behavior completely disappears and a $T^{3/2}$ dependence is observed at the remaining probe layer depths [Figs. 2(b) and 2(c)]. Furthermore, line intensity ratios suggest significantly less spin canting, dropping to 14° at a depth of 5 ML. Theoretical calculations performed by Mills show that a sufficiently strong perpendicular surface anisotropy will put spins lying near the surface out of plane.[11] This indicates that the perpendicular anisotropy in the Mn covered films may be insufficient, compared to the magnetocrystalline anisotropy, to excite surface spin wave modes. In both cases the physical origin of the perpendicular anisotropy is unknown.

Mills' calculation indicates that in spin systems where the perpendicular surface anisotropy is not sufficient to force spin canting at the interface, the quasilinear surface mode contribution to the magnetization is exactly canceled by a hole in the bulk magnon contribution. Our analysis of the Mn capped Fe films support this conclusion.

## CONCLUSIONS

We studied two semi-infinite ferromagnet systems: one capped with $MnF_2$ and the other with Mn. In the $Fe/MnF_2$ system we observed out of plane spin canting ups to 26°. This suggests the presence of a strong perpendicular surface anisotropy. We also observed a liner temperature dependence of hyperfine field that crosses to $T^{3/2}$ dependence at a depth of 10 ML from the interface. We attribute this behavior to the presence of surface spin waves brought about by strong perpendicular anisotropy. The Fe/Mn system exhibited less out-of-plane spin-canting and a very slight linear temperature dependence of hyperfine field at the interface. This behavior is consistent with Mills' cancellation theorem. It should be noted that Mills' calculations explicitly assumed the spins remain in plane, which is clearly not the case in the $MnF_2$ covered films; thus the cancellation theorem is not applicable in this instance. Since the perpendicular surface anisotropy is a local effect, its influence is expected to be greatest at the interface and decay deeper into the bulk. Our spin-canting data confirms this behavior. The interfaces studied are quite complicated and a more detailed calculation in the spin-wave approximation, which takes into account a ground state with spin canting, is necessary to understand the influence of surface modes.

## ACKNOWLEDGMENT

This work was supported by NSF Grant No. 9410148.

[1] G. T. Rado, Bull. Am. Phys. Soc. 2, 127 (1957).
[2] D. L. Mills and A. A. Maradudin, J. Phys. Chem. Solids 28, 1855 (1967).
[3] J. Mathon, Phys. Rev. B 24, 6588 (1981).
[4] G. T. Rado, Phys. Rev. B 26, 295 (1982).
[5] C. J. Gutierrez, Z. Q. Qiu, M. D. Wieczorek, H. Tang, and J. C. Walker, J. Magn. Magn. Mater. 93, 326 (1991).
[6] G. T. Rado and J. R. Weertman, J. Phys. Chem. Solids 11, 315 (1959).
[7] G. T. Rado, Phys. Rev. B 40, 407 (1989).
[8] H. Tang, Z. Q. Qiu, Y. W. Du, G. P. Stern, and J. C. Walker, J. Appl. Phys. 63, 3659 (1988).
[9] D. L. Mills, Phys. Rev. B 40, 11153 (1989).
[10] M. N. Islam, I. L. Siu, and J. C. Walker, J. Appl. Phys. 85, 4625 (1999).
[11] D. L. Mills, Phys. Rev. B 39, 12306 (1989).