4-1997

Structure and perpendicular magnetization of Fe/Ni(111) bilayers on W(110)

D. Sander
Max-Planck-Institut fur Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany

Axel Enders
University of Nebraska at Lincoln, a.enders@me.com

C. Schmidthals
Max-Planck-Institut fur Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany

J. Kirschner
Max-Planck-Institut fur Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany

H. L. Johnston
McMaster University

See next page for additional authors

Authors

D. Sander, Axel Enders, C. Schmidthals, J. Kirschner, H. L. Johnston, C. S. Arnold, and David E. Venus

Structure and perpendicular magnetization of Fe/Ni(111) bilayers on W(110)

D. Sander, A. Enders, C. Schmidthals, and J. Kirschner
Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany

H. L. Johnston, C. S. Arnold, and D. Venus
Department of Physics, McMaster University, Hamilton L8S 4M1, Canada

Scanning tunneling microscopy and low energy electron diffraction show that high quality fcc Ni(111) films can be prepared on W(110). The subsequent coverage of this Ni template by monolayers of Fe leads to a Fe/Ni bilayer with striking magnetic properties. The Fe cap layer induces a spin reorientation of the easy axis of magnetization from in-plane to perpendicular to the film, as checked with the magneto-optic Kerr effect. At higher Fe coverages, an in-plane magnetization of the bilayer is found, which is proposed to be caused by the fcc to bcc transition in the Fe layer. © *1997 American Institute of Physics.* [S0021-8979(97)47208-0]

I. INTRODUCTION

The magnetic properties of bilayers, consisting of two ferromagnetic materials with thicknesses of several monolayers (ML) are best studied on nonferromagnetic substrates. This enables the investigation of the small magnetic response from the ultrathin film, without having to contend with an overwhelming contribution from the bulk of a ferromagnetic substrate. In this study we demonstrate that less than one monolayer of iron induces a reorientation of the easy axis of magnetization of a fcc Ni(111) film from the previously reported[1] in-plane orientation to perpendicular to the film. We find that this spin reorientation takes place over a wide range of Ni and Fe thicknesses, as long as the Fe film grows in a fcc structure.[2]

II. STRUCTURAL PROPERTIES

Our investigations revealed the necessity for high quality Ni templates for the subsequent Fe growth to ensure an exclusive out of plane easy axis of magnetization. A Ni template with a low island density was obtained, only if the first Ni monolayer was annealed to 900 K for several minutes before subsequent Ni layers were grown at room temperature. This is illustrated in the scanning tunneling microscopy (STM) pictures of 2 ML Ni on W(110) in Fig. 1(a). Note the almost perfect layer-by-layer growth, with a very low density of Ni islands of the third layer. Figures 1(b) and 1(c) reveal the relevance of the annealing step for the quality of the subsequently deposited Fe layer. Figure 1(b) shows a STM image of the relatively smooth Fe film with a low step density deposited on the annealed Ni layer of Fig. 1(a), whereas Fig. 1(c) depicts the much higher step density and considerably decreased island size of 0.8 ML Fe deposited on a Ni template which was not annealed. The film of Fig. 1(c) showed in-plane and out of plane easy axes of magnetization. In our low energy electron diffraction (LEED) studies the effect of annealing of the first Ni layer resulted in a somewhat sharper 7×1 diffraction pattern with a slightly decreased background intensity compared to the as-grown film. A detailed growth study on Ni/W(110) including STM, LEED, and stress measurements will be published elsewhere.[3]

To clarify whether Fe grows in the fcc structure, angle-resolved Auger electron spectroscopy (ARAES)[4] was performed. To a good approximation, high energy Auger electrons are emitted isotropically by any one atom. In a crystalline environment, the positive atom cores focus the Fe Auger electrons along the directions where the nearest neighbor atoms lie. This leads to maxima in the Auger electron intensity when it is measured as a function of the detection angle. As is shown in Fig. 2(a), fcc growth can be distinguished from bcc growth by the different angles, under which the maxima are observed. Figure 2(b) clearly shows the absence of any structure around 45°, indicative of bcc growth, but the characteristic fcc maxima at 35° and 55° are obvious for 2 and 3 ML of Fe. The small size of these peaks in the curve for 1 ML Fe indicates minimal intermixing between Fe and Ni, for which fcc like maxima had to be anticipated.

III. MAGNETIC PROPERTIES

In situ magneto-optical Kerr effect measurements[5] in the polar and longitudinal geometry with sample fields of up to 0.3 T were employed to investigate the perpendicular and in-plane magnetization, respectively. As an example of the Fe induced perpendicular easy axis of magnetization we present in Fig. 3(a) a polar hysteresis loop of 1 ML Fe/2 ML Ni. A number of such experiments were done for different Fe

 0021-8979/97/81(8)/4702/3/$10.00

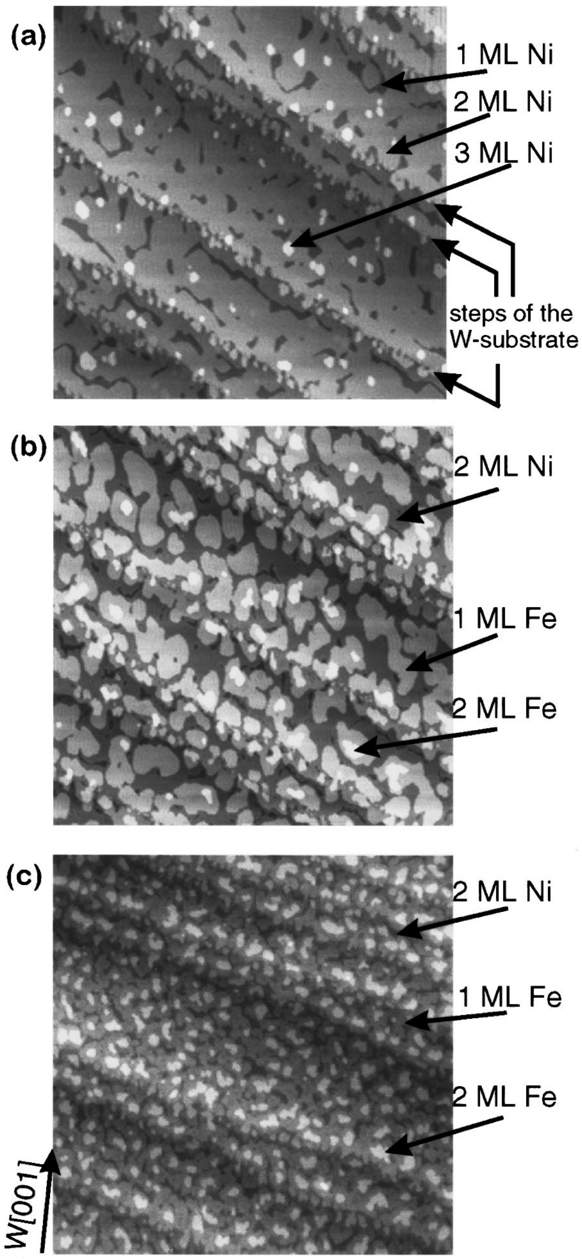

FIG. 1. STM images of Ni/W(110) and Fe/Ni/W(110). Image size is 250 nm×250 nm. Terraces of the W substrate, separated by monoatomic steps running from the upper-left to the lower right hand side of the images are apparent. (a) Deposition of 2 ML Ni on W(110). Anneal at 900 K after deposition of the first ML Ni. (b) Deposition of 0.8 ML Fe on (a) at 300 K. (c) 0.8 ML Fe on 2 ML Ni/W(110). First Ni layer not annealed. Note the considerably increased island density compared to (b).

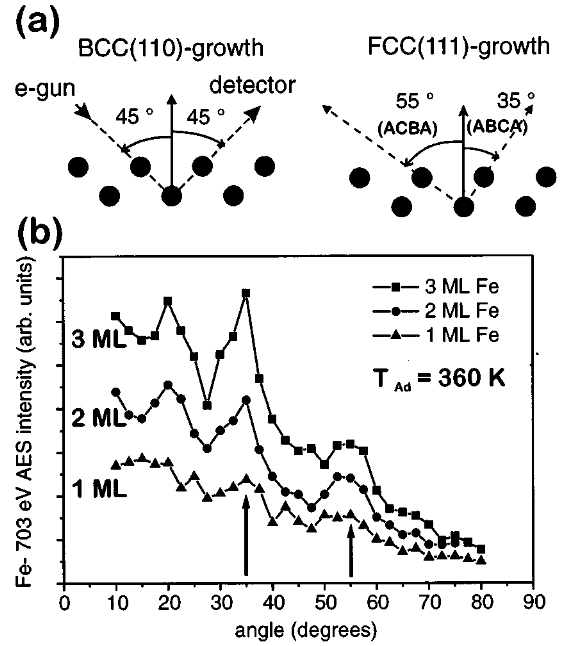

FIG. 2. Angle-resolved Auger-electron spectroscopy, (a) experimental procedure. Different growth modes can be distinguished from the respective position of the intensity maxima. Note that two stacking sequences are expected for fcc growth. (b) Fe Auger electron intensity for different Fe coverages on 2 ML Ni. The maxima at 35° and 55° found for 2 and 3 ML indicate fcc growth. The absence of clear structure in the 1 ML curve indicates no significant intermixing between Fe and Ni.

and Ni thicknesses as a function of temperature. The results of our Kerr effect measurements are summarized in Figs. 3(b) and 3(c).

First, we want to elucidate the question of how much Ni can be made to switch to a perpendicular easy axis of magnetization by a single monolayer of Fe. The corresponding magneto-optic Kerr effect (MOKE) results are summarized in Fig. 3(b). Our results indicate, that the in-plane magnetization reported[1] for thicker Ni films on W(110) does not occur for Fe covered Ni thicknesses of up to 5 ML. For low Ni coverages, we did not observe any magnetic response for 1 ML Fe on 1 ML Ni, either in the polar nor in the longitudinal Kerr geometry. We tentatively assign this to the special morphology of this 1 ML Fe/1 ML Ni bilayer. It is well known from earlier experiments[6] that Ni undergoes a series of different atomic arrangements on the W(110) substrate, starting from a 1×1 structure at low coverage, showing a 8×1 coincidence structure for increasing coverage before a 7×1 structure indicates the completion of the first monolayer. This first Ni layer is not yet sufficiently fcc-like to allow the growth of smooth fcc Fe, whereas a 2 ML Ni template is. There are indications from STM experiments[3] of a slight 7×1 corrugation even in the second layer of Ni. To what extent this minute structural distortion might influence the magnetic properties of the bilayer remains to be investigated. Thus, our maximum magnetic field of 0.3 T might not be sufficient to rotate the film magnetization to the direction of the external field, diminishing our chances to observe any magnetic response with MOKE. This behavior is different from the magnetism of the bare Ni and Fe monolayers: in-plane magnetization has been reported[7] for 2 ML Ni on W(110), and for 1 ML Fe on W(110).[8] In conclusion, we suggest that more than 1 ML of Ni is necessary for the Fe induced spin reorientation to occur.

We find an increase of the remanent polar Kerr signal for increasing the Ni thickness from 2 to 3 ML, but a further increase of the Ni coverage up to 5 ML does not lead to a larger Kerr intensity. Although this almost constant remanent

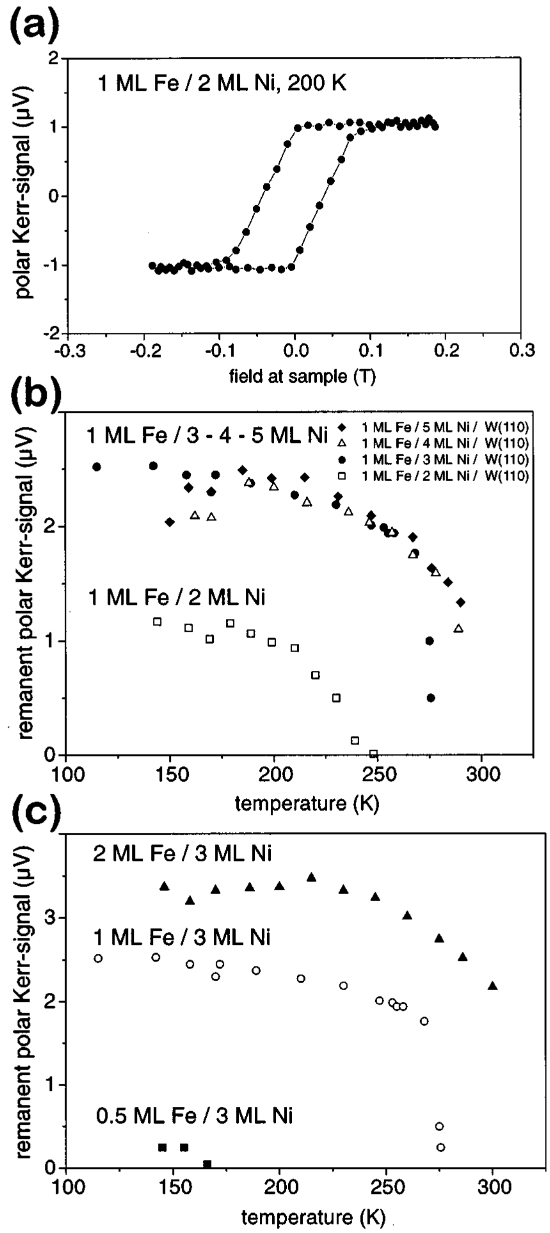

FIG. 3. MOKE results for Fe/Ni bilayers on W(110). First Ni layer annealed. (a) Hysteresis curve measured by the polar Kerr effect, (b) remanent polar Kerr intensity for 1 ML Fe on various Ni coverages, (c) remanent polar Kerr intensity for 0.5–2 ML Fe films on 3 ML Ni.

Kerr signal might indicate that only 2 ML Ni underneath the Fe cap layer contribute to the polar magnetization, only quantitative magnetometry can clarify this issue. Relying solely on the Kerr signal can be misleading, as demonstrated in a recent work on the perpendicular magnetization of Co/Ni/Co multilayers.[9] There, magnetometry revealed that the saturation magnetization increases linearly with Ni thickness, whereas the Kerr intensity is actually decreasing for increasing Ni thickness.[9]

Finally, we discuss the dependence of the polar Kerr signal on the Fe coverage, as shown in Fig. 3(c). Already half a monolayer[10] of Fe is sufficient to induce the reorientation of the easy axis of magnetization (bottom curve). Comparing the remanent polar signals for 0.5, 1, and 2 ML Fe, an increase of the polar Kerr signal with increasing Fe coverage is found. To what extent the magneto-optics of the bilayer or differences in the saturation magnetization are responsible for this increase of the Kerr signal is difficult to judge, especially with the data for 0.5 ML being so close to the transition temperature. More work has to be done to clarify the magnetic Fe/Ni bilayer coupling. A discussion of the influence of the fcc to bcc transition of the Fe film at higher Fe coverages around 4 ML that was found to induce in-plane magnetization of the bilayer will be given elsewhere.[2]

[1] M. Farle, A. Berghaus, Y. Li, and K. Baberschke, Phys. Rev. B **42**, 4873 (1990).
[2] H. L. Johnston, C. S. Arnold, and D. Venus (unpublished).
[3] D. Sander, A. Enders, C. Schmidthals, and J. Kirschner (unpublished).
[4] W. F. Egelhoff, Jr., in *Ultrathin Magnetic Structures I*, edited by J. A. C. Bland and B. Heinrich (Springer, Berlin, 1994).
[5] S. D. Bader, J. Magn. Magn. Mater. **100**, 440 (1990).
[6] J. Kolaczkiewicz and E. Bauer, Surf. Sci. **144**, 495 (1984).
[7] Y. Li and K. Baberschke, Phys. Rev. Lett. **68**, 1208 (1992).
[8] D. Sander, R. Skomski, C. Schmidthals, A. Enders, and J. Kirschner, Phys. Rev. Lett. **77**, 2566 (1996).
[9] P. J. H. Bloemen and W. J. M. de Jonge, J. Magn. Magn. Mater. **116**, L1 (1992).
[10] We found perpendicular magnetization even for 0.25 ML Fe on 2 ML Ni.