Exchange bias in Co/Fe/Fe_xMn_{1-x}/Cu(100) ultrathin films

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Stable and well-grown face-centered-cubic Fe films were prepared on buffer layers with varying lattice constants by depositing Fe_xMn_{1-x} alloy film on Cu(100) single crystal. No ferromagnetic ordering was observed at the stage of 30 ML Fe on the Fe_xMn_{1-x}/Cu(100) systems in the temperature range from 100 to 350 K. Furthermore, capping of Co on Fe/Fe_xMn_{1-x}/Cu(100) was employed as the probe of antiferromagnetic ordering by study of exchange bias coupling in these films. The exchange bias of the hysteresis loops can be observed after field cooling of the films. Further analyses by varying the measurement temperature and Fe coverage of the films were also carried out to clarify the origin of the exchange bias coupling observed. The exchange bias field found here is attributed to the interlayer coupling between the Co and Fe–Mn films through the spacing layer Fe. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1540136]

Much attention has been directed to ultrathin fcc iron films, not only because of the artificial structure not found in nature, but also because of the interesting magnetic behaviors that are extremely sensitive to crystalline structures.[1] In theoretical aspects, the antiferromagnetic (AF) phase of fcc Fe on the Cu(100) substrates was proposed by *ab initio* calculation with both the local spin-density approximation and generalized gradient approximation.[2] In experimental aspects, the fcc-like phase of iron can be epitaxially grown on the fcc Cu(100) substrate.[3,4] The AF phase of fcc iron with ferromagnetic (FM) top layers was observed for room-temperature-grown films, while the coverage of iron ranged from 6 to 11 ML.[1,5] On the other hand, the exchange bias, another fascinating phenomenon for AF materials can be observed for the FM/AF bilayer systems.[6,7] There is a shift of the magnetic hysteresis loops from the origin of the applied field due to the interlayer coupling of AF and FM layers. However, no exchange bias was observed for fcc Fe/Cu(100) films up to now. This can be attributed to the following reasons: First, there are two structures, fcc and fct, mixed in Fe/Cu(100) films for coverage from 6 to 11 ML. It could affect exchange bias coupling, which is sensitive to the FM/AF interface. Second, the blocking temperature (T_B), at which the exchange bias coupling vanishes, for Fe/Cu(100) films could be too low due to the finite size effect in low coverage films.[8,9] Furthermore, the instability of Fe/Cu(100) upon thickness results in low Néel temperature (T_N), or probably in weak exchange bias coupling.

In order to study the inquiries mentioned above, we tried to deposit more stable and thicker iron films with only one fcc crystalline structure for investigation of the exchange bias induced by fcc iron films. This can be done by depositing fcc Fe_xMn_{1-x} films on Cu(100) single crystal as a new synthetic substrate. The Cu(100) single crystal was prepared by sequential sputtering and annealing in an ultra-high-vacuum chamber.[10] The coverage and alloy composition of the Fe_xMn_{1-x} alloy films in our experiments can be precisely controlled with the benefit of a codeposition technique.[11,12] The interlayer distance of Fe_xMn_{1-x}/Cu(100) can be manipulated by varying the alloy composition x.[13,14] In this study, we fixed the alloy composition of the Fe_xMn_{1-x} alloy at $x\sim50\%$, where the Fe–Mn alloy can be grown on Cu(100) substrates in layer-by-layer mode and Fe can be deposited on top with a stable fcc structure, as shown in Fig. 1. Figure 1 complies with the medium energy electron diffraction (MEED) [Fig. 1(a)] as well as intensities of the (00) beam of low energy electron diffraction (LEED) [Fig. 1(b)] for Fe/FeMn/Cu(100) and Fe/Cu(100) films. It is obvious that the fcc structure, which corresponds to the plateau of MEED intensity, in Fe/FeMn/Cu(100) is more stable than that in Fe/Cu(100). The fcc iron can be grown on an FeMn/

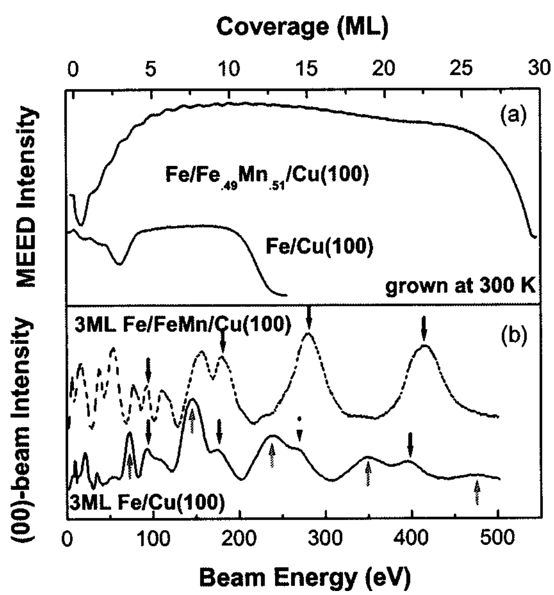

FIG. 1. (a) MEED intensity oscillations of Fe/FeMn/Cu(100) and Fe/Cu(100) films grown at 300 K. (b) LEED (00)-beam intensity as a function of beam energy for Fe/FeMn/Cu(100) and Fe/Cu(100) films. Up and down arrows indicate the characteristics of fct and fcc structures, respectively.

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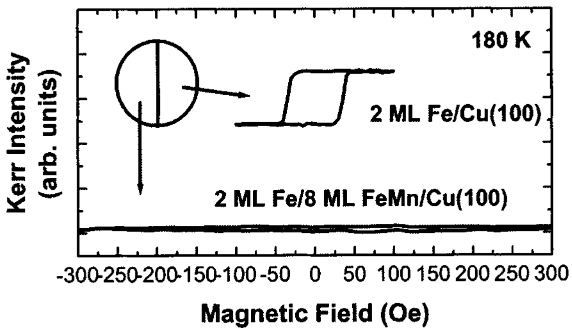

FIG. 2. MOKE measurements of Fe/Cu(100) and Fe/FeMn/Cu(100) films in the polar configuration at 180 K. The films were deposited on one Cu(100) single crystal, as indicated by the top view of the schematic geometries.

Cu(100) substrate up to 30 ML, while it can be observed on the Cu(100) substrate up to only 12 ML, as depicted in Fig. 1(a). In addition, the (00) beam of the LEED $I(E)$ spectrum in Fig. 1(b) reveals the mixing of fcc and fct structures corresponding to the magnetic structures of the mainly antiferromagnetic phase (fcc) with the top-most ferromagnetic layers (fct).[15] However, there is only one fcc phase observed in the Fe/FeMn/Cu(100) films, which is compatible with our magnetic measurements by magneto-optical Kerr effect (MOKE)[14] and the results shown in Fig. 2.

In order to clarify the magnetic structure of Fe/FeMn/Cu(100) and exclude the unexpected effect, such as the contamination, from our investigation, comparison of the magnetic properties between the Fe/Cu(100) and Fe/FeMn/Cu(100) films was carried out, as shown in the schematic diagram of the Fig. 2. The $Fe_{50}Mn_{50}$ film was deposited on half of the Cu(100) substrate before the growth of the iron film. Thus, the magnetic hysteresis loops of Fe/Cu(100) and Fe/FeMn/Cu(100) films can be taken *quasisimultaneously* in this way with variation of the measurement temperature. Figure 2 shows the hysteresis loops for Fe/Cu(100) (right half) and Fe/FeMn/Cu(100) (left half) in the polar configuration of MOKE at 180 K. The out-of-plane magnetization can be observed for Fe/Cu(100) up to 220 K. However, no ferromagnetic phase was observed for Fe/FeMn/Cu(100) at all temperatures investigated (100–350 K) and magnetic field (up to 350 Oe) in our experiments in both polar and longitudinal configurations.

The investigation of exchange bias in the Fe/FeMn/Cu(100) films was carried out by depositing 3 ML cobalt films on top of it at room temperature. There is no significant exchange bias for the as-deposited Co films. After deposition, the films were cooled down to 100 K with a 350 Oe applied field in in-plane orientation (field cooling). The exchange bias as well as the coercive field of the hysteresis loops were enhanced after the field-cooling procedure, as shown in Fig. 3 (140 K). The magnetic hysteresis loops of 3 ML Co on the Fe/14 ML FeMn/Cu(100) film for various temperatures are compiled in Fig. 3. The hysteresis loop at lower temperature reveals both larger coercive field (~50 Oe) and larger bias field (~7 Oe). The bias field (H_{ex}) decreases rapidly as the temperature increases, as shown for the loop at 160 K (~2 Oe). H_{ex} vanishes for the temperature above 180 K. It means that the blocking temperature, the

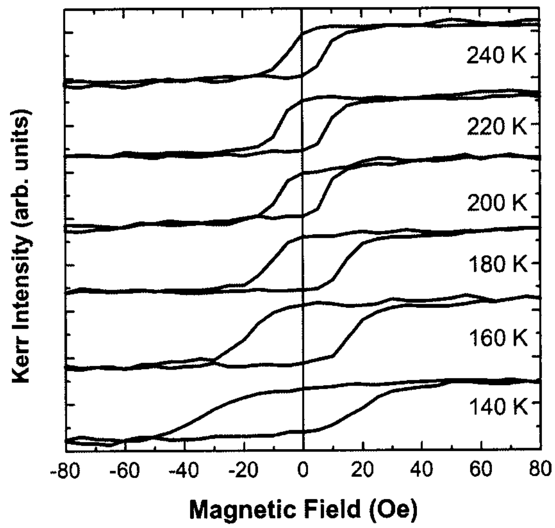

FIG. 3. Magnetic hysteresis loops of the 3 ML Co/8 ML Fe/14 ML FeMn/Cu(100) film at various measurement temperatures after the field-cooling procedure.

characteristic temperature of the exchange bias coupling between the ferromagnetic and antiferromagnetic layers, is around 180 K. This can be easily observed in the bias field versus temperature diagrams, as indicated in Fig. 4. In addition, Auger electron spectroscopy was utilized before and after all of the magnetic property measurements. It confirms that there is no CoO antiferromagnetic layer formed in our systems.

As expected, there exists an exchange bias coupling in the Co/Fe/FeMn/Cu(100) films. However, these films are more complicated than a simple FM/AF bilayer system. The exchange bias field found in these films can be attributed to either the interlayer coupling between Co and Fe films or that between Co and Fe–Mn alloy films. In order to distinguish the interlayer coupling between Co and Fe from that between Co and Fe–Mn, further studies of Co/Fe/FeMn/Cu(100) films were carried out. There is an easy way to

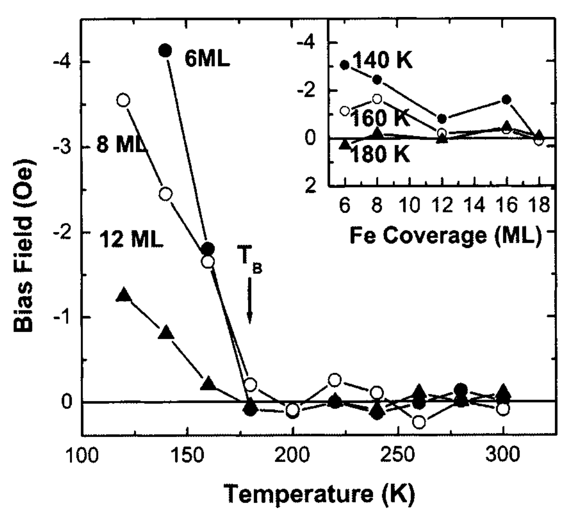

FIG. 4. Bias field of the hysteresis loops as a function of temperature for Co/Fe/FeMn/Cu(100) films with variation of Fe coverage. Inset: bias field vs Fe coverage at 140, 160, and 180 K.

make clear the ambiguity by preparing the Co/Fe/FeMn/Cu(100) films with variation of Fe coverage and measurement temperature. The coverage of the Fe film adopted in our study increases up to 18 ML for avoiding the complicated mixture of the fcc and bcc structures near the phase transition of fcc to bcc. Figure 4 represents the results of our attempt on solving this problem. It complies with the bias field as functions of Fe coverage (inset) and measurement temperature. The exchange bias field for all of the films in our experiments decrease rapidly and vanish at almost the same temperature around 180 K. In addition, the bias field at the same temperature decreases with a small oscillation as the coverage of Fe increases. The bias field should become larger as the Fe coverage increases if it is attributed to the interlayer coupling between Co and Fe films. On the contrary, if the bias field is attributed to the interlayer coupling between Co and Fe–Mn alloy films, one can expect a decrease of bias field while increasing the Fe coverage because the iron film plays the role of a spacing layer and makes no contribution to the exchange bias coupling. From the bias field versus Fe coverage diagram, one can conclude that the exchange bias found here should be attribute to the interlayer coupling between Co and Fe–Mn through the Fe spacing layer. The small oscillation observed here is due to the long-range interlayer exchange coupling overcoming the antiferromagnetic coupling and dominating the exchange bias coupling of the film, which is similar to our previous experiments on the NiO/Cu/NiFe system.[7] Furthermore, this conclusion also can be verified by the behavior of the bias field as a function of temperature in Fig. 4. It indicates that the exchange bias of the hysteresis loops observed in our study is not contributed by Fe, but contributed by the Fe–Mn alloy films since all the bias field versus temperature curves for different Fe coverages vanish at the same temperature.

The reason responsible for the results that the Fe film in Co/Fe/FeMn/Cu(100) makes no contribution to the exchange bias coupling could be twofold. First, the magnetic structures of the fcc Fe/Cu(100) films were found to be out of plane.[5] However, Co on the Fe/FeMn/Cu(100) reveals in-plane magnetization. The exchange coupling may only provide very weak unidirectional anisotropy in this geometry. Furthermore, the detailed spin structure in the fcc AF Fe layers was recently reported to be a complicated spin-density-wave configuration,[16] which may result in the absence of the significant exchange bias field, in contrast to the well-ordered AF spin configuration as usual.

In conclusion, exchange bias coupling was found for Co/Fe/FeMn/Cu(100) films by varying Fe coverage and measurement temperature. The bias field for the hysteresis loops of Co decreases as the coverage of Fe increases. The blocking temperature for films with different Fe coverages in our study remains the same, indicating that the bias field of the hysteresis loops is attributed to the interlayer exchange bias coupling between Co and Fe–Mn alloy films. The fcc Fe film in the Co/Fe/FeMn/Cu(100) system plays the role of a spacing layer to modify the interlayer coupling between Co and Fe–Mn films.

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[1] S. Müller, P. Bayer, C. Reischl, K. Heinz, B. Feldmann, H. Zillgen, and M. Wuttig, Phys. Rev. Lett. **74**, 765 (1995).
[2] M. Friák, M. Šob, and V. Vitek, Phys. Rev. B **63**, 052405 (2001).
[3] W. A. A. Macedo and W. Keune, Phys. Rev. Lett. **61**, 475 (1988).
[4] J. Thomassen, F. May, B. Feldmann, M. Wuttig, and H. Ibach, Phys. Rev. Lett. **69**, 3831 (1992).
[5] D. Li, M. Freitag, J. Pearson, Z. Q. Qiu, and S. D. Bader, Phys. Rev. Lett. **72**, 3112 (1994).
[6] J. Nogués and I. K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999).
[7] M.-T. Lin, C. H. Ho, C.-R. Chang, and Y. D. Yao, Phys. Rev. B **63**, 100404(R) (2001).
[8] C. M. Schneider, P. Bressler, P. Schuster, and J. Kirschner, Phys. Rev. Lett. **64**, 1059 (1990).
[9] T. Ambrose and C. L. Chien, Phys. Rev. Lett. **76**, 1743 (1996).
[10] C. C. Kuo, W. C. Lin, C. L. Chiu, H. L. Huang, and M.-T. Lin, J. Appl. Phys. **89**, 7153 (2001).
[11] M.-T. Lin, W. C. Lin, C. C. Kuo, and C. L. Chiu, Phys. Rev. B **62**, 14268 (2000).
[12] W. C. Lin, C. C. Kuo, C. L. Chiu, and M.-T. Lin, Surf. Sci. **478**, 9 (2001).
[13] F. Offi, W. Kuch, and J. Kirschner, Phys. Rev. B **66**, 064419 (2002).
[14] W. Pan, C. C. Kuo, Y. C. Chen, and M.-T. Lin (unpublished).
[15] R. D. Ellerbrock, A. Fuest, A. Schatz, W. Keune, and R. A. Brand, Phys. Rev. Lett. **74**, 3053 (1995).
[16] D. Qian, X. F. Jin, J. Barthel, M. Klaua, and J. Kirschner, Phys. Rev. Lett. **87**, 227204 (2001).