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Effect of interface roughness on the exchange bias for NiFe/FeMn

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The effect of interface roughness on exchange bias for NiFe/FeMn bilayers is investigated for polycrystalline films and epitaxial films. Three different systems were investigated: polycrystalline Ta (10 nm)/Ni₈₀Fe₂₀ (10 nm)/Fe₅₀Mn₅₀ (20 nm) films on oxygen plasma-etched Si(100) or Cu/H-Si(100) and epitaxial Ni₈₀Fe₂₀ (10 nm)/Fe₆₀Mn₄₀ (20 nm) films on Cu/H-Si(110). For films grown on plasma-etched substrates, as the etching time is increased, film roughness increases up to 12 nm. For the polycrystalline films grown on ultrathin Cu underlayers, x-ray diffraction shows the fcc (111) texture is greatly reduced as the thickness is increased. The epitaxial Cu/Si(110) buffer layer induces fcc (111) epitaxial growth and modifies the interface morphology. The dependence of exchange bias on roughness for each set of samples is explained in terms of a competition between the interfacial exchange coupling and the uniaxial anisotropy. © 2000 American Institute of Physics. [S0021-8979(00)93708-3]

In recent years, there has been extensive interest in exchange anisotropy, which was first observed forty years ago.¹ A shift in the hysteresis loop along the field axis called the exchange-biasing field is often observed in systems that have exchange anisotropy. This shift can be used in spin valves to ‘pin’ one ferromagnetic layer. The exchange anisotropy is a unidirectional anisotropy originating from exchange interaction between ferromagnetic (F) spins and antiferromagnetic (AF) spins at their interface. The NiFe/FeMn F/AF system may be the most extensively studied model system however, a detailed microscopic description of the mechanism of exchange bias remains elusive. Fundamentally, exchange anisotropy is an interfacial phenomenon. So any modification of the interface structure may have a significant effect on it. One of the most important issues is the interfacial roughness. The effect of roughness on exchange bias was studied both theoretically and experimentally by different authors.²⁻⁸ Interestingly, different models gave totally different predictions. Sometimes even opposite conclusions were achieved.³⁻⁵ On the other hand, experimental results appear to depend sensitively on differences in sample preparation as well as on the specific system being studied.⁶⁻⁸ All these reflect the complication of this phenomenon and the importance to probe more details of the microstructure at the interface.

In this experiment, we tried to change the F/AF interface morphology using different methods. The effect of roughness on the exchange bias and the coercivity of the pinned layer was studied systematically with the roughness ranging from less than 1 Å to more than 100 Å. The possible reasons

for the magnetic behaviors of the Ni₈₀Fe₂₀/FeMn F/AF system in different ranges of interfacial roughness are discussed.

In the first approach, Si(100) substrates were reactive ion etched (RIE) for varying etch time to obtain rough surfaces. Ta (10 nm)/Ni₈₀Fe₂₀ (10 nm)/Fe₅₀Mn₅₀ (20 nm) films were dc sputtered with a base pressure of less than 3×10^{-7} Torr. A magnetic field of ~ 100 Oe was applied during film deposition. The surface morphology of the samples was measured by atomic force microscope (AFM). Film structure was characterized by x-ray diffraction (XRD) and hysteresis loops were measured using a vibration sample magnetometer (VSM). The roughness of Si(100) substrates increases with reactive ion etching time, from about 3 to 12 nm. The AFM images taken before and after depositing the film confirm that the surface morphology is conformal during film growth.

In a previous paper, we studied the effect of interfacial roughness that was modified by the introduction of Cu underlayer, for polycrystalline NiFe/FeMn bilayers. The change in surface morphology is a reflection of the initial growth of Cu on Si(100) substrates. Cu grows in islands on Si(100) at the first stage, followed by a coalescence of the islands. The measured roughness of bilayer films grown on these Cu underlayers follows the initial roughness of the Cu film.

Both types of polycrystalline films exhibited fcc (111) texture from the XRD patterns. For the films deposited on RIE etched Si(100) substrates, there is a general trend of decreasing FeMn(111)/NiFe(111) peak to peak ratio as the surface becomes rougher. These measurements show that the crystallography also changes with the interfacial roughness, so any observed changes in magnetic parameters may be at least partially due to the different crystallography of the interface. A study of the orientation dependence on exchange

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bias found a maximum exchange bias for (111) oriented layers, where the interface is fully compensated.² However, for the films deposited on Cu/H-Si(100), the reduction of NiFe/FeMn fcc (111) texture does not lead to a decrease of exchange bias. This suggests crystallography does not play a major role for these films.

To obtain a better understanding of the effect of roughness, we prepared another set of samples in an ultrahigh vacuum system with a starting pressure of less than 5×10^{-9} Torr. H-Si(110) substrates were used as the substrate. To obtain fcc (111) epitaxial growth, a Cu buffer layer with varying thickness was deposited prior to the deposition of a Ni₈₀Fe₂₀ (10 nm)/Fe₆₀Mn₄₀ (20 nm) multilayer.⁹ These films were dc sputtered at a deposition rate of approximately 0.5 Å/s. A magnetic field of ~100 Oe was applied during film deposition to define the pinning direction. Low-energy electron diffraction (LEED) patterns were observed for the substrate and for Cu buffer layer, and the pattern possesses a sixfold symmetry, confirming epitaxial growth. Moreover, the spots become sharper as the buffer layer thickness increases, an indication of better crystallinity. Reflection high-energy electron diffraction (RHEED) patterns are observed after the deposition of the Ni₈₀Fe₂₀ (10 nm)/Fe₆₀Mn₄₀ (20 nm) bilayer, which implies epitaxial growth of the entire film.

The roughness parameters are determined from the height-height correlation function.¹⁰ The height-height correlation function $H(r)$ is defined as $H(r) = \langle [h(r) - h(0)]^2 \rangle$, where $h(r)$ and $h(0)$ are the heights at the coordinate $r(x, y)$ and the reference position (0,0), respectively. The roughness parameters include the vertical interface width w , i.e., rms roughness, the lateral correlation length ξ and the roughness exponent α . They are obtained by fitting the calculated correlation function from the AFM data to the equation $H(r) = 2w^2[1 - \exp(-r/\xi)^{2\alpha}]$. From α , a measure of the surface roughness in the short range ($<\xi$) is obtained.¹⁰ All the α values are larger than 0.5, indicating the short-range surface structure is actually smooth textured.¹¹ The determination of the short-range structure is limited by the radius of the AFM tip, which is <10 nm for the Olympus Tapping Mode Etched Silicon Probes¹² used to measure the epitaxial films.

A detailed analysis of the epitaxial films is presented here. AFM images show the surface roughness and correlation length both increase steadily with increasing Cu buffer layer thickness. In Fig. 1(a), surface roughness is plotted as a function of Cu buffer layer thickness. For the growth of Cu on Cu(100), the dependence of rms roughness on Cu thickness was found to obey a power law with a power law exponent of 0.45.¹³ From the slope of the linear fit to our data, we obtain a power law exponent of 0.16. The power law exponents contain information essential for determining the growth process.¹⁴

In Fig. 1(b), the correlation length is plotted as a function of Cu buffer layer thickness. For the growth of Cu on Cu(100), the dependence of correlation length on Cu thickness was found to obey a power law with a power law exponent of 0.25.¹³ From the slope of the linear fit to our data, we obtain a power law exponent of 0.15. A power law exponent of less than 0.25 for the correlation length implies

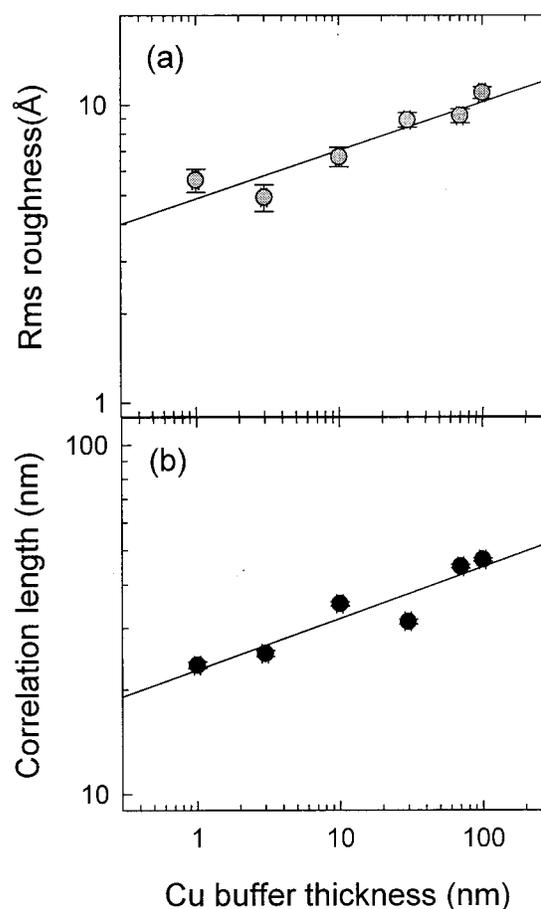


FIG. 1. (a) rms roughness vs Cu buffer layer thickness for H-Si(110)/Cu/Ni₈₀Fe₂₀ (10 nm)/Fe₆₀Mn₄₀ (20 nm). (b) Correlation length vs Cu buffer layer thickness for H-Si(110)/Cu/Ni₈₀Fe₂₀ (10 nm)/Fe₆₀Mn₄₀ (20 nm).

that the surface diffusion process is irreversible, i.e., there is a barrier for downhill diffusion of adatoms. From Fig. 1 we can then conclude that the rms roughness and correlation length are linearly related and can be varied continuously.

Figure 2 is a summary of the magnetic measurements for all the samples discussed above, where the exchange bias and coercive fields are plotted as functions of rms roughness.

For the polycrystalline films deposited on RIE etched Si(100) substrates, the coercive and exchange bias fields are relatively insensitive to the change of roughness.

For the polycrystalline films grown on Cu/H-Si(100), the exchange bias increases with roughness, from <60 Oe for atomically smooth layers to >100 Oe for films with a rms roughness of a few angstroms. The coercive field also increases with the initial increase of roughness.

For epitaxially grown films, no simple correlation is found between exchange bias field and interfacial roughness. The exchange bias fields all lie between approximately 70 and 100 Oe and show variations which are not correlated with the rms roughness. The coercive field increases dramatically with roughness, reaching 50 Oe for the film with 10 Å roughness.

The dependence of exchange bias and coercive fields on roughness is totally different for differently prepared samples. This is explained as resulting from the competition

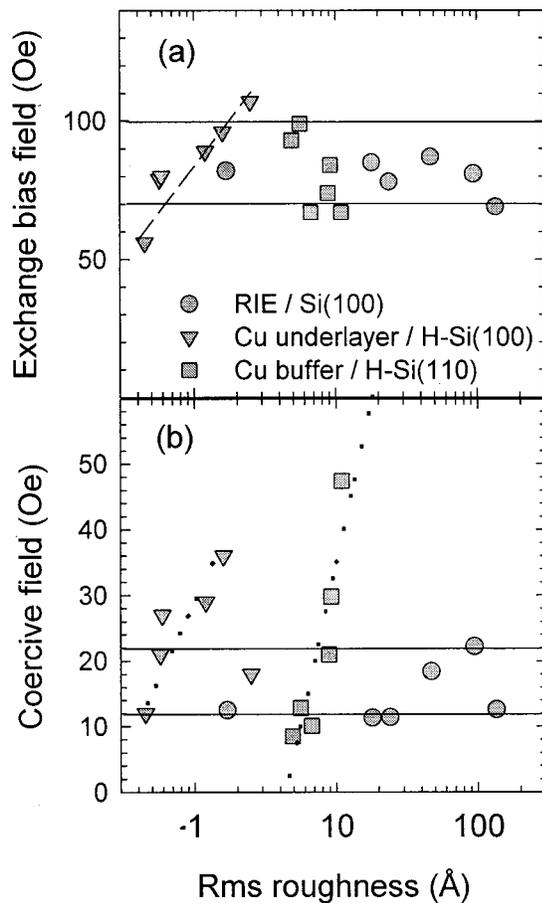


FIG. 2. Exchange bias field and coercive field vs interfacial roughness for RIE etched substrates (circles), Cu underlayer substrates (triangles), and epitaxial Cu/Si(110) (squares). The symbol size is larger than error bars.

of the interfacial exchange coupling and AF uniaxial anisotropy.

In F/AF systems, it is commonly believed that different parts in the antiferromagnet are responsible for the exchange bias and the enhancement of coercivity: those with higher uniaxial anisotropy will remain fixed upon the reversal of the ferromagnet, they contribute to the exchange bias; those with lower uniaxial anisotropy will switch upon the reversal of the ferromagnet, they contribute to the enhancement of coercivity.

For the polycrystalline films deposited on RIE etched Si(100) substrates, the surface correlation lengths are greater than 200 nm and the size of the "mounds" on the surface is much larger than the antiferromagnet grain size. So the roughness has little effect on the AF grain size. As a result, the strength of the interfacial exchange coupling and the anisotropy in the antiferromagnet do not change much with roughness. The exchange bias and coercive fields are insensitive to the roughness.

For the polycrystalline films grown on Cu/H-Si(100), the correlation length of the roughness is about four times smaller and the size of the "mounds" on the surface is com-

parable to the antiferromagnet grain size. The film grown on a rougher surface will have a smaller grain size. Since FeMn(111) is a compensated AF interface, the strength of the interfacial exchange coupling between the ferromagnetic film and the antiferromagnetic grain is inversely proportional to the AF grain size. The increase of exchange bias and the initial increase of coercivity with roughness are results of the increase of strength of the interfacial exchange coupling.¹⁵ Typically, in polycrystalline films, the antiferromagnet anisotropy energy is larger than the interfacial exchange energy. So the increase of interfacial exchange coupling strength not only results in an increase of exchange bias, since a larger field will be required to reverse the ferromagnetic layer, but also an increase of coercivity, since more AF grains will switch upon the reversal of the ferromagnetic layer.

In epitaxially grown films, the induced uniaxial anisotropy is much smaller than that in polycrystalline films. As pointed out previously, the crystallinity improves as the Cu buffer layer thickness increases. This will cause a decrease of the induced uniaxial anisotropy in the AF layer. In this case, the interfacial exchange coupling is as strong as or even stronger than the AF anisotropy. With the decrease of AF anisotropy, more AF grains switch upon the reversal of the ferromagnetic layer, which causes the increase of coercivity. The exchange bias no longer increases since fewer AF grains remain fixed.

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