Journal of Magnetics 5(1), 23-25 (2000)

Effect of ECR-Ion Milling on Exchange Biasing in NiO/NiFe Bilayers

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(Received 20 December 1999)

We have investigated the effects of Ar and O_2-ion milling on the exchange coupling field (H_{ex}) and coercive field (H_c) at the interfaces between substrates and NiO/NiFe films, to understand the exchange biasing mechanism. The O_2-ion milling was successfully performed by means of the electron cyclotron resonance (ECR) process. We found that the local roughness gradient of the NiO surface increased by O_2-ion milling. The ratio of H_{ex}/H_c increased from 0.87 to 1.77, whereas H_c decreased by almost a half as a results of the ion milling. The decrease in H_c could be interpreted as due to the refinement of magnetic domain size, which arose from the increase of the local roughness gradient of the NiO surface. The decrease in low H_c and increase in H_{ex} in NiO spin valves by ECR-ion milling are in the right direction for use in magnetoresistance (MR) heads.

1. Introduction

One of the interesting problems in NiO-based spin-valves is the effect of the interfacial topology on exchange biasing and coercivity. Recently, it has been reported that roughness and grain size are important for the control of exchange biasing. The exchange coupling field (H_{ex}) is known to depend mainly on the degree of interfacial roughness rather than on crystallographic texture [1-3]. A few groups reported that H_{ex} increased with increasing interfacial roughness in NiFe/CoO(111) [4]. On the other hand, it was reported that the grain-size of NiO, rather than the roughness, might be more important to control H_{ex} [5]. Despite extensive work, many questions remain regarding the role of interface structure.

In our previous work, values of H_{ex} and H_c in NiO spin-valves were attributed to the local gradient of surface features rather than rms roughness and crystal texture [6]. In this work, we report the effects of Ar and O_2-ion milling of the interfaces between substrates and NiO/NiFe bilayers, to get a better understanding of the influence of local roughness gradient on H_{ex} and H_c.

2. Experimental

The Ar and O_2 ion milling process was performed using ECR milling of the substrate/NiO interface, where Corning glass 7059 and MgO (100) were used as substrates. The ion milling conditions were: acceleration voltage 800 V, beam current 5 mA, milling time 30 minutes. Both O_2 and Ar gas pressures were 1 mTorr. The incident angle of the ion beam was 45° to the plane of the glass substrates. Since the surface morphology of a single crystal varies with incidence angle, the incident beam was varied in both the incident angle θ and the azimuthal angle φ (measured from the [001] direction), as follows i) θ, φ=0°, ii) θ, φ=45°, and iii) θ=45°, φ=0°, to obtain various surface morphologies of the MgO (100) substrates.

The NiO(450 Å)/NiFe(50 Å)/Cu(18 Å)/NiFe(60 Å) spin valves and NiO(350 Å)/NiFe(50 Å) bilayers were deposited by means of rf and dc magnetron sputtering at rates of about 6~10 Å/min and 1.5 Å/sec in an Ar pressure of 1.5 mTorr, respectively. A uniaxial magnetic field of 320 Oe was applied during deposition. The H_{ex} and H_c values of the NiO/NiFe bilayers were obtained from magnetoresistance (MR) and M-H curves. The surface morphologies of the NiO films were examined using an atomic force microscope (AFM).

3. Results and Discussion

Figure 1 shows the surface morphologies of glass/NiO(350 Å) and the M-H curves of glass/NiO(350 Å)/NiFe(50 Å) with and without ECR Ar and O_2-ion milling of the glass/NiO interface. The values of H_{ex} and H_c of the bilayers without ion milling were 117 Oe and 135 Oe, respectively. After Ar-ion milling, both H_{ex} and H_c decrease, to 100 Oe and 65 Oe, respectively. In the case of O_2-ion milling, H_{ex} increases to 129 Oe and H_c decreases to 73 Oe. The ratio H_{ex}/H_c increases from 0.87 to 1.77 by O_2 ion milling. The rms surface roughness of the glass substrates after Ar and O_2 ion milling increased slightly from 0.98 Å before milling to 2.0 Å and 2.6 Å after milling. These results indicate that the ion milling caused interfacial roughness to increase, and enhanced the H_{ex}/H_c ratio in the NiO/NiFe bilayers.

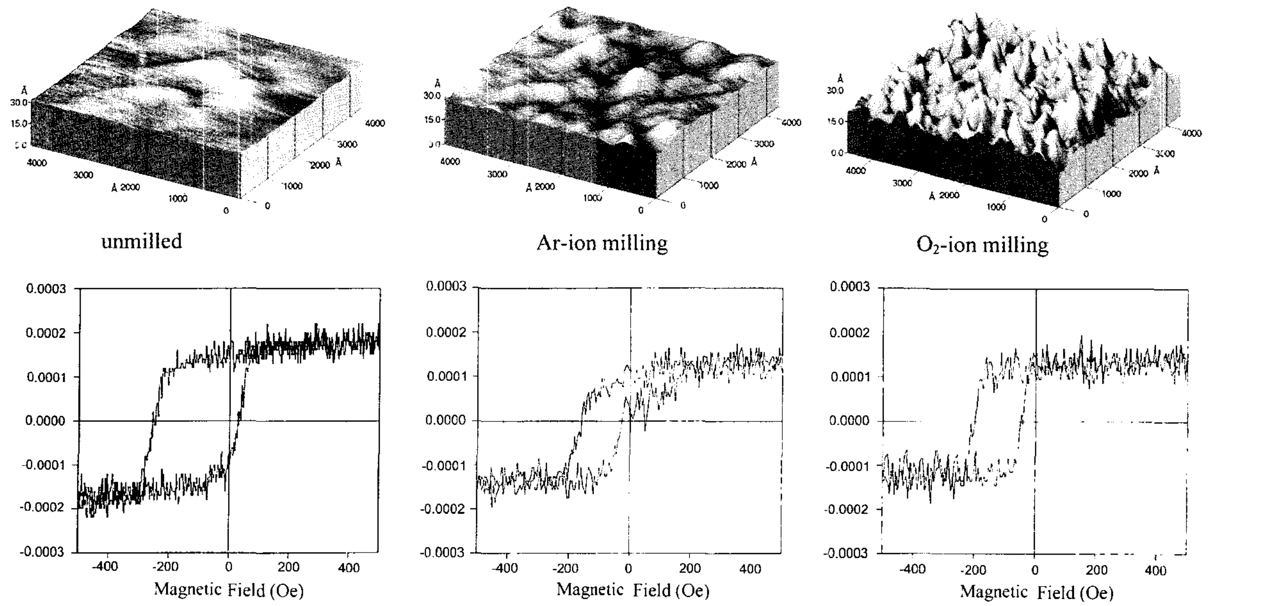

Fig. 1. The surface morphologies of glass/NiO(350 Å) and M-H curves of glass/NiO(350 Å)/NiFe(50 Å) with and without ECR O_2 and Ar ion milling.

The local roughness gradient (R_{grad}), defined as the ratio of average wavelength to peak-to-valley height of clusters in the AFM image, was introduced in order to explain the dependence of exchange biasing on roughness. The quantity R_{grad} was called the slope of roughness R_s in our earlier works [6, 7]. Rms roughness (R_{rms}) does not specify the local gradient of a cluster, because R_{rms} is calculated from the heights of an individual AFM image. The R_{grad} values of two surfaces can be different, even if their R_{rms} values are identical. The values of H_{ex} and H_c in NiO spin valves are attributed to R_{grad} rather than to R_{rms}, because the high gradient could both increase the magnetostatic energy and decrease the antiferromagnetic domain size.

The R_{grad} of NiO film surfaces increases by a factor of 10, from 1/200 to 1/20, by O_2-gas ion milling, while R_{rms} increases about 2.6 times, as shown in Table 1. The change in H_{ex} by ion milling is not very significant, but that in H_c is appreciable. Such changes may be due to the reduction of magnetic domain size in the NiFe film. The high gradient increases the local demagnetization field, and the magnetic domain size is reduced in order to decrease magnetostatic energy. The reduced domain size aids in easy displacement of domain walls [7].

Table 1 shows the ECR ion milling conditions, the rms roughness, the local roughness gradient, and H_{ex} and H_c, in NiO/NiFe bilayers deposited on Corning glass 7059 and MgO(100). We expected that the MgO(100) substrates milled with various incident angles of the O_2-gas ion beam, would have different anisotropic surfaces. However, only surface roughness was changed. NiO films deposited on milled MgO(100) have a larger roughness than those on glass substrates. For a specimen without ion milling, the H_{ex} and H_c values are 93 Oe and 116 Oe, respectively. Both these values are lower than those on glass, [H_{ex}=117 Oe and H_c=135 Oe], but the H_{ex}/H_c ratio is almost the same, about 0.8. The H_{ex}/H_c ratio for the perpendicular incident beam (θ=0°, φ=0°) is slightly smaller (0.74) than that for the specimen without ion milling (0.8), and that for the

Table 1. Effects of ion milling of substrates on roughness and magnetic properties

Substrate	Milling conditions	rms roughness	local roughness gradient	H_{ex}	H_c	H_{ex}/H_c
Corning 7059	none	0.98 Å	1/200	117 Oe	135 Oe	0.87
	Ar-ion milling	2.0 Å	1/80	100 Oe	65 Oe	1.54
	O_2-ion milling	2.6 Å	1/20	129 Oe	73 Oe	1.77
MgO (100)	none	8.3 Å	1/10	93 Oe	116 Oe	0.80
	θ=0°, φ=0° O_2-ion milling	10 Å	1/6	100 Oe	135 Oe	0.74
	θ=45°, φ=0° O_2-ion milling	11 Å	1/3	99 Oe	91 Oe	1.09
	θ=45°, φ=45° O_2-ion milling	13 Å	1/4	85 Oe	77 Oe	1.10

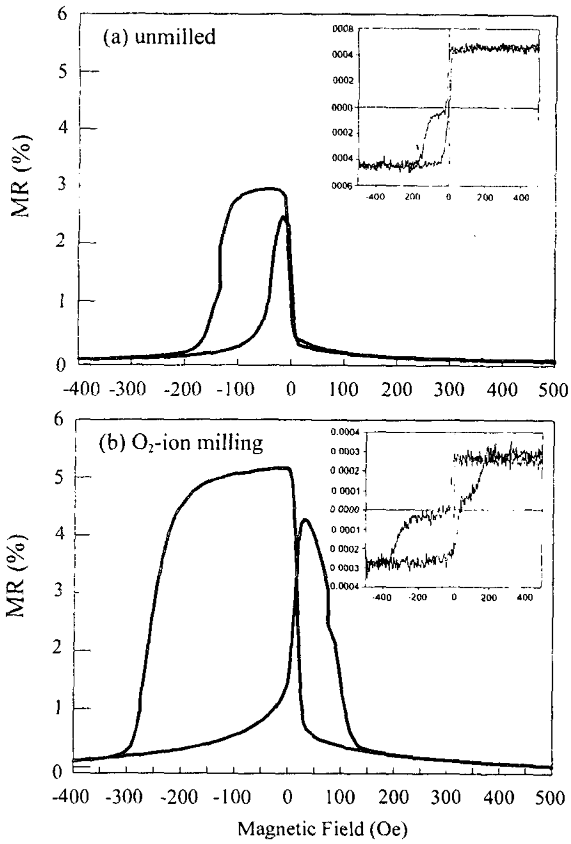

Fig. 2. The magnetoresistance and M-H (inset) curves of glass/NiO(450 Å)/NiFe(50 Å)/Cu(18 Å)/NiFe(60 Å) spin valves (a) with and (b) without O_2 ion milling, where the deposition rate of NiO is 10 Å/min.

inclined (θ=45°, φ=0°) or rotated (θ=φ=45°) ion milling beam increases to about 1.1. Therefore, ECR-ion milling of both glass and MgO substrates enhances the H_{ex}/H_c ratio.

Figure 2 shows the MR and M-H curves of glass/NiO(450 Å)/NiFe(50 Å)/Cu(18 Å)/NiFe(60 Å) spin valves with and without O_2-ion milling, where the deposition rate of NiO is 10 Å/min. From the M-H curve, it is seen that ion milling increases H_{ex} and H_c. The MR curve of the unmilled spin valves has an MR ratio of 3%. However, by O_2-ion milling, the MR ratio increases to 5.2%. The difference between the H_{ex} and H_c of the spin valves and the bilayers is caused by the different deposition rate and thickness of the NiO layer, and the exchange coupling between the pinned NiFe and free NiFe. These results show that the MR ratio and exchange biasing field are improved by the O_2-ion milling process. Large MR ratio and high exchange biasing in NiO spin-valves are advantageous for application in magnetoresistive read heads.

4. Conclusions

The effects of ECR-ion milling of the substrate on exchange biasing and coercivity in NiO/NiFe bilayers deposited on glass and on MgO(100) have been investigated. The ECR-oxygen ion milling process improves the H_{ex}/H_c ratio. Especially for glass substrates, H_c decreased by one-half, and the MR ratio in the spin-valves doubled, as a results of milling. Therefore the oxygen ion milling process is a useful method to improve MR and the H_{ex}/H_c ratio.

Acknowledgement

The authors would like to acknowledge gratefully that the present work was supported by the Nano Structure Technology Project of MOST.

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