Highly oriented NiFe soft magnetic films on Si substrates

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Highly oriented NiFe thin films have been produced via sputter deposition on HF etched Si substrates. Cu and Ag are used as underlayers to induce the epitaxial growth of NiFe films. The orientation relationships between NiFe, Cu, Ag, and Si have been determined by x-ray diffraction measurements and transmission electron microscopy. Magnetic properties have also been characterized. [S0021-8979(99)45808-6]

INTRODUCTION

Due to their high magnetic moment and low magnetostriction, NiFe films are very important soft magnetic materials. They are widely used in magnetic data storage technologies, as the soft underlayer for perpendicular recording media, the flux path of inductive recording heads, the sensor element of magnetoresistive and giant magnetoresistive playback heads, and the sensor element in magnetic random access memories. In most cases, a very smooth, highly oriented film structure is desired. Previously, single crystal substrates such as MgO have been used to achieve highly orientated film structures.[1] In this study, highly oriented (111) and (100) NiFe films were epitaxially grown by sputter deposition using HF-etched Si(111) and Si(100) substrates. As reported[2–5] the very long range order of the single crystal Si surface and the very close 4 unit cell to 3 unit cell lattice match between Ag and Si, respectively, yields Ag(100)‖Si(100)-HF, Ag(110)‖Si(110)-HF and Ag(111)‖Si (111)-HF single crystal templates for the growth of other films. While the lattice match between NiFe and Ag is better than that of NiFe and Si, the lattice matches between NiFe/Cu, Cu/Ag, and Ag/NiFe are far superior and provide a multiple layer pathway to obtaining highly oriented NiFe films. The methodology, crystalline quality, and magnetic characteristics of these films are described below.

EXPERIMENT

Si wafers were first ultrasonically cleaned in organic solvents and rinsed in de-ionized water. Clean wafers were then immersed in HF to remove the native SiO_2 and to obtain a hydrogen-terminated surface. The etched wafers were blown dry using N_2 gas, then placed into the sputtering system, and heated to about 250 °C in vacuum before deposition. Ag, Cu, and NiFe thin films were deposited by rf diode sputtering in a Leybold–Heraeus Z-400 sputtering system. The base pressure was below 5×10^{-7} Torr. The Ar sputtering gas pressure was fixed at 10 mTorr and the sputtering power density was about 2.3 W/cm^2. The composition of permalloy used in this work is $Ni_{79}Fe_{21}$ in weight percent. The microstructures of the films were studied by x-ray diffraction and TEM. X-ray rocking curve measurements were employed to investigate the dispersion of the orientation textures. Magnetic hysteresis loops were measured using a *BH* loop tracer.

RESULTS AND DISCUSSION

Since permalloy is either fcc or an fcc derivative crystal structure ($L1_2$) with its easy magnetic axes along the ⟨111⟩ crystalline directions, a (111) textured film, along with the out-of-plane demagnetization effects, results in a threefold magnetic easy axis symmetry lying in the crystallite film plane. For commonly prepared polycrystalline films these characteristics, along with exchange coupling between the crystalline grains, results in low coercivity films. To gain even better control of the coercivity, one desires that the magnetic properties be isotropic in the film plane. It should be possible to achieve low coercivity and isotropy in the plane provided $K_1<0$, $K_2=0$, that the film is a single crystal with a (111) orientation perpendicular to the film plane. In an attempt to achieve these characteristics NiFe films were deposited on single crystal Si(111) oriented substrates. When the NiFe is deposited directly on HF etched Si there was no obvious improvement in the (111) texture over films deposited on glass. This is probably largely due to the large lattice mismatch between Si and NiFe. Figure 1 schematically shows the atomic spacings with the (111) plane of Si, Ag, Cu, and NiFe. However, since Ag(001) films epitaxially grow on a clean Si(001) substrate surface,[1] it was conjectured that a similar result might occur for the (111) orientation. An improved texture was obtained for the film structure NiFe/Ag/Si(111) HF etched as evidenced by the strong x-ray diffraction peak shown in Fig. 2(a). While we found that by our cleaning and deposition technique, Cu did not epitaxially

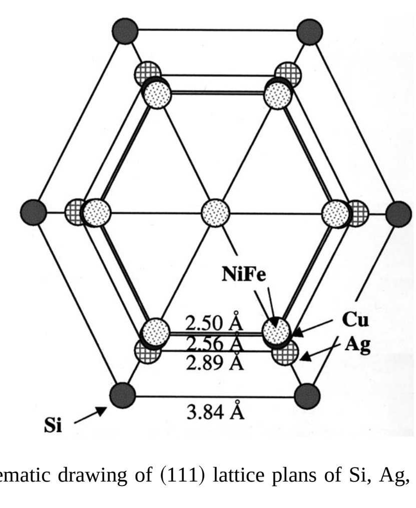

FIG. 1. Schematic drawing of (111) lattice plans of Si, Ag, Cu, and NiFe.

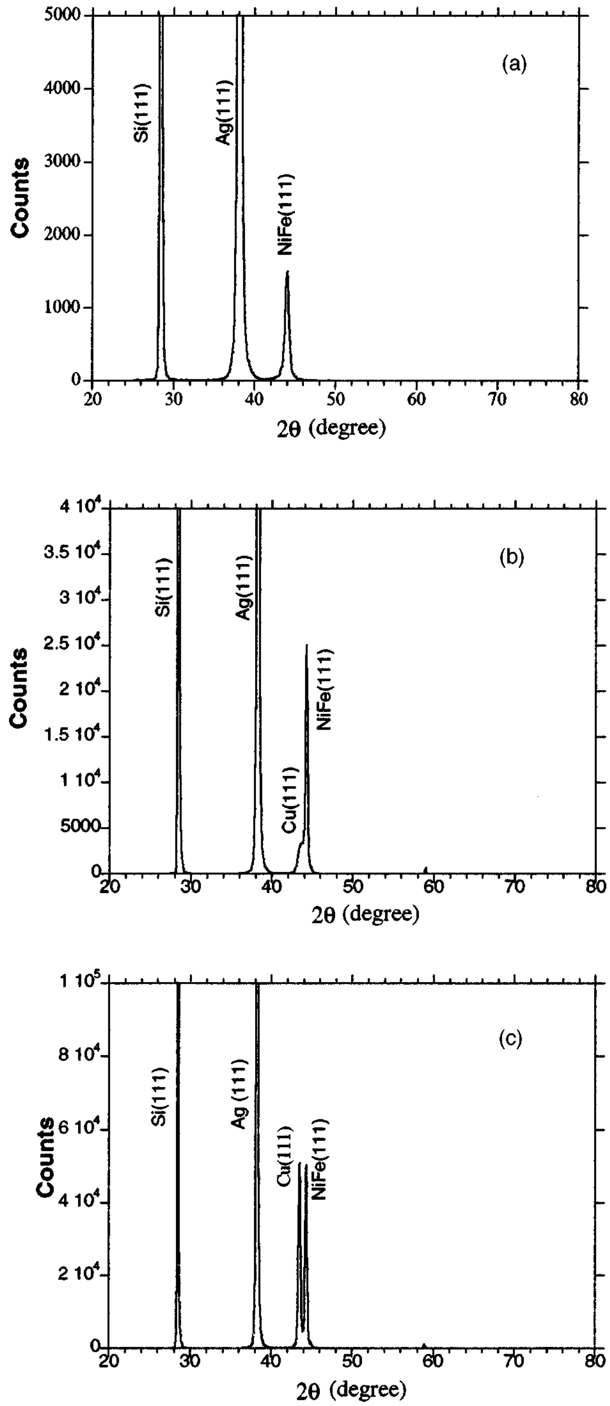

FIG. 2. X-ray diffraction spectrum of samples deposited on HF etched Si(111) substrates. (a) NiFe 50 nm/Ag 100 nm; (b) NiFe 50 nm/Cu 10 nm/Ag 100 nm; (c) NiFe 50 nm/Cu 50 nm/Ag 100 nm.

grow well directly upon HF-etched Si, we did find that the texture of the NiFe could be further improved and epitaxial orientation induced by inserting a Cu underlayer between the Ag and the NiFe. The lattice mismatch between the Cu(111) and the NiFe(111) is only about 2% while the mismatch between Ag and Cu is large (12%). Nevertheless, epitaxy between the three layers and the substrate is very good. In fact, it was found that the Ag layer thickness could be less than 10 nm and still induce good Cu epitaxy.

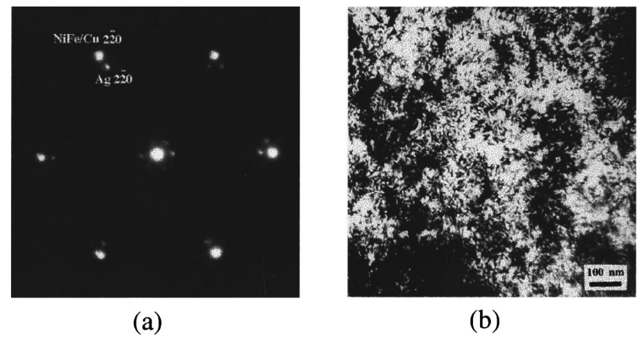

FIG. 3. (a) TEM selected area diffraction pattern (SADP) of the (111) zone axes of the NiFe, Cu, Ag layers for a NiFe 50 nm/Cu 50 nm/Ag 100 nm/HF etched Si(111) sample. (b) Corresponding bright field image.

Figure 2(b) shows the x-ray diffraction of a NiFe 50 nm/Cu 10 nm/Ag 100 nm/HF-etched Si(111) sample. In comparison to Fig. 2(a), it is observed that the (111) NiFe peak has been significantly improved via the introduction of the 10 nm Cu layer. Figure 2(c) shows that further improvements in the NiFe(111) texture can be obtained by increasing the thickness of the Cu layer to 50 nm. We believe that increase in the Cu layer thickness relieves some of the strain in the Cu due to the lattice mismatch between the Cu and Ag.

To further confirm the epitaxial nature of the NiFe films, transmission electron microscopy (TEM) was employed. Figure 3(a) shows a TEM selected area diffraction pattern of the (111) zone axes of the NiFe, Cu, and Ag layers of a NiFe 50 nm/Cu 50 nm/Ag 100 nm/HF-etched Si(111) sample. The reflections from the Cu and NiFe nearly overlap due to their closely matched lattice parameters. The high quality epitaxial relationship of NiFe(111) [220]‖Cu(111)[220]‖Ag(111)[220] is evident from this diffraction pattern. Combined with our previous results,[3] which confirmed the epitaxial relationship of Ag(111) on Si(111) as Ag(111) [220]‖Si(111)[220], the epitaxial relationship of this structure was determined to be NiFe(111)[220]‖Cu(111)[220]‖Ag(111)[220]‖Si(111)[220].

Figure 3(b) shows the corresponding bright field TEM image. The Moiré fringe-like contrast arises due to the double diffraction spots surrounding the transmitted beam in the SADP shown in Fig. 3(a). The selected area aperture used in bright field imaging includes these spots in addition to the transmitted beam. The fringe spacing closely matches that predicted from the difference in the {220} d spacings between NiFe and Cu.

To investigate the texture dispersion out of the film plane, x-ray rocking curve measurements were performed on the NiFe 50 nm/Cu 50 nm/Ag 100 nm /HF–Si(111) sample. The measured rocking curve for the Ag(111) peak at the 38.3° 2θ position of the x-ray diffraction (XRD) pattern showed that the $\Delta\theta_{50}$ is 0.73°, indicating that the dispersion is very small. For the Cu(111) peak in which the 2θ position is 43.4°, the $\Delta\theta_{50}$ was determined to be 0.6°. The NiFe(111) peak in which the 2θ position in the XRD spectrum is 44.3° is very close to the Cu(111) peak. However, due to the high degree of orientation (see Fig. 2), the rocking curves are distinguishable. The measured $\Delta\theta_{50}$ for NiFe(111) was only 0.78°.

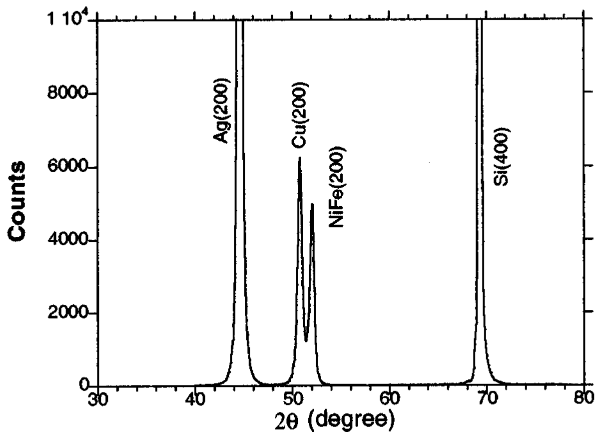

FIG. 4. X-ray diffraction spectrum of NiFe 50 nm/Cu 50 nm/Ag 100 nm deposited on HF etched Si(100) substrate.

From the rocking curves described, we note that the dispersion of the (111) texture of Ag, Cu, and NiFe are all very small, indicating good quality of epitaxial growth. Moreover, the measured $\Delta\theta_{50}$ values are about the same for the three layers. This implies that there is no obvious degradation of the epitaxial quality in going to the Cu and NiFe film layers.

Using the same multilayered approach, NiFe(100) films have also been epitaxially grown on HF-etched Si(100) substrates via rf diode sputtering. Figure 4 shows the x-ray diffraction spectrum of the layered structure of NiFe 50 nm/Cu 50 nm/Ag 100 nm on HF-etched Si(100).

The soft magnetic properties have been observed via in-plane magnetic hysteresis loops measured using a *BH* loop tracer. For example, the sample with structure of NiFe 50 nm/Cu 50 nm/Ag 100 nm/Si(111) has a maximum in-plane coercivity of 2.64 Oe and minimum coercivity of 1.65 Oe, depending upon the orientation of the sample relative to the applied field. This difference is suspected to be partly due to the earth's magnetic field being applied during deposition, which induces a weak in-plane uniaxial anisotropy. However, since the earth field is not large, the observed easy and hard axes are not well defined. It is anticipated that the magnetic properties can be optimized by controlling the applied magnetic field during deposition. For the (100) textured NiFe film mentioned above, the in-plane coercivity is larger and measured to be greater than 20 Oe. This difference is suspected to be mainly due to the crystalline anisotropy. At the composition of Ni 79 wt %, the K_1 of NiFe is small and negative,[6] so $\langle 111 \rangle$ directions become the easy axes of magnetization.

CONCLUSIONS

In this study, highly oriented NiFe films have been achieved via the employment of HF-etched Si substrates. Ag and Cu underlayer depositions on Si substrates are used to induce the epitaxial growth of NiFe films. The orientation relationships between the layers were determined by x-ray diffraction spectra and TEM. Soft magnetic properties were observed in NiFe(111) films.

ACKNOWLEDGMENT

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