Microstructural study of ion-beam deposited giant magnetoresistive spin valves

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Detailed microstructural investigation of ion beam deposited giant magnetoresistance (GMR) spin valves has been carried out using various techniques of transmission electron microscopy (TEM) and x-ray diffraction. Two fcc phases, i.e., FeMn and NiFe/Co/Cu/Co/NiFe have been identified in ion-beam deposited Ta (50 Å)/FeMn (80 Å)/NiFe(30 Å)/Co(15 Å)/Cu(33 Å)/Co(15 Å)/NiFe(60 Å)/Ta(25 Å)/Si(001) spin valves. The Ta buffer layer is amorphous, while the 50-Å-thick Ta cap layer consists of a 25-Å-thick amorphous layer and on top of which a Ta oxide layer. The lattice constants of the fcc FeMn and the fcc NiFe/Co/Cu/Co/NiFe increase with the ion-beam voltage. Both the FeMn and the NiFe/Co/Cu/Co/NiFe layers are (111) textured. The misfit strain between the FeMn layer and the pinned NiFe layer is released by the formation of dome shape FeMn surface rather then by the formation of misfit dislocations at the interface between the two layers. The peak to valley height of the domes seems to have little effect on the GMR properties of the ion-beam deposited spin valves. It was found that large columnar grain width gives large exchanged field and $\Delta R/R$ of the spin valves. [S0021-8979(97)32708-X]

Giant magnetoresistance (GMR) spin valves are promising candidates for high density magnetic recording read head sensors.[1] Currently spin valves of the form FeMn/NiFe/Co/Cu/Co/NiFe are under intensive investigation due to their large $\Delta R/R$.[2] Microstructurally, the major concerns in spin-valve multilayers are the identity of the phases, their texture, the grain size, the roughness of each individual layers, and the interfacial structure between the layers. These microstructural parameters of a spin valve are believed to be closely related to its magnetic and magnetotransport properties, such as the exchange field between the FeMn and the pinned NiFe layers, the coercivity of each ferromagnetic layers and magnetic coupling between them, as well as the $\Delta R/R$ and its low field sensitivity. It should also be pointed out that the microstructure of a spin valve is strongly dependent on the processing methods and conditions. It has been reported that a more stable spin-valve microstructure could be achieved by ion-beam deposition than that by sputter deposition.[3] This may be beneficial to the integration of the spin-valve element with other head components since it usually takes many steps to fabricate a head and a stable starting spin-valve microstructure is desirable. In this article, we report results of detailed microstructural characterization of FeMn/NiFe/Co/Cu/Co/NiFe spin valves prepared by ion-beam deposition under different conditions. Correlation between the microstructure and magnetic/magnetotransport properties of the spin valves will also be addressed.

Three Ta(50 Å)/FeMn(80 Å)/NiFe(30 Å)/Co(15 Å)/Cu(33 Å)/Co(15 Å)/NiFe(60 Å)/Ta(25 Å)/Si(001) spin valves were deposited using a dual ion-beam deposition chamber. The beam voltage used for depositing the three spin valves was 300, 500, and 850 V and the beam current was 150 mA. The depositions were made in an Ar atmosphere at a deposition rate that ranged between 0.2 and 1.5 A/s. Magnetotransport properties of the spin valves were measured using a four point probe. θ–2θ x-ray diffraction spectra of the spin valves were obtained using a Cu $K\alpha$ radiation. Philips 420T and JEOL 4000 transmission electron microscopes (TEM) were used to investigate the plan-view and cross-section microstructure of the spin valves, respectively.

Table I lists the $\Delta R/R$ values, and the exchange field between the FeMn layer and pinned NiFe layer of the spin valves deposited at different ion-beam voltage. It can be noted from Table I that the exchange field and $\Delta R/R$ increase from 135 Oe and 2.5% for the spin valve deposited at 300 V to 165 Oe and 4% when the ion-beam voltage is increased to 500 V. A further increase in ion-beam voltage to 850 V, however, reduces both the exchange field and $\Delta R/R$ to 130 Oe and 1.8%, respectively.

For each spin valve, only two peaks were detected in the θ–2θ x-ray spectrum (Fig. 1). The larger peak for each spin valve in Fig. 1 is the fcc 111 peak of NiFe/Co/Cu/Co/NiFe and the smaller one is the fcc FeMn 111 peak. Increasing the ion-beam deposition voltage, however, reduces the intensity of both the NiFe/Co/Cu/Co/NiFe 111 and FeMn 111 peaks. Furthermore, the peaks shift slightly toward lower 2θ angles

TABLE I. Magnetic and magnetotransport properties of the spin-valves deposited with different ion-beam voltage.

Ion beam voltage (V)	Exchange field (Oe)	$\Delta R/R$(%)
300	135	2.5
500	165	4
850	130	1.8

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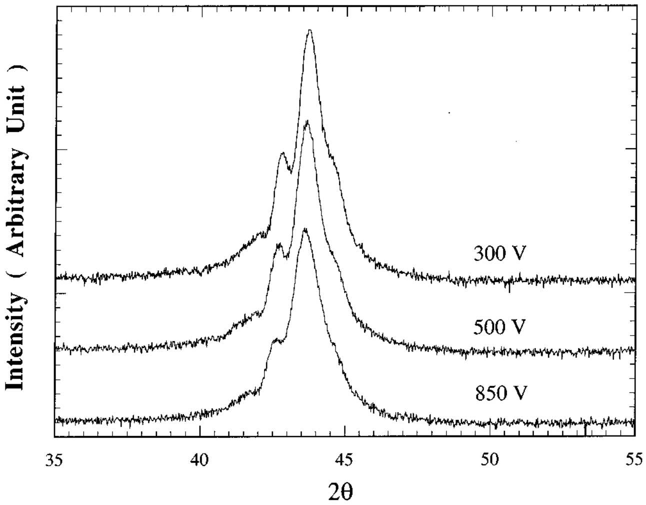

FIG. 1. θ–2θ x-ray diffraction spectra of the spin valves deposited by ion beam with different voltage.

(larger d spacing) with increasing ion-beam voltage, indicating that high voltage ion beam deposited films are more compressive stressed. The lattice constants of the spin valves determined from the x-ray data are: 3.59 (300 V), 3.60 (500 V), and 3.60 Å (850 V) for NiFe/Co/Cu/Co/NiFe; 3.66 (300 V), 3.67 (500 V), and 3.68 Å (850 V) for FeMn. The plan-view TEM images of the three spin valves are similar. Figure 2(a) shows the bright field TEM image of the spin-valve deposited with an ion beam of 300 V at 0° tilt, i.e., when the electron beam direction is parallel to the film normal (Si [001] direction). The image is characterized by a very fine grain structure with the average grain size of about 100 Å. These fine grains are believed to be the partially oxidized Ta cap layer. Figures 2(b) and 2(c) are the diffraction patterns of the spin valve at 0° and 40° tilt. Figure 2(b) consists of the Si [001] zone axis diffraction spots and the diffraction rings of the spin valve. Two fcc 200_0 rings can be clearly identified in

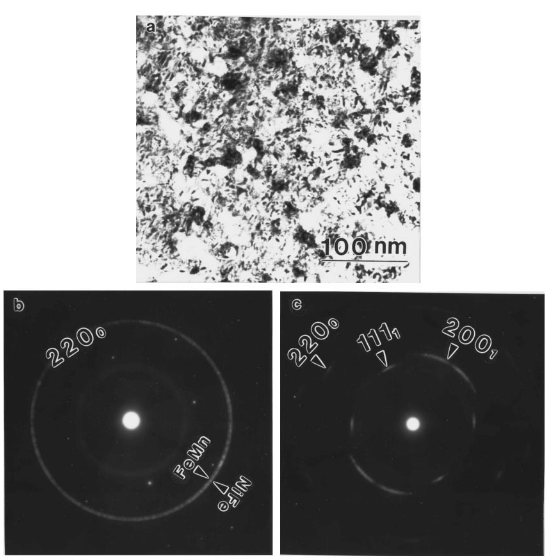

FIG. 2. (a) Bright field image at 0° tilt; diffraction patterns (b) 0° tilt, and (c) 40° tilt of the spin valve deposited by an ion beam at 300 V.

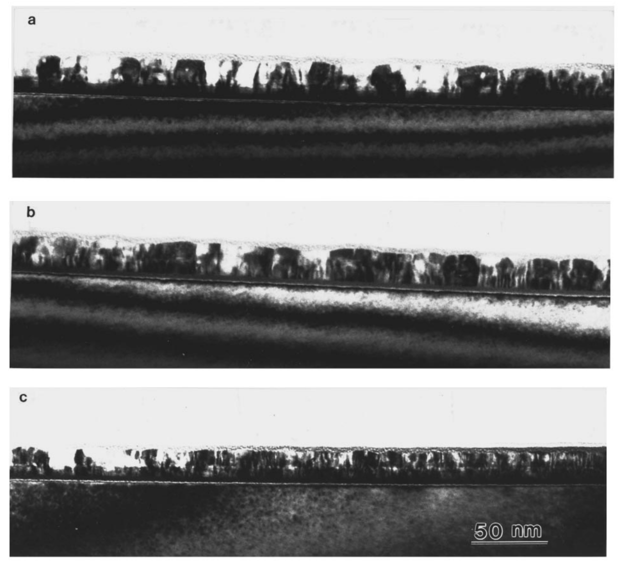

FIG. 3. Cross-section TEM bright field images of the spin valves deposited by an ion beam at (a) 300, (b) 500, and (c) 850 V.

Fig. 2(b), which arise from the Co/NiFe/Cu/NiFe/Co and FeMn layers, respectively.[4,5] Using the Si spots as standards (a=5.43 Å), the lattice constants of the fcc Co/NiFe/Cu/NiFe/Co and the fcc FeMn layers are determined to be 3.60 and 3.66 A, respectively. This agrees with the x-ray measurements. Also the Co/NiFe/Cu/NiFe/Co and FeMn layers are strongly (111) crystallographically textured as can be seen from the absence of 111_0 and 200_0 rings in Fig. 2(b). This conclusion is further confirmed by the electron diffraction pattern at 40° tilt [Fig. 2(c)].[6] The above results suggest that fcc Co and Cu layers are strain matched with the NiFe layers while the strain due to the misfit (2.2%) between the FeMn and the pinned NiFe layers has been released. Figures 3(a)–3(c) are the bright field cross-section TEM images of the spin-valves deposited with ion-beam voltage of 300, 500, and 850 V, respectively. The cross-section morphologies of the spin valves are characterized by columnar grains growing from the free NiFe layer all the way through the FeMn layer. These columnar grains have a dome shape interface with the Ta cap layer. The average columnar grain widths are measured to be: 220 Å for 300 V, 250 Å for 500 V, and 190 Å for 850 V deposited spin valves. Nevertheless, the cross-section electron diffraction patterns of the three spin valves are similar. Figure 4(a) is the cross-section electron diffraction pattern of the 850 V deposited spin valve. This pattern is the diffraction pattern expected for an almost perfectly [111] textured film as can be seen from Fig. 4(b) which shows a schematic of the intersection of the Ewald sphere (the paper plane) with the reciprocal lattice of a [111] textured fcc polycrystalline film. From Fig. 4(a), the distribution angle of the [111] texture axis is determined to be about 2° which matches with the measurements of the x-ray rocking curves.[7] Figure 5 shows the high resolution cross-section TEM image of the spin-valve deposited with an ion beam at 850 V. It can be seen that the Ta buffer layer is amorphous while the 50-Å-thick Ta cap layer consists of a 25 Å amorphous layer and on top of which a Ta oxide layer. Also, no hcp Co phase has

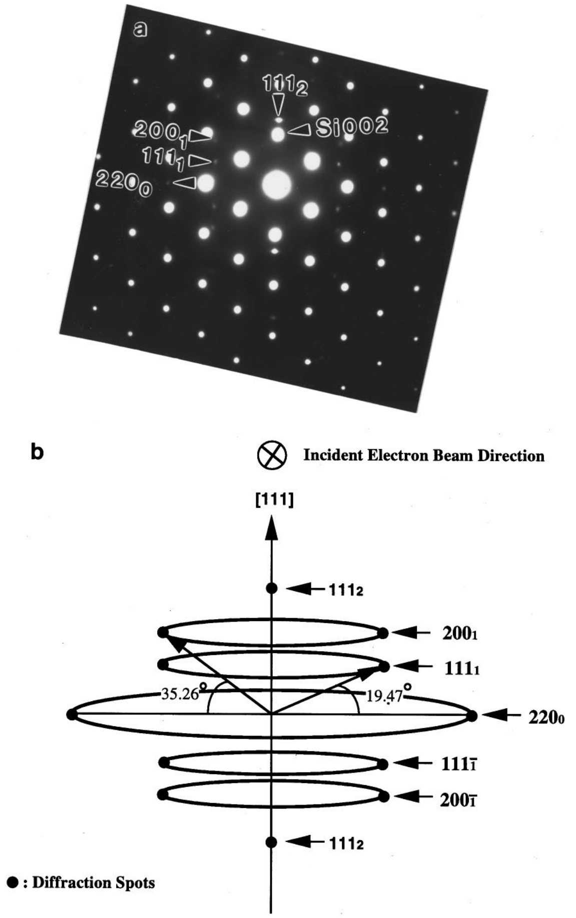

FIG. 4. (a) Cross-section electron diffraction pattern of the spin valve deposited by an ion beam at 850 V, and (b) schematic of the intersection of the Ewald sphere with the reciprocal lattice of a [111] textured fcc film when the incident electron beam is perpendicular to the [111] texture axis.

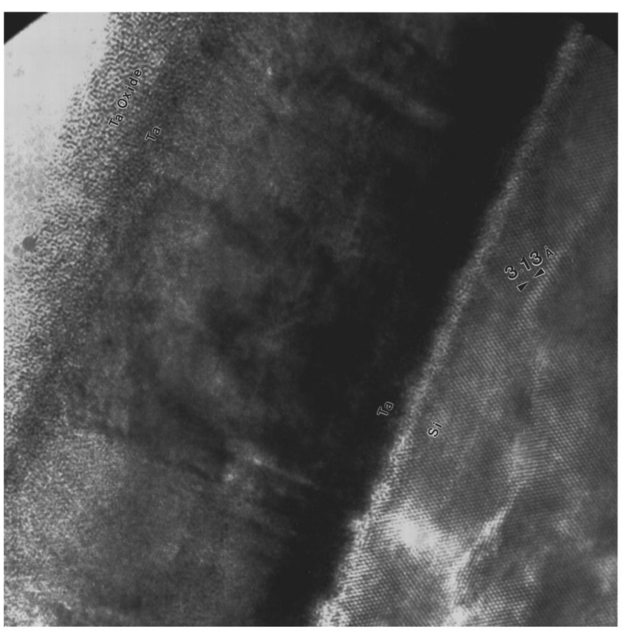

FIG. 5. High resolution TEM cross-section image of the spin valve deposited by an ion beam at 850 V.

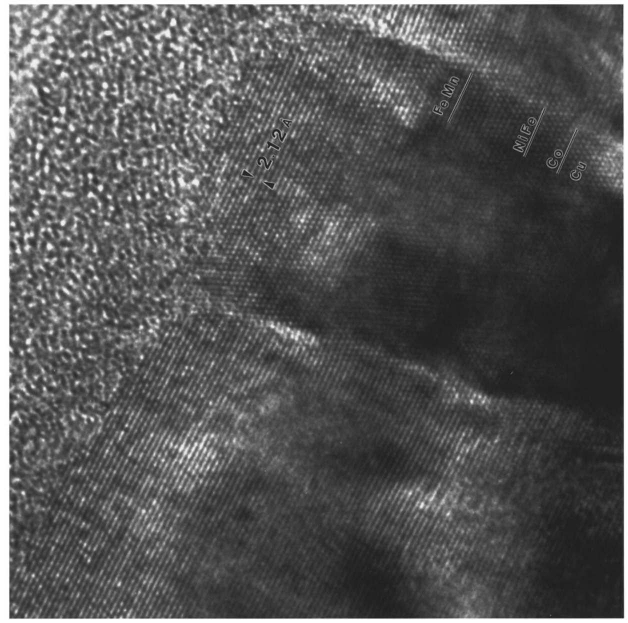

FIG. 6. High resolution TEM cross-section image of two grain boundaries between FeMn/NiFe/Co/Cu grains of the spin valve deposited by an ion beam at 850 V.

been identified. Two grain boundaries between two FeMn/NiFe/Co/Cu grains with dome shape surfaces are shown in Fig. 6. It can be seen clearly that (111) planes are continuous across the grain boundaries. In both Figs. 5 and 6, no misfit dislocations at the interface between the FeMn and pinned NiFe layers have been observed indicating that the compressive strain (~2.2%) due to the misfit between the two layers was probably released via the formation of FeMn surface domes. The critical thickness at which domes form is that when surface energy increase due the surface doming is less than the compressive misfit strain energy.[8] Nevertheless, the peak to valley (PV) height of the FeMn surface domes for the three spin valves investigated is about the same (~15 Å) indicating that the PV has little effect on both the magnetic and magnetotransport properties of ion beam deposited spin valves.

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