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Effect of an Fe–Si buffer layer on the magnetoresistance of a Co/Cu multilayer

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Co/Cu multilayers were fabricated on a thermally oxidized Si wafer (SiO_2 substrate) as well as a bare Si wafer (Si substrate). The multilayer had an Fe buffer layer and was produced in a sputtering atmosphere into which oxygen was introduced. In the case of the Si substrate, the magnetoresistance (MR) ratio increased as the partial oxygen pressure decreased below 3×10^{-8} Torr, whereas it steeply decreased in the case of the SiO_2 substrate. The increase in the MR ratio in the case of the Si substrate was due to an enlargement of the lateral grain size of the multilayers, which reduced the interfacial roughness of the multilayer. When Fe–Si was used as the buffer layer, the MR ratio of the multilayer on the SiO_2 substrate drastically changed in relation to the buffer layer's Si content. A maximum MR ratio of 40% was obtained at 16% Si, corresponding to the enlargement in the lateral grain size. The MR ratio of the multilayer fabricated on the $Fe_{82}Si_{18}$ buffer layer remained 28% after annealing at 350 °C. We therefore conclude that the Fe–Si buffer layer is effective in facilitating the lateral grain growth of Co/Cu multilayers and in attaining high thermal stability of the MR ratio. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1459105]

I. INTRODUCTION

The giant magnetoresistance (GMR) effect in metallic multilayers as applied to magnetic sensors has been actively investigated because of the multilayers' high magnetoresistance (MR) ratio. The interfacial flatness of the multilayers has been found to be one of the most important factors in obtaining a high MR ratio.[1–3] Nevertheless, certain technical factors necessary in realizing flat interfaces in actual multilayers have not been sufficiently clarified in the fabrication process.

We have previously reported that the interfacial flatness of Co/Cu multilayers fabricated on a thermally oxidized Si wafer is significantly improved by introducing oxygen gas into the sputtering atmosphere during the deposition (with the background pressure having been suppressed in extremely high vacuum regions), thus drastically increasing the MR ratio.[4] The most probable mechanism for improving the interfacial flatness by introducing oxygen involves the partial oxidation of the multilayers, which prevents grain growth in the multilayers. On the other hand, in view of thermal stability, multilayers having few grain boundaries (namely, having large grain size) are required while also retaining a high MR ratio.[5] One of the key issues in obtaining a large grain size without any change in the interfacial roughness regards controlling the initial growth layer in the multilayers. Lateral grain growth in the flat surface of the initial deposition layer will provide a desirable template for subsequent multilayer growth. One technical candidate for producing this template is the use of buffer layers on the substrates.

An Fe layer is generally believed to be the most probable buffer layer for use with Co/Cu multilayers.[1,2,6–8] However, one should notice that the effect of the buffer layer on the initial growth of the multilayers might easily be masked by impurities in the sputtering atmosphere, as mentioned earlier in regard to oxygen. Therefore, in the present study, in order to eliminate the effects of impurities on the initial growth, we first fabricated Co/Cu multilayers on an Fe buffer layer while changing the amount of oxygen introduced into the sputtering chamber. Both Si wafers with and without a thermally oxidized layer were used as substrates in this case. Based on an analysis of the present experimental results, an Fe–Si buffer layer was then used to improve the lateral grain growth in Co/Cu multilayers in an extremely clean sputtering process. The thermal stability of the MR ratio of the multilayers on the Fe–Si buffer layer is discussed in connection with the microstructures of the multilayers.

II. EXPERIMENTAL PROCEDURES

Multilayers, in the formed substrate/Fe(–Si) 50 Å/(Co10 Å/Cud_{Cu})$_{30}$/Cu20 Å, were deposited on Si(100) wafers with and without a thermally oxidized layer at room temperature using a specially designed magnetron-sputtering cluster tool that was capable of pumping gases down to an extremely-high vacuum region (4×10^{-11} Torr). The Fe(–Si) buffer layer was fabricated using an rf magnetron sputtering chamber in which the base pressure was less than 1×10^{-10} Torr. No impurities were introduced into the chamber. Ultraclean Ar gas (UC–Ar), with an impurity level of less than 1 ppb,[9] was used as the process gas. Co/Cu multilayers were fabricated on the buffer layer using a dc magnetron sputtering chamber that was connected to the other chambers through an ultrahigh vacuum-compatible handling chamber. After being pumped down to the ultimate pressure of the chamber, oxygen gas was introduced through a variable leak valve in order to vary the partial pressure of the chamber (P_{O_2}) from 10^{-10} to 3

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$\times 10^{-7}$ Torr. The UC–Ar gas was then introduced in order to attain a total chamber pressure of 0.6 mTorr. The Cu layer thickness, d_{Cu}, was optimized to maximize the MR ratio in the so-called "first peak" of the GMR oscillation, which ranged from 8 to 11 Å. Thermal annealing was subsequently performed under a high vacuum (10^{-6} Torr) on the same multilayer from 150 to 350 °C for 10 min at each temperature. The microstructures of the multilayers were analyzed by x-ray diffraction (XRD), x-ray reflectivity with a Cu $K\alpha$ radiation source, and by atomic-force microscopy (AFM). $M-H$ loops were measured using a vibrating sample magnetometer at room temperature. The magnetoresistance was measured by a dc four-point probe method in a magnetic field up to 13 kOe at room temperature. The MR ratio was defined as $\Delta\rho/\rho_{13\,\mathrm{kOe}} \equiv (\rho_0 - \rho_{13\,\mathrm{kOe}})/\rho_{13\,\mathrm{kOe}}$, where ρ_0 is the maximum resistivity at around a zero field and $\rho_{13\,\mathrm{kOe}}$ is the resistivity under the applied field of 13 kOe. The saturation field, H_s, was defined as the magnetic field in which the resistivity was 1% larger than $\rho_{13\,\mathrm{kOe}}$ in the magnetoresistance curves, with the contribution of the forced effect in the high magnetic field being corrected.[4] An antiferromagnetic (AF) coupling energy, J, between adjacent Co layers in the multilayer was calculated as $M_s H_s d_{Co}/4$, where M_s and d_{Co} are the saturation magnetization and the thickness of one Co layer, respectively.

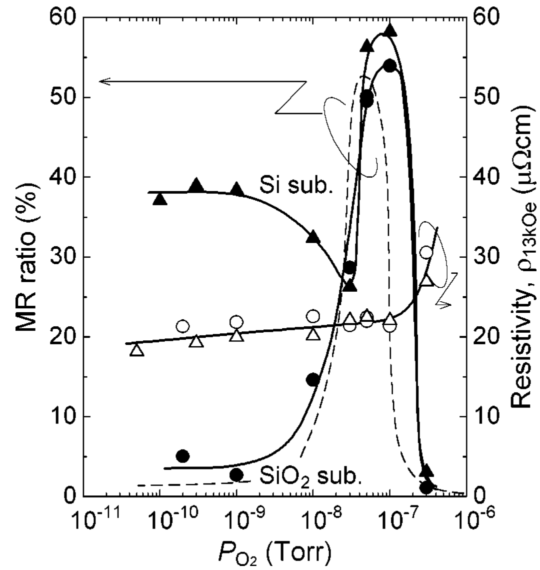

FIG. 1. Changes in the MR ratio (solid marks) and $\rho_{13\,\mathrm{kOe}}$ (open marks) of the multilayers fabricated on a bare Si wafer (Si sub: triangles) and a thermally oxidized Si wafer (SiO_2 sub: circles) as a function of the partial oxygen pressure, which was introduced as an impurity. The dashed line shows the change in the MR ratio of the multilayers fabricated on an SiO_2 substrate without any buffer layers.

III. RESULTS AND DISCUSSION

A. GMR and magnetic properties

Figure 1 shows the MR ratio and $\rho_{13\,\mathrm{kOe}}$ of the multilayers fabricated on Fe buffer layers as a function of the partial pressure of introduced oxygen, P_{O_2}. The substrates used are indicated as SiO_2 sub and Si sub for the Si wafer with a thermally oxidized layer and the bare Si wafer, respectively. Here, the d_{Cu} of the multilayer was optimized at 9 or 10 Å in order to derive the maximum MR ratio on the respective data point. As a reference, the change in the MR ratios of the multilayers fabricated directly on the SiO_2 substrate (without Fe buffer layers), which is reported in Ref. 4, is shown by a broken line in the figure.

In the case of the SiO_2 substrate (the circle symbols), the MR ratio, which was nearly zero at $P_{O_2} = 3\times 10^{-7}$ Torr, steeply increased as the P_{O_2} was lowered, reaching a sharp peak of 54% at around $P_{O_2} = 1\times 10^{-7}$ Torr. The MR ratio then began to decrease, becoming 15% at $P_{O_2} = 1 \times 10^{-8}$ Torr and approximately 5% when P_{O_2} was less than 1×10^{-9} Torr. This change in the MR ratio was very similar to that of the multilayers fabricated directly on the SiO_2 substrate, except for the slight shift in the peak position of the MR ratio, which seemed to be caused by fluctuations in the control of the introduced oxygen's partial pressure. According to Ref. 4, the drastic change in the MR ratio around $P_{O_2} = 1\times 10^{-7}$ Torr originates from an oxidization of the multilayers, resulting in their microstructural changes. In particular, the increase in the MR ratio as P_{O_2} increases from 1×10^{-8} Torr to 1×10^{-7} Torr is due to the partial oxidization of the multilayers, which prevents grain growth in the multilayers and results in a flattening of the interfaces between Co and Cu layers in the multilayer.[4] The drop in the MR ratio beyond $P_{O_2} = 1\times 10^{-7}$ Torr is due to the fatal oxidization of the multilayer, judging from the steep increase in $\rho_{13\,\mathrm{kOe}}$ in that region.[4] From these results, one can say that the Fe buffer layer on the SiO_2 substrate has no remarkable effect on the GMR and the microstructure of the Co/Cu multilayers deposited on it.

In contrast, in the case of the Si substrate (the triangle symbols), one can see a remarkable change in the MR ratio in relation to P_{O_2} below 3×10^{-8} Torr, compared to the case of the SiO_2 substrate. The MR ratio also rose from $P_{O_2} = 3 \times 10^{-7}$ Torr, reaching a peak of 58% at around $P_{O_2} = 1 \times 10^{-7}$ Torr with decreasing P_{O_2}. It then dropped from the peak to 27% at $P_{O_2} = 3\times 10^{-8}$ Torr. It increased again, however, as P_{O_2} declined, recovering to 40% when the oxygen impurity was eliminated from the sputtering chamber (hereafter, a clean process). These changes in the MR ratio are dominated by the magnetoresistance, $\Delta\rho$, because $\rho_{13\,\mathrm{kOe}}$ is almost constant in the same P_{O_2} region. We could not find any remarkable differences between the cases of Si and SiO_2 substrates within the P_{O_2} range beyond 3×10^{-8} Torr, with regard to not only the MR ratio but also to the magnetic properties and the microstructures of the multilayers, as shown in the following. These results suggest that the oxygen impurity in the sputtering atmosphere easily masks the effect of the Fe buffer layer prepared on the bare Si wafer. We thus conclude that an Fe buffer layer strongly affects the GMR and the microstructure of the Co/Cu multilayers deposited on it only when it is fabricated on a bare Si wafer in a clean process. Hereafter, we primarily examine the case of a Si substrate within a P_{O_2} range of below 3×10^{-8} Torr.

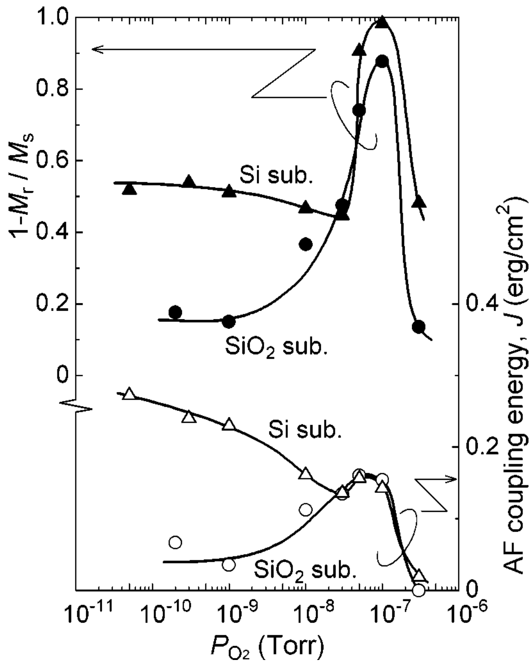

FIG. 2. Changes in $1-M_r/M_s$ (solid marks) and J (open marks) for multilayers fabricated on a bare Si wafer (Si sub: triangles) and a thermally oxidized Si wafer (SiO_2 sub: circles) as a function of the partial oxygen pressure, which was introduced as an impurity.

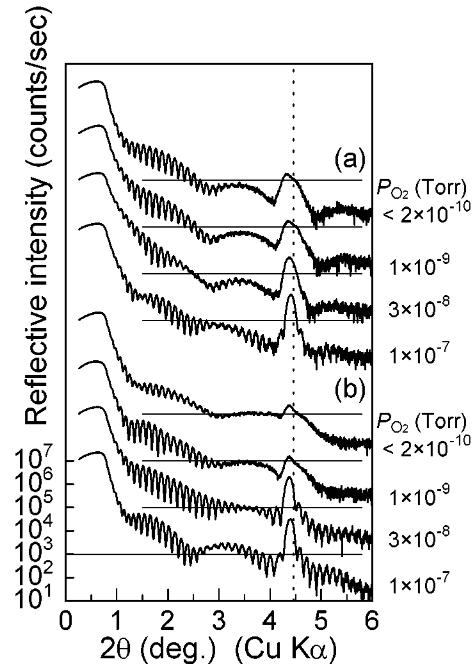

FIG. 3. Changes of x-ray reflectivity profile of the multilayers fabricated on (a) a bare Si wafer and (b) a thermally oxidized Si wafer under various partial oxygen pressures, P_{O_2}. Horizontal lines are the guiding scale for comparison of the profiles and indicate the same reflective intensity of 10^3 counts/s for each profile.

In Fig. 2, $1-M_r/M_s$, the measure of the volume fraction of AF-coupled regions of the Co layers at a zero field, is plotted as a function of P_{O_2}. The AF coupling energy, J, is also shown in the same figure. The remanent magnetization ratio, M_r/M_s was determined from a $M-H$ loop along the easy magnetization axis of the multilayers. Here, the contribution of the Fe buffer layer was eliminated from M_s and M_r.

The changes in both $1-M_r/M_s$ and J in relation to P_{O_2} show contrasting trends depending on the substrates. In the case of the Si substrate, both of the physical quantities increase as P_{O_2} decreases below 3×10^{-8} Torr, contrary to the case of the SiO_2 substrate. These changes correspond well to the changes in the MR ratio shown in Fig. 1, suggesting that the increase in the MR ratio for the Si substrate when P_{O_2} decreases below 3×10^{-8} Torr is caused by the increase in the amount of antiparallel alignment of the magnetization of neighboring Co layers at a zero field, which is associated with an increase of the AF coupling energy, J.

J correlates strongly with the microstructure of the multilayer, especially in regards to interfacial roughness. This roughness induces ferromagnetic (F) ''orange-peel coupling''[10] and reduces AF coupling between the magnetic layers originating from an Ruderman–Kittel–(Kasuya)–Yosida [RK(K)Y]-like interaction. According to Néel's model,[10] the strength of the orange-peel coupling is expressed as

$$J_F=\frac{\pi^2h^2M_s^2}{\sqrt{2}L}\exp\left(\frac{-2\pi\sqrt{2}d_{Cu}}{L}\right), \tag{1}$$

where h and L are the amplitude and the wavelength of the sinusoidal wave function, respectively, which characterize the interfacial roughness.

From the earlier formula, one can expect a reduction in the F-coupling strength, J_F, in response to a decrease in h and/or an increase in L. In the actual multilayers, h and L correspond to the roughness along the film thickness direction and the lateral grain size, respectively. We thus estimate the h and L of the multilayers in the next section.

B. Interfacial roughness

Figure 3 shows the changes of the x-ray reflectivity profile of the multilayers, with a d_{Cu} of 10 Å, fabricated on the (a) Si and (b) SiO_2 substrates under various P_{O_2}, respectively. As a guiding scale for comparison of the profiles, 10^3counts/s of reflective intensity are shown on each profile. The diffraction peaks originating from the artificial period are observed around $2\theta=4.3°$. The observed peak position of these multilayers agrees with the one expected from the reflectivity calculation (a vertical dashed line in the figure) within a 1-Å-thick deviation of the artificial period. In the cases of both the Si and the SiO_2 substrates, the diffraction peaks and finite-size peaks, which appear on the profiles as high frequency oscillations, became large and clear with increasing P_{O_2}.

Figure 4 shows the rms roughness, σ, of the multilayers, a value corresponding to h in the last section, as a function of P_{O_2} for both the Si and SiO_2 substrates. The σ was estimated based on the x-ray reflectivity profiles of the multilayer (Fig. 3), in which the observed x-ray reflectivity at the angle corresponding to the artificial period and the calculated one for

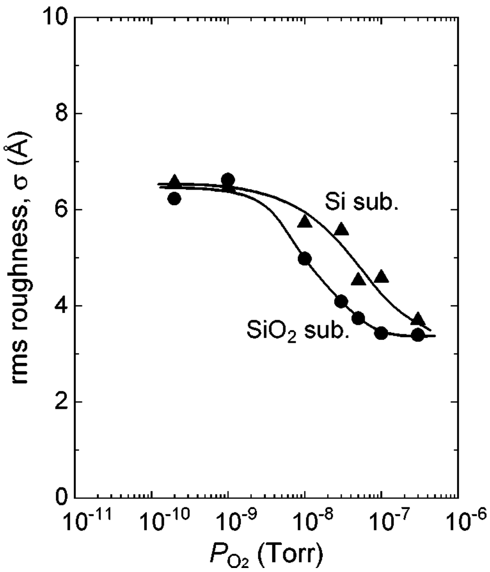

FIG. 4. Changes in the rms roughness, σ, of the multilayers fabricated on a bare Si wafer (Si sub: triangles) and a thermally oxidized Si wafer (SiO_2 sub: circles) as a function of the partial pressure of oxygen, P_{O_2}. The σ was estimated based on the x-ray reflectivity profile of the multilayer.

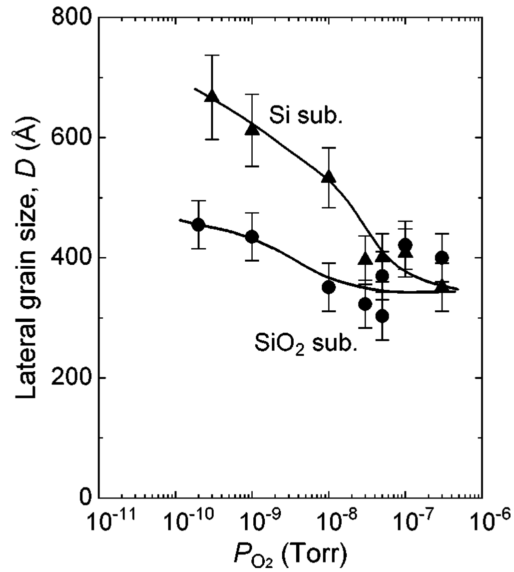

FIG. 6. Changes in the lateral grain size, D, of the multilayers fabricated on a bare Si wafer (Si sub: triangles) and a thermally oxidized Si wafer (SiO_2 sub: circles) as a function of the partial oxygen pressure, P_{O_2}. D was estimated based on the AFM images (Fig. 5) of the top surface of the multilayers.

the ideal multilayer with no roughness were compared.[11] The σ increases from approximately 3.5 to 6.5 Å as the P_{O_2} decreases from 3×10^{-7} Torr to less than 2×10^{-10} Torr, in the case of the SiO_2 substrate. In the case of the Si substrate, the change in σ shows the same trend as that of the SiO_2 substrate, except for a slight difference in the absolute value.

These changes of the σ as a function of P_{O_2} can be verified by direct observation of the multilayer roughness, using an AFM. Figure 5 shows the changes of the AFM image of the top surface of the multilayers, with a d_{Cu} of 10 Å, fabricated on the (a) Si and (b) SiO_2 substrates under various P_{O_2}, respectively. The average surface roughness, R_a, also shown in the figure, increased from approximately 1.5 to 4.1 Å and 1.8 to 5.1 Å with lowering P_{O_2} from 1×10^{-7} Torr to less than 2×10^{-10} Torr, in the cases of the SiO_2 and Si substrate, respectively. This result confirms the similar changes of the rms roughness of both the multilayers fabricated on SiO_2 and Si substrates as a function of P_{O_2} shown in Fig. 4.

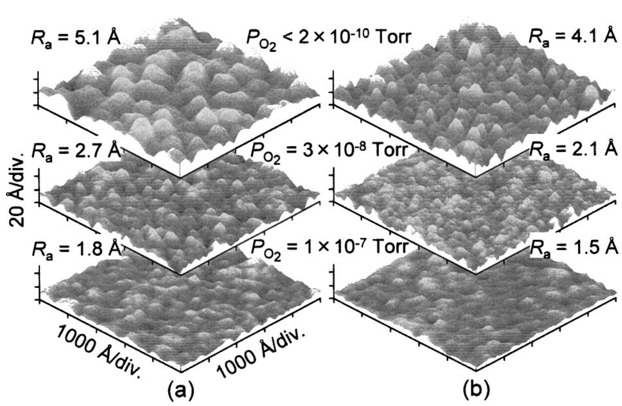

FIG. 5. AFM images of the top surface of the multilayers fabricated on (a) a bare Si wafer and (b) a thermally oxidized Si wafer under various partial oxygen pressures, P_{O_2}.

In contrast to the changes in the interfacial roughness, the changes in the lateral grain size, D, in relation to P_{O_2} differ between substrates when P_{O_2} is less than 3×10^{-8} Torr, as shown in Fig. 6. The D was estimated based on the AFM image of the multilayers as a value corresponding to L in the last section. In the case of the Si substrate, D, which is 350–400 Å beyond $P_{O_2}=1\times10^{-7}$ Torr, monotonously increases as the P_{O_2} decreases and nearly doubles at a 10^{-10} Torr order of P_{O_2}. In contrast, D scarcely increases up to 450Å with lowering P_{O_2} down to 2×10^{-10} Torr in the case of the SiO_2 substrate.

The different trends in the changes in D for each substrate qualitatively explain the different trends of the change in J in relation to P_{O_2} shown in Fig. 2. Specifically, in the case of the SiO_2 substrate, the slight increase in D and the doubling of σ result in an increase in J_F and a decrease in J. In contrast, in the case of the Si substrate, the remarkable increase in D with decreasing P_{O_2} is more than enough to compensate for the increase in J_F due to the doubling of σ. In addition, the enlarged D, indicating a decrease in the grain boundaries, leads to a decrease in the diffusive scattering centers for conduction electrons. This works to increase J, since the conduction electrons mediate the interlayer RK(K)Y-like coupling.

In light of these results, one can say that the Fe buffer layer adjacent to a bare Si substrate on the initial growth of Co/Cu multilayers enhances lateral grain growth.

C. Multilayers fabricated on an Fe–Si buffer layer

As shown in the previous sections, the Fe buffer layer prepared on a bare Si substrate is effective in producing a

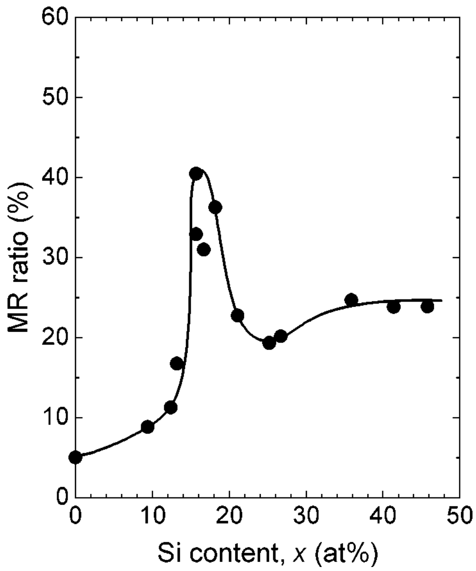

FIG. 7. Changes in the MR ratio of the multilayers fabricated on a SiO_2 substrate with an Fe–Si buffer layer in a clean process as a function of Si content.

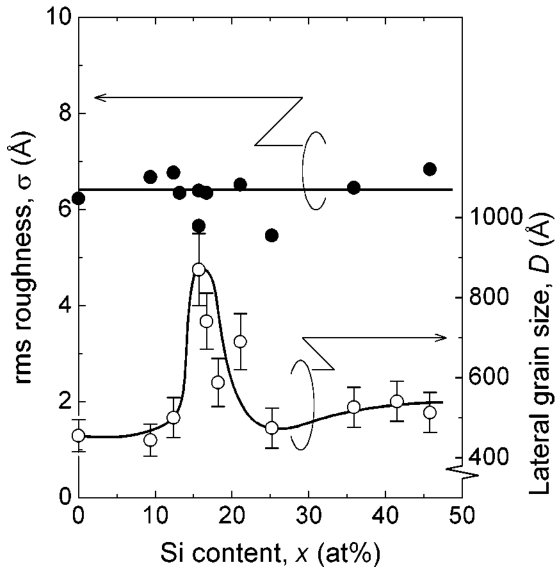

FIG. 8. Changes in the rms roughness (solid marks) and the lateral grain size (open marks) of the multilayers fabricated, using a clean process, on a SiO_2 substrate having an Fe–Si buffer layer as a function of Si content.

high MR ratio in a multilayer having a large lateral grain size. An important factor that should be noticed here is the silicon which comprises the substrate itself, because we could not find any differences regarding the MR ratio and the microstructures between the multilayers fabricated on a SiO_2 substrate *with* and *without* an Fe buffer layer. One can easily imagine a diffusion of Si into the Fe buffer layer on a bare Si substrate.[12,13]

We thus expect a large MR ratio in the Co/Cu multilayer when an Fe–Si buffer layer is used, even in the case of a SiO_2 substrate. Figure 7 shows the change in the MR ratio of multilayers (fabricated in a clean process) as a function of the Si content in the Fe–Si buffer layer. Here, a thermally oxidized Si wafer was used as a substrate. The MR ratio, which was found to be only 5% in the case of a pure Fe buffer layer, increased with solving Si into the Fe buffer layer, and reached a sharp peak of 40% at 16% Si, and then steeply decreased to 19% at 25% Si. The MR ratio gradually increased with a further increase in the Si content until the examined maximum content of 46%. This change in the MR ratio is dominated by the intrinsic change in the magnetoresistance, $\Delta\rho$, because $\rho_{13\,\mathrm{kOe}}$ was almost constant at about 21 $\mu\Omega$ cm over the range of the Si content up to 46%. We otherwise confirmed that the change of $\Delta\rho$ in relation to the Si content originates in the change of the amount of antiparallel alignment of the magnetization of neighboring Co layers at a zero field, which is associated with an increment of the AF coupling energy, J, as well as the change in the MR ratio against P_{O_2} (Fig. 2). Here, the maximum MR ratio of 40% observed in the case of the 16% Si–Fe buffer layer corresponds closely to the MR ratio of the multilayer fabricated on the Si substrate with an Fe buffer layer, shown in Fig. 1. These results suggest that pure Fe is not an effective buffer layer, but that Fe–silicide is. It thus follows that, in the case of a Si substrate, Si migrates into the Fe buffer layer, making it an effective buffer layer.

Figure 8 shows the rms roughness, σ, and the lateral grain size, D, of the multilayers fabricated on the Fe–Si buffer layer, as determined using the method described earlier, as a function of the Si content in the buffer layer. The rms roughness, which is approximately 6.5 Å in the case of a pure Fe buffer layer, does not change significantly in relation to the Si content. In contrast, the lateral grain size, which is 450 Å for the multilayer fabricated on a pure Fe buffer layer, enlarges as the Si content increases, reaching a peak of 870 Å at 16% Si, after which it decreases. This change in D corresponds closely to the change in the MR ratio shown in Fig. 7.

It can therefore be concluded that 16% Si–Fe is the optimum chemical composition of the buffer layer for a Co/Cu multiplayer, facilitating lateral grain growth and producing a high MR ratio.

D. Thermal stability of the MR ratio

Figure 9 shows the changes in the MR ratio and $\rho_{13\,\mathrm{kOe}}$ of the multilayers (measured at room temperature) as a function of the annealing temperature, T_a. The multilayer with a d_{Cu} of 9 Å was fabricated on a SiO_2 substrate having an $Fe_{82}Si_{18}$ buffer layer in a clean process (a). As a reference, the multilayer with an Fe buffer layer fabricated under a sputtering atmosphere with introduced oxygen ($P_{O_2}=1\times10^{-7}$ Torr) is also shown (b). The $\rho_{13\,\mathrm{kOe}}$ of both multilayers was almost constant until $T_a=300\,°\mathrm{C}$. In the former multilayer, with its larger lateral grain size, the MR ratio is almost constant below $T_a=200\,°\mathrm{C}$, then gradually decreases beyond $T_a=250\,°\mathrm{C}$. It remains 28% at $T_a=350\,°\mathrm{C}$. In contrast, in the latter multilayer with its smaller lateral grain size, the MR ratio steeply decreases beyond $T_a=150\,°\mathrm{C}$, reaching a value of 6.5% at $T_a=350\,°\mathrm{C}$. The reduction rate of the MR ratio in relation to T_a up to 350 °C is 24% and 87% in the former and the latter multilayers, respectively.

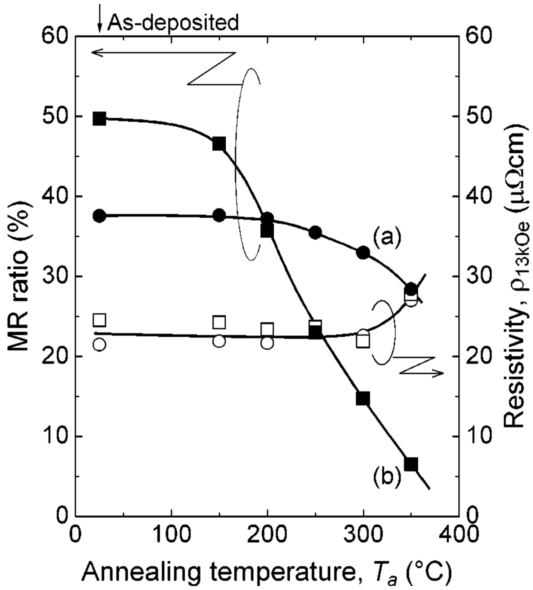

FIG. 9. Changes in the MR ratio and $\rho_{13\,kOe}$ of two different multilayers measured at room temperature as a function of the annealing temperature, T_a. The multilayers were fabricated on a SiO_2 substrate (a), in a clean process, using an Fe–Si buffer layer (circles), and (b) with the introduction of oxygen at $P_{O_2}=1\times10^{-7}$ Torr using an Fe buffer layer (squares).

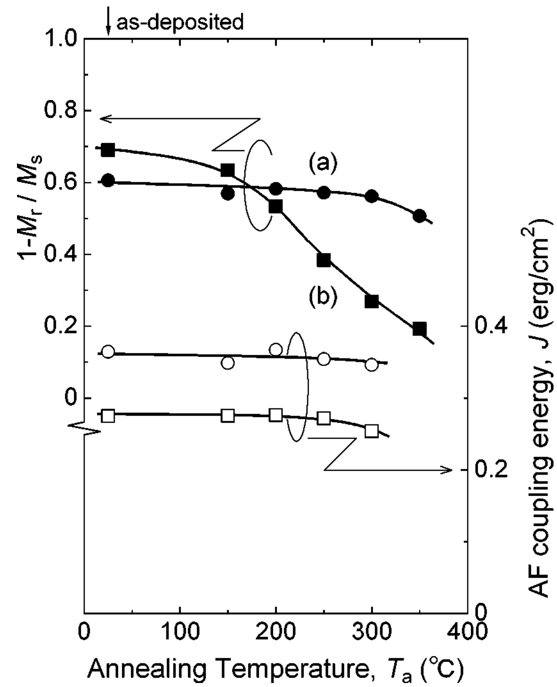

FIG. 10. Changes in $1-M_r/M_s$ (solid marks) and J (open marks) of two different multilayers as a function of the annealing temperature, T_a. The multilayers were fabricated on a SiO_2 substrate (a), in a clean process, using an Fe–Si buffer layer (circles), and (b) with the introduction of oxygen at $P_{O_2}=1\times10^{-7}$ Torr using an Fe buffer layer (squares).

More specifically, the enlarged lateral grain size leads to an improvement in the thermal stability of the MR ratio.

In order to clarify the reason for the different thermal stabilities of the MR ratio between the multilayers, having respective lateral grain size, the changes in $1-M_r/M_s$ and J are plotted as a function of T_a in Fig. 10. The $1-M_r/M_s$ changes respectively, showing a trend similar to the MR ratio in relation to T_a, while J is almost constant below $T_a=250\,°C$ in both the multilayers. In the case of multilayer (b), with its smaller lateral grain size, $1-M_r/M_s$ significantly decreases as T_a rises, indicating that the deteriorating MR ratio is due to the decrease in the volume fraction of AF-coupled regions of the Co layers at a zero field. It should be noticed here that the decrease of $1-M_r/M_s$ is *not* associated with a reduction of J. Taking into account the small change of $1-M_r/M_s$ in the multilayer (a), having a larger lateral grain size, one can say that the most probable mechanism for the decrease in $1-M_r/M_s$ in the multilayer (b) is a formation of direct ferromagnetic coupling between adjacent Co layers, which might be caused by a penetration of Co atoms along the grain boundaries.

We thus conclude that the enlarged lateral grain size and the resultant few grain boundaries in the multilayers, which is realized with the Fe–Si buffer layer, improves the thermal stability of the MR ratio.

IV. SUMMARY

Co/Cu multilayers were fabricated on a thermally oxidized Si wafer (SiO_2 substrate) as well as a bare Si wafer (Si substrate). The multilayers had an Fe(–Si) buffer layer and were produced in a sputtering atmosphere into which oxygen was introduced. The changes in the MR ratio in relation to the partial pressure of introduced oxygen (P_{O_2}) and the Fe–Si buffer layer's Si content were investigated in connection with the microstructures of the multilayers. As a result, we found that: (1) the MR ratio increases remarkably as P_{O_2} drops below 3×10^{-8} Torr in the case of a Si substrate, whereas it steeply decreases in the case of a SiO_2 substrate; (2) the remarkable increase in the MR ratio in the case of a Si substrate is due to the enlargement in the lateral grain size of the multilayers; (3) in multilayers on a SiO_2 substrate fabricated without the introduction of oxygen impurity, the MR ratio drastically changes in relation to the Si content in the Fe–Si buffer layer; (4) a peak value of 40% is obtained for the multilayer when the Si content is 16% in the buffer layer; (5) a remarkable enlargement of the lateral grain size is also obtained in the multilayer on a 16% Si–Fe buffer layer; (6) the MR ratio of the multilayer fabricated on an $Fe_{82}Si_{18}$ buffer layer remains 28% after annealing at 350 °C. We thus conclude that an Fe–Si buffer layer is effective in facilitating the lateral grain growth of Co/Cu multilayers and in attaining the highest possible thermal stability of the MR ratio.

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