Rise in energy product of Sm-Co/Fe spring exchange magnetic bilayers with addition of Cr at interface

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Received 4 February 2010; accepted 18 August 2011

Sm-Co/Fe bilayers are deposited by DC and RF magnetron sputtering on 70 nm Cr buffered Si (100) substrate at an elevated temperature of 650°C. Thickness of Sm-Co and Fe is fixed as 20 nm and 10 nm, respectively. Magnetic behavior with very thin Cr layers (0.3-0.7 nm) at interface of Sm-Co and Fe is studied. All the samples showed strong exchange coupling and single phase hysteresis loops. The energy product \((BH)_{\text{max}}\) value is enhanced to 15% for 0.6 nm Cr layer as compared to the sample without Cr interlayer.

Keywords: Multilayers, Exchange spring magnet, Nanocomposite, \((BH)_{\text{max}}\) product

Experimental Procedure

Bilayers of SmCo/Fe were deposited by magnetron sputtering on 70 nm Cr buffered Si (100)
substrate. Very thin Cr layers were introduced at interface of Sm-Co and Fe. The nominal composition of the samples is Cr (5 nm) /Fe (10 nm) /Cr (x nm) /SmCo$_5$ (20 nm) /Cr (70 nm) /Si (100) where x= 0, 0.3, 0.5, 0.6 and 0.7. Cr buffer layer was deposited at 650°C while other layers were deposited during decreasing of temperature from 650°C. The base pressure was kept in $10^{-5}$ Pa range. Ar pressure during sputtering of Cr and Fe was 0.4 Pa while it was kept as 0.66 Pa for SmCo$_5$. SmCo$_5$ and Cr were sputtered with RF guns and Fe was deposited with DC gun. The deposition rate of the films was measured by weight method.

The sample with x = 0, i.e., without Cr layer at interface was deposited without capping layer too. The deposition rates of Fe, Cr and SmCo$_5$ were 0.325 Å/s at 100 W, 0.204 Å/s at 100 W and 0.092 Å/s at 130 W, respectively. The samples were analyzed by X-ray diffraction (XRD) and magnetic behavior was observed by alternating gradient magnetometer (AGM).

**Results and Discussion**

Figure 1 shows the XRD pattern of SmCo$_5$/Fe bilayers with 0.6 nm Cr interlayer between Fe and SmCo$_5$. The pattern shows the presence of Sm$_2$Co$_7$, SmCo$_5$, Sm$_2$Co$_{17}$, SmCo$_3$, Cr and Fe peaks. However the prominent phase is Sm$_2$Co$_7$. The appearance of different compositions of Sm-Co is due to the local variation of Sm and Co ratio. Ding *et al.*$^{19}$, Benaissa *et al.*$^{20}$ and Zhou *et al.*$^{21}$ have also showed the formation of different phases of Sm-Co while depositing one phase. In the sample of similar thickness, it can be seen that the peaks are of low intensity due to thin films deposited in nano regime$^{22}$.

Figure 2 shows the hysteresis loops of Fe (10 nm) /Sm-Co (20 nm) with Cr thin layers at interface of the Fe and Sm-Co taken by AGM. The loops show single-phase behavior of bilayers without any kink. This means the soft and hard phases are strongly exchange coupled with each other in all of the samples. The saturation magnetization of sample rises from 698 kA/m without Cr interlayer to 814 kA/m with 0.6 nm Cr interlayer. The sample without Cr thin layer at interface of Fe and Sm-Co is without any capping layer however all other samples are with Cr capping layer of 5 nm.

Figure 3 shows the change in energy product with the increasing thickness of Cr thin layer at interface. The solid line of graph is a guide to eye. The energy product with change in Cr interlayers first decreases
up to about 0.3 nm Cr thickness then it increases up to 0.6 nm Cr interlayer then again decreases. It is due to combined effect of the change in exchange coupling between the soft and hard phases and due to inter-diffusion of the nonmagnetic phase Cr into soft and hard magnetic regions. For the insertion of more thick non-magnetic interlayers (more than 0.7 nm), it has already been discovered that the magnetization changes like sinusoidal curve for two soft magnetic layers with very thin non-magnetic layers at interface\(^\text{12}\). The behaviour of the magnetization with increasing interlayer thickness of non-magnetic materials between two soft ferromagnetic materials is periodic. But it is not like ideal periodic wave nature. The results show oscillatory changes but with varying amplitude in non-symmetrical manner as shown elsewhere\(^\text{12-16}\). The oscillatory behavior is due to alternative ferromagnetic and anti-ferromagnetic coupling of the two layers\(^\text{13,14}\). Now it is confirmed that for many combinations of soft magnetic materials and spacer layers, the behavior of the systems is oscillatory between ferro and anti-ferromagnetic coupling, regarding magnetization.

From Fig. 3, it is obvious that there is increase in energy product (9.8 kJ/m\(^3\)) with respect to the sample without interlayer (8.5 kJ/m\(^3\)). The maximum value is around for 0.6 nm of Cr layer. This result is in consistent with our previous observation of the improvement in exchange coupling which showed maximum removal of shoulder in hysteresis loop at 0.7 nm Cr interlayer\(^\text{18}\). As in that series the Cr thickness was varied as 0.3, 0.5 and 0.7 nm only. That is why we fabricated another sample with 0.6 nm Cr layer thickness in present investigation. Figure 3 shows that the optimized value of Cr thickness is close to 0.6 nm. This reveals that with the insertion of Cr interlayer, the energy product increases. The rise in energy product is observed as 15\% as compared to the sample without any interlayer. It should be noted that the optimized interlayer thickness is changed with different annealing conditions too\(^\text{23,24}\). However, there is a optimized value of interlayer for which we can get maximum energy product by inserting at interface of soft and hard magnetic phases.

**Conclusions**

In conclusion, rise and fall in energy product is observed by inserting Cr layer at interface of Sm-Co/Fe layers. The maximum value of energy product \((BH)_{\text{max}}\) is around 0.6 nm of Cr thickness. This shows maximum improvement in exchange coupling at that value. It is concluded that the energy product increases with introducing very thin Cr layers at interface of Sm-Co/Fe layers. The rise in energy product is attributed to improvement in exchange coupling. The maximum rise in energy product is observed as 15\% as compared to the sample without Cr interlayer.

**References**