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Bi- and Al-doped DyIG(y Å)/Fe(x Å) ($y=50$ to 130 Å and $x=5$ to 15 Å) multilayer thin films were made by magnetron sputtering onto Si(111) substrates. Rapid thermal annealing was used to crystallize these garnet multilayers. The crystallized multilayer samples possess well-defined interfaces. Atomic force microscopy showed that the annealed samples had smooth surfaces, with small grain sizes (~30 to 80 nm). All of the samples had perpendicular magnetic anisotropy with very square hysteresis loops. The coercivity was found to vary from 600 Oe to 2 kOe, depending on Fe thickness and annealing conditions. The measured figure of merit $\sqrt{R(\theta_K^2+\epsilon_K^2)}$ at 420 nm was bigger than 0.4, suggesting that Bi- and Al-doped DyIG/Fe multilayers are promising candidates for blue light magneto-optical recording applications.

Bi-doped DyIG (garnet) thin films have moderate perpendicular magnetic anisotropy and large magneto-optical Faraday effect in the blue region of the spectrum. The magnetic parameters such as the coercivity H_c and the saturation magnetization M_s are easily varied through changes in the composition. These properties are the key for the materials to be used as a magneto-optical (MO) recording media at blue laser wavelengths.[1-5] Unfortunately, the garnets are polycrystalline with a large grain size and a rough surface, which will give a substantial media noise which is absent in the rare-earth-transition metal (RE-TM) amorphous MO recording media. Suzuki[5,6] demonstrated that by using rapid thermal annealing (RTA), where the heating ramp rate can exceed 50 °C/s, the grain size can be reduced to about 40 nm and the surface morphology can also be improved. Suzuki[6] also showed that the microstructure of the garnet films could be further improved through multilayering the garnet with Cr, Co, and SiO_2; this is because the space layer will interrupt the growth of garnet. In this paper, we will report the microstructure and the magneto-optical properties of thin films of Bi- and Al-doped DyIG multilayered with Fe.

$Dy_{1.6}Bi_{1.4}Fe_{1-x}Al_xO_{12}$ ($x=0.6$ to 1.0) and Fe multilayers were deposited on Si(111) and quartz room-temperature substrates by rf (for garnet) and dc (for Fe) magnetron sputtering in a pure Ar atmosphere. The Si was used for the purpose the RTA. Standard sintering techniques were used to make the ceramic garnet target. The individual garnet layer thickness was varied between 50 and 130 Å, while the Fe individual layer thickness was varied from 5 to 15 Å. We adjusted the total number of bilayers to keep the total sample thickness roughly at 1000 Å. As-deposited films are amorphous. The samples were then crystallized in air using a home-built rapid thermal annealing system consisting of a 1-kW halogen lamp with the light focused on the sample by an ellipsoidal mirror. The maximum heating ramp rate using this system was about 30 °C/s. The samples were typically annealed at 650 °C for 2 to 5 min. The microstructure and surface morphology of both as-deposited and annealed samples were investigated by atomic force microscopy (AFM). Both large- and small-angle x-ray diffraction were used to characterize the crystalline and multilayer structures. Kerr rotation measurements were carried out over the wavelength range 350–600 nm in magnetic fields up to 12 kOe.

After rapid thermal annealing, large-angle x-ray diffraction spectra shown that a single garnet phase was formed, with no trace of pure Fe diffraction peaks. The garnet grains are totally randomly oriented, with no preferred orientation in these multilayer thin films. Figure 1 shows the small-angle x-ray diffraction spectra both before and after annealing of a [BiAlDyIG(100 Å)/Fe(9 Å)]×10 sample. The two spectra both show six superlattice peaks, indicating that there are well-defined interfaces between the garnet and Fe layers even after a 650 °C RTA for 2 min. One surprising result is that the superlattice peaks of the annealed samples are slightly higher than those of the as-deposited samples, which suggests that the crystallization of the garnet improves the interface definition. However, more detailed studies are needed to fully understand this result. After crystallization, the positions of all the superlattice peaks shift toward larger angles, indicating that the crystallized garnet layers are

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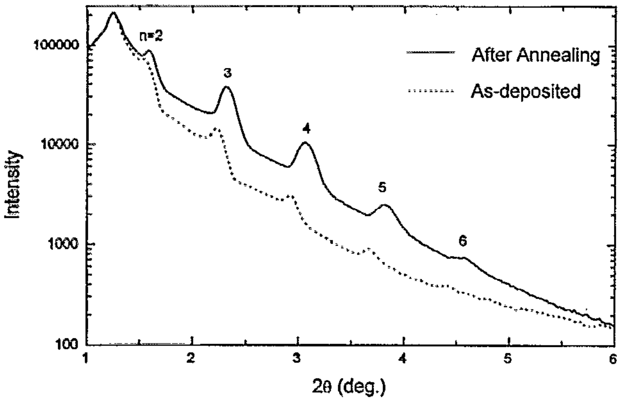

FIG. 1. Small-angle x-ray diffraction spectrum of [BiAlDyIG(100 Å)/Fe(9 Å)]×10 multilayers before (dashed line) and after (solid line) annealing.

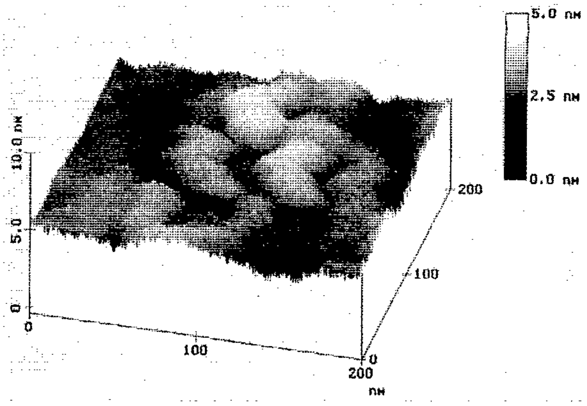

FIG. 3. AFM picture of [BiAlDyIG(100 Å)/Fe(9 Å)]×10 after 2-min rapid thermal annealing at 650 °C.

denser than the as-deposited amorphous layers.

We characterized the microstructure of our multilayer samples using atomic force microscopy. AFM pictures show that as-deposited amorphous multilayer films have little surface structure, with a surface roughness of $\sim$1 nm. Figure 2 shows an AFM picture of [BiAlDyIG(100 Å)/Fe(11 Å)]×9 after 5 min RTA. From this picture we estimate the grain size to be roughly 80 nm, which is much smaller than the grain size of 1 μm typically obtained with oven-annealed single layer garnet films.[7] The surfaces of annealed samples are considerably rougher than those of the as-deposited films. An estimate of the peak-to-peak surface roughness for the sample of Fig. 2 is about 5 nm. Although the observed 80-nm grain size is much smaller than 1 μm, it is still far too large for magneto-optical recording applications. In order to further reduce the grain size and improve the surface smoothness, a shorter annealing time was used. Figures 3 and 4 show AFM pictures of a [BiAlDyIG(100 Å)/Fe(9 Å)]×10 multilayer film with different vertical scales. Assuming that the bumps observed in these figures are grains, we estimate the average grain size to be 20 to 30 nm. A 20 μm×20 μm scan (Fig. 4) shows the surface morphology of this same sample. Comparing Figs. 2 and 4, we can see clearly that shortening the annealing time is a very effective way of obtaining smooth surfaces. We estimate the peak-to-peak surface roughness to be 2 to 3 nm.

Although these results regarding the grain size must be confirmed by transmission electron microscopy (TEM) studies, we can safely conclude that rapid thermal annealing will reduce the grain size and multilayering the garnet with Fe (or other elements) will reduce the grain size further and substantially improve the surface morphology.

Figure 5 shows a Kerr hysteresis loop for a [BiAlDyIG(75 Å)/Fe(5 Å)]×13 sample which had been annealed at 650 °C for 5 min. The very square loop indicates that the sample has perpendicular magnetic anisotropy. Since our x-ray diffraction measurements show that the grains are randomly oriented, this perpendicular anisotropy must come from the stress.[8] The measured Kerr rotation is 1.2° at a wavelength of 410 nm and this value is independent of annealing time after more than 60-s annealing. This measured value is the combination of both Kerr and Faraday rotations, and it includes the effects of optical interference in the sample. The coercivity of this particular sample is $\sim$1 kOe, and it sensitively depends on the annealing conditions and the individual garnet and Fe layer thicknesses. The figure of merit $\sqrt{R(\theta_K^2+\epsilon_K^2)}$ for [BiAlDIG(104 Å)/Fe(5 Å)]×14 with

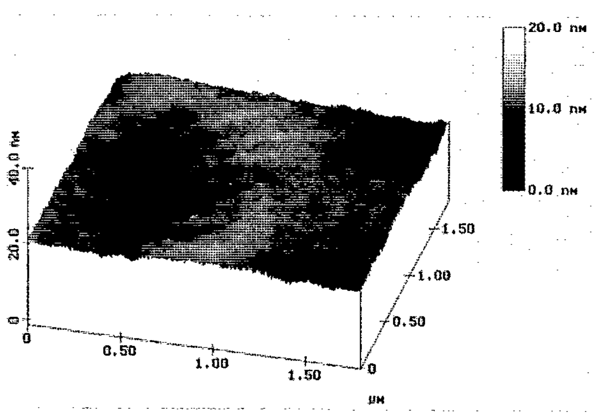

FIG. 2. AFM picture of [BiAlDyIG(100 Å)/Fe(11 Å)]×11 after 5-min rapid thermal annealing at 650 °C.

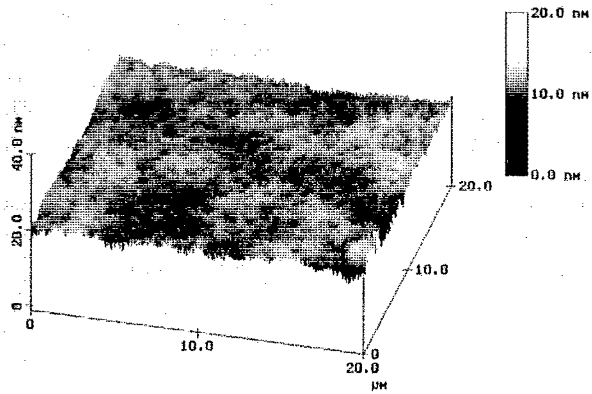

FIG. 4. Surface morphology of [BiAlDyIG(100 Å)/Fe(9 Å)]×10 after 2-min rapid thermal annealing at 650 °C.

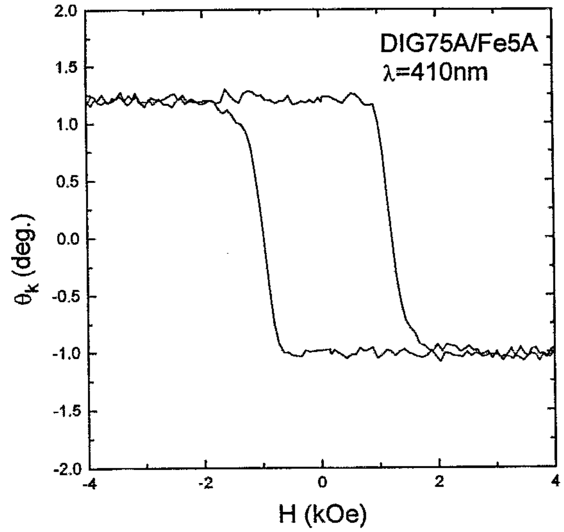

FIG. 5. Kerr hysteresis loop of [BiAlDyIG(75 Å)/Fe(5 Å)]×13 measured at a wavelength of 410 nm at room temperature. The magnitude of the rotation includes contributions from Kerr and Faraday rotations, as well as interference enhancements.

Al reflect layer is 0.4 to 0.6 between the 400- and 500-nm region. In our experiments, we have found that if the individual Fe layer thickness is held fixed at 5 Å, the coercivity oscillates between 0.6 and 1.5 kOe as the individual garnet layer thickness is varied from 50 to 130 Å. This variation is not due to the shifting of the compensation temperature as the compensation temperature is about 170 K for most of our samples and is independent of the individual garnet layer thickness. These oscillations are difficult to understand and they need further investigation. A possible explanation might be related to thickness-dependent defects or inhomogeneities of our samples.

Figure 6 shows the dependence of the coercivity on the total number of bilayers for [BiAlDyIG(90 Å)/Fe(5 Å)]×N, where N is varied from 4 to 24. All these samples were annealed at 650 °C for 2 min with RTA technique. The coercivity decreases with increasing number of bilayers (that is the total thickness of the sample). It should be noted that the samples with N less than ten cannot be crystallized with the annealing condition mentioned above. To crystallize these thin samples either a higher annealing temperature or a longer annealing time is needed. The same situation was also noted for samples with individual garnet layer thicknesses less than 50 Å. This phenomenon is attributed to the increase of the surface-to-volume ratio or the surface tension of the garnet phase with decreasing particle size, as discussed by Cho *et al.*[9] The surface energy and surface stress usually tends to hinder the nucleation and growth of the garnet phase.[10] So the increase in H_c with decreasing number of bilayers may be due to either the smaller grain size or to a mixture of the crystalline and amorphous garnet phases in the thinner samples. The observed smaller saturation magnetization in these samples also support this assumption. Once again, a detailed TEM investigation will be needed to understand these results.

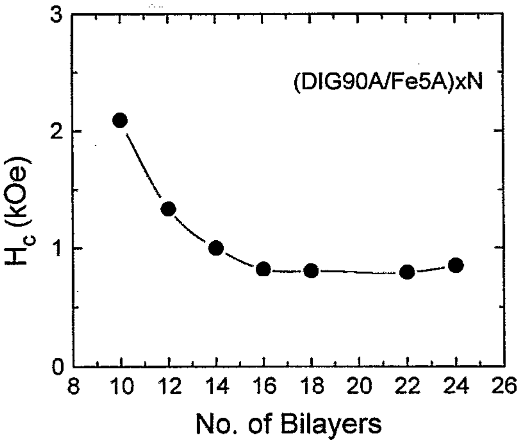

FIG. 6. Coercivity of [BiAlDyIG(90 Å)/Fe(5 Å)]×N as a function of the number of bilayers N after 650 °C 5-min annealing.

We have successfully made garnet/Fe multilayers with relatively sharp interfaces. Small grains (~30 nm) and smooth surfaces were realized by a rapid thermal annealing technique. The multilayers of garnet/Fe have square hysteresis loops with a large coercivity and large magneto-optic activity in the blue portion of the spectrum. These results show that the garnet/Fe multilayers are promising candidates for magneto-optic recording using blue lasers. Systematic studies of how the multilayers affect the magneto-optic behavior and the sample microstructure are underway.

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