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Effect of laser beam parameters on magnetic properties of Nd–Fe–B thick-film magnets fabricated by pulsed laser deposition

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The effects of varying the laser power and the spot diameter of a laser beam on the magnetic properties, morphology, and deposition rate of Nd–Fe–B thick-film magnets fabricated by pulsed laser deposition (PLD) were investigated. Reducing the laser fluence on the target reduces the remanence and increases the Nd content and consequently the coercivity of the prepared films. The spot size of the laser beam was found to affect the film surface morphology, the deposition rate, and the reproducibility of the magnetic properties of the prepared films. Reducing the spot size reduces the number of droplets and the reproducibility of the magnetic properties and increases the droplet size. Controlling the spot size of the laser beam enabled us to maximize the deposition rate. Consequently, a coercivity of 1210 kA/m and a remanence of 0.51 T were obtained at a deposition rate of 11.8 μm/(h·W). This deposition rate is 30% greater than the highest previously reported deposition rate by PLD. © *2011 American Institute of Physics*. [doi:10.1063/1.3566080]

I. INTRODUCTION

Advances in micromachines (e.g., micromotors) urgently require that the magnetic properties of small magnets such as film magnets be further improved. Consequently, thick-film magnets have been extensively studied.[1–4] In addition to the magnetic properties of a film magnet; its deposition rate and the simplicity with which it can be incorporated in a machine are important factors in determining its usefulness. From the perspective of this latter factor,[5] we have studied rapid fabrication of isotropic Nd–Fe–B thick-film magnets by pulsed laser deposition (PLD). We fabricated a film by PLD with a high deposition rate of 9 μm/(h·W); this film had a coercivity of about 1000 kA/m, a remanence of about 0.6 T, and a $(BH)_{max}$ value of 60 kJ/m^3 (Ref. 6).

The laser fluence used in PLD affects target ablation.[7] Thus, the laser fluence is expected to affect both the deposition rate and the magnetic properties of prepared films.

In the present study, we prepared Nd–Fe–B thick-film magnets by PLD by varying the laser beam parameters for ablation, and we investigated the effect of the laser fluence on the magnetic properties, morphology, and deposition rate of the prepared films. We found that controlling the laser energy density enabled us to obtain stable magnetic properties and deposition rates that exceed previously reported rates.[6]

II. EXPERIMENTAL PROCEDURES

A target rotating at a rate of 6.5 rpm and having a nominal composition of $Nd_{2.6}Fe_{14}B$ was ablated for 30 min using Nd:YAG laser pulses ($\lambda = 355$ nm) at a repetition rate of 30 Hz. A film was deposited on a Ta substrate in a vacuum chamber with a back pressure of approximately 10^{-5} Pa. The distance between the target and the substrate was fixed at 10 mm. The Nd:YAG laser beam was 8 mm in diameter, and it was focused on the target by a condensing lens with a focal length of 500 mm. The laser fluence on the target was varied by defocusing the laser beam and by varying the laser output energy. We defined the defocusing rate, DF rate, as DF rate $= (TD - FD)/FD$, where TD is the distance between the condensing lens and the target, and FD is the focal length.

The as-deposited films were amorphous. They were annealed for 1–2 s in an infrared furnace with an output power of 8 kW before being cooled to room temperature. The annealing crystallized the as-deposited films. The annealing times were determined so as to maximize the coercivity. After a film had been magnetized in a pulsed magnetic field of 6.4 mA/m, its magnetic properties were measured using a vibrating sample magnetometer. As all the postannealed films were isotropic, only the in-plane magnetic properties are presented here.

The film thicknesses were determined from in-plane and perpendicular magnetization curves measured for the as-deposited films.[8] The obtained films were 10–60 μm thick. The morphologies of the film magnets were analyzed by scanning electron microscopy (SEM), and their compositions were determined by energy-dispersive x-ray spectroscopy (EDS).

III. RESULTS AND DISCUSSION

The annealed films mainly consist of $Nd_2Fe_{14}B$ and Nd_2O_3 (see Fig. 1). A typical microstructure of the annealed films has been reported elsewhere.[6] Figure 2 shows the coercivity H_c and the remanence I_r of the annealed film magnets prepared from the $Nd_{2.6}Fe_{14}B$ target as a function of DF rate. The error bars in Fig. 2 indicate the maximum and minimum values of 10–12 samples. With increasing DF rate, H_c initially increases while I_r decreases significantly near a DF

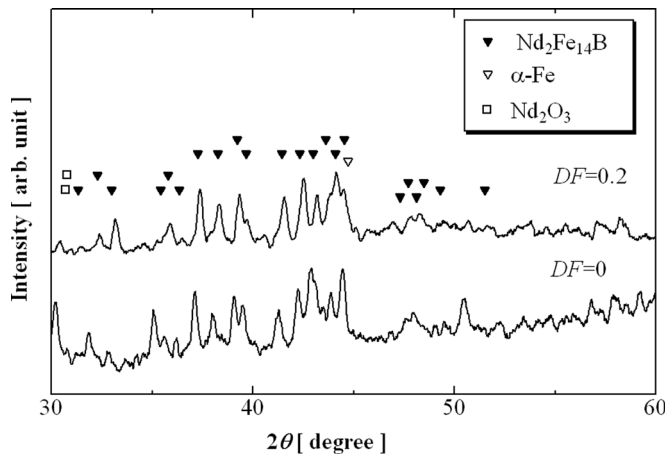a)Electronic mail: fukunaga@nagasaki-u.ac.jp.

FIG. 1. X-ray diffraction patterns of crystallized film magnets.

FIG. 3. Nd content in films prepared from $Nd_{2.6}Fe_{14}B$ target as a function of DF rate. The error bars indicate the maximum and the minimum values for 10–12 samples.

rate of 0.15, which corresponds to an energy density of 7.2 J/cm^2 and they reach nearly constant values of 1200 kA/m and 0.5 T, respectively. These variations in H_c and I_r can be attributed to a variation in the Nd content of the films (see Fig. 3). The deposited films have a much lower Nd content than the target for DF rate < 0.15; their Nd content increases remarkably around DF rate $= 0.15$ until it exceeds that of the target at DF rate $= 0.2$. It is not currently clear what causes this variation in the Nd content.

The scattering in H_c, I_r, and the Nd content is low for films deposited under DF rate > 0.2, which suggests that reproducible magnetic properties can be expected under these conditions. When the laser beam is focused on the target, it forms a deep groove, and the direction in which particles are emitted from the target varies erratically. Thus, this groove may be responsible for the observed scatter in H_c, I_r, and the Nd content.

The effect of the laser power on the magnetic properties was also investigated. Figure 4 shows the results for DF rate $= 0.15$. With increasing laser power, H_c decreases and I_r increases slightly. These trends are consistent with the results shown in Fig. 2 because reducing DF rate increases the laser fluence on the target. H_c and I_r were measured for films prepared using various values for the laser beam parameters. The results are plotted in Fig. 5 as a function of the laser
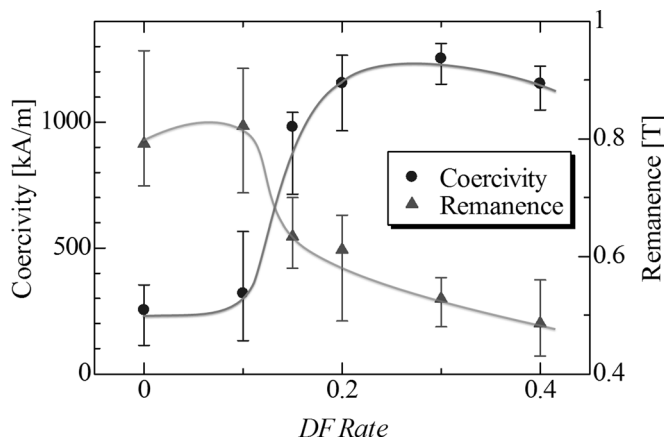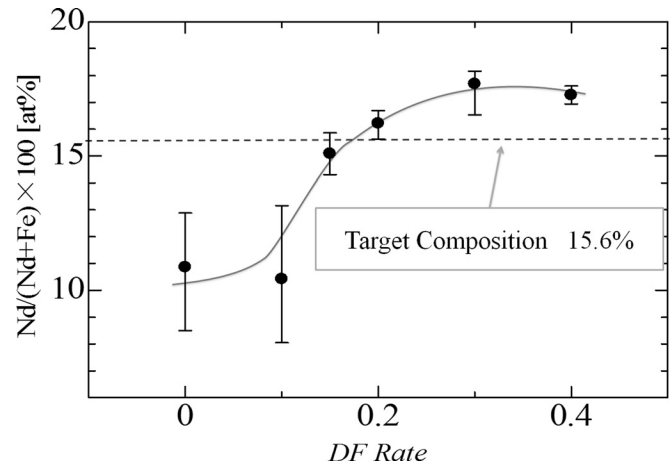
energy density, together with those shown in Figs. 2 and 4. Figure 5 shows that H_c and I_r follow the same trends irrespective of the experimental parameters. These variations in H_c and I_r can be attributed to variation in the Nd content (see Fig. 6). Therefore, it is concluded that the laser fluence affects the Nd content and, consequently, the magnetic properties of the prepared films.

The laser beam parameters also affect the morphology and deposition rate of the films. Figure 7 shows SEM images of film surfaces prepared using DF rate $= 0$ and 0.3, respectively. When the laser beam is focused on a smaller spot, the droplets become larger in size but fewer in number, whereas many small droplets are observed for the film prepared at DF rate $= 0.3$. Consequently, the film prepared at DF rate $= 0$ has a lower average surface roughness R_a than that prepared at DF rate $= 0.3$.

Figure 8 shows a plot of the deposition rate DR as a function of DF rate. The deposition rate is a maximum at DF rate $= 0.2$, independent of the laser power. The maximum obtained DR is 11.8 $\mu m/(h \cdot W)$, which is 30% larger than the highest previously reported deposition rate by PLD.[6] As Fig. 2 shows, the film magnets obtained for DF rate > 0.2 have reproducible magnetic properties. Therefore, we can obtain thick-film magnets with reproducible magnetic properties at

FIG. 2. Coercivity and remanence of films prepared from $Nd_{2.6}Fe_{14}B$ target as a function of DF rate. The error bars indicate the maximum and the minimum values for 10–12 samples.
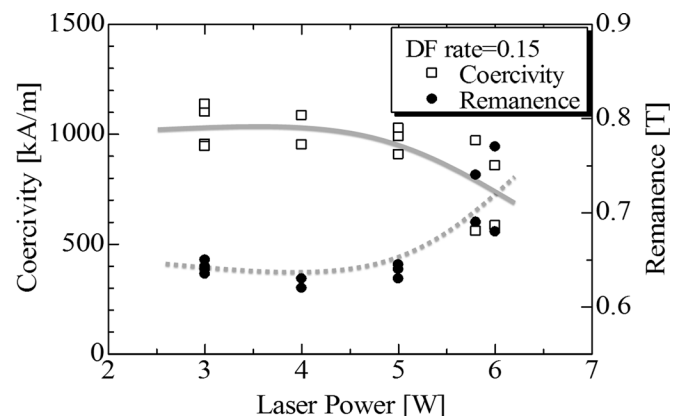

FIG. 4. Coercivity and remanence as a function of laser power. DF rate was set to 0.15.
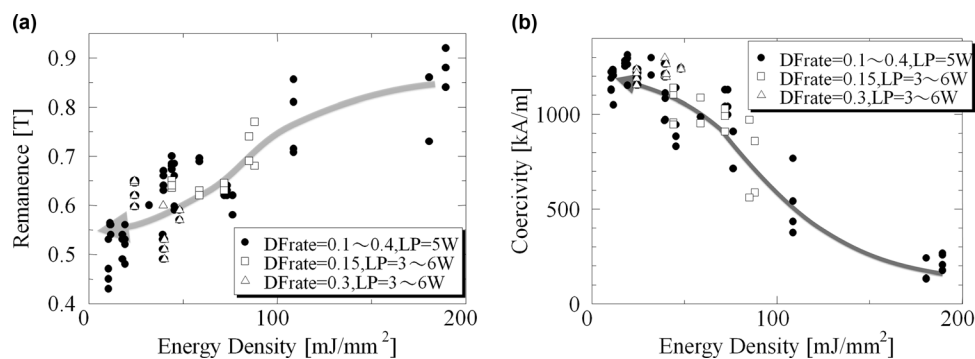
FIG. 5. Effect of laser energy density on the (a) coercivity and (b) remanence. The laser power *LP* and DF rate were varied independently.
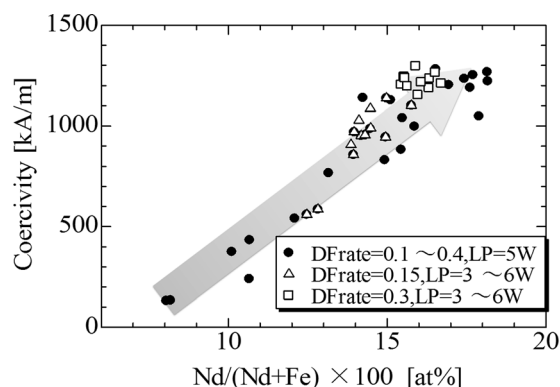

FIG. 6. Relationship between coercivity and Nd content for different values of DF rate and laser power.
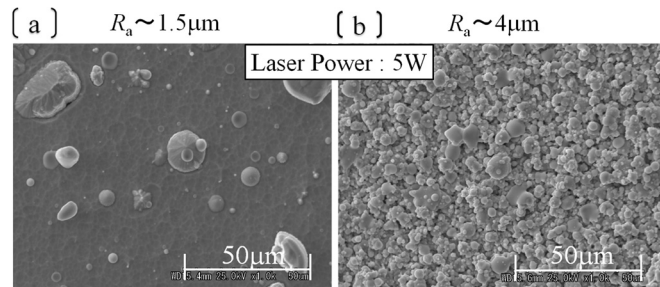

FIG. 7. SEM images of the film surface prepared using DF rate = (a) 0 and (b) 0.3. The average surface roughness is also shown.
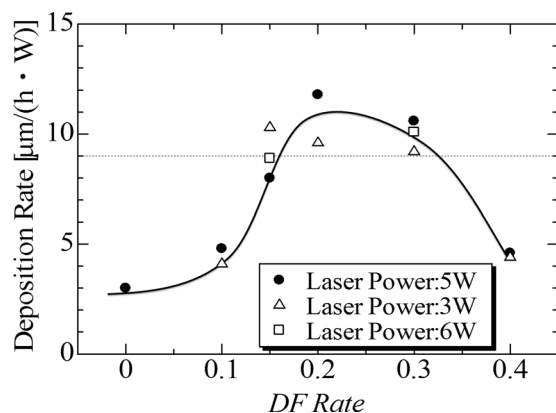

FIG. 8. The deposition rate, DR, as a function of DF rate.

a high deposition rate for DF rate = 0.2–0.3. The values of DR, H_c, and I_r obtained at DF rate = 0.2 were 11.8 μm/(h·W), 1211 kA/m, and 0.51 T, respectively.

IV. CONCLUSIONS

The effects of varying the laser beam parameters on the magnetic properties, morphology, and deposition rate of Nd–Fe–B thick-film magnets fabricated by PLD were investigated. Reducing the laser fluence on the target reduces the remanence I_r and increases the Nd content and the coercivity H_c of the prepared films. The spot size of the laser beam on the target affects the film surface morphology, the deposition rate DR, and the reproducibility of the magnetic properties of the prepared films. Reducing the spot size reduces the number of droplets and the reproducibility of the magnetic properties and increases the droplet size. The reproducibility of magnetic properties is improved by using a defocusing rate, DF rate, of over 0.15. The deposition rate can be maximized by varying the laser beam spot size. The ratio of the deposition rate to the laser power is a maximum at DF rate = 0.2, independent of the laser power.

In conclusion, we produced thick-film magnets with reproducible magnetic properties at a high deposition rate for DF rate = 0.2–0.3. The values of DR, H_c, and I_r obtained at DF rate = 0.2 are 11.8 μm/(h·W), 1210 kA/m, and 0.51 T, respectively. This deposition rate is 30% larger than the highest previously reported deposition rate by PLD.

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