# Achieving high energy product in anisotropic Nd-Fe-B/Fe composite thick films by Dy co-sputtering

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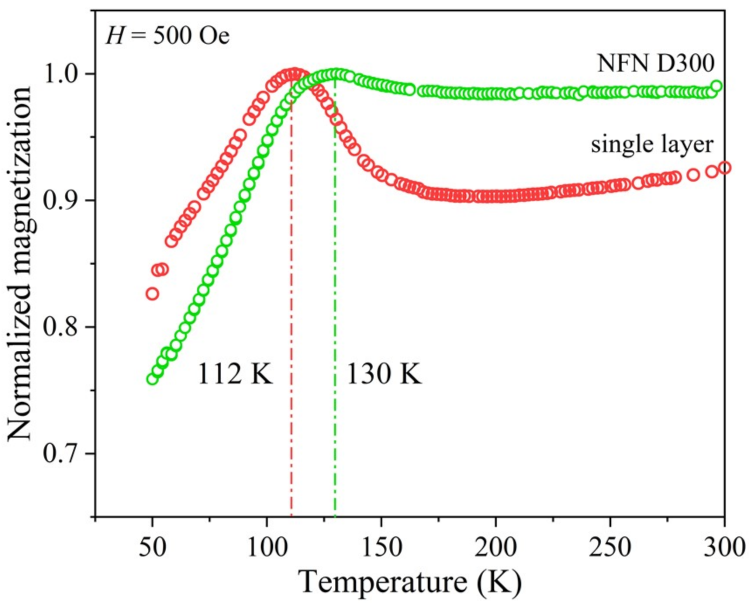


**Figure S1 Temperature-dependent curves of normalized magnetization for Nd-Fe-B single layer and NFN D300 films under a 500 Oe external magnetic field**

Figure S1 shows the temperature-dependent curves of normalized magnetization for Nd-Fe-B single layer and NFN D300 films. The measurements were performed using the zero-field cooling method, where the magnetization was recorded during heating from 50 K to 300 K in a 500 Oe magnetic field. The magnetization of both the Nd-Fe-B single layer and the NFN D300 films initially increases then decreases with rising temperature, finally stabilizing near room temperature. This behavior arises from the spin reorientation transition (SRT) occurring in $Nd_2Fe_{14}B$. Therefore, the SRT temperature for the Nd-Fe-B single layer film is 112 K. The SRT temperature of the Dy co-sputtering NFN D300 film is 130 K, significantly higher than that of the NdFeB single layer film. Since the high magnetocrystallographic anisotropy of $(Nd, Dy)_2Fe_{14}B$ leads to an increased SRT temperature, this further confirms the effective doping of Dy, consistent with the XRD results.

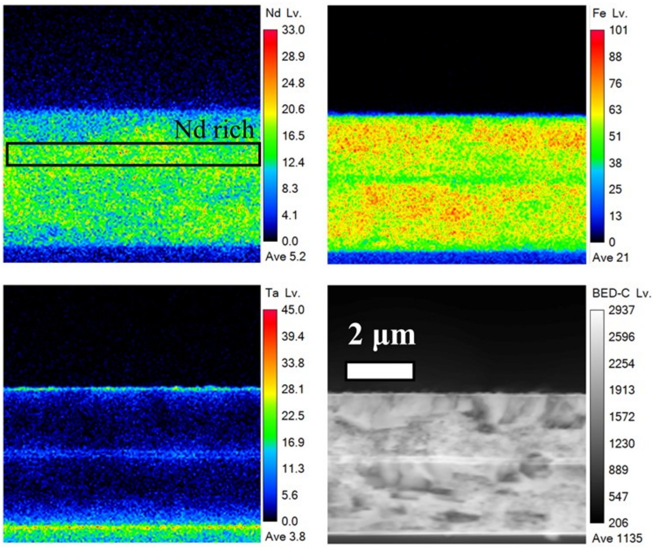


**Figure S2 Cross-sectional BSD-SEM image of NFN film, along with elemental distribution maps for Nd, Fe, and Ta**

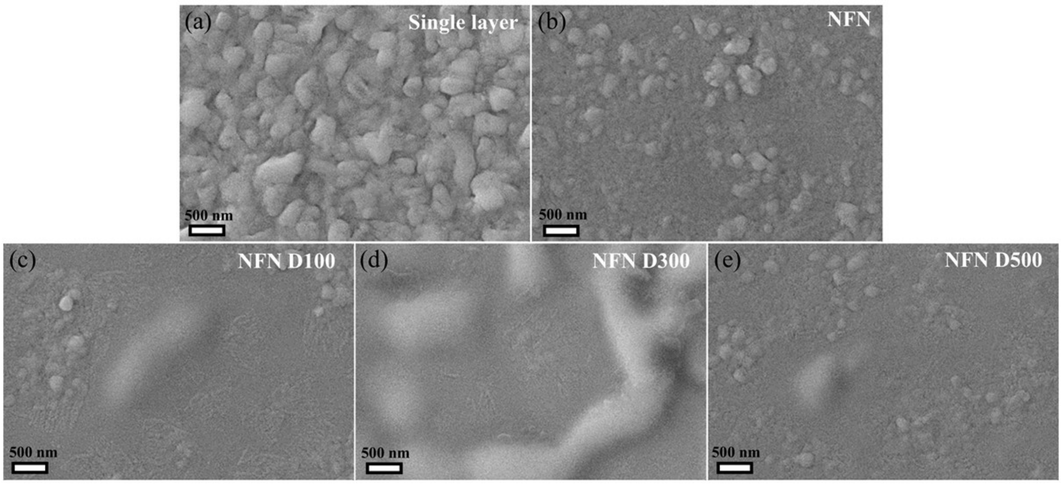


**Figure S3 SEM images of the surface of thick films. (a) Nd-Fe-B single layer film, (b) NFN film, (c) NFN D100 film, (d) NFN D300 film, and (e) NFN D500 film**

The surfaces of Nd-Fe-B single layer film and Dy co-sputtering NFN film were characterized by SEM, as shown in Fig. S3. The Nd-Fe-B single layer film surface exhibits uniformly distributed particles of approximately 500 nm. This is attributed to the deviation from c-axis orientation in $Nd_2Fe_{14}B$. This results in a relatively high surface roughness for the Nd-Fe-B single layer film. In contrast, the NFN film exhibits a marked reduction in granular grains and a significantly smoother surface, corresponding to the improved c-axis orientation observed in XRD analysis. Following additional Dy co-sputtering on the surface and interface, the granular features on the

NFN D100 film diminished further, replaced by island-like protrusions. In NFN D300 film, these island-like protrusions became more apparent, with a width of approximately 500 nm. Beyond these protrusions, the surface appeared flat. For NFN D500 film, the island-like protrusions decrease, and granular grains reappear. The literature indicates that these island-like protrusions result from the enrichment and solidification of the Nd-rich liquid phase between the Ta capping layer and the Nd-Fe-B layer[1]. Thus, surface Dy co-sputtering plays a role in altering the distribution of the Nd-rich phase, transforming the surface morphology from granular to island-like, thereby improving surface roughness.

## Reference

[1] Y. Zhang, D. Givord, N.M. Dempsey, The influence of buffer/capping-layer-mediated stress on the coercivity of NdFeB films, Acta Mater, 2012 **60** 3783-3788.