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# Effects of High Magnetic Field on the Structure and Magnetic Properties of Molecular Beam Vapor Deposited $Fe_{60}Ni_{40}$ Thin Films

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**Abstract:** The $Fe_{60}Ni_{40}$ (in atomic %) polycrystalline thin films with 90 nm thickness were prepared on 200 $^o$C quartz substrate by using molecular beam vapor deposition method. The influence of 0 T and 6 T magnetic fields on the structural evolution and magnetic properties of thin films was studied by using EDXS, XRD, AFM and VSM. In this study, only $\alpha$ phase was formed in both thin films. It was found that the application of a 6 T magnetic field obviously decreases the RMS of surface roughness and the grain size. For the magnetic properties of the thin films, the 6 T magnetic field increases the saturation magnetism *Ms* in-plane and the squareness (*Mr/Ms*) of the hysteresis loop and decreases the coercive force *Hc*. This indicates the soft magnetic properties of the thin films have been notably enhanced in-plane by a high magnetic field. The relationship between the structural evolution and magnetic properties was discussed in details.

**Keywords:** Thin film, high magnetic fields, Fe-Ni, structure, magnetic property.

## 1 Introduction

Soft magnetic thin films have been widely applied to step motors, magnetic sensors, MEMS, transformers, magnetic recording heads and so on [Osaka et al. (1998)]. The Fe-Ni alloy thin films play significant roles in the soft magnetic materials, especially, the application in the magnetic head industry due to its high saturation

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magnetism, high magnetic permeability and low coercive force [Ross (1993); Lopusnik et al. (2003)]. As a result of the continuous increase of hard disc area density, the coercive force of magnetic recording media was also greatly increased. This requires that the writing magnetic materials must have higher saturation magnetism (*Ms*) and lower coercive force, so that the magnetic signal can been written into the magnetic recording media [Osaka et al. (1999)]. In order to make the Fe-Ni thin film exhibit excellent soft magnetic properties, the increase of soft magnetic properties of Fe-Ni polycrystalline thin films plays a key role [Nakatani et al. (1989)]. Therefore, the research on controlling the structural parameters, such as grain size, magnetocrystalline anisotropy, internal stress, the orientation, shape, defect of nanocrystal [Ross (1993); Hayashi et al. (1996)], has become a hot topic.

A high magnetic field is a noncontact environment field. Many studies have indicated that magnetization energy can influence the material texture, grain size, magnetic properties and so on [Liu et al. (2009a, 2009b, 2011); Wang et al. (2009); Wang, Ma, and Watanabe (2008); Wang et al. (2004)]. Some studies have also indicated that high magnetic fields can change the microstructure and magnetic properties of nanocrystalline thin films [Li et al. (2012); Du et al. (2013)]. H. Y. Wang et al. found that the ordering rate in FePt films was enhanced by applying a magnetic field during postdeposition annealing, and Y. W. Ma et al. found that $\gamma$-$Fe_2O_3$ nanotubes have been formed under a 12 T magnetic field. Therefore, in this study, by making use of the superiority of the high magnetic field, the Fe-Ni binary alloy polycrystalline thin films will be prepared by using molecular beam vapor deposition. And the $Fe_{60}Ni_{40}$ polycrystalline thin films are grown on 200 $^o$C quartz substrate. 0 T and 6 T magnetic fields are used to consider the influence of magnetic fields on the structural evolution and magnetic properties of the Fe-Ni thin films. The thickness, grain size, texture and magnetic properties of the $Fe_{60}Ni_{40}$ films are analyzed with and without magnetic fields. The relationship between the structure and magnetic properties of the thin films is discussed.

## 2 Experimental procedure

Molecular beam vapor deposition device was put into the 300 mm bore of a 6 T superconducting magnet device, as shown in Figure 1. The device mainly includes superconducting magnet, vacuum system, Fe and Ni heating sources and substrate temperature control system. The 6 T superconducting magnet was manufactured by Kawasaki in Japan. The vacuum system mainly includes mechanical pump and molecular pump. The pressure is $8.5\times10^{-5}$ Pa before deposition and it increases to $2.0\times10^{-4}$ Pa during deposition process. The shape of heating source is like hollow pipe, and the alumina crucible was put into the centre of the heating source. The source materials (granulated iron and nickel) with the purity of 99.999% were

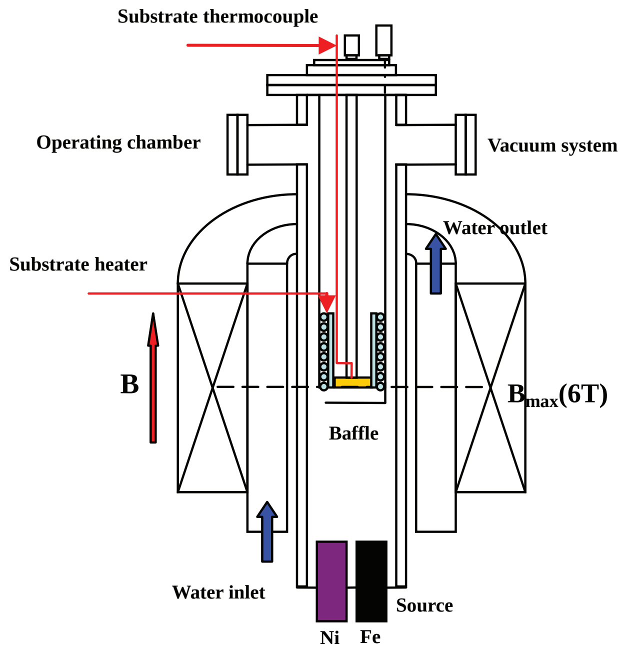


Figure 1: The schematic diagram of experimental apparatus

put into the alumina crucible. The substrate is quartz glass (10×10×1 mm), and the place of the substrate is the centre of the maximum intensity (6 T) of the 6 T superconducting magnet device. The 200 $^{o}$C substrate temperature was controlled by using substrate temperature control system. The thin films were prepared under 0 T and 6 T magnetic field conditions. All prepared $Fe_{60}Ni_{40}$ films were silvery-bright and showed good adherence to the quartz glass substrate surface.

The quartz substrate was cleaned by using ultrasonic cleaning device. The details are as follows. Firstly, the quartz glass was washed by deionized water for 10 minutes. Then the quartz glass was washed by acetone which includes a little chlorylene for five minutes. After that the quartz glass was washed by ethanol for ten minutes. Finally, the quartz glass was dried by using high pressure Ar gas.

Component of the thin film was obtained from OXFORD INCA energy dispersive X-ray spectroscopy (EDXS) on SUPRA35 SEM equipment. The thickness of the film is measured by dektak150 Stylus Surface Profiler. The morphology of the film surface is observed by Digital instruments Nanoscope IIIa AFM equipment. The texture of the films was characterized with X-ray diffractometer (XRD) with DMAX 2400 XRD equipment. The angle of incidence is 2 degree, and the step length is 1 degree/min. The wavelength of copper target is 0.154 nm. The magnetic properties of the thin films were measured with Lakeshore 7407 VSM equipment.

## 3 Results and discussion

The concentrations of the thin films under 0 T and 6 T magnetic fields were measured by area scanning in three different areas, and the area is 10×10 $\mu$m. The average concentrations are almost same ($Fe_{60}Ni_{40}$), and the concentration fluctuation is 2 % within the scope of the error in EDXS (the error in EDXS is 5 % [Kao and Kasiraj (1991)]). The result shows that the concentration of the thin films is not effected by the 6 T magnetic field. The thickness of both thin films is about 90 nm.

The AFM results of the $Fe_{60}Ni_{40}$ thin films under 0 T and 6 T magnetic fields are as shown in Figure 2.

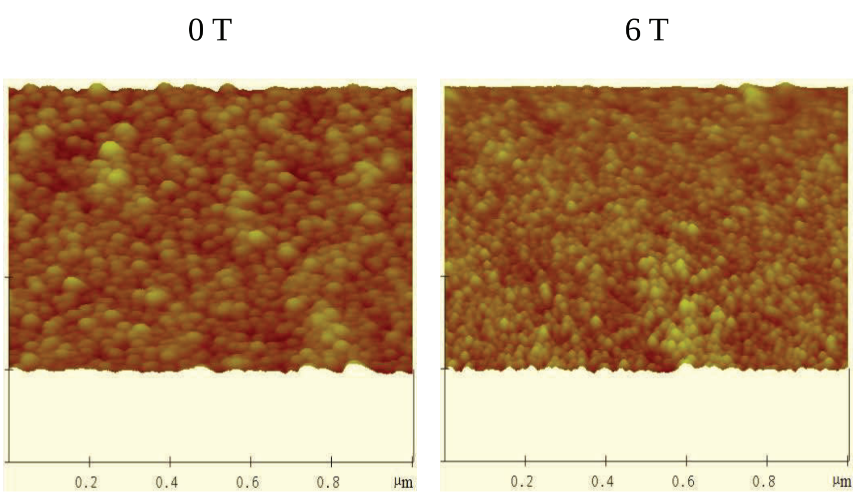


Figure 2: AFM images of the $Fe_{60}Ni_{40}$ thin films under 0 T and 6 T magnetic fields

The results show that the shapes of all the grains are similar sphere, but the grain size is prominently different. The statistics about the grain sizes of the thin films are shown in Figure 3. With a 6 T magnetic field, the grain size was refined, and the distribution range becomes smaller than that without magnetic field. The grain size was refined by 28.5 % with a 6 T magnetic field. It is an important reason that the soft magnetic property of the film was enhanced by the 6 T magnetic field, as will be discussed later. Without magnetic field, the RMS of the surface roughness is 1.04 nm. With a 6 T magnetic field, the RMS of the surface roughness is 0.85

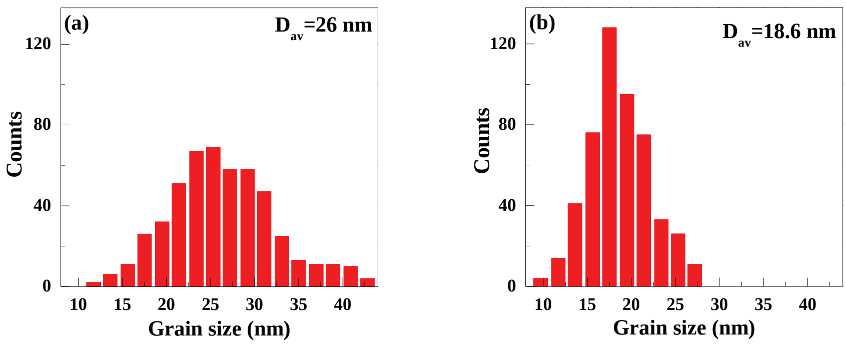


Figure 3: Grain size distribution of the $Fe_{60}Ni_{40}$ thin films under 0 T and 6 T magnetic fields, (a) 0 T, (b) 6 T.

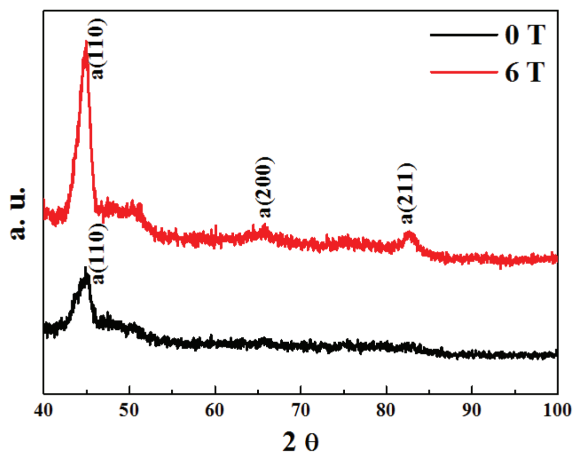


Figure 4: The XRD patterns of the $Fe_{60}Ni_{40}$ thin films under 0 T and 6 T magnetic fields

nm. The reduction of the RMS of the surface roughness is another important reason that the soft magnetic property of the film was enhanced by a 6 T magnetic field.

XRD patterns of the $Fe_{60}Ni_{40}$ thin films under 0 T and 6 T magnetic fields are shown in Figure 4. Without magnetic field, the peak only contains $\alpha$ (110). It shows the growth of the film is along <110> orientation, because the $\alpha$ (110) plane is dense plane and the films along <110> orientation have the minimum energy. With the 6 T magnetic field, the intensity of $\alpha$ (110) peak becomes larger. Moreover, weak $\alpha$ (200) and (211) peaks appear. Because <110> orientation is not the easy-axis of Fe-Ni film, the 6 T magnetic field has influenced the growth process of Fe-Ni films. The orientation of the grain growth will be along the easy-axis, so the (200) and (211) peaks appear. The degree of order of the film was enhanced by the 6 T magnetic field.

The hysteresis loops of $Fe_{60}Ni_{40}$ thin films under 0 T and 6 T magnetic fields in-plane are showed in Figure 5. The coercive force, saturation magnetism and *Mr/Ms* of hysteresis loop are listed in Table 1. In Table 1, the soft magnetic properties can be clarified clearly as follows: the easy axis of $Fe_{60}Ni_{40}$ polycrystalline thin films is parallel with surface. The coercive force decreases by 36 %. The saturation magnetism increases by 14 %. The grain refinement and the reduction of the RMS of surface roughness make the film have a better soft magnetic property with the 6 T magnetic field than that without magnetic field.

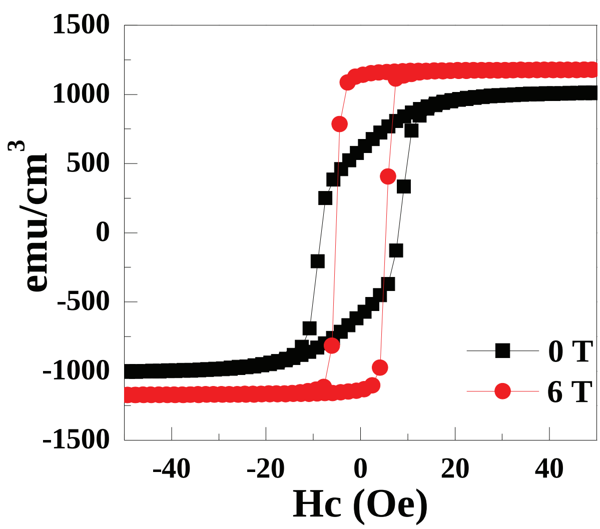


Figure 5: Hysteresis loops of the $Fe_{60}Ni_{40}$thin films in-plane under 0 T and 6 T magnetic fields.

Table 1: Magnetic properties of $Fe_{60}Ni_{40}$ thin films under 0 T and 6 T magnetic fields.

| Experiment condition | Field direction | *Hc* (Oe) | *Ms* (emu/cm$^3$) | *Mr/Ms* |
|---|---|---|---|---|
| 0 T | // | 8.22 | 1012.73 | 0.64 |
| 6 T | // | 5.25 | 1176.52 | 0.96 |

Through the analysis of the relationship between structure and magnetic properties, it can be concluded that: (1) The enhancement of crystallinity under a 6 T magnetic field contributes to the increase of *Ms* of soft magnetic materials. K. Tamura et al. found that the spontaneous magnetization of pure Ni films in amorphous state showed a marked decrease compared with the crystalline state [Tamura and Endo (1969)]. Moreover, S. Iwatsubo et al. [Iwatsubo, Takahashi, and Naoe (1999)] found that pure Fe films prepared by dual ion beam sputtering got the highest *Ms* when thin films had the highest degree of crystallinity from XRD result. (2) The refined grains, narrow grain size distributions and the small RMS of the surface roughness under a 6 T magnetic field contribute to the decrease of *Hc*. According to random anisotropy model [Herzer (1990)], the refined grains can make *Hc* decrease when the grain size is less than the ferromagnetic exchange length $L_{ex}$ ($L_{ex} \approx$ 86-155 nm for $Fe_{60}Ni_{40}$ [Qin, Kim, and Lee (1999)]). H. Chong et al. [Chong et al. (2009)] found that the coercivity of permalloy films could be decreased with a narrower size distribution of the feedstock particles. H. Y. Wang et al. [Wang et al. (2003)] found that the grain growth and the surface roughness of $\alpha\prime$-FeN films were suppressed under high magnetic field, and the coercivity became much lower. (3) The strong exchange coupling between magnetic grains due to good crystallinity under a 6 T magnetic field contributes to increasing *Mr/Ms* value. It is because that the strong exchange coupling makes the moment aligning easily in the same direction in the remanent state.

## 4 Conclusions

Metallic films with composition $Fe_{60}Ni_{40}$ were prepared by using molecular beam vapor deposition with and without a 6 T magnetic field. The structural evolution and soft magnetic properties were studied. With a 6 T magnetic field, the grain size was refined and the RMS of surface roughness was decreased. Moreover, the degree of order of the film was enhanced. These structural changes make the saturation magnetization of the films increase, and the coercive force decreases. Moreover, the *Mr/Ms* of the film was also enhanced with a 6 T magnetic field. Nanocrystalline metallic thin films prepared with a high magnetic field will be a feasible way to enhance the properties of thin films.

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