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Spin-wave resonance in FeNiBSi films

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Ferromagnetic resonance (FMR) measurements have been performed on thin films of $\text{Fe}_{80-x}\text{Ni}_x\text{B}_{15}\text{Si}_5$ alloys ($x = 5, 40, \text{ and } 60$). The effective magnetization ($4\pi M_{\text{eff}}$), magnetic anisotropy field (H_A), and g factor were measured. The values of g for all the films ranged between $1.90 < g < 2.11$. Spin-wave resonance (SWR) excitations were observed for H , the magnetic field, applied perpendicular to the film plane. SWR fields were found to obey the n^2 law and yielded exchange constants in the range of $A = 0.2\text{--}1.9 \times 10^{-6}$ ergs/cm. The nearest-neighbor exchange parameter J was deduced from A and implies that J varies within a factor of 2 as the value of x changes. In one of the nickel-rich samples, the SWR fields appear to be linear with n implying nonuniform distribution of magnetization in the film.

I. INTRODUCTION

Thermal, magnetic, and magnetomechanical properties of amorphous ribbons of $\text{Fe}_{80-x}\text{Ni}_x\text{B}_{15}\text{Si}_5$ have been studied.¹ This system of materials exhibited ferromagnetic ordering with high effective magnetization and relative low magnetic anisotropy field (in the order of 1–10 Oe). In this paper we explore this system in a thin-film configuration. In particular, the ferromagnetic resonance (FMR) and vibrating sample magnetometer (VSM) measurements are reported on $\text{Fe}_{80-x}\text{Ni}_x\text{B}_{15}\text{Si}_5$ ($x = 5, 40, \text{ and } 60$) and $\text{Fe}_{20}\text{Ni}_{80}$. The thin films were prepared with an ion beam sputtering technique. The effective magnetization, magnetic anisotropy field, and g factor were measured as a function of x . In addition, spin-wave resonance (SWR) has been observed so that the exchange stiffness constant was determined.

In our experimental results, the values of g for all samples were in the range of $1.90 < g < 2.11$. The SWR fields were found to obey the n^2 law and the exchange constants were in the range of $A = 0.2\text{--}1.9 \times 10^{-6}$ ergs/cm. The exchange integral parameter J varies within a factor of 2 as the value of x varies from 5 to 60. In addition, the SWR linewidth increased as the spin-wave mode number n increased.

II. EXPERIMENT

We fabricated thin films of $\text{Fe}_{80-x}\text{Ni}_x\text{B}_{15}\text{Si}_5$ with an ion beam sputtering technique. The composition x was varied from 5 to 60 at. %. The thickness ranged from 2160 to 3690 Å. All films were annealed at 275 °C in order to improve the FMR linewidth. Before annealing the FMR linewidth was approximately 100 Oe. But after annealing the linewidth ranged between 30 and 50 Oe in all tested samples.²

The FMR experiments were performed in a microwave cavity which is connected to a 9.5-GHz klystron. The sample was put in the center of the TE_{102} cavity with a teflon sample holder which was rotated in the cavity. Conventional FMR techniques were used to measure the derivative absorption of the sample versus the dc magnetic field on a X - Y recorder. The dc magnetic field was applied in the film plane and normal to it.

From the FMR derivative absorption versus the dc magnetic field curve we obtained the resonant fields of the films. We define H_{\parallel} (film plane parallel to the dc field) and H_{\perp} (film plane perpendicular to the dc field). The FMR linewidth, ΔH , was also obtained directly from the resonance curve. The FMR conditions are given below:

$$(f/\gamma)^2 = (H_{\parallel} + 4\pi M_{\text{eff}})H_{\parallel}, \quad (1)$$

$$f/\gamma = H_{\perp} - 4\pi M_{\text{eff}}, \quad (2)$$

$$4\pi M_{\text{eff}} = 4\pi M_s - H_A, \quad (3)$$

where M_s is the saturation magnetization measured in VSM apparatus and H_A is the magnetic uniaxial anisotropy field. H_A may be deduced from VSM and FMR experiments. The VSM measurement measures $4\pi M_s$ in a saturated magnetic field condition. Thus, by subtracting $4\pi M_s$ from $4\pi M_{\text{eff}}$, H_A is deduced. If H_A is greater than zero, it implies that the easy axis of magnetization is normal to the film plane. If H_A is smaller than zero, the easy axis is in the film plane. γ is the gyromagnetic ratio. f is the frequency of rf field.

H_{\parallel} and H_{\perp} were determined by changing the film orientation to minimize and maximize the FMR field near the parallel and perpendicular sample positions, respectively. The g factor as well as $4\pi M_{\text{eff}}$ are obtained from Eqs. (1) and (2).

The spin-wave resonance absorption spectra was measured for H perpendicular to film plane. The SWR fields and linewidths were measured as functions of n , the spin-wave mode number.

TABLE I. Experimental results of $\text{Fe}_{80-x}\text{Ni}_x\text{B}_{15}\text{Si}_5$ thin films.

Sample no.	x	d (Å)	g	$4\pi M_{\text{eff}}$ (kG)	$4\pi M_s$ (kG)	$-H_A$ (kG)	A (10^{-6} ergs/cm)
1	5	2400	1.92	15.9	12.5	3.4	1.37
2	5	2700	2.09	15.8	11.7	4.1	1.87
3	40	2160	2.10	10.7	7.9	2.8	0.68
4	40	2400	2.10	10.8	9.1	1.7	0.80
5	60	2230	1.91	6.0	5.4	0.6	0.70
6	60	3690	2.01	6.1	4.6	1.5	0.20
7	60	2700	1.97	6.5	4.8	1.7	...

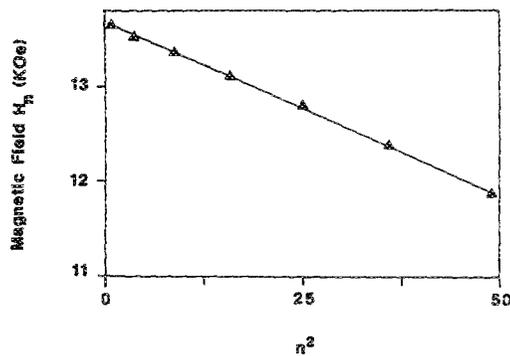


FIG. 1. SWR field H_n in a $\text{Fe}_{40}\text{Ni}_{40}\text{B}_{15}\text{Si}_5$ film vs SWR mode number square, n^2 .

The SWR data was fitted with the following spin-wave dispersion relation:

$$f = \gamma [H_n - 4\pi M_{\text{eff}} + (2A/M_s)(n\pi/d)^2], \quad (4)$$

where d is the thickness and H_n is the SWR resonant field for the n th spin-wave mode, $n = 1, 2, 3, \dots, n = 1$ was assigned to the very first spin-wave resonance next to the main ferromagnetic resonance. By plotting H_n vs n^2 we verified the n^2 law³ of the SWR spectra and calculated the exchange constant A of the ferromagnetic film from the slope of the curve.

In analyzing the data for A , we assumed that the local structure of the amorphous film is bcc for $x < 20$ and fcc for $x > 20$.⁴ Clearly, it is meaningless to describe amorphous films in terms of a crystal structure. However, the coherent or coordination length in amorphous films is about 15 Å which is greater than the basic unit cell or local structure. We are saying that this local coordination within that one or two unit cells is bcc or fcc. The exchange interaction is of short range; we, therefore, believe that it is meaningful to explain our data in terms of an exchange parameter. The nearest-neighbor exchange integral J was obtained from

$$A = 2JS^2/a \quad (\text{bcc structure}) \quad (5)$$

and

$$A = 4JS^2/a \quad (\text{fcc structure}), \quad (6)$$

where S is the spin quantum number and a is the lattice constant.

III. RESULTS AND DISCUSSION

Table I summarizes the FMR and VSM results for our films. The exchange constant A , g factor, $4\pi M_{\text{eff}}$, $4\pi M_s$,

TABLE II. Spin-wave resonance data of a $\text{Fe}_{40}\text{Ni}_{40}\text{B}_{15}\text{Si}_5$ film at 9.5 GHz. n is the spin-wave mode number, ΔH_n is the SWR linewidth, I_n is the intensity of the n th SWR derivative absorption, I_0 is the intensity of the main resonance, i.e., the FMR, and H_n is the magnetic field at the n th SWR.

n	1	2	3	4	5	6	7
ΔH_n (Oe)	31.6	36.0	44.3	47.5	63.3	79.1	126.6
I_n/I_0 (%)	24	3.2	0.32	0.53	0.27	0.056	0.019
H_n (kOe)	13.7	13.5	13.4	13.1	12.8	12.4	11.9

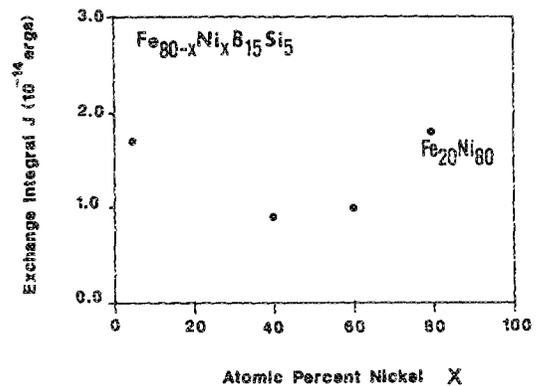


FIG. 2. Exchange integral J of $\text{Fe}_{80-x}\text{Ni}_x\text{B}_{15}\text{Si}_5$ and $\text{Fe}_{20}\text{Ni}_{80}$ thin films vs atomic percent nickel, x .

thickness d , and the composition x are listed in Table I. For most samples the n^2 law was obeyed very well and the exchange constants are in the range of $A = 0.2-1.9 \times 10^{-6}$ ergs/cm. The g factors for all the samples lie in the range $1.90 < g < 2.11$ which is close to published values for permalloy films.⁵ For the samples which have the same value of x , A varied a little for different thicknesses. This is due to experimental error.

The SWR fields versus the SWR mode number square, n^2 , curve is shown in Fig. 1. The SWR linewidth increases and the SWR intensity decreases as the spin-wave mode number n increases. This is shown in Table II.

Figure 2 shows that the exchange integral J varies within a relative small range of $J = 0.97-1.70 \times 10^{-14}$ ergs as the value of x changes from 5 to 60. This is understandable in view of the fact that the exchange integral J describes the interaction between two nearest neighbor ions in the material. Hence, it is affected only by the local coordination. The point here is that although the films are amorphous, the local coordination is maintained such that ferromagnetic exchange is possible.

For one nickel-rich film H_n scales linearly with n instead of n^2 . The exchange constant A cannot be obtained by using Eq. (4). It is well known that this type of scaling can be explained in terms of nonuniform distribution of magnetization within the film.⁶ There are many suggestions which imply that the nonuniformity in magnetization may be due to clusters being formed in the film. At this stage in time it is not clear what the source of the nonuniformity is. The sample number of this film is 7 shown in the Table I.

In summary, we studied thin films of $\text{Fe}_{80-x}\text{Ni}_x\text{B}_{15}\text{Si}_5$ ($x = 5, 40$, and 60) by FMR and VSM techniques. The effective magnetization, g factor, anisotropy field H_A , the exchange constant A and exchange integral J were obtained from the experimental results. The spinwave excitations obey the n^2 law and the FMR conditions are explained in terms of the well-known Kittel relations. In conclusion, although the films are amorphous, it is still meaningful to introduce parameters, such as exchange constant, which are related to short-range interactions.

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