THE TEMPERATURE DEPENDENCE OF THE MAGNETIZATION OF THE AMORPHOUS $Co_{80+x}TM_{12}B_{8-x}$ (TM = Ti, Zr, Hf, Nb) ALLOYS

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Abstract - Amorphous $Co_{80+x}TM_{12}B_{8-x}$ (TM = Ti, Zr, Hf, Nb and x = 0, 2, 4 at%) alloys were prepared by single roll melt spinning technique. Saturation magnetization of the amorphous ribbons was measured by SQUID and vibrating sample magnetometer from 5 to 800 K under applied fields up to 10 kOe. Typical thermo-magnetization curves were observed and the average values of the spectroscopic splitting g factor were estimated from the ferromagnetic resonance curve. For all the amorphous alloys studied here the saturation magnetization in the temperature range 5 K up to about $0.3T_c$ can be described by the Bloch relation: $M_s(T) = M_s(0)(1-BT^{3/2}-CT^{5/2})$. From the values of $M_s(0)$, B and spectroscopic splitting g factor the spin wave stiffness constants were calculated.

I. INTRODUCTION

Substitution of Ti, Zr, Hf and Nb for Co-based amorphous alloys has a remarkable influence on the magnetic and electric properties [1,2,3]. To obtain a better understanding of the magnetic properties, it is essential to examine the spin wave excitations in these materials. In general, it has been found that such glasses exhibit well-defined long-wavelength spin wave excitations with a conventional ferromagnetic dispersion relation given by

$$E_q = \Delta + D(T)q^2 + \cdots \quad (1)$$

where D(T) is the spin wave stiffness constant, q is the magnitude of the magnon wave vector, and Δ is an effective (small) anisotropy gap due to the dipole-dipole interactions [4]. At low temperature, the magnetization exhibits the usual ferromagnetic behavior

$$M_s(T) = M_s(0)(1 - BT^{3/2} - CT^{5/2}), \quad (2)$$

which is characteristic of the thermal excitation of long-wavelength spin waves. Although both crystalline and amorphous ferromagnets follow the general predictions of eqn. (1) and (2), details of the magnetization results for the amorphous alloys differ from those of the crystalline ferromagnets. In the simple spin wave theory [4], the $T^{3/2}$ coefficient B can be related to the spin wave stiffness constant D by the equations

$$B = \zeta(3/2)[\, g\mu_B / M_s(0)\,]\,(k_B/4\pi D)^{3/2} \quad (3)$$

where $\zeta(3/2)$ is the Riemann zeta function, and g is the spectroscopic splitting factor can be obtained from a ferromagnetic resonance (FMR) experiment.

In this paper we report results on the saturation magnetization of the amorphous $Co_{80+x}TM_{12}B_{8-x}$ (TM = Ti, Zr, Hf and Nb, x = 0, 2 and 4, respectively) alloy system and on the spectroscopic splitting g factor which were estimated from the FMR experiment. Finally, spin wave stiffness constants were calculated.

II. EXPERIMENT

The amorphous alloys of $Co_{80+x}TM_{12}B_{8-x}$ (TM = Ti, Zr, Hf and Nb, x = 0, 2 and 4) used in our measurements were prepared in ribbon form by rapid quenching techniques in Ar atmosphere, and were 1 - 2 nm wide and 20 - 30 μm thick. X-ray diffraction test was employed to confirm that the alloys studied were amorphous. The temperature

dependence of the saturation magnetization was measured from 5 up to 800 K in an applied field of 10 kOe using a SQUID and vibrating sample magnetometer. The absolute value of the moment is accurate to better than 1% and relative precision of the thermal variation is 0.2%. The several rectangular-shaped samples had dimension of approximately 1 mm × 2 mm × 30 μm with the field applied in the sample plane to minimize demagnetizing field effect. In order to get the values of the spectroscopic splitting factor g, FMR experiments were carried out using a round-shaped sample with 1 mm diameter at room temperature. A Varian X-band electron paramagnetic resonance spectrometer was used in the experiment. Specifically, the TE_{102} resonance mode in the rectangular cavity was employed. The differential absorption line was observed by varying the angle between the d.c. static magnetic field and the surface of the sample, which was mounted on a goniometer. The values of the angle ψ_H were varied from 0° to 90° in steps of 30° .

Ⅲ. RESULTS AND DISCUSSION

Much experimental evidence exists in the literature indicating that the decrease in magnetization with increasing temperature at low temperature both in crystalline [5] and amorphous [6] ferromagnets can be adequately described by Bloch's relation as given by eqn.(2). Although both crystalline and non-crystalline ferromagnets follow the general predictions of the Heisenberg model, details of the magnetization results for the glassy alloys differ from those of the crystalline ferromagnets [7,8].

Figure 1 exhibits typical temperature dependent saturation magnetization curves of amorphous $Co_{80}TM_{12}B_8$ alloys with H = 10 kOe. The saturation magnetization M_s at 0 K, $M_s(0)$ = 91.35 emu/g ($Co_{80}Ti_{12}B_8$), 86.64 emu/g($Co_{80}Zr_{12}B_8$) and 76.61 emu/g($Co_{80}Hf_{12}B_8$), were obtained by extrapolating M_s to 0 K via a simple spin wave approximation from the saturation magnetization, $M_s(T)$, measured

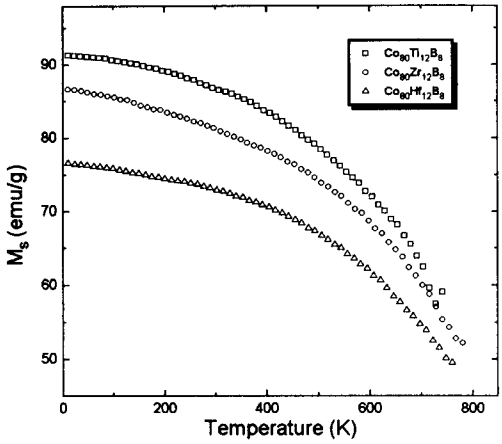

Fig. 1. Temperature dependence of saturation magnetization on amorphous alloys under an applied field of 10 kOe

at various temperatures above 5K. By substituting either Zr or Hf, which belong to the same column as Ti in the periodic table, in place of Ti, the saturation magnetization at 0 K, $M_s(0)$, decreases in steps of about 8 emu/g.

As we can see in figure 2, almost the same tendencies were observed in the other amorphous $Co_{80+x}TM_{12}B_{8-x}$ alloy systems. $M_s(0)$ increased with the increasing concentration of cobalt, as expected.

Figure 3 shows the $T^{3/2}$ behaviour of the low temperature magnetization. The decrease of the reduced magnetization is plotted vs. $T^{3/2}$ below

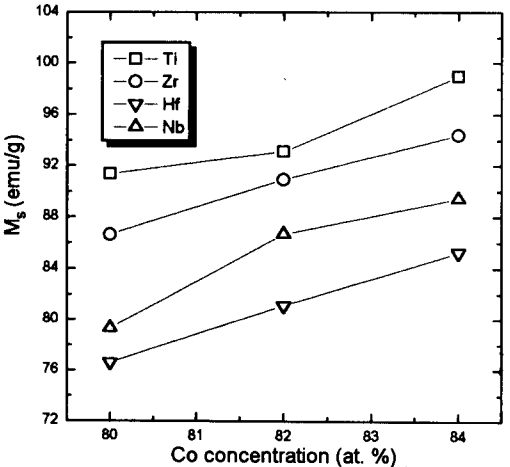

Fig. 2. Saturation magnetization at 0 K, $M_s(0)$ for amorphous $Co_{80+x}TM_{12}B_{8-x}$ alloys.

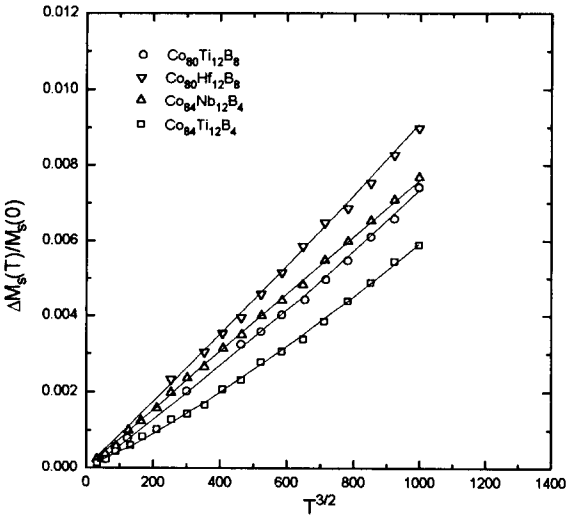

Fig. 3. $T^{3/2}$ dependence of reduced magnetization of the amorphous $Co_{80+x}TM_{12}B_{8-x}$ alloys.

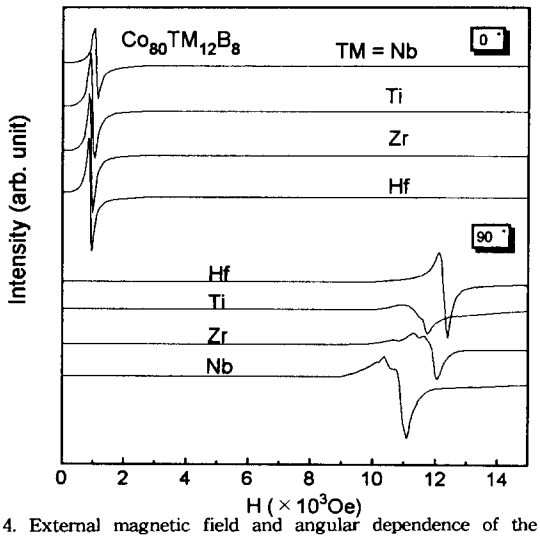

Fig. 4. External magnetic field and angular dependence of the derivative absorption curves of amorphous $Co_{80}TM_{12}B_8$ alloys.

$T \approx 0.3T_c$. $M_s(T)$ is well represented by Bloch's relation, eqn.(2), as indicated by the full curves in the figure. From this figure, Bloch coefficients of B were obtained by the least squares fitting.

Figure 4 shows the angular dependence of the derivative absorption curves for the amorphous $Co_{80+x}TM_{12}B_{8-x}$ alloy. The theoretical description of the FMR signal is based on the analysis in the free energy density F [9] given by

$$F = - HM_s\sin\theta\cos(\psi_H - \psi) + 2\pi M_s^2\sin\theta\sin^2\psi - K_u\sin^2\theta\sin^2\psi \quad , \qquad (4)$$

where terms represent the Zeeman energy density, the magnetostatic energy density, and the uniaxial anisotropy energy density, respectively, K_u is the uniaxial anisotropy constant. Since the equilibrium conditions of the magnetization are given by the relations

$$\left.\frac{\partial F}{\partial \theta}\right|_{\theta=\theta_{eq}} = 0$$

and

$$\left.\frac{\partial F}{\partial \psi}\right|_{\psi=\psi_{eq}} = 0$$

the equilibrium position of magnetization is given

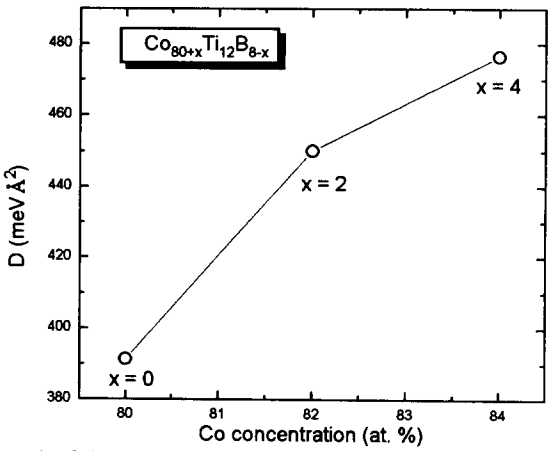

Fig. 5. Spin wave stiffness constant D for amorphous $Co_{80+x}Ti_{12}B_{8-x}$ alloys.

by $\theta_{eq} = \pi/2$ and for ψ_{eq} by the relation

$$2H\sin(\psi_H - \psi_{eq}) = 4\pi M_{eff}\sin(2\psi_{eq}) \qquad (5)$$

The resonance field H_r can be calculated using the free energy density and the general resonance equation derived by Smit and Beljers [9]:

$$(\omega/\gamma)^2 = H_r^2\cos^2[(\psi_H - \psi_{eq})^2] + H_rH_k\cos(\psi_H - \psi_{eq})(3\sin^2\psi_{eq} - 1) + H_k^2(1 - 2\cos^2\psi_{eq})\sin^2\psi_{eq} \qquad (6)$$

Table 1 saturation magnetization at 0 K, Bloch coefficient, spectroscopic splitting factor, spin wave stifness constant and Curie temperature of the $Co_{80+x}TM_{12}B_{8-x}$ alloys

Alloy	$M_s(0)$	$B(\times 10^{-6})$	g	D	T_c (K)
$Co_{80}Ti_{12}B_8$	91.35	6.175	2.240	391.3	755
$Co_{82}Ti_{12}B_6$	93.10	3.761	2.190	450.2	762
$Co_{84}Ti_{12}B_4$	98.95	4.010	2.188	476.5	770
$Co_{80}Zr_{12}B_8$	86.64	4.678	2.229	476.6	800
$Co_{82}Zr_{12}B_6$	90.91	2.174	2.202	693.1	820
$Co_{80}Hf_{12}B_8$	76.61	8.221	2.238	324.2	817
$Co_{82}Hf_{12}B_6$	81.11	6.116	2.197	355.0	825
$Co_{80}Nb_{12}B_8$	79.31	11.22	2.201	278.5	755
$Co_{84}Nb_{12}B_4$	89.43	6.520	2.194	355.3	790

where $H_{k'} = H_k - 4\pi M_s$ is the effective magnetization and $H_k = 2K_u/M_s$ is the uniaxial anisotropy field. Finally, the spectroscopic splitting factor g is estimated to be about 2.2 by fitting eqns. (5) and (6) to the experimental results for ψ_H and H_r.

As is given in eqn. (3) by conventional linear spin wave theory, the Bloch coefficient B is related to the spin wave stiffness constant D through

$$D = (2.612)^{2/3} \left[\frac{g\mu_B}{M_s(0)} \right]^{2/3} \frac{k_B}{4\pi}$$

The spin wave stiffness constant D is shown in Fig. 5 as a functions of Co concentration in amorphous $Co_{80+x}Ti_{12}B_{8-x}$ alloy system. It is noted that D increases with the concentration of Co, indicating a "hardening" of the exchange interaction by Co substitution. All obtained physical parameters are listed in table 1.

Ⅳ. CONCLUSIONS

The saturation magnetization at 0 K, $M_s(0)$, of the $Co_{80+x}Ti_{12}B_{8-x}$ alloy system increased as the concentration of Co increased. The temperature dependence of these alloys follow the predictions of spin wave excitation theory. The values of the spectroscopic splitting factor g for this system are estimated to be about 2.2. The spin wave stiffness constant D increase with the concentration of Co element.

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