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Low Temperature Magnetization and Spin Wave Excitations in Amorphous $Fe_{67}Co_{18}B_{14}Si_1$

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The temperature dependent saturation magnetization curve of amorphous $Fe_{76}Co_{18}B_{14}Si_1$ alloy was measured using a SQUID magnetometer and vibrating sample magnetometer from 5 K up to 800 K. Inelastic neutron scattering measurements also have been used to study the long wavelength spin dynamics of this high T_c amorphous ferromagnetic alloy. The magnon dispersion curve exhibit the conventional quadratic relationship $E = D(T)q^2 + \triangle$, typical of an isotropic ferromagnet. An estimate of the $T = 0$ value of spin wave stiffness constant, $D(0) \simeq 144$ meVÅ² value was obtained from a low temperature magnetization curve, which was consistent with the value obtained from the analysis of inelastic neutron scattering data after consideration of its temperature dependence.

I. Introduction

The magnetic properties of metallic glasses produced by rapid quenching have been the subject of considerable scientific and technological interest approximately the last 20 years. In the past few years a number of studies have been reported of the low-temperature magnetic properties and of the magnetic excitations of locally isotropic amorphous metallic ferromagnets [1, 2]. In general, it has been found that such glasses exhibit well-defined long-wavelength spin-wave excitations with a conventional ferromagnetic dispersion relation

$$E = \triangle + D(T)q^2 + \cdots \tag{1}$$

where $D(T)$ is the spin-wave stiffness constant, q is the magnitude of the magnon wave vector, and $\triangle$ is an effective (small) anisotropy gap due to the dipole-dipole interactions [3]. The stiffness constant typically exhibits a leading-order temperature dependence of the Dyson form.

$$D(T) = D(0)\,[1 - a\,(T/T_c)^{5/2}] \tag{2}$$

in agreement with the two-magnon interaction theory of a Heisenberg ferromagnet. This dependence has been observed over an unusually wide range of temperature in the present amorphous metal system, as well as in many other amorphous ferromagnets [1].

$$\frac{\triangle M_s(T)}{M_s(0)} = BT^{3/2} + CT^{5/2} + \cdots \tag{3}$$

At low temperature, the magnetization is observed to exhibit the usual ferromagnetic behavior characteristic of the thermal excitation of long wavelength spin waves.

In simple spin-wave theory[3], the $BT^{3/2}$ coefficient Bcan be related to the spin-wave stiffness constant D by the equations

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

where $\zeta\left(\frac{3}{2}\right)$ is the Riemann Zeta functions and $\langle r^2 \rangle$ is the square of the average exchange interaction range.

In order to obtain a better understanding of the high T_c amorphous alloys, we report results on the saturation magnetization of commercially available amorphous $Fe_{67}Co_{18}B_{14}Si_1$ ribbons in the range from 5 K to 800 K and in applied fields up to 10 kOe. We also have undertaken neutron scattering studies at high temperature to determine the wave vector dependence of spin wave excitations. Spin wave stiffness constant derived from both experiments are compared and discussed.

Ⅱ. Experimental

The sample of $Fe_{67}Co_{18}B_{14}Si_1$ used in our measurements was prepared in ribbon form from the melt by rapid quenching technique in vacuum. The temperature dependence of saturation magnetization was obtained using SQUID magnetometer and vibrating sample magnetometer (VSM) from 5 K up to 800 K under the external field of 10 kOe. The absolute value of the moment is accurate to better than 1 % and the relative precision of the thermal variation is 0.2 %. The temperature was controlled to within ± 0.3 K. The square-shaped samples had dimensions of approximately 3 mm × 3 mm × 20 μm with the field applied in the sample plane to minimize demagnetizing field effects. Approximately 17 g of the ribbon 20 μm thick and 4.5 cm wide were loosely wound at a cylindrical aluminum sample holder for the neutron scattering experiment. This was mounted in a vacuum cryofurnace, and the inelastic neutron scattering measurement were taken on the E1 triple-axis spectrometer at Hahn-Meitner-Institut in Berlin. The amorphous nature of the system required that measurements be taken near the forward (000) beam position, and precautions were taken to minimize air and sample-container scattering at the small wave vector (q) transfers required in the experiments. A fixed incident energy of 13.5 meV was used. A pyrolitic graphite (PG) monochorometer and analyser crystal were employed together with a PG filter placed in front of the monochrometer to suppress high order incident wavelength contamination. Soller slit horizontal collimation of 20′-10′-10′-20′ were used to minimize the width of energy and momentum resolution function of the instrument. The Q-constant method was used to search for the magnon excitation. The wave vector transfer examined was 0.055 and 0.065 Å^{-1}, and the measurement was carried out at 643 K and 700 K. At lower temperature the spin wave energies were too high to measure with these experimental conditions.

Ⅲ. Results and Discussion

Much experimental evidence exists in the literature to show that the decrease in magnetization with increasing temperature at low temperature both in crystalline ferromagnet materials, and in amorphous ferromagnets, is adequately described by the Heisenberg model as given by eq. (3). Although both crystalline and non-crystalline ferromagnets follow the general predictions of the above mentioned model, details of the magnetization results for the glassy alloys differ from those of the crystalline ferromagnets.

3. 1 Temperature dependence of magnetization

Figure 1 shows temperature dependent saturation magnetization curve measured with H = 10 kOe. The saturation magnetization decreased until to 708 K, and suddenly increases above this crystallization temperature is much lower than the Curie temperature which is not common in the amorphous alloys. The $T = 0$ saturation magnetization, $M_s(0)$ = 185 emu/g, was obtained by extrapolating to 0 K the saturation magnetization $M_s(T)$ measured at various temperature above 5 K. The Curie temperature, T_c = 770 (± 3) K, also can be estimated from the isofield magnetization curve.

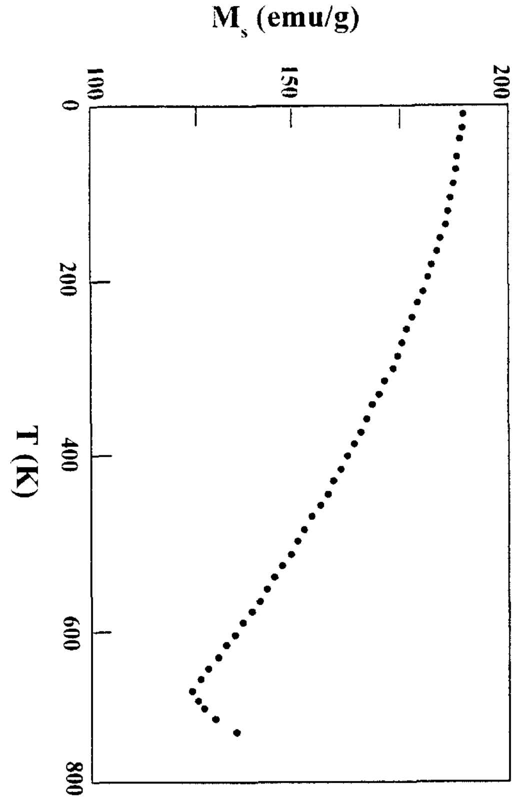

Fig. 1. Temperature dependence of saturation magnetization curve of the amorphous $Fe_{67}Co_{18}B_{14}Si_1$ alloy in an external field of 10 kOe.

Figure 2 shows $T^{3/2}$ temperature dependence of reduced saturation magnetization $\Delta M_s(T)/M_s(0)$. For temperature below $T \simeq$ 150 K, reduced saturation magnetization is seem to be well represented by the spin wave expression of eq. (3), indicated by solid line. The results of a least-squares fit give values of $M_s(0)$ = 185 emu/g (16 kG), and $B = 13.1 \times 10^{-6}$ K$^{-3/2}$. As given in eq. (4) by conventional linear spin-wave theory, the constant B is related to the spin-wave stiffness constant D through.

$$D = (2.612)^{2/3}\left[\frac{g\mu_B}{M_s(0)}\right]^{2/3}\left(\frac{k_B}{4\pi}\right) \qquad (5)$$

Using the values of B and M_s (0), we calculate the spin wave stiffness constant, $D(0)$ = 144 meVÅ^2. The g value of 2.02 has been obtained from the ferromagnetic resonance experiment.

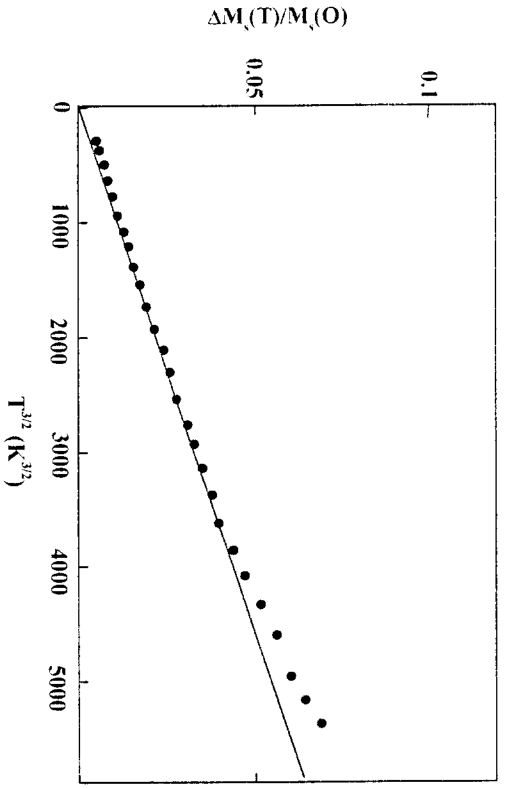

Fig. 2. Renormalized saturation magnetization vs. $T^{3/2}$ obtained by least square fitting to the relation $M_S(T)/M_S(0)(1 - BT^{3/2} - CT^{5/2})$

3. 2 Spin wave measurements

Value of the spin-wave energies for various wave-vector transfers q and temperatures T were obtained by convoluting a theoretical cross section with the experimental resolution and least-squares fitting to the observed spectra. The spectral weight function used in the convolution was a double Lorentzian-type cross section [1, 2]. Figure 3 shows a set a typical constant q neutron scans at q = 0.045, 0.055 and 0.065 Å^{-1} for T = 700 K. The background and elastic scattering which arise principally from the furnace and sample holder.

Figure 4 shows a set of typical constant-q neutron scans at 0.055 Å^{-1} for 600, 650 and 700 K, respectively. Spin waves for both neutron energy gain (E < 0) and energy loss (E > 0) are easily observable and well resolved. The dashed lines are the result of the least-squares fits, and spin wave energies are indicated by arrows. The actual spin-wave energies occur at an energy which is lower than the observed peak position due to the resolution effect [2]. We observed broadening of the peak with increasing temperature. The spin-wave energies were found to obey a quadratic dispersion relation as expected (eq. (1)) for an isotropic ferromagnet [4]. From plot of E vs. q^2, we found a gap of $\Delta \approx 0.04$ meV independent of temperature over the range of the measurements, which is almost similar with other amorphous alloy [5]. The spin wave stiffness constant at 700 K was obtained from the two small peaks to be about 99 meVÅ^2. As discussed earlier, the spin wave stiffness constant estimated from the low temperature magnetization, $D(0)$, was about 144 meVÅ^2. The spin wave stiffness constant, D, has an initial temperature dependent give as eq. (2). As a result, the coefficient of temperature, a = 0.4 was obtained and this value is in good agreement with other amorphous alloys [1].

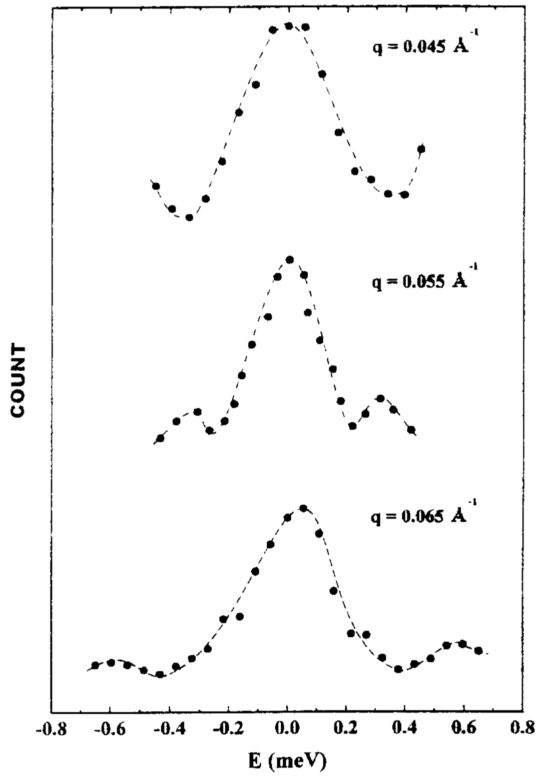

Fig. 3. Scattered neutron intensity (relative units) versus neutron energy transfer for the $Fe_{67}Co_{18}B_{14}Si_1$ amorphous ribbon alloy at 700 K. Data are shown for wave vector transfer q of 0.045, 0.055, and 0.065 Å^{-1} and were taken with an incident energy of 13.5 meV. The arrows indicate the positions of the resolution corrected spin wave energies. Spin-wave peaks are shown for both neutron energy gain (E < 0) and energy loss (E > 0).

Ⅳ. Conclusion

The elementary excitations of this amorphous ferromagnets are, at first sight, conventional spin waves. The magnetization follows a Bloch law and spin waves exhibit quadratic dispersion and a Dyson-like temperature renormalization. Spin wave stiffness constant estimated from the low temperature saturation curve was consistent with the value obtained from the analysis of inelastic neutron scattering data after consideration of its temperature dependence.

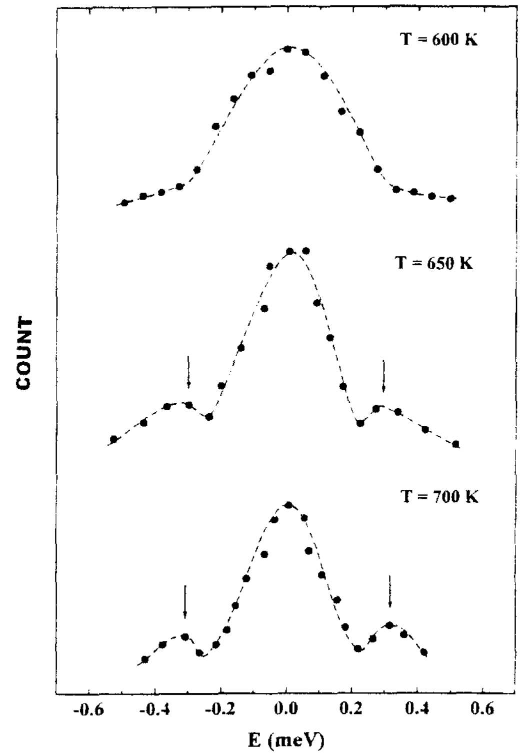

Fig. 4. Temperature dependence of spin wave excitations in amorphous $Fe_{67}Co_{18}B_{14}Si_1$ alloy at q = 0.055 Å^{-1}. The dashed lines are the least squares fits to the convolution of the cross section with the instrumental resolution.

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