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The Nature of Exchange Interaction in Amorphous Alloys Based on Metals of the Iron Group with Metalloids

O. K. Kuvandikov, I. Subxankulov, D. H. Imamnazarov, and Sh. A. Khomitov

Samarkand State University,
15 University Blvd.,
UZ-140104 Samarkand, Uzbekistan

The temperature dependence of magnetization is studied to obtain information about the nature of structural and magnetic transformations in amorphous alloys. Low-temperature magnetization provides information on spin waves, *i.e.*, the law of 'three second' $T^{3/2}$ is fulfilled. The spin-wave rigidity constant D, a characteristic property of an amorphous ferromagnetic, is determined from these dependencies.

Key words: amorphous alloys, spin waves, magnetization, magnetic moment, Curie temperature, exchange interaction parameter.

Для одержання інформації про характер структурних і магнетних перетворень в аморфних стопах досліджується температурна залежність намагніченості. Намагніченість в області низьких температур дає інформацію про спінові хвилі, тобто виконується закон «трьох других» $T^{3/2}$. З цих залежностей визначається константа спін-хвильової жорсткости D, яка є характерною властивістю аморфного феромагнетика.

Ключові слова: аморфні стопи, спінові хвилі, намагніченість, магнетний момент, температура Кюрі, параметр обмінної взаємодії.

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Corresponding author: Oblakul Kuvandikovich Kuvandikov
E-mail: quvandikov@rambler.ru

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1. INTRODUCTION

To obtain information on the nature of structural transformations occurring in amorphous alloys, the temperature dependence of the saturation magnetization was studied using a vibration magnetometer [1].

Unfortunately, little study of ferromagnetism amorphous systems at low temperatures. The first steps in this direction showed that there is the possibility of creating based on amorphous metal alloys a fundamentally new storage medium with ultrahigh information density (alloys with spin glass properties).

In order to verify the conclusions of the quantum theory on the dependence of spontaneous magnetization on temperature for amorphous alloys and to clarify the dependence of the parameter B in the 'three-second' law, which characterizes the exchange energy, on the composition of the alloy with different concentrations of metalloids and on heat treatment, an experimental investigation of the dependence of the saturation magnetization was carried out for the indicated alloys on temperature in the region of low temperatures.

2. MATERIALS AND METHODS

Amorphous alloys of the Co–Fe–Si–B system in the form of a strip were obtained by rapid quenching of a liquid sample on the surface of a fast-rotating disk, 15 mm wide, ~ 12 μm thick and 10–15 m long [2].

To study the stages of crystallization and to identify intermediate phases, we can use cyclic thermomagnetic analysis, which consists in heating the alloys to appropriate temperatures with subsequent cooling. The use of the methods of thermomagnetic analysis, in contrast to the analysis of the change in electrophysical properties depending on temperature, allows obtaining reliable information about the Curie temperature T_C, temperatures of various stages of crystallization T_K and T_C of crystallizing phases [3].

In addition, the magnetization at low temperatures contains information of spin waves; the decrease in magnetization at low temperatures in ferromagnetic amorphous alloys in comparison with crystalline ones is explained by thermal excitation of the long-wavelength part of the spin wave spectrum [4, 5].

3. RESULTS AND DISCUSSION

The change in magnetization with temperature is determined by the following relationship [4]:

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

$$\frac{I_s(0) - I_s(T)}{I_s(0)} = \frac{\Delta I_s(T)}{I_s(0)} = BT^{3/2}. \quad (2)$$

Here

$$B = 2.612 \frac{g\mu_B}{I_s(0)} \left(\frac{k_B}{4\pi D} \right)^{3/2}, \quad (3)$$

where g is the spectroscopic splitting factor or Lande factor ($g = 2.0023$), μ_B is the Bohr magneton, k_B is Boltzmann's constant, $I_s(0)$ is saturation magnetization at temperature $T = 0$ K and in zero magnetic field, D is spin-wave rigidity constant, which is a characteristic property of a ferromagnetic, both the saturation magnetization and the Curie temperature.

If a collectivized electron with a wave vector $\mathbf{k}$ is excited into a state with a wave vector $\mathbf{k} + \mathbf{q}$, and its spin changes direction to the opposite, then it can form an electron–hole pair with an energy $\hbar\omega$ with a hole, which has arisen during its excitation, for which at small values of $\mathbf{q}$ appropriate the relation $\hbar\omega = Dq^2$, where for a simple cubic lattice

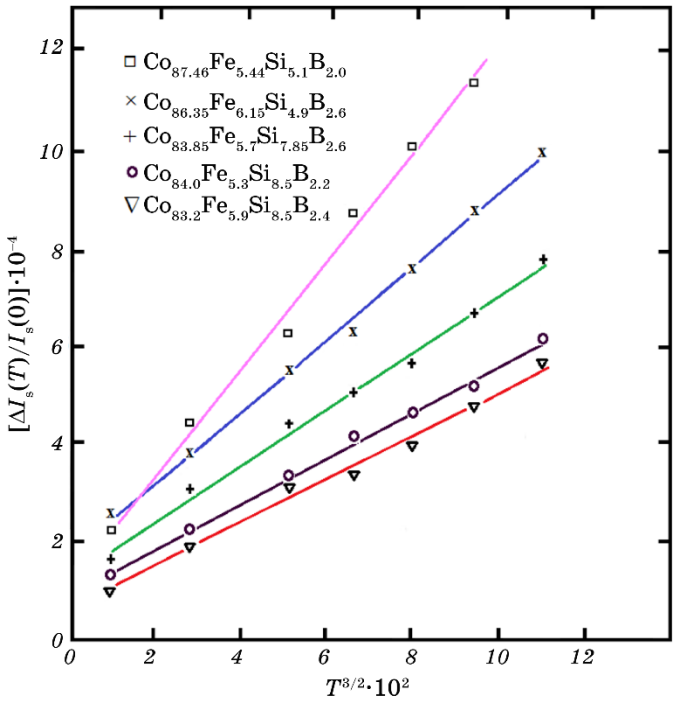

Fig. 1. Dependence of the relative saturation magnetization $\Delta I/I$ on temperature $T^{3/2}$ for the alloys of the Co–Fe–Si–B system.

$D = 2ASa^2$, S is the spin quantum number (equal to 1/2 for an electron and 5/2 for the Fe^{3+} ion—the main magnetic ion in most magnetic materials), A is the exchange integral, the energy of the exchange interaction of two spins located at a distance a (constant of the magnetic lattice) from each other, **q** is the wave vector.

The value of the constant D can be determined both from the neutron diffraction data and from the determination of the temperature dependence of the saturation magnetization.

From equation (2), plotting the dependence of $\Delta I/I$ on $T^{3/2}$ we can determine B, and then from equations (3) and (1) the coefficient D and the Curie temperature T_C.

Figure 1 shows the relative change in $\Delta I/I$ dependent on $T^{3/2}$ for amorphous alloys of the Co–Fe–Si–B system depending on the content of metalloids. Figure 2 shows the dependences of the magnetic moment and Curie temperature of the studied amorphous alloys Co–Fe–Si–B on the content of metalloids.

The value of the exchange constant A can be determined within the framework of the molecular field model (Heisenberg model) and the theory of spin waves.

According to the molecular field model, the exchange constant A between magnetic atoms can be expressed by the following formula

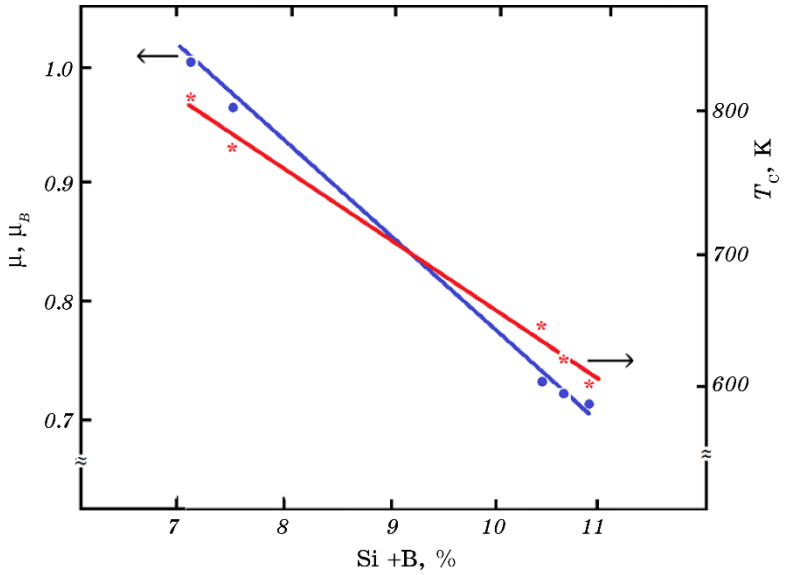

Fig. 2. Dependence of the magnetic moment μ and Curie temperature T_C of amorphous alloys of the Co–Fe–Si–B system on the concentration of metalloids.

TABLE 1. Values of magnetic parameters for amorphous alloys of the iron group.

No.	Alloy composition	S	T_C, K	B, $10^{-5}\cdot K^{-3/2}$	D, eV·A^2	A_{eff}, eV	A_H, eV	μ_A, μ_B	A_{eff}/A_H	D/T_C, eV/K
1	$Co_{87.46}Fe_{5.44}Si_{5.1}B_{2.0}$	0.512	810	0.424	0.422	0.0263	0.027	1.030	0.97	5.9
2	$Co_{86.35}Fe_{6.15}Si_{4.9}B_{2.6}$	0.450	770	1.08	0.252	0.0222	0.036	0.975	0.62	3.6
3	$Co_{83.85}Fe_{5.7}Si_{7.85}B_{2.6}$	0.364	650	1.03	0.294	0.0260	0.045	0.737	0.61	4.5
4	$Co_{84}Fe_{5.3}Si_{8.5}B_{2.2}$	0.362	620	1.05	0.291	0.0270	0.043	0.729	0.64	4.7
5	$Co_{83.2}Fe_{5.9}Si_{8.5}B_{2.4}$	0.361	600	1.07	0.289	0.0277	0.042	0.722	0.66	4.8

$$A = \frac{3k_B T_C}{2zS(S+1)}. \tag{4}$$

In the model of spin waves, the effective value of the exchange constant between neighbouring magnetic atoms can be obtained if we assume that, in the case of amorphous alloys, the expression for the dispersion coefficient found for crystalline alloys with an f.c.c. lattice is valid [5]

$$D = \frac{1}{3} z R_1^2 A_{eff} S. \tag{5}$$

where R_1 is the radius of the first coordination sphere containing z atoms.

The calculated values of some magnetic parameters for iron group alloys are shown in Table 1.

As can be seen from Table 1, the value of the magnetic moment of the studied amorphous alloys increases with a decrease in the concentration of metalloids. The Curie temperature T_C also increases with a decrease in the concentration of metalloids. The change in T_C is explained by the dependence of the exchange interaction on the distance between iron atoms: with a decrease in its ferromagnetic interaction weakens and eventually becomes antiferromagnetic. These structural changes are characterized by high values of coordination numbers in the first coordination sphere, which are higher than those for the b.c.c. structures. Amorphous structures are also characterized by large coordination numbers in the first coordination sphere. In this respect, the most important assumption may be that, the ferromagnetism, associated with iron atoms in close-packed structures with high coordination numbers, tends to disappear. This may be due to the enhancement of the antiferromagnetic interaction between iron atoms. Co–Fe–Si–B alloys have a high Curie temperature. This reflects the nature of exchange interactions

between the magnetic moments of atoms, which are stronger between atoms of different types than between atoms of the same type.

The change in the magnitude of the magnetic moment can be explained within the framework of the concept of the transfer of electron charge from metalloid atoms (Si–B) to the *d*-band of the transition metal. The magnetic moment with an increase in the content of metalloids decreases due to the fact, that the magnetic states lose their *d*-character due to their participation in the bond with metalloid atoms (*p*–*d*-hybridization).

4. CONCLUSION

As a result of the study, it was found:
1. The law of 'three second' describes quite well the temperature dependence of the saturation magnetization of amorphous Co–Fe–Si–B alloys for the all studied concentrations.
2. According to the obtained experimental results, the dependence of the average magnetic moment per atom of the alloy on the concentration of the metalloid was established. It was found that the dependence of the magnetic moment on the concentration of the metalloid is linear, and with a decrease in the concentration of the metalloid, the magnetic moment of the amorphous alloy increases.
3. The obtained experimental results were used to determine the Curie temperature T_C and the parameters of the exchange interaction of the investigated alloys. It is shown that amorphous Co–Fe–Si–B alloys have a high Curie temperature and have a linear dependence of magnetic moment on the content of metalloids.

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