Magnetization and its temperature dependence in compositionally modulated amorphous $Fe_{70}B_{30}$-Ag films

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Compositionally modulated amorphous $Fe_{70}B_{30}$-Ag films have been prepared by dc magnetron sputtering. The thickness of the magnetic layer (d) ranged from 3 to 90 Å, while the Ag layer thickness was always kept at four times as large. The multilayer structure is well established by the cross-sectional transmission electron micrograph. The magnetic properties of the system were investigated with a SQUID magnetometer. The spontaneous magnetization (M_s) at $T = 8$ K remains constant over the thickness range studied, indicating the absence of magnetically dead layers at the interfaces. The temperature dependence of M_s follows Bloch's law for $d \geqslant 6$ Å, with the spin-wave constant inversely proportional to d. This is explained by an interface effect on spin-wave excitation. As the thickness is reduced to 4 Å, a linear temperature dependence of M_s is observed, indicating a magnetic 3D-to-2D transition.

Studies of compositionally modulated materials represent a new trend in condensed matter physics. Although a number of metallic superlattices have been made with new exotic properties, superlattices with coherent structures are severely limited by the requirements of structural similarities, lattice matching, etc. The lack of crystalline order in amorphous materials makes them suitable for making compositionally modulated solids. In addition, amorphous materials often have distinctive properties not possessed by crystalline solids, such as an absence of grain boundaries and a freedom to change their composition which allows their properties to be tailored.

In this work, we have studied the magnetic properties of a new compositionally modulated amorphous $Fe_{70}B_{30}$-Ag system. Magnetization and its temperature dependence have been measured at different modulation wavelengths. Bulk amorphous Fe-B is the most studied amorphous alloy system. The composition of amorphous $Fe_{70}B_{30}$ has the highest magnetic ordering temperature of about 750 K and superior resistance against crystallization.[1] The function of the Ag layers is to well separate the magnetic layers. The mutual solubility between Ag and Fe and the diffusion at the Fe-Ag interface are very small; both are desirable in our study.

The $Fe_{70}B_{30}$-Ag films were prepared using a sputtering system with two dc magnetron guns and a rotating platform. The vacuum prior to sputtering was in the 10^{-8}–10^{-7} Torr range. The sputtering rates monitored by a thin film thickness controller were fixed at 8 and 32 Å/s for $Fe_{70}B_{30}$ and Ag, respectively. A digital servo motor system controlled the speed of the rotating platform and hence the modulation wavelength of the films. The thickness of the $Fe_{70}B_{30}$ layers ranged from 3 to 90 Å, and that of the Ag layers was always kept at four times as large. The films, of thicknesses of 0.5–1 μm, were deposited at room temperature onto both single-crystal Si wafer and Kapton substrates in an Ar plasma with 6 mTorr pressure.

A SQUID magnetometer with a magnetic field range of 0–50 kOe and a temperature variation of 2–400 K, was used to study the magnetic properties.

The structure of the $Fe_{70}B_{30}$-Ag films was studied by x-ray diffraction and transmission electron microscopy (TEM). Figure 1 displays a cross-sectional TEM micrograph of a film with a modulation wavelength of $\lambda = 51$ Å. The excellent layer structure is clearly resolved. The light regions are the amorphous $Fe_{70}B_{30}$ layers with a thickness of 10 Å and the dark regions the Ag layers with a thickness of 41 Å. Both regions are continuous and flat over a large lateral distance. The Ag layers are composed of crystalline grains that are responsible for the changing contrast within the layers. It is a common concern that ultrathin films may form

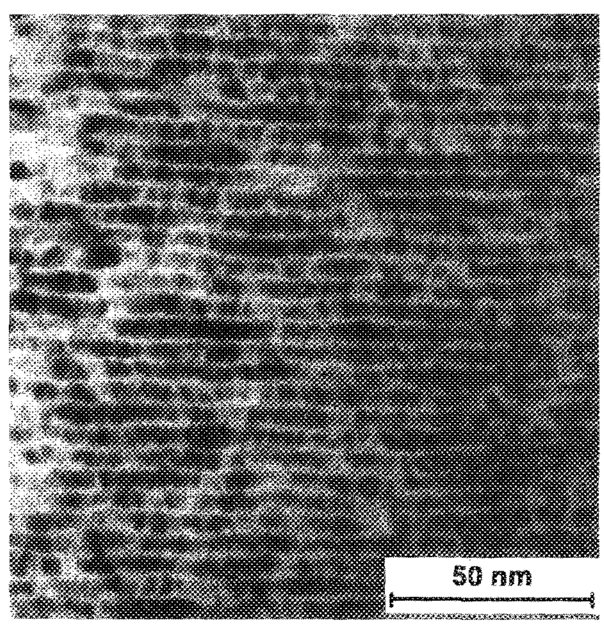

FIG. 1. Cross-sectional TEM micrograph of a compositionally modulated $Fe_{70}B_{30}$-Ag film. The light regions are amorphous $Fe_{70}B_{30}$ layers with thickness of 10 Å, and the dark regions the Ag layers with thickness of 41 Å.

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island structures that can alter the magnetic behavior of the films and complicate the data interpretation. The cross section clearly shows that the island structure is absent in the amorphous $Fe_{70}B_{30}$ layers even down to 10 Å thickness, a feature required in the study of magnetic properties of multilayer systems.

A magnetometry measurement yields the magnetization of the entire magnetic layers and is not surface selective. In order to elucidate the interface effect on magnetization, we have measured $Fe_{70}B_{30}$-Ag films with layer thickness (d) ranging from 3 to 90 Å, as well as a bulk film of thickness 3500 Å. Figure 2(a) shows typical magnetization curves $M(H)$ at several temperatures with the external field parallel to the plane of the sample. The magnetization is fully saturated above an anisotropy field. Detailed study of magnetic surface anisotropy of the system will be presented elsewhere.

Spontaneous magnetizations (M_s) at $T = 8$ K were obtained by extrapolating the $M(H)$ curves to $H = 0$. The M_s data are presented in Fig. 2(b) as a function of $1/d$. The uncertainty in M_s is about 10%, resulting from sample area determination, thickness control, and to a lesser extent, the magnetometer. Within our experimental uncertainty, M_s remains practically constant and independent of d in the range from 3 to 3500 Å. We therefore conclude that there are no magnetically "dead" layers[2] at the interfaces and that the interface does not cause any change in the surface magnetization of $Fe_{70}B_{30}$ layers.

Our results are in sharp contrast to those obtained from amorphous $Fe_{80}C_{20}$-Si multilayers.[3] Kazama *et al.* have measured the M_s of that system at $T = 5$ K as a function of $Fe_{80}C_{20}$ thickness with the fixed thickness ratio of $d_{Si}/d_{Fe(C)} = 3.2$. The magnetization decreases with decreasing $Fe_{80}C_{20}$ thickness below $d_{Fe(C)} = 30$ Å and eventually disappears at $d_{Fe(C)} = 6.7$ Å. The authors attributed such reduction in M_s to interface diffusion that was confirmed from x-ray diffraction analysis. The fact that M_s remains constant in our $Fe_{70}B_{30}$-Ag multilayers clearly demonstrates the apparent lack of interface diffusion, and therefore their suitability for the study of interface magnetism.

One of the interesting problems in a magnetic multilayer system is that of spin-wave excitations. There are two aspects to it. First, as the thickness of the magnetic layer is reduced, the temperature dependence of the magnetization may show a dimensional crossover effect. Second, the excitation of surface spin waves is quantitatively very different from that of the bulk spin waves.[4-6] As the thickness of the magnetic layer is reduced, the effect due to surface or interface will play an increasingly important role.

The spontaneous magnetization at a particular temperature was obtained by extrapolating the field to $H = 0$. The contribution from any diamagnetic or paramagnetic impurities can be eliminated this way. The normalized magnetiza-

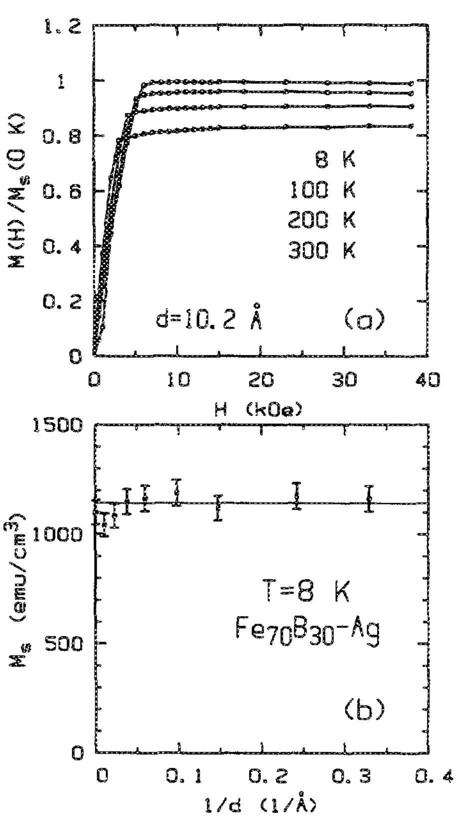

FIG. 2. (a) Magnetization curves of modulated $Fe_{70}B_{30}$-Ag films with $d = 10.2$ Å at $T = 8$, 100, 200, and 300 K. (b) Spontaneous magnetization of modulated $Fe_{70}B_{30}$-Ag film as a function of the inverse of the $Fe_{70}B_{30}$ layer thickness ($1/d$).

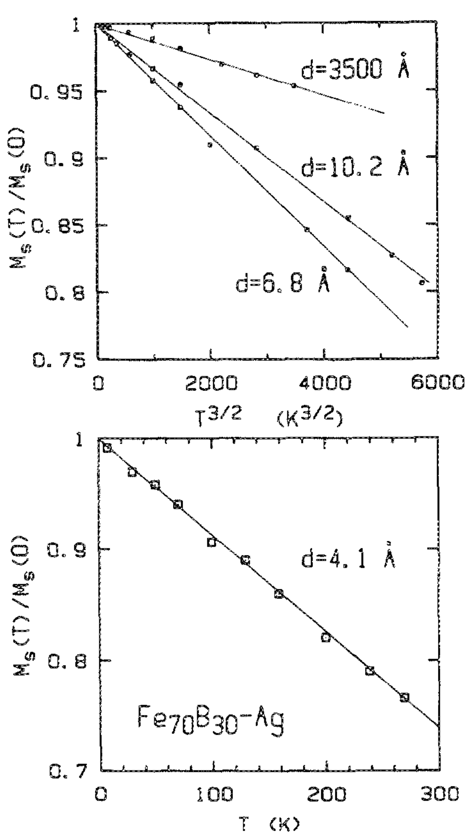

FIG. 3. Temperature dependence of spontaneous magnetization for modulated $Fe_{70}B_{30}$-Ag films. All the samples show $T^{3/2}$ dependence, except that of $d = 4.1$ Å that shows a linear temperature dependence.

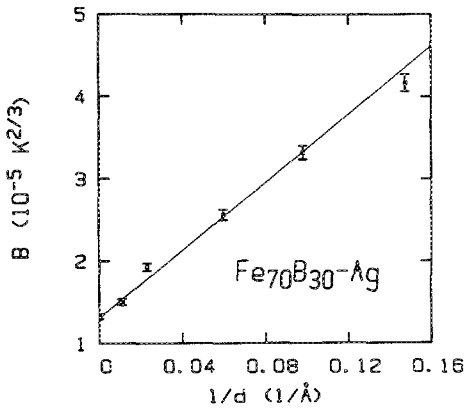

FIG. 4. Spin-wave constant (B) of $Fe_{70}B_{30}$-Ag films as a functions of $1/d$.

tion of a few samples is plotted in Fig. 3 (top) as a function of $T^{3/2}$. All the data can be fitted by straight lines, indicating that Bloch's law

$$M_s(T) = M_s(0)(1 - BT^{3/2}) \tag{1}$$

is well obeyed. However, as the $Fe_{70}B_{30}$ thickness is reduced to 4.1 Å, M_s decreases *linearly* with temperature, as shown in Fig. 3 (bottom), indicating a magnetic 3D-to-2D dimensional transition.

A particularly interesting behavior is observed when the spin-wave constant (B) in Bloch's law is plotted against the inverse of the $Fe_{70}B_{30}$ thickness ($1/d$), as shown in Fig. 4. The value B is *linearly* dependent on $1/d$ over the range of 6.8–3500 Å. This can be explained as follows. Each $Fe_{70}B_{30}$ layer consists of interfaces and interior, the spin deviation on the interface being larger than that of the interior. As the layer thickness is reduced, the interface contribution becomes progressively more dominant. Therefore, the effective spin-wave constant B increases as d decreases. Quantitatively we can consider that the spin-wave constant of the interface layer having a thickness d_s (including both interfaces) is B_{surf}, and that of the interior is B_{bulk}. Both the interface and the interior follow Bloch's law, i.e.,

$$M_{surf}(T) = M_{surf}(0)(1 - B_{surf}T^{3/2}), \tag{2}$$

$$M_{bulk}(T) = M_{bulk}(0)(1 - B_{bulk}T^{3/2}). \tag{3}$$

$M_{surf}(0)$ and $M_{bulk}(0)$ are proportional to d_s/d and $(d - d_s)/d$, respectively. The measured magnetization is then

$$M_s(T) = M_{surf}(T) + M_{bulk}(T)$$
$$= [M_{surf}(0) + M_{bulk}(0)](1 - BT^{3/2}), \tag{4}$$

$$B = B_{bulk} + (d_s/d)(B_{surf} - B_{bulk}). \tag{5}$$

Relation (5) shows that the effective B constant is inversely proportional to d, which is experimentally observed as shown in Fig. 4. The slope gives $d_s(B_{surf} - B_{bulk})$. Using $d_s \leqslant 6.8$ Å, one finds that $B_{surf} > 3.2\,B_{bulk}$ from Fig. 4. Therefore, the surface magnetization does decrease more rapidly with temperature than that of bulk.

In summary, compositionally modulated amorphous $Fe_{70}B_{30}$-Ag films have been synthesized. The spontaneous magnetization at low temperatures remains practically constant over the entire thickness range, indicating the absence of magnetically dead layers at the interfaces. The temperature dependence of M_s in the range of 6.8–3500 Å satisfies Bloch's law with the spin-wave constant B inversely proportional to the thickness of $Fe_{70}B_{30}$. This is explained by a large spin deviation in the interface regions. A magnetically dimensional transition from 3D to 2D is observed as d is reduced to 4 Å.

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[1] C. L. Chien and K. M. Unruh, Phys. Rev. B **25**, 5790 (1982).
[2] U. Gradmann, J. Magn. Magn. Mater. **6**, 173 (1977).
[3] N. S. Kazama, H. Fujimori, I. Yuito, and H. Kronmüller, IEEE Trans. Magn. **MAG-20**, 1296 (1984). N. S. Kazama, in *Rapidly Quenched Metals*, edited by S. Steeb and H. Warlimont (North-Holland, Amsterdam, 1985), p. 1177.
[4] D. L. Mills, Comments Solid State Phys. **4**, 28 (1971); **4**, 95 (1972).
[5] G. T. Rado and J. C. Walker, J. Appl. Phys. **53**, 8055 (1982).
[6] D. T. Pierce, R. J. Celotta, J. Unguris, and H. C. Siegmann, Phys. Rev. B **26**, 2566 (1982).