Magnetic properties of Fe/Tb multilayers

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Multilayered Fe/Tb samples were prepared under ultrahigh vacuum conditions ($p < 10^{-9}$ mbar) on kapton substrates. A total of four different samples were prepared. Three of them correspond to a series where the Tb thickness is constant at 26 Å and Fe varies from 10 to 30 Å. The fourth one is the first of a new series where Tb is 7 Å thick and Fe 40 Å. The samples were investigated by means of SQUID magnetometry and Mössbauer spectroscopy. All samples show perpendicular magnetic anisotropy at low temperature (4.2 K), but only two of them are able to show it at room temperature.

The origin of perpendicular magnetic anisotropy in thin-film materials of rare-earth and transition-metal alloys is not yet fully understood. Many are the models proposed to explain what the origin of perpendicular anisotropy is: local atomic ordering, exchange interactions, local anisotropies, dipolar interactions, stress-induced anisotropy, and single-ion anisotropy. In the case of compositionally modulated thin films, the presence of interfaces between the single element layers seem to be the determinant for the existence of perpendicular magnetic anisotropy. In this case, the single-ion anisotropy of the rare-earth ions has been proposed and discussed very extensively very recently.[1,2] In most of the cases studied previously, the samples were prepared by sputter techniques.[1–5]

Our aim is to study the magnetic properties of rare-earth transition-metal multilayers prepared in ultrahigh vacuum (UHV) with thermal evaporation techniques. Transmission ^{57}Fe-Mössbauer spectroscopy has been used to study the local magnetic properties of the iron atoms. The global macroscopic magnetic properties has been studied using a SQUID magnetometer.

The systems studied are compositionally modulated Fe/Tb multilayers. The samples were prepared by thermal evaporation in a UHV chamber. The pressure during the evaporation process was always lower than 10^{-9} mbar. Kapton foil has been used as a substrate. The temperature of the substrate during evaporation raise to about 400 K due to the radiation heating from the evaporation sources. The evaporation rates were 0.2 Å/s for Tb and 0.3 Å/s for Fe. The thicknesses for the prepared samples are shown in Fig. 1.

The samples were investigated by means of transmission ^{57}Fe-Mössbauer spectroscopy in the temperature range of 4.2–450 K and external magnetic fields between 0 and 5 T parallel and perpendicular to the γ radiation, and by means of SQUID magnetometry in the temperature range of 4.2–300 K and external magnetic fields between -5 and 5 T, parallel and perpendicular to the sample plane.

The Mössbauer spectra were measured using the "magic angle" method.[6] This technique allows us to determine the distribution of the magnetic hyperfine fields independent of any possible magnetic texture. The technique consists of assembling the sample in such a way that the normal to the sample plane form an angle of 54.7° with the direction of the γ ray. Then the sample is rotated in the sample plane in four steps of 90° each and the Mössbauer spectra measured for equal times per step are added. The spectra were fitted by assuming uniform Mössbauer-line intensities $3{:}b{:}1{:}1{:}b{:}3$. The relative intensity b is related with the average "canting angle" $\langle\theta\rangle$ between the spin direction and the γ-ray direction (perpendicular to the film plane) by $\langle\sin^2\theta\rangle = 2b/(4+b)$. This allows us to determine the average orientation of the iron spins with respect to the sample normal.

The Mössbauer spectra for samples (10 Å Fe)/(26 Å Tb) and (20 Å Fe)/(26 Å Tb) both show that there is a distribution of hyperfine fields for the iron spin. The average canting angle for these samples at 4.2 K are 38.4° and 40.9°, respectively, indicating that there is perpendicular magnetic anisotropy. Sample (30 Å Fe)/(26 Å Tb) shows six well-defined peaks and the average canting angle is 32.4° at 4.2 K (Fig. 2). Sample (40 Å Fe/(7 Å Tb) also shows a well-defined six-line pattern. In this case $\langle\theta\rangle$ is of about 36°. For samples (10 Å Fe)/(26 Å Tb) and (40 Å Fe)/(7 Å Tb) the perpendicular anisotropy is kept until room temperature. The dependence of the spectra with external magnetic fields parallel and perpendicular to the sample indicates that Tb aligns preferentially along the external field direction and that Fe and Tb moments are on average coupled antiparallel,[7] in a similar way as Fe-Tb alloys.[8] Due to the conditions of the preparation method the samples show that there is some mixing between the iron and terbium layers, as also observed in other multilayered systems.[9] For sample (30 Å Fe)/(26 Å Tb), the thickness of the interface deduced from the distribution of hyperfine fields is of about 2 ML of iron. If we assume this value to be the same for all samples, this would mean that for sample (10 Å Fe)/(26 Å Tb) almost all of the iron layer is alloyed with the terbium. This indicates that between the iron and terbium layers there is a layer of amorphous Tb-Fe alloy. These alloys show noncollinear magnetic structures called sperimagnetic structures.[10] In this structure the Fe and Tb spins are coupled antiparallel on average but the moments open in a cone structure. These orderings show freezing phenomena for the magnetic moments similar to what is observed in disordered systems.

The temperature dependence of the magnetization was investigated by means of SQUID magnetometry. For sample (10 Å Fe)/(26 Å Tb), we first investigate this depen-

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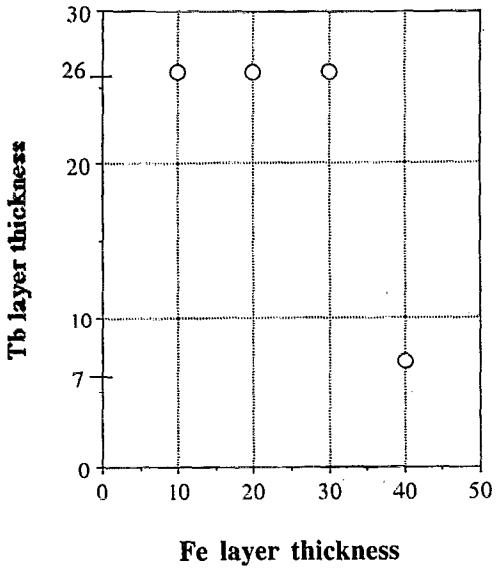

FIG. 1. Samples studied are (10 Å Fe)/(26 Å Tb), (20 Å Fe)/(26 Å Tb), (30 Å Fe)/(26 Å Tb), and (40 Å Fe)/(7 Å Tb).

dence by applying a low field (200 Oe) parallel to the sample plane (see Fig. 3). The temperature was varied between 4.2 and 270 K. Up to 120 K the samples is continually demagnetized when the temperature is raised in the same way as any ferromagnetic material. Above this temperature one can observe (Fig. 3) a change in the concavity of the curve and that it reaches a minimum value at about 220 K from which the magnetization slightly increases. This minimum value is at the same temperature where the terbium would lose its ferromagnetism, becoming paramagnetic at 230 K. This coincidence suggest that the phenomena might be related.

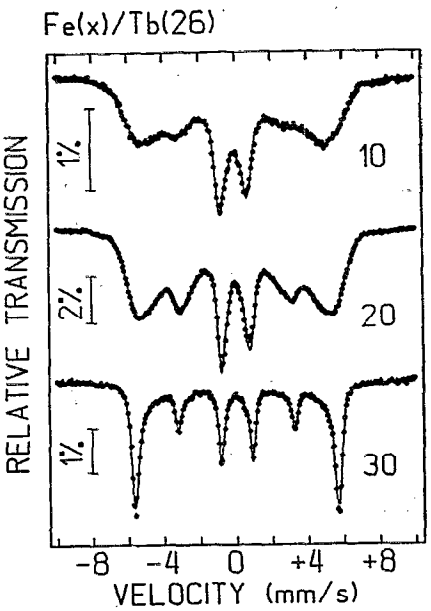

FIG. 2. Mössbauer spectra for samples (10 Å Fe)/(26 Å Tb), (20 Å Fe)/(26 Å Tb), and (30 Å Fe)/(26 Å Tb) at 4.2 K. The first two samples show some distribution of hyperfine fields. The larger the iron layer, the narrower this distribution becomes.

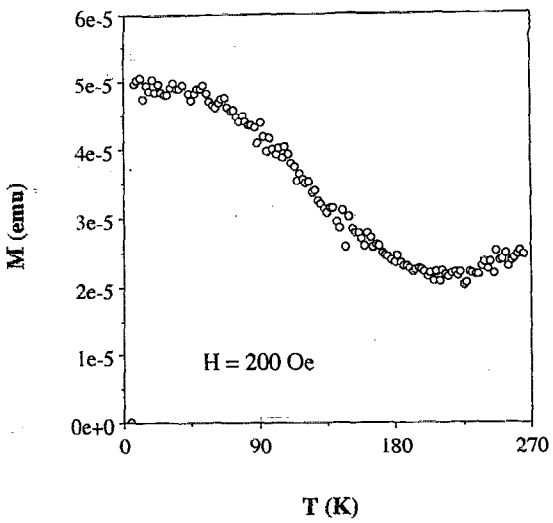

FIG. 3. Magnetization vs temperature curve for sample (10 Å Fe)/(26 Å Tb) with external field of 200 Oe.

The same experiment was done but with an external magnetic field of 50 000 Oe. In this case the observed behavior has a new ingredient in the low-temperature regime (Fig. 4). As the temperature is increased from 4.2 to 20 K, an increase for the magnetization is observed with a broad maximum at around 20 K. Above this temperature the magnetization decreases continually as the temperature is raised, and between about 90 and 150 K the law can be well fitted to a $T^{3/2}$ dependence. There is also a change in the concavity in the same temperature range as before. The shape of this curve is similar for samples (10 Å Fe)/(26 Å Tb) and (20 Å Fe)/(26 Å Tb). These two samples correspond to the samples where a large distribution of hyper-

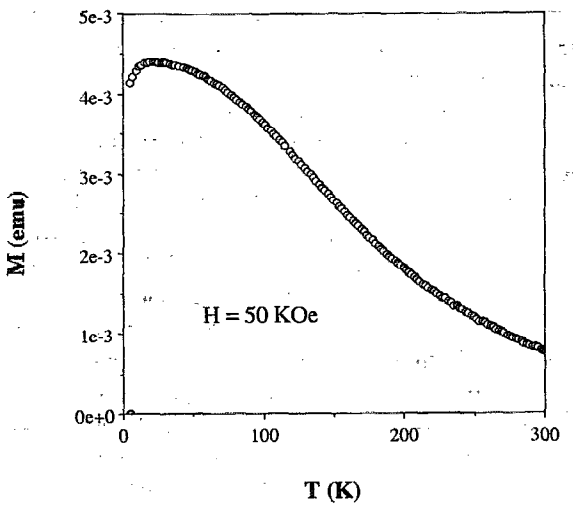

FIG. 4. Magnetization vs temperature curve for sample (10 Å Fe)/(26 Å Tb) when the external field is 50 000 Oe. The decrease of the magnetization under 20 K when the lowest temperature is approach is interpreted in terms of freezing phenomena associated with the interface alloying.

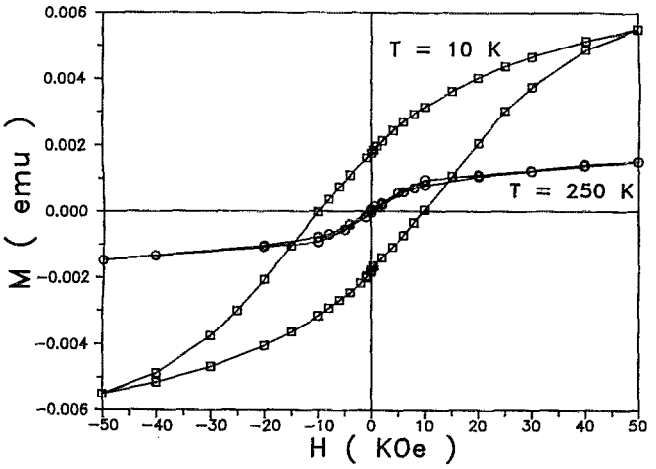

FIG. 5. Hysteresis loops for sample (10 Å Fe)/(26 Å Tb) at 10 and 250 K.

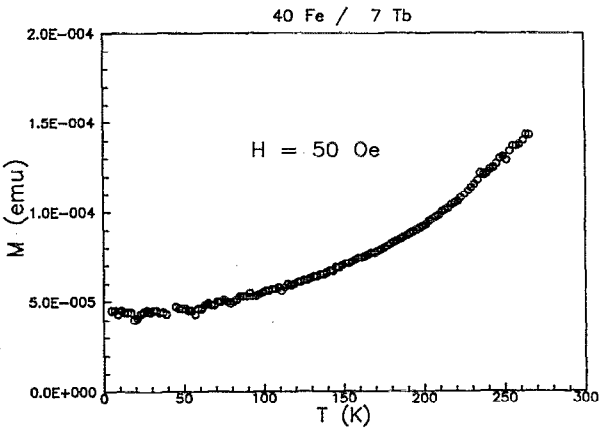

FIG. 6. Magnetization vs temperature curve for sample (40 Å Fe)/(7 Å Tb) under external field of 50 Oe.

fine fields is observed in the Mössbauer spectra. The maximum for the magnetization at around 20 K in these samples is interpreted as a freezing process typical of the noncollinear structure of the amorphous alloy of iron and terbium. In our case this alloy is located at the interfaces and, as stated above, is due to the preparation conditions. As the temperature is raised from 4.2 K in the presence of a strong magnetic field, part of the noncollinearity is removed and the magnetic moments are able to rotate and orientate in the direction of the external applied field. The hysteresis loops for these samples measured at low temperature show that the saturation is not reached for fields of 50 000 Oe applied parallel to the sample plane (Fig. 5). For sample (10 Å Fe)/(26 Å Tb) the hysteresis loops were measured for different temperatures from 10 to 250 K. In any case the saturation is not reached for fields as large as 50 000 Oe. The coercive field decreases as the temperature increases. This decrease is quite fast up to 100 K, becoming slower for higher temperatures. At 10 K the value for the coercivity is 9934 Oe (almost 1 T). Two are the contributions that produce this decrease in H_c. On the one hand, we have the decrease of anisotropy, K_u. (The measurements were taken with the field applied parallel to the sample plane.) On the other hand, the raising of the temperature is helping the breaking of the frozen sperimagnetic structure, making the reversal of the magnetization easier. The values for the remanence are very low: at 10 K the value of the remanence is only about 32%, the value corresponding to an external field of 50 000 Oe (where the sample is not yet saturated). This percentage decreases as the temperature is increased, and for 250 K, where the coercivity is only 100 Oe, that percentage is lower than 5%. This behavior is consistent with the presence of an amorphous Fe-Tb layer at the interface. At low temperatures the large freezing present produces the need for very large magnetic fields to take the magnetization from one direction and put it in the opposite one. When these freezings are overcome as a consequence of a sufficiently high temperature, the rotation of the magnetization is much easier because the energy barriers between different directions of magnetization are lower.

For sample (40 Å Fe)/(7 Å Tb) the temperature dependence of the magnetization measured under different external applied field conditions show a steady increase of the magnetization as the temperature is raised from 4.2 up to 270 K (Fig. 6). This behavior suggests the existence of a strong antiferromagnetic coupling in the sample. If we assume the interface thickness deduced from the Mössbauer measurements, we come to the conclusion that the sample is, in fact, a multilayer of iron and an amorphous alloy of Fe-Tb. The most important difference between this sample and the (30 Å Fe)//(26 Å Tb) sample is that for the (40 Å Fe)/(7 Å Tb) sample there is no single Tb layer. Since we can observe strong perpendicular anisotropy for the iron moments even at room temperature, the single Tb layer is not the origin of this perpendicular anisotropy but the presence of the alloying at the interface.

In conclusion, we have studied multilayered samples of Tb/Fe. All of them show perpendicular magnetic anisotropy at low temperature but only two of them [(40 Å Fe)/(7 Å Tb) and (10 Å Fe)/(26 Å Tb)] are able to keep it at room temperature. When the Tb layer is very thin (7 Å), the thickness of the iron can be larger without losing the perpendicular anisotropy at room temperature. If local random anisotropy were the origin of perpendicular anisotropy in this sample, the correlation length for the easy axes should be very large.

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