Structural- and magnetic properties of $\text{Co}_{68}\text{Fe}_{24}\text{Zr}_8/\text{Al}_2\text{O}_3$ multilayers

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Abstract.

The structural and magnetic properties of $\text{Co}_{68}\text{Fe}_{24}\text{Zr}_8/\text{Al}_2\text{O}_3$ multilayers grown by using magnetron sputtering were investigated with x-ray reflectivity, transmission electron microscopy and magneto-optical Kerr effect. The $\text{Co}_{68}\text{Fe}_{24}\text{Zr}_8$ form amorphous islands when the nominal thickness of the $\text{Co}_{68}\text{Fe}_{24}\text{Zr}_8$ layers is 10 Å, exhibiting an isotropic superparamagnetic behavior. Continuous layers with mostly a nano-crystalline structure are instead formed when the nominal thickness of the $\text{Co}_{68}\text{Fe}_{24}\text{Zr}_8$ layers is increased to 20 Å. The continuous layers exhibit random, in-plane, magnetic anisotropy resulting from the growth process. However, induced uniaxial anisotropy is obtained when growing the sample in the presence of an applied magnetic field, regardless of the combination of amorphous and nano-crystalline material.

1. Introduction

There is an increasing interest for the properties of amorphous ferromagnetic thin films and multilayers. Amorphous multilayers are found to exhibit useful properties in tunneling magnetoresistance structures [1] and also the possibility of inducing in-plane magnetic anisotropy in the films [2, 3, 4, 5]. The growth mode and structural stability of amorphous heterostructures depends strongly on interface related effects. For example, crystallization of an amorphous metal can even take place at an amorphous oxide interface [6]. Crystalline grains, with the size of approximately 3-4 nm, were formed mainly at the oxide interfaces partially caused by the dewetting properties of the metal. Having a combination of amorphous and crystalline material is often undesirable, since it may alter the magnetic properties in a negative sense. A way to avoid the formation of nanocrystallites is to use a metal [7, 8, 5] as a nonmagnetic spacer in the multilayer. However, for some applications (such as for tunneling magnetoresistance) it is unavoidable to have an insulating barrier between ferromagnetic layers. Thus, the influence of the oxide must be considered when tailoring the structural and magnetic properties of amorphous multilayers.

In our previous study [6] we focused on the dewetting and crystallization within thicker (up to 13 nm) $\text{Fe}_{91}\text{Zr}_9$ magnetic layers, when using Al_2O_3 as a spacer in the multilayers. Here we address the structural and magnetic properties of $\text{Co}_{68}\text{Fe}_{24}\text{Zr}_8$ layers (up to 3 nm), deposited in a multilayer stack with Al_2O_3 as a spacer. The substitution of Fe by Co increases the Curie temperature [2, 9] by almost a factor of 3, while no significant change in growth is expected. $\text{Co}_{89-x}\text{Fe}_x\text{Zr}_{11}$ has by Suran et al. [10] been found to grow amorphous at room temperature, independently of the amount of Fe. Typically, 10% of Zr is found [11] to be the limit for forming an amorphous structure of CoFeZr . From a magnetic point of view it is desirable to keep the Zr concentration as low as possible while sustaining a stable amorphous structure.

In this paper we focus on the growth, structure and the magnetic properties of $\text{Co}_{68}\text{Fe}_{24}\text{Zr}_8/\text{Al}_2\text{O}_3$ multilayers. The influence of an applied magnetic field during growth on the resulting magnetic properties is also discussed.

2. Experiment

The multilayers were all grown on Si(111) substrates by magnetron sputtering at room temperature. All substrates were prior to deposition annealed at 530°C for 1 h in order to out-gas the Si surfaces. Two series of $[\text{Co}_{68}\text{Fe}_{24}\text{Zr}_8(\text{X})/\text{Al}_2\text{O}_3(20 \text{ \AA})]_{10}$ multilayers were grown on Si(111)/ $\text{SiO}_2/\text{Al}_2\text{O}_3(20 \text{ \AA})$ stacks, one in the presence of an applied magnetic field during deposition and one without. Each series contain three multilayer samples with nominal thicknesses of $\text{X}=10, 20$ and $30 \text{ \AA}$. The multilayers were finally capped with $20 \text{ \AA}$ Al_2O_3 to prevent oxidation. The magnetic flux while growing the samples in the field was generated by two flat permanent magnets [5], providing approximately 10 mT of magnetic flux over the sample region (parallel to the substrate). Samples grown

without an applied magnetic field is hereafter referred to by their layer thicknesses, 10/20, 20/20 and 30/20, and correspondingly samples grown in the field as F10/20, F20/20 and F30/20. The nominal thickness of the Al_2O_3 layers were kept constant at 20 Å, and is assumed to grow fully amorphous [12]. The deposition rates were obtained by calibration samples grown under identical conditions as the sample series by using x-ray techniques. Most of the results discussed here were obtained from samples with $X=10$ Å and $X=30$ Å.

CoFeZr layers were deposited from a target with nominal composition of $\text{Co}_{60}\text{Fe}_{25}\text{Zr}_{15}$ by using DC magnetron sputtering, while the Al_2O_3 layers were grown by RF magnetron sputtering. The base pressure of the deposition chamber was below 2×10^{-9} Torr and the pressure of Ar gas, with a purity of 99.9999 %, was kept at 2.0 mTorr during the deposition. The chemical composition of the resulting CoFeZr layers was determined in our previous work [5] by Rutherford Back Scattering spectrometry (RBS) which yielded $\text{Co}_{68}\text{Fe}_{24}\text{Zr}_8$.

Structural analysis were performed by x-ray reflectivity (XRR) and transmission electron microscopy (TEM). The x-ray analyses were performed using a Philips PW3020, with CuK_α ($\lambda=1.5418$ Å) radiation and a graphite monochromator in a standard Bragg-Brentano geometry. For the TEM analysis, samples were prepared both in cross section and top view geometry. Diffraction patterns were acquired with the samples in top view geometry since it enables measurements from a larger part of the sample. In cross section a conventional preparation technique [13] was used, which includes dimple grinding and ion bombardment. A similar method was used for the top view samples, including ultrasonic cutting of a $\phi 3$ mm disc, which was thinned using dimple grinding and ion bombardment from the substrate side. All samples were thinned to electron transparency using a low angle (approximately 8°) Ar ion beam in a Gatan PIPS (3.5 keV and finally 1.4 keV). The TEM measurements of the samples in cross section were performed using a FEI Tecnai F30ST microscope operated at 300 kV, while the diffraction patterns from top view prepared samples were acquired using a JEOL JEM-2000FXII at 200 kV. By acquiring the diffraction patterns of the layers while including the Si substrate allowed for an accurate calibration of the patterns. The Si substrate was in the top view geometry oriented along the [111] zone axis, which is the direction of the surface normal in the Si substrate. Diffraction patterns were acquired from a region with the size of approximately $2.1 \mu\text{m}$ in diameter, as defined by the aperture.

Magnetization measurements were performed by using Magneto-Optical Kerr Effect (MOKE) setup in the longitudinal geometry [14]. This experimental set up allows rotation of the sample around its surface normal making the measurements of remanence in arbitrary in-plane directions.

Table 1. Thicknesses of the CoFeZr and Al₂O₃ layers of the samples 10/20 and 30/20 as determined from simulations of the XRR measurements shown in figure 1. The Al₂O₃ and CoFeZr thicknesses refer to the weighted average of all the Al₂O₃ and CoFeZr layers in each sample.

Sample	CoFeZr (Å)	Al ₂ O ₃ (Å)
10/20	$7.7^{+0.8}_{-0.4}$	$22.7^{+0.4}_{-0.8}$
30/20	$25.0^{+0.29}_{-<0.01}$	$24.0^{+0.05}_{-0.4}$

3. Results

3.1. Structural and compositional characterization

XRR was used to explore the layering and the bilayer thicknesses over a large part of the sample. Results obtained from two of the samples, 10/20 and 30/20, accompanied by simulations, are illustrated in figure 1. Both the samples show well defined reflectivity patterns. Particularly, the sample 30/20 exhibits a large number of multilayer peaks up to 7th order, which indicates a well defined bilayer thickness. Its pronounced Kiessig fringes [15] indicates a well-defined total thickness. The simulations of the results were performed using the *GenX* [16] software and the obtained layer thicknesses are listed in Table 1. The thickness variation of the CoFeZr layers in the 10/20 and 30/20 samples extracted from simulation gives 5.5 ± 0.1 Å and 3.0 ± 0.1 Å respectively. Thus, the thickness variation of the 10/20 sample is comparable with the intended thickness of the FeCoZr layers. This is also seen in the intensity of the first order reflectivity peak, which has substantially lower intensity than what would be expected for a continuous layer.

Figure 1. Low-angle x-ray reflectivity measurement and corresponding simulation for the samples with 10 Å (10/20) and 30 Å (30/20) CoFeZr layers. The 30/20 sample shows the best defined bilayer structure of the two. The scans were offset for clarity.

Figure 2 shows rocking curve measurements at the first reflectivity multilayer peaks for the 10/20 ($2\theta \approx 3^\circ$) and 30/20 ($2\theta \approx 2^\circ$) samples. Both the curves consist of a sharp and wide component, which correspond to specular and diffuse scattering, respectively. The integrated diffuse intensity amounts to 4% of the integrated specular part for the 10/20 sample, whereas for the sample 30/20 it is only 0.3%. Thus, the 10/20 sample shows considerably larger thickness variation of the layers. Steep decrease in the diffuse scattering with $\Delta\omega$, as seen in the 30/20 sample, is a signature of good layering and small thickness variation (roughness). XRR measurements were also performed on the F10/20 and F30/20 samples, revealing similar results (not shown).

Figure 2. X-ray rocking curve measurements over the first reflectivity multilayer peak of the 10/20 and 30/20 samples. The steep decrease in the diffuse scattering with increasing/decreasing $\Delta\omega$ in the 30/20 sample is a signature of good layering and less roughness in comparison to the 10/20 sample. The scans were offset for clarity.

High resolution TEM (HRTEM) and selected area electron diffraction (SAED) in the TEM was used for obtaining real space information from the structure. Firstly, the two samples 10/20 and 30/20 were studied with HRTEM in cross sectional view, see figure 3. A clear distinction in structure is found between the two samples. In the 10/20 sample the CoFeZr forms islands, embedded in Al_2O_3 . The thickness of the Al_2O_3 is, however, sufficient to fill up the space in-between the islands and therefore sustaining a clear layer structure throughout the stack. From the HRTEM image it becomes clear that the off-specular diffuse x-ray scattering of this sample, as shown in figure 2, arises from the anti-correlated interfaces formed by the islands. The HRTEM image in figure 3a shows mainly an amorphous structure of the CoFeZr islands, while some of them are nanocrystalline. From the analysis of HRTEM- and dark field images (not shown) the mean in-plane and out-of-plane size was by measuring on 80 islands found to be 2.7 nm (standard deviation 0.7 nm) and 1.9 nm (standard deviation 0.3 nm), respectively. The average out-of-plane island size, which is bigger than the value given by XRR simulations, is in consistence with the large (70%) thickness variation of the CoFeZr layers in this sample.

As the nominal thickness of the CoFeZr layer is increased the layers become continuous, as seen in figure 3b for the 30/20 sample. The well defined bilayer thickness and good layering as observed from XRR (see figure 1) agrees well with the appearance of the layers in the corresponding HRTEM image. Another significant change of the CoFeZr layers can also be seen – the layers are to a large extent found to have a polycrystalline structure. Estimating the size of the grains from HRTEM- and dark field images (not shown) yields an in-plane and out-of-plane size, averaging on 55 grains, of 6.4 nm (standard deviation 3.3 nm) and 2.4 nm (standard deviation 0.4 nm), respectively. The Al_2O_3 is found to be fully amorphous in all samples, consistent with previous results [17, 18].

Figure 3. High-resolution TEM images of the CoFeZr/ Al_2O_3 samples in cross-section for two different thicknesses of the magnetic layer, in a) the 10/20 sample and in b) the 30/20. In a) islands of CoFeZr (darker) are found to show mainly an amorphous structure, isolated from each other by the Al_2O_3 . Well defined layers are observed for the thicker CoFeZr in b), showing mainly a crystalline structure. The Al_2O_3 layers (brighter) show in both samples an amorphous structure. The single crystalline Si substrate is seen at the bottom of each image ([110] zone axis).

X-ray diffraction is in most cases an excellent tool for analyzing the atomic structure

of a sample. However, for structural analysis of amorphous and nanocrystalline layers, x-ray diffraction is not suitable due to the background intensity caused by the amorphous and the weak signal of the nanocrystalline material. The structure of the multilayers were therefore analyzed using SAED in the TEM. The corresponding diffraction patterns of the 10/20 and F30/20 samples are shown in figure 4a and b, respectively. The results are consistent with the HRTEM images in figure 3 where the 10/20 sample shows an amorphous signature, while the 30/20 sample consist of a combination of polycrystalline (sharp rings) and amorphous material. No significant difference in the crystalline to amorphous signature of the SAED patterns were observed for samples grown in or without an applied field. The sharp spots in the diffraction patterns originate from the Si substrate and the white line is a beam stopper, used for reducing the intensity of the transmitted beam.

Since the Al_2O_3 from HRTEM is known to grow amorphous, the polycrystalline rings observed in figure 4b must be attributed to a crystallization in the CoFeZr. The presence of an applied magnetic field during growth has for a similar, but fully amorphous system, found to induce uniaxial anisotropy [5]. Here a structural change because of magnetism, induced in the polycrystalline material, should be obtained by comparing the diffraction patterns of the 30/20 and F30/20 sample. The diameter of the rings (seven rings were observed) were measured in the directions of the Si 220 reflections, i.e. three directions in the plane separated by 60° . The measured atomic plane spacings for the 30/20 and F30/20 samples are summarized in Table 2. Since the atomic structure of the nanocrystals are unknown, each measured spacing is named d_1 to d_7 in Table 2. The standard deviation shows how the d-spacing of the CoFeZr material is varying in the three directions. Additionally, the error in each measurement of d_i is calculated by assuming that the distance in the diffraction pattern can be obtained within ± 3 pixels (including both the measurement of Si spots and the ring), where each pixel corresponds to $0.0012 \text{ \AA}$, resulting in $\pm 0.004 \text{ \AA}$. Comparing the results in Table 2 reveals only minute fluctuations of the measured d-spacing, as described by the standard deviation. Thus, no measurable change in the atomic plane spacing is observed for these two samples within the error of the measurement.

3.2. Magnetic characterization

The magnetic measurements were performed using the Magneto Optical Kerr Effect (MOKE). In figure 5, a variable temperature MOKE measurement ($10 \text{ K} \leq T \leq 301 \text{ K}$) of the 10/20 sample is shown. The S-shaped loops with very low coercivity resembles a superparamagnetic behavior. No significant difference between the hysteresis loops is observed at the different temperatures and the highest obtainable applied field in the instrument (400 mT). A slight decrease in the magnetization (top inset in figure 5) is observed with increasing temperature and as well as a small increase in the coercivity (bottom inset of figure 5) from 4.1 mT at 10 K to 6 mT at 301 K. The change in magnetization was fitted to an equation analogous to Blochs law [19] by using

Figure 4. Selected area electron diffraction patterns of the samples 10/20 and F30/20, obtained in top-view geometry. For the 10/20 sample in a), only an amorphous signature of the layers is seen (from CoFeZr, Al₂O₃ and SiO₂). For the F30/20 sample in b), a combination of polycrystalline (sharp rings indicated by the arrows) together with diffuse amorphous rings are observed. The spots originate from the Si substrate (oriented in [111] zone axis). To maximize the visibility of weak features in the patterns, different contrast and brightness adjustments are applied to the two halves and inverted for clarity.

$m(T)/m(0) = 1 - \alpha T^\gamma$ resulting in $\gamma = 3.0 \pm 0.1$. These magnetic properties can be attributed to a superparamagnetic contribution from the CoFeZr islands, separated by Al₂O₃ and interacting by dipole fields. Consequently, the ferromagnetic islands are randomly oriented in the absence of magnetic field. These results are consistent with a structural percolation in the 10/20 sample, as observed in the TEM results of figure 3a.

Figure 6 shows a room temperature MOKE measurement of the 30/20 sample, revealing a ferromagnetic response. This sample, grown without an applied magnetic field, is found to show an almost constant coercivity field (varying by 10%) while its remanences varies from 0.65 to 0.90 of the saturation magnetization when measuring

Table 2. The average atomic plane spacings measured from the diameters of polycrystalline rings as seen in figure 4b. The Si $\langle 220 \rangle$ reflections were used as a calibration, measuring in the three directions (separated by 60°) from where the standard deviation was calculated. The error in the measurement in the diffraction pattern is given by $\pm 0.004 \text{ \AA}$, assuming an accuracy of ± 3 pixels.

Sample	$d_1(\text{\AA})$	$d_2(\text{\AA})$	$d_3(\text{\AA})$	$d_4(\text{\AA})$	$d_5(\text{\AA})$	$d_6(\text{\AA})$	$d_7(\text{\AA})$
30/20	2.181	1.534	1.255	1.088	0.969	0.887	0.821
Std.dev.	0.007	0.003	0.002	0.001	0.002	0.001	0.001
F30/20	2.186	1.536	1.259	1.090	0.973	0.890	0.822
Std.dev.	0.002	0.005	0.002	0.001	0.002	0.003	0.001

Figure 5. Measured hysteresis loops from 10 K to room temperature of the 10/20 sample. The remanence of the hysteresis loops is very small at all the measured temperatures. The saturation magnetization is not fully reached even at 400 mT. Scans are offset for clarity. The bottom inset shows the coercivity of the hysteresis loop taken at 301 K whereas the top inset shows the reduced magnetization at maximum field (400 mT) versus temperature.

in different spots on the sample. The probed area is about 1 mm, defined by the illumination from the laser. Variations of the remanences can be attributed to random anisotropy in the sample (wandering axis). Thus, fluctuations in magnetic stray fields during deposition of the layers may cause an imprinted local easy axes in the sample. Although it is only the thickness of the CoFeZr that is changed between the 30/20 and 10/20 samples, a striking difference in the magnetic properties are observed as a consequence of the different growth modes of the samples.

The MOKE measurements of the F30/20 sample, seen in figure 7, shows a very similar magnetic behavior as in our previous work [5] where we showed how magnetic anisotropy can be induced in fully amorphous CoFeZr layers, when grown using AlZr

Figure 6. Magnetization vs. applied magnetic field for the sample 30/20, measured in an arbitrary direction in the plane. The magnetic characteristics of this sample indicates a ferromagnetic response from the CoFeZr layers. The measurement was performed at room temperature.

as a spacer. Clear easy- and hard magnetization axes are observed when measuring at two perpendicular directions with respect to the direction of the applied field during growth. Surprisingly, the saturation field of the nanocrystalline sample is similar to what is observed in completely amorphous layers [5]. It is, therefore, possible to control and induce magnetic anisotropy in a multilayer sample containing both amorphous and nano-polycrystalline CoFeZr. The F10/20 sample did not show any induced anisotropy, as expected from the much larger saturation of the islands as compared to the field applied during the growth.

Figure 7. Magnetization vs. applied magnetic field for the F30/20 sample at $\theta=0^\circ$ and $\theta=90^\circ$ with respect to the direction of the applied field during growth. The magnetic characterization shows an uniaxial anisotropy in the sample. The measurements were performed at room temperature.

4. Discussion

Growing metal on oxides often result in island formation [20, 21, 22] (giving rise to discontinuous layers) until the amount of deposited metal is sufficient to merge the islands, forming a continuous layer. The island growth results from the large difference in surface energy between the metal and oxide. In this work the thinnest 10/20 sample was found to be amorphous, whereas for thicker CoFeZr layers a mainly polycrystalline structure was observed.

A possible explanation of the crystallization within the amorphous layers was put forward in [6]. Considering the difference in the activation energy for surface diffusion between Fe and Zr atoms, local changes of the chemical composition is to be expected. The crystalline grains were there found to have a lower concentration of Zr (estimated to $6\pm 2\%$) than the surrounding amorphous matrix (9.3% to 9.6%). However, such estimation is not possible here since the structure of the crystalline CoFeZr grains is unknown. Following the argumentation in [6], similar behavior is to be expected here since the activation energy for surface diffusion of Co is very similar to that of Fe. When the islands of CoFeZr are small, as in the initial stage of the growth, the difference in diffusion rate will not have a significant influence on the local chemical composition, since each island consist of not too many atoms. Therefore, under a certain size the islands will show an amorphous structure, while the effect of changes in the chemical composition will become more significant with increasing size and thereby induce crystallization. The size of the islands in the 10/20 sample is therefore typically small enough to show mainly an amorphous structure, whereas for the thicker layers the nucleated grains eventually form a uniform nano-polycrystalline layer due to a segregation of Zr. Analyzing the average in-plane island and grain size of the 10/20 and 30/20 sample shows that they are typically more than twice as big in the thicker sample. A sample with 20/20 layer thicknesses was also analyzed with HRTEM (not shown here), revealing a combination of CoFeZr islands but with better layering than the 10/20 sample. This sample exhibited also clear polycrystalline rings in the SAED pattern (as for the sample shown in figure 4b) and similar magnetic properties as the 30/20 sample.

Our measurements show that the in-plane size of the grains in the 30/20 sample is somewhat bigger than those typically found in [6]. Although, polycrystalline layers were also found when the thickness of the FeZr layer was smaller than the typical size of embedded grains (3 to 4 nm) found in the thicker samples. This is believed to be related to the dewetting of the metal at both the oxide interfaces around the metal layer.

It is difficult from the TEM results to estimate the degree of crystallization of the CoFeZr layers. To observe a crystal structure of a grain in an HRTEM image, the electron beam must travel along (or very close to) a column of atoms in the sample. Here, several grains will typically be on top of each other, resulting in a strong alteration of the phase contrast in the image and may therefore wrongly being interpreted as amorphous. An estimation from the SAED patterns is unfortunately complex due to

the overlapping intensity from the amorphous Al_2O_3 and SiO_2 . However, by comparing the diffraction patterns in figure 4 shows that polycrystalline rings appear for the 30/20 sample. Nevertheless, both the 10/20 and 30/20 samples show similar amorphous rings.

The particular composition of CoFeZr used here shows a clear ferromagnetic response at room temperature when grown fully amorphous, as described in our previous work [5, 23]. Since the 30/20 sample consist of both amorphous and nano-polycrystalline regions, the magnetic properties reflect that particular combination. As shown in figure 6 and 7, a clear ferromagnetic response is observed (showing both coercivity and a defined saturation magnetization), which affirm that the Curie temperature is for these samples well above room temperature.

Assuming that the majority of the CoFeZr layer in the F30/20 sample is nano-crystalline, its uniaxial anisotropy (as seen in figure 7) would originate in a small change in the nearest neighbor distances (giving a strain) of the atomic planes in the grains. The measurements of the polycrystalline rings in SAED patters (figure 4b) revealed no significant difference between the sample grown in and without the applied magnetic field. However, the corresponding changes in the atomic distances are expected to be minute. It should, additionally, be noted that the diffraction patterns were obtained in the presence of a strong magnetic field (typically 1-2 T) in the out of plane direction, originating from the objective lens in the TEM.

Due to the overlap of the amorphous rings of CoFeZr with Al_2O_3 and SiO_2 , we can not extract the radial distribution function from our diffraction data. Zweck et al. [24] measured a difference in radial distribution function before and after annealing of amorphous FeTb alloy in an applied magnetic field. If the CoFeZr layer in our work shows an induced magnetic anisotropy effect in the polycrystalline material, any change in atomic plane spacing should be smaller than typically 10^{-3} in order to be observed by using SAED. Therefore, from this work we cannot exclude the presence of induced magnetic anisotropy in the polycrystalline CoFeZr. Though, the comparison with the hysteresis curves from our previous work suggests that the amorphous part in the CoFeZr layers is at least to some extent responsible for the induced magnetic anisotropy observed here.

5. Conclusion

In this article, we study the growth of CoFeZr deposited in the thickness range of 10 to 30 Å on Al_2O_3 as a multilayer. It is shown that the layer perfection in the multilayers strongly depends on the thicknesses of constituents, which in turn affects its magnetic properties. In the case of the thinnest CoFeZr layers, mainly amorphous islands form on the oxide surface, arising from dewetting. A superparamagnetic behavior is observed due to the isolated magnetic islands embedded in the oxide layers; the reduced saturation magnetization is found to decrease as $m(T)/m(0) = 1 - \alpha T^3$. For the thickest CoFeZr, instead uniform layers of amorphous and nano-crystalline material is observed, as a consequence of the difference in diffusion rates of Fe, Co and Zr on the oxide surface.

Fluctuations in orientation of the local easy axis results in a random magnetic anisotropy in this sample. However, when the layers were grown in the presence of an applied magnetic field an induced macroscopic anisotropy is obtained, even though it contains a mix of amorphous and nanocrystalline material.

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