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Effect of interface structure on magnetic and magnetoresistive properties of Fe/Cr multilayers

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Abstract

The influence of growth temperature on atomic and magnetic interface structure was traced in Fe/Cr multilayers grown with MBE at different substrate temperatures in the range 20–480°C. Proper growth was found to be possible only in a narrow temperature range about 140–180°C, deviations from optimal temperature causing drastic increase in interface roughness. Giant magnetoresistive effect was shown to be in close correlation with the interface structure. © 2001 Published by Elsevier Science B.V.

Keywords: Multilayers, metallic; Interface structure; Magnetoresistance, giant; X-ray reflectivity

Interface structure is believed to play an important role in forming physical properties of magnetic multilayers. By tuning interface properties of a multilayer, it is possible to influence its macroscopic behaviour. One of the ways to make an impact on interface is to vary growth conditions. Growth temperature is known to be one of the governing factors in multilayer growth [1]. In the present work, we report on the study of the dependence of magnetic and transport properties of Fe/Cr multilayers on their interface structure. In order to reveal the role of the interface structure, we have studied a series of multilayers grown at different substrate temperatures and therefore having different atomic and magnetic interface structure.

The investigations were carried out on a series of $[Cr(9\,Å)/^{57}Fe(20\,Å)]_8$ multilayers MBE grown on $(1\,0\,\bar{1}\,2)Al_2O_3$ substrates covered by 70 Å-Cr buffer layer at different substrate temperatures in the range 20–480°C. The crystalline structure was studied with transmission electron microscopy. The investigated multilayers were found to consist of a large arrangement of fine crystallites with close orientation. The crystallites are equiaxial in the layer plane, their (0 0 1) plane being parallel to the substrate plane. The interface structure was investigated by combining X-ray reflectometry (XR) and Mössbauer spectroscopy (MS). X-ray measurements were made with Co K_α radiation. Mössbauer spectroscopy investigations were made in transmission geometry for absorption set-up using a ^{57}Co source in a Cr matrix. Magnetic properties were studied by SQUID and VSM magnetometry; magnetoresistance measurements were made in standard DC four contact scheme. All the investigations were carried out at room temperature.

The layer structure and vertical rms interface roughness were determined by fitting X-ray reflectivity curves. The X-ray reflectivity profiles were treated within a dynamical approach based on recurrent scheme [1], the rms interfacial roughness being included through Debye–Waller factors [2,3]. As an example of fitting results in Fig. 1 experimental and fitted reflectivity curves obtained for the multilayer grown at 240°C are shown.

The structural information obtained from the X-ray data is summarised in Fig. 2. In this figure, the rms roughness at Fe-on-Cr and Cr-on-Fe interfaces reduced

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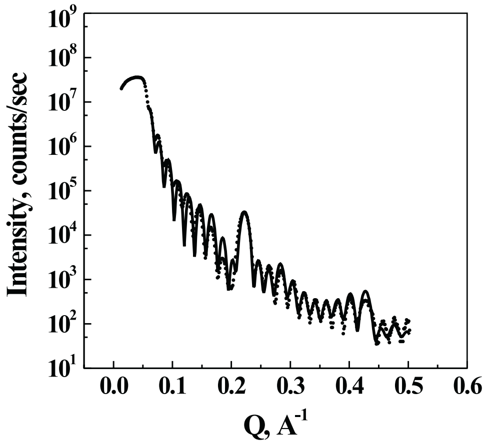

Fig. 1. Experimental (points) and fitted (line) X-ray reflectivity spectra measured at Co K_α radiation from the Fe/Cr multilayer grown at substrate temperature $T = 240°C$.

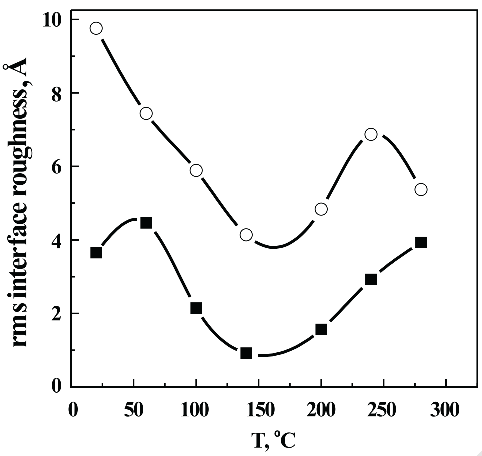

Fig. 2. Substrate temperature T dependence of vertical rms roughness at Fe-on-Cr (squares) and Cr-on-Fe (circles) interfaces in Fe/Cr multilayers deduced from XR data.

from XR data is depicted. As follows from the X-ray results, the substrate temperature has a profound effect on the rms interface roughness. The best interface structure was observed at growth within a narrow temperature range of about 140–180°C. The lowest rms interface roughness is observed in the multilayer grown at 140°C. A specific feature of the best multilayers is a strong difference between Fe-on-Cr and Cr-on-Fe interface structures. Whereas the Fe-on-Cr interface is sharp, the Cr-on-Fe one is diffusively intermixed at 2–3 atomic monolayers in thickness. Deviation from the optimal growth temperature region causes interface degradation, preferably at the Fe-on-Cr boundary.

Interface structure and hyperfine-field distribution were estimated by comparing multilayer Mössbauer spectrum with that corresponding to "bulk" α-Fe. The MS results are depicted in Fig. 3. In the main part of the figure, the growth temperature dependence of relative area of "bulk" α-Fe subspectrum in resulting multilayer spectrum is shown. In the Insets of Fig. 3, a typical multilayer Mössbauer spectrum composed of "bulk" and interface subspectra and the corresponding hyperfine-field distribution are shown. An important point is that while the XR is sensitive to interface imperfections originating from both interface roughness and diffuse intermixing, the MS shows the last contribution only. By comparing the XR and MS data we can conclude that the loss of interface quality is connected with interface roughening at lower growth temperatures and with Fe–Cr interdiffusion at higher growth temperatures.

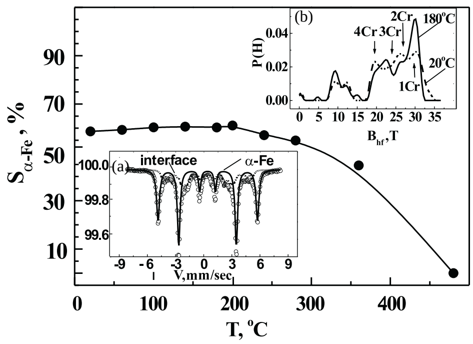

Fig. 3. Growth temperature dependence of relative area $S_{\alpha-Fe}$ of α-Fe subspectrum in the resulting Mössbauer specrum. Insets: (a) typical multilayer Mössbauer spectrum; (b) reduced hyperfine-field B_{hf} distributions for multilayers grown at 20 and 180°C.

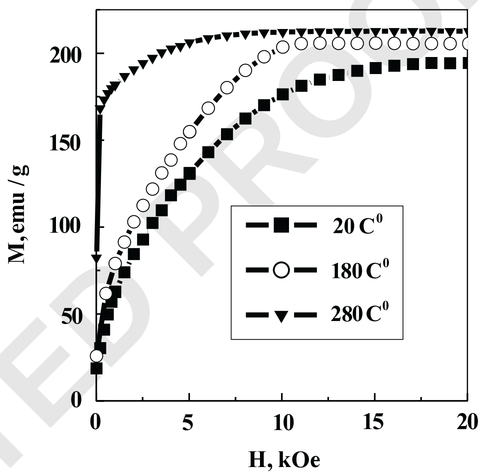

Fig. 4. Magnetisation curves measured with a SQUID magnetometer for multilayers grown at 20, 180 and 280°C.

The macroscopic magnetic and transport properties were revealed to be in close correlation with the interface structure. In Fig. 4 magnetisation curves measured for

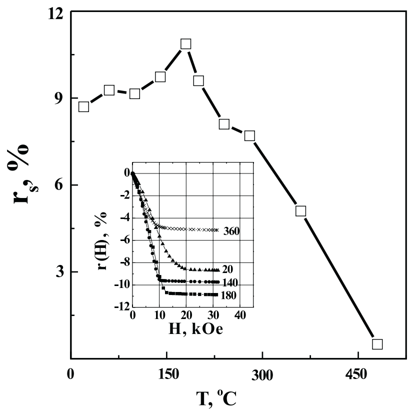

Fig. 5. The value of the giant magnetoresistance effect as a function of growth temperature. The insets show magnetic field dependences of magnetoresistance in some multilayers grown at different temperatures. The sample grown at 480°C displays insignificant magnetoresistance effect due to complete degradation of the layer structure.

multilayers grown at different temperatures are shown. The Cr layer thickness (9 Å) in the series was chosen to be corresponding to the first antiferromagnetic maximum. As a general tendency we note clear evolution of magnetic ordering from an antiferromagnetic structure to a ferromagnetic one as the growth temperature increases. It is interesting that in multilayers with rough interfaces grown at lower temperatures we found a near-antiferromagnetic ordering in contrast to more perfect multilayers grown at higher temperatures. The tendency of slow variation of antiferromagnetic exchange coupling with increasing growth temperature is in line with results reported earlier for similar systems (see review [5] and references therein). Most likely the reason for it is the formation of FeCr interlayer causing additional ferromagnetic contribution to magnetisation.

Magnetoresistance $r(H) = [R(H) - R(0)]/R(0)$ as a function of growth temperature is shown in Fig. 5. We note that the saturation magnetoresistance value r_s throughout the series depends non-monotonically on the substrate temperature, with the maximum magnetoresistance effect being observed in multilayers with close-to perfect interface structure. The multilayer grown at the optimal substrate temperature of 180°C was shown to display the maximum magnetoresistive effect. The reduction of giant magnetoresistance with increasing interface roughness is also observed in work of Schad et al. [6] who observed the maximum giant magnetoresistance value at 240°C.

In conclusion, we have systematically studied the influence of growth temperature on the interface structure in Fe/Cr multilayers and traced the correlation between interface properties and macroscopic behaviour of multilayers. We established that there is a clear correlation between magnetic interface structure and the resulting magnetic and magnetoresistive properties. The maximum magnetoresistive effect is observed in multilayers with the best interface structure, both interface roughening and interface intermixing reducing the value of giant magnetoresistance effect.

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