Indirect exchange coupling and spin polarization in Fe/AlFe/Fe trilayers

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Abstract

(Al/Fe)$_n$ superlattices were grown by the alternate deposition of $n$ Al and Fe monolayers on a Fe (0 0 1) buffer layer on cleaved MgO (0 0 1) substrates. LEED and CEMS measurements proved that $^{57}$FeAl ordered alloy (CsCl-type) was formed. The (AlFe)$_n$ monoatomic superlattices were then used as non-magnetic spacers in MgO (1 0 0)/Fe/(AlFe)$_n$Al$_1$/Fe trilayers. The magnetic hyperfine field at the nuclei of a $^{57}$Fe probe layer in the center of the nonmagnetic spacer, being a measure of the spin polarization from the ferromagnetic Fe layers, was investigated as the function of the total spacer thickness. A non-monotonous dependence of the polarization effect vs. the spacer thickness was found. The magnetic hyperfine field data were correlated with the MOKE measurements, which revealed a strong ferromagnetic coupling between the Fe layers. © 1999 Elsevier Science B.V. All rights reserved.

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Ferromagnetic (FM) films separated by a non-ferromagnetic (NM) spacer have been widely investigated because of the indirect magnetic couplings observed in these systems and potential magnetic recording applications [1]. The indirect exchange interaction is mediated by the spin polarization of the conduction electrons via the RKKY interaction. The coupling is very sensitive to any structure modification but the microscopic mechanism of these phenomena remains often unexplained. Therefore, it is very important to link the resulting macroscopic properties with their microscopic origin that is reflected in the conduction electron polarization of the spacer. There are only few methods capable to measure the spacer magnetism directly. The Mössbauer spectroscopy is used rather frequently [2–8], despite of a limited number of ‘easy’ Mössbauer isotopes. Among them $^{197}$Au was used to study the hyperfine interactions due to a conduction electron spin polarization in Fe/Au/Fe and Ni/Au/Ni systems [2,3,8], which contain the Mössbauer isotope in the spacer inherently. The hyperfine interactions were in this case too small to be detected. Moreover, the information came from the whole spacer layer because for Au, for which natural abundance of $^{197}$Au is 100%, the depth-selective enrichment is not possible.

A more sophisticated idea is to measure the hyperfine interaction with a spatial resolution, using a probe layer of Mössbauer isotope that is placed during the film deposition at a different position [4,9,10]. Unfortunately, for spacer magnetism studies, the probe layer of $^{57}$Fe or $^{119}$Sn was always different from the spacer material. Especially the probe layer of $^{57}$Fe [4,10] seems to be inappropriate because the magnetic Fe atoms, imbedded in the spacer, strongly modify its magnetic properties.

In this paper, we report on the first experiment in which the $^{57}$Fe probe layer analysis is applied to a chemically homogeneous spacer. It was possible using a Fe–Al ordered alloy as the spacer. We monitored, using...
conversion electron Mössbauer spectroscopy (CEMS), a local behavior of the conduction electron spin polarization in the spacer for Fe/FeAl/Fe trilayers as a function of the spacer thickness.

A strong ordering mechanism is reported for Fe and Al compounds in a wide range of their relative concentrations [11,12]. Near the 1:1 concentration, which is of our particular interest, the B2-CsCl structure appears. The ordered alloy is for this concentration paramagnetic even at low temperatures. If a weak ferromagnetism appears, it is usually connected with defects: vacancies and iron anti-structure atoms (ASA). The defects disturb the environmental symmetry of the iron nucleus, which results in an electric field gradient easily detectable in the Mössbauer experiments as contributing to a quadrupole doublet [13].

The FeAl ordered alloy seems to be an ideal spacer material for Mössbauer studies – it is paramagnetic and contains Fe naturally. It is also well suited to be obtained layer-by-layer, accordingly to its layer-like structure composed of the alternating (0 0 1) Fe and Al monolayers. If a monoatomic Fe/Al superlattice is grown by molecular beam epitaxy (MBE), it is possible to change layers. If a monoatomic Fe/Al superlattice is grown by molecular beam epitaxy (MBE), it is possible to change between two iron isotopes ($^{56}$Fe and $^{57}$Fe), restricting in this way the Mössbauer information to a pre-selected depth.

FeAl monoatomic superlattices were grown in a UHV system equipped with the MBE, LEED and AES. The deposition was made on a 20 nm thick Fe$^{56}$ buffer layer grown on a cleaved MgO(0 0 1) single crystal substrate held at room temperature. For an extremely clean preparation we were able to obtain LEED patterns from surface of superlattices, which indicates a high degree of the structural order. The samples were covered with 5 nm of Al and then CEMS spectra could be measured ex situ using a conventional He-CH$_4$ flow-detector. In the resulting spectrum for the (Al$_1$Fe$_{10}$)$_{50}$ sample (Fig. 1) no magnetic splitting is observed at room temperature. The best fit was obtained assuming two spectral components. A relatively narrow (HWHM = 0.26 mm/s) single line comes from the ideal iron environments for which all n.n. of Fe atoms are Al atoms. The second subspectrum, the asymmetric quadrupole doublet, is due to defects existing in the neighborhood of the iron atom [13]. A rough estimation gives the defect concentration of about 5%.

The (Al$_1$Fe$_{10}$)$_{50}$ monoatomic superlattices, forming the B2-FeAl ordered alloys, were then used as non-magnetic spacers in MgO(1 0 0)/Fe$_1$/(Al$_1$Fe$_{10}$)$_{50}$Al$_1$/Fe$_{11}$/Al samples. The thickness of the FeI and FeII layers (made of $^{56}$Fe) was 20 and 5 nm, respectively. The number $n$ of the double layers in the spacer was varied from 5 to 13, which corresponds to the spacer thickness variation between 1.6 and 3.8 nm. Sharp (1 x 1) LEED patterns observed for FeI and FeII surfaces prove that the transitional symmetry is conserved across the whole multilayer. In the center of each spacer (containing otherwise $^{56}$Fe) few $^{57}$Fe layers (usually three) were situated during the deposition, forming the Mössbauer probe.

The measured Mössbauer spectra and fits are presented in Fig. 2. For the thick spacers ($n = 11,13$), the spectra are very similar to that one obtained for the Fe–Al monoatomic multilayers. The spectra for $n = 5, 7, 9$ show the existence of a magnetically split component superimposed on a broadened single line. These spectra reveal the influence of the magnetic polarization from FM layers. They were fitted assuming a distribution of the hyperfine magnetic field $B_{hy}$ acting at the Mössbauer probe nuclei. To interpret the spectra we assume that the probe nuclei with the defected environments are stronger affected by the influence of the FM iron layers than the nuclei with the ideal environments. This assumption comes from our knowledge that ASA enhances magnetism of the FeAl ordered alloy. Some of Fe atoms in the alloy carry a magnetic moment, and for these atoms the spin polarization affects not only the conduction

![Fig. 1. Room temperature CEMS spectrum of the (Al$_1$Fe$_{10}$)$_{50}$ monoatomic superlattice.](image1)

![Fig. 2. Room temperature CEMS spectrum measured for Fe/(Al$_1$Fe$_{10}$)$_{50}$Al$_1$/Fe trilayers in which only 3 iron monolayers in the spacer center were replaced by the Mössbauer $^{57}$Fe isotope.](image2)
The coupling character in the samples was checked using the magnetooptic Kerr effect. For all spacer thickness, rectangular hysteresis loops were observed revealing a ferromagnetic coupling. It may be caused by the presence of iron magnetic moments in the spacer. There is however certain correlation between local and macroscopic magnetic properties. The maximum of average $B_{hf}$ for $n = 7$ coincides with a maximum value of the coercive force.

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**References**