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Long range electron spin polarization in the Ag layer of a Fe/Ag film

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Abstract

The depth dependence of the induced electron spin polarization below the magnetic interface of an epitaxial 4 nm Fe/300 nm Ag(0 0 1) bilayer has been investigated by means of low energy muon spin rotation (LE-μSR, Appl. Magn. Reson. 13(1997) 219). The mean stopping depth of the muons in the Ag layer can be tuned between 10 and 110 nm. A long range spin polarization is deduced from the μSR data. These measurements complement earlier investigations on a 4 nm Fe/20 nm Ag/4 nm Fe(0 0 1) trilayer (Phys. Rev. Lett. 91 (2003) 017204).

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1. Introduction

The oscillating interlayer exchange coupling (IEC) [1] observed for ferromagnetic films separated by a non-magnetic metallic spacer can be well described by Ruderman–Kittel–Kasuya–Yosida (RKKY) [2] and quantum well (QW) [3,4] models. While the first model is adopted from the indirect coupling mechanism of magnetic impurities in metals, the second has its origin in a spin-dependent confinement of conduction electrons within the spacer. The oscillation periods of the IEC are determined by extremal spanning vectors connecting parallel regions of the spacer's Fermi surface. In the Fe/Ag system, for example, two oscillation periods are found belonging to electron states from the neck and from the belly of the Ag Fermi surface [5]. Both models imply the existence of a spatially oscillating electron spin polarization $M(x)$ within the spacer. While the IEC can be investigated by experimental methods that probe the ferromagnetic layers, it is more difficult to get access to information on the spatially dependence of $M(x)$. Recently, an oscillating $M(x)$ was observed in the Ag layer of a high quality 4 nm Fe/20 nm Ag/4 nm Fe epitaxial trilayer by LE-μSR [6]. The oscillation period was found to be consistent with the one from the belly states. However, the observed $M(x)$ exhibited a much longer range than expected from measurements of the IEC and simple RKKY type models. Here, we report on a complementary LE-μSR [7] study on a 4 nm Fe/300 nm Ag(0 0 1) bilayer. To examine $M(x)$ at different depths x below the magnetic interface, the muons were implanted with various kinetic energies (3–30 keV). Typical transverse field LE-μSR data are

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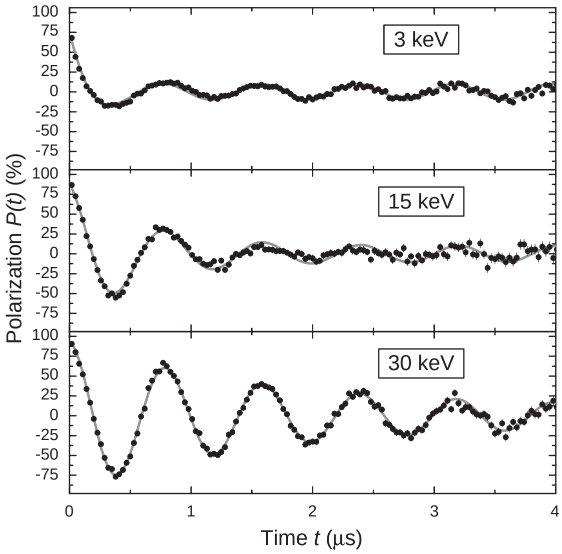

Fig. 1. Time-dependent muon ensemble polarization for muon implantation energies of 3, 15, and 30 keV with a mean implantation depth of 9, 48, and 107 nm beneath the Fe/Ag interface, respectively. The spectra were taken with an external field $B_{ext} = 9.2$ mT at 20 K.

shown in Fig. 1. The damping λ of the μSR signal is due to the distribution of hyperfine fields sensed by the muon ensemble. The relatively strong damping indicates large and spatially varying fields $B(x)$ even for the highest muon energy of 30 keV with a mean implantation depth of 113 nm. In Fig. 2, the measured λ is compared to model calculations using $B(x) \propto M(x)$ with

$$M(x) = M_{Fe} \sum_i C_i \, x^{-\alpha_i} \sin(2\pi \, x/\Lambda_i + \phi_i), \qquad (1)$$

weighted with the energy dependent muon stopping distribution $n(x, E)$. The fit is not sensitive to the detailed shape of $M(x)$ due to the large width of $n(x, E)$ compared to the oscillation periods. Therefore, the fit has been performed by using literature values for Λ_{belly} and ϕ_{belly} only [2]. Nevertheless, our data show unambiguously the existence of rather large positive and negative hyperfine fields at depths of the order of 100 nm in the Ag layer beneath the magnetic interface.

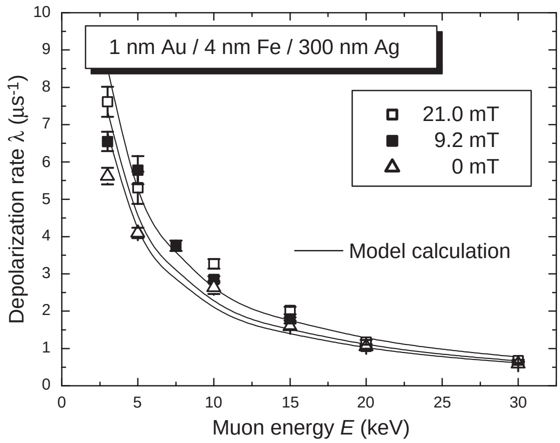

Fig. 2. Muon-spin depolarization rates λ, obtained at different applied fields ($B_{ext} = 0$–21 mT), as a function of the muon implantation energy E together with the model calculation described in the text.

Within the model used, the data are best described by an oscillating long range electron spin polarization $M(x) \propto x^{-0.4(1)}$. This is in contradiction to the x^{-2} dependence predicted by simple RKKY models. A possible explanation of this slow decay of $M(x)$ may be found in theories that include the confinement of electrons in the spacer. Semi-analytical calculations for the Co/Cu system [8] reveal deviations from the usual x^{-2} behavior for confined electron states. This mechanism might also be relevant for the Fe/Ag system, since the belly states are fully confined in Ag [9].

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