Hyperfine Fields in a Ag/Fe Magnetic Multilayer Probed with Low Energy Spin Polarized ^{8}Li

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Abstract

A beam of low energy ^{8}Li has been used to probe the hyperfine field distribution in a magnetic multilayer composed of Au(4nm)/Ag(80nm)/Fe(2nm) grown on a GaAs substrate. The β-NMR frequency spectrum is shown to be a strong function of the implantation energy reflecting the depth dependence of the local hyperfine fields. Correlating the spectra with TRIMSP implantation profiles allows us to identify signals from the GaAs, Ag and Au layers. The frequency spectrum in Ag is a strong function of energy. A very narrow line, and corresponding distribution of hyperfine fields, is observed when the beam in centered well away from the Fe whereas a much broader distribution is observed when the Li stops close to the Fe. These results demonstrate that low energy β-NMR can act as a sensitive probe of the induced magnetism in the otherwise non-magnetic Ag spacer layers.

Key words: β-NMR, Interlayer exchange coupling, magnetic multilayers, hyperfine coupling

1. Introduction

Interest in studying magnetic multilayered structures has grown steadily since it was shown by Grunberg *et al* [1] that the magnetization of two thin layers of Fe separated by Cr may, under some circumstances, align antiferromagnetically in the absence of any external magnetic fields. Later it was found that interlayer exchange coupling (IEC) of magnetic layers oscillates as a function of spacer thickness [2–4], and that this phenomenon occurs with almost any transition metal as spacer material [5]. Magnetic multilayers are of interest to the burgeoning spintronics industry because of their possible use in engineering devices that utilize both the spin and charge of the electron.

IEC mediated by the non-magnetic layer has been theoretically described by various models. There are two approaches that have had the most success; one based on quantum confinement[6] of the conduction electrons within the non-magnetic spacer layer, like particles in a box with spin dependent potential, and the other is an extension of the Ruderman-Kittel-Kasuya-Yosida (RKKY)

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theory [7,8] describing the coupling between a magnetic impurity and the electrons of the metallic host. The common feature of these models is they both predict inhomgeneous spatially oscillating hyperfine fields within the non-magnetic spacer layer. The existence of these oscillations has been found to depend sensitively on the quality of the magnetic/non-magnetic interface. The effect of interface roughness has been examined [8], and it was concluded that it acts to average out the coupling and breaks in-plane translational invariance over distances on the order the diameter of the flat regions at the interface.

Experimentally, IEC has been investigated primarily by probing the ferromagnetic layers, as measurements of the induced polarization of conduction electrons within the nonmagnetic spacer layer are more difficult. Quantitative measurements of polarization within the spacer material are mostly indirect bulk measurements of average polarization across the entire spacer, or studies of the surface of a nonmagnetic layers grown on a ferromagnetic substrate. Recently it has been demonstrated that low energy muons can be used to probe more directly the induced magnetism in the spacer layers in a multilayer [9]. In this work we show low energy spin polarized ^{8}Li and β-detected NMR [10–12] can provide similar but complementary information. As an example we present depth resolved measurements of the β-NMR resonance in epitaxial heterostructure of Au(4nm)/Ag(80nm)/Fe(2nm) on a GaAs substrate.

The sample was grown epitaxially on a GaAs (001) single crystal substrates 8 mm by 10 mm by 0.5 mm thick. The substrate surface was prepared in situ by sputtering and annealing the surface prior to deposition. The 2 nm of Fe was grown on the cleaned GaAs surface, followed by 80 nm of Ag, and a protective cap of 4 nm of Au. Films were grown at room temperature at a rate of approximately 1-2 monolayers (ML)/min with thickness monitored during growth using RHEED intensity oscillations as well as a quartz crystal microbalance calibrated to the sample position. Pressure in the MBE chamber during growth was on the order of 10^{-10} Torr. Ferromagnetic (FM) Fe grows epitaxially on GaAs [13] due the good match between the lattice constant for Fe (2.87 $\mathring{A}$) and half that of GaAs (5.65 $\mathring{A}$). It has been shown that growth at room temperature results in a high step density at the Fe/Ag interface owing to the vertical mismatch of 0.8 % between bcc Fe (001) and fcc Ag (001) [14], resulting in a lateral correlation length of 20 nm [15]. Mismatch of this type has been found in theoretical studies to wipe out long-period oscillations [16].

The β-NMR experiment was carried out at the ISAC radioactive ion beam facility at TRIUMF using a beam of highly polarized radioactive ^{8}Li$^+$ (τ=1.2 s, I=2, γ=6.301 MHz/T). Details on the polarizer and spectrometer can be found elsewhere[12,10]. The high magnetic field (9T) spectrometer sits on a high voltage platform so that the implantation energy of the polarized ^{8}Li$^+$ can be varied anywhere from $\sim$ 500 eV up to 30 keV. In analogy with μSR the nuclear polarization in monitored through the anisotropic β-decay of the highly polarized ^{8}Li. Resonance measurements are carried out with a continuous beam of ^{8}Li in the presence of a large static magnetic field $H_0 = 4.5T$. The frequency of a small amplitude RF magnetic field is swept through the region of the nuclear Larmor frequency. On resonance, when the RF frequency matches the Larmor frequency of the Li in its local magnetic field, it induces spin transitions of the Li nucleus and consequenctly there is loss in the measured β-decay assymetry. The resulting spectrum of resonance frequencies is a direct measure of the distribution of internal magnetic fields in the sample. This neglects any possible electric quadrupolar interaction, an assumption that is reasonable for materials such as Ag, Au and GaAs where both interstitial and substitutional sites have cubic symmetry.

2. Experimental results

Before presenting results on the multilayer it is useful to review previous work where we have characterized the β-NMR resonances of ^{8}Li in Au[17], Ag[12], and GaAs [18] separately. In both Ag and Au at room temperature narrow resonances, due to Li at the substitutional site, are observed with intrinsic linewidths of only a few hundred Hz due

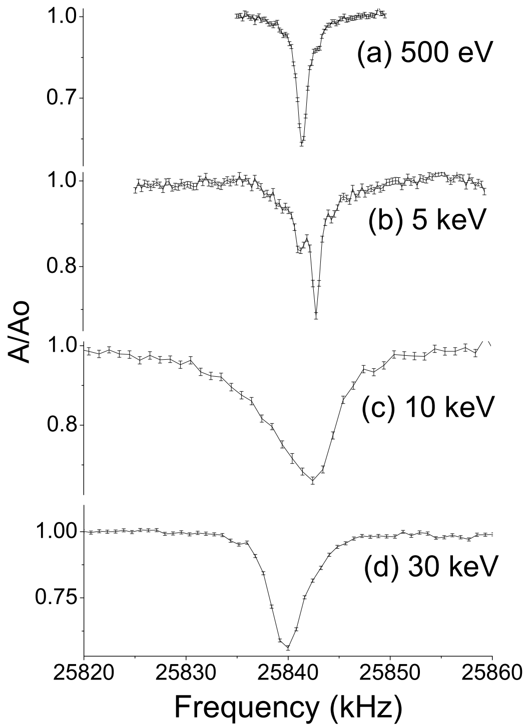

Fig. 1. β-NMR spectra taken at various implantation energies. The resonance at 500 eV is mostly Au whereas at 30 keV the spectrum is dominated by the signal from the GsAs substrate. The spectra at 5keV and 10keV are attributed mostly to the 80 nm Ag spacer layer.

to the small abundance and magntiude of the nuclear moments. The Knight shifts in Ag and Au relative to the insulator MgO are +120(12) ppm [12], and +60(20) ppm, respectively. In the semiconductor GaAs there is no Knight shift but the line is considerably broader (3-4 kHz) due to the large ^{69}Ga, ^{71}Ga and ^{75}As nuclear moments[18]. The resonance in Fe should not be visible in our frequency range due to the large hyperfine field present in a ferromagnet.

Fig.1 shows the frequency spectrum observed in the Ag/Fe multilayer sample for various implantation energies between 500 eV and 30 keV. Assignments of the various features can be made by correlating the spectra with the implantation profiles calculated with the TRIMSP Monte Carlo code (see Fig. 2). For example the main resonance in Fig. 1a is seen only at the lowest energies near

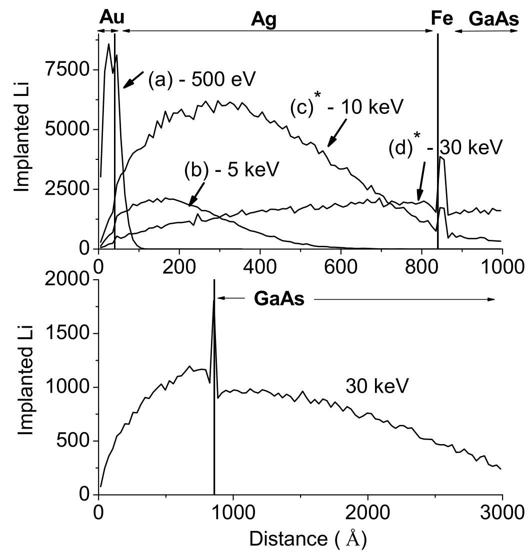

Fig. 2. Top: Calculated TRIMSP results showing the Li stopping distribution for various energies. The curves for 10 and 30 keV have been scaled up by a factor of 5 to show the shape more clearly. The bottom panel shows the 30 keV profile on a longer length scale.

E=500 eV and is therefore attributed to the Au overlayer. This is supported by the TRIMSP calculations which predict the largest signal at 500 eV to be from Au. Similarly, the broad resonance at E=30 keV (Fig. 1d) is attributed to the GaAs substrate since at the highest energy the mean depth of implantation is in the GaAs (see Fig. 1d). Furthermore the linewidth is close to what we have observed recently in a GaAs crystal[18]. Note also the frequency shift between the GaAs and Au is about 80 ppm which is in good agreement with the Knight shift we have measured previously in Au. Above 500 eV the amplitude of the Au resonance diminishes sharply as predicted by TRIMSP while a second narrow line a slightly higher frequency increases (see Fig. 1b). The frequency shift relative to GaAs is about +120 ppm. Comparing with the implantation profiles it is clear the new line is associated with the Ag close to the Au and more distant from the Fe e.g. more than 40 nm. The central part of this line has a width which is close to that of pure Ag indicating that the induced hyperfine coupling is negligibly small in this region of the multilayer. Note however there is evidence of a broad base to the line which is attributed to those Li stopping closer to the Fe. This interpretation is confirmed by the spectrum at 10 keV (see Fig. 1c) where TRIMSP indicates a much larger fraction of the beam stops close to the Fe (see Fig. 2). The peak frequency at 10 keV is almost the same as at 5 keV but the line is much broader on both the high and low frequency sides. This is attributed to the induced hyperfine fields in the Ag from the Fe layer. There is also an asymmetry to the line which we attribute to a small fraction of beam reaching the GaAs. Since the resonance in GaAs occurs at a lower frequency this contributes additional weight to the low frequency tail. The linewidth at its base indicates the amplitude of the induced hyperfine fields close to the Fe is on the order of $\pm 1mT$. Detailed modeling of the field distribution and resulting frequency spectrum is in progress.

In conclusion we have shown that β-NMR coupled with a low energy radioactive ion beam is a sensitive technique for measuring hyperfine fields in magnetic multilayers and thin nanostuctures. This utility is based on the fact that β-NMR is a highly sensitive nuclear method and that the depth of implantation can be controlled on a nm length-scale.

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