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Magnetic depth profiling of Fe/Au multilayer using neutron reflectometry

SURENDRA SINGH[1,*], SAIBAL BASU[1] and M GUPTA[2]
[1]Solid State Physics Division, Bhabha Atomic Research Centre, Mumbai 400 085, India
[2]UGC-DAE Consortium for Scientific Research, Bhabha Atomic Research Centre, Mumbai 400 085, India
[*]Corresponding author. E-mail: surendra@barc.gov.in

Abstract. We present unpolarized and polarized neutron reflectometry data on Fe/Au multilayer sample for characterizing the layer structure and magnetic moment density profile. Fe/Au multilayer shows strong spin-dependent scattering at interfaces, making it a prospective GMR material. Fe/Au multilayer with bilayer thickness of 130 Å was grown on Si substrate by RF magnetron sputtering technique. Unpolarized neutron reflectivity measurement yields nuclear scattering length density profile. The magnetic scattering length density profile has been obtained from polarized neutron reflectivity measurements.

Keywords. Neutron reflectomery; magnetic moment density profile.

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1. Introduction

Multilayers consisting of magnetic layers separated by non-magnetic spacers, exhibit giant magnetoresistance (GMR) and oscillatory exchange coupling, both of which have been studied extensively. The magnitude of the GMR and the strength of the oscillatory exchange coupling are strongly dependent on the asymmetry of the spin-dependent interface scattering [1]. The effect of the associated interface roughness on transport and coupling has been examined by a number of groups [2]. Stiles [3] has shown that Fe/Au system presents particularly strong spin-dependent interfacial reflection probability, which shows high asymmetry for majority and minority carriers. Such behaviour strongly depends on interface roughness and interface magnetic moment, which can be studied by polarized neutron reflectivity. Polarized neutron reflectometry (PNR) provides a unique ability to probe depth profile of the structure, and of the vector magnetization in thin film samples [4]. The reflectivity data can be fitted [5] using a depth-dependent scattering length density (SLD) profile $\rho(z)$ (where z is the film depth) with nuclear and magnetic components,

$$\rho(z) = \rho_{\text{nuc}}(z) \pm \rho_{\text{mag}}(z);$$
$$\rho_{\text{nuc}}(z) = \sum_i N_i(z) b_i; \quad \rho_{\text{mag}}(z) = C \sum_i N_i(z)\mu_i, \tag{1}$$

where the summation is over each type of atom in the system, N is the in-plane average of the number density, b is the nuclear scattering length, and μ is the magnetic moment in Bohr magnetons. The constant $C = 2.69$ fm/μ_{B}. The sign before ρ_{mag} in eq. (1) depends on the orientation of the magnetization relative to the neutron polarization and correspondingly we get two reflectivity patterns for two spin of neutrons, i.e. '+' for spin-up (parallel to H) and '$-$' for spin-down neutron (antiparallel to H). By model-fitting polarized neutron reflectometry data, one can obtain physical and magnetic moment depth profiles in the sample. In this paper, we present nuclear and magnetic moment depth profiles of a Fe/Au multilayer grown on Si substrate by sputtering, using neutron reflectometry. Physical density profile, averaged over sample plane, was extracted from unpolarized neutron reflectometry measurement. Polarized neutron reflectivity experiment gave magnetic moment depth profile in the sample.

2. Experimental details

A Fe/Au multilayer with repeated Fe/Au bilayer thickness of 130 Å was deposited on Si substrate using RF magnetron sputtering technique with a base pressure of 10^{-6} Torr at room temperature. A Fe layer of thickness ∼100 Å was deposited on Si substrate, followed by Au layer of thickness ∼30 Å. Ten such bilayers were deposited in the present case. The designed structures of the multilayer samples can be represented as Si substrate/[$Fe_{100\text{Å}}/Au_{30\text{Å}}$] × 10. During deposition, thickness of each layer was monitored using a water-cooled quartz crystal thickness monitor.

Neutron reflectometry experiments both in polarized as well as unpolarized modes were carried out at polarized neutron reflectometer instrument at Dhruva, India [6]. The neutron reflectometry data, both polarized and unpolarized modes have been analysed using a genetic algorithm (GA) based χ^2 minimization program [7], which uses a matrix method [8] for generating the reflectivity pattern for a given set of physical parameters of the system.

3. Results and discussion

Figure 1 shows the unpolarized neutron reflectometry profile from the Fe/Au multilayer sample. Closed circles and continuous line are the measured neutron reflectivity data and fit to measured data, respectively. The inset of the figure shows the nuclear scattering length (SLD) profile of the film as extracted from the measured unpolarized neutron reflectivity data. The average thicknesses of Fe and Au layer in a bilayer of sample, obtained from the unpolarized NR measurements, are 105±2 Å and 34±1 Å, respectively. The densities of Fe and Au layers are 7.85 g/cc and 19.0 g/cc, respectively, close to their bulk values. The interface roughness of Fe/Au and Au/Fe interfaces are 10 Å and 4 Å, respectively. We could see second-order

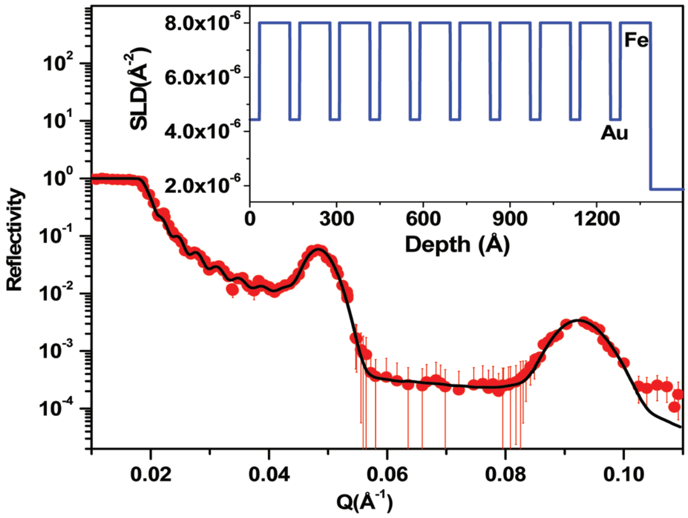

Figure 1. Unpolarized neutron reflectivity pattern from Fe/Au multilayer sample. Closed circles are experimental data whereas continuous line is fit to measurements. The inset shows the nuclear scattering length density (SLD)–depth profiling of multilayer.

Table 1. Parameters extracted from neutron reflectometry data for Fe/Au multilayer sample.

Element	Thickness (Å)	Density (g/cc)	Roughness (Å)	Magnetic moment (μ_B)
Au	34±1	19.0±0.2	4±1	–
Fe	105±2	7.85±0.12	10±2	2.18±0.01
Si	–	2.10±0.1	4.5±1	–

Bragg peak in the NR data, indicating low roughness at the interfaces. The parameters extracted from the fit to unpolarized neutron reflectometry data are given in table 1.

Figure 2 shows the PNR pattern from Fe/Au multilayer sample. Closed and open circles are measured neutron reflectivity data for spin-up (R^+) and spin-down (R^-) neutrons respectively, whereas the continuous lines are fits to the data. Inset shows the magnetic scattering length density (msld)–depth profile of the sample. We obtained an average magnetic moment of Fe atom ($\sim$2.18 μ_B) in each Fe layer in multilayer sample from PNR measurements, which is comparable to its bulk value (2.22 μ_B).

The spin asymmetry (ASYM) parameter defined as ASYM $= (R^+ - R^-)/(R^+ + R^-)$, which is less sensitive to interface roughness (σ) than the reflectivity, has also been plotted in figure 3. The open circles and solid lines in figure 3 show the experimental data and fit to the ASYM. The fit to spin asymmetry over the

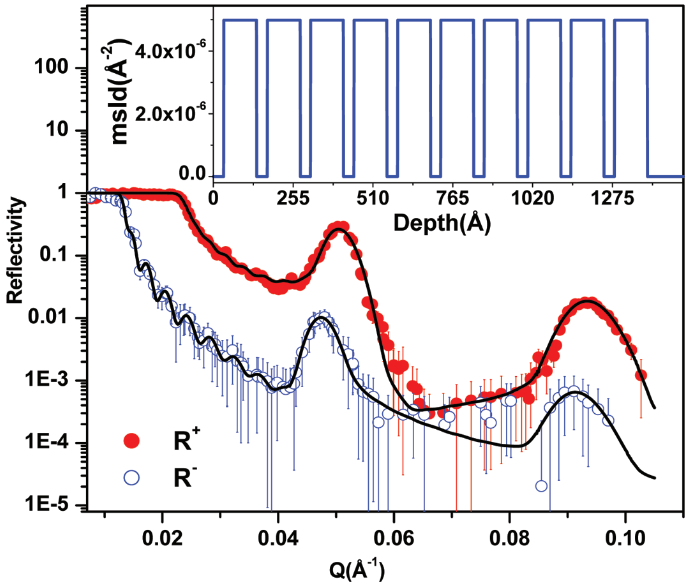

Figure 2. Polarized neutron reflectivity (PNR) pattern from Fe/Au multilayer sample. Closed and open circles are measured neutron reflectivity data for spin-up (R^+) and spin-down (R^-) neutrons, respectively, whereas the continuous lines are fit to measurements. Inset shows the magnetic scattering length density–depth profile of the sample.

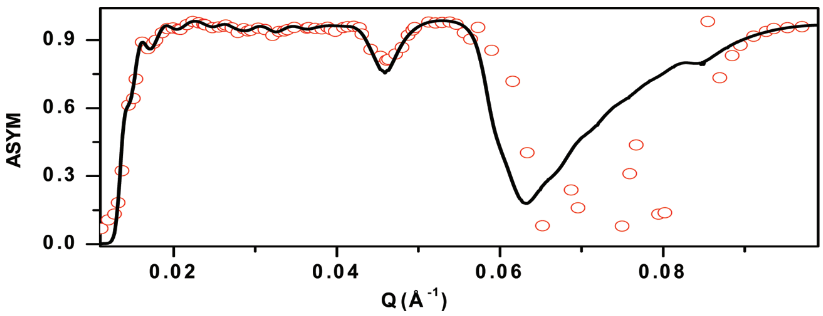

Figure 3. The spin asymmetry (ASYM) is plotted against Q. Open circles and continuous lines are the experimental data and corresponding fit to data, respectively.

entire Q range increases the confidence in magnetic scattering length density depth profiling obtained from PNR measurements.

In short, we have characterized a Fe/Au multilayer by neutron reflectometry. The data show that both Fe and Au layers have a physical density close to their bulk density with low interface roughness. Magnetic moment of Fe is about 2.18 μ_B in the Fe layers, close to the bulk value of 2.2 μ_B for iron.

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