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Noncontact GMR Measurements of Synthetic Spin Valves Using IR Reflection Spectroscopy

M. Vopsaroiu, J. A. D. Matthew, K. A. McNeill, and S. M. Thompson

***Abstract*—The magnetorefractive effect has been used in infrared reflection spectroscopy to study the magnetotransport properties of synthetic spin valves. This optical noncontact technique shows excellent correlation with the electrical giant magnetoresistance data.**

***Index Terms*—Giant magnetoresistance (GMR), infrared (IR) reflection spectroscopy, magnetorefractive effect (MRE), synthetic spin valves.**

I. INTRODUCTION

IN THIS paper, we describe an optical noncontact method for the measurement of the magnetotransport effects in giant magnetoresistance (GMR) materials, which has been applied to spin valve samples. The method is based on the magnetorefractive effect (MRE) [1]. The infrared dielectric properties of metals are well described by the Drude model in which the complex dielectric function is related to the complex conductivity and the frequency of the incident light. Hence, changing its conductivity modifies the dielectric function of a metal. In the case of GMR materials, spin-dependent phenomena are based on the principle that the conductivities for spin-up and spin-down electrons are different. As a consequence, altering the microscopic magnetic configuration through the application of an external magnetic field can control the transport properties of GMR materials, which in turn affects the dielectric properties through the changes in the conductivity. Transport properties depend mainly on the electron transitions inside the conduction band, the intraband transitions, which dominate the dielectric properties in the infrared (IR) spectral region (2–20 μm). Determining its reflectivity/transmissivity coefficients can therefore perform a direct measure of the changes in the dielectric properties of a material. Hence, IR transmission/reflection spectroscopy as a function of the applied magnetic field can provide a direct tool for probing the spin-dependent conductivities in GMR materials. The spin properties of the conduction electrons and the effects of the external magnetic field are contained in an extended Drude model of the form

$$\varepsilon_r(\omega) = \varepsilon_{st} + \left(\frac{\omega_p}{\omega}\right)^2 \cdot \frac{i\omega\tau_{\mathrm{sal}}}{1 - i\omega\tau_{\mathrm{sal}}} \cdot \left(1 + \frac{m^2 \cdot \beta_{\mathrm{sal}}^2}{(1 - i\omega\tau_{\mathrm{sal}})^2 - m^2 \cdot \beta_{\mathrm{sal}}^2}\right) \quad (1)$$

where ε_r is the complex dielectric function, ε_{st} is the frequency independent contribution to ε_r, ω_p is the plasma frequency, ω the frequency of the incident light, $m = M/M_s$ is the normalized magnetization, τ_{sal} is the conduction electron scattering rate in the self-averaging limit (SAL) [2], and β_{sal} is the spin asymmetry constant also obtained in the SAL formalism [1]. Relation (1) describes the MRE and was first theoretically and experimentally demonstrated in 1995 [1]. The MRE is defined as the variation of the refractive index (or dielectric function) of a material due to a change in its conductivity when a magnetic field is applied. Since the MRE is related to the intraband transitions of the conduction electrons, it is fundamentally different from the magnetooptic Kerr effect or Faraday effect in which the interband transitions dominate rather than the intraband transitions. It is important to stress that only GMR materials show the MRE and this is also clear from the relation (1), where if either m or β_{sal} is zero the relation reduces to the Drude dielectric function. The MRE has previously been used to study granular GMR materials such as $(\mathrm{Co})_x\mathrm{Ag}_{1-x}$ [3], $(\mathrm{CoFe})_x(\mathrm{Al_2O_3})_{1-x}$ [4] and exchange-biased GMR multilayers [5]. In this paper, the MRE has been used for the first time to measure magnetotransport properties of synthetic spin valves. The results reported here are compared with the electrical magnetotransport data and show an excellent correlation between the electrical GMR measurements and optical MRE, leading the way to noncontact GMR measurements of synthetic spin valves.

II. EXPERIMENT

Synthetic spin valve systems have been experimentally investigated in this paper. They are different from conventional spin valves, in that the pinned FM layer is replaced by a pinned trilayer structure [synthetic antiferromagnet (SAF)] consisting of two antiferromagnetically coupled FM layers separated by a nonmagnetic layer (usually Ruthenium). This design has the advantage of improved thermal and magnetic performances [6] compared to conventional spin valves. The synthetic spin valve samples studied in this paper were sputtered by Seagate Technology. They consisted of a pinned layer of an antiferromagnetically coupled CoFe–Ru–CoFe trilayer in direct contact with a layer of AFM PtMn. The pinned layer is separated from the free CoFe–NiFe bilayer by a layer of Cu. The total thickness of the resulting stack is around 450 Å, which is well within the limits of the IR skin penetration depth (around 600 Å for good conducting metals). Two variations of this structure were studied: a top spin valve (TSV) with the pinned layer at the top of the stack and a bottom spin valve (BSV) with the pinned layer at the bottom of the stack (see the inserted diagrams in Figs. 4 and 5). Current in plane (CIP) dc magnetotransport measurements

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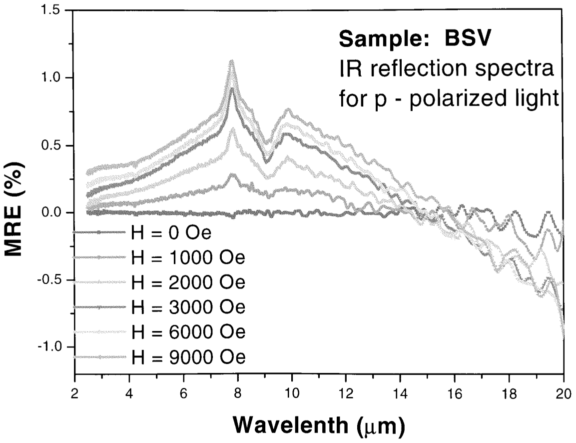

Fig. 1. MRE as a function of the wavelength in a BSV sample for decreasing positive applied fields (9000 to 0 Oe).

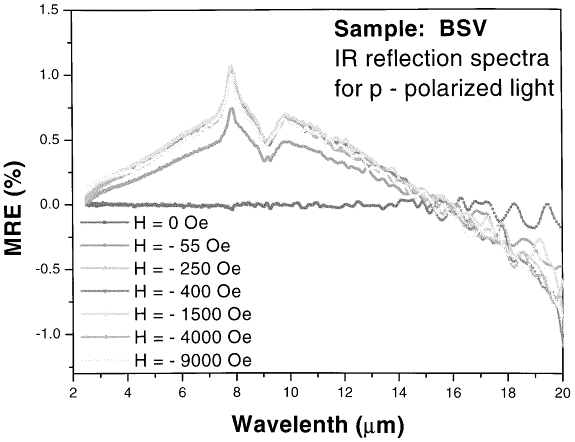

Fig. 2. MRE as a function of the wavelength in a BSV sample for increasing negative applied fields (0 to −9000 Oe).

were made using a four-point probe with a 1-mA applied current in a maximum applied magnetic field of ±9 kOe (Figs. 4 and 5). The electrical GMR was calculated using the relation

$$\mathrm{GMR}(\%) = \frac{\rho(H) - \rho(0)}{\rho(H)} \times 100 \tag{2}$$

where $\rho(H)$ is the resistivity of the sample in an applied magnetic field and $\rho(0)$ is the maximum resistivity that corresponds to zero magnetization of the sample.

IR spectra were acquired between 2.5 and 20 μm using a Fourier transform IR reflection spectrometer with 0.25-μm resolution and a liquid nitrogen-cooled HgCdTe detector. Although s polarized light gives the highest reflectivity, the optimum MRE was obtained for p polarized light using a KRS-5 grid polarizer and for an incidence angle of 65° with respect to the surface normal. The spectra were collected at room temperature in an applied magnetic field up to a maximum of ±9 kOe. The measurements were made in decreasing field order following saturation in a positive applied field in order to make a direct comparison with the GMR measurements. The MRE infrared spectrum for a particular applied field shows the percentage change in the reflection of IR light due to the application of the magnetic field as a function of wavelength and it was calculated according to the relation

$$-\mathrm{MRE}(\%) = \frac{S_2 - 0.5 \cdot (S_3 + S_1)}{S_2} \times 100. \tag{3}$$

S_1, S_2, S_3 are three consecutive spectra where S_1 and S_3 are taken in zero applied field and S_2 is the spectrum acquired at an applied magnetic field. S_1 and S_3 were then averaged in order to take in account any time variations in the background. For both the electrical and optical measurements, the pinning field was always parallel to the applied positive magnetic field direction.

III. Results and Discussions

IR reflection spectroscopy has been performed at different positive (Fig. 1) and negative (Fig. 2) applied magnetic fields. The MRE spectra for both the BSV (Figs. 1 and 2) and TSV show a broadly similar shape to those observed in CoAg granular GMR films [3] in that there is a broad positive peak in the MRE followed by a crossover into a negative reflection region at higher wavelengths. This is consistent with magnetically induced modification of the scattering of Drude like free electrons responsible for the GMR. The crossover occurs at much longer wavelengths in the synthetic spin valves, typically 15 μm compared to 10 μm in the CoAg. This is attributed to the different spin-independent resistivities in the two types of material [3]. The other significant feature is the presence of sharp positive and negative excursions around 8 μm, which are likely to be due to Si–O–Si vibration modes in the substrate. Close inspection of the MRE curves reveals that they follow the same asymmetric behavior as the electrical resistance under an applied magnetic field.

The rapid switching of the free layer is observed as a sudden change in both the electrical resistance and the IR reflection. The slow magnetic reversal of the synthetic antiferromagnet is observed as the smoother variation with field of both the GMR and MRE.

Although the absolute value of the MRE depends on the choice of the wavelength, there is a high degree of correlation between MRE and GMR, which is also insensitive to the precise choice of the wavelength. Usually, the magnitude of the MRE is taken as the absolute value between the lowest and the highest point of the MRE spectrum and that normally corresponds to the highest MRE. However, in this case, we chose to quantify the MRE values between 10 μm and the lowest point of the spectra that corresponds to a 20-μm wavelength (Fig. 3). By plotting the MRE values as a function of the applied magnetic field, direct correlation between the MRE and the GMR is obtained (Figs. 4 and 5). The strong asymmetry in the electrical properties is reproduced by the MRE, with very similar behavior for the TSV and BSV. Although the two curves correlate very well, the constant of proportionality is different than unity. Alternative measures of the MRE (e.g., only the absolute values at one wavelength) show similar correlations.

The maximum GMR values obtained are 7.2% for the BSV sample and 6.6% for the TSV sample, while the maximum MRE values are 1.8% for the BSV and 1.7% for the TSV.

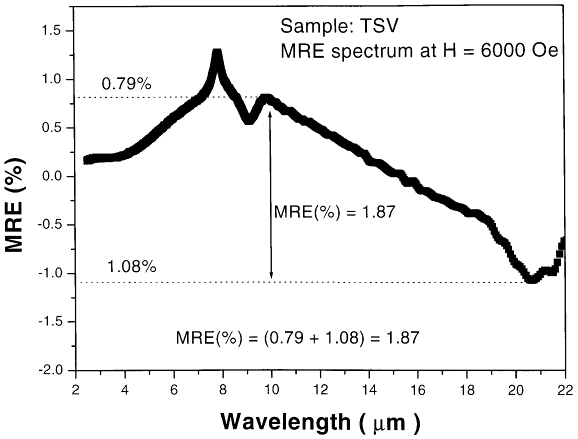

Fig. 3. Example of an MRE reflection spectrum taken at $\mathrm{H} = 6000$ Oe for a TSV sample. Magnitude of the MRE effect is taken as the absolute value between the value at 10 μm and the lowest value at 20 μm.

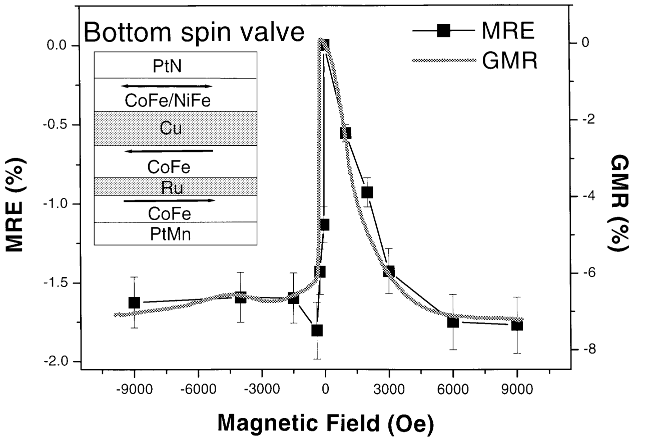

Fig. 4. GMR and MRE data for a BSV measured as a function of the applied field, after saturation in positive field.

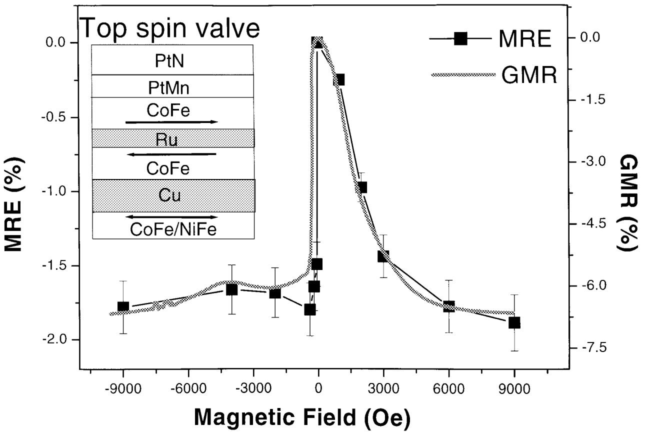

Fig. 5. GMR and MRE data for a TSV measured as a function of the applied field, after saturation in positive field.

Moreover, the IR reflection spectroscopy is highly sensitive to the changes in conductivity when the permalloy switches and these changes were detected in the IR spectra with a precision as small as ±2 Oe (the free layer of the BSV switches at -55 and -70 Oe for the TSV). The field step was varied more slowly for the MRE, resulting in a sharper transition at the switching of the free layer. A closer look at the correlation diagrams (Figs. 4 and 5) shows that the MRE follows not only the main peak in the GMR data, which is related to the reversal of the free layer, but also increases around the small broad peak (around -3.5 kOe) that is associate d with the *spin flop transition* occurring in the SAF. Spin flop of the magnetization in the SAF occurs when an external magnetic field is applied parallel to SAF layers. Both theoretical [7] and experimental studies [6] have demonstrated that under a certain applied field the minimization of the total energy of the system occurs when the SAF orients orthogonally to the applied magnetic field. Increasing the external magnetic field further, the flopped spins scissor toward the axis of the magnetic field orienting parallel when a high magnetic field is applied.

IV. CONCLUSION

IR reflection spectroscopy on synthetic spin valves has demonstrated that this technique is suitable for high-resolution noncontact measurements of GMR with the ability to detect electric conductivity variations under an applied magnetic field with a precision as small as ±2 Oe. The technique has been shown to be sensitive to the GMR intraband scattering and the effects on the GMR due to spin flop transitions occurring in the SAF. IR spectroscopy therefore has the potential for detailed experimental studies including the ability to perform *in situ* measurements, making it a very attractive and powerful investigation tool for both academic research and industry.

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