Second-Harmonic Magneto-Optic Kerr Effect from Spin-Valve Test Structures: Correlation with Magnetoresistance Response

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***Abstract*—We have simultaneously measured the second-harmonic magneto-optic Kerr effect and the magnetoresistance of patterned Ta/$Ni_{81}Fe_{19}$/Cu/$Ni_{81}Fe_{19}$/Ta spin-valve test structures. For fields applied parallel to the bias-current direction, we observed a one-to-one correlation between the magnetoresistance and the magnetization-dependent second-harmonic intensity. The dependence of the second-harmonic intensity on magnetic field indicates that the detected second-harmonic response arises largely from the top $Ni_{81}Fe_{19}$/Ta interface. The existence of this one-to-one correlation implies that the second harmonic depends linearly on magnetization, thus offering a method for interface-specific magnetometry.**

INTRODUCTION

The discovery of giant magnetoresistance (GMR) and its dependence on interfacial properties has provided a strong motivation for the study of surface and interface magnetism [1], [2]. The presence of strong surface anisotropies in ultrathin magnetic films offers additional motivation for understanding surface magnetic properties [3]. While there are numerous techniques for studying magnetic properties at a surface, it is difficult to study the properties of "buried" magnetic interfaces in a multilayer. In the case of large surface anisotropy, an optical technique such as the magneto-optic Kerr effect (MOKE) is commonly used to measure ultrathin films and infer the surface magnetic properties [4].

The *second-harmonic* magneto-optic Kerr effect (SH-MOKE) provides a means of probing surfaces *and* buried interfaces, while offering more than three orders of magnitude contrast enhancement over that obtainable with MOKE. Electric dipole second-harmonic generation (SHG) typically does not occur in materials with inversion symmetry [5]. In particular, for cubic materials such as Cu and $Ni_{81}Fe_{19}$, SHG is not observed in the bulk. However, interfaces and surfaces in these systems break the inversion symmetry, allowing dipole SHG in the interfacial and surface regions. The use of SH-MOKE to detect surface and interface magnetization was proposed theoretically by Shen and coworkers [6]. It was first observed experimentally from a Fe surface in ultrahigh vacuum [7]. Further measurements indicated that SH-MOKE could resolve buried interfaces in Co/Au multilayers [8]. We have applied this technique to study surfaces and buried interfaces of $Ni_{81}Fe_{19}$, a material of great technological importance to the magnetic recording industry [9], [10]. SH-MOKE from $Ni_{81}Fe_{19}$ exhibits contrasts of greater than 60% in the transverse geometry and Kerr rotation angles greater than 32 degrees in the longitudinal geometry [10]. Further, we have employed SH-MOKE to study the sub-component interfaces found in GMR spin-valves [11]. SH-MOKE clearly detects the presence of a 2 nm Co "dusting" at the interface between Cu and $Ni_{81}Fe_{19}$.

In order to "observe" a buried interface, a model for the detected SH-MOKE signal must be employed, since the total detected second-harmonic intensity results from all multilayer surfaces and interfaces within the optical penetration depth. Spectroscopic ellipsometry has been employed to determine the linear optical properties of the actual materials being measured [11]. These models have been used with good success to fit SH-MOKE from Co/Au and $Ni_{81}Fe_{19}$ multilayers [9] - [12].

In this paper, we report measurements of SH-MOKE from actual spin-valve GMR device stripes. By observing GMR devices, we can simultaneously measure and correlate magnetoresistance (MR) and SH-MOKE.

EXPERIMENT

The spin-valves used in this study are multilayers of Ta (5 nm)/$Ni_{81}Fe_{19}$ (7.5 nm)/Cu (3 nm)/$Ni_{81}Fe_{19}$ (7.5 nm)/Ta (5 nm) and have no pinning layer. The films are polycrystalline and were deposited by rf diode sputtering on 7.6 cm (001) Si substrates. The substrates were precoated with 200 nm of amorphous Al_2O_3 to remove any substrate orientation effects. The two $Ni_{81}Fe_{19}$ films were deposited in a magnetic field oriented so that the resulting uniaxial anisotropy axes are perpendicular to each other. The multilayers were patterned using photolithography with ion-milling to etch the base layer, followed by electrode deposition and lift-off. The electrodes were deposited so as to permit four-terminal resistance measurements. The devices measured were 50 μm high by 90 μm long, allowing easy optical access to the magnetic stripes for the SH-MOKE measurement.

A current supply capable of delivering a maximum dc current of 1 A provides bias current to the devices. An additional 1 mA ac current (25 Hz) was added to the dc current bias, provided by the reference channel of a lock-in amplifier. The lock-in is used to measure the voltage drop in

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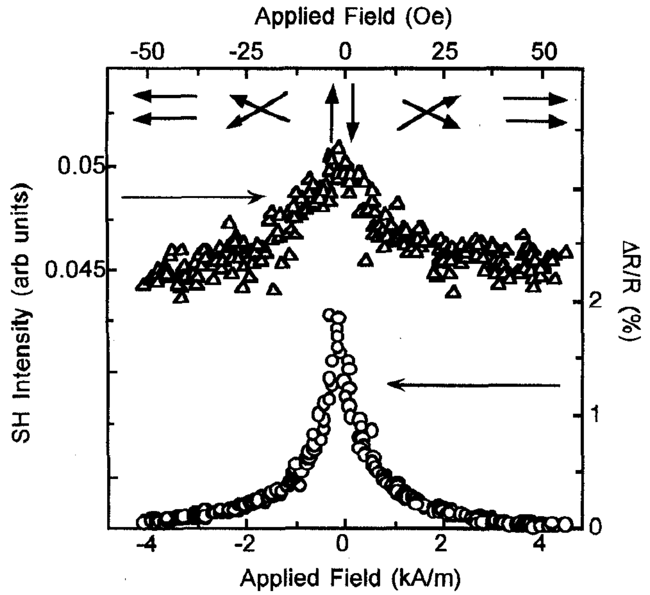

Fig. 1: SH-MOKE and MR as functions of longitudinal applied field. Bias current is +100 mA (0.5 kA/m current-induced field). The arrows at the top represent magnetization orientation in the $Ni_{81}Fe_{19}$ layers.

the direction of current flow along the stripe and probe the device MR. A two-axis electromagnet provides in-plane fields which may be parallel (longitudinal) and/or perpendicular (transverse) to the long axis of the device stripe.

The SH-MOKE measurements are performed using a mode-locked Ti:sapphire laser operating with a repetition rate of 100 MHz and at a wavelength of 810 nm. The width of the laser pulses is about 50 fs. We focus the beam to generate peak intensities of 1 to 3 GW/cm^2 at the stripe surface. The input fundamental beam is polarized parallel to the plane of incidence (p-polarized, parallel to the stripe). The detection optics filter out the fundamental light at 810 nm and detect only the second-harmonic (SH) light at 405 nm, using an IR-blind photomultiplier tube. We measured the SH-MOKE signal and the MR simultaneously.

For saturation fields in the two transverse directions (+y, −y), the SH polarization is parallel to the plane of incidence, with an intensity that changes with magnetization direction. This geometry is analogous to its MOKE counterpart.

RESULTS

Fig. 1 shows SH-MOKE and MR data for an unpinned spin-valve as a function of applied longitudinal field. The DC bias current used in this measurement is +100 mA (J = 7 x 10^6 A/cm^2), corresponding to a current-induced field of about 0.5 kA/m (~6 Oe), which acts in the −y direction on the top $Ni_{81}Fe_{19}$ layer and in the +y direction on the bottom $Ni_{81}Fe_{19}$ layer. The data show an increase in MR as the layers rotate from longitudinal parallel alignment at large fields into transverse antiparallel alignment at zero applied field. This antiparallel alignment is caused by the current-induced field. The SH-MOKE signal exhibits a peak near zero applied field, at a value which corresponds to the −y transverse intensity. The signal has the same intensity at longitudinal saturation fields in both directions. Fig. 2 shows SH-MOKE and MR data for the same spin-valve as a function of applied longitudinal field, only now the DC bias current is oppositely directed (−100 mA). While the MR is identical in Figs. 1 and 2, the SH-MOKE intensity change in Fig. 2 is opposite that in Fig. 1, decreasing to the value given by the +y transverse intensity near zero longitudinal field.

Fig. 3 shows SH-MOKE and MR data as a function of *transverse* applied field on an expanded field scale. Here, the MR curve shows a flat-topped peak, indicating that the applied field is acting parallel or antiparallel to the current-induced field, causing an abrupt change in MR as the applied field is reduced below the current-induced field. The SH-MOKE signal also changes abruptly from the −y transverse intensity to the +y intensity as the field is increased in the +y direction. The hysteresis in the MR curve

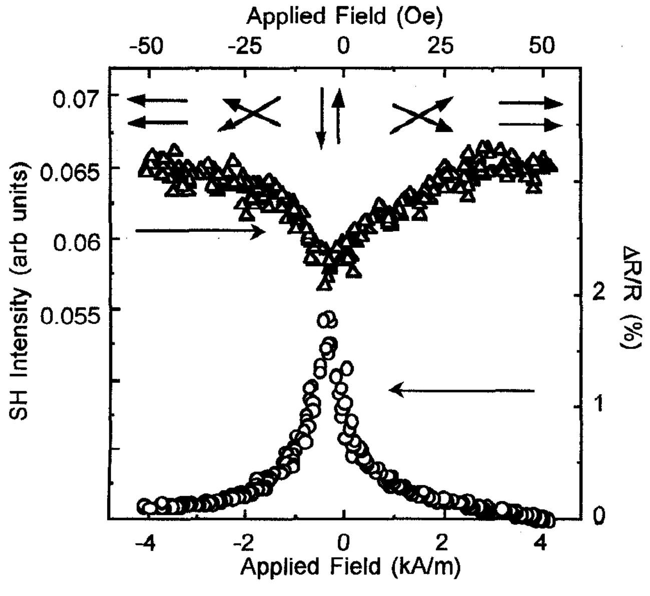

Fig. 2. SH-MOKE and MR as a function of longitudinal applied field. Bias current is −100 mA.

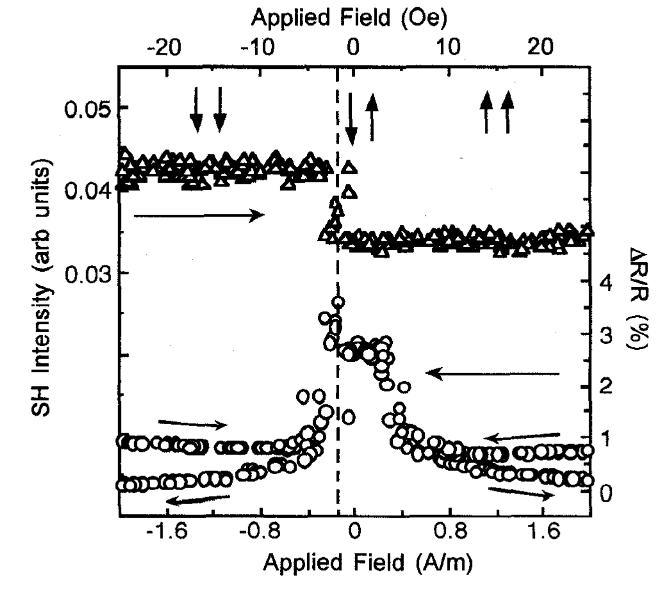

Fig. 3. SH-MOKE and MR as a function of transverse applied field. Bias current is -100 mA. Note the expanded field scale.

in Fig. 3 is probably due to an imperfect alignment of the applied field transverse to the spin-valve stripe.

All of the SH-MOKE and MR measurements were taken simultaneously, and the switch in the SH-MOKE signal shown in Fig. 3 correlates closely with the decrease in MR, as shown by the dotted line in Fig. 3. The SH-MOKE percentage change from these structures is 13%, which is reduced from the 60% observed for a $Ni_{81}Fe_{19}$ surface, possibly due to the different optical properties of a $Ni_{81}Fe_{19}/Ta$ interface.

Discussion

The MR from this spin-valve is proportional to the cosine of twice the angular difference in the $Ni_{81}Fe_{19}$ layer orientations [13]. An MR measurement allows us to determine the relative orientation of the two layers, while the actual orientation is inferred from knowing the applied fields. However, the SH-MOKE signal is proportional to the absolute orientation of the contributing interfacial magnetic moments with some phase relation between the SH generated fields and some odd dependence on the interface magnetization.

For longitudinal applied fields, the $Ni_{81}Fe_{19}$ moments are rotating coherently. If we assume that the "odd" SH intensity, defined as the difference in SH intensities for oppositely directed magnetizations, is linear in **M**, then we can rewrite the second-harmonic intensities in terms of M_y, which depends on the sine of the magnetization angle. The

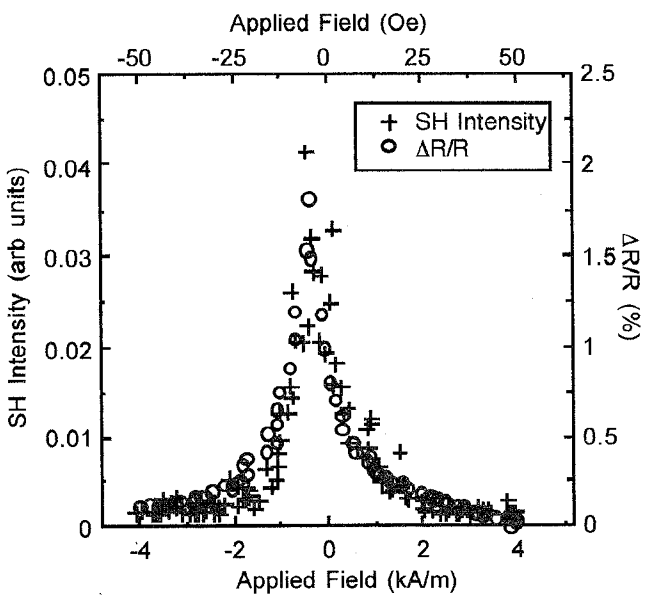

Fig. 4. Normalized SH-MOKE and MR as a function of longitudinal applied field. The SH-MOKE intensity was normalized assuming a linear dependence of SH-MOKE on magnetization.

second-harmonic intensity may then be normalized to obtain a relationship between MR and SH-MOKE,

$$\Delta R/R \propto 1 - 2\sin^2(\theta_M) \propto 1 - 2\left(I(M)/I_{\max}\right)^2 \qquad (1)$$

Fig. 4 shows an overlay of the MR curve and the normalized SH-MOKE intensity as calculated from (1). The two curves coincide within experimental error. The "odd" SH-MOKE intensity does appear to depend linearly on magnetization for this system.

It has been shown, in the case of $Cu/Ni_{81}Fe_{19}/Cu$ multilayers, that the presence of a mirror symmetry leads to a cancellation of the SH light generated at the two $Ni_{81}Fe_{19}$ interfaces when the $Ni_{81}Fe_{19}$ film thickness is less than 5 nm [11]. Interference effects have also been observed for Co/Au multilayers [12]. One expects a similar effect for $Ni_{81}Fe_{19}/Cu/Ni_{81}Fe_{19}$. Since the deepest $Ta/Ni_{81}Fe_{19}$ interface is close to the optical penetration depth at 23 nm, these results suggest that our SH-MOKE measurements from these spin-valves are sensing only the uppermost $Ni_{81}Fe_{19}/Ta$ interface. This hypothesis is supported by both the observation of a SH-MOKE transition on only one side of the MR curve in Fig. 3 and the modeling results.

The unique symmetry properties of SH-MOKE allow the isolation of a single interface in a multilayer, even when other interfaces are contained within the optical penetration depth. Combined with traditional magneto-transport measurements, SH-MOKE provides a powerful tool to monitor absolute interfacial moment orientations in GMR spin-valves. Further studies are needed to conclusively determine the relationship between interfacial moments and MR in these structures.

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