THERMOMAGNETIC WRITING AND TIME RESOLVED IMAGING IN A [Tb(7.9 Å) / Fe(11 Å)]$_{20}$ MULTILAYER.

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Abstract - The origin of the thermomagnetic writing of information bits in magnetooptical recording media is not completely solved. The formation of magnetic bubbles during or after the short time local heating of the medium by a focussed laser beam is not yet well understood. Precise time resolved measurements and corresponding calculations are still challenging. The difficulty of the data analysis comes mainly because thermal and magnetic experimental length scales are of the order of the light wavelength. We present here coupled nanosecond time resolved measurements of the heat diffusion and of the writing process in a TbFe multilayer with a compensation point below room temperature. This enables us to deduce the spatio-temporal variation of the temperature and to prove that the formation of the magnetic bubble occurs during the cooling of our sample. A good fit of our thermal data can only be obtained if the thermal conductivity of our magnetic multilayer is supposed to be more than one order of magnitude smaller than the bulk alloy conductivity.

KEYWORDS: MAGNETIC THIN FILMS, MULTILAYERS, MAGNETOOPTICS, THERMOMAGNETIC RECORDING, IMAGING, THERMAL CONDUCTIVITY

INTRODUCTION.

Due to the development of magnetooptical data recording, it is important to understand the magnetization switching of a thermomagnetically written bit of information by a focussed laser beam (typical diameter < 1 µm) in the realistic case of a spinning disc, but the case of a stationary medium is also interesting and reduces the complexity of the analysis. The spatio-temporal study of the thermal and magnetic behaviour of a small area allows to deduce pertinent physical parameters which govern the generation and stabilization of the written bit. We have to determine experimentally the spatial distribution of the temperature and its evolution at short time, as well as to predict the magnetic behaviour of the film at the same time.

In the case of a stationary film, theoretical predictions on the generation of circular domains in a TbFe magnetic layer have been reported since 1988 [1] where, in difference with the older Huth model [2], the wall width was introduced. Observation of written bubble domains under various experimental conditions has been reported together with calculations of the thermal profiles in a TbFe thin film [3]. The final size of the bubble was theoretically determined and compared with experiment, but there was no discussion on its evolution during the local heating and cooling of the sample. Applying a magnetic field along the direction of the previous saturation, time resolved magnetooptical Kerr imaging allowed to follow the 2D thermal diffusion of heat which was compared to calculations [4]. They have shown that the values of the thermal parameters in a TbFeCo film are far smaller than their bulk values; no prediction about the domain dimension under writing conditions has been reported. Hall micro-probe measurements [5] were used to study the full dynamics of the magnetization reversal during thermomagnetic writing and showed that, depending on the writing laser power, the domain could form during the heating or the cooling of the magnetic layer.

On the other hand, the case of a moving medium has been examined by several groups. Reference [6] reports a real time simulation determining the temperature distribution as a function of time, using the Green function technique. Green function and the finite-difference methods have been found to give very close results for the thermal evolution [7] in the dynamic regime but, again, no magnetic behaviour has been calculated. From the observation and modeling of magnetization dynamics [8] in a GdTbFe thin film, it has been deduced that the thermal conductivity value is smaller by almost an order of magnitude in the thin film than in the bulk.

In this paper, we report on nanosecond time resolved measurements of the spatial distribution of temperature during and after heating as well as that of the process of magnetic writing in a TbFe multilayer.

EXPERIMENTAL

The Tb/Fe multilayers deposited on a float glass substrate by Ar r.f. sputtering in high vacuum are promising materials for thermomagnetic writing [9][10]. Our sample is a stack of Si$_3$N$_4$ (105Å) / [Tb(7.9Å)/Fe(11Å)]$_{20}$ / Si$_3$N$_4$(678Å) deposited on float glass. The relative thickness values of the Tb and Fe layers, corresponding to the composition of the homogeneous Tb$_{0.21}$Fe$_{0.79}$ alloy, are chosen so that its compensation temperature $T_{comp}$ lies beneath, but near to, 0 °C. In this thickness range, the Tb and Fe layers are amorphous [11]. The thickness (678Å) of the Si$_3$N$_4$ top layer has been determined to maximize the absorbed energy at the
laser diode wavelength (801 nm).

The magnetic properties of the multilayer, important for recording, are displayed on Fig. 1. The magnetic anisotropy is perpendicular to the film plane. The sample Curie temperature $T_C$ is close to 100 °C and its compensation temperature $T_{\text{comp}}$ is estimated to be about -50 °C, as indicated by the divergence of the coercive field, consistent with the general magnetic behaviour at this composition [12]. The magnetization reversal is dominated by domain wall propagation, as indicated by the perfect squareness of the hysteresis loop and observed by imaging of the wall motion under short field pulses. Furthermore, Faraday rotation ($\pm 1^\circ$) and ellipticity ($\pm 0.5^\circ$) are important in the red part of the optical spectrum.

The experimental set-up is a laboratory designed polarimeter dedicated only to a stationary configuration of the sample and of the light sources. The light source used for the optical spectrum.

The high sample quality and experimental stability, allow to perform stroboscopy and to accumulate more than one thousand images to further improve the SNR. The images are formed in Faraday configuration, using a microscope objective (N.A.=0.85), on a cooled CCD camera. The writing beam is focussed on the sample by the same microscope lens. The magnification of the optical bench, lets each pixel of the camera correspond to a 0.2 x 0.2 µm² area on the sample. Image processing is done partly by the camera control unit, partly on a personal computer.

Each final image is formed, after dark current compensation, by applying a “shading correction” using a reference image obtained with the heating pulse switched off.

RESULTS AND DISCUSSION.

TIME-RESOLVED TEMPERATURE MAPPING.

In order to understand the short time magnetization reversal process in a localized sample area, it is first necessary to analyze the heat diffusion process during heating and cooling. Fig. 2a shows the timing of the different phases of one heating/cooling cycle.

After having magnetically saturated the sample in a field $H_{\text{sat}}$, the multilayer is heated locally by the focussed laser diode beam in a bias field $H_b = 300$ Oe applied in the same direction as $H_{\text{sat}}$ and larger than the local dipolar field in the heated area, but smaller than the room temperature coercive field. No domain can be stabilized in this case upon heating or cooling and magnetooptical imaging should reveal the local temperature distribution. The magnetic state of the
sample is probed by the reading pulse during ($\delta t<0$) or after ($\delta t>0$) occurrence of the heating pulse.

**Fig. 3a** displays images obtained during (heating) and after (cooling) the laser irradiation. The pulse duration is 1000 ns. The origin of time is chosen at the end of the pulse so negative times correspond to heating and positive times to cooling. The white part at the center of each image during heating corresponds to a low (or even zero) magnetized area.

**Fig. 3a.** Images of the sample taken with $H_b$ in the same direction as $H_{sat}$ at different times during heating (-900 to 0 ns) and during cooling (0 to +500 ns). Black color corresponds to saturation magnetization $+M_s$, and white to zero magnetization.

The purpose of our time-resolved experiments is to determine the $(r,t)$ magnetization distribution. The heated spot on the sample has geometric dimensions close to the light wavelength so that the intensity distribution of the magnetooptical image results from the convolution of the true magnetooptical characteristics of the sample by the point spread function or PSF of the optical bench.

Thus, in a first attempt, we have to determine the PSF. For that purpose, a uniformly magnetized cylindrical domain were generated in the film, from which we determined the symmetric intensity distribution $I_{exp}(r)$ of the magnetooptical image. Independently, we calculated the shape function $I_{calc}(r)$ obtained from the convolution of a square function by a normalized Airy function standing as a reasonable approximation of the PSF. Finally, the width at half height $\Delta$ of the PSF were adjusted to provide a perfect coincidence between the $I_{calc}(r)$ and $I_{exp}(r)$ functions. The best fit was obtained for a PSF width $\Delta$ of 0.8 $\mu$m.

In time resolved experiments, the nonuniformity of the laser diode irradiation together with the heat diffusion mechanism generates a temperature profile and consequently a non uniform local magnetization whose observation is affected by the optical PSF. The true magnetization profile has to be determined, basically by a deconvolution process, in order to obtain finally the distribution of the temperature over the sample at a given time during or after irradiation.

Straightforward deconvolution gives at best very noisy and often non-unique results. We propose a slightly less direct solution to the problem:

**Fig. 4.** Method of obtaining temperature profiles from the measured intensities of Fig. 3a. The image (a) is transformed into an intensity profile $I_1(r)$ (b). An idealized Gaussian temperature profile (c), with height h and width w adjustable, is transformed by the measured functions $M/M_s(T)$ and magnetooptical sensitivity $I(M/M_s)$ (d) into an idealized magnetooptical response function (e). Convolution of (e) with a normalized point-spread function (Airy disk) describes the imaging process (diffraction). The resulting intensity profile $I_2(r)$ (g) is then matched to $I_1(r)$ by adjusting h and w in function (c).

From the experimental magnetooptical images (**Fig. 4a**), it is easy to extract the temperature profile $I_{exp}(r,t)$ (**Fig. 4b**) at different times. On the other hand a function $I_{calc}(r,t)$ may be calculated by the following procedure. One assumes that the temperature profile $T(r)$ of the heated area
has a circular Gaussian distribution (Fig. 4c) with amplitude "h" and width "w". Considering the thermal variation of the magnetization (Fig. 4d) of our sample, we determine in Fig. 4e the magnetization profile M(r,t). After convolution with the optical PSF (Fig. 4f) determined above, we deduce in Fig. 4g, the calculated intensity function I_{calc}(r,t). Adjusting the parameters "h" and "w", the function I_{calc}(r,t) can be made to fit exactly the I_{exp}(r,t) profile.

Using this procedure, we obtain the variation with time of the temperature profiles (Fig. 5) from the images of Fig. 3.

![Fig. 5a. Experimental temperature profiles as obtained by fit for different times during heating. 0 ns corresponds to the end of the heating pulse. Steady-state temperature was included in the fit, the variations are a indication of the the error on temperature.](image)

![Fig. 5b. Experimental temperature profiles as above during cooling. 0 ns correspond to the end of the heating pulse.](image)

Fig. 5a. Experimental temperature profiles as obtained by fit for different times during heating. 0 ns corresponds to the end of the heating pulse. Steady-state temperature was included in the fit, the variations are an indication of the error on temperature.

Fig. 5b. Experimental temperature profiles as above during cooling. 0 ns correspond to the end of the heating pulse.

\[ \delta = (r \cdot D \cdot t)^{1/2} \]

Where D is the thermal diffusivity of the substrate or the cover layer.

Fig. 6 gives a comparison between the experimental and best calculated temperatures as a function of time at several distances from the center. While the value of the peak temperatures are reasonably well reproduced, the calculation does not well describe the dynamic aspect, especially during cooling. This calculation shows however, that in order to obtain a reasonable likeness at all, one has to assume a reduction of one order of magnitude of the thermal conductivity of thin films as compared with the bulk values (\( k_{\text{TbFe(thin film)}} = 7 \text{ J m}^{-1} \text{s}^{-1} \text{deg}^{-1} \) and \( k_{\text{bulk}} = 40-80 \text{ J m}^{-1} \text{s}^{-1} \text{deg}^{-1} \)). This fact was already pointed out by other authors [14], [15].

**TIME-RESOLVED WRITING EXPERIMENTS**

Knowing the time dependence of the temperature distribution inside and close to the heated area, we have investigated the magnetization switching process, when H_b...
is applied in the opposite direction to the saturation field \( H_{\text{sat}} \) (fig. 2b). A local induced magnetic reversal can occur either during the heating or the cooling of the multilayer and, later on, if the energy balance is favourable [2], a magnetic domain stabilizes: the conditions for thermomagnetic writing are then fulfilled. In Fig. 3b, the domain formation is observed under the same conditions as for Fig. 3a. The time dependent magnetization distribution of the written bit can be extracted from these images and since the previous experiments give the corresponding temperature distribution profile, it is in principle possible to evaluate the various energy terms competing in this phenomenon and study the time range for the onset of stability of the domain.

Analysis of the images of fig. 3b shows that the magnetic domain stabilizes during cooling down of the sample, approximately 200 ns after the end of the heating pulse.

For TbFe alloy thin films, the magnetic structure of the written domain as observed after cooling of the sample, depends on the bias field value and on the relative position of \( T_{\text{comp}} \) and room temperature \( T_a \) [3]. Our TbFe multilayer behaves consistently with these results. Lorentz micrographs in TbFe films show that if \( T_{\text{comp}} < T_a \), which is also our case, then a single homogeneous circular domain is written in a large enough bias field.

CONCLUSION

The thermal calculation is one of the most difficult problems to solve in these ultra-thin film structures. Moreover, from an experimental point of view, there is a lack of a reliable probe at a microscopic level to get rid of the diffraction limited temperature determination. In spite of more than a decade of experiments, it is only recently that authors were obliged to assume that the thermal conductivity had to be much smaller in thin films than in the bulk. Nevertheless, to solve definitely the problem, one would need a thermometer with a surface of less than 0.1 \( \mu \text{m}^2 \).

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