Article:

Holliday, N.T., Hill, E.W., Marrows, C.H. et al. (2 more authors) (2000) Time dependence studies on giant magnetoresistive Co/Cu multilayers. IEEE Transactions on Magnetics, 36 (5 (par). pp. 2847-2849. ISSN 0018-9464

https://doi.org/10.1109/20.908605

Time Dependence Studies on Giant Magnetoresistive Co/Cu Multilayers

Nigel T. Holliday, Ernie W. Hill, Chris H. Marrows, Fay E. Stanley, and Bryan J. Hickey

***Abstract*—Time dependence studies consisting of applying current steps at fixed applied fields have been carried out on bilinear and biquadratic giant magnetoresistive (GMR) Co/Cu multilayers in a temperature controlled environment. It has been shown that the voltage responses to current steps of these aged multilayers are greater in magnitude before field cycling compared to those made after field cycling. Normalized voltage measurements for some samples suggest a magnetic viscosity effect due to a current step at zero-field is present and before field cycling. The effect is reduced after field cycling. This behavior suggests that the effect being seen is purely magnetic in origin, as only the field is being varied. A $\ln(t)$ type function has been curve fitted to the zero field voltage response to a current step before field cycling. Voltage measurements made on the Co/Cu films at different field values show that as the applied fields are increased the voltage response has a reduced $\ln(t)$ character.**

***Index Terms*—Co/Cu multilayers, giant magnetoresistance, magnetic viscosity, time dependence.**

I. Introduction

IT HAS been reported that the initial magnetoresistance curve for GMR films show an enhanced magnetoresistance change over that of the hysteretic magnetoresistance curve [1]. Other workers have also shown that the magnetoresistance change for an ac-erased Co/Cu multilayer can be larger than that for a multilayer that has been field-cycled [2]. The purpose of this work is to investigate the effects of time dependence in Co/Cu multilayers at different fields. Prior to these investigations, the Co/Cu multilayers used had been left undisturbed for several months after being field cycled to determine their giant magnetoresistance and saturation field values.

II. Experimental

Bilinear and biquadratic coupled Co/Cu GMR multilayers prepared by the Leeds University group were used in this investigation [3]. These multilayers were sputtered on native oxide silicon wafers and had a nominal interlayer thickness of Co 9 Å/Cu 9 Å. The biquadratic samples were obtained by moving the silicon wafers away from the magnetrons during the sputtering process so impurities in the chamber would settle on the deposited surface before returning the wafers to the magnetrons.

Manuscript received February 15, 2000. This work was supported in part by the EPSRC and Penny and Giles Controls Ltd.

N. T. Holliday and E. W. Hill are with the Electronic and Information Storage Systems Research Group, Department of Computer Science, University of Manchester, Manchester, M13 9PL, UK (e-mail: nigel.holliday@stud.man.ac.uk).

C. H. Marrows, F. E. Stanley, and B. J. Hickey are with EC Stoner Laboratory, Department of Physics and Astronomy, University of Leeds, Leeds, UK.

Publisher Item Identifier S 0018-9464(00)08663-5.

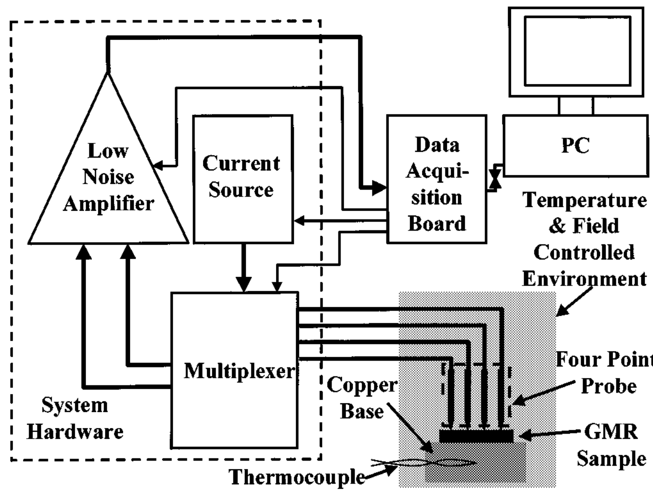

Fig. 1. A block diagram showing the main blocks of the sensitive automated measurement instrument used. The temperature and field controlled environment were provided by a black box type enclosure and an electromagnet, respectively.

Fig. 1 shows the main blocks of the sensitive automated low noise measurement system used in these time dependence studies [4]. The multiplexer is PC controlled and switches the GMR film into the measurement circuit while switching out a dummy resistor of a similar resistive value to that of the film. This is done to prevent current spikes on the sample and allows the current source to remain stable. The low noise amplifier has an input impedance that closely matches that of the multilayer films on which the measurements were made. This allows low noise measurements to be carried out. The data acquisition board has a 16-bit analog-to-digital converter that is capable of detecting very small changes in a signal. In order to minimize thermal drift in the electronics, the instrument was left powered up for several days prior to any measurements being made.

An electromagnet was used to generate the required fields for the experiment. The power supply for the magnet was also left powered up so as to minimize thermal drift. The power supplies were set so that they provided a constant current to the electromagnet. This provided very stable fields from the electromagnet for the time dependence measurements.

The measurements were made on these samples using a four-point probe that was designed to fit between the pole gap of the electromagnet. The base of the four-point probe was copper and fitted with a thermocouple so the temperature of the sample, which sits on the base, could be monitored.

In order to make accurate measurements it is necessary to carry them out at a constant temperature. It was therefore necessary to create a black box type enclosure for the four-point probe

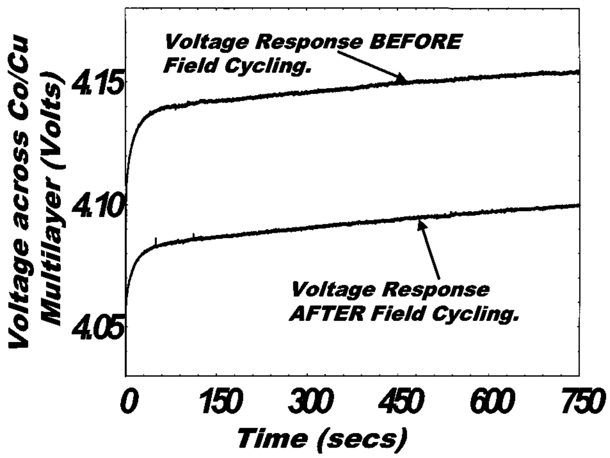

Fig. 2. A plot showing the measured voltage response to a 3 mA current made at zero field before and after field cycling. The voltage response after field cycling is clearly less than before field cycling. The gain in the measurement system was 500.

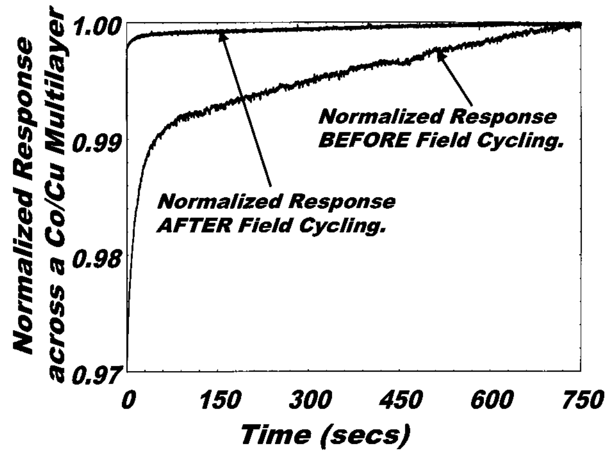

Fig. 3. A plot showing the normalized voltage response to a 5 mA current step for a bilinear film before and after field cycling. The differences between the two responses in this film are nearly as much as 3% of the normalized output.

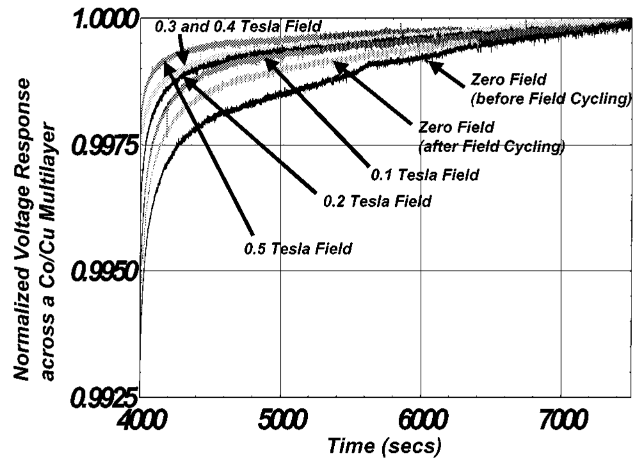

Fig. 4. A plot showing the normalized voltage response for a bilinear film made at different fields. The zero field measurement made after field cycling was carried out after the 0.5 Tesla measurement. A steady current of 2.5 mA was applied at zero time then at 4000 seconds the current was increased by another 2.5 mA step taking the total current through the sample to 5 mA.

between the poles of the electromagnet where the temperature was at least stable for the duration of the measurement cycle.

A temperature control unit was used to control the temperature in the pole gap. This unit is capable of generating stable temperatures between $-10°C$ to $80°C$ by pumping liquid of the desired temperature through copper tubing that is wrapped around the perimeter of the pole gap of the electromagnet. Insulation foam was then used to provide thermal lagging around the pole pieces and enhance the thermal stability of the black box type chamber. Once the temperature of the controller had been set time had to be allowed for the black box environment to thermally stabilize. The access point for the four-point probe to the pole gap was between the inlet and the outlet of the copper tubing.

III. Results

A. Time Dependence Measurements

Field dependent GMR measurements have been made on as deposited and field cycled Co/Cu multilayer thin films. Initially some preliminary time dependence measurements were made by applying current steps of magnitude 4.75 mA giving a current density of 1.76×10^7 Am^{-2} to samples starting in the zero current state. These measurements revealed that some films appeared to exhibit time dependence of the resistance over the short time period over which the measurements were made.

Subsequent measurements based on those made earlier were repeated on several of the films. It was found that successive measurements, one made before field cycling and one made after field cycling yielded significantly different absolute resistance changes.

The results for one film can be seen in Fig. 2. Here a current step was applied to a bilinear film that was initially in the zero current state. The voltage measurements were started as soon as the current step had been applied. The measurement period was 750 seconds with 30 minutes between each measurement in which time the Co/Cu sample was exposed to a saturating field. These measurements were carried out in a temperature-controlled environment. It can be seen clearly that the voltage measured after field cycling is lower than that measured before field cycling.

When the voltage measurements before and after field cycling were normalized significant differences between the two measurements for the films were seen.

Fig. 3 shows one such example. Here the difference between the two measurements is around 3%. The main point of interest though is the time dependence nature of the normalized plot before field cycling. Once this sample had been saturated the time dependent characteristic is reduced significantly. The difference between the two responses recorded in the biquadratically coupled Co/Cu multilayers are negligible compared to that seen in some of the bilinear coupled multilayers.

More recent time dependence measurements have concentrated on investigating responses of Co/Cu samples to current steps with a current already flowing through the samples. These measurements have been made on films over time periods extending up to 3500 seconds. Here the films were subjected to a fixed current step for 4000 seconds after which a further current step doubling the total current on the sample was applied.

Fig. 4 shows the results for a series of these measurements made at different fields on a bilinear sample. The results in Fig. 4

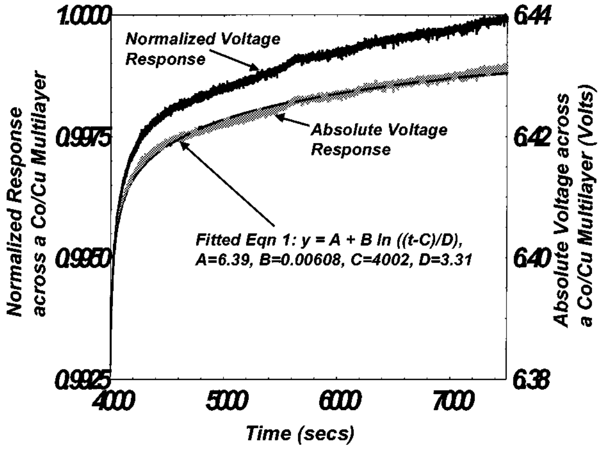

Fig. 5. A plot showing the normalized and absolute voltage response for a bilinear film before field cycling. Also shown is a curve fits for a $\ln(t)$ type curve.

show the effect that applying a field has on a sample left undisturbed for six months which has a current step superimposed upon a steady current. The same time dependence effect is seen as that in Fig. 3 but now the normalized results show the time dependence effect being swept out by the field as it increases. The zero field measurement made after the field cycling show a reduced effect.

B. Curve Fitting

All materials subject to hysteresis exhibit time dependence of magnetization under constant field conditions [5], [6]. In the materials under consideration in this study, interest is in the change in resistance $R(t)$ of the films with time. Wherever a distribution of energy barriers is being overcome the following expression to relate the resistance $R(t)$ to $\ln(t)$ can be considered

$$R(t) = C \pm S \ln(t) \tag{1}$$

where C is some constant and S is the time dependence or viscosity coefficient.

Some experimentally obtained curves have been fitted with a relationship like that in (1). Fig. 5 shows an example of an experimentally obtained voltage response to a current step of 2.5 mA for a bilinear Co/Cu film. Shown are the absolute voltage and the normalized voltage. The curve fits have been made to the absolute voltage responses.

The equation fit in Fig. 5 above is essentially that in (1). It fits this particular curve well but other data gave a poorer fit. Fitting this form of equation to field cycled experimental curves is not straightforward but it does give a more sensible value for the initial time constants. However if a term allowing for a heating transient is included all data obtained could be fitted. This did not necessarily give physically meaningful values for the fitting constants and further work is required to produce more realistic expressions.

IV. Conclusion

It has been found that on the application of a current step to the Co/Cu multilayer films used in this study the absolute voltage measured across the films drops after field cycling to saturation. This is the case even when a current is already flowing through sample. The normalized voltage response shows that there is a pronounced viscosity effect to these current steps in samples before field cycling. The magnitude of the effect was observed to be dependent on the film structure and in particular the nature of the inter-layer coupling. As these measurements were made at a constant temperature it is postulated that this viscosity is magnetic in origin, as the applied magnetic field is the only parameter being varied.

The voltage response to the current step before field cycling follows a $\ln(t)$ type behavior. However on field cycling to gradually higher fields the voltage response to a current step loses the $\ln(t)$ type response. Curve fitting has been carried out in an attempt to describe the behavior of the voltage due to the current step even after field cycling by inclusion of an exponential term to account for any heating transient effects in the films due to the current step. This has been met with some success. Work is in progress to obtain information on the energy barrier distribution that describes the physical processes that occur in the films on application of a current step and to study the changes in magnetization occurring after the application of a current step.

References

[1] R. J. Pollard, M. J. Wilson, and P. J. Grundy, *J. Magn. Magn. Mater.*, vol. 148, p. L375, 1995.
[2] R. Mattheis *et al.*, *J. Magn. Magn. Mater.*, vol. 121, p. 242, 1993.
[3] C. H. Marrows, R. Lolee, and B. J. Hickey, *J. Magn. Magn. Mater.*, vol. 184, p. 37, 1998.
[4] N. T. Holliday and E. W. Hill, *Sensors and Actuators A: Physical.*, vol. A81, p. 385, 2000.
[5] R. Street and J. C. Woolley, *Proc. Phys. Soc A*, vol. 62, p. 562, 1949.
[6] M. El-Hilo, K. O'Grady, and R. W. Chantrell, *J. Magn. Magn. Mater.*, vol. 109, p. L164, 1992.