High Current Density Measurements of Giant Magnetoresistive Spin-Valves for Magnetic Recording and Sensor Applications

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***Abstract*—High current density measurements on giant magnetoresistive NiFe-Cu-NiFe-FeMn spin-valve devices are presented. The spin-valve magnetoresistive response, ΔR/R, is highly temperature dependent; at temperatures near the blocking temperature there is a considerable reduction of pinning field and decrease in device response. It is desirable to measure certain high current density effects such as electromigration and self-field effects separately from the effects of ohmic heating. For this purpose, we introduce pulsed current techniques necessary to reduce ohmic heating in wafer-level device measurements and we deduce a required pulse width of 15 ns to minimize device heating.**

I. Introduction

Giant magnetoresistive (GMR) spin-valve devices have recently been engineered for use as sensors in magnetic recording heads [1]. These devices have the pinning fields and applied fields perpendicular to the air bearing surface of the device. The free layer, initialized in an orthogonal, medium resistance state, rotates from an antiparallel (high resistance) state to a parallel (low resistance) state with the application of a reasonably small, ±1.6 kA/m (±20 Oe), applied field.

To achieve the largest ΔR/R and highest signal-to-noise ratio, it is necessary to operate these devices at relatively high current densities (10^7 A/cm^2 to 5×10^7 A/cm^2). Several effects arise from the application of high current densities to these structures, including electromigration, self-field effects, sample annealing and thermal diffusion between layers due to the temperature rise from ohmic heating [2].

In this paper we present data showing how GMR response as a function of applied field varies with current density, device size and temperature. We introduce a pulsed-current technique which can be used to isolate and measure the electromigration and self-field effects separately from thermal effects.

II. Sample Fabrication

The samples were fabricated by sputtering Ta(5 nm)/NiFe(7.5 nm)/Cu(3.5 nm)/NiFe(7.5 nm)/FeMn(10 nm)/Ta (5 nm) onto a silicon substrate precoated with Al_2O_3(200 nm). The NiFe layers were deposited in field to give an easy axis with H_k ~0.4 kA/m (5 Oe) perpendicular to the long dimension of the device. Patterning of the devices was accomplished using optical lithography and ion beam etching. Au contact pads were then deposited using a lift off process. The wafer level magnetoresistive response was typically 2 to 3%.

III. Experiment and Results

A. DC measurements

High current density measurements were made on spin-valve devices with stripe heights of 2 μm, 8 μm, and 16 μm as a function of current density. Measurements were made with current densities up to 2.9×10^7 A/cm^2. We define current density in an average sense, dividing the device current by the product of the stripe height and the total device thickness (which includes the two tantalum layers). The track width (separation between Au contacts) was equal to half the stripe height for all devices. Here we present results of DC measurements at current densities approximately 20% below the point where irreversible changes occur in the device saturation resistance and the devices enter a thermal runaway condition and melt open.

The magnetoresistive response of an 8 μm device at current

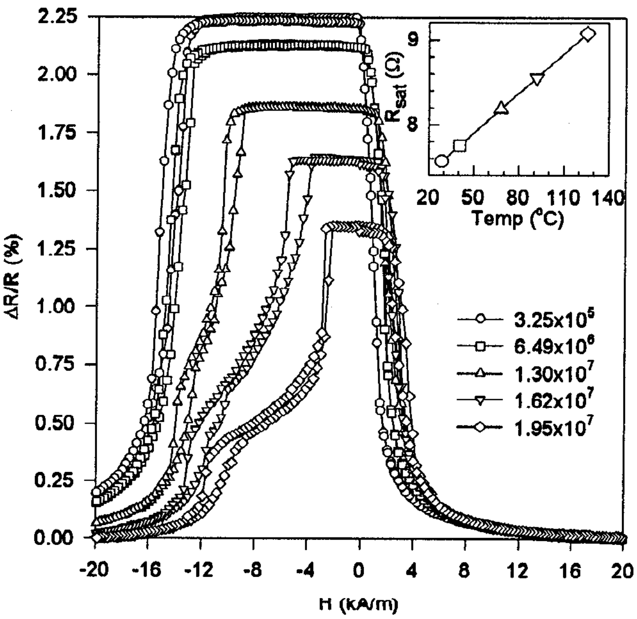

Fig. 1. Magnetoresistive response of an 8 μm high device at current densities of 3.25×10^5 A/cm^2 to 1.95×10^7 A/cm^2. The device shows a decrease in ΔR/R and pinning field as the current density is increased due to ohmic heating. Self-field effect is evident due to high currents generating fields within the device.

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densities of 3.25×10^5 to 1.95×10^7 A/cm^2 is shown in Fig. 1. The measurement uncertainty for data presented are: temperature ±5%; magnetic field ±2%; resistance ±1%; and current density ±2%. The device shows a decrease in ΔR/R and pinning field due to ohmic heating as the current density is increased. The decrease in ΔR/R is due to a decrease in ΔR accompanied by an increase in R. Additionally, there is an increase in the maximum sensitivity bias point (the point of maximum slope in the free layer switching response) due to self-field effects. The inset of Fig. 1 shows the temperature of the device which is inferred from its positive-field saturation resistance. This saturation resistance is used in a linear fit equation derived from the data shown in Fig. 2 to calculate the average device temperature. Fig. 2 shows the GMR response of an 8 μm device measured at low (less than 10^6 A/cm^2) current densities, from 35 °C to 207 °C. The inset of Fig. 2 shows the data used to derive the linear fit parameters.

The GMR response versus temperature shows that high enough temperatures can cause loss of ΔR/R and pinning field. If, however, we apply a constant 20 kA/m (250 Oe) field, heat the device to about 200 °C, then field-cool the device, the ΔR/R reduction and most of the pinning field can be restored, as shown in Fig. 3.

Fig. 4 shows the response of a 16 μm device measured at current densities from 3.25×10^5 A/cm^2 to 1.79×10^7 A/cm^2. The 16 μm device shows properties similar to the 8 μm device. The inset of Fig. 4 shows the device positive saturation resistance as a function of its temperature as derived from measurements made on the 8 μm device shown in the inset of Fig. 2.

The magnetoresistive response of a 2 μm device at current densities of 6.49×10^5 A/cm^2 to 2.86×10^7 A/cm^2 is shown in Fig. 5. The device is noisier than the 8 μm and 16 μm devices and the pinning field is less well defined but the self field change in maximum sensitivity bias point and reduction in ΔR/R and pinning field are clearly evident.

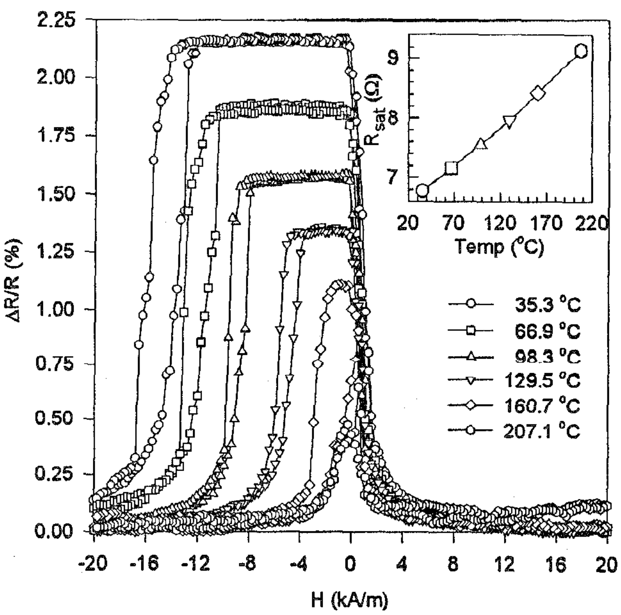

Fig. 2. Magnetoresistive response of an 8 μm device, measured at low current densities (< 10^6 A/cm^2), over a temperature range from 35 °C to 207 °C. The device shows a decrease in ΔR/R and pinning field as the temperature increases.

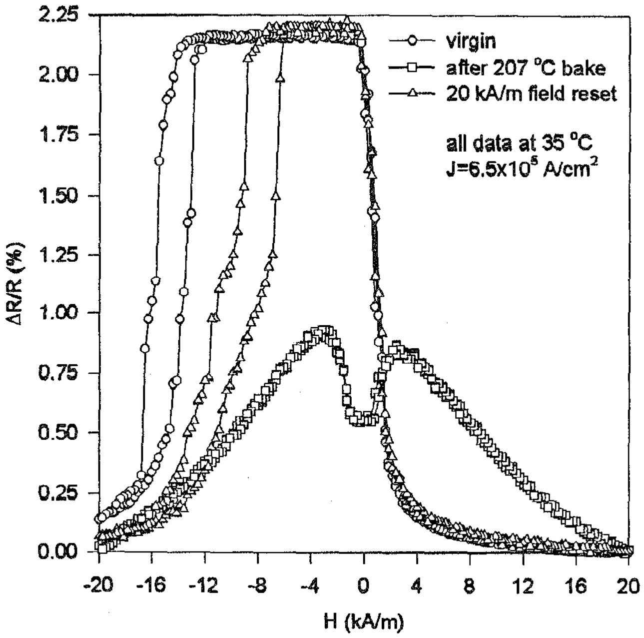

Fig. 3. Magnetoresistive response of an 8 μm device showing the ability to reset pinning field with 20 kA/m field cooling from about 200 °C. This indicates irreversibility is due to annealing and not electromigration.

B. Pulsed measurements

In order to separate current density effects (electromigration, self-field) from the effects of ohmic heating, we used a pulsed current technique to measure the GMR response of the above suite of device sizes. The measurement is the same as before, except that the device current is applied in 80 ns pulses (at about a 20 Hz repetition rate) rather than continuously, and the device voltage and current are measured with a fast digitizing oscilloscope (instead of using a current source and voltmeter).

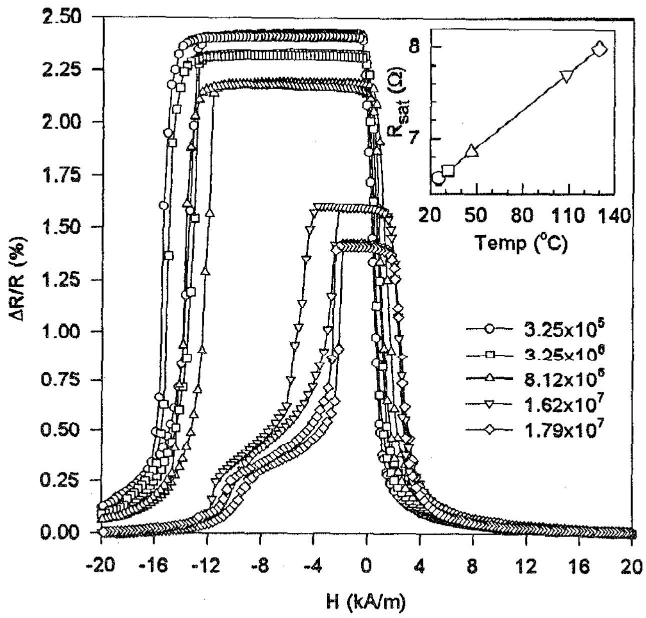

Fig. 4. Magnetoresistive response of a 16 μm device at current densities of 3.25×10^5 A/cm^2 to 1.79×10^7 A/cm^2.

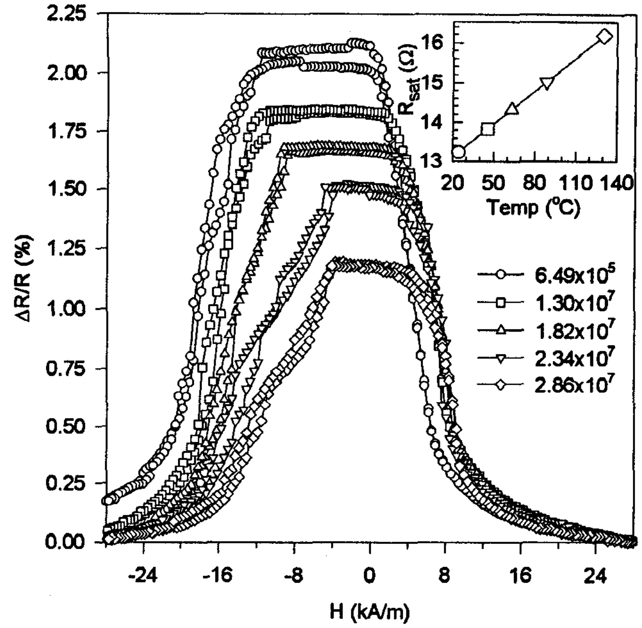

Fig. 5. Magnetoresistive response of a 2 μm device at current densities of 6.49×10^5 A/cm^2 to 2.86×10^7 A/cm^2.

Fig. 6 shows the combination of three measurements on 8 μm high samples. First, the DC response at 129.5 °C shows pinning field reduction and loss of ΔR/R to 1.35% (note that there is no self field effect at low current densities). Second, the DC response at 1.95×10^7 A/cm^2 (which ohmically heats to the same average temperature as (a)) shows pinning field reduction and loss of ΔR/R to 1.35% (note large self field effect). Third, the device response at an 80 ns pulse current of 1.95×10^7 A/cm^2 shows significantly less heating and less ΔR/R and pinning field loss. The positive saturation-resistance-inferred temperature is 70 °C less than that of the other two measurements and the ΔR/R is reduced to only 1.9% (from the original ΔR/R value at low current density of 2.25%). The device saturation-resistance-inferred temperature is not, in this experiment, reduced to near room temperature as would be required for an unambiguous electromigration measurement.

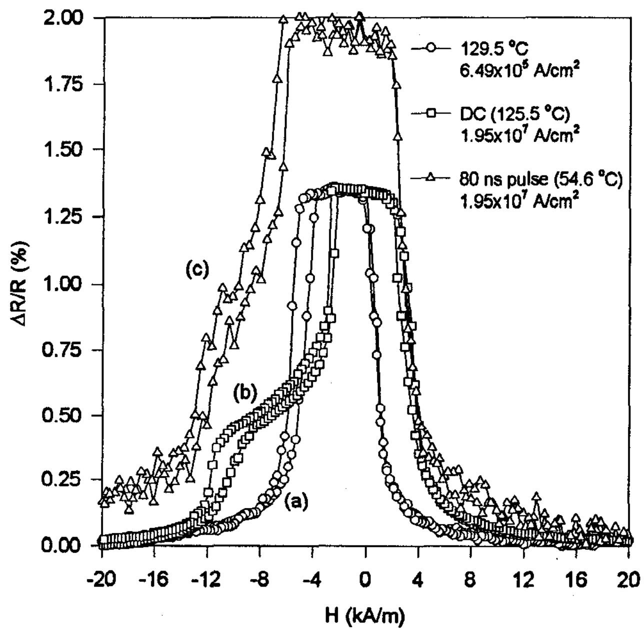

Fig. 6. Magnetoresistive device response (a) at 129.5 °C (low current) showing pinning field reduction and loss of ΔR/R to 1.35%, (b) at 1.95×10^7 A/cm^2 (DC) showing pinning field reduction and loss of ΔR/R to 1.35%, and (c) at an 80 ns pulse current of 1.95×10^7 A/cm^2 showing significantly less heating and less ΔR/R and pinning field loss.

The thermal properties of GMR devices engineered for magnetic recording applications depend greatly on how heat sinking of these devices is accomplished. The wafer-level devices used in this study are fabricated on 200 nm of Al_2O_3 on a Si substrate whereas typical read heads are normally sandwiched between ~100 nm thick Al_2O_3 films with significant heat sinking to the shields. It could nonetheless be necessary to characterize high current density effects, specifically electromigration, in wafer-level device structures. However, at these high current densities, ohmic heating will alter the GMR response in wafer-level devices due to thermal annealing and diffusion before electromigration is observed.

To completely separate thermal effects from electromigration, the pulse current must be faster than the device's ability to thermally respond. The thermal time constant of these devices can be deduced by making pulsed measurements as a function of pulse width. Measurements at 1.95×10^7 A/cm^2 made on the 8 μm device with pulse widths from 80 ns to 700 ns followed a simple exponential which yielded a time constant of approximately 165 ns. Extrapolating this exponential backward indicates that the pulse width must be less than 15 ns to limit device heating to less than 10 °C.

IV. Conclusions

We measured the magnetoresistive response of GMR spin-valve devices as a function of temperature, current density, and device size. The response suffers significantly from exposure to high temperatures, regardless of the cause. The pulse current measurement method can significantly reduce temperature rise at high current densities. To keep the temperature rise below 10 °C above room temperature, the pulse width must be sub-15 ns for these devices. To propagate these short pulses it is necessary to adapt microwave probing techniques, i.e. fabricating devices in a transmission-line structure (microstrip or coplanar waveguide). It should be noted that a sample which is better thermally anchored to the substrate (and thus has a longer thermal time constant) would allow use of the existing apparatus.

References

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[2] R. W. Cross, S. E. Russek, S. C. Sanders, M. R. Parker, J. A. Barnard, and S. A. Hossain, "Size and Self-Field Effects in Giant Magnetoresistive Thin-Film Devices," *IEEE Trans. Mag.*, vol. 30, pp. 3825-3827, November 1994.