FABRICATION OF MICROMECHANICALLY-MODULATED MGO MAGNETIC TUNNEL JUNCTION SENSORS

Gerardo Jaramillo, Mei Lin Chan, André Guedes, David A. Horsley
University of California, Davis, USA

ABSTRACT

We have developed a hybrid magnetoresistive (MR)-MEMS sensor based on the monolithic integration of magnetic thin films and SOI MEMS fabrication techniques. MgO magnetic tunnel junctions (MTJ) on bulk micromachined silicon structures form a hybrid sensing platform in which the MEMS structure is used to mechanically modulate the magnetic field signal detected by the MTJ. We demonstrate the modulation of DC magnetic field through the mechanical motion of the cantilever at resonance. This allows for the improved detection of small DC or low frequency magnetic signals modulated into the high frequency region where the $1/f$ noise is lower.

INTRODUCTION

MTJ's are highly sensitive magnetic field devices used in a large spectrum of different applications, such as in hard disk drives and in the new generation of non-volatile memories known as MRAM. More recently MTJ sensors have been tested for sensing low magnetic fields [1]. The main challenge for making them suitable for this application is to reduce the noise affecting them, mainly in the low-frequency region which is dominated by $1/f$ noise. The noise in a MTJ sensor is given by a sum of frequency dependent ($1/f$ noise) and independent (thermal and shot noise) contributions. It can be expressed by:

$$S_V = S_{1/f} + S_{thermal+shot}$$

$$S_V = \alpha \frac{I^2 R^2}{Af} + 2eIR^2 \coth\left(\frac{eV}{2k_B T}\right) \qquad (1)$$

where α is the $1/f$ parameter, I, R, A and V the MTJ biasing current, resistance, area and output voltage respectively, f the frequency, e the electron charge, k_B the Boltzmann constant and T the temperature.

Here, we demonstrate modulation of DC magnetic fields using a mechanical carrier at a higher frequency (> 10 kHz), which can improve the MTJ signal-to-noise ratio by transforming the operating frequency to the high frequency range where $1/f$ noise is minimal. If successful, chip-scale MR sensors with picoTesla sensitivity may be possible. In the devices described here, the MR element is integrated on the surface of a moving micromechanical device. Similar work has demonstrated field modulation using moving micromechanical flux guides adjacent to fixed MR elements using either flip chip bonding [2] or on-chip integration [3].

FABRICATION

A SOI wafer passivated with a 600 nm layer of thermal oxide is used as the base substrate on which the MTJ sensors are first fabricated through a series of metal and dielectric depositions, ion milling and liftoff processes (Micro Magnetics Inc.) [4]. Subsequently, MEMS fabrication begins with backside lithography to pattern an opening beneath each actuator (see Figure 1). A DRIE step is used to remove the handle-wafer (500 µm) silicon, after which the 1 µm buried oxide is removed using RIE. The MEMS actuator structure is then lithographically patterned on the device layer. A three step RIE process is carried out to remove the three oxide layers (evaporated SiO_x, MgO and thermal SiO_2) above the device silicon using CF_4 (for SiO_x) and Cl chemistry (for MgO). The final DRIE step defines and dry releases the 40 µm thick MEMS structure.

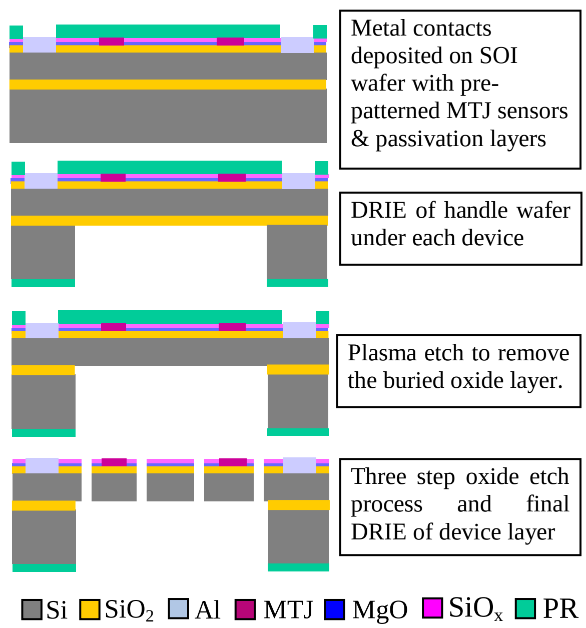

Figure 1: *Simplified fabrication process flow.*

To confirm that MEMS processing did not damage the MTJ sensors, we investigated the effect of RIE (1800 W source power and 20 W DC bias, 10 min etch time) on the MR response of the MTJ, with a thick (>3 µm) photoresist (KMPR 1005, Microchem Inc.) protecting the MTJ during the RIE step. Measurement of the device resistance as a function of magnetic field before and after etching shows no observable changes in the MR ratio (~33%), indicating that the large DC bias in the plasma processing step does not affect the sensors' integrity. An alternative release process using HF vapor etching was also investigated, where a two minute exposure to HF vapor was found to cause degradation in the MTJ multilayer stack.

RESULTS AND DISCUSSION

MTJ characterization

The MTJ sensors are composed of two magnetic layers separated by a dielectric tunneling barrier: a free magnetic layer and a pinned magnetic layer which is magnetized along the z-axis, parallel to the length of the cantilever. The sensor resistance is minimized when the magnetizations are in the parallel state and is maximized when they are in the antiparallel state. An external bias field oriented along the y-axis, orthogonal to the sensitive z-axis, is used to rotate the free layer magnetization to an intermediate angle, thereby linearizing the sensor's response to z-axis field.

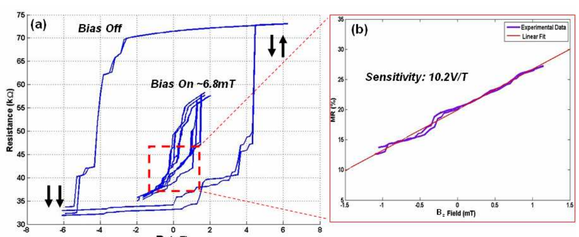

Figure 2: *(a) MR transfer characteristic of the MTJ sensor obtained at a 100 mV bias voltage, measured with and without an orthogonal bias field. A bias field of ~6.8 mT reduces the hysteresis and puts the sensor in a linear regime across small range of applied field. (b) Linear region of the MR transfer curve over a small field range yielding a sensitivity of ~10.2 V/T.*

High resistance prototype MTJs were fabricated with a resistance-area (RA) product in the range of ~500 kΩ-µm^2. The MR transfer characteristic of the MTJ is first characterized using two orthogonal coil pairs, the first of which generates the z-axis sensing field (B_z = ±2 mT) and the second of which generates the orthogonal bias field (B_y = 6.8 mT). The MR transfer curve of a device with a nominal resistance of 40 kΩ is shown in Figure 2, where a 120% change in resistance is observed going from the parallel to antiparallel state without the orthogonal bias field. As the orthogonal bias field is increased to 6.8 mT, the hysteresis loop is reduced and the MTJ is linear within a small field range with a sensitivity of 10.2 V/T.

The MTJ noise spectral density is acquired in a non-shielded environment using a preamplifier (SR560) and a spectrum analyzer (HP 3859A) with and without mechanical actuation of the cantilever. Figure 3 shows the noise spectral density when the MTJ is biased at the center of the transfer curve (bias on state) and when it is saturated (bias off state) both with and without mechanical oscillation of the cantilever structure. The results show that other than a sharp increase at frequency of the first resonance mode, the mechanical motion of the MTJ does not introduce more noise nor change the profile of the noise spectrum of the MTJ sensor.

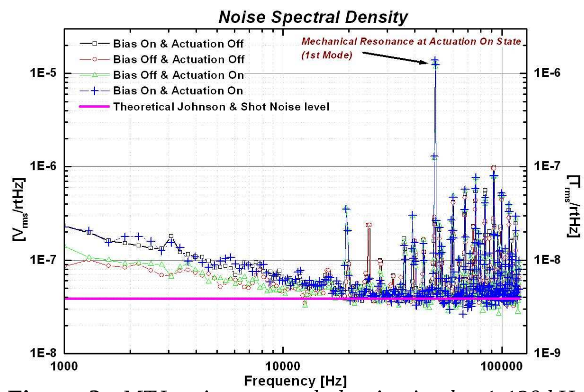

Figure 3: *MTJ noise spectral density in the 1-120 kHz range for a linear (bias on state) and saturated (bias off state) MTJ sensor with a biasing voltage of ~100 mV across the sensor. The noise floor reaches ~4 nT/√Hz at 40 kHz which is around the theoretical Johnson and shot noise limit shown by the solid line.*

Mechanical characterization

Silicon cantilevers with 40 µm thickness, 50 µm width, and varying lengths to achieve first natural frequencies ranging from 22 kHz to 200 kHz (as shown in Table 1) were used as the test structures for demonstrating mechanical modulation of the MTJ sensor. The MTJ element is located at the free end of the cantilever, with the metal film electrical leads running along the whole length of the cantilever to the bond pads, as shown in Figure 4.

Table 1: Summary of the measured cantilever parameters.

Cantilever	1	2	3	4	5
Length [mm]	0.5	0.75	1.0	1.25	1.5
f_n [kHz]	220	87.9	49.7	35.46	22.8
Q-factor (in air)	-	500	813	478	504

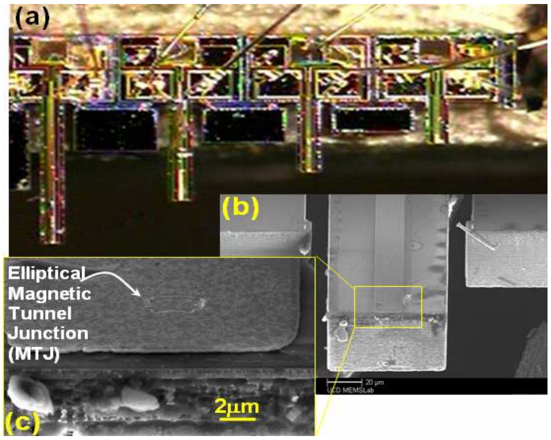

Figure 4: *(a) Optical micrograph of an array of MTJ-MEMS cantilevers, (b) SEM micrograph of the DRIE etched cantilever and (c) zoom in view of the (2x6µm) elliptical magnetic tunnel junction at the cantilever tip.*

The base of the cantilever is excited with a piezoelectric actuator (Thorlabs) achieving a displacement range of ±15 µm at the cantilever tip at a voltage of ±2 V. The frequency response of the tip displacement was measured on each cantilever using a laser Doppler vibrometer (Polytec). The result for a typical 1.0 mm long cantilever is shown in Figure 5.

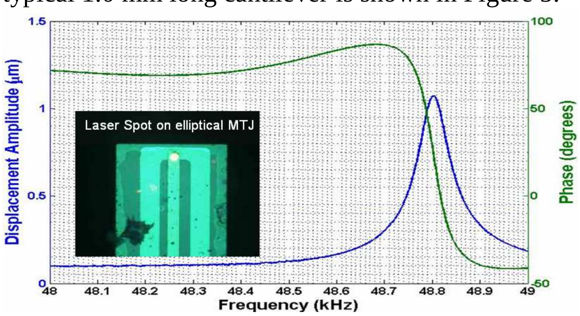

Figure 5: *Experimental frequency response plot of the MTJ-MEMS cantilever structure measured using the LDV. The first natural frequency of the sensor is at 48.8 kHz with a Q of 813. Inset: Optical micrograph of the LDV laser spot on the MTJ sensor located at the free end of the cantilever to capture the actual displacement of the sensor.*

DC field modulation

We measured the modulation of DC magnetic field using a MTJ on the tip of a 1 mm long cantilever as illustrated on Figure 6(a). Measurements were performed with orthogonal bias $B_y = 6.8$ mT. The cantilever is driven at its first resonant mode ($f_n = 49.7$ kHz) with a force of ~4.6 mN resulting in 7.12 µm peak displacement. Figure 6(b) shows a schematic of the angle of the sensitive axis with respect to the applied field vector. The field component along the sensitive axis varies as the cantilever tip angle moves from θ_0 to $\theta_0+\theta_1$. This difference in field results in AC field modulation at twice the vibration frequency (2*f*) as shown in Figure 6(c).

For a cantilever with length *l*, the tip angle θ and displacement *x* are related by $\theta = 4x/3l$. With $x = 7.12$ µm, we obtain $\theta = 9.49\times10^{-3}$ rad. Assuming the resting angle of the cantilever is aligned with the field ($\theta_0 = 0$) and sinusoidal oscillation at the natural frequency of the cantilever $\theta(t) = \theta_1 \sin(2\pi f_n t)$, the relationship between the tip angle and the field along the sensitive axis of the sensor is:

$$B_z(t) = B_{DC}\cos(\theta(t)) \approx B_{DC}(1 - 1/2\,\theta^2(t)) \quad (2)$$

The time varying component of the field is given by:

$$B_{AC}(t) = 1/4\, B_{DC}\,\theta_1^2 \cos(2\pi f_n t) \quad (3)$$

where B_{DC} is the DC applied field in the easy axis of the MTJ at θ_1. Using $B_{DC} = 1.98$ mT, $B_{AC} = 44.58$ nT.

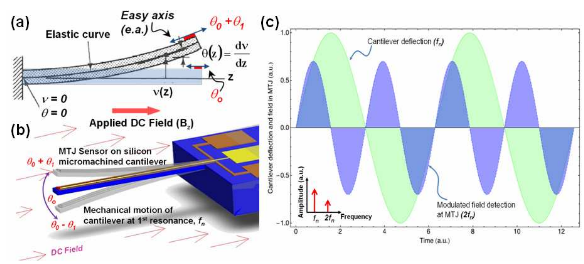

Figure 6: *(a) Euler beam model used to approximate the slope at the end of the beam to account for the change in the easy axis direction from θ_0 to $\theta_0+\theta_1$, (b) Schematic of the experimental setup for mechanical modulation of the MTJ in the presence of a small DC magnetic field. As the cantilever is driven at resonance, f_n, the MTJ easy axis will rotate to the min sensitivity at two locations, and (c) The expected sensor output changing due to the direction of the easy axis detected at $2f_n$.*

In the ideal condition, where θ_0 is aligned with the external magnetic field, field modulation would solely occur at 2*f*. Since the cantilever positioning between the coils is not perfect, the peak-to-peak deflection will not be symmetric along the external applied field direction. This asymmetry leads to an additional 1*f* modulation component superimposed on the capacitive feedthrough at 1*f*. Figure 7 shows the 1*f* and 2*f* field modulation resulting from cantilever motion, using the MTJ sensor to detect the modulated field signal. The field modulation increases at resonance with the displacement of the cantilever, leading to a higher magnetic output across the MTJ.

From Figure 7, we see that the 2*f* modulated field induced a voltage variation across the MTJ of 380 nV (460-80 nV). Considering that the MTJ element has a sensitivity of ~10.2 V/T, this leads to a calculated modulated field of B_{AC} = 38 nT, which agrees well with the theoretical result given by expression (3). The modulation efficiency (η) is defined as the ratio between the modulated AC field and the external applied DC field:

$$\eta = \frac{B_{AC}}{B_{DC}} = \left(\frac{dB}{dx}\right)\frac{\Delta x}{B_{DC}} \qquad (4)$$

The modulation efficiency, η, for the 2*f* modulation is 0.0019 % (38 nT / 1.98 mT).

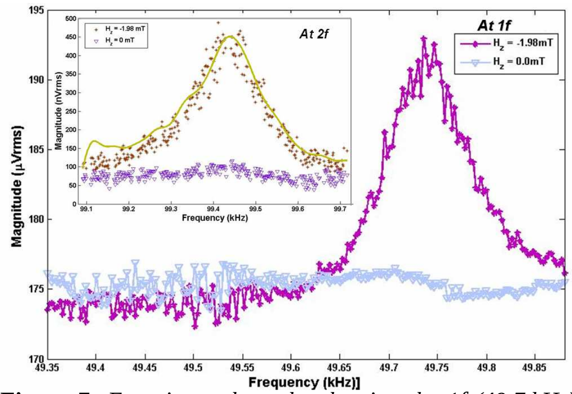

Figure 7: *Experimental results showing the 1f (49.7 kHz) and 2f (99.4 kHz) component measured across the MTJ sensor when in the cantilever is vibrating at resonance with an AC actuation voltage of 2V_{pp} at 49.7 kHz.*

CONCLUSIONS AND FUTURE WORK

Using a MTJ-MEMS device we were able to generate high frequency AC fields by mechanically modulating an external applied DC field. This technique was successfully used to detect the MEMS cantilever resonance using the MTJ as sensing device. The main drawback and future challenge of this hybrid device is the low modulation efficiency, calculated as 0.0019 %. As mentioned before, the 2*f* magnetic modulation efficiency of the device is proportional to the small angle θ created between the MTJ easy axis and the external magnetic lines during deflection, resulting in equally small modulation efficiency. In order to improve the efficiency, work is being done to integrate a thin film magnetic flux guide with thickness less than the peak to peak deflection of the cantilever and located close to the cantilever (see Figure 8). The diverging magnetic flux lines coming out of the flux guide create a localized field gradient that can largely improve modulation efficiency, η. Figure 8 shows the magnetic simulations reflecting the predicted modulation efficiency as a function of the cantilever peak-to-peak deflection and the distance *D* between the MTJ sensor and the flux guide.

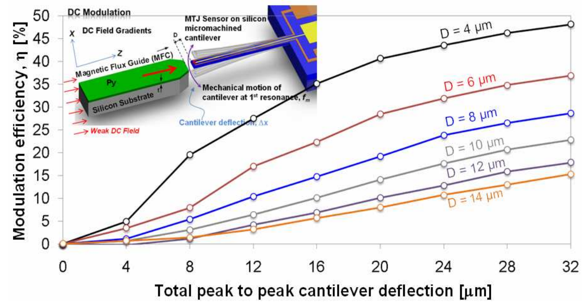

Figure 8: *The modeled modulation efficiency parameter,η showing a high sensitivity to the separation between the MTJ and flux guide, D. Inset: Schematic of the improved experimental setup using a magnetic flux guide to amplify the DC applied field and create field gradients along the edge of the flux guide.*

ACKNOWLEDGEMENT

This work is supported in part by the National Science Foundation (ECCS-0601383) and by the Materials Design Institute at UC Davis which is funded by the Los Alamos National Laboratory/UC Davis Educational Collaborative (Subcontract No. 2511-002-06). The authors would like to thank the support of Dr. Jack Skinner, Micro Magnetics Inc. and the UC Davis Nanofabrication Center.

REFERENCES

[1] R.C. Chaves, P.P. Freitas, B. Ocker and W. Maass, "Low frequency picotesla field detection using hybrid MgO based tunnel sensors," *Appl. Phys. Lett.*, vol. 91, pp. 102504-3, 2007.
[2] A.S. Edelstein, G.A. Fisher, M. Pedersen, E.R. Nowak and S.F. Cheng, "Progress toward a thousandfold reduction in 1/f noise in magnetic sensors using an ac microelectromechanical system flux concentrator (invited)," *J. Appl. Phys.*, vol. 99, 2006.
[3] A. Guedes, S.B. Patil, S. Cardoso, V. Chu, J.P. Conde and P.P. Freitas, "Hybrid magnetoresistive/ microelectromechanical devices for static field modulation and sensor 1/f noise cancellation.", *J. Appl. Phys.*, vol. 103, pp. 07E924, 2008.
[4] W.J. Gallagher, S.S.P. Parkin, Y. Lu, X.P. Bian, A. Marley, K.P. Roche, R.A. Altman, S.A. Rishton, C. Jahnes, T.M. Shaw and G. Xiao "Microstructured magnetic tunnel junctions" *J. Appl. Phys.*, vol. 81, pp. 3741-3746, 1997.