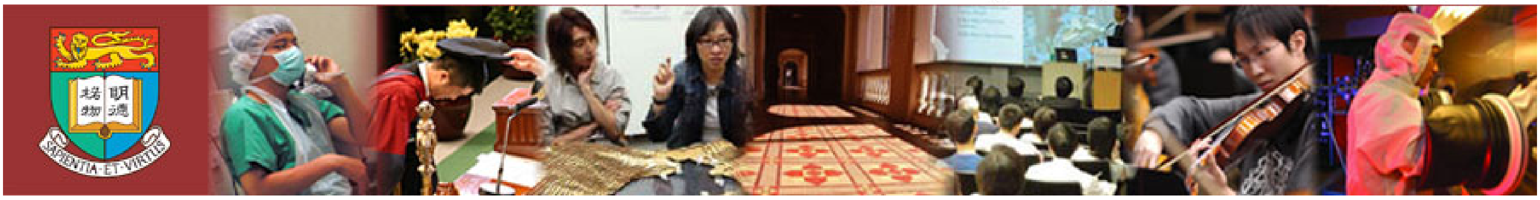

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Magnetic Tunnel Junction Sensors With Conetic Alloy

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Al_2O_3 magnetic tunneling junction (MTJ) sensors were fabricated with Conetic alloy $Ni_{77}Fe_{14}Cu_5Mo_4$ deposited as the free layer and pinned layer for its soft magnetic properties. It was observed that the Al_2O_3 MTJ sensors with Conetic exhibited relatively small easy-axis coercivity. Tunneling magnetoresistance (TMR) and noise measurements were carried out to characterize the sensors. TMR of 9.5% and Hooge parameter of 3.825×10^{-7} μm^2 were achieved without any hard-axis field. Hard-axis bias field was applied to eliminate the hysteresis and improve the linear field response of the MTJ sensor. The hysteresis was removed by applying an external magnetic field along the hard axis at 8 Oe and the sensor sensitivity was 0.4 %/Oe within a linear region at room temperature. The relationship between the Hooge parameter and hard-axis field was also investigated and the result demonstrated that the 1/f noise can be suppressed by an optimized hard-axis bias field. This work shows that it is feasible to use Conetic alloy as the soft magnetic layers in MTJ sensors for its small coercivity, and a hard-axis bias field can be used to linearize the sensor response and suppress the 1/f noise.

Index Terms—**1/f Noise, Conetic, hard-axis bias field, magnetic sensor, magnetic tunnel junction (MTJ).**

I. Introduction

MAGNETIC TUNNEL JUNCTIONS (MTJs) have drawn tremendous attentions for their applications in magnetic field sensors [1], hard disk drive (HDD) read heads [2], and magnetic random access memory (MRAM) [3], [4] due to their high tunneling magnetoresistance (TMR), low cost, and high sensitivity. MTJs with 1000% TMR [5] were theoretically predicted and 604% TMR [6] were experimentally demonstrated at room temperature. Thus MTJs are regarded as a promising candidate for ultra-low magnetic field detection.

However, hysteresis-free and linear field responses are needed for practical sensor applications and much effort has been paid for obtaining MTJs with small coercivity [7]–[12]. Previous work utilizing Conetic alloy exhibited large TMR and small saturation fields [12]. The Conetic alloy is the soft magnetic material NiFeCuMo of mu-metal family. They possess relatively small easy-axis coercivity ($H_{\rm EC} \sim 10^{-1}$Oe) and large hard-axis magnetic susceptibility ($\chi \sim 10^4 - 10^5$) in both single-film and synthetic antiferromagnet (SAF) multilayer configurations [11], [13]. These magnetic properties of Conetic thin films are close to those of the corresponding bulk material [14]. Hence, Conetic alloy is a competent alternative magnetic thin film of MTJ stacks for ultra-low magnetic field detection.

Another limiting factor of MTJ sensitivity is intrinsic noise problem, especially in the low-frequency regime. It is because the ultimate detectivity of a sensor is determined by the noise floor at the operating point. The dominant noise source in MTJs is $1/f$ noise in the low-frequency regime which can be parameterized by the Hooge parameter [15]

$$\alpha = A\frac{f \cdot S}{V_j^2} \tag{1}$$

where A is the junction area, f is the frequency, S is the voltage power of $1/f$ noise, and V_j is the voltage across the junction. The $1/f$ noise was reported to originate from both electrical mechanism (charge trapping of electrons in the tunneling barriers) and magnetic mechanism (magnetization fluctuations in the magnetic layers), and it deteriorates the sensitivity of MTJs in low-frequency sensing applications [16]–[21]. Therefore, in order to realize ultrasensitive magnetic field sensors, the MTJs must possess large TMR, low saturation field, low noise, and linear response [22].

In this work, Conetic was deposited as the magnetic free layer and the pinned layer of the MTJs for its soft magnetic properties and small coercivity. Both TMR and noise measurements were carried out. Hard-axis bias field was used to eliminate hysteresis and obtain linear-field response. The relationship between the Hooge parameter and hard-axis bias field was also investigated.

II. Experiment

The MTJ stack structure was substrate/ $Ni_{77}Fe_{14}Cu_5Mo_4$ 200/ $Co_{50}Fe_{50}$ 10 / Al 10, plasma oxidation, $O_2 = 10^{-3}$ Torr, / $Co_{50}Fe_{50}$ 10/ $Ni_{77}Fe_{14}Cu_5Mo_4$ 25/ Co $_{50}Fe_{50}$5/ $Ir_{20}Mn_{80}$ 100/ Ru 70 (units in angstrom), as shown in Fig. 1(a). The thin films were deposited by dc magnetron sputtering on thermally oxidized silicon wafers in an ultra-high vacuum chamber with a base pressure of 2×10^{-10} Torr. The Al_2O_3 barrier layer was made by first depositing Al metal and then oxidizing it in oxygen plasma. The sample was annealed at 200°C for 15 min. The junctions were fabricated by self-aligned UV photolithography and etching processes with the junction area of 20×20 μm^2. Four-probe electrical measurement was performed with 50 μA dc current. Two pairs of Helmholtz coils, one along the easy-axis and another along the hard-axis, were used to provide magnetic field ranging from -200 Oe to $+200$ Oe. The noise measurement was carried out in a Wheatstone bridge configuration to reduce the effect of thermal drift and dc offset. The Helmholtz coils and bridge circuit are shielded in a mu-metal shielding box. A low-noise low-frequency instrumentation preamplifier (FEMTO DLPVA-100-BLN-S) with a gain of 40 dB is equipped to amplify the output signal from the bridge

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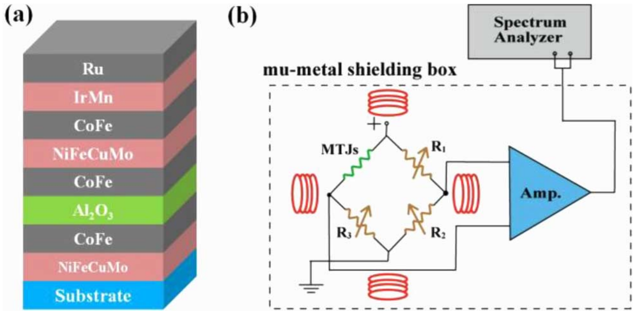

Fig. 1. (a) Schematic drawings of MTJ structure: substrate/ $Ni_{77}Fe_{14}Cu_5Mo_4$ 200/ $Co_{50}Fe_{50}$ 10 / Al 10 (oxidized) / $Co_{50}Fe_{50}$ 10/ $Ni_{77}Fe_{14}Cu_5Mo_4$ 25/ $Co_{50}Fe_{50}$ 5/ $Ir_{20}Mn_{80}$ 100/ Ru 70 (units in angstrom). (b) Diagram of noise measurement setup in a Wheatstone bridge configuration. The MTJ is mounted in one leg of the bridge. R_1, R_2 and R_3 are variable resistors. Two pairs of Helmholtz coils are along the easy- and hard- axis respectively. The setup is shielded in a mu-metal shielding box (dashed rectangle). The low-noise amplifier is employed to amplify the output signal to the spectrum analyzer.

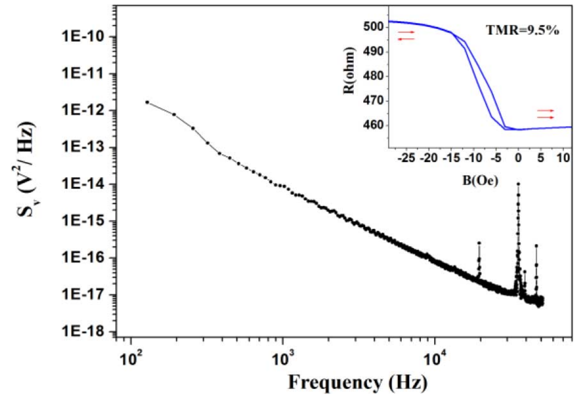

Fig. 2. Noise power spectrum of the MTJs without any hard-axis bias field. The Hooge parameter is 3.825×10^{-7} μ m^2 calculated by (1). The inset is the MR loop. The MTJ exhibited TMR of 9.5% in absence of hard-axis bias field.

circuit. The schematic diagram of the noise measuring circuit is shown in Fig. 1(b). Noise power spectrum of the sample was detected by a dual-channel spectrum analyzer (Stanford Research SR785) with cross-correlation mode to effectively reduce the background noise floor of the measuring system. All the measurements were performed at room temperature.

III. Result And Discussion

Fig. 2 shows the TMR and noise measurement results with an external magnetic field applied along the easy-axis in absence of any hard-axis bias field. The TMR ratio is 9.5% and the value of α is $3.825 \times 10^{-7} \mu m^2$ calculated by (1). The easy-axis coercivity is ~3 Oe. A hard axis bias field was subsequently applied to remove the hysteresis. The influence of the hard-axis bias field on the TMR transfer curves is presented in Fig. 3. As the hard-axis bias field increased from 2 Oe to 20 Oe, the hysteresis reduced and it was eliminated at 8 Oe. The sensitivity of the MTJ sensor under this configuration was found to be 0.4%/Oe from the slope of the transfer curve at low field. Further increase of the hard-axis bias field from 8 Oe to 20 Oe made the slope of the transfer curve less steep and thus reduced the sensor sensitivity. The elimination of hysteresis can be interpreted by Stoner-Wohlfarth (SW) model [23].

Our results are compared with some previous works on Al_2O_3 MTJs without Conetic alloy. Tondra *et al.* [1] showed MTJs with 20% TMR ratio and they used 20 Oe hard-axis field to reduce the hysteresis of the MR curve. Liu *et al.* [9] achieved MTJs with 35% TMR ratio and applied less than 10 Oe hard-axis field to eliminate the hysteresis. Nowak *et al.* [16] reported MTJs with 35% TMR and Hooge parameter of 10^{-7}–10^{-6} μm^2. Nor *et al.* [18] obtained MTJs with 19.5% TMR and Hooge parameter of 10^{-6}–10^{-5} μm^2. Compared with these results, although the Al_2O_3 MTJ sensors with Conetic alloy have small TMR ratios, they exhibit relatively small coercivity (hysteresis was removed with only 8 Oe hard-axis field) while retaining a moderate α for the $1/f$ noise. This indicates that Conetic alloy is effective for reducing the magnetostriction constant and magnetocrystalline anisotropy while retaining a moderate noise level. However, more work should be done in the future to enhance the TMR ratio for improving the MTJ sensor performance.

After the eradication of hysteresis in the MTJs, noise measurement was performed over a range of hard-axis bias field. Fig. 4 shows the measurement results of the Hooge parameter versus the hard-axis field. Below 60 Oe, the Hooge parameter decreases with the hard-axis bias field and it decreases to $3.567 \times 10^{-7} \mu m^2$ at 60 Oe. This indicates the $1/f$ noise has a magnetic-field dependent component and it can be reduced by applying hard-axis field. The decline of magnetic $1/f$ noise was attributed to the reduction of thermally magnetic fluctuations provoked by hopping of domain walls in the metastable free layer of MTJs [20], [21], [24], [25]. When the hard-axis field is applied, the domains of the free layer start to be aligned and they overcome the thermal energy to avoid the thermally induced hopping response. With the increase of the hard-axis biasing field, the number of aligned magnetization domains increases. At 60 Oe, the Hooge parameter reached a minimum value. In order to confirm that the decline of the Hooge parameter was resulted from the magnetic $1/f$ noise rather than the frequency-independent thermal magnetic noise, we carried out an analysis on the MTJ noise power based on the theoretical model published previously [22]. The calculation result shows that the noise power of thermal magnetic noise is around two orders of magnitude smaller than the magnetic $1/f$ noise and around three orders of magnitude smaller than the electronic $1/f$ noise at low-frequency regime. As such, when evaluating the Hooge parameter of our samples, the thermal magnetic noise was negligible compared with magnetic $1/f$ noise and electronic $1/f$ noise. Therefore, the decline of Hooge parameter below 60 Oe was most likely associated with the reduction of magnetic $1/f$ noise. Beyond 60 Oe, the Hooge parameter slowly increases as we can see from the right of the dash line in Fig. 4. This increase may be due to the magnetization rotation of the pinned layer of MTJs. Due to the large hard-axis bias field, the magnetization of the pinned layer changes slightly from its original pinned direction towards the hard axis. This leads to the change of the angle between the magnetization directions of the pinned layer and the free layer, resulting in a reduction of junction resistance. As such, the voltage across

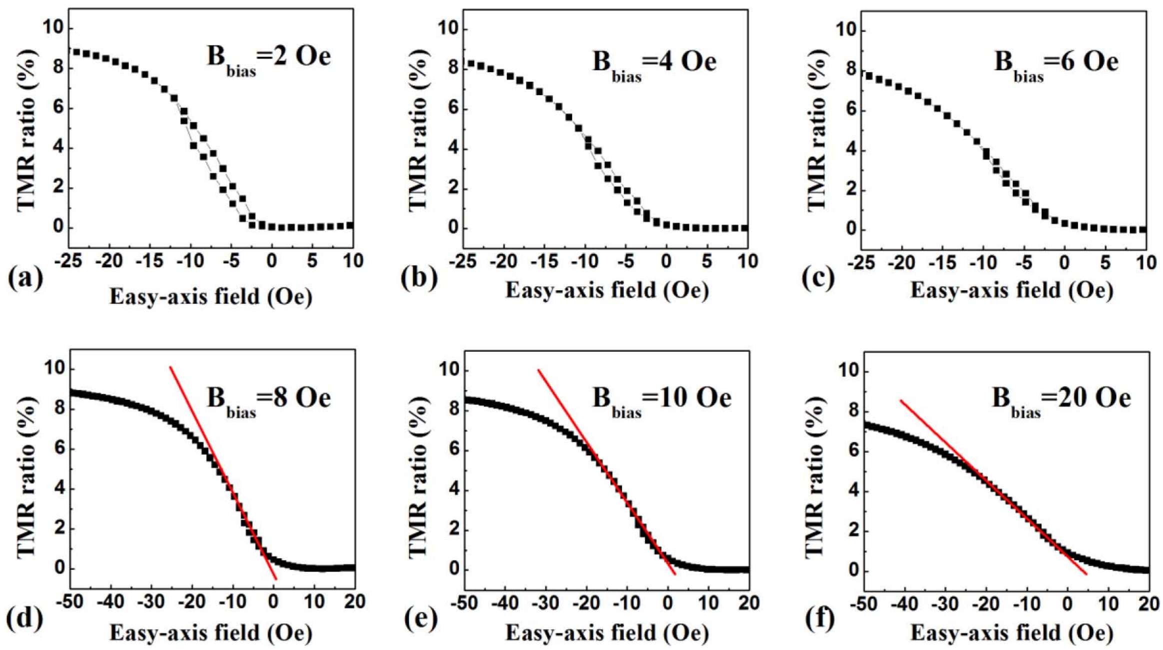

Fig. 3. TMR loops of MTJs with different biasing fields along the hard-axis. From (a), (b), and (c), we can see the hysteresis reduced with the hard-axis bias field. (d) The hysteresis is removed at 8 Oe of hard-axis bias field and the sensor sensitivity is 0.4%/Oe. (e) and (f) show that further increase of hard-axis bias field reduces TMR and the slope of the linear region.

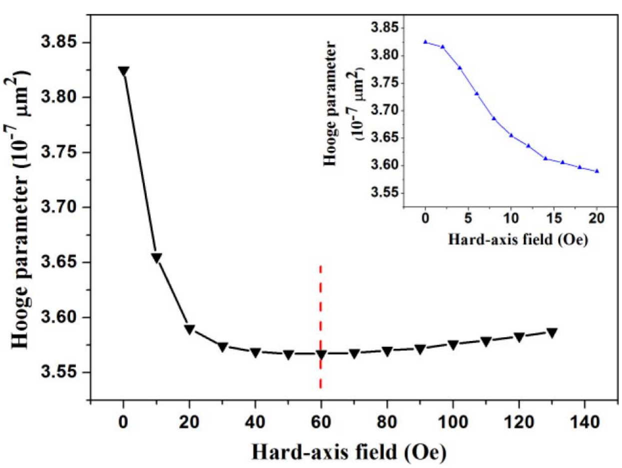

Fig. 4. Hooge parameter measurements at different hard-axis bias fields from 0 Oe to 130 Oe. The dash line is a guide for eyes. On the left of the dash line, the Hooge parameter decreases with the hard-axis field down to 3.567×10^{-7} μm^2 at the hard-axis bias field of 60 Oe. On the right of the dash line, the Hooge parameter increases with the hard-axis bias field up to 3.587×10^{-7} μm^2 at the hard-axis bias field of 130 Oe. The sharp decrease of the Hooge parameter from 0 Oe to 20 Oe of hard-axis bias field is elaborated with more detailed noise measurement in this range of hard-axis bias field as shown in the inset.

the junction decreases. Subsequently, the Hooge parameter increases with the decrease of junction voltage according to (1). These results are significant for MTJ sensing applications because it indicates that an optimized hard-axis bias field must be used in order to minimize the $1/f$ noise.

IV. Conclusion

We fabricated Al_2O_3 MTJs with Conetic alloy as the magnetic layers due to its soft magnetic properties. The MTJs exhibited TMR of 9.5% and coercivity of 3 Oe. A small value of coercivity is critical for the sensitivity of MTJ sensors. Noise measurement was carried out and the Hooge parameter was 3.825×10^{-7} μ m^2 (without hard-axis bias field). These Al_2O_3 MTJ sensors with Conetic alloy have relatively small coercivity while retaining a moderate α. These results indicate that MTJ sensors with Conetic alloy are promising for further applications in low magnetic-field sensing because it does not deteriorate the $1/f$ noise and it has the advantage of having small coercivity. A hard-axis bias field of 8 Oe was applied to eliminate the hysteretic response and improve the linearity of the Conetic MTJ sensors. An optimized sensitivity of 0.4%/Oe was obtained. The noise measurement results over a range of hard-axis bias field demonstrate that the hard-axis bias field (<60 Oe) can reduce the $1/f$ noise level of MTJs while a hard-axis bias field larger than 60 Oe increases the $1/f$ noise. Therefore, a hard-axis bias field with an appropriate magnitude not only enables to eliminate the hysteretic response but also reduce the magnetically derived $1/f$ noise of the MTJ sensors.

Acknowledgment

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References

[1] M. Tondra *et al.*, "Picotesla field sensor design using spin-dependent tunneling devices," *J. Appl. Phys.*, vol. 83, pp. 6688–6690, 1998.

[2] T. Kagami *et al.*, "A performance study of next generation's TMR heads beyond 200 Gb/in^2," *IEEE Trans. Magn.*, vol. 42, pp. 93–96, 2006.

[3] R. W. Dave *et al.*, "MgO-based tunnel junction material for high-speed toggle magnetic random access memory," *IEEE Trans. Magn.*, vol. 42, pp. 1935–1939, 2006.

[4] X. F. Han, Z. C. Wen, and H. X. Wei, "Nanoring magnetic tunnel junction and its application in magnetic random access memory demo devices with spin-polarized current switching (invited)," *J. Appl. Phys.*, vol. 103, pp. 07E933–6, 2008.

[5] J. Mathon and A. Umerski, “Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/Fe(001) junction,” *Phys. Rev. B*, vol. 63, p. 220403, 2001.
[6] S. Ikeda *et al.*, “Tunnel magnetoresistance of 604% at 300 K by suppression of Ta diffusion in CoFeB/MgO/CoFeB pseudo-spin-valves annealed at high temperature,” *Appl. Phys. Lett.*, vol. 93, p. 082508, 2008.
[7] P. Wisniowski, J. M. Almeida, S. Cardoso, N. P. Barradas, and P. P. Freitas, “Effect of free layer thickness and shape anisotropy on the transfer curves of MgO magnetic tunnel junctions,” *J. Appl. Phys.*, vol. 103, pp. 07A910–3, 2008.
[8] Y. Lu *et al.*, “Shape-anisotropy-controlled magnetoresistive response in magnetic tunnel junctions,” *Appl. Phys. Lett.*, vol. 70, pp. 2610–2612, 1997.
[9] X. Liu, C. Ren, and G. Xiao, “Magnetic tunnel junction field sensors with hard-axis bias field,” *J. Appl. Phys.*, vol. 92, pp. 4722–4725, 2002.
[10] J. M. Almeida *et al.*, “1/f Noise in linearized low resistance MgO magnetic tunnel junctions,” *J. Appl. Phys.*, vol. 99, p. 08B314, 2006.
[11] W. F. Egelhoff *et al.*, “Soft magnetic layers for low-field-detection magnetic sensors,” *Thin Solid Films*, vol. 505, pp. 90–92, 2006.
[12] W. F. Egelhoff *et al.*, “Magnetic tunnel junctions with large tunneling magnetoresistance and small saturation fields,” *J. Appl. Phys.*, vol. 107, pp. 09C705–2, 2010.
[13] J.-G. Choi, D.-G. Hwang, J.-R. Rhee, and S.-S. Lee, “Comparison of the soft magnetic properties of permalloy and conetic thin films,” *J. Magn. Magn. Mater.*, vol. 322, pp. 2191–2194, 2010.
[14] C. W. Chen, *Magnetism and Metallurgy of Soft Magnetic Materials*. New York: Dover, 1986.
[15] F. N. Hooge, “1/f Noise,” *Physica* $B + C$, vol. 83, pp. 14–23, 1976.
[16] E. R. Nowak, M. B. Weissman, and S. S. P. Parkin, “Electrical noise in hysteretic ferromagnet-insulator-ferromagnet tunnel junctions,” *Appl. Phys. Lett.*, vol. 74, pp. 600–602, 1999.
[17] W. K. Park *et al.*, “Noise properties of magnetic and nonmagnetic tunnel junctions,” *J. Appl. Phys.*, vol. 93, pp. 7020–7022, 2003.
[18] A. F. M. Nor *et al.*, “Low-frequency noise in MgO magnetic tunnel junctions,” *J. Appl. Phys.*, vol. 99, pp. 08T306–3, 2006.
[19] R. Stearrett *et al.*, “Evolution of barrier-resistance noise in CoFeB/MgO/CoFeB tunnel junctions during annealing,” *J. Appl. Phys.*, vol. 107, pp. 064502–7, 2010.
[20] L. Jiang *et al.*, “Low-frequency magnetic and resistance noise in magnetic tunnel junctions,” *Phys. Rev. B*, vol. 69, p. 054407, 2004.
[21] C. Ren, X. Liu, B. D. Schrag, and G. Xiao, “Low-frequency magnetic noise in magnetic tunnel junctions,” *Phys. Rev. B*, vol. 69, p. 104405, 2004.
[22] W. F. Egelhoff *et al.*, “Critical challenges for picoTesla magnetic-tunnel-junction sensors,” *Sens. Actuators, A*, vol. 155, pp. 217–225, 2009.
[23] E. C. Stoner and E. P. Wohlfarth, “A mechanism of magnetic hysteresis in heterogeneous alloys,” *Philos. Trans. R. Soc. London, Ser. A*, vol. 240, pp. 599–642, 1948.
[24] H. T. Hardner, M. J. Hurben, and N. Tabat, “Noise and magnetic domain fluctuations in spin-valve GMR heads,” *IEEE Trans. Magn.*, vol. 35, pp. 2592–2594, 1999.
[25] S. Ingvarsson *et al.*, “Low-frequency magnetic noise in micron-scale magnetic tunnel junctions,” *Phys. Rev. Lett.*, vol. 85, p. 3289, 2000.