# MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE

by
Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

## Abstract

Pinned Spin Dependent Tunneling (SDT) devices have been fabricated into high sensitivity magnetic field sensors with many favorable properties including high sensitivity (~ 10 μOe / $\sqrt{Hz}$ @ 1 Hz and ~ 100 nOe / $\sqrt{Hz}$ @ > 10 kHz), a linear bipolar output vs. applied field, high processing yields, and high temperature stability and operability (over 200 $^0$C). However, the performance of fabricated sensors has not yet approached the theoretical limit one calculates assuming ideal behavior of the sensors' ferromagnetic layers' magnetizations. Given a total magnetoresistive signal of 30%, and typical anisotropy fields and hard axis biasing conditions, there should be a region of linear non-hysteretic response at zero field with a slope of greater than 20% / Oe. Measured responses are 1% to 3% / Oe, and exhibit some hysteresis. These less than desirable effects are the result of several factors including: 1) self-demagnetizing fields of the soft (sensing) layer, 2) stray fields from the hard (pinned) layer, 3) imperfect pinning of the hard layer, and 4) interlayer magnetic coupling across the tunnel barrier. This paper describes, in detail, the extent to which these factors affect sensor performance, and specific steps to be taken in order to minimize their deleterious influence. Specifically, the simple pinned layer is replaced by an exchange coupled synthetic antiferromagnet (CoFe / Ru / CoFe), the soft layer is made to be significantly larger in the plane than the pinned layer, and the soft layer is made as thin as possible.

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

## I. INTRODUCTION

Following demonstrations of significant room temperature magnetoresistance[1,2] and compatibility with standard integrated circuit lithographic processes[3], Spin Dependent Tunneling (SDT) materials have rapidly been developed for a wide variety of solid state magnetic devices. These applications appear feasible in virtually every application presently using anisotropic magnetoresistance (AMR) and Giant Magnetoresistance (GMR) including sensors [4], MRAM [5,6], and hard disk read heads. Their most obvious advantages are higher magnetoresistance at lower saturation fields (>25% in less than 10 Oe), and their relative insensitivity to magnetic film shape and layer thicknesses. And demonstrated bandwidth (1/RC > 1GHz) and temperature stability (> 250 $^{o}$C) [7] appear to be sufficient for all foreseeable applications. This paper focuses on the aspects of SDT devices as they relate to low frequency magnetic field sensing applications, and special shape and size issues of the junctions themselves.

## II. SENSOR CONSTRUCTION

### A. Material

The initial deposition of SDT material takes place in a Perkin Elmer 2400 with a background pressure of less than $1.5x10^{-7}$ Torr. Layers of NiFeCo

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

(65/15/20 atomic %), Al, CoFe (95/5 atomic %) and IrMn are deposited using RF diode sputtering in a 20mTorr Ar environment with 175W sputtering power. The $Al_2O_3$ layer is formed using plasma oxidation by introducing $O_2$ into the sputtering system at the end of the Al deposition. The layers are deposited in the following thicknesses: [Si / 200nm $Si_3N_4$ substrate] / NiFeCo 12.5 / $Al_2O_3$ 1.6 / CoFe 5 / IrMn 10 / Al 36 (all thicknesses in nm).

**B. Patterning**

Once the SDT material is deposited, it is patterned into a sensor using semiconductor photolithography techniques. A critical step in this process is the etch of the top electrode, which must stop on or just below the $Al_2O_3$ barrier. This etch is repeatably performed with depth control better than 2 nm using a Commonwealth ion mill. The SDT sensors are designed as a Wheatstone bridge, each leg having many tunnel junctions connected in series. Alternating legs of the bridge are either in the gap between two permalloy flux concentrators, or underneath (thus shielded by) the flux concentrators. This arrangement is shown in Fig. 1. Two integrated coils are provided, patterned from 1.5 μm thick Al, above the SDT devices but beneath the flux concentrators. The first coil is for providing a bias perpendicular to the sensitive axis, while the second is for feedback parallel to the sensitive axis. With this arrangement, one can apply sufficient orthogonal biasing and still have considerable off-axis immunity.

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by
Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

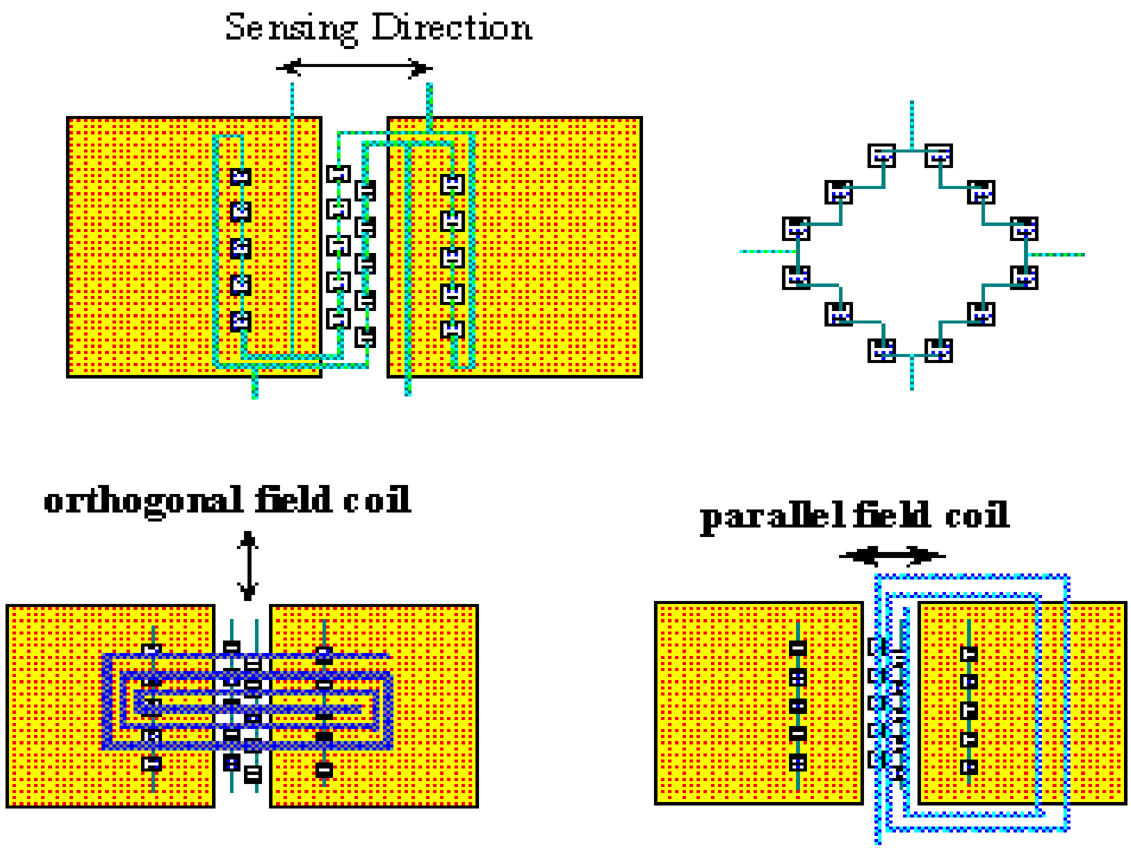


FIG. 1: Schematic representations of the various elements of an SDT sensor. The upper right drawing shows a Wheatstone bridge with legs comprising three pairs of tunnel junctions. The upper left shows that bridge as it is configured with permalloy flux concentrators so that one pair of opposite legs is in the “gap” while the other pair of opposite legs is “shielded” by the concentrators. The bottom two drawings show the arrangements for the integrated planar orthogonal and parallel field coils. These components are all present in a completed SDT sensor.

## III. SENSOR PERFORMANCE

### A. Noise floor

The SDT sensors have a noise floor that follows a typical 1/f characteristic with a corner frequencies between 10 and 100 kHz. The Johnson noise-limited

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

high frequency region has a floor of a few hundred nOe / $\sqrt{Hz}$ while the noise at 1 Hz is 10's of μOe / $\sqrt{Hz}$. Representative data are shown in Fig. 2.

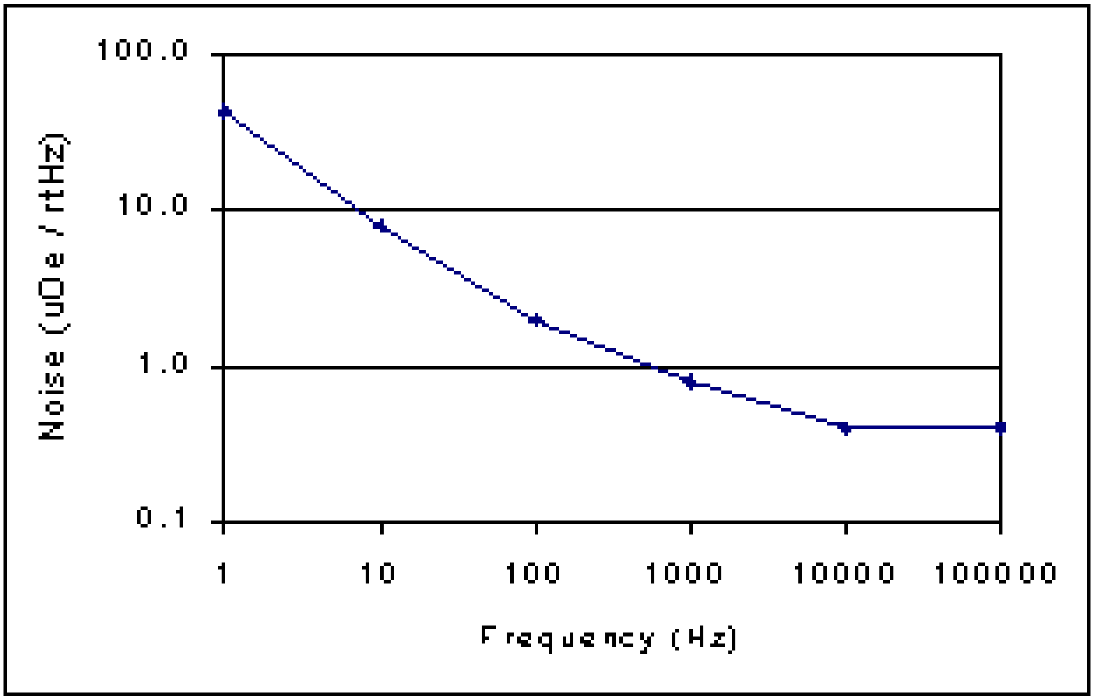


FIG. 2: Typical wideband SDT sensor noise floor. Data courtesy of Anthony Starr at Tristan Technologies.

**B. Voltage vs. magnetic field**

The voltage vs. field behavior of the SDT bridge sensors depends strongly on the amount of current driven through the integrated orthogonal biasing straps. The orthogonal biasing field is directly proportional to this current. With no current, there is considerable hysteresis and non-repeatable behavior. An intermediate value of 8 mA results in some hysteresis, and generates repeatable

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

sensor behavior. 20 mA is sufficient to saturate most of the sensitive film and eliminate most hysteresis (see Fig. 3). Unfortunately, this reduction in hysteresis comes with a loss of sensitivity. The ideal is to retain the steep slope of the no-bias condition while getting rid of the hysteresis.

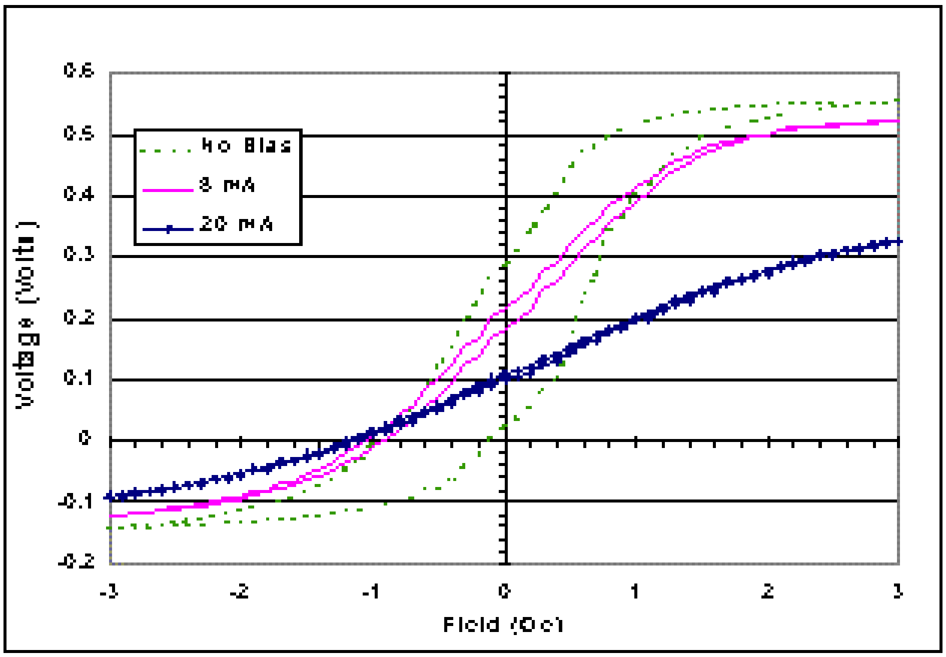


FIG. 3: V vs. H of a typical SDT sensor with flux concentrators using three different orthogonal biases. The varying bias currents are applied through an on-chip coil with approximately 600Ω resistance and a field efficiency of roughly 1 Oe / mA. The bridge has a resistance of about 15 kΩ and has a 10 Volt power supply.

# MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

## IV. MICROMAGNETIC DESIGN DETAILS

### A. Ideal Magnetics

The magnetic mode of operation involves applying an orthogonal field bias to the sensing layers so that the soft layer is saturated at a right angle to the pinned layer and the easy axes of the films. In the static case where the magnetization of the sensitive layer (assumed to be uniform) is at an angle $\theta$ from the normal zero-field position under the influence of an orthogonal bias field $H_{bias}$, and an external field being sensed $H_{sense}$, the torque equation is written as follows:

$$H_{sense}\mathrm{Cos}(\theta) - H_{bias}\mathrm{Sin}(\theta) + H_k\,\mathrm{Sin}(\theta)\mathrm{Cos}(\theta) = 0. \qquad (1)$$

A drawing of the coordinate axes in Fig. 4 shows how $\theta$ is defined. If $H_{bias}$ is just over the anisotropy field $H_k$ by a field $\delta H_k$, and substituting $H_s = H_{sense} / H_k$ , and using small angle approximations for trigonometric functions of $\delta$ and $\theta$,

$$\theta = H_{sense} / \delta H_k. \qquad (2)$$

In the orthogonally biased mode, the effective resistance varies with $\theta$ as:

$$R(\theta) = \tfrac{1}{2}(\Delta R / R)_{total}\,\sin(\theta) \cong \tfrac{1}{2}(\Delta R / R)_{total}\,H_{sense} / \delta H_k. \qquad (3)$$

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

Using values for $H_k$ = 15 Oe, $(\Delta R / R)_{total}$ = 30%, and $\delta$ = 0.05. The sensitivity for small angles about zero is: $(\Delta R / R) / H_{sense}$ = 20% / Oe.

**B. Sensor Output**

While the preceding analysis assumes idealized magnetic behavior, data in Fig. 3 show that there are undesirable features in the V vs. H curve including excess hysteresis and a slope of about 2% / Oe rather than 20% / Oe. The origin of these features and the extent to which they do not conform to the predicted behavior can be understood by examining the major sources of non-ideal fields on the soft magnetic sensing film. They are: 1) stray fields from the pinned top layer, 2) internal soft layer demagnetizing fields, 3) imperfect pinning of the hard layer, 4) resistance noise from horizontal conduction in the soft bottom magnetic layer, and 5) magnetostatic coupling across the tunnel barrier. The first two problems are depicted in Fig. 4. The stray fields and demagnetizing fields

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

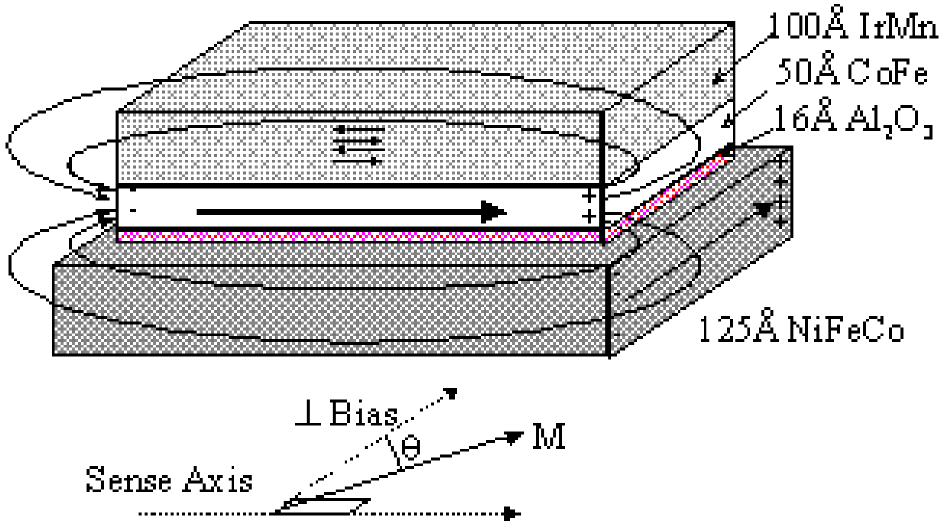


FIG. 4: The curved lines represent the stray fields from the pinned CoFe layer. The coordinate axes at the bottom describe the biased operating mode, with the dashed lines being the sense and perpendicular bias axes while the solid vector is the soft layers magnetization, rotating an angle $\theta$ from the $\perp$ axis under the influence of a field along the sense axis.

problems because they create a non-uniform magnetic environment in the soft sensing film. Consequently, when one region of the soft layer is biased precisely for high sensitivity, another region may be over biased (no hysteresis but low sensitivity) while yet another region will be under biased (excess hysteresis and unstable operation). The magnitude of these nonuniformities can easily be 10 Oe.

### C. Design Improvements

Several improvements upon the existing design will result in better performance. Incorporating a synthetic antiferromagnetic (SAF) structure for the

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

pinned layer reduces stray fields from the pinned layer by a factor of > 10 and enhances the pinning effect of the pinning layer. The effects of demagnetizing fields within the soft layer can be reduced by thinning the layer itself, and by increasing the distance from the edge of the soft layer to the edge of the tunnel junction from 2 to 10 μm.

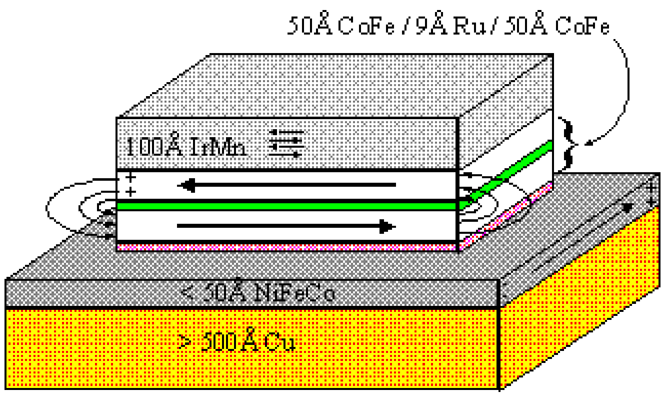


FIG. 5: A cross section of the improved SDT sensor design. The single pinned CoFe layer has been replaced by a synthetic antiferromagnetic layer. The stray fields incident on the bottom soft layer are much smaller than from the single pinned layer. Also, the “overlap” from the edge of the top electrode to the edge of the bottom electrode is increased. The added Cu reduces the undesirable series resistance from about 10 Ω / junction to < 1 Ω / junction.

Adding a thick conductive nonmagnetic layer (Cu) beneath the bottom interfacial magnetic layer reduces the resistance of horizontal interconnections which in turn reduces noise from non-sensing resistive components. The interlayer coupling can be reduced by making a smoother layered structure. A structure incorporating these improvements is shown in Fig. 5.

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

### C. Tunnel Junction Noise

The focus of this paper has been on the effects of magnetic design and structure on the sensor response to external fields. It should be noted that improvements in the intrinsic noise of the sensor will also go directly towards improving the sensor's signal to noise ratio. Several groups have noted that the noise in SDT devices appears to be related primarily to intrinsic tunneling noise rather than magnetic fluctuation noise [8,9]. Consequently, there is good reason to expect that better signal to noise ratios will be demonstrated due to continued improvements in tunnel junction quality as well as these advances in the magnetic design of SDT sensors.

## V. CONCLUSIONS

While SDT sensors have rapidly been proven to be appropriate for ultra-low field sensing, significant work remains before they will have reached their potential. Areas where advances are expected include: 1) higher magnetoresistance, 2) better barrier noise figures, 3) lower resistance-area product (less Johnson noise), and 4) better micromagnetic design. Based on the performance of existing sensors and projected improvements, a noise floor of 10 nOe / $\sqrt{Hz}$ is expected. In any case, the present SDT sensors already have advantages over other magnetoresistive sensors including single valued bipolar output at zero field, and a very high voltage output (>20 mV / V / Oe).

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

## ACKNOWLEDGMENTS

The authors wish to thank Rich Seeger for his ion mill expertise, Seraphin Akou and Dave Cheney for wafer and sensor testing, John Anderson and Dan Reed for data processing, Ken Jorissen for data acquisition instrumentation, and Geometrics, Blackhawk-Geometrics, Sanders, and ONR for continued support of this work.

**MICROMAGNETIC DESIGN OF SPIN DEPENDENT TUNNEL JUNCTIONS FOR OPTIMIZED SENSING PERFORMANCE**

by

Mark Tondra, James M. Daughton, Catherine Nordman, Dexin Wang, John Taylor
Nonvolatile Electronics, 11409 Valley View Rd., Eden Prairie, MN 55344

## References

[1]J.S. Moodera, Lisa R. Kinder, Terrilyn M. Wong, and R. Meservey, PRL **74**, 16, 3273, (1995).

[2]T. Miyazaki and N. Tezuka, J.Magn. Magn. Mater. **139**, L231, (1995).

[3]R.S. Beech, J. Anderson, J.M. Daughton, B.A. Everitt, and D. Wang, IEEE Trans. Magn. **32**, 4713, (1996).

[4]M. Tondra, J.M. Daughton, D. Wang, R.S. Beech, A. Fink, and J.A. Taylor, J. Appl. Phys. **83**, 6688 (1998).

[5]J. M. Daughton, J. Appl. Phys. **81**, 3758, (1997).

[6] W. J. Gallagher, S. S. P. Parkin, Yu Lu, X. P. Bian, A. Marley, and K. P. Roche, R. A. Altman, S. A. Rishton, C. Jahnes, and T. M. Shaw, G. Xiao, J. Appl. Phys. **81**, 3741 (1997)

[7]D. Wang, M. Tondra, C. Nordman, J.M. Daughton, IEEE Trans. Magn. **35**, 2886, (1999).

[8]E.R. Nowak, M.B. Weissman, S.S.P. Parkin, Appl. Phys. Lett. **74**, 600 (1999).

[9]E.R. Nowak, R.D. Merithew, M.B. Weissman, I. Bloom, S.S.P. Parkin, J. Appl. Phys. **84**, 6195 (1998).