Critical challenges for picoTesla magnetic-tunnel-junction sensors

W.F. Egelhoff Jr. a, P.W.T. Pong a,∗, J. Unguris b, R.D. McMichael b, E.R. Nowak c, A.S. Edelstein d, J.E. Burnette d, G.A. Fischer d

a Metallurgy Division, National Institute of Standards & Technology, Gaithersburg, MD 20899-8552, United States
b Center for Nanoscale Science and Technology, National Institute of Standards & Technology, Gaithersburg, MD 20899-8552, United States
c Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, United States
d U.S. Army Research Laboratory, Adelphi, MD 20783-1197, United States

Article history:
Received 7 April 2009
Received in revised form 24 August 2009
Accepted 26 August 2009
Available online 2 September 2009

Keywords:
picoTesla
Magnetic-tunnel-junction
Magnetic sensors
Tunneling magnetoresistance

The extension of small, inexpensive, low-power, low-frequency, ultra-sensitive magnetic sensors to fields between 1 nT and 1 pT, an area currently dominated by fluxgates, optically pumped magnetometers, and SQUIDS, would be a paradigm shift for the field of magnetic sensors. The necessary elements for picoTesla magnetic-tunnel-junction (MTJ) sensors have been identified by modeling the noise characteristics. The results help identify the experimental challenges involved in the integration of these necessary elements into actual sensors, illustrate the trade-offs faced if there are losses in performance upon integration. Scanning electron microscopy with polarization analysis (SEMPA) of the pinned layer provides insights into problems and possible solutions. Issues associated with real-world applications of these sensors to ultra-low field measurements are discussed.

© 2009 Published by Elsevier B.V.

1. Introduction

The number of applications for magnetic sensors has grown explosively in the past two decades [1]. In particular, the growth in small, low-power magnetic sensors has been exponential [2]. Applications abound to meet the needs of users in the medical, military, information technology, and industrial communities [3]. However, one area in which little progress has been made in recent years is small, inexpensive, low-power low-frequency sensors capable of detecting ultra-low magnetic fields. By small we mean sub-millimeter. By inexpensive we mean a few tens-of-dollars each. By low-power we mean the sensor elements consume a few milliWatts or less. By low frequency we mean approximately 0.01 Hz to 100 Hz. Currently, the detection of fields between 1 nT (10−5 Oe) and 1 pT (10−8 Oe) is dominated by relative large, expensive, power-hungry sensors such as fluxgates, optically pumped magnetometers and SQUIDS [4]. If small, inexpensive, low-power, low-frequency magnetic sensors could make serious progress in this regime the technological impact would likely be great [4].

The most likely sensor technology to make such progress is a Wheatstone bridge of magnetic-tunnel-junctions (MTJs) combined with a micro-electro-mechanical system (MEMS) of frequency-modulated magnetic flux concentrators to suppress 1/f noise [5,6]. An important aspect of this approach is that magnetic flux concentrators do not contribute significantly to 1/f noise [5]. To evaluate the combined effect of this approach, a theoretical model was derived and incorporated in a spreadsheet for evaluation and optimization of the expected performance of the sensor.

2. Theoretical model

The sensor design has N MTJs in each leg of a Wheatstone bridge. On each side of the bridge one leg of MTJs is shielded from the applied magnetic field and one is exposed (Fig. 1a). The applied field is amplified by MEMS flux concentrators that provide a field gain β [6].

2.1. Performance

When the resistance of the two active legs changes by δR, the output voltage of the bridge is

$$V = V_0 \frac{\delta R}{2R} \approx V_0 \frac{\delta R}{2R} \quad (1)$$

Here $V_0$ is the supply voltage and $R$ is the resistance of one leg of the bridge. The sensitivity of the bridge is determined by the

Disclaimer: The identification of a commercial software and sensors is to specify the experimental conditions and does not imply any NIST endorsement or recommendation that it is necessarily the best for the purpose.

∗ Corresponding author. Present address: Department of Electrical and Electronic Engineering, University of Hong Kong, Pokfulam Road, Hong Kong.
E-mail address: ppong@eee.hku.hk (P.W.T. Pong).
change in resistance due to the applied field. For an applied field \( B \), and assuming a linear response, the resistance changes by

\[
\delta R = \frac{R_{\text{max}} - R_{\text{min}}}{2} \frac{B}{B_{\text{sat}}} \tag{2}
\]

The sensitivity of the bridge is therefore

\[
dV = \frac{\delta R}{B} \frac{V_0}{R} \tag{3}
\]

Note that the fraction \( \frac{\delta R}{B} \) is explicitly, \( 2(\frac{R_{\text{max}} - R_{\text{min}}}{R_{\text{max}} + R_{\text{min}}} \), which is different from the value usually published, \( (\frac{R_{\text{max}} - R_{\text{min}}}{R_{\text{max}} + R_{\text{min}}} \) (Fig. 1b). It may be more convenient for design purposes to write the supply voltage in terms of the junction voltage \( V_j = \frac{V_0}{2N} \), where \( N \) is the number of MTJs per leg.

\[
dV = \frac{\delta R}{B} \frac{N V_j}{R} \tag{4}
\]

The overall power dissipated by the device is

\[
W = 4N \frac{V_j^2}{[\text{RAP}]} \tag{5}
\]

where \( A \) is the area of each MTJ and [RAP] is the resistance-area product. In this analysis, the junction voltage \( V_j \), the junction area \( A \) and the number of MTJs per leg \( N \) are used as design parameters for the bridge circuit. Other quantities are expressed in terms of these three, when possible.

### 2.2. Noise sources

For a Wheatstone bridge, the field noise power, \( S_B \) (units of \( T^2/Hz \)) at the output is equal to the noise in one leg, assuming that the four legs all have equivalent noise sources. The analysis below includes amplifier noise, Shot and Johnson noise, electronic 1/f noise, thermal magnetic noise, and magnetic 1/f noise [11,17–19].

The detection limit will be determined by a field noise floor

\[
S_B = S_{B}^{\text{Amp}} + S_{B}^{\text{shot}} + S_{B}^{\text{elec.1/f}} + S_{B}^{\text{therm.mag.}} + S_{B}^{\text{mag.1/f}} \tag{6}
\]

### 2.2.1. Amplifier noise

An amplifier connected to the output of the bridge will have internal noise that will limit the field noise power floor. The amplifier noise level can be expressed as noise voltage power \( S_{V}^{\text{Amp}} \) in units of [\( V^2/Hz \)]. The effective noise field power due to the amplifier noise is given by

\[
S_{B}^{\text{Amp}} = \left( \frac{dB}{dV} \right)^2 S_{V}^{\text{Amp}} \tag{7}
\]

where \( dB/dV \) is the inverse of Eq. (4).

For convenience, all parameters are defined in Table 1.

### 2.2.2. Shot and Johnson noise

Shot noise and Johnson noise are intertwined in tunnel junctions [7]. The general expression for this noise voltage power is

\[
S_{V}^{\text{shot}} = N 2 e v R_s \coth \left( \frac{e V_j}{2 k_B T} \right) \tag{8}
\]

Note that for small junction voltages, less than about 50 mV at room temperature, Eq. (8) reduces to \( N 4 k_B T \), the expression for Johnson noise, because electron transport tends to be diffusive across the junction. At higher junction voltages, as current flow becomes unidirectional, Johnson noise fades away, and shot noise (the statistics of counting electrons) dominates. In terms of our design parameters, the junction resistance \( R_j = [\text{RAP}] / A \) where [RAP] is the resistance-area product and \( A \) is the area of each tunnel junction. The current is \( I = 2 N V_j / 2 N R_s \), and the junction voltage is \( V_j = 2 N V_j / 2N \). In terms of the design parameters,

\[
S_{V}^{\text{shot}} = N 2 e v [\text{RAP}] / A \coth \left( \frac{e V_j}{2 k_B T} \right) \tag{9}
\]
2.2.3. Electronic 1/f noise

The electronic 1/f noise voltage power (units of V²/Hz) varies among MTJs, but it is typically written as [7]

\[ S_{V}^{-1/f} = N \frac{\alpha_{\text{elec}} V_{J}^{2}}{A f} \quad (10) \]

where \( f \) is the detection frequency and \( \alpha_{\text{elec}} \), the electronic Hooge parameter, acts as a constant of proportionality to enable modeling of the 1/f noise voltage power for differing values of \( N, V_{J}, A, \) and \( f \) in a bridge of MTJs. The prefactor of \( N \) results from the noise voltage (the square root of the noise voltage power) of the MTJs adding in quadrature so the noise voltage power of each MTJ in the leg adds linearly to give \( N \). The same principle will apply to the next two types of noise in Sections 4 and 5 below.

Note the Hooge parameter may need to be recalculated for different MTJs, although trends in its value as a function of RAP have been noted for different MTJs [8]. In terms of our design parameters, the 1/f noise voltage power becomes

\[ S_{V}^{-1/f} = N \frac{\alpha_{\text{elec}} V_{J}^{2}}{A f} \quad (11) \]

2.2.4. Thermal magnetic noise

The thermal fluctuations of the free-layer magnetization will contribute to sensor noise. The thermal magnetic noise power for a single junction is given by

\[ S_{M}^{\text{mag}} = \frac{2k_{B} T \chi'(f)}{\pi \Omega \mu_{0}} \quad (12) \]

where \( \Omega \) is the free-layer volume [9]. The imaginary part of the susceptibility, \( \chi'(f) \), is usually thought of as the coefficient that describes losses driven by applied fields. In this context, it describes how the thermal bath couples to the magnetization. At least two mechanisms may contribute to \( \chi'(f) \), including uniform rotation of the free-layer magnetization and metastability of ripple states. The part attributable to uniform rotation is generally referred to as thermal magnetic noise. The part attributable to ripple is generally referred to as magnetic 1/f noise.

Since here we consider frequencies far below ferromagnetic resonance, we can write for the free-layer uniform-rotation mechanism,

\[ \chi' = \frac{\alpha_{C} M_{s} \omega}{\gamma H_{k}^{2}} \quad (13) \]

Here we give the Gilbert damping parameter \( \alpha_{C} \) a subscript to separate it from the Hooge parameters, and \( H_{k} \) is the in-plane stiffness field of the magnetization. For susceptibility due to magnetization rotation, the magnetization noise power is [9]

\[ S_{M}^{\text{mag}} = \frac{4k_{B} T \alpha_{C} M_{s} \mu_{0}}{\Omega^{2} \gamma H_{k}^{2}} \quad (14) \]

The output noise voltage power due to the magnetization fluctuations of the free-layer rotation is given by

\[ S_{V}^{\text{mag}} = N \left( \frac{dV}{dM} \right)^{2} S_{M}^{\text{mag}} = N \left( \frac{V_{J} (\Delta R/ R)}{2 M_{s}} \right)^{2} S_{M}^{\text{mag}} \quad (15) \]

and using the inverse of Eq. (4) to calculate the effective field noise power due to magnetization fluctuations [9]

\[ S_{B}^{\text{mag}} = \left( \frac{dB}{dV} \right)^{2} S_{M}^{\text{mag}} = \frac{1}{2} \frac{4k_{B} T H_{k} \alpha_{C}}{N \gamma \mu_{0} M_{s}} \quad (16) \]

2.2.5. Magnetic 1/f noise

The other mechanism that will contribute to \( \chi' \) is magnetization hopping between metastable ripple states [5,10]. Since there will be a distribution of energy barriers, there is a likelihood that this mechanism will lead to a 1/f-type noise, [5,10] or, if the density of these ripple-based flip-flopers is small, to telegraph noise. Using Eq. (12) to describe this mechanism, the lossy part of the susceptibility has a precessional part given by Eq. (13), and a hysteretic part which is nearly frequency independent. Then summing the magnetic 1/f voltage noise power over the N MTJs in the bridge,

\[ S_{V}^{\text{mag,1/f}} = N \left( \frac{dV}{dM} \right)^{2} S_{M}^{\text{mag,1/f}} = N \left[ \frac{V_{J} \Delta R/ R}{2 M_{s}} \right]^{2} \frac{2k_{B} T \chi'(f)}{\pi \Omega \mu_{0}} \quad (17) \]

The sensitivity of an MTJ is

\[ dV = \frac{dV}{dM} \frac{dM}{dH} = \frac{V_{J} \Delta R}{2 M_{s}} \chi' \quad (18) \]

where \( \chi' \) is the real part of the susceptibility and \( V_{J}, \Delta R, R, \) and \( M_{s} \) are all constants independent of applied field. The only field-dependent quantities in Eqs. (17) and (18) are \( \chi' \) and \( \chi'' \). To a first approximation, \( \chi' \) and \( \chi'' \) are linearly related as a function of applied field (at least at low fields and low frequencies, i.e., \( < \text{kHz} \)). Consequently, \( S_{V} \) and \( dV/dH \) are linearly related, as demonstrated in Ref. [8].

Then, \( S_{B}^{\text{mag,1/f}} \) becomes, from \( S_{V}^{\text{mag,1/f}} \),

\[ S_{B}^{\text{mag,1/f}} = \frac{(dB/dV)^{2} S_{M}^{\text{mag,1/f}}}{N} = \frac{2k_{B} T}{N \pi \mu_{0}} \left[ \frac{\chi''}{\chi'} \right]^{2} B_{\text{sat}}^{2} \frac{M_{s}}{M_{s}} \quad (19) \]

Recognizing that \( M_{s}/B_{\text{sat}} \) is our assumed model for \( \chi' \),

\[ S_{B}^{\text{mag,1/f}} = \frac{1}{N \pi \mu_{0}} \left[ \frac{\chi''}{\chi'} \right] B_{\text{sat}}^{2} \frac{M_{s}}{M_{s}} \quad (20) \]

and the quantity in parentheses is the fraction of the susceptibility that is irreversible. Note that the magnetic 1/f noise \( \alpha_{\text{mag}} \) parameter, much like the above Hooge parameter, acts as a constant of proportionality to enable modeling of the magnetic 1/f noise field power for differing values of \( N, V_{J}, \Omega, \) and \( f \) in a bridge of MTJs. The value we use for \( \alpha_{\text{mag}} \) in our modeling is an experimental derived one 1.83 × 10⁻¹² μm²/T [12].

It is a critical distinction that an increase in MTJ sensitivity can overcome amplifier, Johnson, shot, and electronic 1/f noise but might not be expected to do so for magnetic 1/f noise. Magnetic 1/f noise represents fluctuations in the direction of the magnetization that might seem fundamentally indistinguishable from fluctuations caused by an external magnetic field that one wants to detect. It might appear that no amount of sensitivity would help the sensor distinguish a real external signal from magnetic 1/f noise. However, reality is more complex. The \( B_{\text{sat}} \) in Eq. (21) means that if MTJ sensitivity is increased by decreasing \( B_{\text{sat}} \), the magnetic 1/f noise can be suppressed without limit. This result has practical consequences since the magnetic 1/f noise is often dominant, and Eq. (21) points to a new way to suppress it.

2.2.6. Total system noise

The grand total system field noise power is then given by

\[ S_{B} = \left( \frac{dB}{dV} \right)^{2} \left( S_{V}^{\text{Amp}} + S_{V}^{\text{shot}} + S_{V}^{\text{elec,1/f}} \right) + S_{B}^{\text{therm,mag}} + S_{B}^{\text{mag,1/f}} \quad (23) \]
### Table 2
A set of "best compromise" input parameters for Eq. (24) corresponding to reasonably achievable values for an MTJ-based sensor that would yield a noise floor of 1 pT/rt(Hz). Note, the spreadsheet converts the entered value of \((R_{\text{max}} - R_{\text{min}})/R_{\text{min}}\) into the appropriate \(2(R_{\text{max}} - R_{\text{min}})/(R_{\text{max}} + R_{\text{min}})\) for Eq. (3).

<table>
<thead>
<tr>
<th>Bridge Parameters</th>
<th>Resulting Circuit Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Drop Each Junction</td>
<td>1.00E-01 V</td>
</tr>
<tr>
<td>MTJs Per Leg</td>
<td>16</td>
</tr>
<tr>
<td>Area of Each Junction</td>
<td>8000 (\mu\text{m}^2)</td>
</tr>
<tr>
<td>Resistance per Junction</td>
<td>125.00 Ohms</td>
</tr>
<tr>
<td>Current Through Each Leg</td>
<td>8.00E-004 A</td>
</tr>
<tr>
<td>Power (All 4 Legs)</td>
<td>5.12E-03 W</td>
</tr>
<tr>
<td>Operational Parameters</td>
<td></td>
</tr>
<tr>
<td>Free layer Saturation Field</td>
<td>3.00E-004 T</td>
</tr>
<tr>
<td>TMR (enter: delta-R/R-min)</td>
<td>100%</td>
</tr>
<tr>
<td>Flux concentrator gain</td>
<td>5</td>
</tr>
<tr>
<td>Amplifier Noise</td>
<td>1 nVHz(^{0.5})</td>
</tr>
<tr>
<td>Temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>Junction Resistance Area</td>
<td>1.00E+00 MOhm (\mu\text{m}^2)</td>
</tr>
<tr>
<td>Ms</td>
<td>8.00E+005 (\text{A/m})</td>
</tr>
<tr>
<td>Damping alpha</td>
<td>0.01</td>
</tr>
<tr>
<td>Electronic 1/f noise alpha</td>
<td>1.00E-009 (\mu\text{m}^2)</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>1.00E+04 Hz</td>
</tr>
<tr>
<td>Free layer Thickness</td>
<td>1.00E+00 um</td>
</tr>
<tr>
<td>Magnetic 1/f noise alpha</td>
<td>1.83E-12 (\mu\text{m}^2)</td>
</tr>
<tr>
<td>e</td>
<td>1.60E-019 A.s</td>
</tr>
<tr>
<td>kB</td>
<td>1.38E-023 J/K</td>
</tr>
<tr>
<td>Gamma</td>
<td>2.21E+031 (\text{A}^1\text{s}^1)</td>
</tr>
<tr>
<td>mu zero</td>
<td>1.28E-036 Tm(^{-1})</td>
</tr>
<tr>
<td>Physical Constants</td>
<td></td>
</tr>
<tr>
<td>Magnetic 1/f noise</td>
<td>5.30E-020 (\text{V2Hz})</td>
</tr>
<tr>
<td>Electronic 1/f noise</td>
<td>2.00E-19 (\text{V2Hz})</td>
</tr>
<tr>
<td>Thermal Mag noise</td>
<td>1.41E-009 (\text{V2Hz})</td>
</tr>
<tr>
<td>1.83E-014 (\text{T})</td>
<td></td>
</tr>
</tbody>
</table>

### 3. Results and discussion

To characterize the expected performance of sensors the field noise (the square root of the field noise power) was studied as a function of the input variables for Eq. (24), using an Excel\(^1\),\(^2\) spreadsheet for the calculation. Table 2 presents the starting point for this work. It assumes that reasonable values for the three key properties can be integrated into a sensor. For TMR a value of 100% is assumed, although values above 400% have been reported\([13–15]\). For the saturation field, \(B_{\text{sat}}\) of the free layer \(3 \times 10^{-4} \text{T} (3 \text{ Oe})\) was assumed, although values almost 100 times smaller have been demonstrated in magnetic thin films not incorporated in MTJs\([16]\). Incorporation of ultrasoft magnetic films in MTJs typically results in exposure to stray fields that raise \(B_{\text{sat}}\) significantly. For the magnetic flux concentrator a gain of 5 with an operating frequency of 10 kHz was used since these values have recently been demonstrated\([6]\). The resulting noise floor is 1 pT/rt(Hz).

A key point about the magnetic flux concentrator is that it acts to modulate the magnetic field. Thus, the magnetic sensor is operating in a higher frequency region where the 1/\(f\) noise is much lower. The signal appears as sidebands to the signal of the output voltage at the resonant frequency of the MEMS structure. The signal can be demodulated using a lock-in amplifier.

For other parameters, the assumptions were as follows:

1) A Wheatstone bridge with 16 MTJ sensors in each leg, a supply voltage of 3.2 V to hold the drop across each MTJ at 0.1 V.
2) Rather large junction areas of 8000 \(\mu\text{m}^2\) and free-layer thicknesses of 1 \(\mu\text{m}\) to increase the volume and thereby reduce thermal magnetic noise.
3) A large RA product of 1 \(\Omega\text{m}^2\) to raise the resistance of the large-area MTJs, thereby limiting the current and holding the power consumption to 5 mW.
4) A saturation magnetization, \(M_s\), corresponding to permalloy.
5) A typical Gilbert damping parameter of 0.01.
6) A electronic Hooge 1/\(f\) noise parameter of \(1 \times 10^{-9} \mu\text{m}^2\) which is typical for the RA product value.
7) A typical magnetic Hooge 1/\(f\) noise parameter for MTJs of \(1.83 \times 10^{-12} \mu\text{m}^2\) T.

The above key parameters and other enumerated parameters do not place any great demands on MTJ fabrication or performance. The challenge lies in integrating the components without significant loss of the performance demonstrated separately.

First, it is important to validate the theoretical model in Eq. (24). If the parameters for current commercial sensors are use in Eq. (24), the experimental results are predicted quite accurately. For example, Fig. 2 is adapted from Ref.\([17]\) which published results on

---

\(^1\) The identification of a commercial software is to specify the experimental methods and does not imply any NIST endorsement or recommendation that it is necessarily the best for the purpose.

\(^2\) The identification of commercial sensors is to specify the experimental methods and does not imply any NIST endorsement or recommendation that they are necessarily the best for the purpose.
several commercial sensors. Note Ref. [17] uses the term detectivity in the same sense we use total noise floor. The orange dots are the values we obtained using Eq. (24) for the sensor labeled NVE SDT, using appropriate values for the parameters of that sensor [18]. The agreement is excellent. Table 3 shows the spreadsheet values for 1 Hz.

Note that the 1 pT/rt(Hz) prediction in Table 2 above is frequency independent below 10 kHz because of the effect of the oscillation flux concentrator. Note also that 1 pT is a factor-of-ten below the abscissa in Fig. 2. The potential improvement in the type of sensors we analyze here is especially important for detecting low-frequency signals, with over a thousand-fold improvement, from 13 nT/rt(Hz) to 1 pT/rt(Hz), projected by Fig. 2 at 0.1 Hz, in agreement with the conclusions of Ref. [6]. The key factors in this huge improvement are the use of the oscillating MEMS flux concentrator and the large free-layer volume.

We have found the spreadsheet based on Eq. (24) to be a valuable tool for

1) providing quick evaluations of the effect of changing the sensor parameters,
2) formulating a best compromise solution to the inevitable trade-offs,
3) analysing existing sensors to see where improvements may be made,
4) gaining deeper insights into how existing sensors perform.

Fig. 3 presents the spreadsheet projections for the effect of changing the TMR. Clearly, there is not much gained by TMR values above 100%, while the losses below 50% become severe.

---

**Table 3**

A set of input parameters for Eq. (24) used to calculate the orange dot at 1 Hz in Fig. 2.

<table>
<thead>
<tr>
<th>Bridge Parameters</th>
<th>Resulting Circuit Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Drop Each Junction</td>
<td>1.0E-01 V</td>
</tr>
<tr>
<td>MTJ's Per Leg</td>
<td>20</td>
</tr>
<tr>
<td>Area of Each Junction</td>
<td>300 μm²</td>
</tr>
<tr>
<td>Resistance per Junction</td>
<td>3333.33 Ohms</td>
</tr>
<tr>
<td>Current Through Each Leg</td>
<td>3.00E-05 A</td>
</tr>
<tr>
<td>Temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>Junction Resistance Area</td>
<td>1.0E+00 MΩ·μm²</td>
</tr>
<tr>
<td>Amplifier Noise</td>
<td>500 nV/√Hz</td>
</tr>
<tr>
<td>Damping alpha</td>
<td>0.01</td>
</tr>
<tr>
<td>Physical Constants</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>1.60E-19 As</td>
</tr>
<tr>
<td>iB</td>
<td>1.33E-02 JK</td>
</tr>
<tr>
<td>Gamma</td>
<td>2.21E+05 m²/A²</td>
</tr>
<tr>
<td>μ₀</td>
<td>1.26E-06 TmA²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Noise Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifier Noise</td>
</tr>
<tr>
<td>Johnson/Shot Noise</td>
</tr>
<tr>
<td>Shot, Dominated</td>
</tr>
<tr>
<td>Total Noise Floor</td>
</tr>
</tbody>
</table>

---

![Fig. 2](image-url) An adaptation of a figure in Ref. [17] comparing the detectivity versus frequency for commercial sensors. The orange dots are our results predicting the behavior of the NVE SDT sensor using Eq. (24). Ref. [17] uses the term detectivity in the same sense we use total noise floor. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

![Fig. 3](image-url) The projection for the effect on detectivity of changing TMR when all other parameters are held at the “best compromise” values presented in Table 1. No frequency is specified for the detectivity since the MEMS flux concentrator should make it frequency independent below 10 kHz.
Lessons such as this one are extremely valuable in finding the optimum allocation of available resources. Since the high-TMR limit is 0.5 pT/rt(Hz) which is only slightly below our 1 pT/rt(Hz) “best compromise”, striving for TMR values significantly above 100% would be a poor appropriation of resources.

Fig. 4 presents the spreadsheet projections for the effect of changing \( B_{\text{sat}} \), the free-layer saturation field. In this case, the low-\( B_{\text{sat}} \) limit for the detectivity is 0.09 pT/rt(Hz), but such values require an unrealistic \( B_{\text{sat}} \) of \( \approx 10^{-6} \) T. Unfortunately, we have found experimentally that reducing \( B_{\text{sat}} \) below \( \approx 10^{-4} \) T in MTJs is very challenging. Nevertheless, the payoff from reducing \( B_{\text{sat}} \) is significant, and an appropriation of resources might be productive in this area, particularly in the form of higher-gain flux concentrators. Our assumption of a gain of 5 is moderate. At least, we know from the spreadsheet projections that there is the potential for a large improvement in MTJ sensors by lowering \( B_{\text{sat}} \).

In existing MTJ sensors, \( B_{\text{sat}} \) values tend to be in the range of \( 10^{-3} \) T or more. There are two primary difficulties in achieving such \( B_{\text{sat}} \) values. One is orange-peel coupling and the other is magnetization ripple.

Orange-peel coupling is a well-known problem in MTJs [19] and we have found ways to reduce its effect to the level of \( 0.1 \) mT (1 Oe) [20,21]. Magnetization ripple is less familiar and more difficult to deal with. It is illustrated in Fig. 5.

The image is recorded with scanning electron microscopy with polarization analysis (SEMPA) [22]. The sample is Si(1 0 0):250 nm thermal oxide; 10 nm IrMn; 5 nm Co. The color wheel in the lower left corner indicates the direction of the local magnetization in the image. The arrow in the color wheel points in the yellow direction meaning that direction is the mean magnetization direction, \( M_{\text{mean}} \). The green and red bands are magnetization ripple. They are caused by the polycrystalline IrMn grains having different preferred pinning axes. Exchange stiffness prevents the local magnetization from aligning perfectly with the pinning axis of each IrMn grain. The ripple bands are local minimum energy configurations that establish local magnetization directions to balance the energies from the exchange bias by the IrMn, the exchange stiffness of the Co, and the stray fields above and below the Co layer.

On the right side of Fig. 5 are plots of scans of the magnetization direction parallel and perpendicular to the mean magnetization direction, labeled \( Y \) and \( X \) respectively. In the upper part of the image, the line through the green band defines a \( k \) wavevector \( (2\pi/\text{width of the band}) \) for the green band and an angle \( \phi \) which represents the difference between \( k \) and \( M_{\text{Y}} \), the \( Y \) component of the magnetization. The \( Y \) component of the magnetization is the component parallel to the mean magnetization. The angle between the local magnetization direction and the mean magnetization is \( \theta \). Note that the two angles are not quite equal. The green bands all have the same magnetization direction, but their \( k \) wavevectors vary somewhat.

These terms may be used in the equation

\[
H_{\text{stray}} \approx 4\pi M_s t_C \sin \theta \frac{k}{2} \sin \varphi
\]  

(25)

to provide an estimate of the stray field just above the pinned layer that the free layer will experience in an MTJ. In regions where the ripple bands are not pronounced, such as where the scans are made, this field is estimated to be on the order of \( 10^{-4} \) T (1 Oe) whereas where the bands are intense, as in the green band that defines \( k \), it is estimated to be on the order of \( 17 \times 10^{-4} \) T (17 Oe). The parameters used for the former estimate are the value of Co for \( 4\pi M_s \), \( \varphi = 10^\circ \), \( \theta = 5^\circ \), \( k = 2\pi/1000 \) nm, and \( t_C = 5 \) nm. For the latter estimate, they are the value of Co for \( 4\pi M_s \), \( \varphi = 40^\circ \), \( \theta = 30^\circ \), \( k = 2\pi/1000 \) nm, and \( t_C = 5 \) nm.

Fig. 5. An example of magnetization ripple in the Co film of a Si(1 0 0):250 nm thermal oxide; 10 nm IrMn; 5 nm Co structure. The particulate on the surface is not relevant. It simply facilitates focusing the electron beam. Plots of \( \theta \), the angle between the local magnetization direction and the mean magnetization direction (shown in the color wheel), are given for scans in the directions \( X \) and \( Y \). \( X \) is parallel to the mean magnetization direction and \( Y \) is perpendicular to it. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)
Fig. 6. Plots of $\theta$, the angle between the local magnetization direction and the mean magnetization direction, and the corresponding real space SEMPA images for a) Cu(100)/10 nm IrMn(100)/5 nm Co and b) NiO(100)/5 nm Co. The dashed red lines are the path of the plotted scan. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Eq. (25) may be readily understood on the basis of simple magnetostatics. For any local area, the maximum stray field it can create is $M_x \approx 4\pi M_s t \sin \theta$. However, if it is present in a band for which $\theta = 0^\circ$ there are no free poles to create a stray field. If $\theta = 90^\circ$, the maximum stray field is present. This effect has the functional form $(k/2) \sin \theta$.

Eq. (25) and Fig. 5 indicate that the stray fields emanating from the magnetization ripple caused by polycrystalline IrMn may be a serious problem in making major reductions in $B_{sat}$. Some approaches to the problem that are likely to help are the use of synthetic antiferromagnets in pinned layers to give partial cancellation of stray fields and thinner layers of IrMn to weaken the strength of the pinning. However, one possibility that does not appear to have been investigated is the use of single-crystal pinning layers. We have investigated two types of single-crystal pinning layers by SEMPA. One is NiO(100) grown epitaxially on MgO(100). The other is IrMn(100) grown epitaxially on Cu(100). In both cases, low energy electron diffraction (LEED) was used to confirm the epitaxial growth.

Fig. 6 presents the SEMPA results of 5 nm Co films on these two single-crystal substrates. Clearly, magnetization ripple is not eliminated by single-crystal pinning layers. However, there are major differences. The length scale of the magnetization ripple is about an order of magnitude smaller in Fig. 6 than it is in Fig. 5. This effect is likely the result of the single-crystal pinning layer having little or no contribution to the ripple, with the residual ripple caused by magnetocrystalline anisotropy in the Co. LEED indicates that Co does not grow epitaxially on either of these substrates.

The effect the reduced length scale is to increase $k$ and thus the stray field according to Eq. (25). Also, the bands of Fig. 5 have become patches in Fig. 6, increasing the stray field by tending to eliminate the $(k/2) \sin \theta$ term in Eq. (25). Additional work will be needed to determine the net effect of these two influences on $B_{sat}$ of the free layers in MTJs, but the initial prognosis is not favorable for Co. Fortunately, alloys with nearly zero magnetocrystalline anisotropy should solve the problem.

The use of a MEMS magnetic flux concentrator is critical to achieving high sensitivity at low frequency. It acts to modulate the magnetic field so even a very low-frequency magnetic signal is detected at the oscillating frequency of flux concentrator. As a result, the magnetic sensor is operating in a high frequency region where the $1/f$ noise is much lower. The signal appears as sidebands to the signal of the output voltage at the resonant frequency of the MEMS structure. The signal can be demodulated using a lock-in amplifier. Fig. 7 is an illustration of the device.

Fig. 7. An illustration of the oscillating MEMS flux concentrator that may solve the problem of low-frequency $1/f$ noise in magnetic sensors by shifting the signal to 10 kHz [6].

The use of a MEMS magnetic flux concentrator is critical to achieving high sensitivity at low frequency. It acts to modulate the magnetic field so even a very low-frequency magnetic signal is detected at the oscillating frequency of flux concentrator. As a result, the magnetic sensor is operating in a high frequency region where the $1/f$ noise is much lower. The signal appears as sidebands to the signal of the output voltage at the resonant frequency of the MEMS structure. The signal can be demodulated using a lock-in amplifier. Fig. 7 is an illustration of the device.

Fig. 8 presents the spreadsheet projections for the effect of changing the operating frequency of the MEMS magnetic flux concentrator when all other parameters are held at the “best compromise” values presented in Table 1. The flux concentrator would probably not operate at frequencies below 1 kHz, however values lower than that in Fig. 8 correspond to the detectivity at those frequencies in the absence of an oscillating flux concentrator. Clearly, operating the oscillating flux concentrator at 10 kHz gives orders of magnitude of improvement for frequencies below 1 Hz [6]. Fig. 8 indicates, as seen in Figs. 3 and 4, there is little to be gained by going beyond our “best compromise” value. Shot and amplifier noise are not reduced by using higher frequencies, and they set a noise floor.
Recently, a different design of a MEMS flux concentrator based on a torsional cantilever was published [23]. The detection of a static field of 2.7 μT was reported [23]. The detection of a field of 2.7 μT was reported [23].

Fig. 9 presents the spreadsheet projections for the effect of changing the power dissipation (by varying RA) when all other parameters are held at the “best compromise” values presented in Table 1. For applications in which minimizing the power consumption is an important issue, it may be noted that the spreadsheet projects that if the power consumption is reduced to 1 mW the detectivity increases to 2 pT/rt(Hz). Note that this is the power requirement for the Wheatstone bridge and does not include the power for the amplifier which will require a few additional milli-Watts depending on the application.

For real-world applications, one of the principle considerations will be thermal drift in the control electronics. Thermal drift must be slow on the scale of the frequency of the signal the sensor is attempting to measure. Our preliminary estimates are that to detect 1 pT/rt(Hz), the drift must be less than 0.01 °C per cycle. For example, to observe a signal at 0.1 Hz, the drift must be less than 0.001 °C/s. Clearly, thermal insulation of the sensor, perhaps incorporating a thermal bath for stabilization, will help to enable the detection of signals at the lowest frequencies.

4. Conclusions

The major conclusions of this work may be summarized as follows:

1) Recent advances in TMR, free-layer saturation field, and MEMS oscillating flux concentrators suggest that it may be possible to use small, inexpensive, low-power, ultra-sensitive magnetic sensors to detect 1 pT/rt(Hz) at low frequencies, a regime which is currently dominated by fluxgates, optically pumped magnetometers and SQUIDs.

2) The major challenge is to integrate these advances into sensors with only moderate loss in the separately demonstrated levels of performance.

3) If successful, these sensors will play important roles in a wide range of applications including healthcare, homeland security, and national defense.

Acknowledgements

One of us (ASE) would like to acknowledge valuable discussions on MEMS flux concentrators with Neil Smith (then) of IBM. E.R.N. acknowledges support from ONR under STTR award N00014-07-C-0355 and DOE under award DE-FG02-07ER46374. The authors would like to acknowledge valuable assistance and discussions on various aspects of this work with: Roger Koch, Neil Smith (HGST), Bill Doyle, Mark Stiles, Brian Maranville, Moshe Schmoueli, Cindi Dennis, Mike Donahue, Casey Uhlig, John Bonevich, Dave Pappas, Steve Russekk, Tom Silva, Mike Donahue, Justin Shaw, P.J. Chen, and Audie Castillo.

References

Biographies

W.F. Egelhoff, Jr. is a NIST Fellow at the National Institute of Standards and Technology. He received a PhD in physical chemistry from the University of Cambridge in 1975, where he was a postdoc at Caltech 1976–1977, he was a researcher at the GM Technology. He received a PhD in physical chemistry from the University of Cambridge in 1980. After a two year National Research Council (NRC) postdoctoral fellowship, he joined the permanent staff at NIST where he initially worked on developing new thin films, oscillatory exchange coupling, photoelectron diffraction including semi-classical electron-atom scattering models, and core-level binding-energy shifts.

P.W.T. Pong is a physicist and electrical engineer working on magnetoresistive magnetic field sensors and cancer nanotechnology at the Department of Electrical and Electronic Engineering (EEE), University of Hong Kong (HKU). He received a PhD in engineering from the University of Cambridge in 2005. After working as a postdoctoral researcher at the Magnetic Materials Group at the National Institute of Standards and Technology (NIST) for three years, he joined the HKU engineering faculty where he is now an assistant professor working on magnetic-tunnel-junction (MTJ) sensors, and the application of nanotechnology in cancer research.

James E. Burnett is a physicist working on the development of radiometric sensors at the U.S. Army Research Laboratory. He received his bachelor of science degree from Morehouse College in 1993, majoring in physics. In 1995 he received his master of science degree in physics from Clark-Atlanta University, where his thesis research focused on mathematical modeling of biological systems. In 2004, he received a PhD in physics from North Carolina State University, where his thesis research was focused on the growth and characterization of semiconductor thin films. In 2006, he received a postdoctoral position at the U.S. Army Research Laboratory as an Oak Ridge Associated Universities Fellow. His current research interests include flexible displays, flexible electronics, and biomimetics.

Greg Fischer was born in California, USA, in 1964. He received his bachelor of science in physics at the University of California, San Diego (UCSD) in 1988. From there he went to San Diego State University and worked on high temperature superconductor research, receiving his master of science in physics in 1992. He then returned to UCSD and entered the Materials Science Program. He pursued research on magnetic recording media at the Center for Magnetic Recording Research and received his PhD in materials science in 2000. He received a postdoctoral position at the US Army Research Laboratory in that same year from the American Society for Engineering Education and was subsequently hired on as a Materials Scientist. His fields of interest included magnetic sensors, magnetic recording media, read heads, magnetic modeling, and superconductivity.