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# Theoretical sensitivity in Magnetic field sensors using a spin-torque oscillator

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## Abstract

**Highly sensitive magnetic field sensors are required in many applications such as magnetic hard disk memories, position sensors and magnetic tags, for example. Magnetic tunnel junction (MTJ) is one of very sensitive magnetic field sensors. In addition, its very small size may offer a new application such as a detection of magnetic beads and, in the extreme case, even a single radical molecule detection for medical and/or chemical purpose. Here, we discuss theoretical limits of such sensors, especially, MTJ in auto-oscillation mode using macro-spin model and analytic formulations. The theory provides scaling of the sensor and reveals possibility to detect a single electron spin at room temperature.**

## 1. Introduction

Magnetic tunnel junctions (MTJ) using an MgO layer [1-3] as barrier have been used as read sensors in magnetic hard disc drives. It is known that its very small size and large signal output promoted rapid increase in recoding density.

Here, let us consider other applications of such small and sensitive sensors. For example, even a single electron spin makes considerable magnetic field if distance from the electron is very short. The magnetic dipole field from a single electron spin can be 40 time larger than that of the terrestrial magnetic field if the distance is 1 nm. Even for 100 nm distance, the field is larger than 1 [nT], and is much larger than sensitivity limit of magneto-impedance (MI) filed sensor. However, since MI sensor is large (around 1 mm), it cannot approach in such small distance. In contrast, size of MTJ can be several tens nano-meters. Therefore, it must be interesting to investigate theoretical limit and scaling of MTJ field sensors.

MTJ can be operated as a field sensor by passing a bias current that is smaller than critical current (dc mode). The current larger than the critical current, $I_{c0}$, causes in spin-transfer switching or spin-transfer auto-oscillation (STO). Even under auto-oscillation, the MTJ expected to work as a field sensor. Here, we compare theoretical detection limit (noise equivalent signal (NES)) of MTJ in dc mode and STO mode by employing a simple macro-spin model. In addition, size dependence of the NES will be also discussed.

## 2. Macro-spin model

The MTJ consist of two ferromagnetic layers, which is separated by an insulator barrier. Magnetization of one ferromagnetic layer is fixed (reference layer) and another ferromagnetic layer (free layer) may change its magnetization direction according to the external field. Here, we assume that uniform magnetization inside free layer and treat it as if a single macro-spin. This treatment is correct if the size of magnetic material is smaller than exchange length (about 5 nm, for example). For the free layers in realistic devices are still larger than this size and may include internal magnetic structures because of inhomogeneous demagnetization field or current induced Oersted field distribution. However, the macro-spin model is an effective and reasonable approximation to estimate theoretical limit of those devices.

Because of macro spin approximation, our physical variables are only θ and ϕ in polar coordinate that indicate a direction of spin-angular momentum. To adapt to the Hamiltonian type equation of motion, we take $(x^1, x^2)=(\phi, S(\cos\theta -1))$ as Hermitian conjugate variables. Here, $S$ is a total angular momentum in the free layer. Using these variables, the equation of motion of magnetization (LLG eq.+Slonczewski term) is expressed as follows [4];

$$\dot{x}^i \cong \begin{pmatrix} g^i_j \\ +\alpha S \varepsilon^{ik} g_{kj} \end{pmatrix} \begin{pmatrix} \varepsilon^{jl}\partial_l U \\ +S^{-1}\beta_{ST}\partial^j(\cos\Psi) \end{pmatrix} + F^i(x,t) \quad . (1)$$

Here, α Gilbert damping parameter, $U$ magnetic energy, Ψ angle between free and reference layer spin-angular momentum, $\beta_{ST}$ spin-transfer coefficient and $F^i$ stochastic torque (thermal noise field). $g^i_j$ and $\varepsilon^{ij}$ are Kronecker's delta and Levi-Civita symbol. $g_{ij}$ is the geometric tensor of the space.

After linearization of the eq. (1) around a stable equilibrium point, we may evaluate a linear response (Green) function of the system for an instantaneous input field. Since signal field and thermal noise are inputs for the same response function, NES is determined by a ratio between signal and the input equivalent noise. The NES does not depend on response function neither MR, if MR and electric output is large enough. NES for dc operation of MTJ is,

$$NES \le \sqrt{\frac{8\alpha k_B T \Delta f}{\gamma^2 S}} \quad , \tag{2}$$

where $k_B T$ is thermal energy, $\gamma$ is gyromagnetic ratio, and $\Delta f$ is band width of the detection circuit. Here, one may find that smaller Gilbert damping and larger total angular momentum (magnetic moment) provide better NES.

NES of MTJ in STO mode is given by linearizing eq. (1) around a limit cycle (auto oscillation trajectory). To do so, we further assume a uni-axial symmetry of the system. Under such condition, there will be two types of detection. One is a detection of change in STO power output (STO-power detection), and another is a detection of change in oscillation phase (STO-phase detection) [5] as a consequence of an external signal field application.

NES of the STO-power detection is expressed as follows,

$$NES \le \sqrt{\frac{8 k_B T \Delta f}{\alpha \gamma^2 S}} \quad . \tag{3}$$

Here, one may find that now $\alpha$ is a part of the denominator. Since $\alpha$ is a small value (0.01 for example), eq. (3) predicts worse sensitivity than dc mode operation. NES for the STO-phase detection mode is expressed as follows for a case of small agility;

$$NES \le \sqrt{\frac{2\alpha k_B T \Delta f}{\gamma^2 S}} \quad . \tag{4}$$

One may find that the STO-phase detection provide best NES.

These results are summarized in Fig. 1. Scaling rules are same for all detection modes. Since $S$ is proportional to the volume of the free layer, NES is inversely proportional to the sensor size if the film thickness is fixed. Apparently, larger MTJ provide better NES. In the figure, NES data estimated from literatures [5, 6] are also plotted. In the figure 1, dipole magnetic field from a single electron spin is plotted as function of distance from the electron. MR and STO-phase detection sensors show cross-point with the dipole field from a single electron spin at around several tens nm size. This means that such small MTJ field sensors have potential to measure a stray field from a single electron in principle.

## 3. Conclusions

We developed a micro-spin theory about detection limit of MTJ sensors. As results, we found that STO-phase detection and dc mode MR sensor should show best sensitivity to the small magnetic field. For a fixed free layer thickness, detectable filed strength is inversely proportional to the detector size. The small MTJ of several tens nm may detect a stray field from single electron spin in principle.


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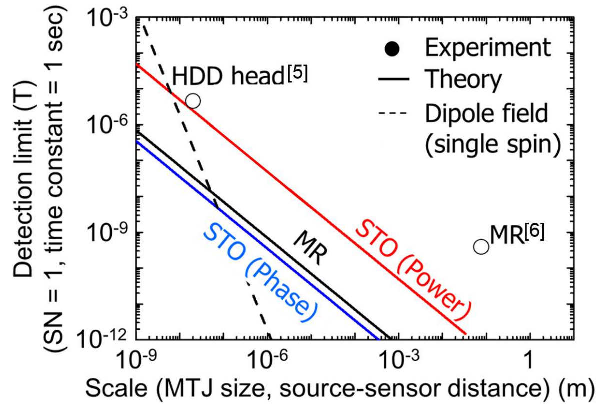


Fig. 1 Detection limit of MTJ sensor as a function of size. Theoretical prediction of 3 different detection modes are plotted by solid lines. Magnetic field from a single electron spin is indicated by dotted line. Estimated sensitivities obtained from literatures [5, 6] are also plotted.