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Magnetic Tunnel Junction Magnetic Field Sensor Design Tool

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Abstract- **A spreadsheet-based magnetic tunnel junction (MTJ) sensor design tool is presented in this paper. The system is developed using Excel and Visual Basic Application. It allows users to optimize the various parameters of the sensor design with the goal of SQUID-like sensitivity. Users can input parameters of the design including magnetic properties, junction areas, and free layers thicknesses. The design tool will then calculate and display automatically various noise sources including Johnson noise, shot noise, 1/f noise, and thermal magnetic noise that must be considered when building MTJ magnetic field sensors. Graphs predicting the sensitivities, operating current and power of the finished sensors are shown and fine tuning of each design parameter is allowed using the scrollbars provided. Using this design tool, effects of changes made to any design parameter can be clearly observed and detailed noise analysis can be studied without manually repeating complex calculations.**

I. INTRODUCTION

To design a ultrasensitive magnetic tunnel junction (MTJ) magnetic field sensor with sensitivity down to 1 picoTesla, calculations needs to be performed iteratively to plot noise analysis graphs for analyzing the MTJ sensor performance [1-3]. Moreover, there are 15 design parameters needed to be studied and their effects on sensor performance are intertwined. The complexity and the time needed for a complete noise analysis make the design optimization task impossible to be handled manually. An automatic calculation system that enables scientists to observe the influence of each design parameter on sensor performance in real-time will be greatly conducive to the development of MTJ sensors.

II. MTJ MAGNETIC SENSOR DESIGN TOOL

A spreadsheet-based MTJ magnetic sensor design tool is presented in this paper. It can re-calculate the entire sheet automatically whenever an update to a single cell is made [4]. The system was developed using Microsoft Excel and Visual Basic Application (VBA). Eq. (1) and (2), based on our mathematical derivations [5], show the calculation of the total

noise composed of amplifier noise, shot and Johnson noise, electronic 1/f noise, thermal magnetic noise, and magnetic 1/f noise.

$$S_B = S_B^{Amp} + S_B^{shot} + S_B^{elec.1/f} + S_B^{therm..mag} + S_B^{mag.1/f}$$

eq. (1)

$$S_B = \frac{4B_{sat}^2}{(\Delta R/\overline{R})^2 N^2 V_J^2}\left[S_V^{Amp} + N\frac{2eV_J[RAP]}{A}\coth\left(\frac{eV_J}{2k_BT}\right) + N\frac{\alpha_{elec.}V_J^2}{Af}\right]$$
$$+\frac{1}{N}\frac{4k_BT\mu_0\alpha_G}{\Omega\gamma M_s}+\frac{2B_{sat}}{N}\frac{\alpha_{mag}}{\Omega f}$$

eq. (2)

In eq. (2), α_{mag} is magnetic 1/f noise Hooge parameter, A is MTJ area, [RAP] is resistance-area product, f is detection frequency, $\alpha_{elect.}$ is electronic Hooge parameter, Ω is free-layer volume, α_G is Gilbert damping parameter, V_J is junction voltage, and N is number of MTJs per leg. The sensor model in this design tool is a MTJ sensor integrated with a MEMS flux concentrator which is used to eliminate 1/f noise [6]. Users can input sensor design parameters including junction voltage, number of MTJs in each leg of the Wheatstone bridge, junction area, saturation field, tunneling magnetoresistance (TMR), flux concentrator gain, amplifier noise, operating temperature, junction resistance-area product (RA), magnetic free layer saturation magnetization, damping alpha, electronic 1/f noise alpha, operating frequency, free layer thickness, and magnetic 1/f noise alpha. The effects on various kinds of MTJ sensor noises are calculated by eq. (1) and (2) and visualized immediately through graphical displays. Fine tuning on each design parameter is enabled using the scrollbars provided in the Tool Menu and the noise analysis is displayed in real-time.

III. RESULTS AND DISCUSSION

This Excel spreadsheet design tool is divided into the (i) design mode (fig. 1) and (ii) implement mode (fig. 2). In the design mode, modifications of equations and input of various data can be carried out and the sensor performance calculation results are shown in numerical forms. In the implement mode, performance of the sensor defined in the design mode is shown in graphical forms. By using this design tool, a possible sensor design with sensitivity close to 1 picoTesla per sqrt Hz is obtained.

[1]Department of Electrical and Electronic Engineering, University of Hong Kong, Pokfulam Road, Hong Kong, *Email: ppong@eee.hku.hk
[2]Center for Nanoscale Science and Technology, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland MD 20899, USA
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[5]Metallurgy Division, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland MD 20899, USA

No. of point 1000   No. of record 400

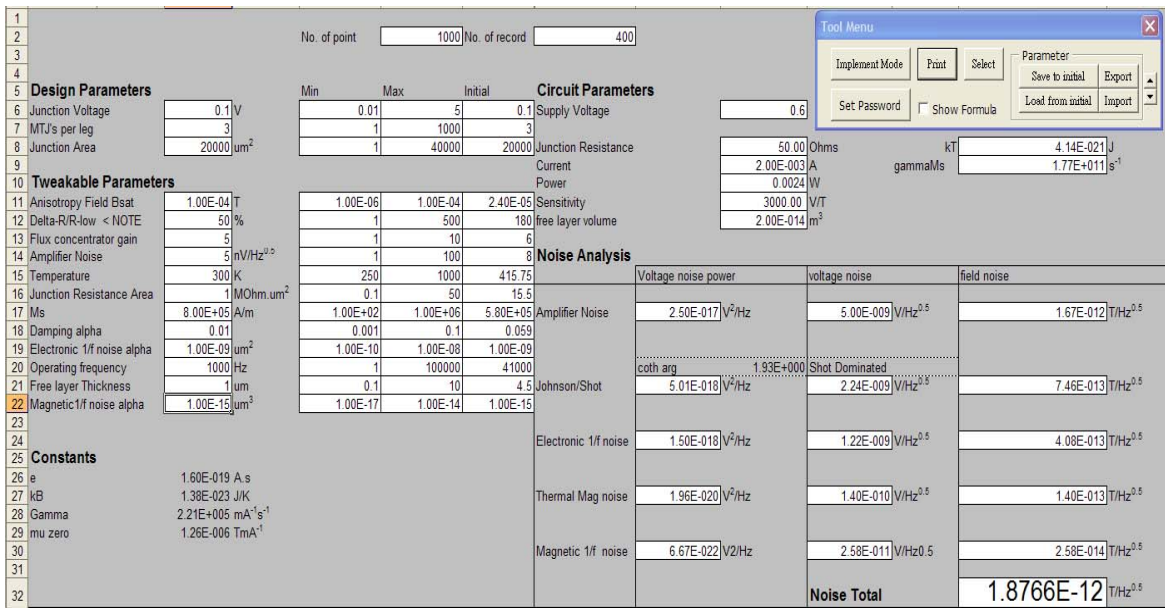| Design Parameters		Min	Max	Initial	Circuit Parameters				
Junction Voltage	0.1 V	0.01	5	0.1	Supply Voltage	0.6			
MTJ's per leg	3	1	1000	3					
Junction Area	20000 um²	1	40000	20000	Junction Resistance	50.00 Ohms	kT	4.14E-021 J	
					Current	2.00E-003 A	gammaMs	1.77E+011 s⁻¹	
Tweakable Parameters					Power	0.0024 W			
Anisotropy Field Bsat	1.00E-04 T	1.00E-06	1.00E-04	2.40E-05	Sensitivity	3000.00 V/T			
Delta-R/R-low < NOTE	50 %	1	500	180	free layer volume	2.00E-014 m³			
Flux concentrator gain	5	1	10	6					
Amplifier Noise	5 nV/Hz⁰·⁵	1	100	8	**Noise Analysis**				
Temperature	300 K	250	1000	415.75		Voltage noise power	voltage noise	field noise	
Junction Resistance Area	1 MOhm.um²	0.1	50	15.5					
Ms	8.00E+05 A/m	1.00E+02	1.00E+06	5.80E+05	Amplifier Noise	2.50E-017 V²/Hz	5.00E-009 V/Hz⁰·⁵	1.67E-012 T/Hz⁰·⁵	
Damping alpha	0.01	0.001	0.1	0.059					
Electronic 1/f noise alpha	1.00E-09 um²	1.00E-10	1.00E-08	1.00E-09	coth arg	1.93E+000	Shot Dominated		
Operating frequency	1000 Hz	1	100000	41000	Johnson/Shot	5.01E-018 V²/Hz	2.24E-009 V/Hz⁰·⁵	7.46E-013 T/Hz⁰·⁵	
Free layer Thickness	1 um	0.1	10	4.5					
Magnetic1/f noise alpha	1.00E-15 um³	1.00E-17	1.00E-14	1.00E-15					
					Electronic 1/f noise	1.50E-018 V²/Hz	1.22E-009 V/Hz⁰·⁵	4.08E-013 T/Hz⁰·⁵	
Constants									
e	1.60E-019 A.s								
kB	1.38E-023 J/K				Thermal Mag noise	1.96E-020 V²/Hz	1.40E-010 V/Hz⁰·⁵	1.40E-013 T/Hz⁰·⁵	
Gamma	2.21E+005 mA⁻¹s⁻¹								
mu zero	1.26E-006 TmA⁻¹				Magnetic 1/f noise	6.67E-022 V2/Hz	2.58E-011 V/Hz0.5	2.58E-014 T/Hz⁰·⁵	
					Noise Total			**1.8766E-12** T/Hz⁰·⁵	

Fig. 1. Interface of the design mode with Tool Menu. This is for users inputting design parameters (left hand side of the interface) and displaying sensor performance calculation results in numerical forms (right hand side) in real-time. The Tool Menu (top right corner) enables switching between implement mode and design mode, exporting and importing design configurations, saving graph data, and printing the results.
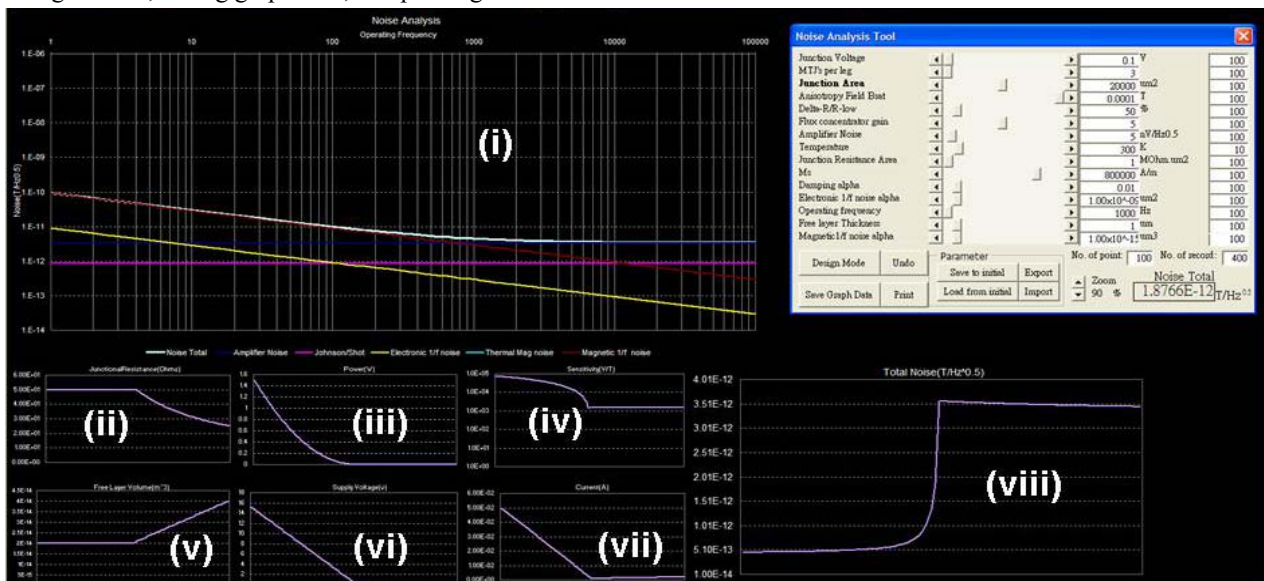
Fig. 2. Interface of the implement mode with (i) Noise Analysis Graph (ii) Junction Resistance Graph (iii) Power Graph (iv) Sensitivity Graph (v) Free Layer Volume Graph (vi) Supply Voltage Graph (vii) Current Graph (viii) Total Noise Graph and Tool Menu at the top right corner. Graph (i) displays the amplifier noise, shot and Johnson noise, electronic 1/f noise, magnetic 1/f noise, and thermal magnetic noise. The graphs (ii) to (vii) and graph (viii) show the present and previous values of the design parameters and the total noise level to illustrate the effects of design parameter changes on total noise level.

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