Comprehensive noise characterisation of magnetic tunnel junction sensors for optimising sensor performance and temperature detection

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Noise performance of magnetic tunnel junction (MTJ) sensors is impacted by various factors including junction structure, post-deposition treatment, and operating parameters. The optimisation of these factors can lead to a better MTJ sensor design with minimised noise level and enhanced detectivity for functioning as a magnetometer. In this paper, the authors studied the influence of several parameters (bias voltage, temperature, magnetic field, and junction area) on the noise performance of MTJ sensors. Relatively high bias voltage and low ambient temperature were suggested to be helpful in reducing the electronic 1/*f* noise. A mechanism of utilising MTJ as a temperature sensor by making use of the mid-frequency noise (from 10.0 kHz to 22.8 kHz) was proposed. The relation between temperature and noise power was obtained by numerically fitting the measured noise power with an equation composing of three components representing background noise, intertwined thermal and shot noise, and non-linear noise source, respectively. Temperature of the junction could be determined by measuring the mid-frequency noise power at certain bias voltage and substituting it into the equation. This provides a possible route of using a MTJ as a multifunctional sensor for sensing both magnetic field and temperature.

Keywords: Magnetic tunnel junction (MTJ), Noise performance, Electronic 1/*f* noise, Temperature detection

Introduction

Magnetic tunnel junction (MTJ) devices have become promising candidates for magnetic field sensing applications[1–3] owing to their high stability and sensitivity. Although research endeavour on boosting up tunneling magnetoresistance (TMR) of MTJ sensors can enhance their sensitivity, noise investigation can lead to MTJ sensors with lower noise floor and thus better detectivity. Noise sources in MTJ sensors from different mechanisms, including thermal noise,[4] shot noise,[5] electronic 1/*f* noise,[6] random telegraph noise (RTN),[7] thermal magnetic noise,[8] and magnetic 1/*f* noise,[9] have been studied over the past couple of decades. The frequency-independent component of the noise floor is typically contributed by the thermal noise and shot noise, whereas the 1/*f* noise or sometimes RTN dominates in the low-frequency range.[10] The noise spectrum of a MTJ sensor is impacted by various factors, such as bias voltage,[11] temperature,[12] magnetic field,[13] junction size,[9] free-layer thickness,[9,14] and post-deposition treatment,[15,16] etc. The optimisation of these factors can lead to a better MTJ sensor design with minimised noise level and enhanced detectivity for functioning as a magnetometer.

As a fundamental quantity, temperature was reported to show correlation with white noise.[6] At low bias voltage, the combination of the thermal noise and shot noise is given by $S_V = 4K_BTR + 2FR[eV\,coth\,(eV/(2K_BT) - 2K_BT]$.[6,12] Here T, R, V, e, and K_B represent the temperature, resistance of the junction, bias voltage, electron charge, and Boltzmann constant, respectively. F is the Fano factor. Quantitative analysis of the white noise at low temperature (3.3, 6.8, and 12 K) was reported by Sekiguchi's group.[12] White noise power at certain bias voltage was found to monotonically increase with the temperature. This phenomenon provides a possible route of using a MTJ as a temperature sensor. Spietz *et al.* proposed a shot noise thermometer based on a metallic tunnel junction.[17] Temperature of the junction can be determined by fitting the measured white-noise power as a function of bias voltage. However, this method requires high-precision radio frequency (RF) measurements and a large amount of data to determine the complete temperature response.

In this paper, the authors first studied the relation between noise performance of the MTJ sensors and four factors: bias voltage, temperature, magnetic field, and junction area. Some strategies for optimising MTJ sensor performance are suggested. Then temperature

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dependence of the measured noise power was investigated. The authors proposed a simple and feasible mechanism of utilising MTJ as a temperature sensor by making use of the temperature-dependent noise.

Experimental methods

MTJ thin films were deposited on thermally oxidised silicon wafers by magnetron sputtering under a base pressure of 2.66×10^{-7} Pa (2×10^{-9} Torr). The samples have the following structure (units in angstroms): substrate/Ta (25)/Au (25)/IrMn (100)/CoFe (40)/Al (10) + plasma oxidisation, O_2=0.133 Pa (1×10^{-3} Torr)/CoFe (50)/Ta (50)/Ru (70). The Al_2O_3 tunnel barrier was made by depositing a layer of Al metal and subsequently oxidising it in an oxygen plasma. After deposition, the samples were annealed at 280°C for 1 h. A self-aligned photolithography and etching processes were then carried out to pattern the MTJ thin films into 20 μm × 20 μm junctions.

Noise measurements were performed in a cryostat (ARS DE202§) at 5 K, 80 K, 175 K, and 300 K, with temperature stability of ± 0.1 K. The schematic diagram of the noise measurement setup is displayed in Fig. 1*a*. In order to eliminate the noise from the mains supply, a battery and a variable resistor were used to provide a stable DC current to the MTJ. The magnetic field was generated by an electromagnet (GMW 3470§) mounted along the easy-axis of the MTJ. The voltage signals across the junction were amplified individually using two low-noise voltage amplifiers (FEMTO DLPVA-100-BLN-S§) operated at room temperature and then inputted to a dual-channel dynamic spectrum analyser (HP 35670A§). The spectrum analyser carried out measurement in cross-correlation mode in order to effectively reduce the external noise floor. The compressor and chiller of the cryostat were switched off during the noise measurement to avoid any noise from them. The error bars in the figures represent one standard deviation from the mean. §Disclaimer: The use of manufacturer names and trademarks are only for the purpose of completely describing the experimental conditions and does not imply an endorsement of the authors or their organisations.

Noise was measured from 0.1 kHz to 22.8 kHz. The low-frequency spectrum (0.1 kHz to 10.0 kHz, 1600 points) was used to characterise the frequency-dependent noise of our MTJ sensors, whereas the mid-frequency spectrum (10.0 kHz to 22.8 kHz, 1600 points) was used to characterise the frequency-independent noise and analysed for temperature detection. The frequency-dependent noise was extracted by numerically fitting the spectra with an equation,

$$S_V = \alpha V^2 / A f^{\gamma} + S_0 \quad (1)$$

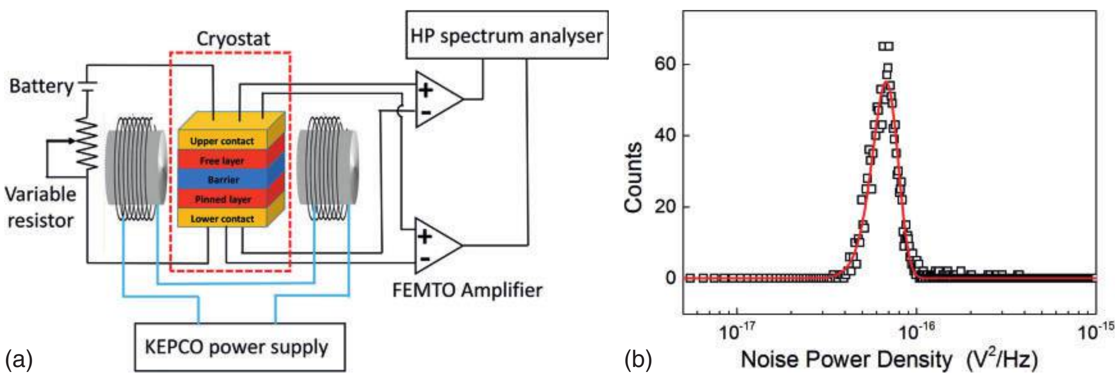
where α is the Hooge parameter, V is the bias voltage across the junction, A is the junction area, f is the frequency, γ is the exponent of the 1/f noise that is usually close to 1, and S_0 is the white noise component. The magnitude of the mid-frequency noise power was estimated by performing histogram analysis[12] of the measured noise power spectrum between 10.0 kHz and 22.8 kHz. As shown in Fig. 1*b*, the peak of the Gaussian fitting curve of the histogram was considered as the magnitude of the mid-frequency noise power.

Results and discussion

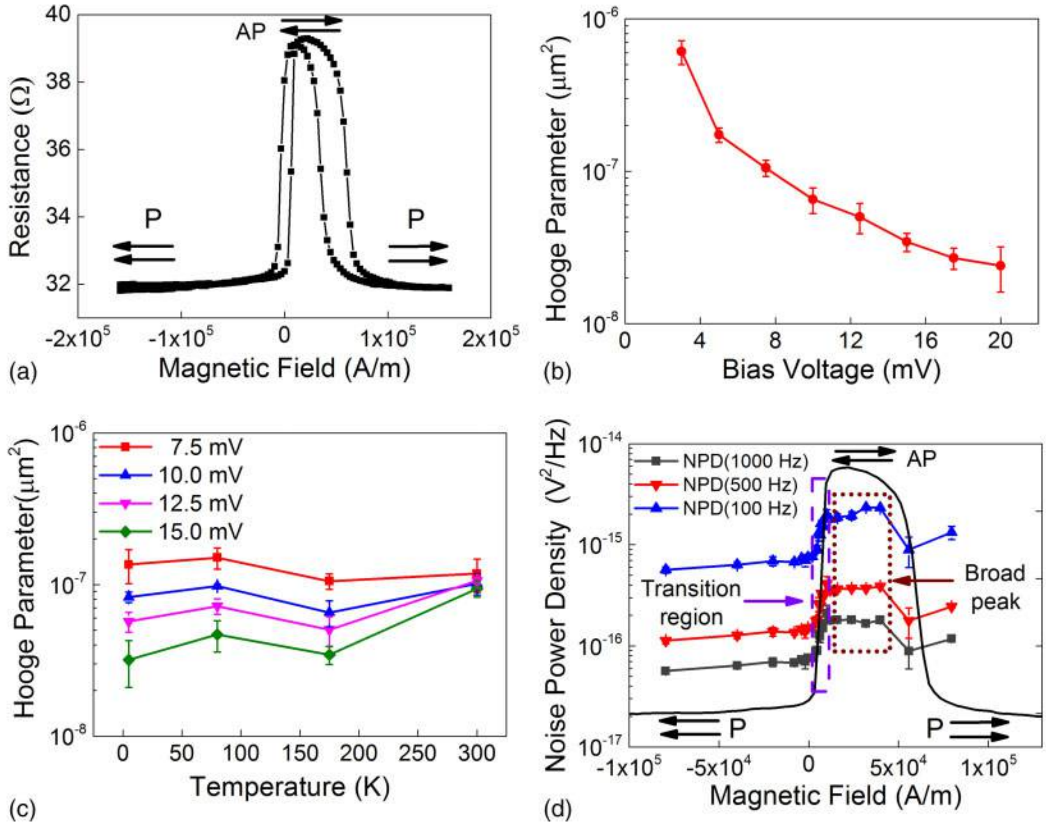
Influence of bias voltage, temperature, magnetic field, and junction area on noise performance

The magnetoresistance (MR)[18] transfer curves of the MTJ samples were characterised at 300 K, and a typical transfer curve is shown in Fig. 2*a*. The resistance of the junction in parallel (P) magnetisation configuration is ≈32.0 Ω, while the resistance in antiparallel (AP) magnetisation configuration is ≈39.3 Ω. The MR ratio defined by $(R_{AP} - R_P)/R_P$ is ≈22.8%.

The influence of bias voltage on the frequency-dependent noise of our sensor was investigated. Figure 2*b* shows the Hooge parameter (α) as a function of the bias voltage for the MTJs in the P state under -7.96×10^4 A m^{-1} (−1000 Oe) measured at 175 K. A decrease in α with the increasing bias voltage was observed, which was also reported by other groups.[10,19] As the bias voltage increased, more localised states in hopping channels were formed.[19] The hopping process in the insulating layer was then enhanced, which reduced the population of trapping electrons and thus suppressed the resistance fluctuation caused by the trapping electrons. These results indicate that a high bias voltage could suppress the electronic 1/f noise. However, the optimal bias voltage should not be too large to avoid the RTN that could possibly occur at high bias voltage.[10]



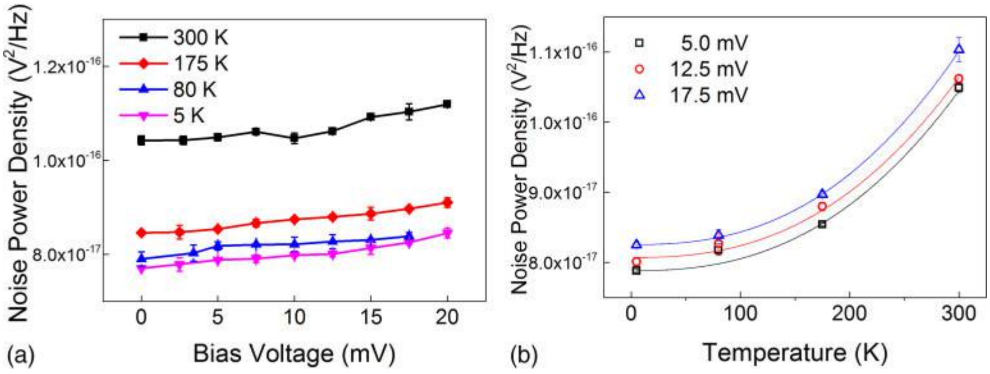
1 *a* Schematic diagram for noise measurement setup. The magnetic tunnel junction (MTJ) sample was housed in a cryostat represented by the *red* dotted line. A DC bias was applied under a constant current condition by using a battery through a variable resistor. An electromagnet was used to apply external field longitudinally to the MTJ sensor. The voltage signals across the junction were first amplified and then inputted to a spectrum analyser; *b* Gaussian fitting of the histogram of the noise spectrum was carried out to determine the magnitude of the noise power



2 ***a*** **Typical magnetoresistance transfer curve of the magnetic tunnel junction (MTJ) measured at 300 K;** ***b*** **Hooge parameter as a function of the bias voltage for the MTJ in P state measured at 175 K;** ***c*** **Hooge parameter as a function of temperature for the MTJs in P state measured at various bias voltages;** ***d*** **Noise power density (NPD) as a function of magnetic field for the MTJs measured by sweeping the magnetic field from -7.96×10^4 A m^{-1} to 7.96×10^4 A m^{-1} (from -1000 Oe to 1000 Oe)**

The α was not only dependent on the bias voltage but also affected by the temperature. Figure 2*c* exhibits the temperature dependence of α at several bias voltages. Typically, a decrease in α at bias voltage of 10.0 mV, 12.5 mV, and 15.0 mV was observed as the temperature decreased from 300 K to 175 K. This phenomenon suggests that the lifetime of the generated localised states in hopping channels can probably be elongated as the temperature decreased.[20] As a result, number of trapping electrons could be reduced, leading to the decline in α. However, α at the smaller bias voltage (7.5 mV) only exhibited a trivial decrease. This behaviour is probably because the number of localised states at low bias voltage is relatively small as compared to that at higher bias voltage, and thus the influence of elongated lifetime of these states on the population of the trapping electrons is insignificant. Below 175 K, no obvious change in α was observed, suggesting that the trapping process was nearly temperature-independent at low temperature.[21] Further study on temperature dependence of the emission rate and capture rate of the trapping electrons is needed to understand this phenomenon. However, in most cases, MTJ sensors work at around room temperature, the sensor performance therefore might be improved at lower ambient temperature that leads to decreased $1/f$ noise. Noise measurements between 175 K and 300 K are in progress to verify this suggestion.

To study the magnetic origin of the frequency-dependent noise in our junctions, the authors measured the noise spectra while sweeping the external magnetic field from -7.96×10^4 A m^{-1} to 7.96×10^4 A m^{-1} (from -1000 Oe to 1000 Oe) to switch the magnetisation alignment of the MTJ from P to AP and back to P. Figure 2*d* shows the dependence of noise power on the applied magnetic field, which was slightly different from the typical results reported by other groups.[6,9,22–24] The noise power was boosted up in the transition region (indicated by the dash rectangle) just like reported in the literature;[9,20] however, an abnormally high noise power broad peak (indicated by the dot rectangle) was exhibited in the AP state and this peak remained plateau for the most part of the AP state without responding to the increasing magnetic field. This indicated that this broad noise peak was non-magnetic in origin. The $1/f$ noise of magnetic origin appeared to be overwhelmed by this non-magnetic broad noise peak even in the transition region. By analysing our own data and comparing with the published literatures, some of its characteristics could be stated as follows: (1) it usually appears at high frequency such as 20 kHz[22] but could be easily overwhelmed by the magnetic $1/f$ noise in some cases;[9,24] (2) it is likely to appear in relatively large junction area.[9] A similar non-magnetic $1/f$ noise was reported to be present in Fe/MgO/Fe junctions with the larger junction size (20 μm × 20 μm), but totally absent in the smaller ones (2 μm × 2 μm, 5 μm × 5 μm);[25] (3) it appears to be independent of the barrier material and ferromagnetic layer/barrier interface. Both our samples (CoFe/Al+plasma oxidisation/CoFe) and the published results (Fe/MgO/Fe)[25] exhibited this non-magnetic $1/f$ noise. Based on the aforementioned discussion, shrinking the junction area could be an effective way to minimise this non-magnetic $1/f$ noise and improve the detectivity of MTJ sensors.



3 ***a*** **Mid-frequency noise power as a function of the bias voltage for the magnetic tunnel junctions (MTJs) in P state measured at 5 K, 80 K, 175 K, and 300 K;** ***b*** **mid-frequency noise power against temperature and the fitted curves at bias voltage of 5.0 mV, 12.5 mV, and 17.5 mV**

Temperature detection based on MTJ sensor

The mid-frequency (10.0 kHz to 22.8 kHz) noise is relatively independent of frequency. The magnitude of the mid-frequency noise power was estimated by performing histogram analysis, as mentioned earlier. The temperature dependence of the mid-frequency noise was investigated in order to reveal their correlation. Figure 3*a* shows the measured mid-frequency noise as a function of the bias voltage for the MTJs in P state at 5 K, 80 K, 175 K, and 300 K, respectively. In order to describe the temperature response of the noise power mathematically, numerical fitting was carried out on the measured mid-frequency noise power. The mid-frequency noise power data at different bias voltages were fitted by the following equation

$$S_v(T) = S_{bg} + aV\coth\ (bV/T) + cT^{\beta} \qquad (2)$$

Here, S_{bg} is the background noise floor, $aV\coth\ (bV/T)$ is the contribution of thermal noise and shot noise and V represents the bias voltage, cT^{β} is the non-linear component. Constants a and b are $2eR$ and $\frac{e}{2K_B}$, respectively. e is the electron charge. R is the resistance of the junction. The exponent β (≈2.5) was obtained by fitting equation (2) to the measured mid-frequency noise with the largest R^2 (the coefficient of determination). Figure 3*b* shows the plot of mid-frequency noise power versus temperature and the fitted curves at different bias voltages. The fitted curve at each bias voltage closely resembles the trend of the measured data with the values of R^2 close to 1, as given in Table 1. In addition, the fitting equation (2) with the same β can fit the measured temperature-dependent noise power at various bias voltages very well, indicating the temperature response of this mid-frequency noise is nearly the same at different bias voltages. This behaviour provides a broad range of choice for selecting an optimal bias voltage for a MTJ to function as a temperature sensor.

Table 1 R^2 **versus various bias voltages**

Bias voltage/mV	R^2
5	0.99277
7.5	0.99086
10	0.98829
12.5	0.99687
15	0.99981
17.5	0.99927

In order to enhance the detectivity of the proposed MTJ temperature sensor, some improvements of our system need to be carried out. The frequency range (10.0 kHz to 22.8 kHz) of the measured noise spectrum was not high enough to evade the influence of 1/*f* noise and thus the measured mid-frequency noise was weakly frequency-dependent rather than purely white, resulting in the measured noise power being larger than the theoretical predicted white noise. The noise can be measured with a larger frequency range so that the mid-frequency noise can be defined at a higher frequency where the noise would be even more frequency-independent. Also, the temperature-independent portion of the total noise could degrade the sensor detectivity because as the temperature-independent noise increases, the temperature-dependent portion of the total noise would become smaller, making the detection of the temperature-induced variation in the measured noise more difficult. The noise floor of this temperature-independent noise can be suppressed by eliminating the influence from the frequency-dependent noise and external noise sources, such as the background noise from ambience and intrinsic magnetic field fluctuations of the electromagnet. The contribution of frequency-dependent noise on the noise floor can be minimised by measuring the mid-frequency noise at a higher frequency range, as discussed earlier. A Wheatstone bridge configuration[13] of the sensor and a mu-metal shielding can be used to reduce the background noise. The magnetic field fluctuations can be suppressed by utilising an electromagnet powered by a current source with higher stability and precision.

Conclusion

The influence of several parameters on the noise properties of the MTJ was investigated to optimise sensor performance. High bias voltage and low ambient temperature were suggested to be helpful in reducing the electronic 1/*f* noise. Fabricating MTJs with small junction sizes may effectively eliminate the non-magnetic 1/*f* noise, which still requires further studies for verification. However, please note that these strategies may contradict with each other and trade-off is needed in order to optimise noise performance and sensor's detectivity. Then, a mechanism of utilising MTJ as a temperature sensor by making use of the mid-frequency noise was proposed. The temperature response of the noise power was studied, and it was numerically fitted with an equation. This equation describes the relation between the noise power and the temperature. As such, the whole temperature response curve of the noise power could be pre-determined. Temperature of the junction could then be determined by measuring the mid-frequency noise power at a certain bias voltage and substituting it in the corresponding fitting equation. This work provides a possible route of using a MTJ as a multifunctional sensor for sensing both magnetic field and temperature.

In order to enhance the detectivity of magnetic field of our sensor, the authors will aim to minimise noise level by optimising sensor geometry and material compositions and improving junction quality with smoother interlayer interface and reduced barrier defects. For achieving better temperature detectivity based on MTJ sensor, future work on reducing the temperature-independent portion of the total noise is needed to minimise its overshadowing on the temperature-dependent noise.

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