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MgO-based magnetic tunnel junction sensors array for non-destructive testing applications

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A MgO-based magnetic tunnel junction (MTJ) sensor including 72 MTJs in series with 50 × 50 μm² was successfully microfabricated. Due to a two-step annealing strategy, a linear transfer curve was obtained. The tunneling magnetoresistance (TMR) value is as high as 159% and the sensitivity reaches 2.9%/Oe. The field detectivity exhibits the lowest value at 1 V bias current, attaining 1.76 nT/Hz⁰.⁵ for 10 Hz and 1 kHz, respectively. The results show that the sensor could be applied in non-destructive testing systems which are used for detecting small defects inside conductive materials. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4863933]

I. INTRODUCTION

In the past few years, magnetoresistive (MR) sensors have been investigated and used on non-destructive testing (NDT) of conducting materials (eddy currents) as an alternative to established sensing technologies based on inductive probes.¹,²,³ The main advantages of MR sensors resides in their high sensitivity at low frequencies which allow the detection of defects located inside conductive materials. Presently, commercial MR sensors, mainly based on anisotropic magnetoresistance (AMR) and giant magnetoresistance (GMR) technologies mounted on a bridge configuration, have proved their ability for detecting buried defects. However, at our knowledge, there are few reports using a probe based on Magnetic Tunnel Junctions (MTJs) sensors. The main reason of the lower popularity of MTJs is that commercial MTJ sensors have not reached the required detectivity levels (hundreds of pT/Hz⁰.⁵ at 1 kHz), and therefore, it is still unable to compete with AMR and GMR sensors yet.¹,² In this work, an optimized MTJ sensor was fabricated to reach competitive levels of detectivity.

In non-destructive testing of buried defects using eddy currents, the defect sizes typically have dimensions of few millimeters and are located some millimeters deep inside a conducting material.⁴ Therefore, the magnetic field variations sensed at the surface of the material due to the defect will be almost constant over a relatively large area. Taking advantage of it, the MTJ sensor presented in this work was designed with an active area of 0.5 × 0.5 mm². This area was filled with a series of MTJs with large areas allowing improved signal and detectivity.⁵,⁶

At low frequencies, the noise spectrum is dominated by the 1/f noise and sometimes random telegraph noise (RTN). It was proved that the RTN is strongly dependent on particular bias voltages and can be minimized by the proper annealing procedures.⁷,⁸ Therefore, the main low-frequency noise contribution is the 1/f noise. In a series of N MTJs, the noise spectral density is given by

\[ S_N(V^2/Hz) = N \left[ 2eVR \coth \left( \frac{eV}{2k_BT} \right) + \frac{2V^2}{NF^2} \right] \quad (1) \]

The first term represents the white background noise, and the second one is the 1/f noise. In Eq. (1), V is the bias voltage, R is the resistance, e is the electron charge, k_B is the Boltzmann constant, and T is the temperature. In the second term, A is the area of the junction, f is the frequency, γ is the exponent (usually ~1), and α is the Hooge-like parameter.⁹,¹⁰ As observed in this equation, the 1/f noise can be reduced by increasing the area of the MTJs. Furthermore, although the noise power of the series of MTJs is increased by a factor of N², the signal power is also increased by a factor N, which makes an overall increase of the signal to noise ratio by a factor of \( \sqrt{N} \) as demonstrated in Refs. 7, 9, and 11.

In this work, we propose a sensor geometry based on MTJs for detection of buried defects inside conducting materials. A series of 72 MTJs, each 50 × 50 μm², is placed in a square array (0.5 × 0.5 mm²). Bias voltages dependence of low frequency noise and field detectivity of the device has been further investigated.

II. EXPERIMENTS

The MgO-based MTJs stack was deposited at INL in an automated sputtering system (Singulus Timaris tool) and consists of SiAlO₃ 100/Ta 5/Ru 15/Ta 5/Ru 15/Ta 5/Ru 5/IrMn 4/Co₅Fe₃₅ 2/Ru 0.85/Co₁₆Fe₇₂ 2.6/MgO 1/CoFe₁₆B₂₀ 2/Ta 0.21/NiFe 4/Ru 0.20/IrMn 20/Ru 2/Ta 5/Ru 10/TiW(N) 15 (thicknesses in nanometers). The resistance-area (R × A) product of the stack is about 20 kΩ μm². For this stack, two high vacuum annealing steps were performed: (i) at 330 °C (first anneal) and (ii) 150 °C (second anneal) under an applied magnetic field of 1 T for 2 h. The applied magnetic field in

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the second annealing is perpendicular to the first field direction, which aims to set an orthogonal configuration between the pinned layer and free layer allowing a linear response of the sensor. The sample was then patterned at INESC-MN by optical lithography and ion beam milling, defining the 72 individual MTJ elements with an area of $50 \times 50 \mu m^2$. The 72 MTJs were then connected in series by depositing $\text{Al}_{98.5}\text{Si}_{1}\text{Cu}_{0.5}$ $300 \text{ nm/TiWN}_2$ $15 \text{ nm}$ and defining the contacts by lift-off. The magnetoresistance and noise properties of the device were measured at room temperature using the same methods as in Refs. 12 and 13.

III. RESULTS AND DISCUSSION

Figure 1 shows the typical TMR curve of the sensor. The inset is an optical microscope image of the device. It is seen that high TMR value of about $159\%$ and low coercivity ($H_c$) of about $0.96 \text{ Oe}$ are obtained. In addition, the TMR exhibits a good linearity in the range of $-20$ to $40 \text{ Oe}$, which demonstrates the orientation of free and pinned layer’s magnetization is effectively in a crossed configuration. Furthermore, the sensitivity (1/RdR/dH) can be deduced from the TMR curve and shows a maximum of $2.9\%/\text{Oe}$. However, at zero field, the sensitivity is $1.1\%/\text{Oe}$ due to magnetic coupling between free and pinned ferromagnetic layers. This value satisfies the requirement for NDT applications since AMR and GMR sensors typically exhibit much lower sensitivities.

Noise measurements from dc to $200 \text{ kHz}$ and for bias voltages ranging from $0.163 \text{ V}$ to $10 \text{ V}$ are shown in Figure 2. The measured data clearly indicate a $1/f$ dominated regime at frequencies below $1 \text{ kHz}$. For lower voltages (i.e., $163 \text{ mV}-2.3 \text{ mV/MTJ}$ and $250 \text{ mV}-3.5 \text{ mV/MTJ}$), it can be observed that the device is in the thermal noise regime for frequencies above $1 \text{ kHz}$. This is in accordance with Eq. (1), where the usual thermal (Johnson) noise relation ($S_{th}^2 = 4k_BTR$) is obtained for the low bias voltages ($eV \ll k_BT$). Furthermore, as predicted by Eq. (1), the noise of the device increases as the bias voltage increases.

The noise spectrum is fitted by using Eq. (1), and the parameters of $\alpha$ and $\gamma$ are obtained. As seen in Figure 3, the Hooge-like parameter $\alpha$ is constant for all the measured bias voltage, and the value is $(1.70 \pm 0.08) \times 10^{-7} \mu m^2$. Moreover, the $\gamma$ parameter is about 1, which demonstrates that the low frequency noise is effectively dominated by a $1/f$ behavior.

Usually, the field detectivity ($D$) in $T/Hz^{0.5}$ is defined as

$$D = \frac{S_V}{\Delta V/\Delta H},$$

(2)

where $S_V$ is the output noise (in $V/Hz^{0.5}$) of the sensor and $\Delta V/\Delta H$ is the sensitivity (in $V/Oe$). As observed in the inset of Figure 4(a), an increase in the sensitivity up to $0.16 \text{ V/Oe}$ is obtained as the bias voltage increases. However, the increment of the sensitivity is not directly proportional to the increase of the bias voltage since the TMR decreases at higher bias voltages. Furthermore, Figure 4(a) shows that the field detectivity decreases as the frequency increases, and the lowest value is $16.9 \text{ pT/Hz}^{0.5}$ at $200 \text{ kHz}$. For frequencies above $1 \text{ kHz}$, at lower voltages, this detectivity reduction is limited because of the thermal background. Therefore, for high frequency, the optimum detectivity is obtained at large bias voltage where the noise level is still in the $1/f$ regime. On the other hand, at low frequency, the detectivity seems to be roughly the same for all voltages (Figure 4(a)). However, going in more detail and plotting the field detectivity as a function of the voltage (Figure 4(b)) at a frequency of $10 \text{ Hz}$.
and 1 kHz, a first decrease followed by an increase of the detectivity with the bias voltage is observed. In fact, it is shown that although a large increase in sensitivity (in V/Oe) is observed by increasing the bias voltage (inset of Figure 4(a)), the field detectivity is better at 1 V than at 10 V (Figure 4(b)). This is due to the fact that the overall noise level of the device increases linearly with the bias voltage (Figure 2, Eq. (1)), while the sensitivity increases with a non-direct proportionality. Therefore, the lowest field detectivity is obtained at a particular bias voltage (Figure 4(b)). Similar results are reported in Refs. 14 and 15. With the sensor geometry presented in this work, the lowest detectivity obtained is 1.76 nT/Hz^{0.5} of 10 Hz and 170 pT/Hz^{0.5} of 1 kHz at 1 V, which is already better than results reported before \cite{1,7,11,14} and fulfills the requirements of non-destructive testing of buried defects in metallic materials (hundreds of pT/Hz^{0.5} at 1 kHz).

Notice that in this application, large noise values may appear from the complex excitation/acquisition electronic system and irregularities in the sample under test, which can lead to an overall noise larger than the sensor noise. In this case, choosing larger bias voltages for obtaining larger signals can be an advantage. This strategy could increase the noise of the sensor, but a larger signal to noise ratio of the overall system (sensor + excitation/acquisition system) will be obtained. Having this in mind, there is a great advantage to have a device composed of a series of MTJs because there is a huge increase (almost 1 order of magnitude) of the sensor’s sensitivity in V/Oe (the inset of Figure 4(a)), while few differences in the detectivity are observed at frequencies below 1 kHz (Figures 4(a) and 4(b)).

**IV. CONCLUSION**

In conclusion, a series of 72 MTJs with 50 \times 50 \mu m^2 has been successfully patterned and a good linear performance is achieved. The resistance-area product of the single junction is about 20 k\Omega \mu m^2. The high TMR of 159% and the largest sensitivity of 2.9%/Oe are obtained for the sensor array. For a particular frequency, the field detectivity shows some dependence on the bias voltage (as expected from the TMR dependence on the voltage bias), and the lowest value of 1.76 nT/Hz^{0.5} and 170 pT/Hz^{0.5} for 10 Hz and 1 kHz at 1 V have been obtained, respectively. The data support the use of this sensor geometry in application of NDT systems requiring low detectivity.

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