Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp561-562

K-7-05

$L1_0$-MnGa based magnetic tunnel junction for high magnetic field sensor

Xupeng Zhao, Jun Lu, Siwei Mao, and Jianhua Zhao

State Key Laboratory of Superlattices and Microstructures, Institute of Semiconductors,
Chinese Academy of Sciences, P. O. Box 912, Beijing 10083, China
Phone: +86-10-82305174 E-mail: lujun@semi.ac.cn

Abstract

We reported on the investigation on the magnetic tunnel junction structure designed for high magnetic field sensors with a perpendicularly magnetized $L1_0$-MnGa reference layer and an in-plane magnetized Fe sensing layer. A large linear tunneling magnetoresistance ratio up to 27.4% and huge dynamic range up to 5600 Oe have been observed at 300 K with a low nonlinearity of 0.23% in the optimized magnetic tunnel junction (MTJ). The field response of tunneling magnetoresistance was discussed to explain the field sensing properties in the dynamic range. These results indicate that $L1_0$-MnGa based orthogonal MTJ is a promising candidate for high performance magnetic field sensor with large dynamic range, high endurance, and low power consumption.

1. Introduction

Magnetic field sensors have attracted much interest in the last few decades for its potential applications in the fields of weak magnetic detection, medical inspection, as well as automotive systems due to its high sensitivity, low power consumption, and long endurance [1]. Currently, Hall sensors are widely used in these areas, especially for high magnetic field sensing with high spatial resolution. However, the Hall snesors have some shortcomings such as poor thermal stability and limited operation frequency range, which restricts their wide applications. Recently, the magnetoresistance (MR) sensors based on spin valves and magnetic tunnel junctions have become new generation magnetic field sensors for its higher sensitivity and smaller size, compared with traditional Hall effect sensors [2-4]. In MR sensors, the basic concerns are to realize a linear and reversible response to the applied magnetic field, high sensitivity and large dynamic range [5, 6]. One approach is utilizing out-of-plane magnetized materials as the reference layer and in-plane one for the sensing layer [7, 8]. It has been widely used in recent designs of tunneling magnetoresistance (TMR) sensors as an alternative one to Hall sensors for high magnetic field sensing with high spatial resolution.

Recently, the linear dynamic range has been extended $[Co/Pt(Pd)]_n$ based MTJ sensor, but still no more than 2500 Oe [9]. Meanwhile, a small MR was always observed in $[Co/Pt(Pd)]_n$ and Pt/CoFe based MTJs, which is attributed to the low spin polarization. In this letter, we investigated the TMR effect in $L1_0$-$Mn_{1.5}$Ga/Co/MgO/Fe MTJs filed sensors with an orthogonal alignment of magnetization. The measured TMR ratio of MTJ device is up to 27.4% with the Co thickness of 0.8 nm at 300 K. In particular, a large dynamic range up to 5600 Oe was observed in our devices with ultra-small nonlinearity and excellent reproducibility. Finally, the mechanism of field sensitivity and nonlinearity properties of MTJ device was analyzed in detail.

2. General Instructions

The MTJ structure consisting of $L1_0$-MnGa(25)/Co(0.8)/MgO(2.3)/Fe(5)/Pd(2) (thickness unit: nanometers) multilayer was deposited on GaAs(001) substrate by molecular-beam epitaxy (MBE) with two growth chambers. A 150 nm thick GaAs buffer layer was first epitaxially grown GaAs (001) substrate to smooth the surface. Subsequently, without breaking vacuum, the sample was transferred via an ultrahigh vacuum channel to the second growth chamber. A 25 nm thick $L1_0$-$Mn_{1.5}$Ga film was then epitaxially grown on GaAs buffer layer at 250 ℃, followed by an *in situ* annealing process at 300 ℃ to improve the $L1_0$ phase order and decrease the surface roughness. The Co layer was inserted between the $L1_0$-MnGa and MgO barrier layer with a thickness of 0.8 nm, which is an optimized value to suppress the defects arising from the lattice mismatch. The MgO barrier layer was subsequently deposited using electron beam evaporation source at room temperature. The films were patterned into pillar shapes with sizes ranging from 10×10 μm^2 to 70×70 μm^2 using typical ultraviolet lithography and Ar plasma milling techniques. After the fabrication processes, the MTJ devices were annealed in a vacuum furnace with high vacuum at 300 ℃ under a magnetic field of 5000 Oe for 30 minutes.

Figure 1(a) shows the TMR curves of MTJ sensors with a 0.8 nm Co insertion layer measured at 5, 100, 200 and 300 K, respectively. Here, TMR ratio was calculated by the formula $(R-R_L)/R_L\times 100\%$, where R_L represents the magneto-resistance of low resistance state. The TMR ratio reaches 27.4% at 300 K and 74.6% at 5 K. Due to the antiferromagnetic coupling between $L1_0$-MnGa and Co insertion layers, the magnetization of thin Co film is antiparallel to that of the $L1_0$-MnGa layer, which results in the high resistance state at high magnetic field in the TMR curves. The $L1_0$-MnGa layer and Co layer show coherent magnetization rotation behavior and thus work together as a reference layer. Moreover, the magnetization reversal behavior of each layer was discussed to gain a deep insight into the TMR loops of the MTJ field sensor device, which is shown in figure 2(b).

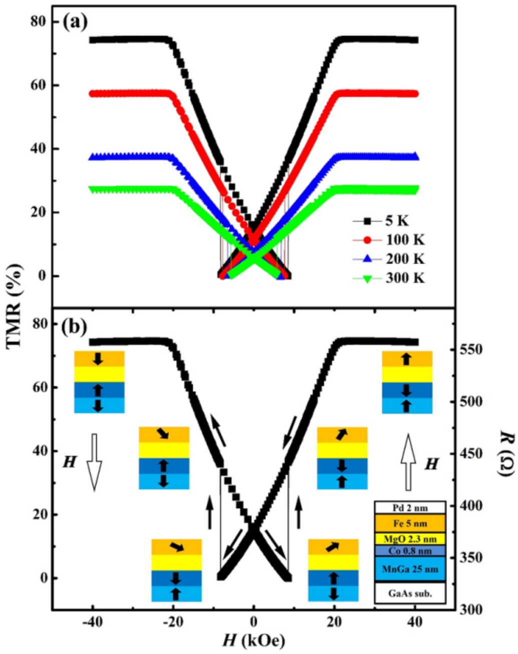

Fig. 1 (a) Magnetoresistance curves of $L1_0$-MnGa based MTJ measured at 5, 100, 200 and 300 K, respectively. The magnetic field was applied perpendicularly to the film. (b) The magnetization rotation process in magnetoresistance curve of $L1_0$-MnGa based MTJ measured at 5 K with the perpendicular field swept from -4 T to 4 T.

In addition, the TMR curves exhibit nearly linear variation from -5600 Oe to +5600 Oe with a maximum nonlinearity of 0.23% as shown in Fig. 2. This result is larger than the typical value reported in CoFeB, $[Co/Pt(Pd)]_n$ and Pt/CoFe based out-of-plane MTJ field sensors, which is not more than 2500 Oe [8-9]. Generally, the large dynamic range will enhance the anti-interference performance and flexibility of magnetic field sensors. In our MTJ structure, the observed field sensitivity is around 0.0011% TMR/Oe, which is close to the value of commercialized semiconductor Hall sensors and large enough for reliable perpendicular magnetic field sensing.

3. Conclusions

In summary, we have proposed a promising field sensor structure based on $L1_0$-MnGa perpendicularly anisotropy reference layer and in-plane magnetized Fe layer. The insertion of thin Co layer between the $L1_0$-MnGa and MgO barrier is an effective approach to improve the interface quality and enhance the MR ratio. The optimized MTJ sensors show a large TMR up to 27.4% at 300 K. Meanwhile, the strong antiferromagnetic coupling between $L1_0$-MnGa reference layer and Co insertion layer has been observed. In particular, for perpendicular field sensing, a huge linear dynamic range up to 5600 Oe was achieved in our structure. The value is much larger than the previous results based on CoFeB, $[Co/Pt(Pd)]_n$ and Pt/CoFe. Moreover, an ultra-low nonlinearity and excellent reproducibility have been confirmed in the huge dynamic range. All these results indicate that $L1_0$-MnGa based orthogonal MTJ structure is a promising candidate for high performance magnetic field sensor.

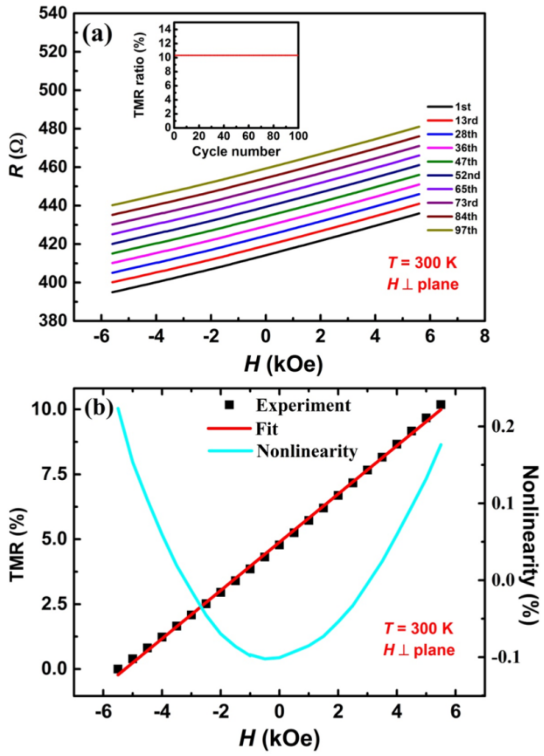

Fig. 2 (a) The randomly selected ten cycle of *R*-*H* curves of the MTJ under the application of a perpendicular field from -5600 to +5600 Oe at 300 K. The ten cycles were stacked in the y-axis with an offset of 5 Ω. The inset shows the cycling performance of the TMR ratio defined in the dynamic range. (b) The nonlinearity characteristics of TMR curves of $L1_0$-MnGa based MTJ in the dynamic range from -5600 to +5600 Oe.

Acknowledgements

The work was supported by the National Hightech R&D Program of China [MOST, Grant Nos. 2014AA032904], National Program on Key Basic Research Project [MOST, Grant Nos. 2015CB921500], the National Natural Science Foundation [NSFC, Grant Nos. 61334006, 11304307, 11474273] and the Key Research Project of Frontier Science of Chinese Academy of Science [Grant Nos. QYZDY-SSW-JSC015].

References

[1] J. M. Daughton *et al*., *J. Phys. D: Appl. Phys.* **22** (1999) R169.

[2] F. B. Mancoff *et al*., *Appl. Phys. Lett.* **77 (**2000**)** 1879.

[3] W. Jin and Y. W. Liu, *Chin. Phys.* **16** (2007)1731.

[4] Y. F. Liu *et al*., *Appl. Phys. Lett.* **96** (2010)1018.

[5] S. Yoon *et al., J., Appl. Phys.* **111** 2012 07E504.

[6] M. Tondra *et al*., *J. Appl. Phys.* **83** (1998) 6688.

[7] H. X. Wei *et al*., *Appl. Phys. Lett.* **94** (2009) 1018.

[8] T. Nakano *et al*., *IEEE Trans. Magn.* 52 (2016) 1.

[9] T. Nakano *et al*., *Appl. Phys. Lett.* **110** (2017) 1.