SCIENCE CHINA
Information Sciences

• LETTER •

June 2024, Vol. 67, Iss. 6, 169405:1–169405:2
https://doi.org/10.1007/s11432-024-4020-y

A high precision two-axis GMR angular sensor manufactured by post-annealing

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Received 18 January 2024/Revised 2 April 2024/Accepted 24 April 2024/Published online 23 May 2024

Angle sensors are widely used in numerous fields such as industry, military, medical care, and the Internet of Things (IoT) [1]. Magnetoresistance angle sensors have become a mainstream approach for angle measurement because of their high precision, good stability, low cost, and low power consumption. The giant magnetoresistance (GMR) sensors exhibit a higher MR ratio and sensitivity than Hall sensors and anisotropic magnetoresistance (AMR) sensors, demonstrating potential for widespread applications. For angle detection, it is necessary to use two sensors whose sensing directions are orthogonal to each other to detect magnetic fields with a 360° range. However, angle sensing is usually achieved by splicing two single-axis sensors, which can lead to alignment errors and increase production costs. It is urgent to propose an easy way to realize an exact two-axis detection. Cao et al. [2, 3] reported that the post-annealing process can effectively achieve different pinning directions. Therefore, we proposed a high-precision two-axis angle sensor based on the post-annealing process which consists of a full-bridge sensor and a half-bridge sensor. The sensitive axes of the two configuration sensors are orthogonal to each other.

The bottom pinned GMR thin-film stack is deposited on a SiO_2/Silicon substrate by an ultra-high vacuum magnetron sputtering system. The free layer (FL) consists of $Co_{70}Fe_{30}/Ni_{81}Fe_{19}$. The $Co_{70}Fe_{30}/Ru/Co_{70}Fe_{30}$ constitutes a synthetic antiferromagnetic (SAF) layer. We define the upper ferromagnetic layer as the P1 and the lower ferromagnetic layer as the P2. The GMR ratio of the stack is 8.8%. The patterns of the two axes consisting of a full bridge and a half bridge are illustrated in Figure 1(a). Define the direction of the annealing magnetic field as 0° ($+X$). The long axis direction of the GMR stripes on the adjacent bridge arm is designed as 45° or 135° in the full-bridge sensor. The long axis of the GMR stripes is 90° in the half-bridge configuration. The strips have a line width of 0.8 µm and an aspect ratio of 100. The devices are annealed in a vacuum with base pressure less than 10^{-6} Pa at 270°C under a 1 T field along the $+X$ axis for 1 h. Then, a small reversed magnetic field is applied along the $-X$ axis for 15 min.

The R-H curves of different designs of GMR stripes with second annealing fields of 80, 95, and 100 mT are discussed in Appendix B. When the second annealing field is 95 mT, the three GMR stripe designs obtain the best output. Therefore, only the results of the stripes under the 95 mT are discussed. To obtain the pinned angles of GMR strips of different designs after the second annealing, a magnetic field rotation experiment was set up. By rotating the direction of the in-plane $H_{\rm ext}$, the R-H loop is detected. When the $H_{\rm ext}$ is orthogonal to the direction of P2, the R-H loop will be symmetrical about the zero axis. Figure 1(a) shows the pinned angle of the 45° design is −48° and the angle of the 135° design is 45°. From these two designs, the sensitive direction of the full bridge will be along the Y-axis. The angle of the 90° stripe is 5°. Using the 90° design as the sensing unit of a half-bridge, the sensitive direction will be along the X-axis. Based on these results, a two-axis sensor, consisting of a full bridge and a half bridge, was designed and fabricated by two times post-annealing. Figure 1(b) is the output of the full-bridge sensor with the sensing axis along the Y-axis. The sensitivity of the full-bridge sensor is 6.59 mV/V/mT and the linear range is −2–2 mT. The output is approximately zero when the external field is along the X-axis. In Figure 1(c), the output of the half-bridge sensor has a linear response to an external field along the X-axis. The sensitivity is 1.68 mV/V/mT and the linear range is −2–2 mT. The voltage offset of the half-bridge sensor is due to the resistance difference between the GMR stripes and the metal wire in the bridge arm.

To verify the accuracy of the experimentally obtained pinning angle and the outputs of the two-axis sensor, a simulation was performed based on a coherent rotation model which is based on the energy minimization principle [2]. The pinning angle is obtained through energy calculation between different layers FL, P1, and P2. The energy includes Zeeman energy, anisotropy energy, exchange coupling energy between the P2 and AFM layers, and interlayer coupling energy between ferromagnetic layers. Figure 1(d) shows the simulation output of the full-bridge sensor based on the parameters $\theta_{45} = -48°$, $\theta_{135} = 45°$. By comparing Figures 1(d) and (f), the trends of the output curves between the experimental results and the simulation results match

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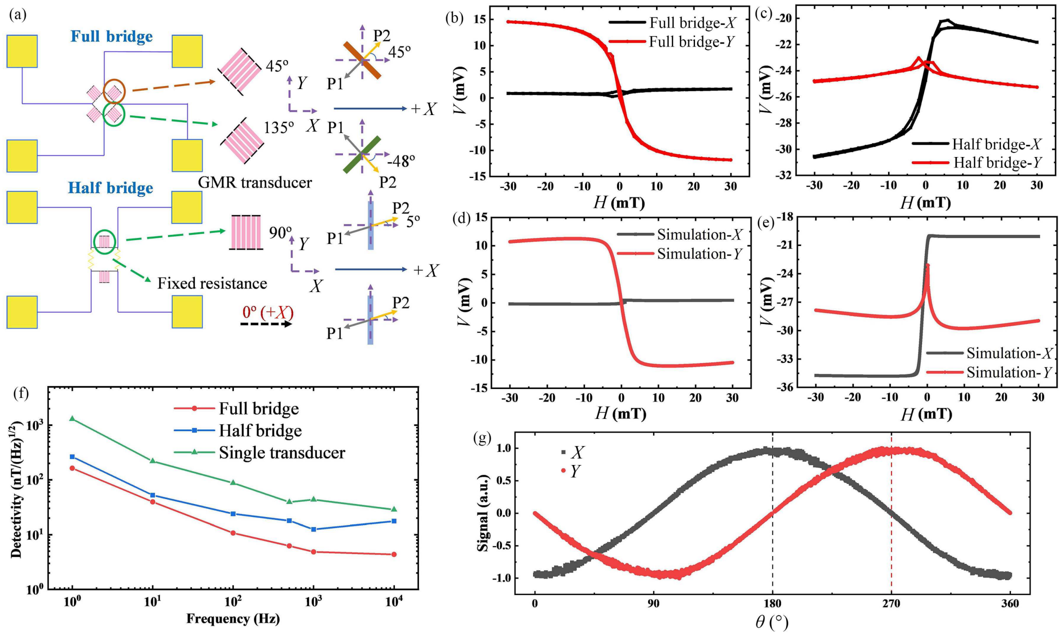

Figure 1 (Color online) (a) Schematic of the full-bridge (up) and half-bridge (down) GMR sensors, and pinned direction of the P1 and P2 in full-bridge structure and half-bridge structure; measured outputs of the (b) full-bridge and (c) half-bridge GMR sensors under 1 V bias voltage under the in-plane magnetic field; simulation output of the (d) full-bridge and (e) half-bridge GMR sensors; (f) detectivity of the full-bridge GMR sensor, half-bridge sensor, and single GMR stripes arm with increasing frequency; (g) relationship between the output voltage of the two-axis sensor and the calculated angle of the geomagnetic field.

well, and the output voltage amplitudes are in good agreement. The simulation results of the half-bridge sensor based on the parameters $\theta_{90} = 5^\circ$ are shown in Figure 1(e). It shows that the trends between experimental and simulated results match each other in the linear region. Since FL and P1 in the model are ferromagnetic coupled, zero field is the lowest point of the curve. The FL and P1 of the actual device are not ferromagnetic coupled, so the curve changes are a little mismatched except in the linear region.

To discuss the detection limit of the sensor, the noise power spectrum density (PSD) of GMR sensors with different structures was tested. Figure 1(f) shows the detectivity (D) of the three kinds of GMR devices, including full bridge, half bridge, and a single transducer, which are calculated by the formula $D = S_v/(V \times (\mathrm{d}V/\mathrm{d}H))$. The S_v is the noise PSD of the test devices. The bridge configurations show better noise performance. For the full-bridge sensor, the detectivity reaches 22 $\mathrm{nT}/(\mathrm{Hz})^{0.5}$ at 10 Hz. And the detectivity of the half-bridge sensor is 88 $\mathrm{nT}/(\mathrm{Hz})^{0.5}$ at 10 Hz.

To observe the response of the two-axis GMR sensor to the geomagnetic field, the sensor is fixed on the turntable, and a bias voltage of 1 V is applied to the two-axis sensor. Figure 1(g) is the output voltage of the two-axis sensor when the angle of the geomagnetic field changes. The 90° phase shift between the X-axis and Y-axis signals indicates the orthogonality of the two-axis sensing directions. The calculated orthogonality error φ [4] of the two-axis output range is smaller than 0.04.

Conclusion. This work demonstrates a high-precision in-plane two-axis GMR angle sensor is prepared by post-annealing. The pinning direction of the GMR strips is modulated by annealing two times to achieve orthogonal sensitive directions of the two sensors. The sensitivity of a full-bridge sensor is 6.59 mV/V/mT, with the sensing direction along the Y-axis and the sensitivity of a half-bridge GMR sensor is 1.68 mV/V/mT with the sensing direction along the X-axis. A simulation of the two-axis sensor output with the field has been performed, which proves the correctness of the P2 direction measured by the angle test. The detectivity of the full-bridge sensor is 22 $\mathrm{nT}/(\mathrm{Hz})^{0.5}$ at 10 Hz and it is 88 $\mathrm{nT}/(\mathrm{Hz})^{0.5}$ at 10 Hz for half-bridge sensor. The orthogonality error of the two-axis sensor for the geomagnetic angle detection is lower than 0.04. The sensor in this study demonstrates higher detectivity than some commercial GMR sensors, such as YAS532 produced by Yamaha and HSCDTD008A produced by ALPS. This work proposes an efficient and simple method for producing two-axis GMR angle sensors, which can be a promising solution for mass production.

Acknowledgements This work was financially supported by National Key Research and Development Program (Grant No. 2021YFB3201800), Taishan Scholars Program, and International Collaboration Project (Grant No. B16001).

Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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