Three-dimensional sensing of the magnetic-field vector by a compact planar-type Hall device

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Smart society is forthcoming with a rapid development in the automation of electric appliances requiring abundant sensors. One of the key sensors is a three-dimensional magnetometer for detecting the motion of objects, which is usually driven by cooperative multiple sensors on three orthogonal planes. Here, we demonstrate the fundamental operation of a three-dimensional magnetometer based on a simple Fe-Sn heterostructure Hall device in a planar geometry. Polar coordinates of the magnetic-field vector are uniquely determined by the combination of the sizable anomalous Hall effect, the anisotropic magnetoresistance, and the unidirectional magnetoresistance. Thanks to the ferromagnetic topological features in the Fe-Sn heterostructure, the above-mentioned device overcomes the limitation of conventional semiconductor devices and is highly sensitive even at room temperature. The compact planar geometry will be particularly useful in versatile electrical applications requiring a low-cost three-dimensional magnetometer with space- and energy-saving features.
As demand for magnetic-field sensing increases in a recently developing internet-of-things (IoT) society, the various types of magnetometers have been developed and immensely contributed to a broad range of applications. The most commonly used two types of magnetometers are semiconductor Hall sensors and ferromagnetic magnetoresistive sensors, which generate the output signal against the scalar quantity of the magnetic field along a principal axis. However, future automation in the automotive industry and robotics requires detecting the motion of objects via determination of the magnetic field (H) vector in three dimensions, enabling the control of precise position, angle, and rotation of fundamental components in an electric appliance. For magnetic-field sensing in three dimensions, individual detection of the three-dimensional (3D) components of the magnetic field is necessary. The classical way to detect 3D components of H includes placing three Hall sensors or magnetoresistive sensors orthogonally (along x-, y-, and z-axis) and attaching magnetic flux guides in the planar devices. However, these techniques face the requirements of three power sources and 3D space arrangement. To expand the 3D sensing of the magnetic field into versatile electric appliances, it is essential to develop the 3D magnetometer based on a single planar-type device with low power consumption and a simple measurement unit. The appealing phenomena in ferromagnetic films such as spin–orbit torque and unidirectional magnetoresistance (UMR) are beneficial to trigger the development of a planar 3D magnetometer beyond the conventional Hall devices.

The 3D sensing of the magnetic-field vector corresponds to the function for the detection of the magnetic field amplitude and direction with polar coordinates. Figure 1a represents the magnetic-field vector H with its amplitude H, polar angle θ, and azimuthal angle φ. The 3D magnetometer has to uniquely determine these polar coordinates via electrical measurements. Typically, the Hall effect is available to measure the amplitude H and the polar angle θ. Conventional semiconductors, such as Si, GaAs, and InAs, have been well applied to practical Hall magnetometers owing to good controllability of sensitivity based on high-mobility charge carriers. Recently, in addition to the conventional semiconductor devices driven by the ordinary Hall effect, ferromagnetic heterostructures with high Curie temperatures have been recognized as a good candidate for the room-temperature Hall magnetometer, driven by anomalous Hall effect (AHE). In particular, the sizable anomalous Hall response for the detection of H is enabled by the intrinsic mechanism owing to the specific band features of the topologically nontrivial ferromagnetic materials. Moreover, the determination of azimuthal angle φ is critically important to develop compact planar-type 3D magnetometers since it is rather difficult for a single semiconductor Hall device. By using magnetic materials, anisotropic magnetoresistance (AMR) is applicable to measure the φ because its amplitude reflects the relative angle between in-plane directions of electric current (I) and magnetization (M).

When the direction of M follows to H, the AMR provides the information of the direction of H. However, the AMR in one component provides four identical values owing to the 180° period, which is insufficient to uniquely determine the φ.

In this study, we apply two AMR probes and UMR effect to solve this problem. Here, we report on the demonstration of magnetic-field vector detection by implementing the AHE, AMR, and UMR effects into a single planar-type 3D magnetometer based on the ferromagnetic Fe–Sn heterostructure.

The device overcomes the limitation of conventional semiconductor devices and is highly sensitive at room temperature.

### Results and discussion

#### Concept of device structure and measurement setup

A SiO₂ capped 4-nm-thick Fe–Sn heterostructure (Fig. 1b) was patterned into a device consisting of two Hall-bar channels oriented along x-axis (channel 1) and −45° from x-axis (channel 2) in series, as shown in Fig. 1c. To disentangle the AMR and UMR signals, harmonics measurements of the sheet and Hall resistance were employed using lock-in amplifiers under the application of the ac current with modulation frequency f = 2πω. The first harmonic Hall resistance RH1 and the first and second harmonic sheet resistance RH2 and RH3 for channel 1, and the first harmonic sheet resistance RH4 for channel 2 were measured simultaneously. Figure 1d summarizes the concept for the determination of the polar coordinates θ1 and φ1 by RH1 and RH2, RH3, and RH4. The polar angle θ (out-of-plane field direction) is monitored by RH via AHE. When usual polar coordinates, the θ should be only defined in 0° ≤ θ ≤ 180°. The azimuthal angle φ (in-plane field direction) is measured by the values of RH3 and RH4 and the sign of UMR in RH4. Judging from the combination of two AMR values RH3 and RH4, four identical values are reduced to two. The UMR signal follows the sign of M × H under broken inversion symmetry along out-of-plane direction, resulting in a 360° period against φ. As a consequence, the combinations of positive and negative values of θ and φ listed in Fig. 1d resolve the unique direction of a magnetic-field vector by simultaneous measurements of AHE, AMR, and UMR in the ferromagnetic heterostructure device.

#### Vector rotation in XZ plane for verification of θ₁₁ detection

The AHE was evaluated to examine the correspondence between the RH₁ and the H direction as shown in Fig. 2. Under the perpendicular H condition in Fig. 2a, the RH₁ increases linearly up to μ₀H = 0.6 T with no hysteresis behavior, being suitable for detection of out-of-plane component of the magnetic field. The measurable amplitude of H is limited to the saturation field of M, which can be modulated by the magnetic shape anisotropy or the

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**Fig. 1** Detection concept for magnetic-field vector by a Fe–Sn heterostructure device. **a** Definition of the polar (θ) and azimuthal (φ) angles of the magnetic-field vector H. **b** Schematic of layer structure consisting of a SiO₂ cap and 4-nm-thick Fe–Sn layer grown on Al₂O₃ substrate. Magnetization of the Fe–Sn layer follows the magnetic field, providing resistance changes with respect to strength and direction of the field. **c** Top-view photograph of the planar Hall device and measurement setup. **d** Summary of the signal output from AHE, AMR, and UMR.
interfacial magnetic anisotropy. The extracted values of $R_{\mu}^1$ at $\mu_0H = 0.3$ and 1 T are plotted as a function of modulation frequency $f$ (Fig. 2b) and current amplitude $I_{ac}$ (Fig. 2c). The Hall resistance $R_{\mu}^1$ is stably maintained against $f$ and $I_{ac}$, meaning that the Ohmic behavior persists in high frequency up to 300 Hz. The large Hall voltage under ac operation is an essential prerequisite for sensor application in terms of detectivity29 and low-energy consumption30. Figure 2d, e represent the polar angle $\theta_H$ dependence of $R_{\mu}^1$ measured at 1 T. The $\theta_H$ is initially positive when $\mu_0H = 1$ T points along $+z$ ($\theta_H = 0^\circ$). With sweeping $\theta_H$ from 0° to 180° in the $zx$ plane, the $R_{\mu}^1$ monotonically decreases with sign reversal at $\theta_H = 90^\circ$. Note that the $R_{\mu}^1(\theta_H)$ did not follow the sinusoidal function of $\theta_H$ (black dashed line), implying that the magnetization was not saturated along the direction of $\mu_0H = 1$ T due to the in-plane magnetic anisotropy (Supplementary Note 3 and Supplementary Fig. 3). While the amplitude of $\mathbf{H}$ should be evaluated from two values of different component $R_{\mu}^1$ and $R_{\mu}^2$ (Supplementary Note 4), the normalized function of $R_{\mu}^1(\theta_H)$ guarantees that the angle of $\theta_H$ is uniquely determined in the range of $0^\circ \leq \theta_H \leq 180^\circ$. Note that $R_{\mu}^1(\theta_H)$ can be a good reference curve for identifying $\theta_H$ even if the magnetization is not saturated along $\mathbf{H}$.

**Vector rotation in xy plane for verification of $\phi_1$ detection.** We here refer to the determination of the azimuthal angle $\phi_1$ using AMR and UMR in the magnetic Fe–Sn Hall-bar device. The primary and secondary harmonic components of $R_{\mu}^1$, $R_{\mu}^2$, and $R_{\mu}^w$ as shown in Fig. 3a were measured during magnetic-field rotation in the $xy$ plane. By contrast to the well-studied 180° period of AMR24, the UMR signal expectedly exhibits 360° period as depicted in Fig. 3b24,25. Figure 3c presents typical AMR, the variations of $R_{\mu}^1$ and $R_{\mu}^2$ (denoted as $\Delta R_{\mu}^1$ and $\Delta R_{\mu}^2$) as a function of $\phi_1$ under $\mu_0H = 1$ T. The periodic functions of $\Delta R_{\mu}^1$ and $\Delta R_{\mu}^2$ with 180° indicate that the resistance variation becomes positively large when the field is parallel to the current whereas it is negatively large when the field is perpendicular to the current. The AMR signal obeys sinusoidal function of $\cos^2\phi_1$ (black dashed lines), implying that the direction of in-plane $\mathbf{M}$ follows that of $\mathbf{H}$. This agreement can be ascribed to the isotropic feature of $\mathbf{M}$ in the sample plane. The AMR amplitude $R_{\mu}^{1\text{AMR}}$ and $R_{\mu}^{2\text{AMR}}$, defined by the half value of the peak-to-peak amplitude of $\Delta R_{\mu}^1(\phi_1)$ and $\Delta R_{\mu}^2(\phi_1)$ (vertical black arrows in Fig. 3c) corresponds to about 0.1% of the base resistance of about 800 Ω, which is a typical value of ferromagnetic metals30. The phase shift $\Delta H_\phi$ between $\Delta R_{\mu}^1$ and $\Delta R_{\mu}^2$ defined in Fig. 3c and AMR signal amplitude are plotted in Fig. 3d as a function of ac injection current $I_{ac}$. The uniform distribution of electric current along the series channel 1 and 2 is maintained in the three orders of magnitude in $I_{ac}$.

Figure 3e shows the UMR of $R_{\mu}^w$ measured with $I_{ac}$ of 0.2 mA, which is 360° period with its sign being positive in $0^\circ < \phi_1 < 180^\circ$ and negative for $-180^\circ < \phi_1 < 0^\circ$ (see also Supplementary Note 7 and Supplementary Fig. 6). This valid judgment enables us to define $\phi_1$ uniquely. The amplitude of UMR signal characterized by $R_{\mu}^{1\text{UMR}} = \frac{\Delta R_{\mu}^{1w}(\phi_H = 90^\circ) - \Delta R_{\mu}^{1w}(\phi_H = -90^\circ)}{2}$ in Fig. 3f linearly increases with increasing the amplitude $I_{ac}$, which is consistent to the origin of UMR effect at the broken inversion symmetry at the interface with Rashba spin-orbit interaction18 or magnetothermal effect25,31. The relative amplitude of UMR to the channel resistance per current density $\frac{R_{\mu}^{1\text{UMR}}}{I_{ac}} = 4.14 \times 10^{-16}$ (m² A⁻¹) with $R_{\mu}^{1\text{UMR}}/I_{ac} = 8.42$ ΩA⁻¹ being a linear slope in Fig. 3f, $t = 4$ nm Fe–Sn film thickness, $w = 10$ μm the channel width, and the $R_{\mu}^0 = 813$ Ω. This value is five times larger than the reported value.
in heavy metal/ferromagnet bilayer heterostructures25 (Supplementary Note 5 and Supplementary Table 2). In the trilayer structure of SiOx/4-nm-thick Fe-Sn/Al2O3 substrate, the band offsets at the top and bottom interfaces may not be perfectly canceled, leading to the broken inversion symmetry along the out-of-plane direction. The amplitude of UMR may be further enhanced by optimizing the layer structure31 or by introducing a superlattice structure. Considering the large AHE of the Fe–Sn nanocrystalline thin films fabricated by sputtering technique, which is probably ascribed to the intrinsic mechanism21,32, the spin-orbit interaction and specific band feature cooperatively contributes to yield the large UMR effect at room temperature. Combining the AMR originated from M and the UMR from broken inversion symmetry and specific band structure, the φH is uniquely determined in a planar-type Hall device based on ferromagnetic Fe–Sn heterostructure.

**Experimental demonstration of 3D magnetic-field sensing.**

Finally, we demonstrated the detection of the magnetic-field vector consisting of θH and φH with a constant magnetic-field strength of 1 T along the flow chart depicted in Fig. 4a. The determination of θH and φH was performed by the evaluation of R1|| using AHE, and R1|| and R2|| using AMR and UMR, subsequently. Here, R1||(θH) at μ0H = 1 T (Fig. 2c) was used for the determination of θH. The beforehand determination of φH is a reasonable route to explore the magnetic-field direction since the Hall effect is a simple and independent measurement. Following the determination of θH, the AMR curve defines two possible in-plane directions φ1 or φ1 = 180°. Note that because the amplitude of AMR depends on θH, the comparison with the normalized reference curves (Supplementary Note 6 and Supplementary Fig. 5) is necessary. Then, the sign of UMR in R2|| is employed to uniquely determine φ1. The reference curves of R1||(θH), R1||(φH), and R2||(φH) depend on the scalar quantity of the magnetic field H. Therefore, for determination of φH and θH, the scalar quantity of H should be first evaluated by the independent analysis of R1|| and R2|| (Supplementary Note 4 and Supplementary Fig. 4) and the cross-checking of the projected value of H along z-direction with θH. As demonstration for the determination of magnetic-field vector H, the intentionally controlled H shown in Fig. 4b was measured with a planar Fe–Sn Hall device in a superconducting vector magnet. In the regions (i)–(iii), the sensing operation was examined along the out-of-plane rotation, in-plane rotation, and diagonal rotation. Figure 4c shows the time evolution of the experimentally detected θH and φH. The θH rotation (blue) at xz
plane in the region (i) is systematically detected by $R_{\text{H}}^{\text{TH}}$, which is consistent to controlled $\theta_1^H$ from 90° to 45°. Then, the $\phi_1$ rotation (green) under $\theta_1^H = 45°$ in the region (ii) is evaluated by the AMR curves of $R_{\text{H}}^{\text{TH}}$ and $R_{\text{S}}^{\text{TH}}$ and the sign of UMR in $R_{\text{H}}^{\text{TH}}$. For the diagonal rotation examination, the subsequent scan of $\theta_1^H$ and $\phi_1$ was performed in the region (iii). At each step of $\theta_1^H$ rotation, the flow chart of Fig. 4a was applied to determine the angles. Overall, the excellent agreement between controlled and experimentally detected magnetic-field angles demonstrates that the planar-type single Fe–Sn device is capable of detecting the magnetic-field vector in three dimensions. Although the present demonstration was performed at $\mu_0H = 1$ T, the flow chart of Fig. 4a is valid by selecting the proper reference curve of $R_{\text{H}}^{\theta_1^H}$, $R_{\text{S}}^{\theta_1^H}$, and $R_{\text{S}}^{\phi_1}$ depending on the field strength (Supplementary Note 4). Along this detection process, the device is capable of detecting the magnetic-field vector in the range of 0.1–1.0 T with a sensitivity of 0.4 V A$^{-1}$degree$^{-1}$ for $\theta_1^H$, 0.04 V A$^{-1}$degree$^{-1}$ for $\phi_1$, and 51.3 V A$^{-1}$T$^{-1}$ for the field amplitude (see Supplementary Note 8 and Supplementary Table 3). The detection functionality may be further extended by evaluating the scalar quantity of the field (Supplementary Fig. 4), such as detecting the position of the moving object.

**Conclusion**

By employing AHE, AMR, and UMR, we have demonstrated a feasible detection of the magnetic field vector with a Fe–Sn heterostructure-based Hall device. Compared with conventional semiconductor Hall sensors and magnetoresistance sensors, the advantages of our device are a compact device in a planar geometry with a single current source and a room-temperature fabrication process with abundant non-toxic elements. The simple configuration of the 3D magnetometer enables us to expand the possibility of implementing the various conventional sensors in smart electronics. The aspect of the low-cost sputtering process of the Fe–Sn-based magnetometers is an advantage in integration into the conventional silicon-based circuits or flexible substrate. The observation of the substantial signal from UMR in a SiO$_2$/Fe–Sn/Al$_2$O$_3$ structure implies the importance of a specific band structure with the spin–orbit interaction at the heterointerface. The device performance will be further improved by applying extensive knowledge of topological material science owing to large AHE and specific UMR effect originating from the electronic band topology and spin–orbit interaction.

**Methods**

**Sample preparation.** The heterostructure consisting of 4-nm-thick Fe$_{0.5}$Sn$_{0.5}$ nanferromagnetic layer and SiO$_2$ cap layer was grown by co-sputtering technique at room temperature on Al$_2$O$_3$(0001) single crystal substrate. The thickness was measured by X-ray reflectivity (Supplementary Note 1 and Supplementary Fig. 1). The Fe/Sn composition ratio was calibrated using electron energy dispersive X-ray spectroscopy in a 48-nm-thick film deposited at the identical condition with the 4-nm-thick sample. We examined the uniformity of the Fe composition in as wide as a few mm$^2$ in the film (Supplementary Note 1 and Supplementary Table 1). The device was fabricated with the SiO$_2$/Fe–Sn/Al$_2$O$_3$ heterostructure by photolithography and Ar ion milling. The Ti/ Pt electrodes were defined by photolithography and deposited by ion beam sputtering at room temperature after in situ Ar ion milling.

**Electrical measurements.** The device was placed in a variable temperature insert equipped with a superconducting vector magnet. Details of the measurement setup are shown in Supplementary Note 2 and Supplementary Figure 2. The measurement was performed by a lock-in technique at 300 K. The primary component of the channel resistance and Hall resistance were measured at the same frequency 13 Hz of the current by lock-in amplifiers. The secondary harmonic component of the resistance was measured by a lock-in amplifier with a second harmonic mode.

**Data availability**

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions
J.S. and A.T. conceived the project. J.S. performed device fabrication and electrical transport measurements with the help of T.N. K.F. fabricated the thin film samples. J.S. and A.T. wrote the paper. All authors discussed the results.

Competing interests
The authors declare no competing interests.

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