

Supplementary material

Perspective on nanoscale magnetic sensors using giant anomalous Hall effect in topological magnetic materials for read head application in magnetic recording

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SNR calculations

The output voltage of the AHE reader can be calculated using the expression:

$$\Delta V_{\text{AHE}} = 2\rho_{xy}J_x t_{\text{SL}}\eta_{\text{AHE}}, \quad (\text{S1})$$

where η_{AHE} is the reader utilization. The output voltage of the TMR reader can be calculated as follows:

$$\Delta V_{\text{TMR}} = \Delta R/R \cdot V_b \eta_{\text{TMR}}, \quad (\text{S2})$$

where $\Delta R/R$ is the TMR ratio. The reader utilization of both types of readers are not necessarily the same. Indeed, η_{AHE} may be larger than η_{TMR} owing to the higher linearity and the perfect symmetry of the $V_{\text{H}}-H_z$ curve of the AHE readers (Figs. 4(f) and (g)). However, for simplicity, we assumed the same reader utilization values: $\eta_{\text{AHE}} = \eta_{\text{TMR}} = 0.3$.

The noise voltage densities in the unit of $V/\sqrt{\text{Hz}}$ were calculated using the following theoretical expressions:

$$\text{Johnson noise (AHE):} \quad N_{\text{Johnson}} = \sqrt{4k_{\text{B}}TR} \quad (\text{S3})$$

$$\text{Shot noise (TMR):} \quad N_{\text{shot}} = \sqrt{2eV_{\text{b}}R \coth(eV_{\text{b}}/2k_{\text{B}}T)} \quad (\text{S4})$$

$$\text{Mag-noise:} \quad N_{\text{mag}} = \Delta V_{\text{max}} \cdot \sqrt{\frac{k_{\text{B}}T\alpha}{\gamma(H_{\text{stiff}})^2 M_{\text{s}} V_{\text{FL}}}} \quad (\text{S5})$$

$$\text{Amplifier noise:} \quad N_{\text{amp}} = \sqrt{V_{\text{n}}^2 + (I_{\text{n}}R)^2} \quad (\text{A6})$$

where k_{B} : Boltzmann constant, T : temperature, R : reader resistance, e : elementary charge, α : magnetic damping constant of SL and FL, γ : gyromagnetic ratio of SL and FL, H_{stiff} : magnetic bias (stiffness) field, M_{s} : saturation magnetization, V_{FL} : volume of the SL and FL, V_{n} : voltage noise of the amplifier, and I_{n} : current noise of the amplifier. ΔV_{max} is the output voltage when $\eta = 1$ in Eqs. (S1) and (S2). The stripe height (SH) was assumed to be $SH = 1.2W$, where W is the reader width. For both the AHE and TMR readers, the following variables were fixed: $T = 350$ K, $\alpha = 0.02$, $\gamma = 1.76 \times 10^{11}$ rad s^{-1} T^{-1} , and $M_{\text{s}} = 1000$ emu/ cm^3 . Although the SL magnetization of the AHE reader may be spontaneously stabilized by the shape anisotropy and its anisotropy depends on the SL dimension as discussed in the main text and in Fig. 4, for simplicity, we assumed $H_{\text{stiff}} = 800$ Oe for both the AHE and TMR readers. We adopted amplifier noise with $V_{\text{n}} = 1.2$ nV/ $\sqrt{\text{Hz}}$ and $I_{\text{n}} = 6$ pA/ $\sqrt{\text{Hz}}$ from Ref.⁶⁶. From Eq. (S6), the amplifier noise is higher for higher R . Thus, the improvement of the amplifier with lower current noise is another critical task. The total noise was calculated from the square root of the sum of the square of each noise (Eqs. (S3)–(S6)), i.e.,

$$N_{\text{total}} = \sqrt{N_{\text{Johnson}}^2 + N_{\text{mag}}^2 + N_{\text{amp}}^2} \quad (\text{S7}) \text{ for AHE reader, and}$$

$$N_{\text{total}} = \sqrt{N_{\text{shot}}^2 + N_{\text{mag}}^2 + N_{\text{amp}}^2} \quad (\text{S8}) \text{ for TMR reader.}$$

The noise voltage was calculated by multiplying the square root of the bandwidth (Δf), which corresponds to the maximum frequency of the AC magnetic field from the recording bits and calculated by the linear density of the recording bit and the disk rotation speed. Table A1 shows the linear densities (in kilo flux changes per inch, kFCI) for ADs in the range of 2.4–6.0 Tbit/in² predicted by Albuquerque et al.⁶⁶ We calculated Δf at the outer diameter of a 3.5-inch disk rotating at 7200 rpm.

Table S1. Linear densities of the recording bit and the recording bandwidths (Δf) for ADs in the ranges of 2.4–6.0 Tbit/in².

AD (Tbit/in ²)	Linear density (kFCI)	Δf (GHz)
2.4	2700	1.78
4.0	3400	2.24
6.0	3900	2.57