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Comment on "Planar Hall resistance ring sensor based on NiFe/Cu/IrMn trilayer structure" [J. Appl. Phys. 113, 063903 (2013)]

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In a recent paper, Sinha *et al.*[1] compare sensitivities of planar Hall effect sensors with different geometries that are all based on the anisotropic magnetoresistance of permalloy. They write that the sensitivity of a planar Hall effect sensor with a ring geometry as shown in Fig. 1(a) is a factor of $\sqrt{2}$ larger than the sensitivity of the so-called planar Hall effect bridge (PHEB) sensor[2] of equal size with the geometry shown in Fig. 1(b). Sinha *et al.*[1] calculate the signal for a ring sensor to

$$V_{\text{Ring}} = \frac{\pi r}{2wt} I_x \Delta\rho \sin(2\theta), \qquad (1)$$

where r, w, and t are the radius, width, and thickness of the ring sensor, I_x is the current applied through the sensor, $\Delta\rho = \rho_\parallel - \rho_\perp$ is the difference in resistivity when the current and magnetization are parallel and orthogonal, and θ is the angle between the magnetization and the x-direction.

Henriksen *et al.*[2] showed that the signal for the PHEB sensor of Fig. 1(b) is given by

$$V_{\text{PHEB}} = \frac{l}{2wt} I_x \Delta\rho \sin(2\theta), \qquad (2)$$

where l is the length of each sensor branch. If the contacts to the two sensors are placed at identical positions, $l = \sqrt{2}\,r$, which leads to a ratio of Eq. (1) to Eq. (2) of $\pi/\sqrt{2}$ instead of the claimed $\sqrt{2}$.

However, we do not agree on the signal calculation for a ring sensor derived by Sinha *et al.*[1] We are able to follow the derivation of the sensor signal until their Eq. (4), which for a general Wheatstone bridge should read

$$V = I_x \frac{R_1 R_4 - R_2 R_3}{R_1 + R_2 + R_3 + R_4}, \qquad (3)$$

where R_i is resistance of the ith element in the bridge and the elements are numbered as shown in Fig. 1. Here, we have chosen to define V such that positive value of θ will give rise to a positive value of V, i.e., such that the sensors have a positive sensitivity (switching the roles of V and ground will give a negative sensor response to a field applied in the positive y-direction).

Below, we calculate the resistance of each element of the ring sensor as well as the resulting Wheatstone bridge voltage. We consider a ring structure for which $w/r \ll 1$ and

we neglect the perturbation of the current distribution near the contacts.

Let us consider the ring sensor shown in Fig. 1(a). The resistance of the infinitesimal piece (red) is given by

$$dR = \frac{1}{wt} \rho_\alpha(\theta, \alpha) dl = \frac{r}{wt} \rho_\alpha(\theta, \pi/2 - \varphi) d\varphi, \qquad (4)$$

where α is the angle between the current and the x-axis, $\varphi = \pi/2 - \alpha$ is an auxiliary angle used for the integration, and $\rho_\alpha(\theta, \alpha)$ is the resistivity projected along the current direction given by Eq. (2) of Sinha *et al.*[1]

$$\begin{aligned}
\rho_\alpha(\theta, \alpha) = {} & (\rho_\perp + \Delta\rho \cos^2\theta)\cos^2\alpha \\
& + (\rho_\perp + \Delta\rho \sin^2\theta)\sin^2\alpha \\
& + \frac{1}{2}\Delta\rho \sin 2\theta \sin 2\alpha.
\end{aligned} \qquad (5)$$

The resistances in the ring sensor are calculated by integrating over the relevant ranges of φ for each of the four branches

$$\begin{aligned}
R_1 &= \int_0^{\pi/2} \frac{r}{wt} \rho(\theta, \pi/2 - \varphi) d\varphi \\
&= \frac{r}{2tw}\left[\frac{\pi(\rho_\parallel + \rho_\perp)}{2} + \Delta\rho \sin(2\theta)\right],
\end{aligned} \qquad (6)$$

$$\begin{aligned}
R_2 &= \int_{\pi/2}^{\pi} \frac{r}{wt} \rho(\theta, \pi/2 - \varphi) d\varphi \\
&= \frac{r}{2tw}\left[\frac{\pi(\rho_\parallel + \rho_\perp)}{2} - \Delta\rho \sin(2\theta)\right],
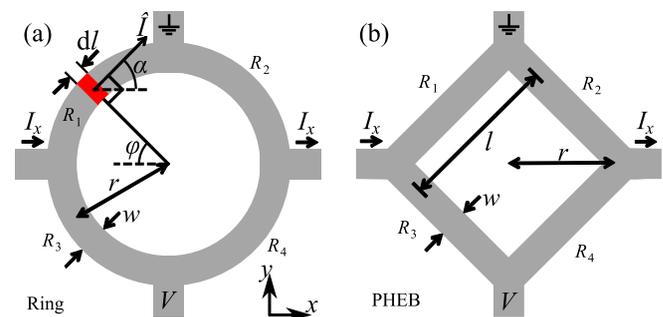\end{aligned} \qquad (7)$$

FIG. 1. Sketch of (a) Ring and (b) PHEB sensors with definitions of dimensions and angles. $\hat{I}$ is a vector along the current forming an angle α to the x-direction.

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$$R_3 = \int_{3\pi/2}^{2\pi} \frac{r}{wt}\rho(\theta, \pi/2 - \varphi)\mathrm{d}\varphi$$

$$= \frac{r}{2tw}\left[\frac{\pi(\rho_\parallel + \rho_\perp)}{2} - \Delta\rho\sin(2\theta)\right], \quad (8)$$

$$R_4 = \int_{\pi}^{3\pi/2} \frac{r}{wt}\rho(\theta, \pi/2 - \varphi)\mathrm{d}\varphi$$

$$= \frac{r}{2tw}\left[\frac{\pi(\rho_\parallel + \rho_\perp)}{2} + \Delta\rho\sin(2\theta)\right]. \quad (9)$$

Insertion of these expressions into Eq. (3) results in

$$V_{\mathrm{Ring}} = \frac{r}{2wt}I_x\Delta\rho\sin(2\theta), \quad (10)$$

which is a factor of π different from Eq. (5) in Sinha *et al.*[1]

Comparing Eq. (10) with Eq. (2), it is clear that the magnetic field sensitivity of the PHEB geometry of Fig. 1(b) is a factor of $\sqrt{2}$ times that of the ring geometry of Fig. 1(a), i.e., 41% larger. The reason for this can be understood directly from Eq. (5). The terms that are quadratic in either $\sin\alpha$ or $\cos\alpha$ are identical upon a sign change of α and hence cancel out for a symmetric bridge geometry. Therefore, the only term contributing to the bridge voltage for a symmetric bridge geometry is that proportional to $\sin 2\alpha$, which comes from the off-diagonal terms of the resistivity tensor. This term clearly assumes its maximum numerical value for $\alpha = \pi/4 + n\pi/2$ with n being an integer and all other values of α will reduce the effect of this term on the bridge voltage. This explains why the PHEB geometry in Fig. 1(b) shows a larger signal than the corresponding ring geometry in Fig. 1(a).

In addition, the length of each of the four sensor branches for the ring sensor is $r\pi/2$, which is 11% longer than the corresponding length of $l = \sqrt{2}\,r$ for the PHEB sensor. Thus, the total resistance of the ring sensor 11% is higher than that of the PHEB sensor. This unnecessarily added resistance contributes to the sensor power dissipation and the sensor noise.

The differences in experimentally observed field sensitivities reported by Sinha *et al.*[1] are due to different length over width ratios for the various sensor designs as well as differences in the magnetic stack. Moreover, the field response may be affected by shape anisotropy, which will influence the two designs differently.

In conclusion, we have analyzed the ring sensor design of Fig. 1(a) and compared it to the corresponding PHEB design of Fig. 1(b). Our analysis shows that the magnetic field sensitivity of the two sensor designs for identically behaving magnetic stacks is 41% higher for the PHEB design than for the ring design and that it can be achieved with an 11% lower bridge resistance.

[1]B. Sinha, T. Q. Hung, T. S. Ramulu, S. Oh, K. Kim, D.-Y. Kim, F. Terki, and C. Kim, "Planar Hall resistance ring sensor based on NiFe/Cu/IrMn tri-layer structure," J. Appl. Phys. **113**, 063903 (2013).
[2]A. D. Henriksen, B. T. Dalslet, D. H. Skieller, K. H. Lee, F. Okkels, and M. F. Hansen, "Planar Hall effect bridge magnetic field sensors," Appl. Phys. Lett. **97**, 013507 (2010).