

Statistical characterization of the spin Hall magnetoresistance in YIG/Pt heterostructures

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The spin Hall magnetoresistance (SMR) is widely used to study the interplay between charge and spin currents in bilayers of a magnetic insulator and a normal metal. However, not much is known about the spatial variation of the SMR across the surface of the same sample. In this work, we investigate the statistical distribution of the SMR in hundreds of nominally identical Hall bar structures patterned into prototypical yttrium iron garnet (YIG)/Pt heterostructures. We find a Gaussian-distributed SMR with a narrow standard deviation of approximately 10% of the mean value in each YIG/Pt bilayer studied. However, the variation of the mean SMR between different YIG/Pt samples can be as large as $\sim 35\%$, despite nominally identical fabrication conditions. Additionally, we compare the SMR statistics in YIG/Pt heterostructures prepared *in-situ* (without breaking the vacuum) and *ex-situ* (with the YIG layer exposed to air before Pt deposition), as well as in CoFeB/Pt. We find the SMR standard deviation to be systematically smaller for *in-situ* interfaces. We conclude that on a microscopic level, local variations of the interface quality captured by the spin mixing conductance are the most likely origin for the observed SMR amplitude variations.

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I. INTRODUCTION

Pure spin current phenomena enable the transfer of spin angular momentum without an accompanying charge flow, which makes them the backbone of modern spintronics [1]. A quantitative understanding of how spin currents are generated, transmitted, and absorbed at interfaces is essential for optimizing spin transport efficiency and for advancing applications such as spin-orbit torque switching for magnetic memories [2,3], spin Seebeck devices [4–6], and magnonic circuits [7–9]. In this context, the spin Hall magnetoresistance (SMR) provides an effective probe of interfacial spin transfer processes. The SMR occurs in bilayers consisting of a magnetic layer (FM) and a normal metal (NM) layer [10–12]. The SMR arises from a magnetization-orientation-dependent spin transfer across the FM/NM interface [10–12], resulting in a change of the resistivity of the NM as a function of the magnetization orientation in the FM. The effect is quantified by the ratio of the magnetization-dependent resistivity change $\Delta\rho$ and the resistivity ρ_0 of the NM itself: $\text{SMR} = \Delta\rho/\rho_0$. Typically, the NM consists of a heavy metal like Pt or Ta featuring a large spin Hall effect [1,13,14]. Magnetic insulators like yttrium iron garnet (YIG) are the prototypical FM layer, as the charge current flow in the FM/NM bilayer is then limited to the NM layer.

After its initial discovery and theoretical description [10,12], the SMR has been extensively studied [15]. Next to the prototypical combination of YIG/Pt, the SMR has been observed in a manifold of different material combinations [11,16–24]. Between these materials, the value of the SMR can vary by multiple orders of magnitude with the largest values reported in YIG/Pt and $\text{Fe}_2\text{O}_3/\text{Pt}$, being $\text{SMR} = 1.6 \times 10^{-3}$ and 2.5×10^{-3} , respectively [11,21]. The SMR can also be the dominant magnetoresistance effect in all-metallic bilayers, for example, in CoFeB/W [19]. While theoretical approaches modeling the SMR have been put forward, a quantitative analysis and comparison of the effect size for different material combinations remains to be performed [25]. Such a modeling is further complicated, as even in YIG/Pt [10,11,26,27], the SMR effect amplitude differs significantly in the literature [11,26,27]. These differences can be traced back to multiple parameters determining the effect: the spin Hall properties of Pt [28], the thickness of Pt [11], and the interface quality defining the spin transparency [27,29]. While the Pt thickness and resistivity can be controlled via the deposition [11,28], its texture, crystallinity, or grain size is more tedious to characterize [30]. Moreover, strong variations in the SMR amplitude can arise due to the interface quality [31]. In particular, the YIG/Pt interface can either be obtained in an *in-situ* [11] or *ex-situ* process [29,32]. The largest SMR in YIG/Pt is observed for *in-situ* interfaces [11], whereas the initial surface treatment of the YIG layer largely impacts the resulting SMR effect size in an *ex-situ* process [27,29,32–34].

Despite the large spread in SMR amplitudes and parameter values, the SMR amplitude for a given FM/NM bilayer sample is commonly extracted from measurements on a single Hall bar device and taken as a representative value for this material combination. Interestingly, not much is known about the reproducibility and the statistical error across the surface of

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a single sample, not to speak of a series of bilayer samples fabricated using a nominally identical fabrication procedure.

In this work, we compare the SMR response of three nominally identical YIG/Pt bilayer samples with an *ex-situ* interface, a YIG/Pt bilayer prepared *in-situ*, and an all-metallic CoFeB/Pt sample also prepared *in-situ*. To quantify the statistical distribution of the SMR amplitude, we systematically study hundreds of Hall bar devices patterned onto each of the above samples, respectively. For the *ex-situ* samples, we find a Gaussian distribution of the SMR on each sample with a narrow standard deviation not larger than $\sim 10\%$, whereas between nominally identical samples the SMR can vary by up to 35%. In turn, the distribution in the two samples prepared *in-situ* is narrower. We conclude from these findings that nonuniform interface properties are the main cause for large SMR amplitude variations in a given bilayer sample.

II. SAMPLE PREPARATION AND EXPERIMENTAL METHODS

For the three YIG/Pt bilayer samples with *ex-situ* interface, referred to as samples SE1, SE2 and SE3 in the following, we utilized commercially available YIG films epitaxially grown via liquid phase epitaxy (LPE) as the magnetic layer. Before the Pt deposition, the surface was cleaned with Piranha-acid ($\text{H}_2\text{O}_2 : \text{H}_2\text{SO}_4$) as detailed in Ref. [35].

A 5 nm Pt layer was then deposited via magnetron sputtering in an ultra-high vacuum (UHV) deposition system with a base pressure smaller than 1×10^{-7} mbar, at a RF power of 50 W, yielding a deposition rate of 1.8 nm min^{-1} . The YIG/Pt bilayer sample denominated SI was deposited *in-situ*, without breaking the vacuum. We used a GGG ($\text{Gd}_3\text{Ga}_5\text{O}_{12}$) single crystal substrate cleaned in acetone and isopropyl alcohol, onto which we deposited a YIG layer via magnetron sputtering in an ultra-high vacuum deposition system with a base pressure smaller than 1×10^{-8} mbar, at a RF power of 80 W, resulting in a deposition rate of 0.3 nm min^{-1} . The deposition and the subsequent annealing in O_2 atmosphere were performed at an elevated temperature of 820°C for 1 h. The sample was then transferred to the Pt deposition chamber (pressure smaller than 1×10^{-8} mbar) via an UHV transfer tube, without breaking the vacuum and a 5 nm Pt layer was deposited at an RF power of 80 W, yielding a deposition rate of 4.1 nm min^{-1} . For the CoFeB/Pt bilayer sample SM, we used a thermally oxidized Silicon wafer [Si/SiOx (1024 nm)] cleaned in acetone and isopropyl alcohol as the substrate, and deposited CoFeB via magnetron sputtering in an ultra-high vacuum deposition system with a base pressure smaller than 1×10^{-8} mbar, at a RF power of 50 W, yielding a deposition rate of 1.9 nm min^{-1} . After the CoFeB deposition, a 5 nm Pt layer is deposited using the same Pt deposition technique as detailed for sample SI.

After deposition, Hall bars are defined using optical lithography and Ar^+ ion etching. Figure 1(a) schematically depicts a Hall bar structure. Figure 1(b) shows a micrograph of the patterned sample. The magnetoresistance response of the Hall bars is characterized in a custom-build probe station. A rotatable permanent magnet Halbach array [36,37] is used to rotate a magnetic field of constant magnitude within the FM/Pt interface plane, and thus to control the in-plane magnetization

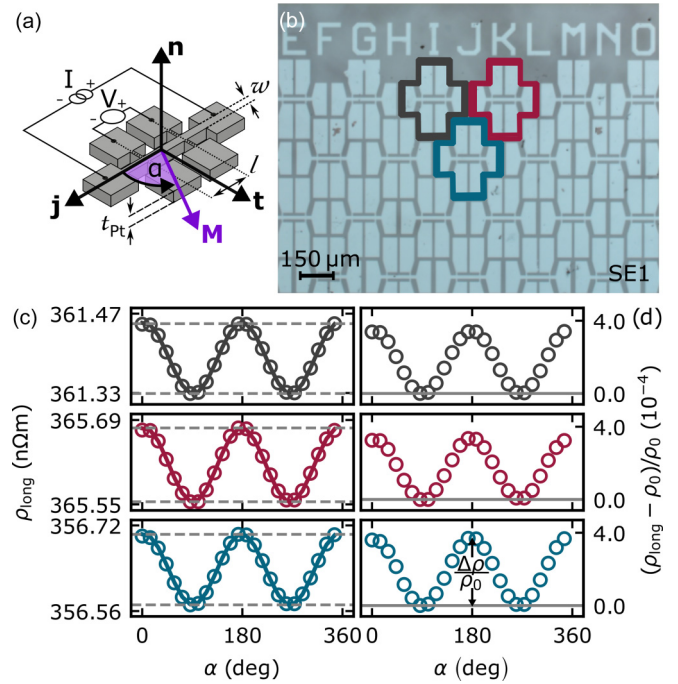


FIG. 1. (a) Hall bar device and coordinate system used throughout this study. Via magnetron sputtering, a Pt layer being t_{Pt} thick is deposited onto a given FM film. By using optical lithography, hundreds of Hall bars with width w and length l are patterned into the Pt layer. A current I is driven through the device, and the voltage V is measured. The magnetization of the FM layer is rotated in the film plane by an external magnetic field applied at a varying angle α . (b) Micrograph of sample SE1. (c) Resistivity modulation and (d) normalized magnetoresistance obtained from the three framed Hall bars in (b). The SMR ($\Delta\rho/\rho_0$) is indicated for the measurement shown in blue.

of the FM layer. The angle between the current direction $\mathbf{j}$ and the magnetization $\mathbf{M}$ is defined as α . Micropositioners with tungsten tips are used to contact a given Hall bar to apply a current I along the Hall bar and to measure the ensuing voltage V . As the sample is mounted onto an x-y-z stage, our probe station allows measuring the SMR in multiple Hall bars in a fully automated fashion. By taking the Hall bar dimensions into account the resistivity ρ_{long} and the field-orientation dependent resistivity change $\Delta\rho$ can be calculated. All magnetotransport measurements are performed with the sample at room temperature, i.e., exposed to ambient conditions in the laboratory.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1(c) exemplarily shows the SMR observed in sample SE1 in three different Hall bars framed in Fig. 1(b). The SMR manifests as a $\cos^2(\alpha)$ modulation of the longitudinal resistivity [10,11]. We fit the data by using

$$\rho_{\text{long}} = \Delta\rho \cdot \cos^2(\alpha + \alpha_0) + \rho_0, \quad (1)$$

and calculate the SMR amplitude as $\text{SMR} = \Delta\rho/\rho_0$. Here, α_0 corresponds to a phase shift of the SMR modulation, which can occur due to a misalignment of the external field with respect to the sample in the measurement setup. The SMR in

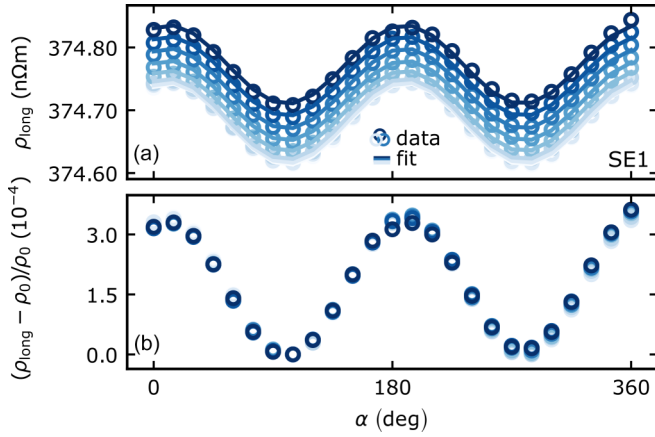


FIG. 2. (a) Repeatability of the measurement scheme on a single Hall bar on sample SE1. The contacting and measuring scheme was performed 8 times over an hour. The total change of the average resistivity corresponds to a temperature change in the laboratory of 0.15 K. The fit to the data yields $\alpha_0 = -11.1$ deg, which accounts for the misalignment of the external field. (b) The normalized data for all performed measurements yield a mean SMR of 3.41×10^{-4} , with the standard deviation $\sigma = 0.04 \times 10^{-4}$, emphasizing the reproducibility of our measuring scheme.

the three Hall bars is $\text{SMR} = 3.48 \times 10^{-4}$, 3.37×10^{-4} , and 3.72×10^{-4} , respectively. This emphasizes a similar SMR effect in all measurements. Small deviations of $\Delta\rho$ and ρ_0 on the scale of 10% and 3% are noticeable between the different devices in Fig. 1(c) and 1(d). Possible causes are discussed in the following.

In a first iteration, we discuss the influence of the external temperature on the measurement results and the extracted SMR. The setup is not temperature-stabilized, and the Pt resistivity is very sensitive to changes in temperature. This influence is highlighted by the Pt temperature coefficient of $5.752 \times 10^{-3} \text{ K}^{-1}$ (determined from a calibration measurement). Thus, changes in resistivity can stem from temperature variations during the measurement of the devices.

To assert that the normalization of $\Delta\rho$ to ρ_0 does not hide additional effects and gauge the reproducibility of the automated contacting, we perform several measurements over the course of an hour on one Hall bar on sample SE1. Figure 2(a) depicts the resistivity of 8 measurements performed on the same Hall bar. The resistivity offset ρ_0 varies significantly between the measurements. Using the temperature coefficient introduced earlier, the change in resistivity can be explained by a laboratory temperature change of 0.15 K. As the heating of the Hall bar owing to the current flow amounts to 3 mK at most, the differences in resistivity can be attributed to changes in the external temperature. After normalization of the data, very similar SMR amplitudes become apparent with a narrow standard deviation of $\sigma = 4 \times 10^{-6}$, which is less than 2% of the SMR amplitude (cp. Fig. 2(b)). This result demonstrates that our measurement technique yields a robust SMR value on each device and is suited for the statistical investigation of the SMR.

We thus turn to the statistical analysis of the SMR by investigating the $N = 225$ Hall bars on sample SE1. We measure

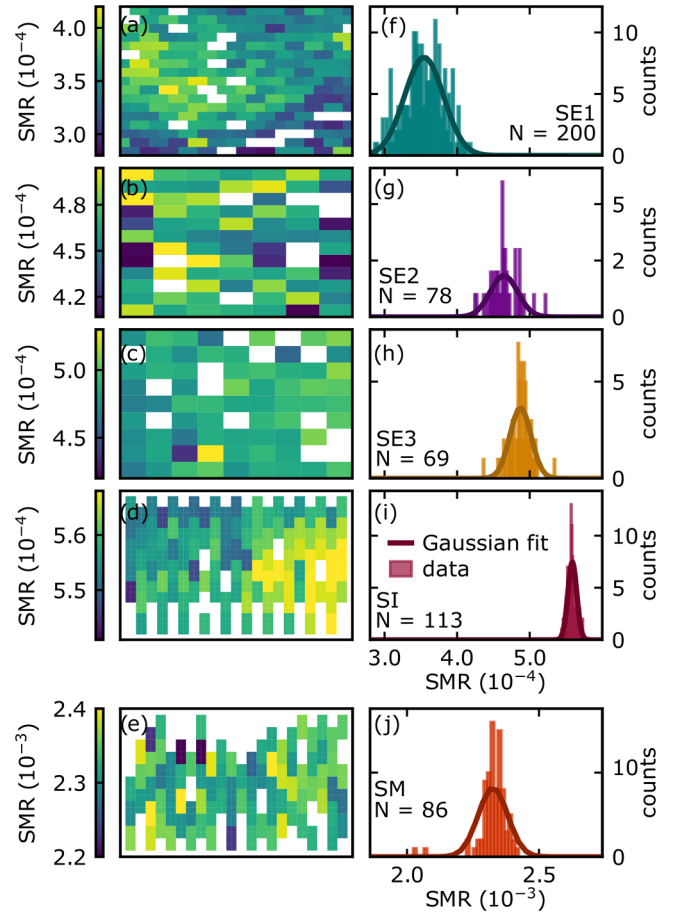


FIG. 3. (a), (b), (c), (d), and (e) Color maps of the SMR response for the different Hall bars on samples SE1, SE2, SE3, SI, and SM where SE1, SE2, SE3, and SI consist of YIG/Pt bilayers and SM is a CoFeB/Pt bilayer. Every rectangle corresponds to a Hall bar, and the color of the individual rectangle represents the value of the SMR. In all five samples, the SMR is quite homogeneously distributed; however, a small scattering of the SMR values is visible. Geometrical factors as well as temperature-dependent effects can be excluded as an explanation (see main text). This leaves intrinsic effects impacting the SMR such as the spin transparency of the YIG/Pt- and CoFeB/Pt-interface as the microscopic mechanism leading to the SMR amplitude distribution. (f), (g), (h), (i) and (j) Histograms of the SMR amplitude distribution for samples SE1, SE2, SE3, SI and SM. Fitting a Gaussian distribution yields mean values μ_{SMR} of 3.54×10^{-4} , 4.61×10^{-4} , 4.87×10^{-4} , 5.59×10^{-4} and 2.3×10^{-3} and standard deviations σ_{SMR} of 0.27×10^{-4} , 0.23×10^{-4} , 0.14×10^{-4} , 0.06×10^{-4} and 0.56×10^{-4} , respectively. Therefore, the variation of the SMR on one sample is as small as 10%. However, the SMR variation across multiple, nominally identical samples can be up to 35%.

the resistivity of all Hall bars and extract their magnetization orientation-dependent resistivity change and resistivity offset. Such a large set of measurements allows us to determine the statistical distribution of the SMR. In Fig. 3(a), the spatial distribution of the SMR in SE1 is depicted. Each rectangle represents an individual Hall bar device, with the positions in the color map corresponding to the position on the sample. White spaces describe shorted or broken devices.

TABLE I. Mean value μ_{SMR} and standard deviation σ_{SMR} of the SMR, as well as the mean resistivity μ_{ρ_0} and corresponding standard deviation, for the five samples investigated. Samples SE1, SE2, SE3 (with *ex-situ* interfaces) and SI (with *in-situ* interface) are YIG/Pt bilayers, SM is a CoFeB/Pt bilayer.

Sample	μ_{SMR}	σ_{SMR}	$\frac{\sigma_{\text{SMR}}}{\mu_{\text{SMR}}}$ (%)	μ_{ρ_0} (n Ω m)	σ_{ρ_0} (n Ω m)
SE1	3.54×10^{-4}	0.27×10^{-4}	7.6	366	10.9
SE2	4.61×10^{-4}	0.23×10^{-4}	5.0	283	6.7
SE3	4.87×10^{-4}	0.14×10^{-4}	2.9	449	11.5
SI	5.59×10^{-4}	0.06×10^{-4}	1.1	239	2.1
SM	2.3×10^{-3}	0.56×10^{-4}	2.4	514	21.6

In total, more than 90% of the devices functioned and were evaluated. A consistently large amplitude around $\text{SMR} = 4 \times 10^{-4}$ is found across the whole sample. However, a slightly brighter area, corresponding to a larger SMR amplitude, can be observed on the left. The SMR amplitude can be expressed via Eq. (2) [12]:

$$\text{SMR} = \frac{2\theta_{\text{SH}}^2 \lambda^2 \frac{\rho_0}{t_{\text{Pt}}} G \tanh^2\left(\frac{t_{\text{Pt}}}{2\lambda}\right)}{1 + 2\lambda\rho_0 G \coth\left(\frac{t_{\text{Pt}}}{\lambda}\right)}. \quad (2)$$

Here, $\theta_{\text{SH}} = \rho_0 \cdot \sigma_{\text{SH}}$ is the spin Hall angle with the spin conductivity σ_{SH} and $\lambda = \sigma_{\text{Pt}} \cdot c$ is the spin diffusion length with $\sigma_{\text{Pt}} = \frac{1}{\rho_0}$ and $c = 0.61 \times 10^{-15} \Omega \text{ m}^2$ [28,30]. Equation (2) implies that the SMR depends on several parameters. Especially, the spin mixing conductance G is demanding to control in the fabrication process. Therefore, variations of the SMR across the surface of a given bilayer sample are most likely to stem from a change of G across the sample.

Figure 3(f) depicts a histogram of the extracted SMR ($\Delta\rho/\rho_0$) for sample SE1, where similar SMR values are binned. Shorted or broken devices are excluded. The histogram reveals a Gaussian distribution of the SMR across the sample. This information is crucial to establish how deviations of the SMR ratio can be associated with variations between devices in a sample. To statistically analyze the distribution of the SMR, the data is fit by:

$$f(\text{SMR}) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\text{SMR}-\mu}{\sigma}\right)^2}, \quad (3)$$

where μ is the mean value and σ the standard deviation. We find $\mu_{\text{SE1}} = 3.54 \times 10^{-4}$ and $\sigma_{\text{SE1}} = 0.27 \times 10^{-4}$, see Table I, where σ_{SE1} is well beyond the measurement reproducibility.

Repeating this statistical assessment of the SMR amplitude for the other two nominally identical samples (SE2 and SE3), with *ex-situ* interfaces, allows comparing the SMR between different YIG/Pt heterostructures. In some more detail, we measured the SMR in all Hall bars on samples SE2 and SE3 using our automated probe station, as described in the previous paragraph. We observe a SMR response very similar to sample SE1, as shown in Figs. 3(b) and 3(c). Figures 3(f), 3(g), and 3(h) depict the corresponding SMR distribution across the respective sample. The Gaussian distribution in Figs. 3(g) and 3(h) correspond to $\mu_{\text{SMR,SE2}} = 4.61 \times 10^{-4}$ and $\mu_{\text{SMR,SE3}} = 4.87 \times 10^{-4}$, the standard deviations are summarized in Table I. The histograms of the SMR of the three

samples (SE1-SE3) can be consistently described via a narrow Gaussian distribution [see Figs. 3(f)–3(h)].

We now turn to the samples SI and SM, which feature FM/Pt interfaces fabricated *in-situ*, without breaking the vacuum. The SMR response of the Hall bar arrays patterned into the YIG/Pt sample SI is shown in Fig. 3(d), and the corresponding amplitude histogram in Fig. 3(i). Note that this sample features the smallest standard deviation of the SMR amplitudes among the YIG/Pt bilayers. For the metallic CoFeB/Pt sample SM, analogous data are depicted in Figs. 3(e) and 3(j), respectively. While the standard deviation of 0.56×10^{-4} might appear rather large at first glance, one has to keep in mind that the SMR magnitude in CoFeB/Pt is also about one order of magnitude larger than the one in YIG/Pt. Thus, the sample SM shows a comparatively small standard deviation of the SMR amplitude.

Overall, all five samples exhibit a robust SMR value in the sense that the standard deviation is much smaller than the mean amplitude (see also the ratio $\sigma_{\text{SMR}}/\mu_{\text{SMR}}$ in Table I). Consequently, on hindsight, the measurement of a single device on a YIG/Pt sample provides a reasonable representation of the sample quality and the actual size of the SMR. However, as revealed by our statistical analysis, the precise magnitude of the SMR amplitude can only be estimated from the response of one single Hall bar with an uncertainty of (several) 10% [11,15,29].

We would like to stress that the mean SMR values of all samples are in good agreement with the literature. For YIG/Pt samples with *ex-situ* interfaces fabricated using a similar treatment as the one we used for samples SE1, SE2, and SE3, SMR values of about 3×10^{-4} have been reported [29]. Moreover, for Pt film thicknesses comparable to the one used for the samples studied here, SMR values ranging from 1.6×10^{-3} for *in-situ* interfaces [11] to 6.2×10^{-5} without prior surface treatment [27] have been reported. The mean SMR of samples SE1, SE2, SE3, and SI is thus well within the expected range. Similarly, the SMR amplitude extracted from sample SM is comparable to the values reported for CoFeB/Pt bilayers (2.6×10^{-3} , [38]). However, while the SMR of the individual samples is robust and well-defined, the sample-to-sample deviations are well beyond the standard deviations. This suggests that despite nominally identical preparation conditions, a significant variation of the observed SMR is present. We now discuss the variation of the SMR in a single sample and between different samples, and further its dependency on the resistivity. To that end, Fig. 4 summarizes the SMR versus the corresponding ρ_0 for every Hall bar of all five samples SE1, SE2, SE3, SI and SM [see Figs. 4(a)–4(f)]. The dashed lines indicate the standard deviation of the SMR and of the resistivity (see also Table I).

The Hall bar geometry, temperature, and the YIG/Pt interface quality could influence the correlation of the SMR and the resistivity. As already observed in Fig. 2, the temperature strongly influences the resistivity ρ_0 . By assuming that the temperature does not change more than 5 K during the entire measurement run, only a resistivity change of 3.19 n Ω m can be explained. However, the standard deviation clearly exceeds this by a factor of 3.4. Additionally, a minor impact of the temperature on the SMR is well established [39] and is assumed to behave linearly in a range from 150 K to 300 K.

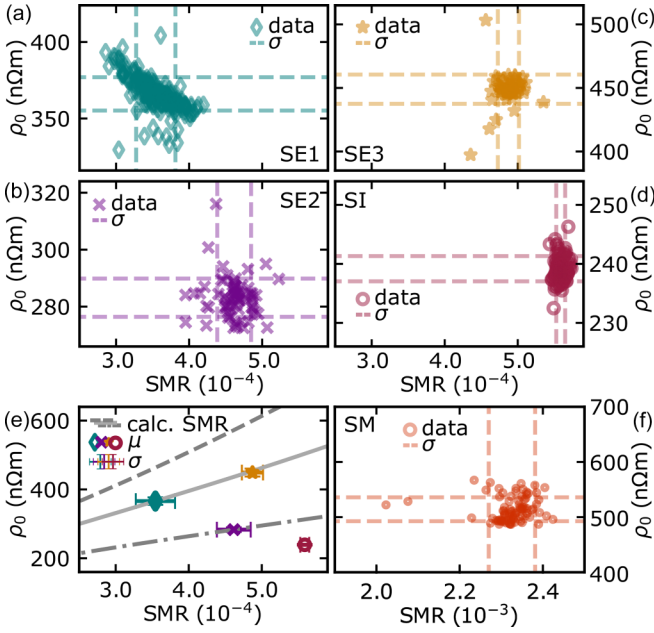


FIG. 4. (a), (b), (c), (d), and (f) Correlation of the SMR and the resistivity ρ_0 for every Hall bar measured on SE1, SE2, SE3, SI, and SM. The dashed lines indicate the standard deviation of the SMR amplitude and ρ_0 , respectively. In (a), if the SMR values increase, the resistivity decreases and vice versa, whereas the opposite behavior is expected from Eq. (2). In (b), (c), and (d), this behavior is not reproduced, suggesting that the observed trending is unique to sample SE1. (e) The mean of all SMR values and resistivity values per sample. The error bars indicate the standard deviation of both the SMR and ρ_0 . Additionally, the gray line is a calculation of the SMR according to Eq. (2), revealing a trend depending on ρ_0 , which reproduces the measured data well. We used $G = 3 \times 10^{14} \Omega^{-1} \text{m}^{-2}$ for the dashed line, $G = 5 \times 10^{14} \Omega^{-1} \text{m}^{-2}$ for the solid line, and $G = 3 \times 10^{15} \Omega^{-1} \text{m}^{-2}$ for the dash-dotted line.

A temperature change of 5 K leads to an SMR change of 0.23×10^{-5} , which is almost an order of magnitude smaller than the standard deviations of all measured samples. Ultimately, laboratory temperature variations thus cannot account solely for the observed variations of ρ_0 and the SMR across the sample surface.

In order to exclude the variations of the Hall bar geometries, a few Hall bars were randomly chosen and their width and length measured, yielding a variation of up to 5% in both dimensions. In turn, the thickness t_{Pt} of the Pt layer on SE1 was analyzed via ellipsometry on 6 different locations, all resulting in $t_{\text{Pt}} = 5.1 \text{ nm}$ with variations not larger than 0.3 nm. We thus conclude that the variations in the actual Hall bar geometry are the likely origin of the observed standard deviation in ρ_0 . However, since the geometry does not enter into the SMR due to the normalization of $\Delta\rho$ to ρ_0 , geometrical variations cannot explain the observed deviations of the SMR.

Having excluded extrinsic effects, the observed variation of the SMR evident from Fig. 4 must stem from intrinsic properties of the YIG/Pt heterostructure. In the following, we discuss potential changes in the intrinsic spin Hall properties of the Pt film. Here, the spin Hall angle θ_{SH} and the spin diffusion length λ depend on ρ_0 [28]. Large ρ_0 corresponds to large

θ_{SH} , whereas large ρ_0 corresponds to small λ . Both parameters influence the SMR [see Eq. (2)]. However, in Fig. 4(a), large SMR values systematically correspond to small resistivity values and vice versa. Neither thickness variations nor the scaling of θ_{SH} and λ explain this nontrivial behavior. We interpret this as evidence that θ_{SH} and λ are not the main cause for the variations in the SMR amplitude across the sample surface.

This leaves the YIG/Pt interface quality as a possible cause for the observed variations. Generally, the spin mixing conductance G seems to be rather homogeneous across the sample; however, small deviations cannot be excluded. The trending of the correlation in Fig. 4(a) seems to be uniquely attributed to this sample and is absent in the other samples [see Figs. 4(b), 4(c), and 4(d)]. Consequently, the origin of the correlation cannot be pinpointed further.

Furthermore, the ratio of the SMR standard deviation and the mean SMR value $\sigma_{\text{SMR}}/\mu_{\text{SMR}}$ of the samples SI [Fig. 4(d)] and SM [Fig. 4(f)], being $\sim 1\%$ and $\sim 2.4\%$ is on the lower end than for the other samples. Since both SI and SM feature an *in-situ* interface, we associate the small statistical scatter with the more homogeneous interface quality.

In Fig. 4(e), the mean of all SMR and resistivity values extracted from YIG/Pt bilayers and their corresponding standard deviations is plotted. As stated before, large ρ_0 should be accompanied by large SMR values [cp. Eq. (2)]. Three different spin mixing conductances $G = 5 \times 10^{14} \Omega^{-1} \text{m}^{-2}$ (solid line) $G = 3 \times 10^{14} \Omega^{-1} \text{m}^{-2}$ (dashed line) and $G = 3 \times 10^{15} \Omega^{-1} \text{m}^{-2}$ (dash-dotted line) are used to model the SMR as a function of ρ_0 [see Eq. (2)]. This scaling is depicted in Fig. 4(e). Here, for $G = 5 \times 10^{14} \Omega^{-1} \text{m}^{-2}$, the SMR model resembles the mean SMR obtained in sample SE1 (green) and SE3 (yellow) well. However, in SE2 (violet) and SI (red), a somewhat different spin mixing conductance of $G = 3 \times 10^{15} \Omega^{-1} \text{m}^{-2}$ matches the data best.

The spin mixing conductance (viz., the interface quality) is the only parameter that cannot be controlled easily across the entire sample in this study. Therefore, we conclude that both the scattering of the SMR on an individual sample and the deviations across several samples are most likely attributed to a varying spin mixing conductance between the individual samples and across their surfaces, respectively. This notion is further corroborated by comparison between *in-situ* and *ex-situ* samples. Despite these variations, we can overall reproduce a consistent SMR value across the sample with a narrow standard distribution.

IV. CONCLUSION

In summary, we have investigated the SMR in multiple FM/Pt bilayer samples. Onto each bilayer, we patterned numerous Hall bar devices and investigated the statistics of the SMR. We find a mean value $\mu = 3.54 \times 10^{-4}$ and a standard deviation $\sigma = 0.27 \times 10^{-4}$ for sample SE1 with 225 devices. The standard deviation is approximately 10% of μ , which is reproduced in the other two, nominally identical samples. Two reference samples with *in-situ* interfaces, specifically a YIG/Pt sample and a CoFeB/Pt sample, show a significantly more narrow $\sigma_{\text{SMR}}/\mu_{\text{SMR}}$ of 1% and 2.4%, respectively. We conclude that the SMR is Gaussian distributed and reproducible across a given sample, but can vary significantly

between samples. The dominant source of the scattering of the SMR is found to be the spin mixing conductance, leading to variations of $\sim 35\%$ of the SMR when comparing different samples. Our experiments thus yield insights into the statistical behavior of the SMR, its spatial homogeneity, the impact of the material combination, and the fabrication process. Our results show that spatial variations of the spin mixing conductance must be carefully considered when investigating small variations in the SMR, especially between different samples.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [40].

APPENDIX: DATA ANALYSIS

Since we use a computer-controlled probe station to record the magnetotransport response of hundreds of Hall bar structures on a given sample in a fully automated fashion, we have to identify all acquired data sets and remove data sets jeopardized by contact problems, shorted or broken devices, etc. In the following, we detail the procedure we used to this end. Prior to recording the magnetotransport response of a given Hall bar, an automatic approach step is performed. Hereby, the sample is moved towards the fixed measurement tips while monitoring the voltage drop along the Hall bar. The approach stops if defined conditions (2-wire voltage $V_{2w} \leq 0.25$ V, standard deviation of 5 mV at a current $I = 100$ μ A) are satisfied. These conditions correspond to a bar resistance ≤ 2.5 k Ω , well above the expected device resistance of ~ 400 Ω . Requiring a low standard deviation of repeated voltage readings as a function of time ensures stable contact of the tips with the sample. Broken devices or devices, which cannot be contacted in a stable way, are thus never measured because they do not fulfill the above conditions. For all other Hall bars, the magnetotransport response—or more precisely the longitudinal 4-wire voltage drop V_{4w} detected via a second set of probe tips as shown in Fig. 1(a)—is recorded and stored on the computer. For the sake of clarity, we will refer to the set of voltages $V_{4w}(\alpha)$ as a function of magnetic field orientation α recorded in one given Hall bar as one dataset in the following.

Next, the longitudinal resistivity ρ_{long} of the Hall bars is calculated using

$$\rho_{\text{long}} = \frac{V_{4w}}{I} \cdot \frac{w \cdot t_{\text{Pt}}}{l}, \quad (\text{A1})$$

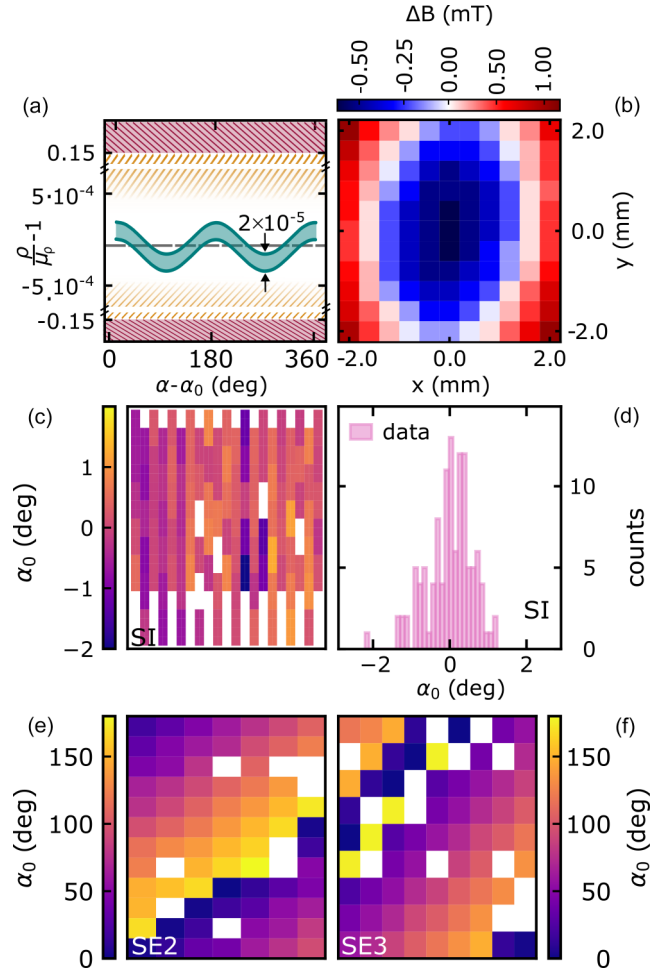


FIG. 5. Data analysis (a) Each data set has to fulfill several conditions in order to exclude shorted or broken devices as well as data sets with large fluctuations to prevent any distortion of the statistical analysis. First, that data have to pass a voltage threshold while contacting. Further, after calculating the median μ_{ρ}^{all} of all data sets, only data sets having their median value falling between $0.85\mu_{\rho}^{\text{all}}$ and $1.15\mu_{\rho}^{\text{all}}$ are evaluated, all others are excluded (red shaded area). Additionally, the verified data is masked to exclude large fluctuations (yellow shaded area) and fit. Lastly, by taking the fit parameters, the data is again masked. Only data points within the green shaded area are finally selected for the evaluation. (b) Spatial mapping of ΔB at $z = 0$ mm. (c) Spatial mapping of α_0 of sample SI. (d) Histogramm of α_0 of sample SI. (e) and (f) Spatial distribution of α_0 of the samples SE2 and SE3 in which the Hall bar structures were systematically rotated by design.

where I is the applied current, w and l are the width and length of the Hall bar, and t_{Pt} is the thickness of the Pt layer [cp. Fig. 1(a)]. We furthermore calculate the median resistivity μ_{ρ}^{ind} for each individual Hall bar from the corresponding dataset, as well as the median resistivity μ_{ρ}^{all} of all datasets. Hall bars for which the individual median μ_{ρ}^{ind} is outside of the interval of $0.85\mu_{\rho}^{\text{all}}$ and $1.15\mu_{\rho}^{\text{all}}$ are discarded [red shaded area in Fig. 5(a)]. This step is crucial to sort out devices that are shorted or not properly contacted. Further, to exclude individual measurement points showing large deviations, e.g., due to vibrations leading to loss of contact only at specific

field angles α , every data set measured in YIG/Pt (CoFeB/Pt) is masked using

$$\text{mask} = \left| \frac{\rho_{\text{long}}(\alpha) - \mu_{\rho}^{\text{ind}}}{\mu_{\rho}^{\text{ind}}} \right| < 5 \times 10^{-4} \quad (5 \times 10^{-3}), \quad (\text{A2})$$

where $\rho_{\text{long}}(\alpha)$ is the longitudinal resistivity for every rotation angle α in a given dataset [see yellow shaded area in Fig. 5(b)]. Then the masked data is fit by using Eq. (1). To avoid errors in the fits due to further outliers that are not excluded by the coarse masking in Eq. (A2), the data is again masked using the fit as a reference:

$$\text{mask} = \left| \frac{\rho_{\text{long}}(\alpha) - \text{fit}}{\mu_{\rho}^{\text{ind}}} \right| < 1 \times 10^{-5}, \quad (\text{A3})$$

after which the data is fit a final time. We note that the two masking steps typically only exclude at most a few points from the measurement. If more than 20% of the points in one dataset are excluded, the entire dataset is discarded and not considered in the statistical evaluation. Taken together, only data points within the green area in Fig. 5(a) are finally considered for the statistical evaluation. Note that α_0 is obtained from the fit of Eq. (1).

Figure 5(b) addresses the spatial homogeneity of the magnetic field for the Halbach array with $B_{\text{mean}} = 106.3$ mT center field. We measured the magnetic field as a function of the (x,y,z) position using a commercial Hall probe. Figure 5(b) shows $\Delta B(x, y) = B(x, y) - B_{\text{mean}}$ at the sample height $z = 0$ mm. Within the x-y plane, B shows a maximum variation

within ± 1 mT of the mean value over the full spatial motion range of the stage.

In Fig. 5(c), the spatial distribution of α_0 of sample SI is depicted. The Hall bars on the sample are aligned parallel to each other, and deviations of α_0 stemming from the lithography process are smaller than 0.2 deg when estimated by optical microscopy. However, larger deviations of α_0 of ± 2 deg are observed in Fig. 5(d). We attribute this to the rather small number of 25 points within one dataset, i.e., one full magnetic field rotation in 15 deg angle steps, which limits the accuracy with which α_0 can be determined from the data.

Variations of B as a cause for different α_0 can be neglected by considering the measurement approach and the small variations of B evident in Fig. 5(b). Specifically, every sample is divided into 4 quadrants, and every quadrant is measured within one measuring sequence consisting of the acquisition of the datasets for the individual Hall bars within this quadrant. After a sequence is measured, the probes are moved to the next quadrant by hand (~ 1.5 mm in x and y), and a new sequence is conducted. For every sequence, B stays exactly the same, because the Hall bars are moved to the exact same position within the external magnetic field. Between different quadrants, B varies by less than 2%.

Finally, the Hall bars patterned onto the samples SE2 and SE3 are systematically rotated in 15 deg steps. This is fiducially reproduced in the spatial distribution of α_0 shown in Figs. 5(e) and 5(f).

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