Spintronics exploit spin-orbit coupling (SOC) to generate spin currents, spin torques, and, in the absence of inversion symmetry, Rashba and Dzyaloshinskii–Moriya interactions. The widely used magnetic materials, based on 3d metals such as Fe and Co, possess a small SOC. To circumvent this shortcoming, the common practice has been to utilize the large SOC of nonmagnetic layers of 5d heavy metals (HMs), such as Pt, to generate spin currents and, in turn, exert spin torques on the magnetic layers. Here, a new class of material architectures is introduced, excluding nonmagnetic 5d HMs, for high-performance spintronics operations. Very strong current-induced torques exerted on single ferrimagnetic GdFeCo layers, due to the combination of large SOC of the Gd 5d states and inversion symmetry breaking mainly engineered by interfaces, are demonstrated. These “self-torques” are enhanced around the magnetization compensation temperature and can be tuned by adjusting the spin absorption outside the GdFeCo layer. In other measurements, the very large emission of spin current from GdFeCo, 80% (20%) of spin anomalous Hall effect (spin Hall effect) symmetry is determined. This material platform opens new perspectives to exert “self-torques” on single magnetic layers as well as to generate spin currents from a magnetic layer.
currents (SHE-type or “magnetization-independent spin Hall current” in the language of ref. [6]). This coexistence has clearly been shown in the experiments of Das et al.[8] and was also found in other recent works.[9–11]

An SAHE-type spin current in a single magnetic layer cannot produce a spin-torque on its own magnetization because its spin polarization is along the direction of this magnetization. In contrast, the SHE-like spin current inside a single magnetic layer can give rise to a torque on the magnetization of the single layer itself,[6,7] namely, a self-torque. The exchange interaction between the spin accumulation of SHE symmetry at interfaces and the magnetization generates field-like (FL)[1] torques (except in the presence of symmetric interfaces and compensated FL torques). Furthermore, the ejection of spin currents outside the magnetic layer and the transfer of spins into neighboring layers generate damping-like (DL)[1] self-torques (except for perfectly symmetric interfaces and symmetric neighboring materials, which leads to compensated spin torques).

Besides the effects described above for charge-spin conversion that are originating from the bulk of the ferromagnet, additional mechanisms for current-induced self-torques on single magnetic layers are related to SOC and the lower symmetry associated with interfaces. Specifically, 1) Rashba interactions[12] generate a spin polarization and ensuing spin currents, and 2) Scattering by interfacial spin-orbit potentials gives rise to spin currents from nonpolarized currents by spin filtering and spin precession.[13] Rashba-induced torques were first discussed by Manchon and Zhang[14] who predicted FL torques caused by the current-induced Rashba spin polarization. More recent works[15–19] have shown that accounting for the diffusion of the Rashba spin polarization followed by its absorption and transfer outside the ferromagnetic layer induces a DL torque, in addition to the FL torque discussed in ref. [14]. The initial model by Manchon and Zhang[14] was developed for in-plane magnetization of the magnetic layer. For the present work, an extension of the theory for any orientation of the magnetization was developed and is presented in Note S1, Supporting Information. Its general result is to show the combination of SAHE and SHE symmetries for the Rashba spin polarization and their resulting spin currents, same combination of SAHE-like

Figure 1. Schematic geometries of SHE and SAHE, composition gradient in GdFeCo and ST-FMR measurements. a) Sketch of the SHE-type spin current symmetry: a charge current $J_c$ along $y$ generates in the $z$ direction a spin current $J_s$ having a spin polarization $\sigma$ along $x$ and equal to $\theta_{SHE} J_c$, where $\theta_{SHE}$ is the spin Hall angle of the metal. b) Sketch of the SAHE-type spin current symmetry for a magnetic layer magnetized in-plane along the unit vector $m$: a charge current $J_c$ along $y$ generates along $z$ a spin current $J_s$ having a spin polarization $\sigma$ along $\pm m$ and equal to $\theta_{SAHE} (J_c \times m) \times z$ where $\theta_{SAHE}$ is the anomalous spin Hall angle of the magnetic layer. c) STEM image of a GdFeCo/Cu based sample. The horizontal line represents the points were EDS analysis was performed. The lower graph depicts the evolution of the ratio of the Gd concentration over the Co+Fe concentration in the GdFeCo layer for the two different locations on the sample. The dashed red line is a linear fit with slope 0.013 nm$^{-1}$. See Supporting Information for more details. In addition to magnetic Rashba interface in GdFeCo/Cu, this composition gradient may be at the origin of additional contributions, namely bulk Rashba interface. d) Schematic of spin-orbit-driven FMR-based measurements. The stripe in the middle of the pictogram has dimensions $W \times L = 10 \times 60$ µm$^2$. The RF frequency and input power are fixed and the DC magnetic field $H_{dc}$ is swept. $H_{dc}$ is applied at 45° of the stripe for optimal detection.[32,33] The RF power is modulated at 426 Hz and the voltage $V_{mix}$ signal is picked-up after the bias-T using a lock-in. An additional DC current is included to study the variation of the FMR linewidth as a function of DC bias current, additional DC current source is included as illustrated. e) Example of raw data $V_{mix}$ for a GdFeCo/Cu/NiFe trilayer at 10 GHz. Two resonance lines are observed namely, for NiFe and GdFeCo.
and SHE-like symmetries as in the bulk spin currents inside the ferromagnet. The second interfacial mechanism,[9,10] namely spin filtering and precession, can generate torques if the interfaces are not strictly symmetric. Its application to experiments on current-induced torques has been discussed by several groups.[9,10] Hence, current-induced torques on single magnetic layers can be generated by different SOC effects: bulk (as SHE-like spin currents coexisting with SAHE-like spin currents)[9] or interfacial, always in the absence of inversion symmetry. Several experiments have shown clear signs of such torques on single layers, although, in most cases, a specific mechanism could not be clearly identified and characterized.[9–11,20–24]

In GdFeCo ferromagnetic alloys, strong spin-orbit interactions are expected from the 5d band introduced by Gd. The presence of large SOC effects is demonstrated by the well-defined Rashba surfaces found on Gd metal.[25] The existence of such Rashba surface states is a common character of rare-earth metals and metallic compounds possessing a conduction band with 5d states.[25–28] For the GdFeCo layers of this article, as we find different signs of the torques for GdFeCo/light metal bilayers with different types of light metal (opposite signs for GdFeCo/Cu and GdFeCo/AlTii, we can identify the SOC interactions at the GdFeCo/Light Metal interface as the predominant source of self-torque and, primarily, interfacial Rashba interactions because large Rashba splitting have been already identified at surfaces of Gd.[25] Additional contributions could come from the above-described bulk SHE-like spin currents preserved from alignment with the magnetization, as described in refs. [6,7]. Note that an additional source of bulk spin current mixing SHE and SAHE symmetries could also be the small composition gradient that we have identified in GdFeCo, Figure 1c. Such a gradient can break the inversion symmetry and generate a “bulk Rashba effect.”[10,22] Notably, Dzyaloshinskii–Moriya interactions (DMI), which is another consequence of SOC and lack of inversion symmetry, have been recently observed and related to composition gradients in single layers of GdFeCo.[24,29,30]

Before our measurements of torque, in a first set of measurements, we demonstrated the large generation of spin current in GdFeCo by measuring the emitted spin currents in experiments of current-induced modulation of the ferromagnetic resonance (FMR)-linewidth of NiFe in GdFeCo/Cu/NiFe trilayers. The effective global spin Hall angle (sum of SAHE and SHE-like Hall angles) is found to be as large as 0.8. This is an important result of our work because 0.8 is considerably larger than the values found in magnetic materials without 5d elements. In addition, we observe much smaller modulations of the FMR-width when GdFeCo is replaced by the heavy metal Pt, which shows that GdFeCo is considerably more efficient than Pt for the generation of spin current.

In our second set of experiments, we employed second-harmonic techniques to measure the current-induced, field-like (FL) and damping-like (DL) torques acting on quasi-isolated single GdFeCo layers. Here, quasi-isolated means that the GdFeCo layer is located between the insulating SiO$_2$ substrate and a top layer with very small SOC (Cu or TiAl). First, we characterize the variation of these torques with temperature in the vicinity of the magnetization and angular momentum compensation temperatures, $T_M$ and $T_K$.[31] The magnetization of Gd sublattice, $M_{Gd}$, and FeCo sublattice, $M_{FeCo}$, are opposite and cancel each other out at $T_M$. Their angular momentum $L_{Gd}=M_{Gd}/g_{Gd}$ and $L_{FeCo}=M_{FeCo}/g_{FeCo}$ cancel each other out at $T_K$ with $T_K$ larger than $T_M$ because the Landé g-factor is larger for Gd ($g_{Gd} = -2.2$) than for FeCo ($g_{FeCo} = -2$).[31] Both the FL and DL self-torques increase as the temperature increases toward $T_M$ and change sign at $T_K$. At higher temperature, the DL torque tends to zero at $T_K$. Second, to compare directly the self-torques on GdFeCo to the torques induced on GdFeCo by the SHE of HMs, we measured the torques after the deposition of a HM-layer of Pt or Ta above Cu.

The materials for our study are Si-SiO$_2$/Gd$_{25}$Fe$_{65.6}$Co$_{9.4}$(10 nm)/Cu(6 nm)/NiFe(4 nm)/Al(3 nm) for FMR experiments and Si-SiO$_2$/Gd$_{25}$Fe$_{65.6}$Co$_{9.4}$(10 nm)/Cu(6 nm)/AlO$_x$(3 nm) or Si-SiO$_2$/Gd$_{25}$Fe$_{50.9}$Co$_{0.1}$(10 nm)/Cu(2 nm)/AlO$_x$(3 nm) for torque measurements. For reference, we used Si-SiO$_2$/Pt(5 nm)/Cu(t nm)/NiFe(4 nm)/Al(3 nm) and Si-SiO$_2$/Cu(6 nm)/NiFe(4 nm)/Al(3 nm) for the first part, that is, current modulation of FMR, and Si-SiO$_2$/Gd$_{25}$Fe$_{65.6}$Co$_{9.4}$(10 nm)/Cu(6 nm)/Pt or Ta(5nm)/AlO$_x$(3 nm) for second-harmonic measurements. The fabrication and pattern of the samples is described in the Experimental Section. The concentration gradients within the GdFeCo alloys were characterized by energy-dispersive X-ray spectroscopy (EDS) STEM as described in Figure 1c and the Experimental Section and Supporting Information. The existence of concentration gradients is usual in such alloys fabricated by sputtering.[24,29] However, the gradients in our samples are small in comparison with those reported in other publications.[24,29]

The studied GdFeCo layers display an out-of-plane magnetization at zero field (see Figure S2, Supporting Information). This is the initial state of our second-harmonic measurements of torque. Magnetoencephalometry experiments (Figure S2, Supporting Information) indicate that the in-plane fields applied during our FMR measurements are large enough to align the magnetization along the field direction for all the frequencies applied (see also Note S2 and Figures S3–S7, Supporting Information). Knowledge about the current densities in the different layers was derived from independent measurements of the resistivities of all layers as described in Experimental Section and Figure S8, Supporting Information. Supporting measurements in Hall bars are discussed in Figures S9–S11, Supporting Information.

The schematic of our set up for the first set of room-temperature measurements is shown in Figure 1d. An applied radiofrequency (RF) current generates an oscillating magnetic field and excites FMR. In this conventional ST-FMR setup,[32,33] the interplay between the voltage due to RF current and the oscillating anisotropic magnetoresistance due to magnetization precession, generates a DC voltage at the resonance field. To optimize the measured signal, the direction of the DC field is applied at 45° from the current direction for $H > 0$ and 225° for $H < 0$. Figure 1e depicts an example of FMR spectra for a GdFeCo/Cu/NiFe sample. Figures S2–S6, Supporting Information describe the derivation of the effective saturation magnetization, the g-factor and the damping coefficient of each magnetic layer. The GdFeCo/Cu/NiFe structure has been optimized such that the FMR modes of NiFe and GdFeCo are distinctly separated for a straightforward identification and investigation of each resonance.

To determine the spin current emitted by GdFeCo in our samples, we injected simultaneously AC (RF) and DC ($i_{dc}$)
The damping modulation in Gd25Fe65.6Co9.4/Cu/NiFe, Pt/Cu/NiFe and Cu/NiFe control samples. a) Schematic of spin-torque FMR experiments at the NiFe resonance condition. The charge current $j$, flowing in GdFeCo is converted into spin current and then injected into the NiFe. This generates an anti-damping torque on NiFe, modifying its precession properties. Its damping (anti-damping) component decreases (increases) the linewidth of the NiFe FMR. b) Linewidth dependence on bias DC current at 11 and 12 GHz for GdFeCo(10 nm)/Cu(6 nm)/NiFe(4 nm), (the in-plane resonance field is large enough to align the magnetizations of both NiFe and GdFeCo along $\varphi = 45^\circ$ or $225^\circ$, which correspond to straight lines with black and blue symbols, respectively). A fit of Equation (2) gives values of $\theta_{\text{eff}}$ in the range $0.75 \pm 0.08$. d) Results for another sample with 4 nm thick Cu-spacer instead of 6 nm in which the field required to align $\mathbf{M}$ in-plane is lower. This allows us to work with $m_{\text{GdFeCo}}$ in-plane at lower FM frequencies (8 GHz in the panel). A fit of Equation (2) with the slopes gives values of $\theta_{\text{eff}}$ in the range $0.82 \pm 0.06$. e) Linewidth dependence on DC current at 8 GHz for Pt(5 nm)/Cu(6 nm)/NiFe(4 nm). The analysis leads to an effective spin Hall angle for Pt of about $\theta_{\text{eff}}^{\text{Pt}} = 0.032$. f) There is no damping modulation in Cu(6 nm)/NiFe(4 nm) control sample.

The SAHE-type and SHE-type spin currents generated by the conversion of a charge current in GdFeCo and injected into the NiFe layer create spin transfer torques on the magnetization $M$ of NiFe (Figure 2a), and subsequently decrease or increase the linewidth of NiFe FMR.[34] The following expression for the total torque includes contributions of both SAHE and SHE symmetry, the first SAHE-like term was derived by Iihama et al.[5] whereas the second term corresponds to the usual expression for the SHE-like spin current:

$$T = -\frac{\gamma}{2\mu_b} M_{\text{NiFe}} \left[ \sigma_{\text{GdFeCo}} \times J_{\text{GdFeCo}} \right] \cdot \mathbf{e}_x$$

where $\gamma$, $e$, $\mu_b$, are respectively the Dirac constant, the electron charge, and the vacuum permeability. $J_{\text{GdFeCo}}$, $M_{\text{NiFe}}$, $\sigma_{\text{NiFe}}$ stand for the g-gyromagnetic ratio of GdFeCo, the saturation magnetization (thickness) of NiFe and the unit vector indicating the magnetization direction of NiFe (GdFeCo). $\sigma_{\text{GdFeCo}}$ stands for the spin polarization of the spin current emitted by the GdFeCo layer. $J_{\text{GdFeCo}}$ is the current density flowing in the GdFeCo layer and $\theta_{\text{SAHE}}$ (or $\theta_{\text{SHE}}$) is the spin Hall angle of the SAHE (or SHE) in GdFeCo layer. Following usual expressions of the linewidth modulation by spin current from SHE[32,34] and SAHE,[5] the change in the linewidth of NiFe due to this torque, $\partial \mu_b \Delta H_{\text{NiFe}} / \partial i_{\text{dc}}$, where $i_{\text{dc}}$ is the total dc current, allows us to estimate the overall effective angle $\theta_{\text{eff}}$:

$$\theta_{\text{eff}} = -\frac{2f}{\hbar} \left[ \frac{H_{\text{res,NiFe}} + M_{\text{eff,NiFe}}}{2} \right] \frac{\sigma_{\text{NiFe}} \times \sigma_{\text{GdFeCo}}}{2\pi f} \partial \mu_b \Delta H_{\text{NiFe}} / \partial i_{\text{dc}}$$

where $\theta_{\text{eff}} = \theta_{\text{SAHE}} + \theta_{\text{SHE}}$ (see Experimental Section), and $M_{\text{eff}}$, $H_{\text{res,NiFe}}$, $\mu_b$, $W$, $I_{\text{GdFeCo}}$ are respectively the effective magnetic saturation, the magnetic saturation, the resonance field, the g-Landé factor of NiFe, the Bohr magnetron, the width of the strip, and the thickness of GdFeCo. Equation (2) is expressed for an applied field and magnetizations of both NiFe and GdFeCo in the $xy$ plane at an angle $\varphi$ from the current direction ($45^\circ$ or $225^\circ$ in our experiments). $\xi_{\text{GdFeCo}}$ accounts for the proportion of current in the GdFeCo layer namely, $J_{\text{GdFeCo}} = \xi_{\text{GdFeCo}} i_{\text{dc}} / W L_{\text{GdFeCo}}$ for the current density in GdFeCo. Its expression is discussed in the Experimental Section.

Figures 2b,c depicts results for a Gd25Fe65.6Co9.4(10 nm)/Cu(6 nm)/NiFe(4 nm) trilayer at 11 and 12 GHz. In this case, the magnetization is aligned in-plane along the dc field as required for resonance at the frequencies studied. The NiFe linewidth varies linearly with $i_{\text{dc}}$ and the slope reverses when the direction
of DC field is reversed. From the slopes at the two different frequencies, Equation (2) gives \( \theta_{GdFeCo/Cu} = 0.75 \pm 0.08 \), that is, 75% efficiency of spin current generation. To the best of our knowledge, this is the highest value reported to date for a magnetic material. We also measured a sample with a thinner Cu layer namely, 4 nm instead of 6 nm, (Figure 2d) and, at magnetic material. We also measured a sample with a thinner Cu layer. There is a clear modulation in the linewidth, albeit considerably smaller than with GdFeCo instead of Pt in Figure 2b–d. The observation of a larger modulation using GdFeCo rather than Pt is even more remarkable if we consider that the charge current density in the Pt layers is definitely larger than in the GdFeCo layers for the same current \( i_x \). Following an equation similar to Equation (2) but now for the SHE \([32,33,36]\) we estimate \( \theta_{Pt/Cu} = -0.032 \pm 0.002 \), in agreement with earliest studies for spin/charge conversion in Pt (see ref. [37]). Crucially, the effective charge-to-spin conversion rate with GdFeCo is 25 times more efficient than with Pt. An additional control experiment is shown in Figure 2f (and Figure S5, Supporting Information) for Cu/NiFe indicating no modulation of the linewidth in the absence of GdFeCo or Pt.

Also, we observed a small current-induced shift in the resonance field, ascribed to the addition of current-induced FL, DL, and Oersted fields to the DC applied field. The second-harmonic measurements described in the next section allows us to separate these current-induced fields.

As mentioned earlier, the magnetization of a single magnetic layer can be submitted to current-induced torques (self-torques) arising from internal SHE-like spin currents or interfacial spin-orbit interactions, an additional condition being the global absence of inversion symmetry. The work presented here is limited to results on GdFeCo layers between a Si/SiO\(_2\) substrate and a Cu layer. However, in further measurements (not in the scope of the present paper) where GdFeCo is interfaced with other light metals than Cu (i.e., 3d-3p TiAl), the sign of self-torques depends on the choice of the light metal. This indicates a predominant contribution from interfacial effects that we ascribe primarily to Rashba interactions in agreement with the existence of well-defined Rashba 2DEG at the surface of Gd metal\([25]\) and, more generally, in different types of rare-earth compounds.\([27,28]\)

We note that similar opposite signs of Rashba splitting have been reported, for example when Cu is replaced by Ag at the interface with Bi.\([38,39]\) As we show in Note S1, such Rashba interactions give rise to spin polarizations and spin currents of both SHE-symmetry and SAHE-symmetry, with only the first generating self-torques. We cannot exclude smaller additional bulk contributions from magnetization independent SHE-like spin currents\([30,32]\) and, as in ref. [10], spin currents related to the moderate composition gradients of our GdFeCo layers shown in Figure 1c and Figures S13–S15, Supporting Information.

Now we focus on the FL and DL torques present when GdFeCo is interfaced with Cu and discuss: i) the temperature dependence of the torques, ii) the tuning of DL self-torque by spin absorption outside GdFeCo and, iii) the efficiency of the self-torques in comparison with torques induced by the SHE of Pt or Ta.

We employed the second-harmonic technique\([16,40–42]\) to determine the amplitudes of the torques on GdFeCo in Si/SiO\(_2\)/Gd\(_{3}FeCo(10\) nm)/Cu(2 nm)/AlO\(_x\), Si/SiO\(_2\)/Gd\(_{3}FeCo(10\) nm)/Cu(6 nm)/AlO\(_x\), and similar samples in which 5 nm of Pt or Ta are inserted between Cu and AlO\(_x\). In the low field limit, considering the ratio \( p \) between the Planar Hall effect (PHE) and the Anomalous Hall Effect (AHE), the component \( H_{\text{FL}} (H_{\text{DL}}) \) along \( y(x) \) of the field \( H_{\text{FL}} (H_{\text{DL}}) \) associated with the FL (DL) torque can be derived from the voltage at 2f between the Hall probes\([40]\) by the following expression:

\[
H_{\text{FL(DL)}}(x,y) = -\Delta V_{x(\pm)} \left( \frac{2}{1+4p^2} \left( \frac{\partial V_{x(y)}}{\partial H_{y(x)}} + 2p \frac{\partial V_{x(y)}}{\partial H_{x(y)}} \right) \right)
\]

Note that, for the present GdFeCo alloys, we find that the PHE is much smaller than the AHE, \( p = \Delta R_{\text{PHE}}/\Delta R_{\text{AHE}} = 7 \times 10^{-3} \) (Figure S10, Supporting Information for Gd\(_{3}FeCo/Cu\)). We also discuss the possible thermal effects in Note S3 and show that they have negligible contributions to Equation (3) in the range of current densities we use.

Figures 3a,b show AHE results for Gd\(_{3}FeCo/Cu\) both below (300 K) and above (340 K) the magnetization compensation temperature \( T_{\text{M}} \). We can see the different signs of the AHE at 300 K and 340 K. The anomalous Hall angle can be estimated from this measurement as explained in Note S4 and Figures S9–S11, Supporting Information. The sample design and field configurations for second-harmonic measurements are shown in Figure 3c. In Figure 3d,e, we present the \( f \) and \( 2f \) components of the transverse voltage and the corresponding components of the FL and DL fields along \( y \) and \( x \) (after subtraction of the current-induced Oersted field for the FL field). \( H_{\text{FL}} \) is along \( +y \) for current along \( +x \) below \( T_{\text{DL}} \) and along \( -y \) above \( T_{\text{DL}} \). \( H_{\text{DL}} \) (for initial state \( M_z > 0 \)) is along \( +x \) below \( T_{\text{M}} \) and along \( -x \) above \( T_{\text{M}} \) and, as expected by symmetry,\([31,33]\) has opposite orientation for \( M_z < 0 \).

The temperature dependence of the FL and DL fields, shown in Figure 3f, agrees with the calculations presented in Note S5 and Figure S1, Supporting Information for a ferrimagnetic alloy such as GdFeCo. As the temperature increases and approaches \( T_{\text{M}} \), both \( H_{\text{FL}} \) and \( H_{\text{DL}} \) increase before their sign changes at \( T_{\text{DL}} \), around 330K on the Figure 3f. Subsequently, the amplitude of \( H_{\text{FL}} \) decreases to an approximately constant value while the amplitude of \( H_{\text{DL}} \) decreases continuously to about zero, consistent with the second inversion predicted to occur at the angular momentum compensation temperature \( T_{\text{M}} \) around 360 K on Figure 3f. Notably, such successive inversions of the DL torque have never been reported in this type of ferrimagnetic alloy. Furthermore, we find both FL and DL torques to be of the same order of magnitude. We also confirmed that \( H_{\text{FL}} \) and \( H_{\text{DL}} \) vary linearly with current density in GdFeCo, as depicted in Figure 4a (at 300K, which is above \( T_{\text{M}} \) for the Gd concentration of this sample, Gd\(_{5}Fe\(_{56.6}\)Co\(_{43.4}\)). In the next paragraph, we show that the DL self-torque can be enhanced by adding Pt or Ta layers on top of GdFeCo/Cu to increase the
spin absorption of the spin current emitted by GdFeCo outside GdFeCo and the corresponding spin-transfer from GdFeCo to outside (confer Figure 2 in ref. [18]).

Figure 4b,c present torque measurements in samples with a Pt or Ta layer inserted between the GdFeCo/Cu bilayer and the AlO_x capping layer in addition to the sample of Figure 4a. With Pt or Ta, two additional effects contribute to the torques. First, SHE of Pt or Ta creates spin currents and the injection of these spin currents into GdFeCo generates additional FL and DL torques on the magnetization of GdFeCo. Second, because HMs such as the Pt or Ta layers have thicknesses larger than their spin diffusion length, they act as spin-sinks to absorb the spin current emitted by GdFeCo much more that the thin layer of the Cu light metal. This spin-sink effect significantly enhances the transfer of spin to outside GdFeCo and the associated DL self-torque. We shall discuss how the enhanced DL self-torque can be separated from the SHE-induced DL torque (the FL self-torque is not expected to be significantly modified by the spin-sink effect).

Figure 4b depicts H_{FL} before and after the addition of Pt and Ta layers to GdFeCo/Cu. The SHE of Pt, as expected from its positive spin Hall angle, increases the negative H_{FL} of GdFeCo/Cu. For a quantitative interpretation, one should consider that the current density is about seven times larger in the Pt layer than in the high resistivity GdFeCo layer, enhancing artificially the contribution of the SHE in Pt to H_{FL} at a given current density in GdFeCo. As expected from the opposite SHE in Ta and Pt, the contribution of a Ta layer is in the opposite direction and decreases H_{FL} by about 25% (the current densities are roughly the same in the Ta and the GdFeCo layers).

Figure 4c shows the FL and DL efficiencies in the GdFeCo(10 nm)/Cu(2 nm)/AlO_x(2.5 nm) sample as a function of temperature (the magnetic compensation temperature T_M is indicated by color code). Both self-torques change sign across T_M (above T_M, H_{DL} is expected to go to zero at the angular momentum compensation temperature T_A, see Note S5, Supporting Information).
contributions of the SHE-induced $H_{DL}$ and the $H_{DL}$ of the self-torque when it is enhanced by the strong absorption of the spin current emitted from GdFeCo in Pt spin-sink. In GdFeCo/Cu(6)/Ta(5) the opposite SHE in Ta is expected to give rise to a positive $H_{DL}$. We find that $H_{DL}$ is indeed positive but extremely small, which corresponds to an almost compensation of the positive $H_{DL}$ from SHE in Ta by the negative self-torque contribution enhanced by the spin-sink effect into Ta. To go further, we decomposed the respective self-torque and SHE (Pt or Ta) contributions to $H_{DL}$ in GdFeCo/Cu(6)/Pt(5) and GdFeCo/Cu(6)/Ta(5) and we obtained consistent results for $H_{DL}$ (self-torque).

For GdFeCo/Cu(6)/Pt(5): The contribution to $H_{DL}$ due to the SHE of Pt can be derived from the results of the previous section on the SHE spin current emitted by a similar Pt layer (Figure 2e) and the corresponding effective Spin Hall Angle in the Pt layer, $\theta_{SHE}^{Pt} = 0.032 \pm 0.002$. The contribution from SHE to the slope of the plot of $H_{DL}$ vs $j_{c}$(GdFeCo) in Figure 4c can be written as $H_{DL}(Pt-SHE) = \frac{h \theta_{SHE}^{Pt}}{2e \mu_{B} M_{S} j_{c}(GdFeCo)}$. Accounting for the different current densities in Pt and GdFeCo, we obtain $H_{DL}(Pt-SHE)/j_{c}(GdFeCo) = -7.3 \times 10^{-10}$ Oe m$^{2}$ A$^{-1}$ for the contribution from the SHE of Pt. Subtracting this value from the experimental value for GdFeCo/Cu/Pt, we find

$$H_{DL}(self)/j_{c}(GdFeCo) = -5.9 \times 10^{-10} \text{ Oe m}^{2} \text{ A}^{-1}$$

for the self-torque, which is represented by the red line in Figure 4c. The blue vertical arrow represents the contribution from the SHE of Pt allowing to go from the red line of self-torque to the experimental data of the trilayers.

GdFeCo/Cu/Ta: For the Spin Hall Angle of Ta, if we assume the generally accepted value $\theta_{SHE}^{Ta} = -0.15$. A calculation similar to that for Pt above, taking also into account the different current densities in GdFeCo and Ta, leads to

$$H_{DL}(self)/j_{c}(GdFeCo) = -3.7 \times 10^{-10} \text{ Oe m}^{2} \text{ A}^{-1}$$

which corresponds to the green dashed line in Figure 4c. This value is in the same range as the one derived with GdFeCo/Cu/Pt, $-5.9 \times 10^{-10}$ Oe m$^{2}$ A$^{-1}$. Such magnitudes of spin-torques are the largest reported for self-torques at room temperature. When we express the $H_{DL}$ induced by Pt or Ta in terms of ratios $H_{DL}(Pt)$/$j_{c}(Pt)$ or $H_{DL}(Ta)$/$j_{c}(Ta)$ instead of $H_{DL}(self)$/$j_{c}(GdFeCo)$, we find values in the range of our results for $H_{DL}(self)/j_{c}(GdFeCo)$. That

Figure 4. Current-induced torques in Gd$_{25}$Fe$_{65.6}$Co$_{9.4}$(10 nm)/Cu(6 nm), Gd$_{25}$Fe$_{65.6}$Co$_{9.4}$(10 nm)/Cu(6 nm)/Pt(5 nm), and Gd$_{25}$Fe$_{65.6}$Co$_{9.4}$(10 nm)/Cu(6 nm)/Ta(5 nm) at 300 K. In the Figure, $H_{FL}$ ($H_{DL}$) is the y(x) component of the FL field (DL field for M along +z) for current along x. $H_{FL}$ is given after correction for the current-induced Oersted field. 300 K is above $T_{M}$ for Gd$_{25}$FeCo. a) $H_{FL}$ and $H_{DL}$ versus current density in the GdFeCo layer of Gd$_{25}$FeCo(10 nm)/Cu(6 nm), Gd$_{25}$FeCo(10 nm)/Cu(6 nm)/Pt(5 nm), and Gd$_{25}$FeCo(10 nm)/Cu(6 nm)/Ta(5 nm). There is only a small $H_{DL}$ in GdFeCo/Cu (orange line) in which the spin absorption in Cu is small. $H_{DL}$ in GdFeCo/Cu/Pt (blue diamonds) and GdFeCo/Cu/Ta (violet stars) corresponds to the addition of the SHE contribution from Pt (Ta) to the self-torque enhanced by the spin absorption outside GdFeCo by the spin sink Pt or Ta. After separation of the two contributions (see text), the red (green) line represents the DL self-torque derived from the sample with Pt (Ta) and the vertical blue (brown) arrow shows the SHE contribution of Pt (Ta). The orange, blue and brown lines in (a–c) represent linear fits.
is, \(H_{\text{DL}}(Pt)/j_0(Pt) = -1.0 \times 10^{-10} \text{ Oe m}^2 \text{ A}^{-1}\) and \(H_{\text{DL}}(Ta)/j_0(Ta) = +4.1 \times 10^{-30} \text{ Oe m}^2 \text{ A}^{-1}\). Our results also show the interest of spin-sinks to optimize the DL self-torques.

The existence of coexisting spin currents of SAHE-like and SHE-like symmetries in ferromagnetic or ferrimagnetic materials has been recently introduced by Amin et al.\[^6\] The FMR linewidth measurements of the first part of the article probe the total emission of the SAHE-like and SHE-like spin currents emitted by GdFeCo and, by averaging the results on two samples, lead to \((\theta_{\text{SAHE}} + \theta_{\text{SHE}}) = 0.78\). In contrast, the self-torque measurements probe only the SHE-like terms and allow us to determine \(\theta_{\text{SHE}}\). Thus, the combination of both types of measurements on the same magnetic materials permits determination of the proportions of the two symmetries. By introducing the experimental result of Equation (1) for \(H_{\text{DL}}(\text{self})\) into the expression

\[
H_{\text{DL}}(\text{self}) = -\frac{h}{2e} \theta_{\text{SHE}} j_y(GdFeCo) / \mu_0 M_{\text{t}}
\]

we find for SHE-like Spin Hall Angle of GdFeCo: \(\theta_{\text{SHE}} = 0.16\), that is about 20% of \((\theta_{\text{SAHE}} + \theta_{\text{SHE}}) = 0.78\). This is a unique information of what can be the relative proportions of the SAHE-like and SHE-like symmetries in a magnetic material, respectively about 80% and 20% for the spin currents emitted by GdFeCo/Cu (overall, including bulk and interfacial contributions).

We note here that a very recent work\[^{44}\] has shown the remarkably efficient generation of spin current by other Gd alloys. In GdPt alloys, the corresponding \(\theta_{\text{SHE}}\) reaches values around 0.27, well above the \(\theta_{\text{SHE}}\) of Pt. This is exploited to switch the magnetization of an attached layer of Co by SOT.\[^{46}\] According to our results, a GdFeCo/Cu bilayer should be even more effective for the global generation of spin current, SHE-like plus SAHE-like. We also suggest that the switching of a magnetic layer deposited on GdFeCo/Cu could take advantage not only on the intensity of the spin current emission by GdFeCo/Cu but also on the combination of torques of different symmetries.

The physics and applications of spin-orbit interactions are much less explored in magnetic materials compared to non-magnetic materials such as 5d metals (Pt, Ta, or W). The main conclusion of our study is that large spin-orbit effects also emerge in single layers of magnetic alloys possessing 5d electrons such as GdFeCo. We find that these spin-orbit effects can be used efficiently for: i) the production of very large spin currents, much larger than those generated by the SHE of HM's and ii) the generation of large self-torques (FL and DL) on the magnetization of single layers, one order of magnitude larger than in other magnetic materials (CoFeB for example\[^{41}\]) and as large as those generated by spin injection of SHE current from HM layers. Both the FL and DL torques are enhanced before their reversal at the magnetization compensation temperature of GdFeCo. In addition, the DL torque can be enhanced by increasing the absorption of spin current in a neighboring layer (spin-sink effect associated with a short spin diffusion length).

In our experiments, the different torques obtained for different types of interfaces indicate dominant interfacial effects (Rashba interaction). We cannot exclude additional contributions as, for example, from inversion symmetry breaking by the (small) concentration gradient in our samples. Experiments on FePt\[^{10}\] and GdFeCo\[^{29,30}\] have already shown that a composition gradient can play an important role for the generation of torques\[^{10,24}\] and “bulk DMI”\[^{29,30}\] in single layers of such magnetic alloys. In the large family of magnetic rare-earth alloys and other 5d magnetic materials, the existence of these different SOC-based mechanisms related to the absence of inversion symmetry and generating spin currents, spin torques and DMI in single layers in the absence of additional HM layers, is of great interest. We can imagine, for example, the generation of skyrmions by “bulk DMI” and their current-induced motion by self-torque in the same single magnetic layer.

Experimental Section

**Sample Deposition:** The heterostructures studied here were grown using d.c. magnetron sputtering at room temperature with Ar sputter gas pressure of 3 mTorr and a background base pressure of \(1 \times 10^{-7}\) Torr. Samples were deposited on thermally oxidized Si wafers. GdFeCo (Gd\(_{25}\)Fe\(_{65.6}\)Co\(_{9.4}\)) was co-deposited using separate Gd, Co, and Fe targets. Composition was controlled by varying the sputter gun power on each target. Deposition rate was calibrated by X-ray reflectivity and lift-off and profilometer measurements of the thickness. All the samples in the present study were capped with Al(3 nm). The net magnetization of SiO\(_2\)/GdFeCo (10 nm)/Cu is parallel (antiparallel) to the magnetization of the FeCo (Gd) sublattice, namely FeCo-rich, controlled by magneto optical Kerr effect loops. Sample in Figure 2 is Gd-rich at room temperature.

**Sample Lithography and ST-FMR-Based Measurements:** Samples were patterned using standard optical lithography which combines ion Ar milling to define the stripes and lift-off of Ti(10 nm)/Au(150 nm) to make the ohmic contacts and define the ST-FMR devices as shown in Figure 1c. The width of the stripes was \(W = 10 \mu\text{m}\) and the distance between ohmic contacts was \(L = 53.5\) or \(60 \mu\text{m}\). ST-FMR measurements were performed using a RF source with modulated power and lock-in detection (modulation frequency was 426 Hz). The frequency and input power were fixed and the external DC magnetic field applied in-plane was swept at 45° degree of stripes. We could observe both FMR lines in the GdFeCo/Cu/ NiFe sample, one corresponding to NiFe and the other one to GdFeCo, as shown in Figure 1e. Frequency dependence for the NiFe (GdFeCo) FMR line could be performed up to 23 GHz (17 GHz) due to field limitation (6 kOe). That allowed to determine \(M_s\) and the damping constant of each magnetic layer. The Landé g-factor for NiFe was fixed (2.10) and for GdFeCo was estimated (2.98 ± 0.01) since the plane film is a hard-plane axes for GdFeCo. The mixed ST-FMR voltage was picked up using a bias-T. A Keithley 2400 was used to additionally inject a DC current in order to study the modulation of damping or FMR linewidth. More details of FMR-based magnetic characterization of anisotropies and damping on the different samples are presented in Supporting Information.

**Second-Harmonic Measurements:** Samples were first patterned in Hall bar geometries using standard optical lithography as described above. An AC voltage of 426 Hz was injected through one of the channel of the Hall bar and the first and second-harmonic transversal voltage were measured simultaneously using a Signal Recovery 7270 lock-in. The total current injected was estimated as the ratio of the voltage amplitude over the longitudinal resistance of the Hall bar devices. The current density flowing in each layer was estimated considering a parallel resistor model. The amplitude of AHE was characterized too. To do so, \(R_{\text{AHE}}\) versus perpendicular field \(H_z\) was performed. That also allowed to estimate the anomalous Hall angle \(\theta_{\text{AHE}}\) of the GdFeCo layer. It was found that, for the different systems, GdFeCo had a \(\theta_{\text{AHE}} = 0.04\) for the nominal composition in the present study. This was close to reported elsewhere for RE-TM amorphous alloy.\[^{43}\] Examples of raw data measurements are displayed in Figure 59, Supporting Information and thermal effects\[^{46}\] are discussed in Note S3, Supporting Information.

**SQUID Measurements:** Saturation magnetization of the different samples were determined using SQUID magnetometry at room
temperature for both in-plane and out-of-plane applied magnetic field. The saturation magnetization value for NiFe is found to be $M_{\text{sat,NiFe}} = 625 \text{ emu cm}^{-3} (= 625 \text{ kA m}^{-1})$. The one of GdFeCo was $M_{\text{sat,GdFeCo}} = 105 \text{ emu cm}^{-3}$ and the saturation field (which correspond to the field to align $m_{\text{GdFeCo, in-plane}}$) was $H_{\text{cGdFeCo}} = 1300$ Oe.

**Resistivities of the Layers in Different Samples:** The resistivity of GdFeCo layer was determined experimentally by studying the thickness dependence in two series of GdFeCo(10 nm)/NiFe and GdFeCo(100 nm)/Cu/NiFe. The sheet conductance ($\sigma$) (sheet resistance) versus $\theta_{\text{GdFeCo}}$ allow us to straightforwardly determine the GdFeCo resistivity. The resistivity of NiFe was then determined in a Pt/NiFe/AIO$_x$ system. Then, the Cu resistivity was estimated from the extrapolation at zero thickness of GdFeCo/Cu/NiFe (See Figure S8, Supporting Information). Moreover, Cu resistivity was also measured independently in Pt/Cu system with a Si-SiO$_2$/Pt(5 nm) and Si-SiO$_2$/Ta(5 nm)/MoGd(7 nm) films. $\rho_{\text{Cu}} = 24.1 \times 10^{-8}$ $\Omega$ m and $\rho_{\text{Pt}} = 200 \times 10^{-8}$ $\Omega$ m were determined.

**Extraction of Effective SAHE+SHE Angle of GdFeCo:** With all the obtained characteristics in the samples, Figure (2) can be used to determine the effective SAHE angle of GdFeCo. The results of Figure 2b can be used which corresponded to a frequency $f = 12$ GHz, $H_{\text{rec,NiFe}} = 1670 \times 10^{-8}$ (4$\mu_{\text{m}}$) A m$^{-1}$, $M_{\text{rec,NiFe}} = 659 \times 10^{-8}$ A m$^{-1}$, $M_{\text{sat,NiFe}} = 625 \times 10^{-8}$ A m$^{-1}$, $\phi = 45^\circ$, $\theta_{\text{NiFe}} = 2.10$, $|\partial H_{\text{NiFe}}/\partial \theta_{\text{NiFe}}| = 0.066 \pm 0.007$ T A$^{-1}$ (average for $\phi = 45^\circ$ and $\phi = 225^\circ$). The shunting factor was calculated using a parallel resistor model and it was given by $\xi_{\text{GdFeCo}} = t_{\text{GdFeCo}}/t_{\text{NiFe}} + t_{\text{Cu}}/t_{\text{NiFe}} + t_{\text{Cu}}/t_{\text{NiFe}}$. Thus, the shunting factor was $\xi_{\text{GdFeCo}} = 0.084$ for GdFeCo(10 nm)/Cu/NiFe. Using all these experimental values and fundamental constants in Equation (2), $\theta_{\text{NiFe}} = 0.9$ was obtained. This was a rather high value, but all the parameters were checked, and control samples and reproducibility were performed as described in main text and detail in the two next sections. The average at different frequencies measured, $11, 12$, and $13$ GHz, different devices and angles gives a value of $\theta_{\text{NiFe}} = 0.75 \pm 0.08$. The algebraic additive of $\theta_{\text{SAHE}}$ and $\theta_{\text{SHE}}$ comes from the following: from Equation (1), the SAHE torque was proportional to the sinus of the angle between the current and the magnetic field aligning the magnetization of GdFeCo. In the same way, the contribution of the SHE torque to the NiFe damping involves the same sinus from the alignment of GdFeCo. Thus, this is evidenced by the fact that the same equation for damping modulation was obtained for SHE [32,34] and SAHE.

**Extraction of Effective SHE Angle of Pt:** Similarly to the previous section, the modulation of damping in a Pt(5 nm)/Cu(6 nm)/NiFe(4 nm) trilayer was studied. Now, frequency $f = 12$ GHz, $H_{\text{rec,NiFe}} = 1683 \times 10^{-8}$ (4$\mu_{\text{m}}$) A m$^{-1}$, $M_{\text{rec,NiFe}} = 659 \times 10^{-8}$ A m$^{-1}$, $M_{\text{sat,NiFe}} = 625 \times 10^{-8}$ A m$^{-1}$, $\phi = 45^\circ$, $\theta_{\text{NiFe}} = 2.10$, $|\partial H_{\text{NiFe}}/\partial \theta_{\text{NiFe}}| = 0.012 \pm 0.001$ T A$^{-1}$ (average for $\phi = 45^\circ$ and $\phi = 225^\circ$). The shunting factor was calculated using a parallel resistor model $\xi = t_{\text{NiFe}}/t_{\text{Cu}} + t_{\text{NiFe}}/t_{\text{Cu}} + t_{\text{NiFe}}/t_{\text{Cu}}$. Experimental values which are $\rho_{\text{NiFe}} = 40 \times 10^{-8}$ $\Omega$ m, $\rho_{\text{Cu}} = 15 \times 10^{-8}$ $\Omega$ m, and $\rho_{\text{Pt}} = 24.1 \times 10^{-8}$ $\Omega$ m were used. Consequently, the shunting factor was $\xi = 0.29$ for Pt(5 nm)/Cu(6 nm)/NiFe(4 nm) trilayer. Using all these experimental values and fundamental constants in equivalent Equation (2), $\theta_{\text{NiFe}} = 0.032 \pm 0.003$ was obtained.

**Reproducibility of the SAHE in GdFeCo:** The optimized sample in this study (Figures 1 and 2b,c) was measured at different times in a period of more than a year; the results were the same showing the stability and robustness of the system. Moreover, more samples were grown such as Si-SiO$_2$/GdFeCo(10 nm)/Cu(4 nm)/NiFe(4 nm)/Al(3 nm) with the same nominal composition of ferromagnetic layer (Gd$_2$Fe$_{65.6}$Co$_{9.4}$). The saturation field to align the GdFeCo magnetization in-plane now was about 650 Oe. The threshold frequency to have the resonance field higher than 650 Oe was now about 7 GHz. So, modulation of damping as in Figure 2b,c were observed for frequencies $\geq$ 6 GHz. An example for $f = 8$ GHz was shown in Figure 2d. Performing similar analysis, $\xi_{\text{GdFeCo}} = 0.82 \pm 0.06$ for the average of $f = 6, 8, 12$, and 14 GHz were obtained. The difference with the first sample study in the main text might arise from slightly different composition of GdFeCo or some coupling with NiFe through a thinner Cu spacer. Anyway, those new results validate the same strong and promising effective spin anomalous Hall angle of GdFeCo.

**FIB Sample Preparation for High-Performance TEM Analysis:** Thin lamellae were extracted by focused ion beam (FIB) milling using an FEI Helios Nanolab dual beam 600i. Transmission electron microscopy (TEM) investigations were carried out using a JEOL-ARM 200F Cold FEG TEM/STEM operating at 200 kV, coupled with a Gif Quantum 965 ER and equipped with a spherical aberration (Cs) probe and image correctors (point resolution 0.12 nm in TEM mode and 0.078 nm in STEM mode).

**Chemical Compositions Were Determined Using EDS:** EDS spectra were recorded by means of a Centurion Jeol silicon-drift detector (SDD) spectrometer mounted on the ARM 200F microscope. The analyses were carried out in STEM mode with a diameter of the probe of 0.5 nm. EDS profiles were carried out systematically on the different samples. Figure 1c shows the results for a Si-SiO$_2$/GdFeCo(10 nm)/Cu system. Additionally, STEM-EELS maps with 1 ev per channel and step of 0.3 nm were measured. Some examples are shown in Figures S13 and S15. Supporting Information for GdFeCo/Cu(4 nm)/NiFe(6) and GdFeCo(10 nm)/Cu(2), respectively.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Author Contributions**

J.-C.R.S. and A.F. conceived the initial study and along with C.P. and V.C. planned the project. J.-C.R.S. and S.P.-W. setup the experiments and design the masks to fabricate the devices. D.C.-B. performed the SQUID measurements, the optical lithography and FMR-based measurements with the assistance of E.M., J.-C.R.S. and S.P.-W. Second-harmonic measurements were performed by D.C.-B., H.D., D.M., A.A.C., S.P.-W., and J.-C.R.S. P.V. grew the first samples. Then successively other series of samples were grown by Y.K., J.L.B., and M.H. S.M. and M.H. supervised the growth facilities. P.T. and S.H. performed the extended model for current-induced Rashba spin accumulation for magnetic layers. S.M. prepared de lamella by FIB. J.G. carried out the HRSTEM, EDS, and EELS measurements along with J.-C.R.S. J.-C.R.S. and A.F. interpreted...
the experimental results and prepared the manuscript with the help of S.Z., V.C., and C.P. All authors commented on the manuscript.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author on reasonable request.

Keywords

amorphous ferrimagnetic GdFeCo, spin-orbit torque, spin-orbitronics, spintronics

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