Current induced torques in structures with ultra-thin IrMn antiferromagnet

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Relativistic current induced torques and devices utilizing antiferromagnets have been independently considered as two promising new directions in spintronics research. Here we report electrical measurements of the torques in structures comprising a ∼1 nm thick layer of an antiferromagnet IrMn. The reduced Néel temperature and the thickness comparable to the spin-diffusion length allow us to investigate the role of the antiferromagnetic order in the ultra-thin IrMn films in the observed torques. In a Ta/IrMn/CoFeB structure, IrMn in the high-temperature phase diminishes the torque in the CoFeB ferromagnet. At low temperatures, the antidamping torque in CoFeB flips sign as compared to the reference Ta/CoFeB structure, suggesting that IrMn in the antiferromagnetic phase governs the net torque acting on the ferromagnet. At low temperatures, current induced torque signatures are observed also in a Ta/IrMn structure comprising no ferromagnetic layer.

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Since the relativistic spin-orbit interaction couples electron’s momentum and spin it can lead to a range of effects when systems are brought out of equilibrium by applied electric fields. Non-equilibrium spin polarization phenomena may occur even in non-magnetic spin-orbit coupled conductors. Prime examples are the spin Hall effect (SHE) and the inverse spin galvanic effect (ISGE) which were experimentally discovered as companion effects in normal semiconductors [1,4]. In the SHE, an electrical current passing through a material with relativistic spin-orbit coupling can generate a transverse pure spin-current polarized perpendicular to the plane defined by the charge and spin-current [2,8]. In the ISGE, a non-equilibrium spin-density of carriers is generated in spin-orbit coupled systems which lack inversion symmetry [4,9,10,12].

Recently discovered relativistic spin torques induced by a lateral current at a normal-metal/ferromagnet (NM/FM) interface are a candidate spintronic technology for a new generation of electrically-controlled spintronic devices [13,14]. Microscopically, they are considered to be related to the SHE or ISGE. In one picture, a spin-current generated in the NM via the SHE is absorbed in the ferromagnet and the spin angular momentum of the carriers is transferred to the magnetization [13,14]. In the other picture, a non-equilibrium spin-density is generated via the ISGE and the corresponding effective field induces the spin torque [13,15,16,17].

Unlike FMs, antiferromagnets (AFMs) have so far only played a static supporting role in commercial spintronic devices by enhancing the magnetic hardness of the reference FM electrode via the interfacial exchange-bias effect [18,20]. However, in thin AFM films, the same interfacial AFM/FM coupling can lead to the exchange-spring effect [21] in which the AFM moments can be reoriented by the neighboring exchange-coupled FM moments. Experimental spintronic devices, including AFM magneto-resistors and memories, have already exploited the manipulation of the AFM moments by external magnetic field via the FM [22,25].

In this paper we combine AFMs with the current induced polarization phenomena in order to explore the electrical manipulation of a FM by an AFM in a NM/AFM/FM stack and to study the current induced effects in a NM/AFM structure comprising no FM component. We use structures comprising ultra-thin (∼1 nm) films of the Ir0.2Mn0.8 AFM. The thickness of the AFM comparable or smaller to the spin-diffusion length in the AFM material [26,27] is not favorable for maximizing the relativistic current induced torque generated by the AFM in the adjacent FM [28]. However, the ultra-thin IrMn films provide a unique insight into the role of the AFM order in the observed current induced phenomena which is the focus of this work.

The Néel temperature of a ∼1 nm thick film of the Ir0.2Mn0.8 is suppressed from the bulk $T_N = 700$ K [29] to well below room-temperature [30]. This allows us in our experiments to compare the observed current induced effects in the NM/AFM/FM structure in the low-temperature AFM phase of IrMn with the high-temperature paramagnetic phase of IrMn. Moreover, by field-cooling from above $T_N$ at external magnetic fields of different angles we can manipulate the AFM spins in a structure comprising no FM [30] and by this identify the magnetic origin of the observed current induced effects. In the NM/AFM structure with no FM, a thickness of
the AFM comparable or smaller than the AFM spin diffusion length has an additional advantage in amplifying the spin-torque signals in the AFM generated at the inversion asymmetric NM/AFM interface.

We start with discussing our experiments in the NM/AFM/FM structure. The materials stack and device geometry of the studied sample are shown in Figs. 1(a),(b). The layers were deposited by UHV RF magnetron sputtering on a thermally oxidized Si substrate (700 nm SiO$_2$ on (001) Si) at a base pressure of $10^{-9}$ Torr and in a magnetic field of 5 mT. After growth, the wafers were annealed at 350$^\circ$C for 1 hour in a $10^{-6}$ Torr vacuum in a magnetic field of 0.6 T applied along the sample edge. Hall bars were defined in the HSQ negative resist by e-beam lithography. The contacts were defined by an aluminum mask and the stack of layers was etched everywhere else by ion milling. The contacts were defined by an aluminum mask and the stack of layers was etched everywhere else by ion milling. The width of the bar is 2 $\mu$m and the distance between longitudinal contacts is 7 $\mu$m. Several samples were patterned from the wafer, all showing similar results.

![Schematic of the stack](image)

**FIG. 1.** Experimental setup and material characterization. (a) Schematics of the stack of layers used to fabricate the Hall bar. (b) Electron microscope image of the Hall bar device and a schematic picture of our experimental setup. (c) X-Ray reflectivity measurement (black dots) and simulation (red line). (d) SQUID magnetization measurement after cooling the sample from 400 K to 5 K in magnetic field +1 T (blue line) and -1 T (red line), and after field cooling to 200 K (green line).

Thicknesses of the layers are confirmed by X-ray reflectivity measurements using a laboratory diffractometer with Cu radiation. The measured data and simulations are shown in Fig. 1(c). From the simulation of the X-ray data we obtain the following structure: Ta(2.2 $\pm$ 0.2)/IrMn(0.6 $\pm$ 0.3)/CoFeB(0.9 $\pm$ 0.2)/MgO(1.4 $\pm$ 0.2) capped with 10 nm of Al$_2$O$_3$. The numbers in brackets correspond to the layer thicknesses in nm and are consistent with the nominal growth values. The root mean square roughness of all interfaces is 0.15 – 0.3 nm.

Magnetic measurements shown in Fig. 1(d) are performed by the superconducting quantum interference device (SQUID). Exchange coupling at low temperatures between the IrMn AFM and the CoFeB FM is confirmed by the expected positive exchange bias and broadening of the hysteresis loop when cooling the sample from 400 K to 5 K in a magnetic field of $\pm$1 T applied along the field direction used during the sample growth and annealing. Consistent with the expected high-temperature paramagnetic phase of our ultra-thin IrMn, the sample showed no exchange bias and no broadening of the hysteresis loop when field-cooled to 200 K.

In electrical measurements, the Hall bar is biased by a low frequency (123 Hz) ac current $I_{AC} = I_0\sin(\omega t)$. We use lock-in amplifiers to measure simultaneously first harmonic (1$\omega$) and second harmonic (2$\omega$) signals [3]. Both longitudinal ($R_{xx}$) and transverse ($R_{xy}$) resistances are detected. The longitudinal resistance measured in the first harmonic signal is 1.7 k$\Omega$. When rotating the CoFeB magnetization in the sample plane by a 1 T magnetic field (well above the saturating field) we detect the longitudinal anisotropic magnetoresistance (AMR) of an amplitude 2.5 $\Omega$ and maximum/minimum $R_{xx}^{1\omega}$ for magnetization angle $\theta = 90^\circ$/$0^\circ$, as defined in Fig. 1(b). The corresponding transverse AMR has an amplitude of 0.6 $\Omega$, consistent with the aspect ratio of the transverse and longitudinal dimensions of the Hall bar, with the maximum/minimum $R_{xy}^{1\omega}$ for $\theta = \pm 45^\circ$. When rotating the magnetization out-of-plane, the $R_{xy}^{1\omega}$ signal is dominated by the anomalous Hall effect (AHE) of an amplitude 13 $\Omega$.

Second harmonic signals, $R_{xx}^{2\omega}$ and $R_{xy}^{2\omega}$, measured at 300 K and magnetization rotated in the in-plane saturating field are plotted in Figs. 2(a),(b). The observed angular dependence is inconsistent with a current induced torque acting on the CoFeB FM due to the Oersted field or the interface ISGE field of Rashba symmetry. Both these in-plane fields are transverse to the applied current and generate a $\cos \theta$ dependence of the second harmonic signals, multiplied by the $\sin 2\theta$ angular dependence of the AMR in case of $R_{xx}^{2\omega}$ and $\sin 2(\theta + 45^\circ)$ in case of $R_{xy}^{2\omega}$. Moreover, for the estimated Oersted field of 0.1 mT, the applied field of 1 T, and for the AMR amplitude in our sample, the $R_{xy}^{2\omega}$ signal due to the Oersted field is $\sim 10^{-4}$ $\Omega$, i.e., within the noise in Fig. 2(a). Similarly, the Oersted field plays a negligible role in the $R_{xx}^{2\omega}$ signal.

The relative amplitudes of signals in Figs. 2(a),(b) scale with the aspect ratio of the transverse and longitudinal dimensions of the Hall bar and the respective $\theta$-dependencies have the same form, off-set by 90°. This all suggests that the $R_{xx}^{2\omega}$ and $R_{xy}^{2\omega}$ signals in Figs. 2(a),(b) are dominated by the same mechanism, unrelied to an in-plane-field driven current induced torque. We attribute the signals to thermal effects which are quadratic in the driving current and can, therefore, contribute to the second harmonic signals for the biasing current...
**FIG. 2.** Angular dependence of the second harmonic signals $R_{xx}^{2\omega}$ and $R_{xy}^{2\omega}$ measured in a saturating in-plane magnetic field in the Ta/IrMn/CoFeB samples at 300 K (a,b), at 5 K (c,d), and in the reference Ta/CoFeB sample (e,f). Results are only weakly dependent on temperature is the reference sample; panels (c,d) show measurements at 5 K. Data measured at two current densities are shown in each panel.

$I_{AC} \sim \sin(\omega t)$. In particular, thermal voltages generated by the anomalous Nernst effect (ANE) or longitudinal spin-Seebeck effect (SSE) [34] have the $\theta$-dependence consistent with the data in Figs. 2(a),(b).

In Figs. 2(c),(d) we show measurements at 5 K where IrMn is in the low-temperature AFM phase. We observe a negligible difference in the $R_{xx}^{2\omega}$ signal from the 300 K data. However, the $R_{xy}^{2\omega}$ signal is clearly enhanced at low temperature. Since $R_{xx}^{2\omega}$ and $R_{xy}^{2\omega}$ do not scale with the Hall bar aspect ratio in Figs. 2(c),(d), we can exclude the in-plane field-driven torque (detected via AMR) or the thermal effects as origins of the enhanced $R_{xy}^{2\omega}$ signal. Instead, an antidamping-like torque driven by an out-of-plane current-induced field and detected by $R_{xy}^{2\omega}$ via the AHE can explain the observed low temperature data.

SHE or Berry curvature ISGE [35] are examples of microscopic phenomena that have been previously considered to generate antidamping-like torques in NM/FM bilayers. To link our experiments in the Ta/IrMn/CoFeB stack to the earlier studies of NM/FM structures we show in Figs. 2(e),(f) our measurements in a reference sample with the same Ta and CoFeB layers but with IrMn removed from the stack. The reference sample shows similar behavior at high and low temperatures (only low temperature data are shown in Figs. 2(e),(f)). The second harmonic $R_{xx}^{2\omega}$ and $R_{xy}^{2\omega}$ signals again do not scale with the Hall bar aspect ratio, suggesting a sizable contribution from the out-of-plane current induced field. The opposite sign of the corresponding $R_{xy}^{2\omega}$ signal seen between the reference sample and the stack with IrMn is consistent with the opposite sign of the SHE angle in Ta and IrMn [14][36].

The $R_{xx}^{2\omega}$ data have also opposite sign in the sample without IrMn and since both the sample without and with IrMn have the same CoFeB layer, a dominant contribution of the ANE to the thermal effect can be ruled out. On the other hand, the SSE mechanism generating the second harmonic voltage via the inverse SHE is consistent with the opposite sign of the SHE angle in Ta and IrMn. Previous studies of the inverse SHE in IrMn concluded that the SHE angle is only weakly dependent on the magnetic order in IrMn. Figs. 2(a) and (c) corroborate this conclusion, assuming that the mechanism generating $R_{xx}^{2\omega}$ in our experiments is due to the spin-current induced by the SSE and detected by the inverse SHE. Remarkably, the ability of IrMn to generate the antidamping-like current-induced torque in the adjacent CoFeB is observed in our measurements only in the low-temperature AFM phase of IrMn, while it is diminished at high temperatures.

A more systematic comparison of the second harmonic signals is presented in Fig. 3. Here we associate the $R_{xx}^{2\omega}$ data with the SSE and by subtracting the SSE contribution from the $R_{xy}^{2\omega}$ data (by taking the Hall bar aspect ratio into account) we express the remaining $R_{xy}^{2\omega}$ signal in terms of the out-of-plane current induced field $H_{AD}$. The recalculation into the field was done by first determining the out-of-plane tilt angle, using the measured AHE amplitude as a calibration. Then $H_{AD}$ was inferred by taking into account the out-of-plane anisotropy field and the applied external magnetic field. The data confirm the opposite sign of the SSE and of $H_{AD}$ in the Ta/CoFeB and Ta/IrMn/CoFeB stacks which we associated above with the opposite sign of the SHE angles in Ta and IrMn. They also confirm the linear dependence of the SSE and $H_{AD}$ signals on the amplitude of the applied current, and vanishing $H_{AD}$ in the high-temperature phase of IrMn. The SSE signal scales linearly with the current amplitude since the thermally generated voltage is quadratic in $I_0$ and the SSE resistances plotted in Figs. 3(b),(d) are obtained by dividing the voltages by $I_0$. (Note that data shown in Figs. 2 and 3 were obtained after subtracting from the measured $R_{xx}^{2\omega}$ and $R_{xy}^{2\omega}$ a component which is independent of the applied current density; this component is even under the in-plane magnetization reversal.) In Fig. 3(e) we highlight that the $H_{AD}$ signal appears in the Ta/IrMn/CoFeB stack only below $\sim 100$ K and is therefore linked to the low-temperature AFM phase of IrMn.

The SHE and inverse SHE are reciprocal phenomena, but clearly the second harmonic voltages we measure in our samples are not reciprocal. Assuming the SHE mechanism behind the $H_{AD}$ signal and the inverse SHE behind the SSE signal is not in conflict with this observation since the spin-current absorption by the antidamping-like torque in the FM and the spin-current injection from the FM by the SSE are not reciprocal processes. It is beyond
Temperature-dependent difference in the ground signal and no net moment in IrMn at 10 K. (c) Temperature-dependent difference in the $R_{\omega}^{2\omega}$ signal measured while cooling the sample in applied in-plane and out-of-plane magnetic fields of 2 T. Both first harmonic (black line) and second harmonic (red line) signals are plotted in the panel. (d) The signals become insensitive to the magnetic field when sweeping magnetic field at a fixed low temperature (5 K).

this report to identify the detailed microscopic mechanism which makes IrMn in the AFM phase an efficient generator of the current induced torque in the adjacent CoFeB FM and why the effect is diminished in the high-temperature paramagnetic phase of IrMn. However, our measurements in a Ta/IrMn stack without the CoFeB layer point out that torques acting in the AFM IrMn cannot be omitted from these microscopic considerations. The results, which are summarized in Fig. 3 also open a possibility for using current induced torques in these transition metal multilayers to manipulate moments in the AFM.

The schematic of the Ta/IrMn stack is shown in Fig. 3 (a). Low-temperature magnetization data plotted in Fig. 3 (b) show only a diamagnetic background signal, confirming the AFM phase of IrMn and the absence of the FM component in the stack. Since the IrMn moments in the low-temperature AFM phase cannot be manipulated by the applied magnetic field we use, instead, a procedure in which magnetic field is applied at different angles while cooling the sample from room-temperature. In earlier studies of similar thin IrMn films embedded in tunnel junctions, this field-cooling procedure enabled us to define states showing a distinct magnetoresistance signal at low temperatures [30]. These distinct states of the AFM IrMn then remained insensitive to the applied magnetic field when staying sufficiently below the Néel temperature [30].

Analogous behavior of our ohmic Hall bar is illustrated on the first harmonic $\Delta R_{\omega}^{1\omega}$ signal, shown in Fig. 4 (c). Here the sample was first cooled from 300 K to 5 K in an applied in-plane magnetic field of 2 T and then the experiment was repeated with field-cooling in a 2 T out-of-plane field. A clear onset of a non-zero difference $\Delta R_{\omega}^{2\omega}$ between the two field-cool measurements is observed in the first harmonics at $\sim 100$ K, consistent with the expected transition into the AFM phase in our thin IrMn film. Remarkably, the onset is also observed in the second harmonic $\Delta R_{\omega}^{2\omega}$, suggesting that these signals are of magnetic origin and that the magnetic moments are torqued in the AFM by the applied current. To confirm that the signals are due to the FM moments rather than due to some uncompensated free moments in the film we show in Fig. 4 (d) the second harmonics while sweeping the external magnetic field between $\pm 2$ T and keeping the temperature at 5K. Similar to the first harmonic magnetoresistance, the second harmonics becomes completely insensitive to the strong magnetic fields in the low-temperature AFM phase of IrMn.

The non-zero first and second harmonic signals are consistently seen in our data at low temperatures when successively thermally cycling the Ta/IrMn sample in magnetic fields. On a quantitative level, however, the data are not sufficiently reproducible for allowing us to explore more systematically the angular dependence of the field-cooled first and second harmonic signals and to infer their angular symmetries and the symmetries of the corresponding torques. Nevertheless, by bringing the re-
sults in all three studied samples together we conclude that current induced torques are likely generated in our AFM IrMn films.

From the second harmonic measurements in the reference Ta/CoFeB sample and estimated 60% of current flowing though Ta we infer an antidamping-like torque of a strength characterized by the Ta SHE angle $\alpha^\text{Ta}_{\text{SH}} \approx -0.036 \pm 0.020$ which is only weakly dependent on the temperature within the studied range of 5 – 300 K. In the Ta/IrMn/CoFeB sample, the torque is absent in the high-temperature phase of IrMn. Assuming that the SHE angle is only weakly dependent on the magnetic order in IrMn and has opposite sign than in Ta, the absence of the torque in CoFeB can result from the competing opposite spin polarizations generated in Ta and in the thin IrMn. At low temperatures, on the other hand, an antidamping-like torque signal emerges in the Ta/IrMn/CoFeB stack corresponding to an IrMn SHE angle $\alpha^\text{IrMn}_{\text{SH}} \approx +0.029 \pm 0.015$ for the estimated 20% of current flowing through IrMn. This indicates that the torque in CoFeB is governed at low temperatures by IrMn and that the spin-current from Ta is absorbed in IrMn, possibly by a torque acting on the IrMn AFM moments, as supported by the measurements in the exchange-coupled Ta/IrMn/CoFeB sample, unparalleled in the NM/FM bilayers studied earlier.

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