All-optical detection of interfacial spin transparency from spin pumping in β-Ta/CoFeB thin films

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Generation and utilization of pure spin current have revolutionized energy-efficient spintronic devices. Spin pumping effect generates pure spin current, and for its increased efficiency, spin-mixing conductance and interfacial spin transparency are imperative. The plethora of reports available on generation of spin current with giant magnitude overlook the interfacial spin transparency. Here, we investigate spin pumping in β-Ta/CoFeB thin films by an all-optical time-resolved magneto-optical Kerr effect technique. From variation of Gilbert damping with Ta and CoFeB thicknesses, we extract the spin diffusion length of β-Ta and spin-mixing conductances. Consequently, interfacial spin transparency is derived as 0.50 ± 0.03 from the spin Hall magnetoresistance model for the β-Ta/CoFeB interface. Furthermore, invariance of Gilbert damping with Cu spacer layer thickness inserted between β-Ta and CoFeB layers confirms the absence of other interface effects including spin memory loss. This demonstrates a reliable and noninvasive way to determine interfacial spin transparency and signifies its role in generation of pure spin current by spin pumping effect.

INTRODUCTION
Development of advanced spintronic (1–4) devices with minimal power dissipation has attracted great interest in recent times. The major goal of modern spintronics is to harness pure spin current (5, 6) to enable more efficient information processing through non-volatility, rapid switching, and energy-efficient on-chip integration of magnetic bits in memory devices. Since pure spin current does not involve net flow of charge, Joule heating and stray Oersted field effects can be avoided in spin current–based devices (7). Pure spin current or flow of spin angular momentum can originate from the spin-dependent scattering in heavy metals such as spin Hall effect (8, 9), Rashba-Edelstein effect (10, 11), spin pumping (12, 13), electrical injection from ferromagnet (FM) in a nonlocal geometry (14, 15), and spin caloritronic effect (16, 17). The fundamental concept of spin pumping is depicted as follows: Precessing spins in FM transfer angular momentum to the conduction electrons of adjacent nonmagnetic (NM) layer. This can act as a sensitive probe for many bulk and interface spin-orbit effects. The extent of spin pumping is calculated from the modulation of the Gilbert damping parameter; the latter plays an important role in determining the switching efficiency of spin transfer torque–based spintronic devices. The plethora of works in the emerging field of spin-orbitronics (18) have revealed that interfacial transport observed in spin Hall effect (8, 9), Rashba-Edelstein effect (10, 11), spin-Seebeck effect (19), spin-Nernst effect (20), etc. is highly influenced by spin conductance at the interface. Interfacial spin transparency (21), as a function of spin-mixing conductance (22), effectively determines the extent of spin current diffused through the NM/FM interface. The role of transparency in a Pt-based interface, while determining the amount of spin Hall effect, has been reported in recent studies (21). Later, the influence of spin transparency on spin pumping effect has been studied in Co₈FeAl/β-Ta interface with electrical detection technique (23). However, to the best of our knowledge, investigation with the perspective of determining spin-mixing conductance and interfacial spin transparency by all-optical excitation and detection technique is missing in the literature. In addition, determination of interfacial spin transparency of technologically important β-Ta/CoFeB is also absent in the literature. Notably, β-Ta has a large spin Hall angle, in addition to being a good spin sink material and cost effective in comparison to Pt. On the other hand, CoFeB is technologically important because of high spin polarization, exhibition of large tunnel magnetoresistance when used as a ferromagnetic electrode in a magnetic tunnel junction, and low intrinsic Gilbert damping. The presence of boron at the interface between β-Ta and CoFeB makes this system intriguing, as some of the earlier studies suggest that a small amount of Boron helps in achieving sharp interface, although excess Boron leads to contamination at the interface.

In an NM/FM bilayer, there are other mechanisms of dissipation of spin angular momentum at the interface than interfacial spin transparency, which may affect the magnitude of spin pumping, i.e., spin memory loss (24), Rashba effect (11), two-magnon scattering (25), interfacial band hybridization (26), etc. However, for the sake of energy-efficient device fabrication, the interface in the engineered structure should have high spin transmission probability. So, it is imperative to get deep insight of the mechanisms involved for optimizing the efficiency of generation and transfer of pure spin current.

Here, we have performed time-resolved magneto-optical Kerr effect (TR-MOKE) measurements (27) to explore the effect of spin pumping phenomena in a β-Ta/CoFeB bilayer system. Measurements of spin pumping effect performed so far by electrical excitation and detection techniques, such as spin-torque ferromagnetic detection technique (FMR) and spin Hall magnetoresistance methods require extremely delicate microfabrication. Extraction of magnetic damping from FMR linewidth measurement, where the excitation of multiple modes and the effect of impurity scattering center, may lead to inhomogeneous line broadening, resulting in an overestimation of damping values. Here, we have reliably probed spin pumping and interfacial spin transparency using a noninvasive all-optical method without the requirement of a complicated microfabrication procedure. Magnetic damping can be directly extracted from the decaying amplitude of time-resolved Kerr rotation data, free from any experimental artifacts. In the case of multimodal oscillation, the time-resolved data can be appropriately analyzed to precisely extract damping of individual modes.
From the modulation of damping with Ta thickness, we have determined the intrinsic spin-mixing conductance of β-Ta/CoFeB interface (which does not involve the backflow of spin angular momentum) and spin diffusion length (28) of β-Ta. Later, effective spin-mixing conductance (which involves backflow of spin angular momentum) is estimated from the dependence of damping on FM layer thickness. Using a spin Hall magnetoresistance model (29), we have calculated interfacial spin transparency of β-Ta/CoFeB. We further investigate the possible effects of other interface phenomena, including spin memory loss, by incorporating a thin Cu spacer layer between the β-Ta and CoFeB layers. The negligible modulation of damping with Cu spacer layer thickness confirms the dominance of spin pumping generated pure spin current and its efficient transport in this system.

RESULTS

Figure 1A shows the x-ray diffraction patterns of Sub/Ta(t)/Co_{20}Fe_{60}B_{20}(3 nm)/SiO_{2}(2 nm) heterostructures at the glancing angle of 1°. The formation of a highly textured β-Ta phase is established from the presence of very intense (002) peaks of the β-Ta phase at a 2θ value of ~33.5°. We have not observed any signature of α-Ta phase, which generally appears at 2θ value of ~38.5°, in our experimental thickness regime. The d value obtained from the β-Ta peak at 33.5° corresponds to ~2.6 Å which ensures the growth of the Ta thin films in the desired tetragonal β phase having a preferential orientation of (002) planes (30).

Furthermore, we measured the thickness-dependent resistivity of the Ta layer from the heterostructures. Charge current was applied along the length of the sample, and the experiment was performed in constant current mode. The sheet resistance (R_s) of the film stack as a function of Ta thickness is plotted in Fig. 1B. The result has been fitted with the parallel resistor model (29). We have obtained the stable phase of β-Ta over the whole experimental thickness regime with a constant resistivity (ρ_{Ta}) of 248 ± 24 μΩ-cm, and for CoFeB, this (ρ_{CoFeB}) is found to be 139 ± 13 μΩ-cm, which is very close to the values reported in the literature (31).

The atomic force microscopy (AFM) images for Sub/Ta(t)/Co_{20}Fe_{60}B_{20}(3 nm)/SiO_{2}(2 nm) samples are investigated to study surface topography, as shown in Fig. 1C. From these images, we obtained the average topographical roughness for the samples with t = 0, 2, 4, 6, 10, 15, and 20 nm as listed in Table 1.

The roughness values vary a little when measured at various regions of space of the same sample. Overall, the topographical roughness is found to be substantially small for all the samples. Because of the small thicknesses of the thin film heterostructures, presumably, the interfacial roughness will show its imprint on the topographical roughness. We thus conclude that the average interfacial roughness, if any, present in these heterostructures is very small and is similar in all samples.

The principle behind the determination of spin pumping

Along with the local damping, which arises because of energy dissipation within the electron and phonon of FM itself, nonlocal damping in the NM/FM system when magnetic energy is dissipated from FM to adjacent NM layer can be present. The optically induced magnetization precession in the FM layer causes the generation of spin current at the NM/FM interface. These spins carry angular momentum to the adjacent NM layer, which acts as a spin sink by absorbing the spin current after traversing the spin diffusion length and leads to an enhancement of the Gilbert damping parameter. This phenomenon is known as spin pumping and can be described by the modified Landau-Lifshitz-Gilbert equation as given below

\[
\frac{dm}{dt} = -\gamma (m \times H_{eff}) + a_0 (m \times \frac{dm}{dt}) + \frac{\gamma}{VM_s} I_s \tag{1}
\]

where \(\gamma = \mu_B/h\) is the gyromagnetic ratio, \(H_{eff}\) is the effective magnetic field, \(a_0\) is the intrinsic Gilbert damping constant, \(V\) is the volume, and \(M_s\) is the saturation magnetization of the FM. The total spin current \(I_s\) consists of the dc current \(I_s^0\) that does not exist in our case, current due to pumped spins from the FM \(I_s^{pump}\), and current returned back to the FM (backflow current) \(I_s^{back}\).

\[
I_s = I_s^0 + I_s^{pump} + I_s^{back} \tag{2}
\]

Those spins that are pumped out can either accumulate at the interface or relax through spin-flip scattering, causing a flow of angular momentum from FM to NM layer through the NM/FM interface. The NM layer does not always act as a perfect spin reservoir because of the spin accumulation effect, which mainly causes \(I_s^{back}\). This backflow of spin current toward FM solely depends on the spin diffusion length of

| Table 1. The average topographical roughness values obtained with AFM for Sub/Ta(t)/Co_{20}Fe_{60}B_{20}(3 nm)/SiO_{2}(2 nm) samples with different Ta thicknesses. |
|---|---|---|---|---|---|---|---|
| t (nm) | 0 | 2 | 4 | 6 | 10 | 15 | 20 |
| Roughness (nm) | 0.16 | 0.15 | 0.19 | 0.13 | 0.16 | 0.25 | 0.17 |

the adjacent NM layer. On the other hand, the flow of spin angular momentum through the NM/FM interface is quantified by spin-mixing conductance.

The theoretical framework described by Tserkovnyak et al. (12, 13) includes a backflow factor of spin angular momentum during relaxation of injected spins into the NM layers, which is given as

$$\beta = \left(2\pi G_{\tau_1} \sqrt{\frac{\varepsilon}{3}} \tanh\left(\frac{l}{2\tau}\right)\right)^{-1}$$

where $\varepsilon$ is the ratio of the spin-conserved to spin-flip scattering times (spin-flip probability), which is material dependent

$$\varepsilon = \frac{(\lambda_d \lambda)^2}{3}$$

where $\lambda_d$ and $\lambda$ are the mean free path and spin diffusion length, respectively.

Nonlocal damping at the NM/FM interface directly depends on spin-mixing conductance. It can be of two types: (i) intrinsic spin-mixing conductance ($G_{\tau_1}$), which does not consider the backflow factor, and (ii) effective spin-mixing conductance ($G_{\mathrm{eff}}$), which considers the backflow of spin angular momentum. $G_{\tau_1}$ describes the electronic conductance property of channels in the interface between NM and FM, where NM thickness is kept much longer than its spin diffusion length so that no backflow can occur. Its dependence on the Gilbert damping parameter and NM thickness is given by (33, 34)

$$G_{\mathrm{eff}} = G_{\tau_1} \left(1 - e^{-\frac{2l}{\tau}}\right) = \frac{4\pi d M_{\mathrm{eff}}}{\gamma \mu_B} (\alpha_{\mathrm{eff}} - \alpha_0)$$

where $\alpha_{\mathrm{eff}}$ and $\alpha_0$ are the angle that can be fitted with the Kittel formula mentioned below

$$\alpha_{\mathrm{eff}} = \frac{1}{\gamma (H + 2\pi M_{\mathrm{eff}})}$$

$$f = \frac{\gamma}{2\pi} (H (H + 4\pi M_{\mathrm{eff}}))^{1/2}$$

where $\gamma = g \mu_B / \hbar$ and $g$ is the Landé g factor. From the fit, $M_{\mathrm{eff}}$ and $g$ are determined as fitting parameters. For these film stacks, we obtained effective magnetization, $M_{\mathrm{eff}} \sim 1200 \pm 100$ emu/cm$^3$ and $g = 2.0 \pm 0.1$. The comparison between $M_{\mathrm{eff}}$ obtained from the dynamic measurement and $M_0$ from vibrating sample magnetometry (VSM).

All-optical investigation of magnetization dynamics

Figure 2A shows the schematic of the spin pumping mechanism along with the experimental geometry. Figure 2B shows the time-resolved Kerr rotation data for the Sub/Co$_{20}$Fe$_{60}$B$_{20}(3 \text{ nm})$/SiO$_2$(2 nm) sample at $H = 1.73$ kOe, which consists of three different temporal regimes. When a femtosecond laser excites the sample, a sharp drop in the magnetization is observed immediately after zero delay, which corresponds to ultrafast demagnetization (regime I). Regime II corresponds to the fast remagnetization due to the spin-lattice relaxation, and regime III consists of slower relaxation along with magnetization precession. The slower relaxation is due to heat diffusion from the lattice to the surrounding volume. We are mainly interested in extraction of decay time from the damped sinusoidal oscillation about a bias magnetic field and its modulation due to the spin pumping effect. The red line in Fig. 2B corresponds to the biexponential background present in the precessional data in regime III. We subtract this background from the raw data and fit the resulting data using the damped harmonic function

$$M(t) = M(0) e^{-\frac{t}{\tau}} \sin(\omega t + \varphi)$$

where $\tau$ is the decay time, $\varphi$ is the initial phase, and $\omega = 2\pi f$, with $f$ being the precessional frequency. From the fit, we estimate the effective damping, $\alpha_{\mathrm{eff}}$, using the expression

$$\alpha_{\mathrm{eff}} = \frac{1}{\gamma (H + 2\pi M_{\mathrm{eff}})}$$

$\gamma = g \mu_B / \hbar$ and $g$ is the Landé g factor. From the fit, $M_{\mathrm{eff}}$ and $g$ are determined as fitting parameters. For these film stacks, we obtained effective magnetization, $M_{\mathrm{eff}} \sim 1200 \pm 100$ emu/cm$^3$ and $g = 2.0 \pm 0.1$. The comparison between $M_{\mathrm{eff}}$ obtained from the dynamic measurement and $M_0$ from vibrating sample magnetometry (VSM).
measurement is described systematically in the Supplementary Materials with varying FM and NM layer thicknesses. For almost all the film stacks investigated in this work, $M_{\text{eff}}$ is found to be close to the saturation magnetization $M_s$, which indicates that the interface anisotropy is small in these heterostructures.

**Modulation of Gilbert damping parameter due to spin pumping**

In Fig. 3A, we have shown the background-subtracted time-resolved data for Sub/Ta(4 nm)/Co$_{20}$Fe$_{60}$B$_{20}$(3 nm)/SiO$_2$(2 nm), where we have varied $t$ from 0 to 20 nm. The intrinsic Gilbert damping ($\alpha_0$) of 3-nm-thick CoFeB layer is found to be 0.006 ± 0.0005 for high-field regime, where the magnetization remains saturated. In the presence of Ta underlayer, effective damping ($\alpha_{\text{eff}}$) is found to be increased non-monotonically in the lower thickness regime, whereas it gets saturated at higher thickness of Ta. As shown in Fig. 3B, the modulation of damping in the FM layer is found to be more than 40% because of the spin pumping in these heterostructures. The $\alpha_{\text{eff}}$ shows exponential dependence with Ta thickness with an asymptotic value of 0.009 ± 0.0005 for $t \to \infty$. Thus, we have fitted our results with Eq. 6, where we determined the intrinsic spin-mixing conductance ($G_{\text{mix}}$) = (7.22 ± 0.05) × 10$^{14}$ cm$^{-2}$. Subsequently, we obtained the spin diffusion length ($\lambda$) of Ta to be 2.44 ± 0.16 nm as a fitting parameter, which is very close to the literature value (23). Using values for $\lambda$ (about 0.5 nm for Ta) (38) and $\alpha_0$ derived for these heterostructures, we have determined the spin-flip probability, $\varepsilon = 1.4 \times 10^{-2}$, from Eq. 4. For an NM metal to be an efficient spin sink, the requirement is $\varepsilon \geq 1.0 \times 10^{-2}$ (15). Thus, we can infer that the model describing the spin pumping effect is applicable to our experimental film stacks and that β-Ta layer acts as an efficient spin sink here. The backflow factor $\beta$ is mainly element dependent and can be extracted from Eq. 3. We have quantified the modulation of backflow factor (Δ$\beta$) to be 61% within our experimental thickness regime of 1 nm $\leq t \leq 20$ nm. The spin transmission probability of the NM/FM interface can be determined from the spin backflow, which is linked to $G_{\text{mix}}$.

To experimentally determine the value of $G_{\text{mix}}$, we have investigated precessional dynamics for Sub/Ta(4 nm)/Co$_{20}$Fe$_{60}$B$_{20}$(d)/SiO$_2$(2 nm) samples by varying FM layer thickness as $1 \leq d \leq 13$ nm at $H = 1.73$ kOe (Fig. 4A). The $\alpha_{\text{eff}}$ is observed to vary linearly with the inverse of ferromagnetic layer thickness and saturates for $d > 10$ nm, while the thickness of the NM layer is fixed at 4 nm (Fig. 4B). This is another confirmation that β-Ta is a good spin sink material resulting in a strong spin pumping effect (15). After fitting those data with Eq. 5, the effective spin-mixing conductance of the Ta/CoFeB interface is found to be (6.92 ± 0.04) × 10$^{14}$ cm$^{-2}$. The variation of $G_{\text{eff}}$ with different thicknesses of Ta is plotted in fig. S4. For energy-efficient applications of spin current in multilayered devices, large interface transparency ($T$) is required, and this primarily becomes associated with $G_{\text{eff}}(t)$ (37). After determining the resistivity of these heterostructures and $G_{\text{eff}}$ experimentally, we have found the value of $T$ as 0.50 ± 0.03 using Eq. 7, which is comparable with Pt/FM interfaces (38). To the best of our knowledge, this is the first measurement of interfacial spin transparency for a β-Ta/CoFeB bilayer, and this shows the formation of a moderately transparent interface.

There is a probability in these heterostructures to have some loss of spin angular momentum because of interfacial depolarization, known as spin memory loss, where spin angular momentum carried by spin current is not transferred to the NM but instead transferred to the lattice through interfacial spin-orbit scattering (22). So, the total transfer of spin current to the NM will be determined by a combined effect of interfacial spin transparency and spin memory loss, which refers to the loss of spin information at the interface due to spin-flip scattering. In this case, the loss of spin polarization occurs because of interfacial spin-orbit scattering, whereas interfacial spin transparency is an electronic property of a material interface and transmission of conduction electrons depends on electronic band matching of two materials on either side of the interface. There can also be other interfacial effects, such as Rashba effect, two-magnon scattering, interfacial band hybridization, and defects, which may affect the net transfer of spin current to the NM. To understand the contributions of the above effects in addition to the spin pumping effect, we have introduced a copper spacer layer of different thicknesses between the Ta and CoFeB layers. Copper has very small spin-orbit coupling and spin-flip scattering parameter, so it shows a very high spin diffusion length (28). Thus, a thin copper spacer layer is not expected to affect the damping of the FM layer because of the spin pumping effect but can change or eliminate other interface effects. Consequently, if other interface effects are substantially present in our samples, then the introduction of copper spacer layer would notably vary the damping with the variation of copper (Cu) spacer layer thickness ($t_{\text{Cu}}$). The time-resolved Kerr rotation data for the Sub/Ta(4 nm)/Cu($t_{\text{Cu}}$)/Co$_{20}$Fe$_{60}$B$_{20}$(4 nm)/SiO$_2$(2 nm) heterostructures with copper layer thicknesses of 0.4, 0.6, 0.8, and 1.0 nm are presented in Fig. 5A at $H = 1.73$ kOe, and Fig. 5B shows the plot of damping as a function of copper layer thickness. Almost no modulation of damping with the thickness of copper.
The heterostructured thin films of Sub/Ta(t)/Co$_{20}$Fe$_{60}$B$_{20}$(d)/SiO$_2$(2 nm), where NM layer thickness t = 0, 1, 2, 3, 4, 5, 6, 7, 10, 15, and 20 nm and FM layer thickness d = 1, 2, 3, 4, 6, 10, and 13 nm, were deposited with radio frequency (rf)/dc magnetron sputtering system on Si (100) wafers coated with 100-nm-thick SiO$_2$. The depositions were done at an average base pressure of 4.0 × 10$^{-7}$ Torr and an argon pressure of about 1.0 mTorr at a deposition rate of 0.2 Å/s. Very slow deposition rates were chosen to have films with uniform thickness even at a very thin regime down to 1 nm. The Ta and SiO$_2$ were deposited with an rf power of 40 and 60 W, respectively, while Co$_{20}$Fe$_{60}$B$_{20}$ (CoFeB) was deposited with a dc voltage of 380 V. All other deposition conditions were carefully optimized and kept almost identical for all samples. In another set of samples, we introduced a thin Cu spacer layer in between the FM and NM layers and varied its thickness from 0.4 to 1 nm. The Cu layer was deposited at a dc voltage of 345 V, an argon pressure of 1.0 mTorr, and a deposition rate of 0.2 Å/s.

TR-MOKE technique was exploited to study the precessional magnetization dynamics of the samples in polar Kerr geometry (shown in Fig. 2A). The fundamental beam (pulse width, ~40 fs; wavelength, ~800 nm; repetition rate, ~1 kHz) of an amplified laser system (Libra, Coherent) was used as probe, while a part of this beam was frequency-doubled (wavelength, ~400 nm; pulse width, ~50 fs) to be used as pump pulse. The probe and pump beams (spot sizes, 100 and 200 μm, respectively) fall noncollinearly on the sample to detect the polar Kerr rotation as a function of the time delay between pump and probe beams introduced through a variable delay generator. The sample was subjected to a magnetic field with 10° to 15° out-of-plane tilt from the sample plane, and the in-plane component of this field is referred to as the bias magnetic field (H$_b$). This introduces a substantial demagnetizing field, which is modulated by the pump pulse to launch the precession in the sample. The probe was placed carefully at the center of the pump spot, so that there was no additional effect on the Gilbert damping due to the dissipation of energy of uniform precessional mode flowing out of the probed area. All the measurements were performed under ambient conditions.

**DISCUSSION**

We have investigated spin pumping phenomena in β-Ta/CoFeB thin films from the modulation of Gilbert damping using an all-optical TR-MOKE magnetometer. For a stable phase of β-Ta over the thickness range between 0 and 20 nm, we have extracted the spin diffusion length as 2.44 ± 0.16 nm and the intrinsic spin-mixing conductance at the Ta/CoFeB interface as (7.22 ± 0.05) × 10$^{14}$ cm$^{-2}$ from the variation of damping as a function of Ta thickness. By considering the backflow factor in our theoretical model, we have extracted the effective spin-mixing conductance at the Ta/CoFeB interface as (6.92 ± 0.04) × 10$^{14}$ cm$^{-2}$ from the variation of damping as a function of CoFeB thickness. By fitting our data with the spin Hall magnetoresistance model, we have obtained the interfacial spin transparency of Ta/CoFeB as 0.50 ± 0.03 for Ta thickness of 4 nm, which shows that the Ta/CoFeB interface is comparable with various studied heavy metal/FM interfaces such as Pt/FM. To understand the impact of other possible interface effects, which may alter the Gilbert damping apart from the spin pumping effect, we have introduced a thin copper spacer layer of varying thickness and found negligible modulation of damping. This is due to similar spin conductivity of copper and Ta and confirms the absence of other interface effects in these structures. The low intrinsic Gilbert damping parameter and the high effective spin-mixing conductance with moderately high transparency of the β-Ta/CoFeB bilayer system make it a key material for spin transfer torque magnetization switching and spin logic devices.

**MATERIALS AND METHODS**

**Sample preparation and measurements**

The heterostructured thin films of Sub/Ta(t)/Co$_{20}$Fe$_{60}$B$_{20}$(d)/SiO$_2$(2 nm), where NM layer thickness t = 0, 1, 2, 3, 4, 5, 6, 7, 10, 15, and 20 nm and FM layer thickness d = 1, 2, 3, 4, 6, 10, and 13 nm, were deposited with radio frequency (rf)/dc magnetron sputtering system on Si (100) wafers coated with 100-nm-thick SiO$_2$. The depositions were done at an average base pressure of 4.0 × 10$^{-7}$ Torr and an argon pressure of about 1.0 mTorr at a deposition rate of 0.2 Å/s. Very slow deposition rates were chosen to have films with uniform thickness even at a very thin regime down to 1 nm. The Ta and SiO$_2$ were deposited with an rf power of 40 and 60 W, respectively, while Co$_{20}$Fe$_{60}$B$_{20}$ (CoFeB) was deposited with a dc voltage of 380 V. All other deposition conditions were carefully optimized and kept almost identical for all samples. In another set of samples, we introduced a thin Cu spacer layer in between the FM and NM layers and varied its thickness from 0.4 to 1 nm. The Cu layer was deposited at a dc voltage of 345 V, an argon pressure of 1.0 mTorr, and a deposition rate of 0.2 Å/s.

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**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/4/eaav7200/DC1

Determination of saturation magnetization of the samples

Variation of effective spin-mixing conductance (G$_{we}$) with Ta thickness

Fig. S1. Determination of saturation magnetization of Sub/Ta(4 nm)/Co$_{20}$Fe$_{60}$B$_{20}$(3 nm)/SiO$_2$(2 nm).

Fig. S2. Determination of saturation magnetization of Sub/Ta(4 nm)/Cu(4 nm)/Co$_{20}$Fe$_{60}$B$_{20}$(3 nm)/SiO$_2$(2 nm).

Fig. S3. Determination of saturation magnetization of Sub/Ta(4 nm)/Cu(4 nm)/Co$_{20}$Fe$_{60}$B$_{20}$(4 nm)/SiO$_2$(2 nm).

Fig. S4. Variation of effective spin-mixing conductance (G$_{we}$) with Ta thickness.

**REFERENCES AND NOTES**


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