Spin Orbit Torque Magnetic RAM (SOT-MRAM) is emerging as a promising memory technology owing to its high endurance, reliability and speed. A critical factor for its success is the development of materials that exhibit efficient conversion of charge current to spin current, characterized by their spin Hall efficiency. In this work, it is experimentally demonstrated that the spin Hall efficiency of the industrially relevant ultra-thin Ta can be enhanced by more than 25× when a monolayer (ML) WSe2 is inserted as an underlayer. The enhancement is attributed to spin absorption at the Ta/WSe2 interface, suggested by harmonic Hall measurements. The presented hybrid spin Hall stack with a 2D WSe2 underlayer has a total body thickness of less than 2 nm and exhibits greatly enhanced spin Hall efficiency, which makes this hybrid a promising candidate for energy efficient SOT-MRAM.

**RESULTS**

Stack deposition and device fabrication

The film stack (starting from the topmost layer) Ta(1)/MgO(1)/Co0.6Fe20B20(1)/Ta(tTa), is prepared by magnetron sputtering for all samples as shown in Fig. 1c. We investigate two types of control samples with tTa = 3.5 nm (stack A) and tTa = 1 nm (stack B), deposited directly on thermally grown SiO2 substrates without any underlayer (Fig. 1a). The test sample (stack C) consists of the film stack with tTa = 1 nm deposited on a WSe2 underlayer, as shown in Fig. 1b. All numbers in brackets above are in nanometer (nm). For the test sample, stack C, we start with the transfer of chemical vapor deposition (CVD) grown flakes of ML WSe2 onto SiO2 substrates, followed by sputtering of the rest of the stack. Raman spectra of the WSe2 film are taken before and after the sputtering deposition, as shown in Fig. 1d. The ML WSe2 peaks are present post sputtering, however with a reduced relative peak magnitude, indicating some physical damage to WSe2. However, this is not of great concern, as the function of the ML WSe2 underlayer is not to facilitate lateral current transport, but rather to absorb spins flowing in the vertical direction (from Ta to ML WSe2). In addition, we independently characterize the channel resistance of exfoliated ML WSe2 films. Figure 1e shows transfer characteristics at a drain bias of Vds = 1 V. It is obvious that the total channel resistance of the ML WSe2 is >1.5 GΩ without applied gate voltage, which is orders of magnitude larger than that of Ta. Hence, we conclude that in our hybrid spin Hall stack the current flows in the Ta layer. Hall bar devices are then fabricated for stacks A, B, and C by e-beam lithography followed by dry etching using Ar plasma. Figure 1f shows the optical microscope image of one representative device.

Extracting the value of spin Hall efficiency

The deposited stacks show perpendicular magnetic anisotropy (PMA) as revealed by anomalous Hall effect (AHE) measurements. Figure 2a shows the measurement configuration. Figure 2b shows the obtained hysteresis loops of the AHE resistance (RΔ) as a function of Z-directed external magnetic field. From these curves, the value of remanent resistance (RΔ) for all three stacks are
obtained. The $R_A$ value for device B is larger than that of A because a larger fraction of the read current ($I_{\text{read}}$) flows through the CoFeB FM layer, owing to the thinner Ta layer. The saturation value of $R_\omega$ for device C (at much larger field, not shown here) is very close to that of device B, consistent with the fact that the additional WSe$_2$ layer results in negligible current shunting. However, its $R_A$ value is smaller, possibly because of the FM film breaking into multiple magnetic domains at zero field. This PMA quality can be improved by engineering the deposition conditions as have been shown in literature for other 2-D material underlayers. However, in this work, the overall lower quality of PMA in case of stack C compared to the other two stacks is captured by the smaller $R_A$ and a lower $H_K$ (shown later), which are then used to calculate the spin Hall efficiencies in the later sections. This ensures that the calculated spin Hall efficiency is not artificially larger due to a weaker magnetic layer.

Next, the effective perpendicular anisotropy field ($H_K$) is obtained by measuring $R_{\omega}$ as the external field is held at a constant magnitude (shown as legends in Fig. 2c) and rotated in the Y–Z plane. $R_{\omega}$ is obtained by dividing the first harmonic in phase component of the anomalous Hall voltage by the R. M.S of the AC current excitation. Measured curves from stacks A, B and C for $R_A$ extraction. Obtained $R_A$ from the remanent values of $R_\omega$ at $B_{\text{ext}} = 0$ are mentioned in blue text. Curves obtained from the rotation experiment. The fits to the measured curves give the value of $H_K$ (which are mentioned in blue text in each figure inset).
SOT produces anti-damping and field like torques\(^1\) on the magnetization that can be characterized as effective fields in the longitudinal \((h_L)\) and transverse \((h_T)\) direction, respectively\(^2\). We obtain the values of \(h_L\) and \(h_T\) from the second harmonic component of the AHE resistance \((R_{2ac})\). The measurement configuration is shown in Fig. 3a. Here, the external field is applied in the plane of the film stack, with a direction that is either parallel or perpendicular to the applied current direction for extracting \(h_L\) and \(h_T\), respectively. In this measurement configuration, \(R_{2ac}\) is given by:

\[
R_{2ac} = \frac{1}{2} \frac{R_X h_T}{|B_x| - H_x} \quad R_{2ac} = \frac{1}{2} \frac{R_X h_T}{|B_x| - H_x}
\]

where the first and the second expressions correspond to cases when \(B_{ext}\) is parallel and perpendicular to the applied current direction, respectively. In these expressions, the previously obtained values of \(R_X\) and \(H_x\) are applied leaving \(h_T\) or \(h_L\) as the only variable in the equation, which can then be obtained by fitting the obtained \(R_{2ac}\) curve, as shown in Fig. 3b–d. This method is also robust against multi-domain issues as the \(h_L, h_T\) are obtained by fitting to the large field regions of the \(R_{2ac}\) curve, where the magnetization is forced to behave as macrospin by the external field. The extracted \(h_L\) and \(h_T\) values are shown in the respective figure insets and table in Fig. 3e. The possible fitting errors in the extraction \(h_L\) and \(h_T\) values are minimal, as shown in Supplementary Fig. 2.

The \(h_L\) and \(h_T\) values, normalized by the applied current density \((J_{ac})\) through the Ta layer are indicative of the spin Hall efficiency\(^3\). For the devices used in our experiments, the width of the current lead is 2 μm. Together with the film thicknesses and resistivities of Ta and CoFeB, \(J_{ac}\) is readily calculated. For simplicity, we have assumed that the resistivities of the Ta and the CoFeB layer are the same (which is true for our films grown on Si(SiO)\(^2\)). If a higher resistivity for the Tantalum layer compared to the CoFeB layer is considered, then later spin Hall efficiency values will be extracted (as the \(J_{ac}\) through the SOt layer will be smaller, hence \(h_L/J_{ac}\) will be larger). Hence, our extracted values for the spin Hall efficiencies are conservative estimates. The obtained \(h_L/J_{ac}\) values for the three stacks are shown in Fig. 4a. For stack A, the control sample with 3.5 nm Ta without the underlayer, our extracted \(h_L/J_{ac}\) value is consistent with previously reported in literature\(^4\). For stack B, the control sample with 1 nm Ta without the underlayer, the \(h_L/J_{ac}\) value reduces as \(R_{ac} = 1\) nm is smaller than the spin diffusion length in Ta, as will be explained in the next section. The \(h_L/J_{ac}\) value for stack C, our test sample with 1 nm Ta and the ML WSe\(_2\) underlayer, has improved significantly (by 26.5×), owing to the suppression of the spin back diffusion since a large fraction of these unwanted spins are absorbed at the Ta/WSe\(_2\) interface. Also shown in the same plot are the ratio of the longitudinal effective field to the transverse effective field (\(h_T/h_L\)). As can be seen, this ratio does not change significantly among the three stacks, which suggests the same SOT mechanism occurring in all three stacks.

The spin sink effectiveness can be directly obtained through spin pumping experiments by measuring the Gilbert damping constant of the CoFeB/Ta stack as a function of the Ta layer thickness, with and without the WSe\(_2\) underlayer as done for other material systems\(^5\). However, the goal in our paper is to focus on the application of this effect to improve the power efficiency of an SOT based device. Therefore, we have measured and quantified the spin Hall efficiency directly and then corroborated it with the spin sink effect.

**DISCUSSION**

The spin Hall angle (\(\theta_{SHE}\)) is the most commonly used metric to evaluate spin Hall efficiency. \(\theta_{SHE}\) can be calculated from the \((h_L/J_{ac})\) values through the following expression\(^2\),

\[
\theta_{SHE} = \frac{2e}{h} \frac{J_{ac} M_y}{f_{FM}}
\]

where \(e\) is the charge of an electron, \(h\) is the reduced Planck constant \((h/2\pi)\), \(f_{FM}\) is the thickness of the FM layer and \(M_y\) is its saturation magnetization. In our stacks, \(f_{FM} = 1\) nm. \(M_y\) is measured using Superconducting Quantum Interference Device (SQUID).
The magnetometry with MPMS-3 to be 1031 emu/cc, which is consistent with the quoted value in literature. The magnetometry data of stacks B and C are shown in Supplementary Fig. 3.

The giant spin Hall effect results in the separation of oppositely polarized spins to the top and bottom surface of Ta. The spins reaching the top surface are absorbed by the FM layer and contribute to the observed SOT. However, the spins reaching the bottom surface of Ta still accumulate and as a result create a concentration gradient in the vertical direction. This leads to back diffusion of the oppositely directed spins into the FM, hence partially nullifying the effect of SOT. This is captured by the following expression for the measured spin Hall efficiency $\theta_{\text{SHE}}$:

$$\theta_{\text{SHE}} = \frac{\rho_{\text{bulk}}}{\rho_{\text{SHE}}} \times \left(1 - \text{sech} \left( \frac{t_{Ta}}{\lambda_5} \right) \right)$$

where $\rho_{\text{bulk}}$ is the spin Hall angle in the bulk limit and $\lambda_5$ is the spin diffusion length in Ta. $\theta_{\text{SHE}}$ obtained from the above expression is plotted as a function of $t_{Ta}$ for various $\lambda_{5}$ in Fig. 4b. From the $\theta_{\text{SHE}}$ values for stacks A and B, we extract $\lambda_{5} = 4.5$ nm and $\rho_{\text{bulk}}/\rho_{\text{SHE}} = 28.7\%$ by fitting the above equation, consistent with previously reported values in literature.

Now, for stack C, the spins reaching the bottom surface of Ta are absorbed by the WSe$_2$ underlayer, resulting in suppressed back diffusion. Hence, the experimentally extracted value of $\theta_{\text{SHE}}$ for stack C should be much closer to the $\rho_{\text{bulk}}$ value, which is indeed confirmed in our experiment, as seen from the experimentally obtained data point (red star) for stack C in Fig. 4b. This indicates that the use of WSe$_2$ underlayer restores the value of spin Hall angle closer to the bulk value even for the case of ultra-thin Ta layers. The improvement in spin Hall angle is quantified by $\Theta_{\text{SHE}}$ (stack C)/$\Theta_{\text{SHE}}$ (stack B) = 26.5.

In order to test the structural differences in the Ta layer itself due to the presence of a WSe$_2$ underlayer in stack C vs. SiO$_2$ in stack B, we fabricated 4 probe devices and measured the resistivities. The resistivity of stack B was measured to be 320-μΩ-cm and that of stack C to be 462-μΩ-cm. These resistivity values are close to the range of values reported in literature. For example, Zhu et al.$^{26}$ report a resistivity value of ~330-μΩ-cm and Tao$^{27}$ reports a value of ~400-μΩ-cm for similar stacks. Yu et al.$^{7}$ and Qu et al.$^{28}$ report values of 400-μΩ-cm and ~530-μΩ-cm respectively for a tantalum layer thickness of 2 nm. Therefore, we believe that the tantalum layer in both of our samples is in the standard β phase. However, there could be contribution to the observed enhancement in spin Hall efficiency coming from slightly changed microstructure of the Ta layer, which requires further study beyond the scope of this paper.

Spin Hall angle, resistivity and the thickness of the SOT layer all are important parameters that impact the power efficiency of an SOT based memory device. Therefore, it is incomplete to consider the improvement in one of these parameters in isolation. We considered a figure of merit that captures their convoluted impact on the SOT switching power in the following way:

The power required for SOT switching of a PMA magnet with an energy barrier ($E_{B}$) can be obtained from the expression for the critical switching current ($I_{c}$)$^{5}$:

$$P_{\text{switching}} = \frac{E_{B}}{WL} = \left(\frac{2e}{h}\right)^2 \frac{E_{B}^2}{WL} \left(\frac{\rho_{\text{SHE}}}{\rho_{\text{bulk}}} \times \frac{t_{Ta}}{\lambda_5} \right)^2$$

Since $E_{B}$ and dimensions of the magnet ($W, L$) are pre-determined by the desired retention time and targeted technology node respectively, the denominator, $\frac{\rho_{\text{SHE}}}{\rho_{\text{bulk}}} \times \frac{t_{Ta}}{\lambda_5}$, becomes an important figure of merit. Figure 4c compares $\rho_{\text{SHE}}$ and this figure of merit, where the presented Ta/WSe$_2$ stack outperforms the conventional giant spin Hall material β-Ta by a factor ~4. Our experiments suggest that efficient absorption of spins at the Ta/ WSe$_2$ interface is responsible for this giant enhancement by preventing spin back diffusion.

In summary, we have demonstrated a hybrid SOT stack that shows enhanced spin Hall efficiency compared to the standard β-Ta. This finding shows a promising integration of 2D materials in spintronics devices for energy efficient SOT-MRAM applications.

METHODS

Sample preparation and characterization

Chemical vapor deposition (CVD) grown monolayer WSe$_2$ flakes were transferred to a silicon substrate with 90 nm thermal SiO$_2$. Raman spectroscopy was performed after this step to confirm the layer number of WSe$_2$ flakes. PVD magnetron sputtering was then used to deposit the stacks A, B, and C mentioned in the main text, followed by another Raman spectroscopy step.

Device Fabrication

The devices were fabricated in a two-step e-beam lithography process. First, the entire stack was etched into a Hall bar shape by e-beam lithography and dry etching using Argon plasma, followed by removal of the HSQ etch mask. Then, the contact pads were formed on the Hall bar by
another e-beam lithography step followed by e-beam evaporation of Ti (20 nm)/Au(100 nm) and liftoff in acetone.

For obtaining the transfer characteristics of the monolayer WSe₂ devices as shown in Fig. 1e, only one e-beam lithography step was used to define the contacts on transferred flakes, followed by e-beam evaporation of Ti (20 nm)/Au(100 nm) and liftoff in acetone.

Measurement setup

The transfer characteristics on Fig. 1e were obtained using Agilent semiconductor parameter analyzer with a Lakeshore probe station. The harmonic Hall measurements were performed by using a sinusoidal current from a Keithley 6221 current source and an SRS 850 DSP lock-in amplifier. These measurements were carried out inside a Quantum Design PPMS Dynacool system, with the sample mounted on a rotatable stage w.r.t to the film normal and current direction from 0° to 90°.

DATA AVAILABILITY

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

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AUTHOR CONTRIBUTIONS

P.D and T.Y.T.H performed the sample fabrication and characterization under Z.C’s supervision. All authors performed data analysis and wrote the manuscript. P.D. and T.Y.T.H. are co-first authors.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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