Abstract—Spin-orbit interaction derived spin torques provide a means of reversing the magnetization of perpendicularly magnetized ultrathin films with currents that flow in the plane of the layers. A basic and critical question for applications is the speed and efficiency of switching with nanosecond current pulses. Here, we investigate and contrast the quasistatic (slowly swept current) and pulsed current-induced switching characteristics of micrometer scale Hall crosses consisting of very thin (~1 nm) perpendicularly magnetized CoFeB layers on β-Ta. While complete magnetization reversal occurs at a threshold current density in the quasistatic case, short duration (<10 ns) larger amplitude pulses (~10 times the quasistatic threshold current) lead to only partial magnetization reversal and domain formation. We associate the partial switching with the limited time for reversed domain expansion during the pulse.

Index Terms—Spin electronics, magnetization dynamics, spin-orbit torques, spin transfer torques, current-induced switching, perpendicularly magnetic anisotropy, ultrathin magnetic films.

I. INTRODUCTION

In heavy metal-ferromagnet thin film heterostructures, current flowing in the plane of the layers can induce magnetization switching through spin-orbit interactions [Miron 2011, Liu 2012a]. This is particularly interesting for ferromagnetic layers with perpendicular magnetization because their large magnetic anisotropy permits very stable magnetic states, even in elements that are nanometer scale in lateral dimension (~20 nm diameter, see, e.g., Kent [2015]). Further, spin-orbit torque switching enables three terminal memory elements with separate write and read current paths [Liu 2012b, Pai 2012, Cubukcu 2014] as well as new types of spin-based logic devices [Datta 2012]. A number of heavy metals have been shown to produce large spin-orbit torque to current ratios, including β-phase Ta and W as well as Pt and, thus, lead to relatively low current densities for magnetization switching [Hao 2015]. However, with a few notable exceptions [Garello 2014, Lo Conte 2014], experimental studies have focused on quasistatic magnetization switching characteristics, i.e., switching for slowly varying (nearly dc) currents. It is clearly interesting for applications and basic understanding to explore the dynamics of magnetization switching for short current pulses.

Here, we present a comparison of the quasistatic and the dynamic switching characteristics of high quality β-Ta/CoFeB/MgO heterostructures with large perpendicular magnetic anisotropy. We find full magnetization reversal at a threshold current for slowly swept current with applied in-plane magnetic fields. The scalar product of the current density and the applied field is shown to determine the sense of the magnetization switching, i.e., whether switching is from magnetized up to down or vice-versa [Park 2014]. However, only partial switching is observed for sub-10 ns current pulses of amplitude 10 times the quasistatic threshold current. We suggest that the origin of the partial switching is the limited time for domain expansion during the pulse.

II. EXPERIMENTAL METHODS

We start with layers grown by magnetron sputtering on oxidized Silicon wafers using a Singulus deposition system. The layer stack is Substrate|5 β-Ta|0.8 Co₈₀Fe₂₀B₁₂|1.6 MgO |2 Ta with the numbers indicating the layer thicknesses in nanometers. The 2 nm Ta top layer serves to protect the sample from oxidization. The samples are annealed at 300 °C for 2 h to crystallize the CoFeB and the presence of the β-phase of Ta was verified by X-ray diffraction. Ferromagnetic resonance spectroscopy was used to determine the effective magnetization of the CoFeB layer defined as the perpendicular anisotropy field 2K₄/Mₑ, minus the demagnetization field μ₀Mₑ = 2K₄/Mₑ − μ₀Mₑ. We found μ₀Mₑ ≈ 0.6 T, indicating a strong perpendicular anisotropy, much larger than demagnetization field, and a magnetic easy axis perpendicular to the film plane. These results are consistent with earlier studies showing a perpendicular magnetic interface anisotropy associated with the CoFeB|MgO and CoFeB|Ta interfaces [Ikeda 2010, Worledge 2011].

Hall bar structures were then fabricated from these films using optical lithography and ion milling. An optical microscope image is shown in Fig. 1(a). The width of the arms of Hall crosses were between 2 to 8 μm and a SiO₂ dielectric protective layer was deposited in situ directly after ion milling. Electric contacts consisting of Ta|Cu were deposited directly on the CoFeB in the arms of the Hall cross after removing the MgO barrier. We note that the CoFeB and β-Ta are in the same micrometer scale Hall bar shape. The results presented here were acquired on a 4 μm cross device. More than 15 devices have been measured and show similar characteristics. All the experiments were done at room temperature.
The hysteresis loop is seen with sharp jumps in the Hall resistance of field applied perpendicular to the film plane. Fig. 1(b) shows the Hall resistance as a function of the average z-component of the magnetization in the area in which data were not taken. With a small dc current (J = 0.125 MA/cm²), we measure the Hall resistance to determine the magnetization state both before and after the pulse injection and, thus, determine whether or not magnetization reversal has been triggered by the pulse.

### III. RESULTS AND DISCUSSION

Fig. 2(a) shows the measurement of the Hall resistance for a slowly swept current with a fixed in-plane applied field (μ₀Hₓ = −100 mT). The current density to switch from magnetized up to down is 4.25 MA/cm² and from down to up is −5.3 MA/cm². Repeating this measurements as a function of in-plane field (10 ≤ |μ₀Hₓ| ≤ 150 mT), we obtain the state diagram in Fig. 2(b), with the color representing the resistance for increasing current minus the resistance for decreasing current. This current-induced switching behavior is characteristic of a spin-orbit torque driven effective field mechanism. Thus, the red and blue colors illustrate the bistable region: the parameter range for which both up and down magnetic states are possible. Different colors to the left and right of Hₓ = 0 show clearly that the field polarity determines the sense of the magnetization switching, i.e., with current ramping up slowly from negative to positive, negative applied field leads to switching from magnetized up to down while positive applied field leads to switching from magnetized down to up. The white stripe in the middle of the figure, near zero field, indicates a small field region in which data were not taken.

This current-induced switching behavior is characteristic of a spin-orbit torque driven effective field mechanism. As β-Ta has a negative spin-Hall coefficient, charge current flow in the x direction leads to a spin accumulation in the +y direction at the interface with the CoFeB, as indicated schematically in Fig. 1(d). This leads to a torque on the magnetization also in the y direction which is equivalent to a spin-torque effective field.
field in the direction $\mathbf{H}_{ST} \propto \mathbf{m} \times \mathbf{y}$, where the spin-torque is then proportional to $\mathbf{r}_{ST} \propto \mathbf{m} \times \mathbf{H}_{ST}$.

It is thus clear that the magnetization must have a component in the $x$ direction for there to be a spin-torque effective field in the $z$ direction to drive magnetization switching (i.e., $m_z \rightarrow -m_z$). An applied field in the $x$ direction leads to a canting of the magnetization in the $x$ direction and, thus, a preferred switching sense for a given current polarity. Thus, the scalar product $J \cdot \mathbf{H}$ determines the sense of the switching: $J \cdot \mathbf{H} > 0$ leads to magnetization down to up switching and $J \cdot \mathbf{H} < 0$ leads to magnetization up to down switching, as seen in Fig. 2. The sense of switching would be reversed if Ta was replaced with a material having positive sign of spin Hall coefficient such as Pt [Liu 2012a]. The Hall resistance (i.e., $R_{H}$), estimated below) adds a fractional contribution to the sum. Thus, we also analyze the distribution of Hall resistances after the pulse to determine whether partial or full magnetization switching has occurred.

Fig. 3 shows the switching probability as a function of pulse duration $t_p$ and amplitude $J$ in an applied field $\mu_0 H_s = -100$ mT. For each pulse amplitude and duration, we apply 100 pulses. The color of each pixel represents the switching probability, which we define as $P = \frac{1}{N} \sum_{i=1}^{N} \frac{R_{\text{after}} - R_{\text{before}}}{R_b}$, where $N$ is the number of pulses applied. With this definition, the measurement of an intermediate Hall resistance (i.e., $R_{\text{after}} \sim R_{\text{before}} < R_b$) adds a fractional contribution to the sum. Thus, we also analyze the distribution of Hall resistances after the pulse to determine whether partial or full magnetization switching has occurred.

Fig. 4(a) shows several linescans for fixed pulse amplitude and varying pulse duration. A switching probability of 0.4 is found with 1 ns duration 83.5 MA/cm$^2$ amplitude pulses. A histogram showing the Hall resistance after a 1.9 ns duration and 66.67 MA/cm$^2$ amplitude pulse is shown in Fig. 4(b). The observation of intermediate resistance states demonstrates the occurrence of partially switched states, states with up and down magnetized magnetic domains in the current path. We observe a switching probability of 0.8 for 10 ns duration $\approx 38$ MA/cm$^2$ amplitude pulses, which is 10 times larger than the switching current density in quasistatic experiments at the same applied field. Additionally, we find partial switched states with 1 ns duration pulses of amplitude 20 times the switching current in quasistatic experiments.

Micromagnetic models and simulations of spin-orbit torque switching in perpendicularly magnetized elements show that it consists of magnetization rotation near the center of the element (where the effective magnetization is the smallest), followed by domain nucleation and propagation [Lee 2014]. If the injected pulse is of sufficient amplitude and duration for magnetization rotation, domain nucleation and propagation to occur, the result is complete magnetization reversal. In other words, for a given pulse amplitude, the pulse duration for magnetization reversal must be $t_p \geq t_{\text{rotation}} + t_{\text{nucleation}} + t_{\text{propagation}}$. In the quasistatic limit ($t_p \rightarrow \infty$), the magnetization reverses when the current induced spin-orbit torque field is comparable with the domain nucleation field (because the domain propagation field is less than the domain nucleation field in our CoFeB layers). We can estimate
the spin-orbit torque effective field at the quasistatic switching current density $J \sim 5 \text{ MA/cm}^2$ using $H_{\text{ST}} = \frac{\hbar J \rho_{\text{SH}}}{m_0} (\mathbf{m} \times \mathbf{y})$, where $\theta_{\text{SH}}$ is the spin Hall coefficient and $d$ is the thickness of the magnetic layer. Taking $\theta_{\text{SH}} = -0.15$, we calculate the $z$-component of $H_{\text{ST}}$ to be 0.5 mT, which is comparable with the measured coercive field of 1 mT shown in Fig. 1(b). In the pulse-current regime, the current density $J$ determines $t_{\text{rotation}}$ and $t_{\text{propagation}}$ because the timescale of magnetization rotation, nucleation, and domain propagation depends on the magnitude of spin-torque effective field. Clearly, the pulse duration must be sufficiently long for a domain to expand across the layer. If we assume that the reversal is by nucleation and reversed domain expansion, we can make a rough estimation of the domain wall velocity from the data in Fig. 4. From the time for the switching probability to change from 0.1 to 0.2 for 59 MA/cm$^2$ pulses, we find 100 m/s assuming that a single reversed domain nucleates in the middle of the device and expand isotropically. This estimate is larger than the domain propagation velocities observed in CoFeB [Ravelosona 2015, Emori 2013], where velocities of $\sim 1$ m/s were found at a current density $\approx 10$ MA/cm$^2$. However, our estimate suggests that domain expansion is the rate limiting process and the origin of our observation of partial magnetization reversal. This may also explain why much higher current densities are found for pulse currents (compared to the quasistatic results); larger current densities are needed to induce faster domain propagation, propagation that can lead a larger region in the current path to reverse during the pulse.

The current pulse increases the device temperature through Joule heating. Using Fourier’s law, assuming a boundary thermal conductance between the substrate and device of $\kappa = 4 \text{ kW/cm}^2$ and resistivity of $\rho = 200 \mu \Omega \cdot \text{cm}$, we estimate that the device temperature can increase as much as $\Delta T = J^2pd/\kappa \sim 160 \text{ C}$ during a $J = 80 \text{ MA/cm}^2$ current pulse. This increase in temperature is expected to decrease the domain nucleation field and increase the domain propagation velocity. However, the effect of device heating during the pulse on the switching is beyond the scope of our study. We note that the zero temperature threshold for magnetization rotation is $H_{\text{ST}} = M_s/2$, which gives a zero temperature threshold current density of $J_0 = 486 \text{ MA/cm}^2$, which is much larger than what we find in both the pulsed and quasistatic limits, highlighting the possible roles of sample heating during the pulse, thermal fluctuations and defect nucleation sites in spin-orbit torque driven magnetization reversal.

In summary, we have observed full magnetization switching in quasistatic current swept experiments and partially switched states with short current pulses. Our results suggest that the origin of the partial switching is the time required for reversed domain expansion. Pulse switching for 1 ns duration pulses requires current densities 20 times the quasistatic switching threshold. It is clearly of interest to image the magnetization dynamics on short-time scales to better understand the magnetization reversal mechanisms. It is also important to optimize materials and element geometries to reduce the switching current densities and time scales for spin orbit torque driven magnetization switching.

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