Thermally assisted current-induced magnetization reversal in $SrRuO_3$

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We inject a sequence of 1 ms current pulses into uniformly magnetized patterns of the itinerant ferromagnet $SrRuO_3$ until a magnetization reversal is detected. We detect the effective temperature during the pulse and find that the cumulative pulse time τ required to induce magnetization reversal depends exponentially on $1/T$. In addition, we find that τ also depends exponentially on the current amplitude. These observations indicate current-induced magnetization reversal assisted by thermal fluctuations.

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I. INTRODUCTION

The interaction of spin polarized current with magnetization gives rise to various fascinating spin-torque effects, such as magnetization reversal of nanomagnets in junction configurations[1–5] and current-induced domain wall motion.[6–11] The interest in these effects is not only theoretically motivated, but also for their expected central role in novel spintronics devices, as they offer efficient and scalable methods to control magnetic configurations on a nanometer scale.

An intriguing current-induced spin-torque effect is expected in a uniformly magnetized system with strong coupling between spin waves and current: in this case, currents above a threshold are expected to induce magnetization reversal.[12–18] The effect was observed for the itinerant ferromagnet $SrRuO_3$ (Curie temperature $T_c \sim 150$ K).[19] However, while some features, such as a weak field dependence of the threshold current, were found consistent with existing models, the magnitude of the threshold current was an order of magnitude smaller than predicted. Furthermore, the existing models ignore the role of thermal fluctuations which may be important for experiments performed at temperatures that are not much smaller than T_c.

Here, we explore the possible contribution of thermal fluctuations to current-induced magnetic instability in $SrRuO_3$ by studying the probability for reversal when the injected current is lower than the threshold current, while monitoring the effective temperature of the sample during the current injection. We determine the probability for reversal for a given current as a function of the temperature during the current injection, and the probability for reversal as a function of current for a given temperature. We find that for a given current the average cumulative reversal time ($\overline{\tau}$) depends exponentially on the inverse temperature, as expected from the Néel Brown model,[20,21] and for a given temperature $\overline{\tau}$ depends exponentially on the current. We find that the corresponding energy barrier is temperature dependent and that it is suppressed linearly with increasing current.

The results clearly show that for currents below the threshold current, current-induced magnetization reversal can be modeled by a thermally activated process with a current-dependent barrier.

II. EXPERIMENTAL DETAILS

Our samples are high-quality epitaxial films of $SrRuO_3$ grown on slightly miscut (2°) $SrTiO_3$ substrates.[22] The films are orthorhombic ($a = 5.53$ Å, $b = 5.57$ Å, and $c = 7.85$ Å) with the c axis in the film plane (perpendicular to the miscut direction) and the a and b axes are at 45° relative to the film plane. The Curie temperature of the films is ∼150 K and they exhibit a uniaxial magnetocrystalline anisotropy with the easy axis changing in the (001) plane between the b axis at $T \geqslant T_c$ to 30° from the film normal at low temperatures.[23,24] The ratio between the resistivity at 300 K and the resistivity at the low temperature limit is greater than 10, indicative of the high quality of the films. The films are patterned for magnetotransport measurements, with a typical current path width of 1.5 μm, using e-beam lithography and Ar^+ ion milling. The data presented here are for a film thickness of 37.5 nm.

The current is injected in one millisecond pulses through the pattern as shown in the inset of Fig. 1. The average temperature of the sample during the current pulse injection is determined with an accuracy of ±0.09 K by measuring the longitudinal resistance during the current injection and using the known temperature dependence of the resistance of the sample (measured with a low current).[19] We cannot exclude a temperature variation along the current path on the order of 1 K. However, as the magnitude and form of the variation are expected to be practically the same in the temperature interval of our experiment, it may have a very minor effect on the analysis of our data.

The average magnetization state of the pattern is monitored by measuring the transverse resistance which consists of both the ordinary Hall effect and the anomalous Hall effect (AHE) related to the perpendicular component of the magnetic field and magnetization, respectively. Since the easy axis for magnetization in $SrRuO_3$ is tilted out of the film plane there is a perpendicular component of the magnetization in the remanent state when no field is applied.[25–27]

III. RESULTS AND DISCUSSION

Figure 1 presents typical measurements of current-induced magnetization reversal performed on a fully magnetized sample when the current amplitude is lower than the amplitude

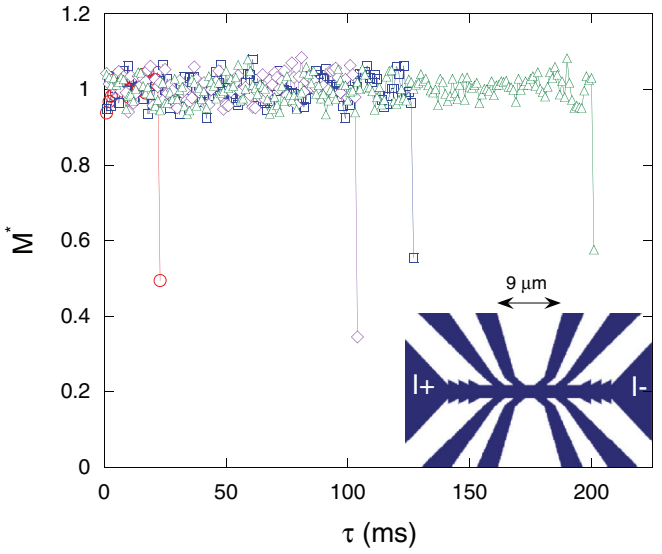

FIG. 1. (Color online) Normalized average magnetization as measured in the last 50 μs of the 1 ms pulse vs the accumulated pulse time τ. The current amplitude is 4.28 mA, the external field is 500 Oe, and the temperature is 107.8 K. The different symbols represent different sets of measurements. Inset: a sketch of the pattern.

of the threshold current for the relevant temperature. We inject a sequence of 1 ms pulses, separated by a 100 ms pause. During the last 50 μs of each pulse we measure the transverse resistance to detect changes in the average magnetization. If the magnetization has reversed, the sequence is stopped, the sample is fully magnetized again, and the sequence of pulses is resumed. The time τ represents the accumulated time of the current pulses and M^* represents the normalized average magnetization extracted from the AHE signal.

The measurements presented here were performed for temperatures between 107 and 110 K with current amplitude between 4.15 and 4.31 mA (for our pattern, 1 mA corresponds to a current density of $\sim 1.8 \times 10^6 \frac{\mathrm{A}}{\mathrm{cm}^2}$). To facilitate the detection of a reversal event, we apply during the experiment a constant magnetic field of 500 Oe, opposite to the perpendicular component of the remanent magnetization, to assist propagation after nucleation. Since this field in the absence of current pulse induced nucleation is only 25 K above the highest temperature at which our experiments are performed, one can conclude that this field has a negligible influence on the measured reversal events.

Figure 2 shows the results of experiments as shown in Fig. 1 with a current of $I = 4.28$ mA for temperatures between 107.3 and 109.3 K (the temperature is measured during the pulse; without current the temperature of the sample is $\sim$50 K lower). At each temperature the experiments were repeated 40–80 times. Figure 2(a) shows the probability of the pattern to remain fully magnetized as a function of the accumulated pulse time. The lines represent the expected probability using the calculated probability for reversal after a single pulse and assuming an exponential distribution; namely, that the current pulses are uncorrelated events and the system has time to recover during the 100 ms between pulses. Based on the fits to exponential distributions, we extract $\overline{\tau}$, the average waiting

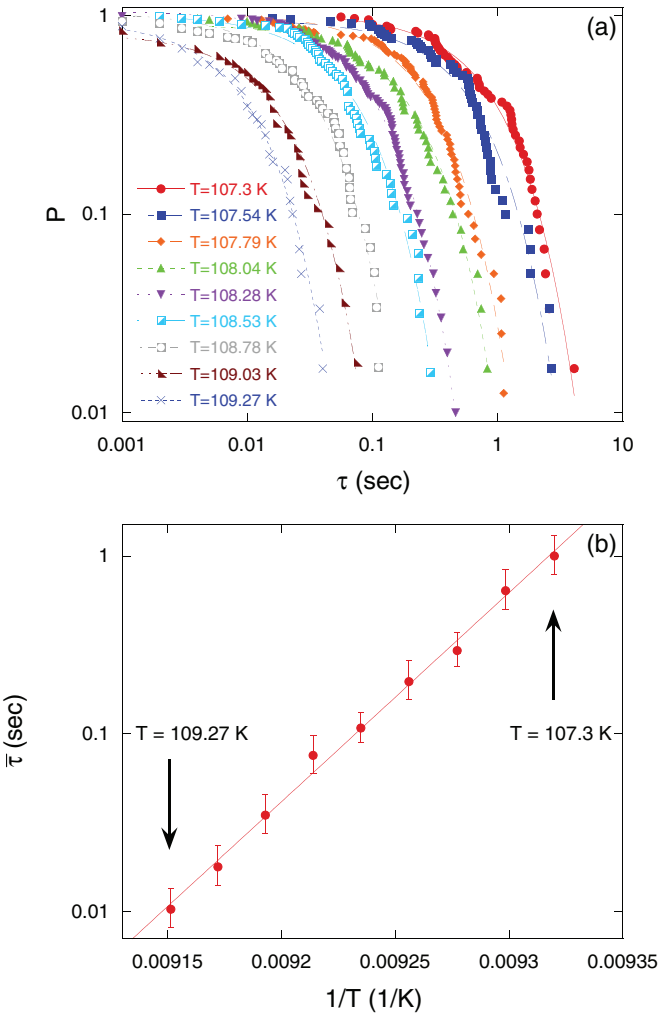

FIG. 2. (Color online) (a) Probability P to remain fully magnetized vs the accumulated time τ, and (b) the average waiting time $\overline{\tau}$ for reversal as a function of the inverse temperature, for a current amplitude of 4.28 mA and an external field of 500 Oe opposite to the perpendicular component of the remanent magnetization. The error bars represent confidence interval of 95%.

time for reversal, for the given current amplitude and the given temperature.

Figure 2(b) shows the temperature dependence of $\overline{\tau}$ for $I = 4.28$ mA (symbols) as a function of $1/T$. The linear fit (with $\overline{\tau}$ in a logarithmic scale) indicates that

$$\overline{\tau} = Ae^{E/(k_B T)}, \tag{1}$$

as expected for a thermally activated process.

Experiments as shown in Fig. 2 were repeated with multiple currents. Based on fits to Eq. (1) we extract by interpolation $\overline{\tau}$ as a function of the current amplitude for given temperatures (see Fig. 3). We note that a change of less than 5% in the current changes $\overline{\tau}$ by almost two orders of magnitude.

While a good fit with Eq. (1) is obtained for all currents, the fit parameters are current dependent. When the current increases, the parameter E that represents the energy barrier for magnetization reversal decreases linearly, which suggests that $E = E_b(1 - I/I_c)$. In addition, we find that with increasing

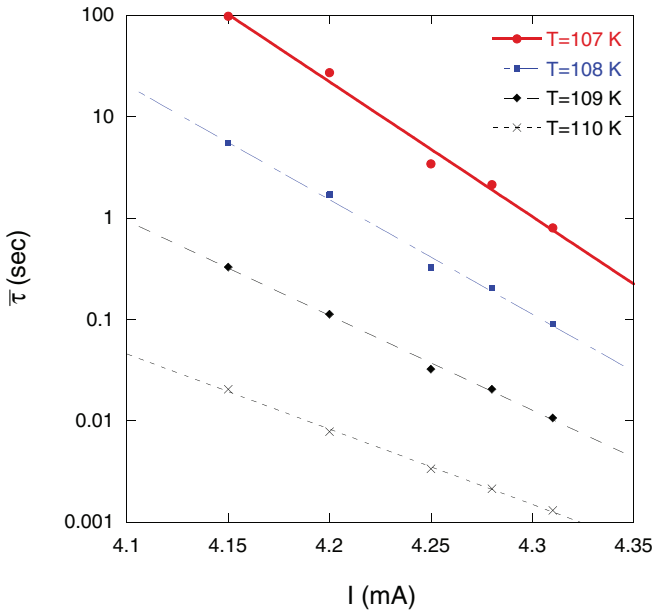

FIG. 3. (Color online) Average waiting time for reversal as a function of the current amplitude for several temperatures. The lines are fits to Eq. (2).

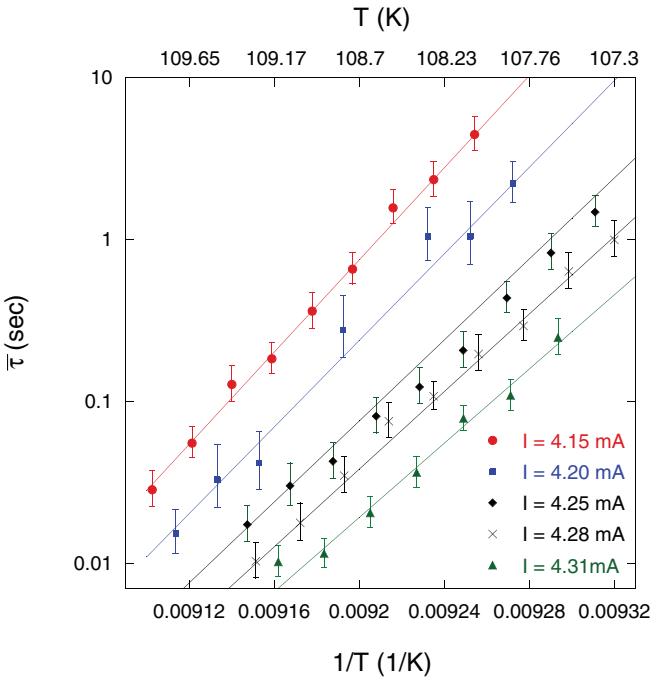

FIG. 4. (Color online) The average waiting time for reversal for several current amplitudes as a function of the inverse temperature (lower axis); the corresponding temperature is also presented (upper axis). The lines are fits to Eq. (2). The error bars represent confidence interval of 95%.

current the parameter A increases exponentially. A possible source of this behavior is a temperature dependence of E_b due to, for instance, the temperature dependence of the magnetization and the magnetic anisotropy in the temperature range of our experiments.

Since the temperature interval of our experiment is rather small (between 107 to 110 K), we use a linear approximation for the temperature dependence of E_b which yields $E = E_b^0(1-\kappa\Delta T)(1-I/I_c)$, where $\Delta T = T - 107$ K. Equation (1) therefore takes the form

$$\overline{\tau} = \tau_0 e^{E_b^0(1-\kappa\Delta T)(1-I/I_c)/(k_B T)}, \qquad (2)$$

where τ_0 is a constant that is temperature and current independent, consistent with the Néel Brown model. Interestingly, the dependence of the energy barrier E_b on the current is very similar to the dependence observed in completely different cases, including the effect of the current on the energy barrier for depinning a domain wall[28] and the energy barrier for the switching of a nanomagnet is incorporated into a spin valve nanopillar.[29]

Using Eq. (2) we fit the data obtained for all the currents with the same fitting parameters (see Fig. 4). We obtain the best fit with $\tau_0 = 4.8 \times 10^{-9}$ s, $E_b^0 = 1.32$ eV, $\kappa = 0.11\frac{1}{\mathrm{K}}$, and $I_c = 4.97$ mA, in agreement with the measured threshold current.[19] Using a bootstrap method, we find that the error bars for a confidence interval of 95% are $E_b^0 \sim 1.28$–1.41 eV, $\kappa \sim 0.07$–$0.15\frac{1}{\mathrm{K}}$, and $I_c \sim 4.7$–5.4 mA. As small variations in these parameters change τ_0 exponentially, its error bars are significantly larger. We find that for a confidence interval of 50% the possible range of τ_0 is $\sim 1 \times 10^{-10}$–8×10^{-8} s.

To estimate the nucleation volume, we use the relation $E_b^0 = K_u V$ expected for coherent rotation, where K_u is the magnetic anisotropy energy density related to the uniaxial magnetocrystalline anisotropy. At low temperatures $K_u \sim 5.6 \times 10^{-3}\frac{\mathrm{eV}}{\mathrm{nm}^3}$ (extracted from the measured anisotropy field of ~ 7 T[30] and saturation magnetization $M_s \sim 250$ kA/m[22]) and using this value yields $V \sim 240$ nm^3. Assuming a nucleation volume of cylindrical shape with the film thickness (37.5 nm) as the cylinder height, the estimated radius of the cylinder is ~ 1.5 nm, on the order of the domain wall width. We should, however, take into consideration that E_b^0 is the barrier at $T = 107$ K, where the magnetization is ~ 0.7 of its saturation value and K_u may also be suppressed.[31,32] Therefore, the volume could be larger although still on the same order.

IV. CONCLUSIONS

In conclusion, we have studied the current-induced switching in a uniformly magnetized ferromagnetic $SrRuO_3$ sample close to the Curie temperature, and we have demonstrated that the switching process can be described as a constant prefactor Néel Brown model with first order corrections to the energy barrier for current and temperature. The observed dependence of the energy barrier on current makes it possible to modulate the energy barrier in itinerant ferromagnets, which might offer opportunities for further study of the switching process and for the development of novel spintronics devices.

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