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Device size dependence of spin-orbit torque induced magnetization switching in W/CoFeB/MgO

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Abstract

We study spin-orbit torque induced magnetization switching in W/CoFeB/MgO heterostructures with different device shapes and sizes ranging from μm to nm scales. For long current pulse width (τ = 100 ms), threshold switching current density J_{th} in a μm-sized circular dot is 9.5 times larger than that in a μm-sized cross-shaped Hall bar device, and, for dot devices, J_{th} increases by a factor of 2.4 as the diameter decreases to 60 nm. From a pulse width dependence of J_{th}, we find that the magnetization reversal mode differs between the μm-sized and nm-sized devices, which mainly accounts for the observed difference in J_{th}.

1. Introduction

Spin-orbit torque (SOT) induced magnetization switching in heavy-metal/ferromagnetic-metal/oxide heterostructrues offers a new writing scheme of information for nonvolatile spintronics devices and has attracted great interest for these years [1-3]. To use the SOT switching in spintronics devices, it is essential to elucidate factors determining the threshold switching current density J_{th}. In our previous work, we found that J_{th} in nanometer-sized devices is one order of magnitude larger than that in micrometer-sized devices [4]. In this work, we investigate the underlying mechanism causing the difference in J_{th} using devices made of W/CoFeB/MgO with various sizes and shapes. From an estimation of Joule heating and measurement of pulse width τ dependence of J_{th}, we discuss the degree of the effect of temperature and spatially-inhomogeneous magnetization reversal on J_{th} for μm-sized and nm-sized devices.

2. Experimental procedures

A stack structure, from the bottom side, W(5)/ CoFeB(1.3)/ MgO(2)/ Ta(1) (numbers in parentheses are nominal thickness in nm), is deposited on a highly-resistive Si wafer using dc/rf magnetron sputtering. Sputtering power and gas pressure during the deposition of W are 100 W and 0.17 Pa, respectively, where β-W with high effective spin Hall angle (~0.4) is expected to be obtained [5]. The stack is fabricated into three kinds of switching devices with different sizes and shapes. The first one is a micrometer-sized cross-shaped Hall bar with 6×12 μm^2 channel (Fig. 1(a)). The other two are Hall devices with a circular CoFeB/MgO dot formed on top of a cross-shaped W channel, where the nominal diameter D of the dot and the width of the channel W are (D, W) = (3.5 μm, 6 μm) and (120 nm, 230 nm), respectively (Fig. 1(b), (c)). The processed wafer is annealed at 300ºC for 1 hour.

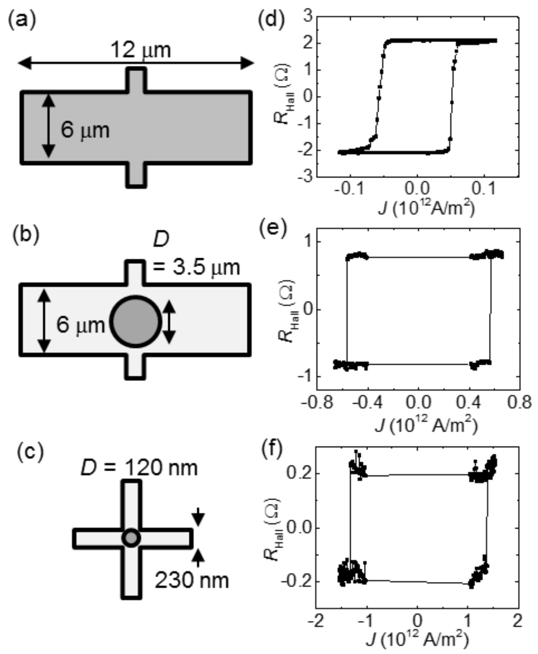

Fig. 1: (a)-(c) The schematics of three kinds of devices. (d)-(f) Corresponding SOT switching property, i.e., Hall resistance R_{Hall} versus current density J, where current pulses with τ = 100 ms are applied under 20-mT external field collinear with the current.

3. Results and discussion

Figures 1(d)-(f) show examples of SOT-induced magnetization switching, where current pulses with τ = 100 ms are applied under an external magnetic field of 20 mT in a direction collinear with the current. J_{th} in the 3.5-μm dot is 0.57×10^{12} A/m^2, which is 9.5 times larger than that in a Hall bar with 6×12 μm^2 channel (J_{th} = 0.06×10^{12} A/m^2). J_{th} further increases by a factor of 2.4 as the dot diameter decreases from 3.5 μm to 120 nm (J_{th} = 1.36×10^{12} A/m^2). The difference in J_{th} between the μm-sized Hall bar and nm-sized dot is consistent with our previous work with Ta/CoFeB/MgO [4].

One possible factor causing the difference in J_{th} is an effect of Joule heating, which is expected to increase with the channel area. Since the effective anisotropy field H_K^{eff}, to which J_{th} is proportional, changes with temperature, J_{th} may become smaller for larger devices. To quantify this effect, we evaluate the device temperature by measuring the variation in channel resistance with current and variation in the resistance with temperature. From this procedure, we find that the device temperature at which switching takes place is 55°C for nm-dot and 74°C for μm-dot samples. Meanwhile, a separate measurement reveals that variation in H_K^{eff} between the above two temperatures is 7%, which is insufficient to explain the observed difference in J_{th} (= 240%).

Another possible factor is an effect of spatially-inhomogeneous magnetization reversal. For larger devices, the reversal may start from a nucleation, followed by a domain wall (DW) propagation, resulting in a reduction of J_{th}. Indeed, the intermediate Hall resistance levels are observed in 6×12 μm^2 Hall bar (Fig. 1 (d)), which is an evidence of the inhomogeneous magnetization reversal. For 3.5-μm dot device (Fig. 1(e)), although the intermediate level is not seen when τ= 100 ms, the similar behavior is found to be observed when τ< 100 μs. To shed light on the effect of inhomogeneous reversal, we study τ dependence of J_{th} down to 500 ps. The results for 3.5 μm dot and 120 nm dot devices are shown in Fig. 2(a). Figure 2(b) shows J_{th} normalized by J_{th} at τ = 100 ms for the two devices. J_{th} increases significantly with decreasing τ shorter than about 100 ns for the 3.5-μm dot device, whereas the significant increase is seen only at τ< 1 ns for 120-nm dot device. J_{th} at τ~ 1 ns, where the DW cannot easily propagate over the large dot, is comparable between the two devices. These results are consistent with the scenario that inhomogeneous reversal is a factor to reduce J_{th}, resulting in the observed device size dependence. We can also speculate that the effect of Oersted field may also contribute to the reduction of J_{th}, especially for μm-sized Hall-bar devices. Furthermore, for the present material system, W/CoFeB/MgO, Dzyalloshinskii-Moriya interaction may also affect the device size dependence.

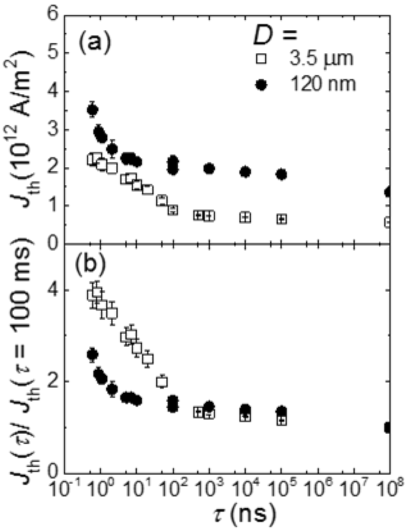

Fig. 2 (a) τ dependence of J_{th} for dot devices with D = 3.5 μm and 120 nm. (b) J_{th} normalized by that at τ = 100 ms as a function of τ.

4. Conclusions

We study the spin-orbit torque (SOT) induced magnetization switching in W/CoFeB/MgO heterostructures with different device sizes and shapes. Significant device size dependences of J_{th} and relation between J_{th} and τ are observed. We find that the results can be mainly explained by considering a different magnetization reversal mode.

Acknowledgements

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