# Switching Mechanism Design for High-speed Voltage-Control Spintronics Memory (VoCSM) Considering the Operation Window

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# Abstract

Dynamics of magnetization reversal for storage layer (SL) in VoCSM was studied with simulation calculation and evaluation of nanometer sized MTJ elements. Magnetization switching by Spin Hall effect (SHE) can be achieved for various magnetization configurations, but its stability against excessive write current was different for each. We clarified that precession-mode (P-mode) switching is quite robust to excessive write current, while direct-mode (D-mode) switching needs more precise control to suppress back hopping fault. It was concluded that P-mode is most suitable for use in VoCSM.

# 1. Introduction

Recently three terminal element using Spin Hall effect (SHE) is attracting attention due to its potential of low energy consumption, high speed writing, and free from read-disturb faults. We have proposed VoCSM, which is a promising candidate for SHE based memory (Fig. 1) [1].

In VoCSM, magnetic cells are fabricated on heavy metal line where in-plane current is applied, so the possible relations between magnetization easy axis of SL and effective field by SHE are both parallel and perpendicular. Fukami et al. reported about two types of mode for magnetization switching by spin-orbit-torque, precession and direct modes, are available for parallel and perpendicular respectively [2].

In this study, we investigated the process of magnetization reversal under the excessive write current more than critical write current, assuming actual production situation where the excessive current is applied for the margin. For D-mode, the excessive write current brings canted magnetization from easy axis, while always parallel for P-mode. The effect of such difference on final state of switching was studied with the simulation calculation and the experiments.

# 2. Results

LLG simulation was performed for the in-plane SL models those magnetic easy axis are parallel and perpendicular to write current direction, corresponding D-mode and P-mode respectively. The parameter of SL are, size of SL is  $30 \text{nm} \times 90 \text{nm}$ , thickness of SL  $t_{SL} = 3 \text{ nm}$ , spontaneous magnetization  $M_s = 1100 \text{ emu/cc}$ , surface



Fig. 1 Schematic view of the voltage-control spintronics memory. A write current and control voltage are applied to the write line and the magnetic tunnel junction (MTJ), respectively when data are written to the MTJ.

anisotropy energy  $K_s = 1.4 \text{ erg/cm}^2$ , stiffness  $A = 1.38 \times 10^{-6}$  $erg/cm^2$ , temperature= 300 K. Memory retention energy  $(K_V/k_BT)$  should come from shape anisotropy, which is estimated 50 here. For D-mode external fields was applied by from 500 Oe to 5 kOe which is necessary to break symmetry [2]. The effective field by SHE was supposed to be originated only from spin-transfer-torque type interaction. Fig. 2(a) and (b) show trajectories of P-mode and D-mode for 5 ns from write current starts. In this condition the required write current density for magnetization switching with D-mode was as five times much as that with P-mode. As Fukami pointed out, for D-mode magnetization reversal happens instantly, while P-mode requires precession time to overcome barrier. Fig. 2(c) and (d) also show trajectories in case write current increases by 70 % compared to the case of (a) and (b) respectively. For D-mode (Fig. 2(d)), magnetization will not get stabilized toward opposite while P-mode gets stabilized as well. direction. Magnetization of D-mode rotates continuously while write current is applied. Fig. 3 shows time dependence of x-component corresponding Fig. 2(d) situation. Magnetization itinerates around half way between both directions on x-axis. This implies there is risk of back-hopping after magnetization reversal.

To investigate this phenomena experimentally, three terminal devices were fabricated. The MTJ film structure is as follows, capping layer/IrMn 8 nm/CoFe 1.8 nm/Ru 0.9 nm/CoFeB 1.8 nm/MgO/FeB 2.2 nm/Ta 10 nm (for SHE)/substrate.  $H_{k-eff\perp}$  of SL was -2.6 kOe, and Ms=1000



Fig. 2 Trajectories of magnetization switching for (a) and (c): P-mode, and (b) and (d): D-mode. For D-mode external magnetic field of 3 kOe is applied to z-axis. Write current direction is x for all cases. The value of write currents in (c) and (d) is larger by 70 % compared to (a) and (b), respectively. Figure (c) indicates the coherency of precession is disturbed, but the magnetization gets stabilized finally. But figure (d) shows the final magnetization is not stabilized and rotates continuously while write current is applied.



Fig. 3 Time dependence of magnetization x-component  $(M_x)$ , corresponding Fig. 2(d) situation. Magnetization itinerates around half way between both directions on x-axis.

emu/cc. MTJ was patterned to 60 nm  $\times$ 180 nm, and bias magnetic field by IrMn was always in long axis. The write current was applied along long and short axis of the patterned MTJ for D-mode and P-mode respectively, by pulse of 20 ns width. SHE layer was also patterned to same width as short axis of MTJ for D-mode, and long axis for P-mode. Magnetization direction was estimated by magnetoresistance, which was measured each time after one pulse was applied. Fig. 4(a) shows the typical magnetization switching behavior of D-mode. Hz= -0.4 kOe was applied continuously during all sequences. Magnetization reversal was achieved at 200  $\mu$ A, but for more than 400  $\mu$ A the



Fig. 4 Typical switching behavior of D-mode (a) and P-mode (b). For D-mode, external magnetic fileld of -0.4 kOe was applied continuously during all sequences. The D-mode device showed write-faults under excessive write current (in the dotted circles), while P-mode remained stable.

switching faults were observed. This phenomenon is consistent with the LLG simulation calculation results that suggests the possibility of back-hopping fault. For P-mode (Fig. 4(b)), once switching was achieved, magnetization remained stable under much excessive current. This result suggests P-mode is more suitable for actual device that requires the margin for design.

### 3. Conclusions

We clarified that precession mode switching is advantageous for broad operation window not only smaller switching current, so most suitable for use in VoCSM. In the presentation we will show more detail about the write current margin against external magnetic field and pulse width of write current, including the case of perpendicular SL.

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# References

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