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From STT-MRAM to Voltage-Control Spintronics Memory (VoCSM) in Pursuit of Memory Systems with Lower Energy Consumption

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We designed a voltage-control spintronics memory unit-cell, VoCSM, with high write-efficiency to prove a potential to reduce writing energy per bit. By optimizing a self-aligned structure, the cell has the critical switching current (I_{csw}) smaller than 50 μA at 20 nsec. for designed MTJ size of about 50 × 150 nm^2. The value is much smaller than that for mature STT-MRAM with the similar dimension. VoCSM also was proved to have unlimited endurance. Finally, with an empirical equation of I_{csw} further reduction of I_{csw} is estimated to clarify that VoCSM has a potential to reduce I_{csw} down to several μA.

Keywords : MRAM, spintronics, spin Hall, voltage-control spintronics memory, voltage-control magnetic anisotropy

1. Introduction

MRAM has been developed since the 1980s but progress has not been smooth. The ultimate objective is to realize non-volatile working memories that save energy consumption, thereby reducing energy consumption to a level comparable to that of conventional volatile working memories such as SRAM and DRAM. However, all non-volatile memories, including MRAM, have been facing the dilemma posed by the fact that non-volatility has hitherto necessitated high energy consumption in their active mode, because non-volatility had led to large writing-energy consumption, E_w.

As a result, they have been used for data storage and none of them overcame this historical dilemma to enter use for busy applications such as mobile phones. This is one of the reasons that a big market for MRAM has yet to emerge.

Possibilities of overcoming the dilemma were demonstrated recently in the case of both STT-MRAM and VoCSM [1, 2].

In addition, several VoCSM architectures were proposed and the key operation principles were demonstrated [2-6].

STT is more mature but has less room for further improvement. On the other hand, VoCSM, or spin-Hall writing memory, has poor maturity but greater potential in terms of higher writing efficiency and better endurance [3].

In this paper, STT technologies and VoCSM, or spin-Hall writing memory technologies, are reviewed with respect to saving energy consumption and the remaining issues are discussed.

2. Possibility of Small Critical Switching Energy Per Bit, e_{CSW}, of VoCSM

An STT cell and a VoCSM cell are shown in Fig. 1. In the VoCSM cell, one electron can apply spin-torque several times, whereas in the STT cell, one electron can apply spin torque once. Application of negative voltage to the VoCSM cell further reduces the critical switching current, I_{csw}, because of the voltage dependence as shown in Fig. 2.

Figure 3 shows the experimental proof of high write efficiency of spin-Hall writing (VoCSM with no voltage applied) compared with STT writing. Self-aligned MTJ elements were fabricated to compare the write efficiency of VoCSM with that of STT writing. Write current is fed across the tunneling barrier to measure shifts in the hysteresis for STT writing, whereas write current was fed

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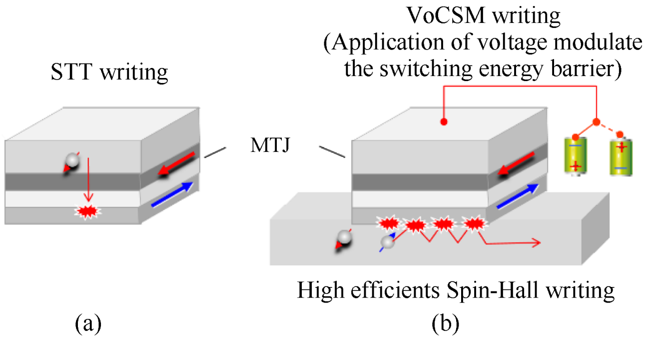

Fig. 1. (Color online) Writing mechanisms and cell structures of STT writing and VoCSM writing.

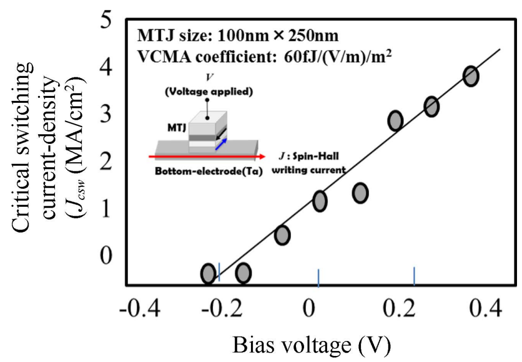

Fig. 2. (Color online) Fundamental VoCSM write property.

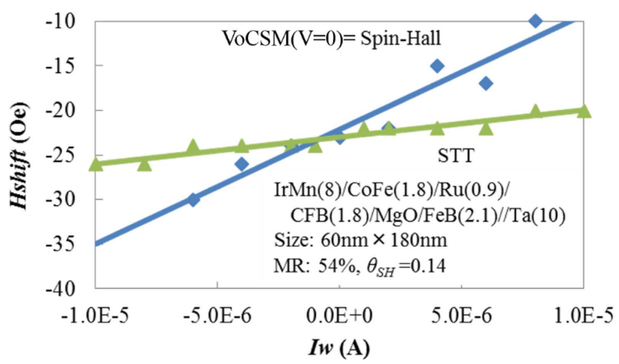

Fig. 3. (Color online) Write efficiency experimental results for STT writing and VoCSM with no voltage applied.

in the spin-Hall electrode to measure shifts in the hysteresis for VoCSM writing. The proportionalities reflect spin torques exerted on the magnetization in the storage layer, i.e., the write efficiencies.

As expected, the write efficiency of VoCSM is proved to be 3-4 times higher than that of STT writing.

The critical switching current for VoCSM with voltage, V, applied is given by Equation (1) [7].

$$I_{csw}(\text{VoCSM}) = 4e\alpha^*_{eff}/\hbar\ \theta_{SH}\cdot\Delta E_{sw}(V)\cdot t_{SH}/w \quad (1)$$

Here, α^*_{eff}, e, $\hbar$, θ_{SH}, ΔE_{sw}, t_{SH}, and w are the effective damping constant, charge of an electron, reduced Planck's constant, the spin-Hall angle (spin polarization), the switching energy barrier, the thickness of the spin-Hall electrode, and the width of the storage layer, respectively. In this case, the width of spin-Hall electrode is assumed to be the same as w, i.e., MTJs are self-aligned with the electrode [11].

Critical switching energy per bit for VoCSM writing, e_{csw} (VoCSM), is the product of I_{csw}, write pulse width (t_p), and voltage across the spin-Hall electrode. It is roughly given by Equation (2), assuming the spin-Hall electrode has square in-plane shape [9].

$$e_{csw}(\text{VoCSM}) = \{4e\alpha^*e_{ff}/\hbar\ \theta_{SH}\cdot\Delta E_{sw}(V)\cdot t_{SH}/w\}^2\cdot t_p\cdot R_{sh} \quad (2)$$

Here, R_{sh} is the sheet resistance of spin-Hall electrode with the typical value of 200-500 Ω.

Similarly, critical switching current and critical switching energy per bit for STT-MRAM are given by Equations (3) and (4) [7, 9].

$$I_{csw}\ (\text{STT}) = 4e\alpha_{eff}/\hbar\ g(\theta)\cdot\Delta E_{sw} \quad (3)$$

$$e_{csw}\ (\text{STT}) = \{4e\alpha_{eff}/\hbar\ g(\theta)\cdot\Delta E_{sw}\}^2\cdot t_p\cdot R_{MTJ} \quad (4)$$

Here, α_{eff}, g(θ), and R_{MTJ} are the effective damping constant, the spin polarization, and the resistance of MTJ with a typical value of 10 kΩ.

Equations (5) and (6) are the ratios of I_{csw} (VoCSM) to I_{csw} (STT) and e_{csw} (VoCSM) to e_{csw} (STT).

$$I_{csw}\ (\text{VoCSM})/I_{csw}\ (\text{STT}) = (g(\theta)/\theta_{SH})\cdot(\Delta E_{sw}(V)/\Delta E_{sw})\cdot(t_{SH}/w) \quad (5)$$

$$e_{csw}\ (\text{VoCSM})/e_{csw}\ (\text{STT}) = (g(\theta)/\theta_{SH})^2\cdot(R_{sh}/R_{MTJ})\cdot(\Delta Es_w(V)/\Delta E_{sw})^2\cdot(t_{SH}/w)^2 \quad (6)$$

Here, α^*_{eff} and α_{eff} are assumed to be the same.

Let's make reasonable assumptions, $g(\theta)/\theta_{SH} = 1$, $R_{sh}/R_{MTJ} = 1/20$, $\Delta E_{sw}(V)/\Delta E_{sw} = 7/10$, and $t_{SH}/w = 1/4$.

Then, I_{csw} (VoCSM)/I_{csw} (STT) and e_{csw} (VoCSM)/e_{csw} (STT) become less than 0.18 and less than 0.0015.

For spin-Hall writing, $\Delta E_{sw}(V)/\Delta E_{sw}$ becomes 1, then I_{csw} (spin-Hall)/I_{csw} (STT) and e_{csw} (spin-Hall)/e_{csw} (STT) become 0.25 and less than 0.0031.

VoCSM and spin-Hall writing memory have the potential to lower both I_{csw} and e_{csw}.

3. Practically Unlimited Endurance of VoCSM

In VoCSM, write current flows in the spin-Hall electrode made of heavy metal such as Ta having high melting temperature. Due to this, unlimited endurance of more than 1E+13 was demonstrated even at write pulse width

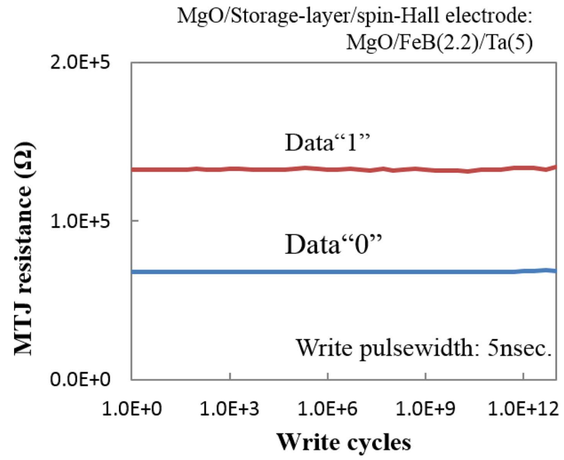

Fig. 4. (Color online) Endurance test results of VoCSM.

of 5 nsec. as shown in Fig. 4 [3].

Recently, unlimited endurance was proved even at write pulse width of 2 nsec [10]. with a possible broad design window for memory operation.

4. MTJ Structure, an Analysis of I_{CSW}, and the Empirical Dependence of I_{CSW} on ΔE_{sw}

The typical MTJ structure for the experiments is Ta (5 nm)/IrMn (8 nm)/CoFe (1.7 nm)/Ru (0.9 nm)/CoFeB (1.8 nm)/MgO (1.6 nm)/CoFeB (1.6 nm) or FeB (2.2 nm)/TaB (3 nm)/Ta (5-7 nm). The film stack is ion milled to a self-aligned structure to reduce I_{csw}. The cross-sectional TEM image is shown in Fig. 5.

The typical properties of the MTJ for VoCSM are the tunnel magnetoresistance (TMR) ratio of 170-180 %, the resistance area product (RA) of 0.8-1.0 kΩμm^2, and the saturation magnetization (M_s) of the storage layer of about 1400-1500 emu/cm^3. The VCMA coefficient was about 70-100 fJ/{(V/m) m^2} and the spin-Hall angle (θ_{SH}) was about –0.09 - –0.18.

Small I_{csw} of 37 μA at write pulse width of 20 nsec. was successfully demonstrated owing to high efficiency of spin-Hall writing combined with the voltage assist [8]. The value of the I_{csw} is almost the same as that for STT writing, even though the size of MTJ for VoCSM writing (50 nm × 150 nm-60 nm × 180 nm) is much larger than that of STT writing (30 nm ø).

The latest data of VoCSM is indicated in Fig. 6 by the star mark. Small I_{csw} of 30 μA at write pulse width of 20 nsec. is successfully demonstrated owing to high efficiency of spin-Hall writing as expected.

The I_{csw} is further reduced to 25 μA for VoCSM writing with –1 V voltage applied.

Even though VoCSM has poor maturity, it realized I_{csw}

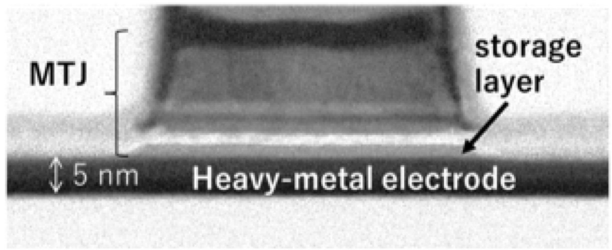

Fig. 5. Cross-sectional TEM image of a typical VoCSM element. The heavy-metal electrode is a spin-Hall electrode made of TaB/Ta.

comparable to that of STT writing.

Figure 6 shows the experimental data of switching energy dependence of I_{csw}. Here, the ΔE_{sw} is calculated by assuming a macro-spin model and the magnetization of the storage layer takes vertical direction during switching.

The figure shows that I_{csw} is almost perfectly proportional to ΔE_{sw}.

5. Reduction Trend of Writing Energys Per Bit, e_{CSWS}, for STT-writing and VoCSM Writing

Figure 7 shows reduction trend of the e_{csw} for STT writing and that for VoCSM writing.

First, e_{csw} is reduced from 1E+7 fJ/bit for field-writing MRAM to about 1E+5 fJ/bit for STT writing with in-plane MTJs.

Second, e_{csw} is reduced from 1E+5 fJ/bit for STT writing with in-plane MTJs to the order of 1E+2 fJ/bit for STT writing with perpendicular MTJs. The data point of 1E+1 fJ/bit is achieved but it sacrifices endurance.

Finally, e_{csw} is reduced to the order of 10 fJ/bit for VoCSM or spin-Hall writing with practically unlimited endurance.

In addition to the I_{csw} comparable to that for STT writing, lower R_{sh} contributed to the e_{csw} of about 10 fJ/

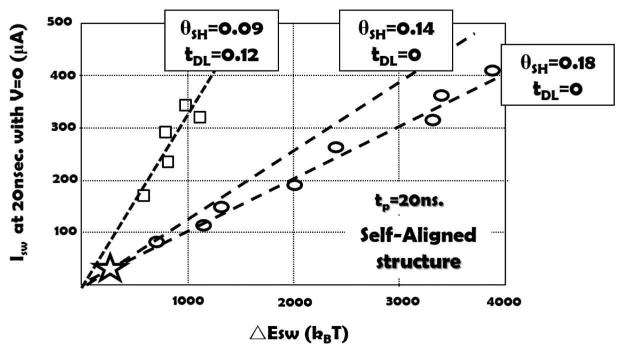

Fig. 6. MTJ size dependence of switching currents of VoCSM writing.

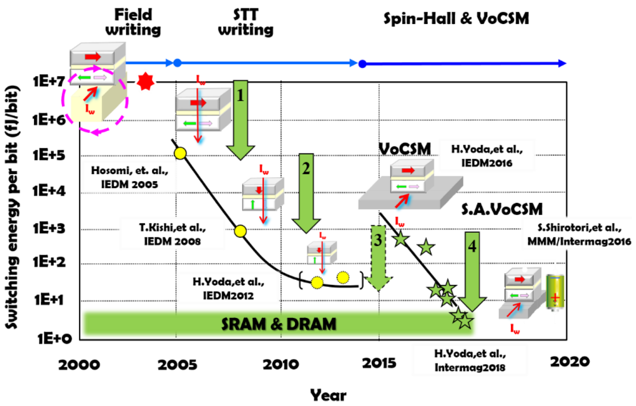

Fig. 7. (Color online) Switching energy reduction trend of spintronics memories. In the figure, arrow 1 is energy reduction by STT writing, arrow 2 is that by perpendicular MTJ, arrow 3 is that by reducing magnetic volume of the storage layer, and arrow 4 is that by VoCSM

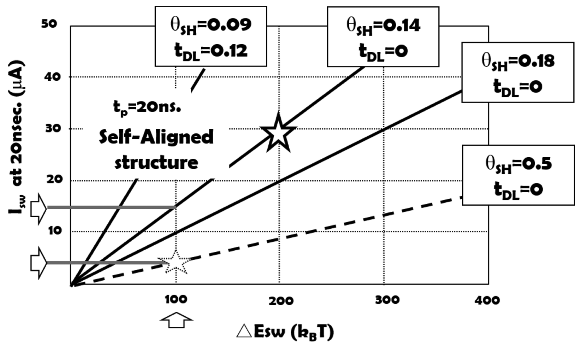

Fig. 8. An estimation of the potential for small current writing by VoCSM writing.

bit. The validity of the discussion in section 2 was proved experimentally.

6. An Estimation of Further Reduction of I_{CSW} and e_{CSW} for VoCSM

Figure 8 shows the estimation of further reduction of Icsw based on the empirical curves. Here, I_{csw} is assumed to scale with ΔE_{csw} down to 100 k_BT.

Then, even with the current MTJ with θ_{SH} of 0.14-0.18, I_{csw} can be reduced to 10-15 μA if ΔE_{sw} is lowered to 100 k_BT.

Large θ_{SH}s of the order of 0.5 were reported recently for W-based alloy in the case of a simulation [12]. If θ_{SH} of 0.5 and ΔE_{sw} of 100 k_BT are assumed, I_{csw} can be lowered to the order of 3 μA for write pulse-width of 20 nsec. even without applied voltage.

The writing charge and the e_{csw} become 60 fcoulomb and less than 1 fJ/bit. The writing charge and the e_{csw} are approaching the values of volatile DRAM of 14 fcoulomb and the order of 10 fJ/bit .

7. Conclusions

The new non-volatile memory VoCSM was introduced and its potential to have small switching current and ultra-low switching energy per bit with unlimited endurance of 1E+13 was confirmed.

The empirical equation was created that matched the experimental data quite well. The estimation of further reductions in switching current and switching energy per bit reveals that VoCSM and spin-Hall writing do have the potential to reach a switching energy per bit comparable to that of volatile memories.

Finally, VoCSM and spin-Hall writing memory are thought to have the potential to resolve the dilemma posed by the fact that non-volatility has hitherto necessitated high energy consumption.

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