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Voltage-Control Spintronics Memory (VoCSM) having a potential of high write-efficiency

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***Abstract*—** 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 spin-Hall structure, the cell has the critical switching current (I_c) of 200 μA at 20 nsec for an MTJ size of 50×150 nm^2. The value is comparable to that for matured STT-MRAM with the similar dimension. By applying a voltage to the MTJ, *Ic* was modulated due to the voltage-controlled magnetic anisotropy (VCMA) effect and the *Ic* reduction was 50 μA at -0.8 V. It is concluded that using both the spin Hall effect and the VCMA effect, the VoCSM has a potential of high write-efficiency.

I. Introduction

In order to reduce energy consumption of memory hierarchy, several non-volatile memories have been developed. However all of the candidates consume more energy in active modes than save in stand-by modes for busy mobile applications. This is a historical dilemma that all the candidates have not solved.

Large write-charge, $Q_w=I_w \times t_p$, is the cause of the large energy consumption and should be reduced for a given V_{dd}. Here, I_w, t_p, and V_{dd} are write-current, write pulse width, and supply voltage, respectively [1].

Voltage-control spintronics memories (VoCSM) have been proposed to solve the dilemma and demonstrated the potentials for both high-density and high-speed applications [2, 3].

In this paper, the VoCSM unit-cell with high write-efficiency was designed, fabricated, and tested to prove and reveal a potential to reduce writing energy per bit.

II. High write-efficiency structure design

The critical switching current in the absence of thermal fluctuations (I_{c0}) is expressed by the equation:

$$I_{c0} \approx \frac{4e}{\hbar}\frac{\alpha_{eff}}{\theta_{SH}}\Delta E_{sw}\frac{t_N w_N}{AR \cdot w_f^2} \qquad (1)$$

Here, e, α_{eff}, $\hbar$, θ_{SH}, ΔE_{sw}, t_N, w_N, w_f and AR are electron charge, effective damping constant, Planck's constant divided by 2π, spin Hall angle, the free energy of the storage layer, the spin-Hall electrode thickness, the spin-Hall electrode width, the storage layer width, the aspect ratio of the storage layer.

First, in order to make the write-efficiency high, i.e. to make I_{c0} small, the spin-Hall electrode width (w_N) should be as small as possible. To do so, the self-aligned spin-Hall electrode shown in Fig.1 was applied [4].

Then, I_{c0} becomes

$$I_{c0} \approx \frac{4e}{\hbar}\frac{\alpha_{eff}}{\theta_{SH}}\Delta E_{sw}\frac{t_N}{w_f} \qquad (2)$$

Second, in order to further enhance the efficiency, ΔE_{sw} was made smaller while the retention energy was not reduced.

To do so, perpendicular surface anisotropy was introduced. In this case, I_{c0} becomes

$$I_{c0} \approx \frac{4e}{\hbar}\frac{\alpha_{eff}}{\theta_{SH}}\Delta E_{sw}^{*}\frac{t_N}{w_f} \qquad (3)$$

with

$$\Delta E_{sw}^{*} = \Delta E_{sw} - \Delta E_{sp} \qquad (4)$$

Here, ΔE_{sw} is the demagnetization energy and ΔE_{sp} is the perpendicular surface anisotropy energy. And for the MTJ size of 50×150 nm^2, the designed values are 1740 k_BT and 1410 k_BT which are modulated by applying the voltage to a MTJ element, respectively.

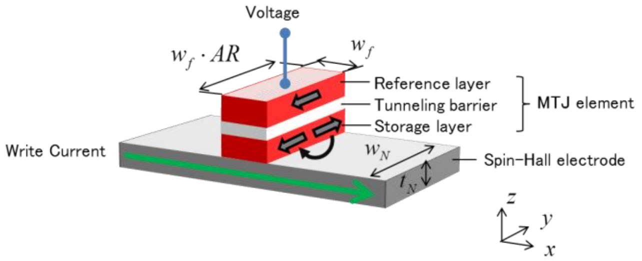

Fig. 1 A schematic drawing of VoCSM unite-cell, which has a MTJ element with a self-aligned spin-Hall electrode

III. Properties of MTJ

In this study, MTJs with in-plane anisotropy are used for demonstrations. The MTJ stack used is Ta (5 nm)/ IrMn (8 nm)/ CoFe (1.8 nm)/ Ru (0.9 nm)/ CoFeB (1.8 nm)/ MgO (1.7 nm)/ CoFeB (1.2 nm). The spin-Hall electrode of Ta (10 nm) was sputter-deposited on a thermally-oxidized Si wafer. The MTJ stack was sputter-deposited on the electrode and was annealed at 300 degree C for 1 hour to pin the magnetization of CoFe. Then, the stack and the electrode were ion-milled to form a MTJ element with the short-axis widths 30-60 nm and the aspect ratios 1.2-12. And its spin-Hall electrode width was almost equal to the long-axis width of the MTJ element. The cross-sectional TEM image along a long-axis direction with its schematic drawing is shown in Fig.2.

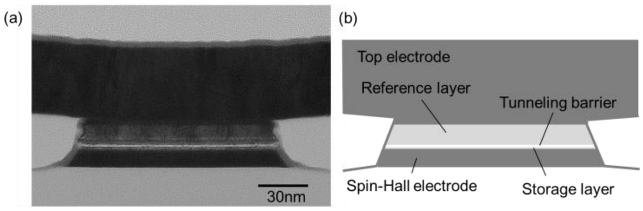

Fig. 2 A cross-sectional TEM image (a) and the schematic drawing (b) of the MTJ element and its electrodes.

The properties of the MTJ film are the tunnel magnetoresistance (TMR) ratio of 174%, the resistance area product (RA) of 1 kΩμm² and the saturation magnetization (Ms) of the storage layer of 1550 emu/cm³.

The VCMA coefficient was about 77 fJ/{(V/m) m²} and the spin Hall angle (θ_{SH}) was estimated to be about -0.09--0.13 by the spin Hall magnetoresistance (SMR) measurement.

IV. RESULTS AND DISCUSSION

Fig.3 shows the critical switching current (I_c) modulation by the voltage (V_{MTJ}) applied to the MTJ element. I_c decreased as V_{MTJ} decreased. I_c of about 350 μA was obtained at V_{MTJ}=0 V and about 270 μA at V_{MTJ}=-0.8 V.

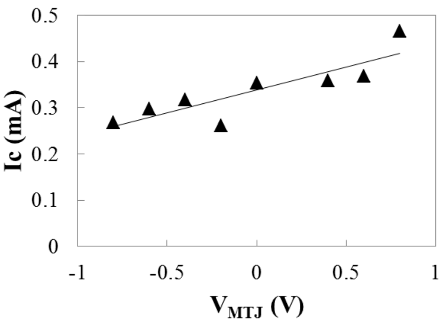

Fig. 3 The critical switching current (I_c) as a function of V_{MTJ}.

Fig.4 shows I_c without V_{MTJ} for a writing pulse width of 20 ns as a function of the MTJ area. We find an intrinsic scalability. I_c decreased as the MTJ size became smaller, and was 200 μA for a MTJ size of 7600 nm². In the previous study [4], I_c of 330 μA was reported for a MTJ size of 12600 nm². By making the MTJ size and its spin-Hall electrode width smaller, I_c was decreased. The value is comparable to that for STT-writing with the similar dimension.

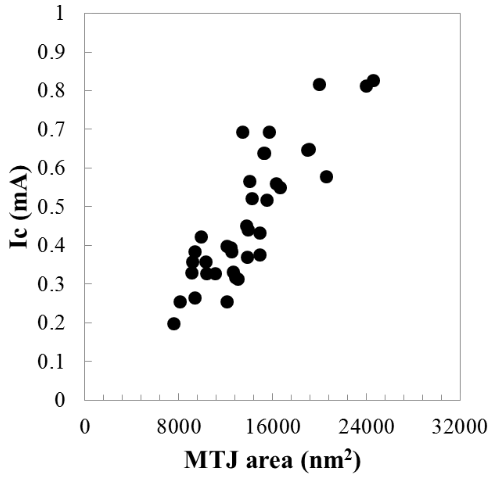

Fig. 4 MTJ area dependence of the critical switching current (I_c) without VCMA. The measured current pulse width was 20 ns. The I_c was 200 μA for a MTJ size of 7600 nm².

V. CONCLUSION

VoCSM unit-cell with high write-efficiency was designed and fabricated. Tested results showed I_c of 200 μA at 20 nsec. The value is comparable to that for matured STT-MRAM with the similar dimension. I_c decreased due to the voltage-controlled magnetic anisotropy (VCMA) effect and I_c reduction was 50 μA at -0.8 V. It was concluded that by applying both the spin Hall effect and the VCMA effect, the VoCSM had a potential of high write-efficiency.

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