Advanced 18 nm Quad-MTJ technology overcomes dilemma of Retention and Endurance under Scaling beyond 2X nm

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Abstract

Advanced quad-interfaces perpendicular magnetic tunnel junction (Quad-MTJ) was developed by engineering a low effective damping constant (α_{eff}) material in free layer with high perpendicular magnetic anisotropy (PMA), and low resistance area product (*RA*) in MgO layers, and stable reference layer. The advanced 18 nm Quad-MTJ fabricated by the developed low-damage 300 mm fabrication process exhibited following performances over those of Double-MTJ; (a) 1.77 times larger thermal stability factor (Δ), (b) 0.83 times smaller writing current (I_c) at 10 ns, (c) 2.1 times higher write efficiency (Δ/I_c) at 10 ns. Thanks to the above excellent MTJ stack design, it is the first time beyond 2X nm generation that the advanced 18 nm Quad-MTJ achieves at least 6×10^{11} endurance with 10 years retention. Consequently, the advanced Quad-MTJ technologies have broken out the dilemma issue of retention and endurance even under scaling of 2X nm.

Keywords: 1X nm, STT-MRAM, p-MTJ, quad interface

Introduction

STT-MRAM has dilemma between retention and endurance due to opposite effect of Δ and endurance on PMA. Scaling down MTJ degrades this trade-off, especially beyond 2X nm. The shape anisotropy MTJ has been demonstrated in principle for an advantage for scaling in Δ by large shape-PMA [1,2], however has not yet verified other performances under practical usage condition. Therefore, a CoFeB/MgO based i-PMA p-MTJ including Quad-MTJ [3-6] keep a promising technology position and is required higher performance. In order to obtain enough endurance in scaling, low resistance product (*RA*) in MgO layers and low damping constant (α_{eff}) in free layer are essential, because these are linear relation to writing voltage (V_c). In this study, the advanced MTJ stack for Quad-MTJ was designed and its excellent performance were successfully demonstrated at 18 nm technology.

Advanced Quad-MTJ with low damage 300 mm process

The advanced Quad-MTJ stacks with low α_{eff} free, low *RA* MgO, and stable reference layers were developed (Fig.1). The advanced Quad-MTJs patterned from 48 nm to 11 nm were successfully fabricated after annealing at 400ºC (Fig.2). Three and two MgO layers were clearly observed, and no re-deposition at side wall was confirmed owing to advanced low-damage integration process (PVD, Etching, *etc.*). The advanced Quad-MTJ showed approximately half α_{eff} and twice PMA of Double-MTJ (Fig.3) together with a low *RA* ~2 $\Omega/\mu m^2$. The large exchange coupling (H_{exc}) in reference layer of more than 0.7 T was achieved by developed reference layer (Fig.4).

Demonstration of 1X nm Quad-MTJ

A. TMR ratio vs. CD

Over 100% TMR ratio, zero-shift magnetic field, and stable reference layer against external magnetic field (H_{ext}) were realized down to 11 nm advanced Quad-MTJ with developing novel free, MgO, and reference layer (Fig.4, 5). The TMR ratio *vs.* CD showed almost constant owing to minimize damaged sidewall layer thanks to the low-damage process (Fig. 5).

B. Thermal stability Δ vs. CD

Figure 6 shows (a) the *R-H* curves measured 100 times for the advanced 18 nm Quad-MTJ, and (b) Δ *vs.* CD for the advanced Quad- and Double MTJs down to 11 nm. Blank circles and solid circles/squares represent Δ evaluated by the pulse magnetic field and current. Δ values obtained from the two different methods are in good agreement. The advanced 18 nm Quad-MTJ shows the 1.8 times larger Δ compared with the Double-MTJ thanks to twice the number of i-PMA interfaces.

C. Write error rate (WER) vs. write voltage

The advanced 18 nm Quad-MTJ achieved small writing current at high-speed of 10 ns (Fig. 7). Because the advanced Quad-MTJ employed stable reference layer (Fig. 4), the back-hopping due to undesirable reference layer flip was not observed even with WER of 10^{-6}. Furthermore, the advanced 18 nm Quad-MTJ has sharp WER curves at small t_w by a large number of i-PMA layers.

D. Switching phase diagram (SFD) under magnetic field

SFD at parallel (P) to antiparallel (AP) switching (write '1') as a function of H_{ext}, and bias voltage (V) was carried out at t_w = 20 and 200 ns (Fig. 8). The influence of H_{ext} on switching boundaries was small in the advanced 18 nm Quad-MTJ due to its large i-PMA. No back-hopping behavior and no ballooning of switch boundary was occurred in SFD thanks to the developed reference layer of the advanced 18 nm Quad-MTJ.

E. Writing current I_c vs. Pulse width t_w

From t_w dependence of I_c, I_c of for the advanced 18 nm Quad-MTJ at t_w of 10 ns has 0.8 times smaller than that of the Double-MTJ (Fig.9); which could be related to low α_{eff} and large Δ (Fig. 3). Writing efficiency Δ/I_c (@10 ns) in the advanced 18 nm Quad-MTJ shows 2.1 times higher owing to large Δ and small I_c in the Quad-MTJ.

F. Enough-Endurance in advanced Quad-MTJ

The advanced 18 nm Quad-MTJ achieves at least 6×10^{11} endurance (Fig.10) with 10 years retention thanks to its higher write efficiency.

Summary

The advanced 18 nm Quad-MTJ (low α_{eff} material with high PMA of free layer, low *RA* MgO layers, stable reference) employed by novel low-damage 300 mm fabrication process overcomes dilemma of retention and endurance under scaling beyond 2X nm (Fig.11). This technology will contribute to 1X nm STT-MRAM available for wide application from SRAM/eDRAM to eFlash, *etc*.

References

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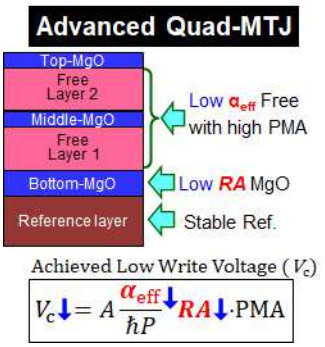

Fig. 1 Developed stack structure of advanced Quad-MTJ.

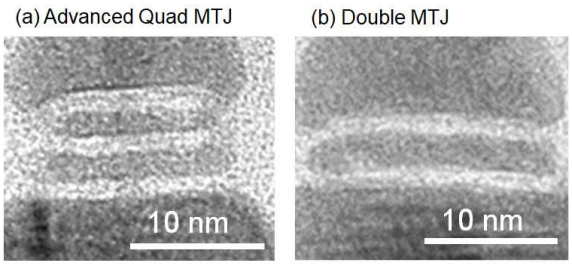

Fig. 2. TEM photographs of advanced 18 nm Quad- and 19 nm Double-MTJs fabricated through our developed low-damage process. A clear stacking structure and etching profile were confirmed.

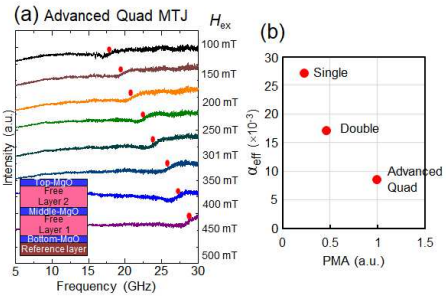

Fig. 3 (a) FMR spectrum of advanced Quad-stack film, and (b) effective damping constant (α_{eff}) *vs.* PMA for Single,[3] Double, and advanced Quad-stack films.

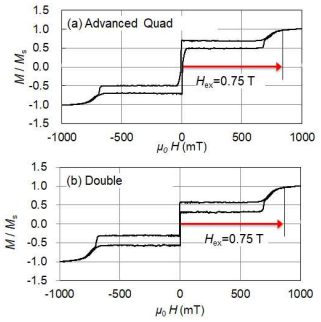

Fig. 4 Magnetization curves of (a) the advanced Quad- and (b) Double-MTJ stack films with novel reference layer.

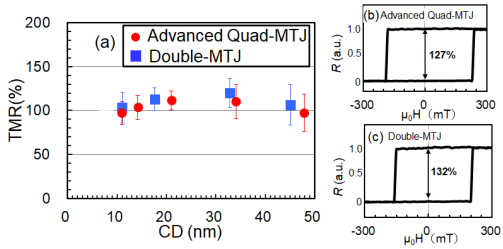

Fig. 5 (a) CD dependence (from 48 nm to 11 nm) of TMR ratio for the advanced Quad- and Double-MTJs. TMR ratio was almost constant with a decrease in the CD. *R-H* curves for the (b) advanced Quad- and (c) Double-MTJs. The bi-stable magnetic switching up to 300 mT and almost zero-shift magnetic field was obtained.

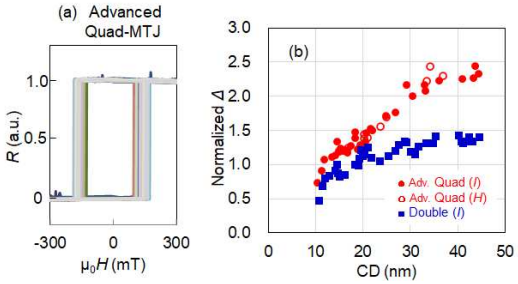

Fig. 6 (a) One hundred *R-H* curves for the advanced 18 nm Quad-MTJ, and (b) thermal stability factor Δ as a function of CD for the advanced Quad- and Double-MTJs. Δs of the advanced Quad-MTJs are almost 1.77–1.83 times larger than those of the Double-MTJs.

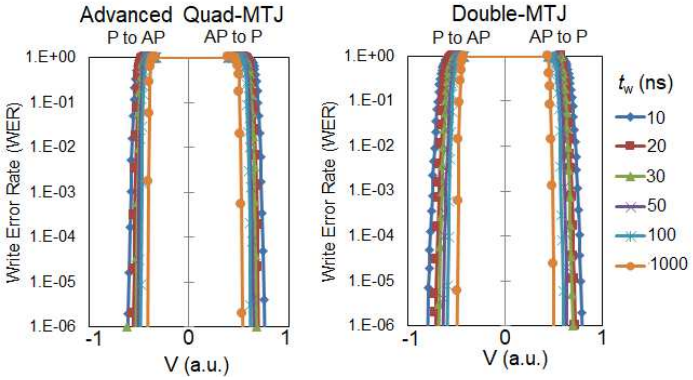

Fig. 7 Write pulse width (t_W) dependence of write error rate (WER) at different write voltage for the advanced 18 nm Quad- and Double-MTJs.

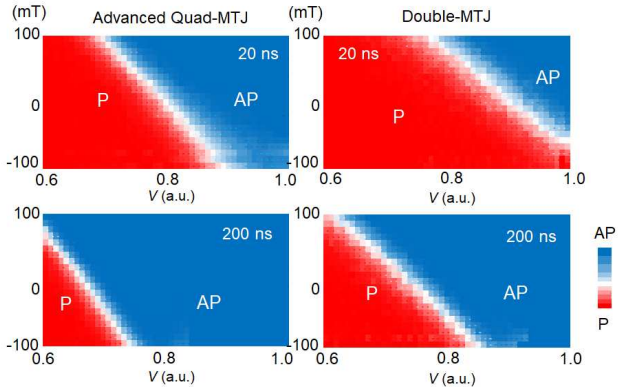

Fig. 8 Switching phase diagram (SPD) as a function of external field (H_{ext}) and bias voltage (V) for the advanced 18 nm Quad-MTJ and Double-MTJs. Switching direction of SPD measurement is P to AP.

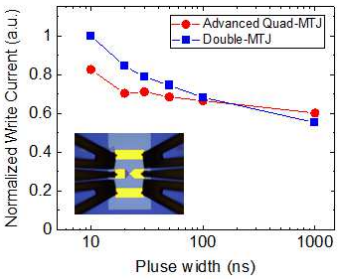

Fig. 9 Write pulse width (t_W) dependence of critical writing current (I_C) for the advanced 18 nm Quad- and Double-MTJs deduced from WER (Fig. 7). The high-speed measurement was carried out by using co-planar waveguide shown in inset.

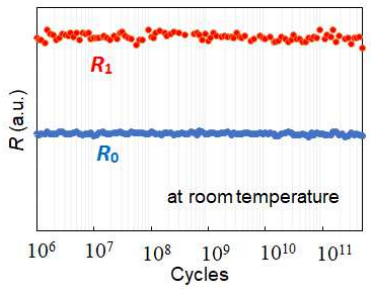

Fig. 10 Endurance of the advanced 18 nm Quad-MTJ. Although the Quad-MTJ enhances Δ, its endurance exceeds at least 6×10^{11} owing to the low *RA* MgO layers and low α_{eff}.

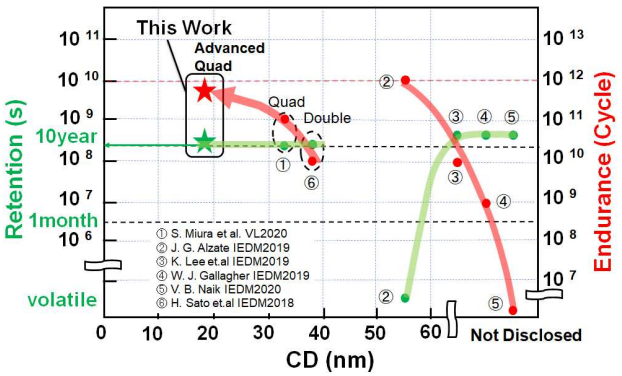

Fig.11 The retention and endurance *vs.* CD. Scaling-down makes the dilemma of retention and endurance more severe. The advanced Quad-MTJ enable us to realized overcome the dilemma issue beyond 2X nm.