WRITE ERROR RATE OF VOLTAGE-DRIVEN MAGNETIZATION SWITCHING IN PERPENDICULARLY-MAGNETIZED MAGNETIC TUNNEL JUNCTIONS

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I. INTRODUCTION

Voltage-controlled magnetic anisotropy (VCMA) in ferromagnetic metal thin films [1] has attracted much attention from both physical and practical points of view, and that has provided a playground for designing a variety of experiments and devices. In particular, the demonstration of magnetization switching in magnetic tunnel junctions (MTJs) by applying sub-nanosecond voltage pulses [2] has opened a new way of developing ultralow-energy-consumption magnetic random access memories (MRAMs), the so-called voltage-torque MRAMs. In the voltage-torque MRAMs, the information is stored in magnetic "free" layers and the writing process is proceeded using precessional dynamics of magnetization induced by VCMA effect. As the amplitude of the voltage required to switch the magnetization is determined by the balance between the VCMA effect and the uniaxial magnetic anisotropy constant (K_u) of free layer, it is very important to realize a large VCMA effect as well as a large K_u in order to minimize the energy consumption while securing an enough thermal stability.

In addition to a large VCMA effect and a large K_u, there is a growing need for improving the writing error rate (WER). In contrast to spin-transfer-torque MRAMs in which the switching direction is determined by the polarity of dc current, the magnetization switching in voltage-torque MRAMs is currently only possible for one voltage polarity, and the WER is sensitive to the duration time of voltage pulse (τ_{pulse}). Recently, we evaluated WER in perpendicularly-magnetized MTJs (p-MTJs) consisting of an MgO/$Fe_{80}B_{20}$/W stacking structure [3]. The WER of the p-MTJs indeed showed a strong dependence on τ_{pulse}, and a minimum WER of ~ 4 × 10^{-3} was achieved at τ_{pulse} corresponding to half the period of magnetization precession. This WER is, however, not sufficient for most of the practical use.

According to the simulation based on a macrospin model in Ref [3], the WER can further be reduced by improving the thermal stability factor and the VCMA effect in the free layer. In this study, we perform a systematic investigation using Ta/$(Co_xFe_{100-x})_{80}B_{20}$/MgO stacking structures. By varying the Co-Fe composition ratio in $(Co_xFe_{100-x})_{80}B_{20}$, we study the dependence of alloy composition and annealing temperature on magnetic properties and VCMA effect in order to gain guidelines to improve the WER. We also study an influence of the change in pulse shape, such as differences in rise and fall time, on the WER.

II. EXPERIMENTAL PROCEDURES

Figure 1 schematically illustrates the p-MTJ along with the measurement circuit used for the evaluation of WER. The p-MTJ consists of a Ta (5 nm)/$(Co_xFe_{100-x})_{80}B_{20}$ (1.1 or 1.2 nm)/MgO (1.4 nm) free layer and a 1.4-nm-thick $(Co_{10}Fe_{90})_{80}B_{20}$ reference layer whose magnetization direction is fixed by a [Co/Pt]-based perpendicularly-magnetized synthetic antiferromagnetic layer. Thin films were prepared on a chemical-mechanical-polished Si substrate with bottom electrode using a sputtering system (Canon ANELVA EC7800) at room temperature. The Fe-Co composition ratio was controlled by co-sputtering an $Fe_{80}B_{20}$ and a $Co_{80}B_{20}$ alloy targets. After an ex-situ annealing, the prepared films were microfabricated into the device structure by combining electron-beam lithography, photolithography, and Ar-ion etching. In order to evaluate WER, the p-MTJ was connected to a pulse generator via a microwave probe and voltage

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pulses were applied through the rf port of bias tee, whereas the resistance change associated with the magnetization switching was monitored by an oscilloscope. All the measurements were performed at room temperature.

III. EXPERIMENTAL RESULTS

As expected from the Slater-Pauling behavior, $(Co_{31}Fe_{69})_{80}B_{20}$ films showed the largest saturation magnetization among the prepared films. Moreover, the largest PMA and the VCMA effect were obtained for $(Co_{31}Fe_{69})_{80}B_{20}$. Owing to the large PMA and thereby the improved thermal stability, at an optimum condition, the p-MTJ with Ta/$(Co_{31}Fe_{69})_{80}B_{20}$ (1.1 nm)/MgO exhibited a minimum WER of 2×10^{-5}, which is two orders of magnitude lower than that obtained for those using MgO/$Fe_{80}B_{20}$/W [3].

Then, we will discuss the influence of the change in pulse shape on WER. Figure 2 displays the minimum WER obtained with changing the slope of voltage pulse, where hollow (filled) symbols correspond to the dependence of WER on the rise (fall) time, $\tau_{\mathrm{rise\ (fall)}}$. It can be seen that WER almost monotonically increases with τ_{rise}. However, interestingly, a slight increase of τ_{fall} exhibits clear improvement in WER under optimal condition. For τ_{fall} = 0.156 ns the WER became about half the value of that for τ_{fall} = 0 ns. This experimental result would be useful to design the device assembly.

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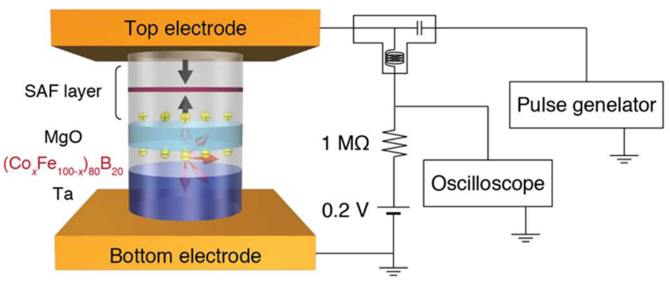

Fig. 1: Schematic illustration of the device structure along with the measurement circuit used for the evaluation of WER.

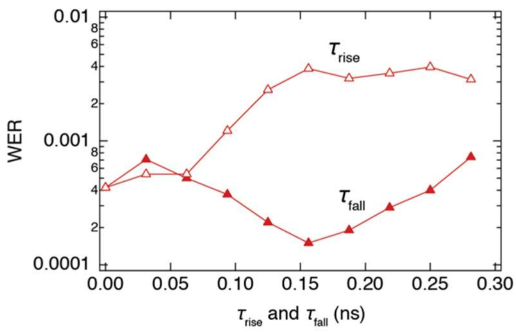

Fig. 2: WER as a function of τ_{rise} and τ_{fall}. Hollow and filled symbols correspond to the dependence of WER on τ_{rise} and τ_{fall}, respectively.