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SPECIFIC NONLINEARITY OF VOLTAGE CONTROLLED MAGNETIC ANISOTROPY IN Fe/MgO LAYERED STRUCTURES

Qingyi XIANG[1], Zhenchao WEN[2], Hiroaki SUKEGAWA[3], Shinya KASAI[3], Takeshi SEKI[4], Takahide KUBOTA[4], Koki TAKANASHI[4] and Seiji MITANI[1]

1) Graduate School of Pure and Applied Sciences, University of Tsukuba & National Institute for Materials Science (NIMS), Tsukuba 305-0047, Japan

2) Center for Spintronics Research Network (CSRN), Tohoku University, Sendai 980-8577, Japan

3) NIMS, Tsukuba 305-0047, Japan

4) Institute for Materials Research & CSRN, Tohoku University, Sendai 980-8577, Japan

XIANG.Qingyi@nims.go.jp

I. INTRODUCTION

Voltage-controlled magnetic anisotropy (VCMA) in a ferromagnetic metal layer attracts a lot of interest in recent years. This technology can help to realize low-power manipulation of spin, which is a key technique for next generation magnetization random access memories (MRAMs). It used to be considered impractical since the insulator barrier layer in a typical magnetic tunnel junction (MTJ) makes the electric field penetrate only into the metal in a limited range, namely, only near the interface. However, recently it has been achieved to realize VCMA effect in an ultrathin Fe layer based all-solid-stat devices [1]. This led to an approach to develop voltage controlled MRAM, via direct manipulation by voltage or assistance to spin-transfer toque. More recently, a large VCMA effect over 200 fJ/Vm has been demonstrated in Fe/MgO structures [2].

The magnitude of perpendicular magnetic anisotropy (PMA) is also a key factor to provide a high memory density and better thermal stability. It was predicted a large PMA can be realized in Fe/MgO structure, and a large PMA around 1.4 MJ/m^3 was reported in a previous work [3]. The mechanisms of PMA and VCMA are somehow different, but both strongly depend on the metal/oxide interface conditions. Considering the Fe/MgO case, hybridization between Fe-3d and O-2p orbitals appears to play a key factor to realize large PMA, meanwhile the spin-dependent screening may also affect the electronic occupancy of 3d orbitals.

In this work, we investigated PMA and VCMA with different annealing conditions, to explore how these two effects interplay with each other. The PMA in this work is roughly 1 MJ/m^3 and the VCMA is as large as 266 fJ/Vm, i.e., both are comparable to the previous works.

II. EXPERIMENT METHOD

A fully epitaxial stack of MgO (5 nm)/Cr (30 nm)/Fe (0.7 nm)/MgO (2.2 nm)/Fe (2 nm)/Ru (15 nm) was deposited on a MgO (100) substrate by molecular beam epitaxy. The substrate was annealed at 800°C for cleaning, followed by depositing a 5-nm-thick MgO at 450°C as a seed layer. The Cr buffer layer was deposited at 150°C, and then a 800°C annealing process was performed to get a flat surface. The ultrathin Fe was grown at the 150°C and post-annealed at 250°C to increase the surface flatness. Then the barrier MgO layer was deposited at 150°C. After the deposition of MgO layer, further annealing was performed at different temperatures of 325°C, 350°C, 375°C, and 400°C to obtain interface PMA at the Fe/MgO with different interface conditions. Subsequently, the in-plane-magnetized reference Fe layer was deposited at 150°C without annealing. Finally, a Ru layer was sputter-deposited at room temperature for capping. The samples were fabricated into $5 \times 10\mu\text{m}$ ellipses by photo-lithography, ion-beam milling and lift-off process. The tunnel magnetoresistance (TMR) ratio was measured using physical property measurement system (PPMS) under an in-plane external field at RT and low temperatures.

III. RESULT AND DISCUSSION

Fig. 1(a) shows a TMR curve for the Fe/MgO MTJ with a 90˚ magnetization configuration. When applying an external field, the magnetization of the top Fe is saturated immediately, and then the resistance

Qingyi Xiang
E-mail: XIANG.Qingyi@nims.go.jp
tel: +81-08091735207

of the junction changes as a function of the relative angel of magnetizations of the bottom Fe and top Fe. Thus, we can write the in-plane magnetization component of the bottom Fe as follows:

$$\frac{M_{in-plane}}{M_s} = \cos\theta = \frac{R_{90}-R(\theta)}{R(\theta)}\frac{R_p}{R_{90}-R_p} \tag{1}$$

Then we can analyze how the perpendicular anisotropy changes depending on the annealing temperatures and different bias voltages. As shown in Fig.1 (b), the different annealing temperatures caused different PMA energy densities. The sample annealed at 350°C has the largest PMA energy density.

Fig. 2 shows the PMA energy density ($K_{eff}t_{Fe}$) as a function of an applied electric field. Large VCMA behavior was obtained, and it took a maximum of 266 fJ/Vm for the post-annealing at 350˚C. More interestingly, despite the difference in annealing temperature, all the VCMA curves show similar non-linear behavior in which there exists a local minimum around 100 mV/nm. Furthermore, it was confirmed that the local minimum around 100 mV/nm appears, being independent of measurement temperature, while the PMA energy densities clearly increase with decreasing temperature (not shown). The local minimum appears to be the VCMA behavior specific to Fe/MgO, which can be experimental evidence for the electronic origin of VCMA phenomena.

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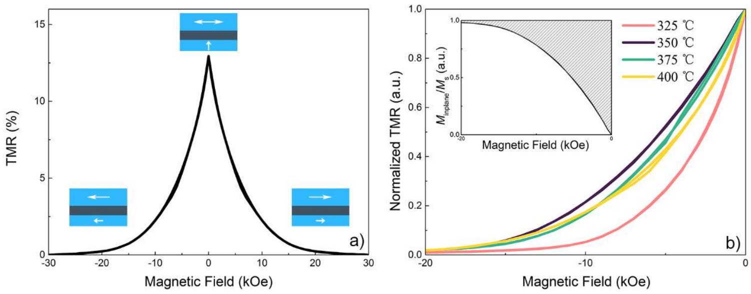

Fig. 1 (a) Typical full TMR curve for a sample annealed at 400°C, (b) normalized TMR curves for different annealing temperatures. The inset is the in-plane component of magnetization where the shadow area represents the PMA energy density.

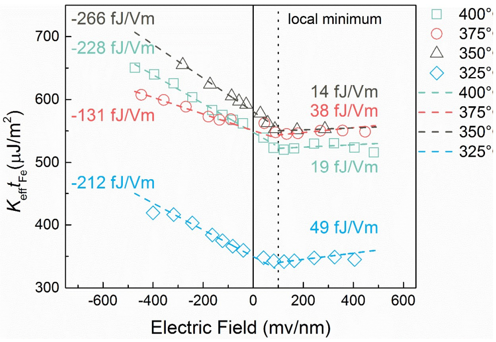

Fig.2 VCMA curves under different annealing temperatures, the dashed line is the linear fitting. A local minimum around 100 mV/nm can be clearly found for different annealing temperatures.