Perpendicular magnetic anisotropy at $Fe/MgAl_2O_4$ interfaces and its voltage effect

Q. Xiang[1, 2], ○H. Sukegawa[1], M. Al-Mahdawi[1], M. Belmoubarik[1], Y. Sakuraba[1], S. Kasai[1], K. Hono[1, 2], S. Mitani[1, 2]
([1]NIMS, [2]Univ. of Tsukuba)

Voltage-controlled magnetic anisotropy (VCMA) [1] in magnetic heterostructures is expected as a key technology for achieving low-power consumption spintronic devices such as voltage-torque magnetoresistive random access memories (MRAMs). However, increase of both the interface perpendicular magnetic anisotropy (PMA) energy (K_i) and the VCMA coefficient (β), i.e., K_i > 2–3 mJ/m^2 and β > 1000 fJ/(Vm), is necessary for high density memory applications. In order to achieve such a giant VCMA effect, exploring the origin of the VCMA effect using "standard PMA heterostructures" without any interfacial defects can be indispensable. Recently, large PMA energies were reported in lattice-matched $Fe/MgAl_2O_4$ [2] and $Co_2FeAl/MgAl_2O_4$ heterostructures [3]. Therefore, we focused in this study on ultrathin $Fe/MgAl_2O_4(001)$ epitaxial interfaces to achieve high K_i and β using an electron-beam evaporation technique. Especially, we precisely investigated the Fe thickness dependence using $Fe/MgAl_2O_4/CoFeB$ orthogonally magnetized MTJs. We report that only a monolayer thickness difference has a significant impact on the PMA energy and VCMA effect.

MTJ stacks of Cr buffer (30)/Fe (t_{Fe} = 0.70, 0.84, 1.0 = 5, 6, 7 monolayers (MLs))/$MgAl_2O_4$ (2)/$Co_{20}Fe_{60}B_{20}$ (5)/Ru (10) (unit in nm) were prepared on an MgO(001) substrate by electron-beam evaporation. The top 5-nm CoFeB is the reference layer with in-plane magnetization for evaluating the VCMA effect of the bottom Fe. The Cr, Fe, $MgAl_2O_4$, and CoFeB layers were post-annealed to improve their crystallinity and flatness. Magnetic properties were investigated using a vibrating sample magnetometer-superconducting quantum interference device. After microfabrication (10 μm scale), magnetotransport properties of MTJs were characterized by a physical property measurement system at room temperature. The positive bias was defined with respect to CoFeB (electron tunneling from the lower to upper electrode).

Figure 1 shows the typical in-plane magnetization curves for the MTJ stacks with different Fe thicknesses. It was found that the 5- and 6-ML Fe layers had perpendicular magnetization. Arial PMA energy density E_{pma} (PMA energy density K_{eff} [unit in J/m^3] × t_{Fe}) for the 5-ML (6-ML) Fe sample was determined to be 0.85 mJ/m^2 (0.77 mJ/m^2). We investigated the bias voltage dependence of E_{pma} for the 5- and 6-ML Fe samples using normalized tunnel magnetoresistance ratios as functions of both bias voltage and in-plane magnetic field. As clearly seen in Fig. 2, E_{pma} values for both the samples show complicated bias voltage dependence. Importantly, the E_{pma} curve shape significantly depends on the Fe thickness; a local minimum appears near +0.2 V for the 5-ML Fe sample, whereas a peak appears at the zero-bias voltage for the 6-ML one. We found that the complicated VCMA effect was associated with the formation of quantum well states [4] for the Δ_1 states in the ultrathin Fe layers between Cr and $MgAl_2O_4$. This work was partly supported by the ImPACT Program of Council for Science, Technology and Innovation, Japan, and JSPS KAKENHI Grant No. 16H06332.

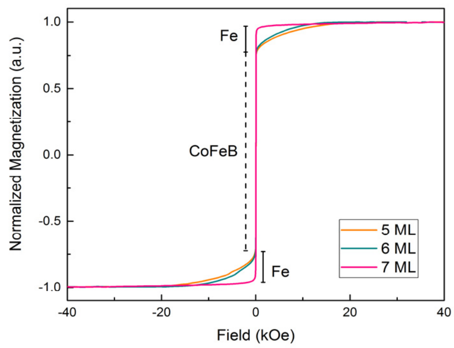

Fig. 1. Magnetizations as a function of in-plane magnetic fields for ultrathin-$Fe/MgAl_2O_4/CoFeB$ MTJs with 5-7 ML thick Fe.

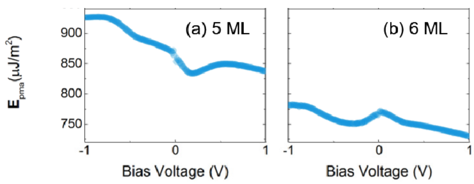

Fig. 2. Bias voltage dependences of $E_{pma} = K_{eff} \times t_{Fe}$ for (a) 5-ML and (b) 6-ML Fe sample.

References
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