I. INTRODUCTION

A magnetoresistive random access memory (MRAM) is expected to realize the ultra-low stand-by power of future computing system using a non-volatile feature of magnetism. However, one of crucial technical challenges is the reduction in operation power, because the magnetization control using electric-current consumes high energy due to Ohmic dissipation. To overcome this fundamental issue, the development of electric-field manipulation of magnetism is strongly demanded. The voltage-controlled magnetic anisotropy (VCMA) effect in an ultrathin ferromagnetic metal layer [1,2] is one of the most promising and practical approaches, because it can be applied in an MgO-based magnetic tunnel junction (MTJ) with high-speed response [3,4]. An important remaining issue of the VCMA effect is to enhance its efficiency to demonstrate the scalability. For example, for giga-bit class memory applications, VCMA coefficient of more than a few hundreds or even 1000 fJ/Vm is required [5,6]. However, the VCMA effect with high speed response is limited to be 100 fJ/Vm at present. In this talk, we’ll introduce recent progresses in the materials research for the large VCMA effect and in the voltage-induced dynamic magnetization switching, and also discuss future prospects and challenges for the realization of voltage-torque MRAM.

II. EXPERIMENTAL RESULTS

To investigate the VCMA effect in a high-quality ultrathin ferromagnetic metal layer, we prepared fully-epitaxial MTJs consisting of MgO seed (3 nm)/Cr buffer (30 nm)/Fe-based ultrathin ferromagnetic metal layer (t < 1 nm)/MgO (2.3 nm)/Fe(10 nm)/Ta(5 nm)/Ru(7 nm). The bottom ultrathin Fe-based layer is the perpendicularly magnetized free layer, whose perpendicular magnetic anisotropy (PMA) can be controlled by voltage application. The top 10 nm-thick Fe is the in-plane magnetized reference layer. Tunneling magnetoresistance (TMR) curves were measured under in-plane magnetic fields and various bias voltage applications. The polarity of the bias voltage was defined relative to the top Fe layer. Two ferromagnetic layers takes orthogonal magnetization
configuration under zero magnetic field. An application of in-plane magnetic field tilts the magnetization of the free layer in the in-plane direction and its behavior can be observed as a gradual decrease of tunneling resistance. Figure 1 (a) shows the bias voltage dependence of normalized TMR curves for the MTJ with the free layer of \( t = 0.82 \) nm. Voltage applications cause clear shift in saturation field, suggesting the voltage-induced PMA change. Effective PMA energy density, \( K_{\text{eff}} \) (J/m\(^3\)) was evaluated from tunneling conductance curves with saturation magnetization value under each bias condition. Figure 1(b) summarizes applied electric-field dependence of the \( K_{\text{eff}} \). Large VCMA coefficient of 320 fJ/Vm was observed under the positive electric-field applications. This value satisfies the required specifications for ultra-large last-level cache voltage-torque MRAM.

In the presentation, we’ll also introduce the evaluation of write error rate (WER) of precessional magnetization switching induced by VCMA effect [7] and discuss future strategy to achieve the practical low WER value for memory applications.

![Graphs showing bias voltage dependence of normalized TMR curves and applied electric-field dependence of perpendicular magnetic anisotropy energy](image)

Fig. 1 (a) bias voltage dependence of normalized TMR curves for the voltage-driven MTJ and (b) Applied electric-field dependence of perpendicular magnetic anisotropy energy, \( K_{\text{eff}} t \).

IV. ACKNOWLEDGEMENT

This work was supported by ImPACT Program of Council for Science, Technology and Innovation, and a Grand-in-Aid for Scientific Research (No. 26709046).

REFERENCES