Evaluation of energy barrier of CoFeB/MgO magnetic tunnel junctions with perpendicular easy axis using retention time measurement

E. C. I. Enobia1, H. Sato1-4, S. Fukami1-4, and H. Ohno1-5

1Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai, Miyagi, 980-8577 Japan
Phone: +81-22-217-5555 E-mail: hsato@riec.tohoku.ac.jp
2Center for Spintronics Research Network, Tohoku University 2-1-1, Katahira, Aoba-ku, Sendai, Miyagi, 980-8577 Japan
3Center for Spintronics Integrated Systems, Tohoku University 2-1-1, Katahira, Aoba-ku, Sendai, Miyagi, 980-8577 Japan
4Center for Innovative Integrated Electronic Systems, Tohoku University 468-1, Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi, 980-0845 Japan
5WPI-Advanced Institute for Materials Research, Tohoku University 2-1-1, Katahira, Aoba-ku, Sendai, Miyagi, 980-8577 Japan

Abstract

We investigate the energy barrier that determines thermal stability factor of CoFeB/MgO magnetic tunnel junctions with perpendicular easy axis using retention time measurements as functions of temperature T and junction diameter D. The energy barrier reduces with increasing T independent of D. The temperature at which any particular value of the energy barrier is obtained tends to decrease with decreasing D. The results indicate that the studied MTJs are dominated by reversal modes other than the nucleation model.

1. Introduction

Magnetic tunnel junctions (MTJs) are intensively developed in the recent years for non-volatile memory applications. The energy barrier E which determines thermal stability factor \( \Delta = E/k_BT \) where \( k_B \) the Boltzmann constant and T the absolute temperature) is one of the important metrics characterizing MTJs, because \( \Delta \) determines retention time of stored information. In general, for evaluation of \( E \) (\( \Delta \)), switching probability is measured as a function of magnitude of either applied magnetic field or current [1-3]. However, the determined \( E \) in this way is dependent on reversal model employed for analysis [4-7]. In contrast, one can determine \( E \) by retention time measurements independent of reversal model. In this study, we investigate energy barrier of CoFeB/MgO MTJs with the perpendicular easy axis using retention time measurement as functions of junction diameter and temperature.

2. Experimental procedures

A stack structure, from substrate side, Ta(5)/Pt(5)/(Co(0.4)/Pt(0.4))/Co(0.4)/Ru(0.4)/(Co(0.4)/Pt(0.4))/Co(0.4)/Ru(0.4)/Co(0.4)/Ru(0.4)/(Co(0.4)/Pt(0.4))/CoFeB(1.0)/MgO/CoFeB(1.5)/Ta(5)/Ru(5) is deposited on thermally oxidized Si substrate using dc/rf magnetron sputtering. The numbers in parentheses are nominal thickness in nm. A 1.5 nm-thick CoFeB layer on MgO is the free layer which has perpendicular easy axis thanks to interfacial anisotropy at CoFeB/MgO interface [8]. The stack is processed into circular MTJs with diameter \( D \).

3. Results

In Fig. 1(a), we show setup for measurement of retention time. A typical voltage waveform taken from magnetic tunnel junction with diameter of 63 nm at temperature of 473 K. An out-of-plane magnetic field \( \mu_0H = 13 \text{ mT} \) (\( \mu_0 \) is permeability in free space) is applied in the measurement.

varied from 32 to 66 nm using electron beam lithography, reactive ion etching, and Ar ion milling. MTJs are annealed at 300°C for 1 hour under out-of-plane magnetic field of 0.4 T. A resistance-area product \( R_D \) is about 11 \( \Omega \mu \text{m}^2 \). The values of \( R_D \) and \( D \) are determined by the same method used in our previous study [9].

Fig. 1 (a) A setup for measurement of retention time. (b) A typical voltage waveform taken from magnetic tunnel junction with diameter of 63 nm at temperature of 473 K. An out-of-plane magnetic field \( \mu_0H = 13 \text{ mT} \) (\( \mu_0 \) is permeability in free space) is applied in the measurement.

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Fig. 2 (a) Natural logarithm plot of number of events as a function of retention time for magnetic tunnel junction (MTJ) with diameter of 63 nm at temperature $T = 473$ K. (b) Time constant of magnetization reversal for parallel (P) and anti-parallel (AP) states $\tau_{P,\text{AP}}$ as a function of $T$. (c) Thermal stability factor at P and AP states $D_{P,\text{AP}}$ as a function of $T$.

![Temperature dependence of energy barrier for magnetic tunnel junctions](image)

Fig. 3 Temperature dependence of energy barrier for magnetic tunnel junctions with various diameters $D$.

used in Fig. 1(b). Based on Arrhenius-Neel law, one can fit a linear function to the results shown as solid line in Fig. 2(a), and the slope of the linear fit corresponds to inverse of time-constant $\tau$ for magnetization reversal [10]. Figure 2(b) shows temperature dependence of the time-constant magnetization reversal for P and AP states $\tau_{P,\text{AP}}$ where subscripts denote magnetization states. We then obtain thermal stability factor $D_{P,\text{AP}}$ at P and AP states using the following equation $D_{P,\text{AP}} = \tau \exp(D_{P,\text{AP}})$. Figure 2(c) shows the temperature dependence of $\Delta E$, $\Delta D_{P,\text{AP}}$, and their average. We obtain almost the same values; therefore, we focus on the temperature dependence of average thermal stability factor $\Delta = (\Delta E + \Delta D_{P,\text{AP}})/2$.

Figure 3 shows temperature dependence of energy barrier $E$ in $\Delta = E/k_B T$ for MTJ with various diameters. As can be seen, in all the MTJs, $E$ reduces with increasing $T$. Although there is some scatter, the temperature at which any particular value of $E$ is obtained tends to decrease with decreasing $D$. Based on the nucleation-type reversal model, the energy barrier is independent of junction diameter [11,12]. Hence, the observed temperature dependence of energy barrier indicates that the MTJs studied here are dominated by other reversal models such as coherent reversal or domain wall propagation models than nucleation model.

4. Conclusions

We investigate the energy barrier of CoFeB-MgO MTJs with perpendicular easy axis using retention time measurement as functions of junction diameter and temperature. The energy barrier decreases with increasing temperature in all the MTJs with various diameters. The temperature at which any particular value of the energy barrier is obtained tends to decrease with decreasing junction diameter, indicating that the switching of the studied MTJs is dominated by reversal modes such as domain wall propagation or coherent magnetization reversal rather than the nucleation model.

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References