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

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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 models 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 Δ (= $E/k_B T$ where k_B the Boltzmann constant and T the absolute temperature) is one of the important metrics characterizing MTJs, because Δ determines retention time of stored information. In general, for evaluation of E (Δ), 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)]$_6$/Co(0.4)/Ru(0.4)/[Co(0.4)/Pt(0.4)]$_2$/Co(0.4)/Ta(0.3)/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

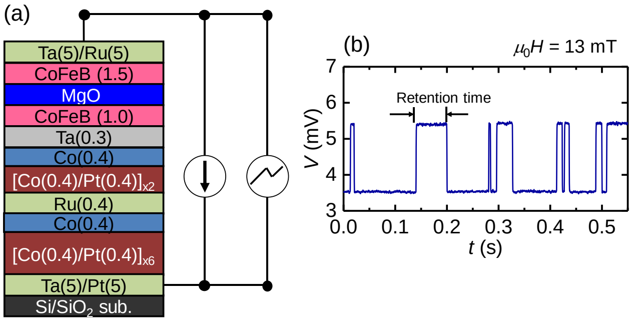

Fig. 1 (a) A setup for measurement of retention time. (b) A typical voltage waveform taken from magnetic tunnel junction with diameter of 63 nm at temperature of 473 K. An out-of-plane magnetic field $\mu_0 H$ = 13 mT (μ_0 is permeability in free space) is applied in the measurement.

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 RA is about 11 Ωμm^2. The values of RA and D are determined by the same method used in our previous study [9].

3. Results

In Fig. 1(a), we show setup for measurement of retention time. A dc current flows to MTJs from dc current source, and a resistance R of MTJ is measured by voltage measured by oscilloscope. Figure 1(b) shows typical voltage waveform taken from MTJ with D = 63 nm at T = 473 K, in which we apply out-of-plane field of 13 mT to compensate a magnetic field from the reference layer acting on the free layer. The transition from parallel (P) to anti-parallel (AP) states and vice-versa can be clearly observed, from which the retention time at P and AP states is determined. We collect the retention time about 1000-10000 times at various temperatures for each MTJ. It should be noted that we increase the temperature such that we can see the transition of the magnetization state within a few seconds.

Figure 2(a) shows natural logarithm plot of number of events as a function of the retention time for the same MTJ

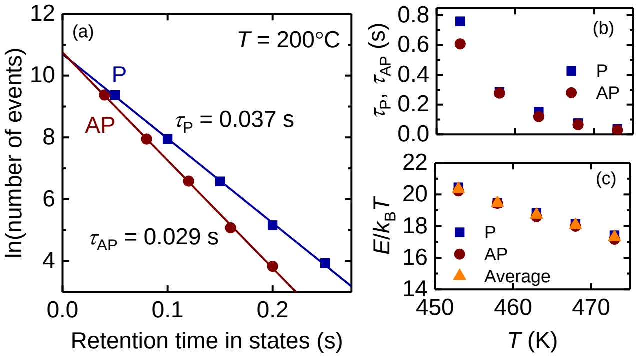

Fig. 2 (a) Natural logarithm plot of number of events as a function of retention time for magnetic tunnel junction (MTJ) with diameter of 63 nm at temperature $T = 473$ K. (b) Time constant of magnetization reversal for parallel (P) and anti-parallel (AP) states $\tau_{P(AP)}$ as a function of T. (c)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

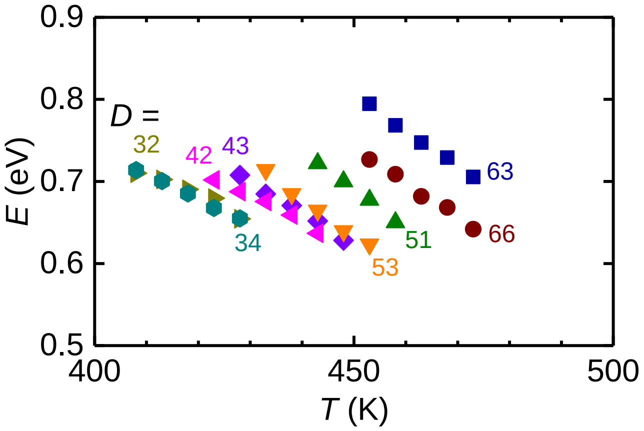

Fig. 3 Temperature dependence of energy barrier for magnetic tunnel junctions with various diameters D.

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 τ for magnetization reversal [10]. Figure 2(b) shows temperature dependence of the time-constant magnetization reversal for P and AP states $\tau_{P(AP)}$ where subscripts denote magnetization states. We then obtain thermal stability factor $\Delta_{P(AP)}$ at P and AP states using the following equation $\tau_{P(AP)} = \tau_0 \exp(\Delta_{P(AP)})$. Figure 2(c) shows the temperature dependence of Δ_P, Δ_{AP}, and their average. We obtain almost the same values; therefore, we focus on the temperature dependence of average thermal stability factor $\Delta = (\Delta_P + \Delta_{AP})/2$.

Figure 3 shows temperature dependence of energy barrier E in $\Delta = E/k_BT$ 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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