Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp329-330

G-3-03

Magnetic field angle dependence of switching field in CoFeB-MgO magnetic tunnel junctions with perpendicular easy axis at low temperature

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Abstract

We investigate magnetic field angle dependence of switching field in CoFeB-MgO magnetic tunnel junctions (MTJs) with recording layer diameter of ~20 nm at a temperature *T* of 5 K. We observe single domain reversal like behavior in the MTJ with a structure where no large inhomogeneous magnetic field from the reference layer acts on the recording layer. In contrast, the MTJ with a structure where an inhomogeneous magnetic field acts on the recording layer shows similar behavior to that expected from domain wall propagation model. The results indicate that the magnetic field from the reference layer plays an important role in determining magnetization reversal mode.

1. Introduction

Understanding of magnetization reversal modes is critical for applications using nano-scale ferromagnets with perpendicular easy axis. This is because, in the applications such as magnetic tunnel junctions (MTJs) and patterned media, it is required to understand the magnetization reversal mode to properly evaluate thermal stability factor Δ which is one of the major indices characterizing their properties [1-5].

The magnetic tunnel junctions currently studied have a junction diameter of less than 20 nm [6-8]. In such small dimensions, it is expected that single domain magnetization reversal takes place. However, it is not obvious that the single domain reversal takes place in the MTJs even at such small dimensions, because an inhomogeneous magnetic field from reference layer acts on the recording layer in the MTJs, which may give rise to incoherent reversal.

In this study, to elucidate the magnetization reversal mode of the MTJ at the reduced dimensions, we investigate magnetic field angle dependence of switching field in the MTJs with the recording layer diameter D of ~ 20 nm.

2. Experimental

The stack structure of the MTJs is, from substrate side, Ta (5)/Pt(5)/[Co(0.34)/Pt(0.4)]$_6$/Co(0.34)/Ru(0.44)/Co(0.34)/[Pt(0.4)/Co(0.34)]$_2$/Ta(0.3)/$Co_{18.75}Fe_{56.25}B_{25}$(1)/MgO(1.1)/$Co_{18.75}Fe_{56.25}B_{25}$(1.5)/Ta(5)/Ru(5). The numbers in parenthesis are the nominal thicknesses in nm. The composition of CoFeB is that of the sputtering target. The film stack is deposited onto a thermally oxidized Si substrate by dc/rf magnetron sputtering and subsequently processed into circular MTJs with D ~ 20 nm using electron beam lithography, reactive ion etching, and Ar ion milling. The fabricated MTJs are annealed at 300°C for 1 h in vacuum under the out-of-plane magnetic field of 0.4 T. The product of resistance in the parallel state and the recording layer area is ~11 Ωμm^2. In this study, we fabricate two types of the MTJ to study the influence of the magnetic field from the reference layer on the magnetization reversal mode. Schematics of the two structures are shown in Fig. 1. One has smaller recording layer size than reference layer size (called step structure) [9], and the other has almost the same size in the recording and reference layers (normal structure). In the step structure, the magnetic field from the reference layer which acts on the recording layer is uniformly out-of-plane, whereas in the normal structure the recording layer is subjected to a non-uniform field from the reference layer with both in-plane and out-of-plane components..

For measurement of magnetic field angle θ_H dependence of switching field, we use a vector magnet equipped with cryostat on which the sample is placed. Resistance versus magnetic field curves (R-H curves) are measured at various θ_H where θ_H is measured from film normal direction. The measurement is done at temperature T of 5 K to minimize the influence of thermal fluctuation on the magnetization reversal.

3. Results

Figures 2 (a) and (b) show the R-H curves of the MTJ with

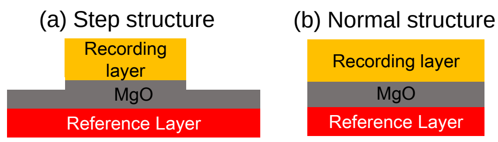

Fig. 1 Schematic of the magnetic tunnel junction structure. (a) step structure and (b) normal structure.

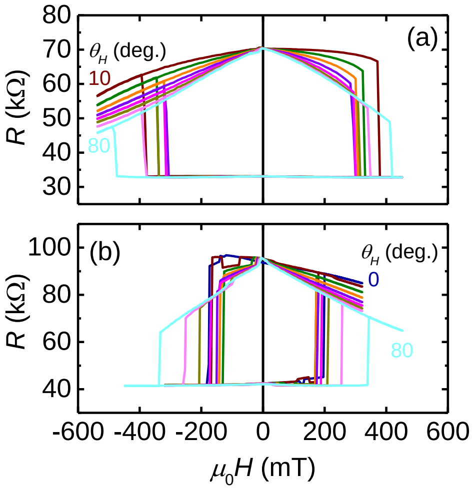

Fig. 2 Resistance vs. magnetic field curves (*R-H* curves) of the magnetic tunnel junction (a) with step structure (the recording layer diameter = 20 nm), and (b) normal structure (the recording layer diameter = 19 nm). The *R-H* curves are measured at 5 K and at various magnetic field angles θ_H.

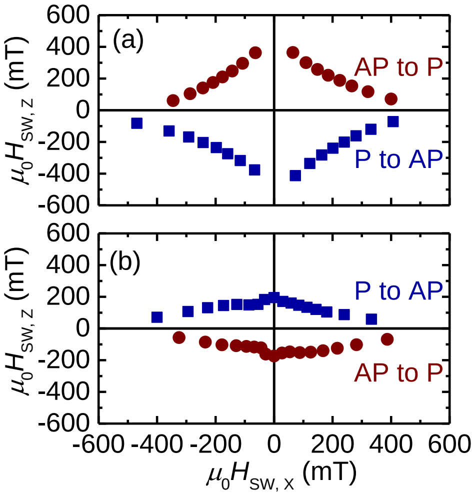

Fig. 3 Out-of-plane (Z) component versus in-plane one (X) of switching field for the magnetic tunnel junction with (a) the step structure and (b) the normal structure. The measurement is done at 5 K.

the step structure (D = 20 nm) and the normal structure (D = 19 nm). One can see that the *R-H* curves show asymmetry with respect to $H = 0$, which is attributed to the difference of magnetization angle in the reference layer between the positive and negative H. In addition, the reduction of R at AP state with increase of H which becomes more significant as the θ_H increases is due to the difference of relative magnetization angle between the recording and reference layers. There are some resistance jumps in addition to the main switching in the normal structure, which may be associated with formation of multiple domains.

From the *R-H* curves, we determine the H_{SW} from parallel (P) to antiparallel (AP) and AP to P. To understand the magnetization reversal mode, we plot Z component of H_{SW} ($H_{SW,Z}$) against X component of H_{SW} ($H_{SW,X}$) where Z is defined as film normal direction (*i.e.* $\theta_H = 0$), and X is orthogonal to Z. The $H_{SW,Z}$ and $H_{SW,X}$ are calculated according to the following equations;

$$H_{SW,X} = H_{SW}\sin(\theta_H),\ H_{SW,Z} = H_{SW}\cos(\theta_H).$$

Figures 3(a) and (b) show the relationship between $H_{SW,Z}$ and $H_{SW,X}$ for the MTJ with the step structure and the normal structure, respectively. The MTJ with the step structure follows the trend expected from single domain magnetization reversal (the so called astroid curve). Note the small shift of the diagram along the vertical direction, which we attribute to the uncompensated magnetic field from the reference layer along the film normal direction. In contrast, the MTJ with the normal structure shows different behavior, closer to that expected from domain wall propagation model rather than single domain reversal. This result is in accordance with the formation of multiple domains suggested from the *R-H* curves shown in Fig. 1(b). The results observed in this study indicate that the magnetic field from the reference layer plays an important role in determining magnetization reversal mode.

4. Conclusions

We evaluate magnetic field angle dependence of the switching field at 5 K for the MTJs with the recording layer diameter of ~20 nm. From the diagram plotting Z component versus X component of the switching field, the MTJ with the step structure, in which a homogeneous out-of-plane magnetic field from the reference layer acts on the recording layer, follows the trend expected from the single domain reversal model. In contrast, the MTJ with normal structure where the reference layer acts on the recording layer with inhomogeneous out-of-plane and in-plane fields shows different behavior, close to that expected from the domain wall propagation model. The present results reveal that the magnetic field from the reference layer plays an important role in determining the magnetization reversal mode.

Acknowledgements

This work was supported by R&D Project for ICT Key Technology to Realize Future Society of MEXT, ImPACT Program of CSTI, and JSPS KAKENHI grant number 16K18084.

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