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A Study of Validation of an Evaluation Model of Accurate Thermal Stability Factor for MTJs Using Its Thermal Dependency

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Abstract

In this paper, we verified the validity of our proposed model of evaluating an accurate thermal stability factor Δ_0 using its temperature dependency for magnetic tunnel junction with perpendicular anisotropy (p-MTJ). In order to verify its validity, we compared the value of Δ_0 extrapolated by this model with accurate one with negligibly small current disturbance. By confirming that the both values corresponded, we revealed that the accurate Δ_0 can be evaluated with our proposed model. Moreover, we verified that its thermal dependency was proportional to the square of the saturation magnetization.

1. Introduction

Spin-transfer-torque magnetoresistance random access memory (STT-MRAM) using p-MTJs is one of the promising candidates for the future non-volatile embedded memory and its logic applications [1]. In order to guarantee data retention of STT-MRAM, a method of evaluating accurate Δ_0 is indispensable. However, accurate evaluation method of Δ_0 for one target MTJ has not been established yet. For example, Δ_0 is evaluated by iteratively applying current pulse [2]. However, it was shown that Δ_0 was underestimated by large current due to distortion of potential caused by current disturbance with short measurement time [3], [4]. This is a major disadvantage in industrial commercialization of STT-MRAM. Therefore we proposed a method of evaluating the accurate Δ_0 for one target MTJ using thermal disturbance in a short time [3]. However, there was an issue in our proposed method, such as the validity of an evaluation model represented by a following formula (1) which extrapolates Δ_0 at room temperature.

$$\Delta_0(T) = E_b(0)\,(1 - \alpha T^{3/2})^2 / k_B T \propto Ms^2(T) \qquad (1)$$

where $E_b(0)$ is the energy barrier between the two stable magnetization configuration at 0 K, k_B is Boltzman constant, T is absolute temperature, α is the material-dependent constant and $Ms(T)$ is the saturation magnetization.

2. Concept of the validation of our proposed model

The concept of validation of our model is shown in Fig. 1. We evaluate an accurate Δ_0 with negligibly small current disturbance due to large pulse duration as shown in Fig. 1(a). After that, we compare this accurate Δ_0 with the values extrapolated by our proposed method as shown in Fig. 1(b). Then if the both values correspond, we can validate the evaluation model in our proposed method. Table. I shows benchmarking table of these evaluation methods.

3. Results and discussion

Fig. 2 shows the measurement setup to evaluate Δ_0. A measured film was deposited onto Si substrate using DC and RF magnetron sputtering system at room temperature. In this study, we employed double CoFeB/MgO interfaces MTJ. The measured MTJ was consist of, from substrate side, bottom electrode/[Co/Pt] based reference layer/MgO/free layer/ MgO/ top electrode. The basic concept of the [Co/Pt] reference layer has been described elsewhere [5], [6]. Table. II shows the properties of a measured MTJ.

First, we evaluated the accurate Δ_0 with negligibly small current disturbance. Fig. 3 shows the switching probability as a function of applied current at 24, 50, 80°C. At each temperature, we evaluated one while changing the pulse duration to 5 ms, 50 μs, 5 μs. As shown in Fig. 3, the applied current decreases as the pulse duration increases. By using these values, we calculated $-\ln(-\tau_0/t\ \ln(1-P))$ vs. current as shown in Fig. 4 where τ_0 is the attempt time (~10^{-9} s), t is the pulse duration, P is the switching probability. In case of 24°C (50°C), the slope recovers due to negligibly small current disturbance using 5 ms (5 ms, 50 μs) current pulse. Therefore the accurate Δ_0 is evaluated under this condition as shown in Fig. 2(a). On the other hand, the slope is almost constant at 80°C. From this results, we plotted the Δ_0(5 μs or 50 μs, T) / Δ_0(5 ms, T) vs. average applied current $I_{ave} = (|I_{P\text{-}AP}|_{P=0.5}| + |I_{AP\text{-}P}|_{P=0.5}|)\ /\ 2$ as shown in Fig. 5 where $I_{P\text{-}AP(AP\text{-}P)}|_{P=0.5}$ denotes the current at switching probability = 0.5 from parallel (antiparallel) to antiparallel (parallel) magnetization configuration. The value of vertical axis is almost 1 when I_{ave} < 29 μA since the current disturbance is negligibly small. This indicates that the accurate Δ_0 can be evaluated under this current condition.

Second, we evaluated the Δ_0 by our proposed method at 170-210°C (interval of 10°C) as shown in Fig. 6. From these values and Eq. (1), we extrapolated Δ_0 at each temperature as shown in Fig. 6. As shown in Fig.6, the value extrapolated by this model almost corresponded with the accurate Δ_0 revealed in Fig. 5. From the above, we revealed that the accurate Δ_0 could be evaluated with our proposed model and its thermal dependency was proportional to $Ms^2(T)$ unlike linear characteristic shown in some papers [7].

4. Conclusions

We verified the validity of our proposed model of evaluating accurate Δ_0 for one target MTJ using its thermal dependency. In order to verify the validity of it, we compared the value of Δ_0 extrapolated by this model with accurate one. We showed that the accurate Δ_0 with negligibly small current disturbance can be evaluated when the average applied current I_{ave} < 29 μA for the measured MTJ. By confirming that these values corresponded with the values extrapolated by our model, we revealed that the accurate Δ_0 could be evaluated with our proposed model and its thermal dependency was proportional to $Ms^2(T)$ unlike the linear characteristic shown in some papers.

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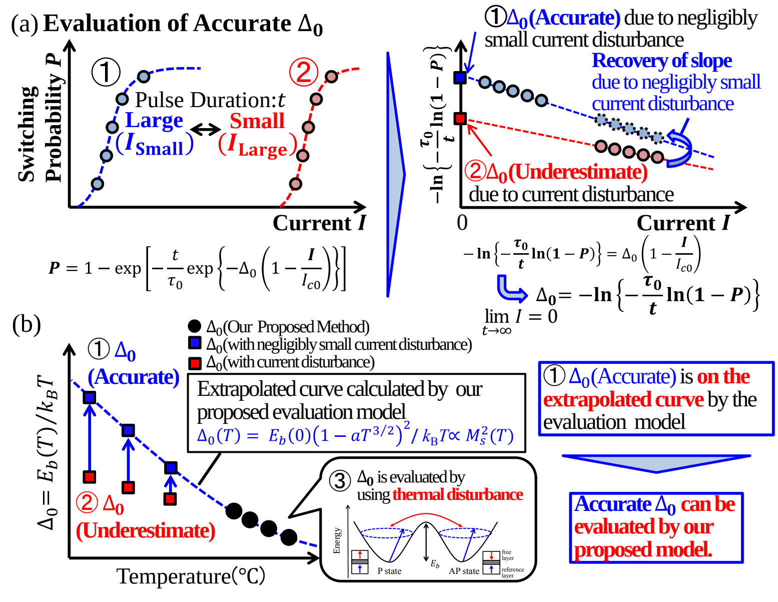

Fig. 1. Concept of the validation of our proposed model.

Table. I. Benchmark of evaluation methods.

	Measurement time	Accuracy
Method in Fig.1(a) @ Large Pulse Duration	Very Long since long pulse duration is required to decrease applied current. As MTJ size increases, measurement time increases sharply.	High due to negligibly small current disturbance
Our Proposed [3]	Short	High

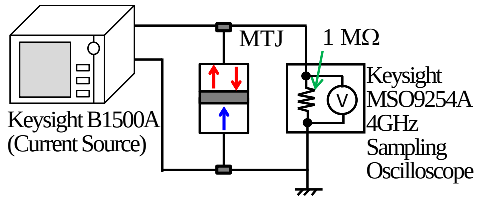

Fig. 2. Measurement setup.

Table. II. The property of measured MTJ.

	p-MTJ (25 nm)
TMR ratio (%)	80.9
RA ($\Omega\cdot\mu m^2$)	10.4

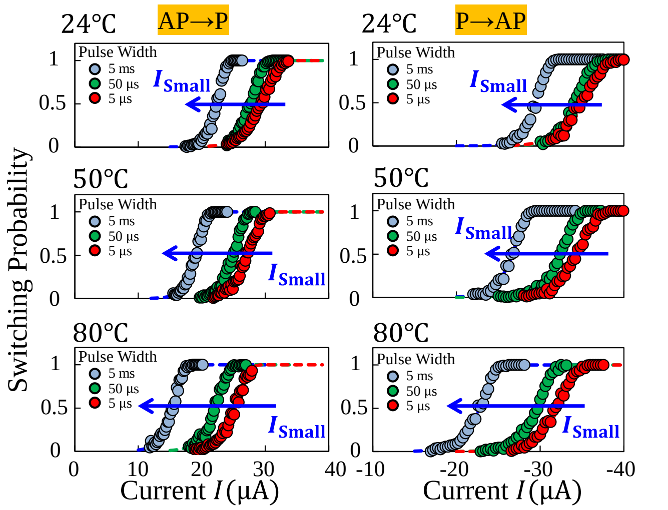

Fig. 3. Switching probability as a function of applied current.

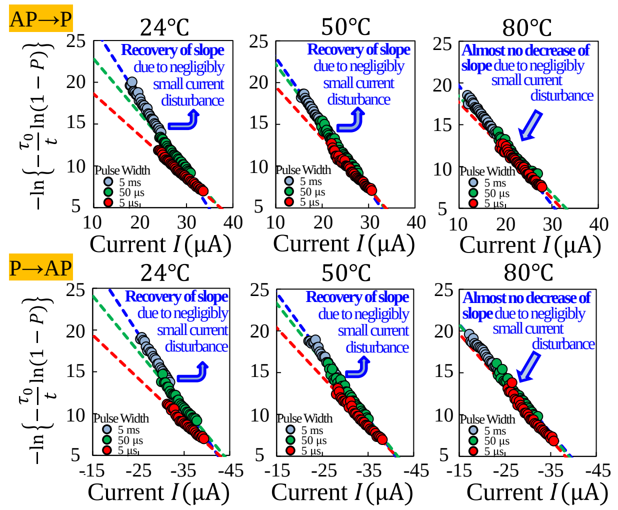

Fig. 4. $-\ln\{-\tau_0/t\,\ln(1\text{-}P)\}$ as a function of applied current.

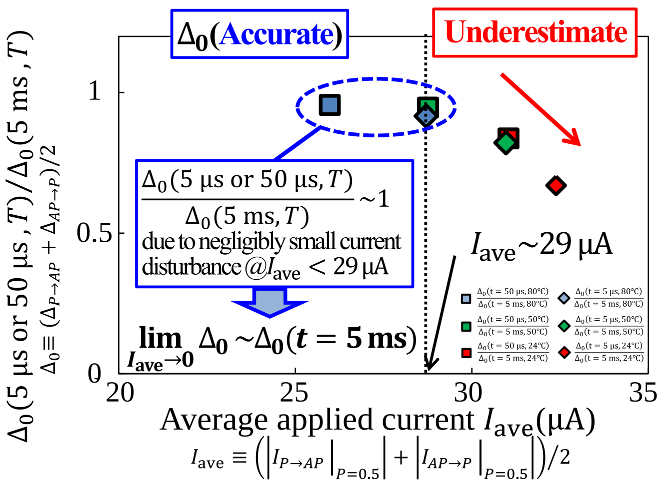

Fig. 5. Δ_0(5 μs or 50 μs, T) / Δ_0(5ms, T) vs. I_{ave}.

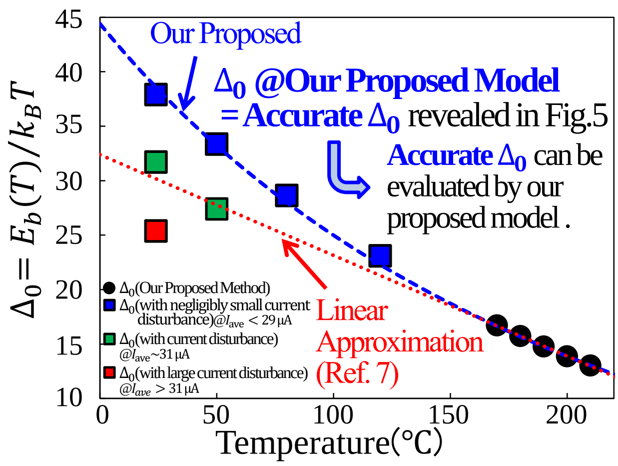

Fig. 6. Δ_0 vs. temperature for double interface p-MTJ.