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Phenomenological model for stress and relaxation processes of resistance drift in magnetic tunnel junctions

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1. Introduction

Resistance drift of magnetic tunnel junctions (MTJs) is one of the main reliability concerns limiting the lifetime of magnetoresistive random access memory (MRAM) [1]. Recently, the switching of MTJs by spin-transfer torque has gained much interest. In terms of reliability, however, it has a negative impact because high current density are required to switch MTJs [2]. Although the detailed investigations for the resistance drift in MTJs with AlO_x [1] and MgO [3] thin films have been reported so far, the fundamental understanding of the mechanism has not been fully established yet.

In this work, we investigate the time evolution of the resistance drift in MTJs under the constant voltage stress (CVS), and the relaxation phenomenon after removing the stress voltage is also studied. Then, an empirical model which can phenomenologically describe the observed characteristics is discussed.

2. Experimental

As shown in Fig. 1, the MTJ cells with a sandwich structure of CoFeB/AlO_x/CoFeB were used in this study. The layers of the MTJ stack were fabricated by sputter-deposition techniques. The AlO_x tunneling barrier ($\sim$ 1.0 nm) was formed by first depositing an Al film and then oxidizing it in an oxygen plasma. To induce the resistance drift, CVS was applied to the MTJs, and the time evolution of the current was monitored. The stress was periodically interrupted, and the degradation recovery was also measured by applying a low bias ($V_{\mathrm{relax}} =$ 0.1 V). All the measurements were done under the elevated temperature of 125°C to enhance the progression rate of the resistance drift.

3. Results and Discussion

Experimental Results: Fig. 2 shows the time evolution of the MTJ resistance $R(t)$ obtained by the stress-relaxation experiment. Gradual decrease of R was observed when $V_{\mathrm{stress}} = 1.2$ V was applied, while it recovered partially during the relaxation stage. The data are replotted in Fig. 3 to compare the curves observed in the each cycle. Note that several distinctive features are found; (i) R change rate becomes slower with repeated stress cycles, but (ii) the curves in the early stage ($<\sim$ 10 s) of the stress after second cycles are similar, and (iii) all the recovery characteristics are almost independent of the cycles. Fig. 4 shows the long time behavior of the relaxation process after stopping the stress application. The data cannot be fitted by, e.g., the exponential decay function with a single time constant, but instead can be well characterized by a logarithmic relation: $a + b\log(t)$ (a and b are constants), as reported in Ref. [1].

Modeling and Simulation: The relaxation characteristics as is observed in Fig. 4 were also confirmed in many other systems, some of which are phenomenologically modeled by the superposition of the mechanical components considering the viscoelastic nature of the materials [4]. By taking an analogy to this approach, we have tried to reproduce the key features of the resistance drift in MTJs. The details of the proposed model are illustrated in Fig. 5. Although the physical mechanisms are still controversial, we supposed the electromigration as a possible origin of the resistance drift [5], and its dynamics was modeled by the Kelvin-Voigt model. We have also assumed that various time constants would be involved depending on, e.g., the atomic configuration at each local spot, and the dynamics of many Kelvin-Voigt components to which the electron wind force (assumed to be proportional to the current density) acts were simulated numerically.

The simulated results are shown in Fig. 6. If we assume that the dynamics are accelerated with increasing V, i.e., the time constants of each component τ_i are enlarged in the relaxation stage, then the key features observed in Fig. 3 can be well reproduced. In the relaxation stage, only the fast components are recoverable, and they easily degraded again by the subsequent stress (which might correspond to the "reversible traps" discussed in Ref. [1]). The model can also predict the response to the more complex stress histories. As shown in Fig. 7, a short high-voltage pulse was inserted during the stress experiment. Note that just after the 1.1 V pulse application, R was once recovered and then degraded again under CVS of 0.9 V. Finally, we have simulated the duty cycle dependence of the unipolar pulsed stress as shown in Fig. 8. As is already reported experimentally [1], the degradation is dependent on the on/off time ratio, which results from relaxation process during the off periods.

4. Conclusions

We have proposed a phenomenological model for stress and relaxation processes of resistance drift in AlO_x based MTJs. The model can well reproduce the distinctive features observed in the various pulsed stress experiments. We believe that the model is useful to predict the reliability of MTJs during the realistic operations in MRAM circuit.

References

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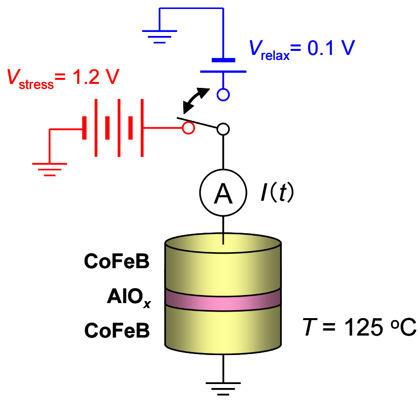

Fig. 1 Schematic view of the experimental method used in this study.

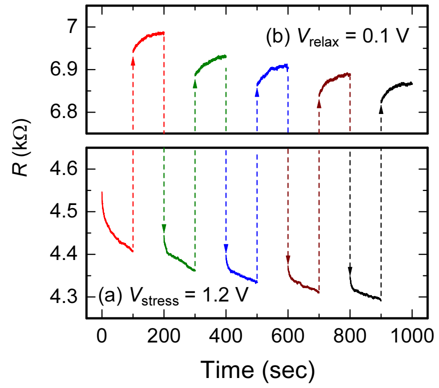

Fig. 2 Resistance drift as a function of time measured with applying (a) $V_{\rm stress} = 1.2$ V and (b) $V_{\rm relax} = 0.1$ V. On/off cycles were repeated for 5 times.

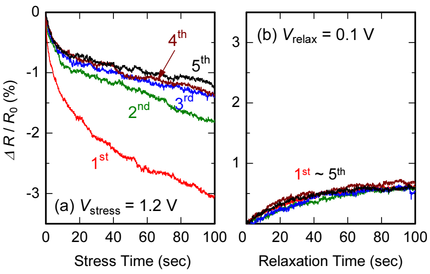

Fig. 3 Change of the resistance shifted during each (a) stress and (b) relaxation stage. The data shown in Fig. 2 are replotted here. The resistance shift ΔR are normalized to the sample initial resistance R_0.

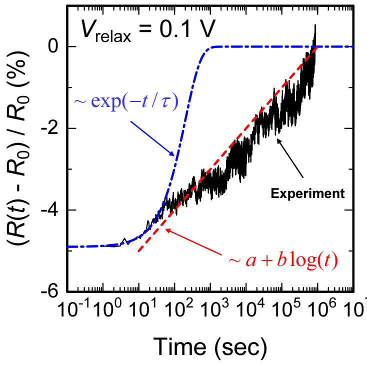

Fig. 4 Long time behavior of the resistance relaxation after applying $V_{\rm stress} = 1.2$ V. The data cannot be fitted by the exponential decay curve with a single time constant, but can be well characterized by a logarithmic relation: $a + b\log(t)$ [1].

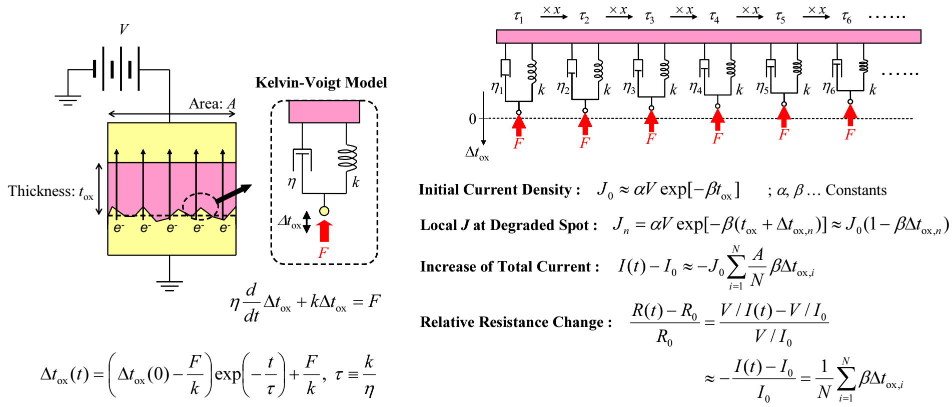

Fig. 5 A phenomenological model proposed to describe the stress and relaxation behaviors of the resistance drift. The sample was divided into N small areas, and the viscoelastic behavior of the metal/insulator interface at each spot was modeled with the Kelvin-Voigt model. The total shift of the MTJ resistance was obtained by superposing the multiple components with different time constants. τ_i were assumed to be distributed in a geometrical progression (τ_1 to τ_N), and behaviors of many components ($N = 2^{12}$) were numerically simulated (N is large enough so that the results are independent of N).

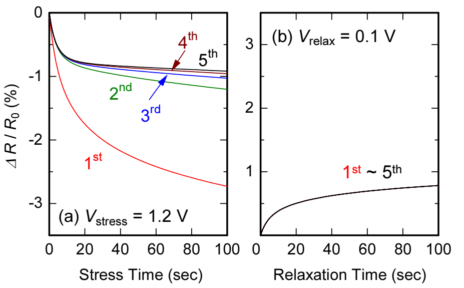

Fig. 6 Simulated resistance drift to reproduce the experimental data shown in Fig. 3. The fitting parameters assumed were, for the stress stage: $\tau_1 = 2$ s, $\tau_N = 2 \times 10^5$ s, $\beta F/k = 0.07$, and for the relaxation stage: $\tau_1 = 2$ s, $\tau_N = 2 \times 10^{16}$ s, $\beta F/k = 0.07 \times (J_{\rm relax}/J_{\rm stress})$.

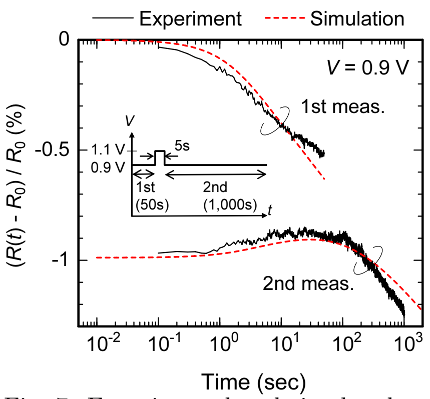

Fig. 7 Experimental and simulated resistance drift. Firstly, the resistance drift was monitored for 50 s under $V = 0.9$ V, and then the higher voltage of 1.1 V was applied for 5 s. After that, the resistance drift at $V = 0.9$ V was measured again.

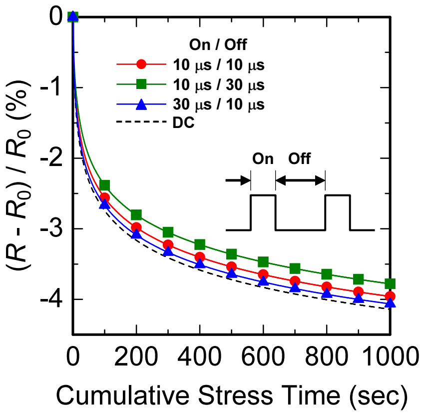

Fig. 8 Simulated results for the on/off ratio dependence of resistance drift under unipolar pulsed stress conditions. The parameter set used is the same as for Fig. 6.