Fabrication of MgO-based magnetic tunnel junctions for subnanosecond spin transfer switching

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Abstract. In the development of spin-transfer torque (STT)-based magnetic random access memories (spin-RAMs), characterizing the physics in sub-ns STT switching is a crucial issue for designing operation schemes. This paper describes the procedure we used to fabricate MgO-based magnetic tunnel junctions for measuring sub-ns STT switching. We also discuss the sub-ns STT switching properties based on the quasi-static properties.

1. Introduction

Spin-transfer torque (STT)-based magnetic random access memories (spin-RAMs) have been widely developed as next generation non-volatile memories. Since one of the features of these memories is a fast write cycle, characterization of the physics in fast STT switching is a crucial issue for the designing of the fast spin-RAMs. Since MgO-based magnetic tunnel junctions (MTJs), which consist of CoFeB ferromagnetic electrodes are promising candidates for the storage element in spin-RAMs, STT switching properties have been widely investigated. Recently, demonstration and the detailed examinations about sub-ns STT switching for MgO-based MTJ were achieved. The higher resistance of MTJ devices than that of metallic spin valves enhances electrical leakage loss via the parasitic capacitance of devices. Therefore, in this paper, we mainly show the details of how to fabricate MgO-based MTJs for sub-ns STT switching measurements.

2. Sample fabrication procedures

The stacking structure of the MTJs used in this study is buffer layers/PtMn/Co₉₀Fe₁₀/Ru/Co₄₀Fe₄₀B₂₀/Mg/MgO/free layer/Ta/Ru on sapphire wafers fabricated by using a UHV magnetron sputtering system. The synthetic anti-ferromagnet (SyF) free layer consists of Co₄₀Fe₄₀B₂₀ (2 nm)/Ru (0.9 nm)/Co₄₀Fe₄₀B₂₀ (2 nm). The MTJs, annealed at 275°C for 1 hour in a 10-kOe magnetic field, were patterned using electron beam lithography and Ar ion milling into a 0.1×0.2 μm² rounded rectangle shape. The devices used in this study had a resistance area product in parallel state of 5.5 Ωμm² and an MR ratio of 46 % at room temperature. Figure 1(a) shows a microscopic image of a fabricated device.

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Figure 1 (a) Microscope picture of a device. Real (b) and imaginary (c) parts of $S_{11}$ for a device without any junctions. Data for the equivalent circuit model (solid blue lines) well matched the experimental data (rounded red marks). (d) Schematic picture of the system for measuring voltage transmit through a MTJ. (e) Observed waveforms of the sub-ns width pulse signals transmitted through a junction by the oscilloscope illustrated in (d).

The electrode was patterned into a grand-signal-grand (G-S-G) transmit type micro-stripe structure. Here, 40 nm thick SiO2 was deposited as insulation material for the 12 μm² cross sectional area of the top and bottom electrodes. Since the parasitic capacitance of MTJ devices is considered as the main microwave loss factor, we estimated it from the analysis of reflectivity $S_{11}$ as shown in Fig. 1(b) and (c). The obtained value of parasitic capacitance was 14 fF, an extremely low value because the barrier capacitance in sub nanometer scaled MTJs is only a few fF. To confirm the pulsed current properly transmitted through the MTJs, without incurring significant losses, we used the circuit diagram shown in Fig. 1(d) to evaluate the actual pulse waveforms through the devices. Figure 1(e) shows the pulse voltage waveforms we observed by the oscilloscope illustrated in (d). Sub-ns pulse signals were clearly observed without significant distortions or losses. In Ref.6, transmit pulse waveforms in the waveguide devices were shown, however, they are not passed through the MTJs.

3. Spin-transfer properties

To show the basic spin transfer properties, we first experimentally analysed the current ($I$) – field ($H$) diagram. The methodology is described below. DC two probe magneto-resistance measurements were performed by applying the fixed sweep rate $R$ (=12 Oe) quasi-static magnetic field. These measurements were performed five times for each sensing DC current value ($I_{dc}$) which was systematically changed from -2 to 2 mA in 0.1 mA steps. We converted $R$ to the effective relaxation time $\tau_p$ shown in Table I following the procedure described in Ref. 8 by assuming the parameters of saturation magnetization $M_S$, volume of free layer $V$, temperature $T$, and attempt time $\tau_0$ shown in Table I. In this way, we performed a fitting analysis based on a thermal activation model on the plots of the coercive force $H_C$ versus $I_{dc}$ obtained through above measurement following the literature in
Table I. Parameters for obtaining analysis results for the $I$-$H$ diagram. $\tau_P, M_S, V, T$, and $\tau_0$ are assumed parameters. $H_{C0}, I_{C0}, \beta$, and $C$ are estimated parameters from the analysis.

| Assumption | $\tau_P$ (s) | $M_S$ (T) | $V$ (m$^3$) | $T$ (K) | $\tau_0$ (s) | $H_{C0}$ (Oe) | $I_{C0}$ (mA) | $\beta$ (K$^2$/mA$^2$) | $C$ (Oe/mA) |
|------------|--------------|-----------|-------------|--------|--------------|---------------|--------------|--------------------|--------------|
| Estimation | 0.09         | 1.2       | $8 \times 10^{-23}$ | 300    | $1 \times 10^{-9}$ | 50            | 5            | 0.6-1.1 $\times 10^5$ | 0            |

Figure 2 $1-P_{SW}$ depending on $I$ for pulse widths of (a) 10 ns, (b) 2.5 ns, and (c) 0.4 ns. Data (colored marks) were measured under various effective easy axis fields. Solid lines in (a)-(c) show fitting or calculation results based on Eq.(1).

Ref. 9. Here, we analysed data independently for each quadrant defined by the polarity of $I_{dc}$ (positive or negative) and magnetization configuration (parallel (P) or anti-parallel (AP)). Consequently, we obtained estimation values of the zero temperature switching current $I_{C0}$, the zero temperature coercive force $H_{C0}$, the hating coefficient $\beta$ and the coefficient of the effective field $C$ which was assumed to be linearly depending on $I_{dc}$. Table I shows the positive $I_{dc}$ and P to AP switching values for our MTJs. Similar analysis results have been reported for MgO-based MTJs 10. In the next paragraph, we discuss the spin transfer switching properties induced by sub-ns current pulses based on the above analytical results.

To show the fast STT switching properties, we measured STT switching probabilities ($P_{SW}$) in the following manner. First we applied a hard-axis external field to cancel the hard axis offset field estimated from an asteroid curve and fixed it. Then, to reset the magnetization configuration into P state, an easy-axis external field (500 Oe) was applied. After that, we approached the field to desirable strength remaining P state and fixed it at that level. We then injected a current pulse into the MTJs, just after we had detected the resistance in order to determine whether or not the magnetization had switched into an AP configuration or not. $P_{SW}$ was obtained through 150 time repeats of the cycle of above easy axis field reset, current pulse injection, and resistance detection. Here, we used current pulses whose rise time and width were 55 ps and 50 - 10000 ps, respectively. The signal line length $L_{line}$ and its width are 150 $\mu$m and 3 $\mu$m, respectively. The $L_{line}$ was much smaller than the maximum voltage wavelength (= 3.3$\times$10$^4$ $\mu$m) corresponding to the pulse rise time of 55 ps used in this study. Therefore, the electrode structure is regarded as a lumped constant circuit. The measurement circuit was constructed by radio frequency (RF) assemblies, each consisting 26 GHz bandwidth coaxial lines, and DC assemblies consisting of lock-in amplifiers in order to measure quasi-static resistance measurement.

Figure 2 shows $1-P_{SW}$ depending on current pulse strength $I$. Pulse widths ($= \tau_P$) of (a) 10 ns, (b) 2.5 ns, and (c) 0.4 ns were used for the measurements. Fitting analyses were performed using the following switching probability formula based on an adiabatic model derived from the thermal distribution of the initial magnetization direction 11.

$$1 - P_{SW} = \exp \left( -2 \alpha_{eff} \gamma \left( H_{C0} + 2\pi M_S \right) \tau_P \cdot \frac{I - I_{C0}}{I_{C0}} + \ln \left[ \frac{\pi^2}{8} \frac{H_{C0} M_S V}{k_B T} \left( 1 - \frac{H_{easy}}{H_{C0}} \right)^2 \right] \right),$$

where $\gamma$ is the gyromagnetic ratio, $k_B$ is the Boltzmann constant, $T$ is the temperature, $H_{easy}$ is the easy axis field, and $\alpha_{eff}$ is the effective anisotropy coefficient.
Here, $\alpha_{\text{eff}}$, $\gamma$, and $H_{\text{easy}}$ are effective Gilbert damping constants of the free layer, the gyro-magnetic momentum ratio, and the effective easy axis external field, respectively. We assumed that $H_{C0}$ and $I_{C0}$ were 50 Oe and 5 mA, respectively. $\alpha_{\text{eff}}$ was treated as a fitting parameter. The solid lines in Fig. 2(a)-(c) show the fitting results based on Eq.(1). As shown in Fig. 2(b) and (c), the model well reproduced the experimental data, which means the switching mechanisms in the sub-ns regime are precession dominated and that the thermal activation effect is negligible except for the initial condition. In addition, here, $\alpha_{\text{eff}}$ was estimated to be 0.03. Hence, the calculation results using Eq.(1) were also shown in Fig. 2(c), in which the assumed $\alpha_{\text{eff}}$ values were 0.02 and 0.04 ($\alpha_{\text{eff}}$ in $I_{C0}$ was also taken into account), clearly disagree with the data. This indicates that the spin transfer property in the sub-ns regime is strongly affected by $\alpha_{\text{eff}}$. The obtained $\alpha_{\text{eff}}$ value is larger than intrinsic damping constant of a 2 nm thick Co$_{40}$Fe$_{40}$B$_{20}$ film (~0.015). The reason for this, however, still unclear. We found that $\alpha_{\text{eff}}$ can be enhanced by the roughness of a free layer, by the dynamic interaction between magnetic layers in SyF via interlayer exchange coupling, or by angular momentum dissipation due to multimode spin wave excitation caused by larger current injection.

4. Conclusions

The device fabrication of MgO-based MTJs for sub-ns STT switching measurement were described. The spin transfer switching properties induced by sub-ns current pulses were strongly affected by $\alpha_{\text{eff}}$.

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