Thermally Assisted Magnetization Switching on Magnetic Tunnel Junctions With Perpendicularly Magnetized TbFe Layer

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Perpendicular magnetized tunnel junctions (MTJs), whose stack is [Co/Pd] / MgO / TbFe, were fabricated since the TbFe memory layer has a large perpendicular anisotropy and a low Curie temperature, which are suitable for thermally assisted (TA) switching. The TA switching of the TbFe layer due to a Joule heating created by a pulse current through the tunnel junction was confirmed. The MTJ with MgO 1.4 nm layer exhibited the MR ratio of 9 %, and the resistance area product RA of $342 \Omega\mu\text{m}^2$ at low bias voltage of 40 mV. The coercivity of TbFe at room temperature was about 1.5 kOe, while the magnetic switching at low magnetic field of 100 Oe was confirmed by the application of a current pulse with duration of 100 msec through the tunnel junction which creates the Joule heating. Moreover, the dependence of the power density necessary to switch the TbFe layer on the external applied field was measured. The required power density to complete the TA switching decreased linearly with the increase of the applied field and the TA switching of TbFe at low external field of 100 Oe was confirmed at the applied power density of $2.2 \text{ mW}/\mu\text{m}^2$.

Key words: thermally assisted switching, magnetic tunnel junctions, TbFe

1. Introduction

Spin transfer torque (STT) switching has been intensively studied as an efficient writing scheme for high density magnetic random access memories (MRAMs). However, one of the problems for the practical application of the STT switching is a large critical current density J_c necessary for the magnetization reversal. A spin polarized current transfers its angular momentum to local spins and excites the magnetization precession^{1), 2)}. If the number of the spin polarized electrons flowing into the magnetic layer is sufficient to overcome the energy barrier of the magnetization switching before decaying the precession, the magnetization of the magnetic layer reverses due to the spin polarized current. Thus the reduction of the J_c is achieved by a magnetic layer with low damping constant to lower the decay and low magnetic anisotropy to reduce the barrier height. On the other hand, the anisotropy should be high enough to prevent the unwanted reversal due to the thermal agitation. The reduction of the damping constant will be effective to reduce J_c but will make slow to settle the magnetization direction after the switching.

Alternatively, thermally assisted (TA) switching has been proposed to reduce the switching current density while keeping the sufficient thermal stability, and could offer ultimate scalability in MRAMs^{3), 4)} as it does in hard disk drive technology⁵⁾. The effect of TA has been

studied in magnetic tunnel junctions (MTJs) with the memory layers of CoFe / MnIr exchange coupled bilayers and Co/Pd multilayers^{6), 7)}, and the reduction of the ratio of J_c to thermal stability factor Δ was reported to be obtained by applying 30 nsec long switching pulse⁷⁾. Previously, we have reported STT switching of GdFeCo layer, and its temperature dependence was discussed to study the effect of TA switching on the rare-earth (RE) transition-metal (TM) memory layer^{8), 9)}, since the RE-TM exhibits a large perpendicular anisotropy, and its magnetic properties, such as magnetization, coercivity and Curie temperature, are easily tuned by its composition. In this report, we discuss the TA switching on the MTJ elements with TbFe memory layer and MgO barrier since the TbFe exhibits higher magnetic anisotropy than GdFeCo, and is considered to be more practical material. This study focuses on the TA “field” switching, not “STT” switching, as preliminary experiments for the future TA STT switching.

2. Experiment

The MTJ stack with substrate / Ta (10 nm) / [Pd (1.0 nm) / Co (0.5 nm)]₇ / (Co₅₀Fe₅₀)₈₀B₂₀ (1.2 nm) / MgO (t_{MgO} nm) / Co₅₀Fe₅₀ (1.0 nm) / Tb₂₀Fe₈₀ (20 nm) / Ta (5 nm) were prepared on thermally-oxidized Si substrate. The MgO and CoFe layers were deposited by a molecular beam epitaxy (MBE) system, while the other layers were deposited by an ultrahigh vacuum

magnetron sputtering system. All the layers were deposited without breaking vacuum. Hysteresis loops of the deposited films were measured by an alternating gradient field magnetometer (AGM). Temperature dependence of the hysteresis loop of the TbFe layer was checked by measuring Kerr loops at various temperatures. MTJs with cell sizes of $2.4 \mu\text{m} \times 2.4 \mu\text{m}$ and $1.2 \mu\text{m} \times 1.2 \mu\text{m}$ were fabricated by photolithography or electron beam lithography followed by Ar^+ ion etching. The Ar^+ ion etching was done by an electron cyclotron resonance (ECR) plasma source, and the end point of the etching was detected by using a secondary ion mass spectrometer (SIMS). Magneto-resistance (MR) effect was measured by DC four-points probe method applying an external field in the film normal direction. The thermally assisted switching was observed by measuring the junction resistance with a read current of 1 mA after applying a switching current ($< 20\text{mA}$) with 100 msec pulse width under a static magnetic field.

3. Results and discussion

Figure 1 shows hysteresis loops of MTJ films having a structure of $[\text{Pd} (1.0 \text{ nm}) / \text{Co} (0.5 \text{ nm})]_7 / (\text{Co}_{50}\text{Fe}_{50})_{80}\text{B}_{20} (1.2 \text{ nm}) / \text{MgO} (t_{\text{MgO}} \text{ nm}) / \text{Co}_{50}\text{Fe}_{50} (1.0 \text{ nm}) / \text{Tb}_{20}\text{Fe}_{80} (20 \text{ nm})$ with $t_{\text{MgO}} =$ (a) 1.6 nm and (b) 1.4 nm. The magnetization reversals at low ((a) ~ 500 Oe, (b) ~ 400 Oe) and high ((a) ~ 3.6 kOe, (b) ~ 2.0 kOe) fields correspond to the switchings of the Co/Pd multilayer and TbFe layer, respectively. In this study, the Co/Pd multilayer was used as a reference layer since it exhibits a large perpendicular magnetic anisotropy and a high Curie temperature. Curie temperature of the TbFe layer is confirmed to be about 130°C from the temperature dependence of Kerr rotations, and this value can be increased by adding Co into TbFe¹⁰. The perpendicular anisotropy constant of our TbFe was 2.7×10^6 erg/cc, which is comparable to the previous report¹⁰.

In Fig. 1, one can see the non-linear component in the in-plane MH loops. This is considered to be due to the insufficient exchange coupling between Co/Pd and $(\text{Co}_{50}\text{Fe}_{50})_{80}\text{B}_{20}$ layers to align the magnetization of CoFeB in the perpendicular direction. Further improvement of the deposition conditions and tuning of the film stacks will be necessary to obtain the linear in-plane loop.

Figure 2 shows MR curves of the micro-fabricated MTJs having a stack of $[\text{Pd} (1.0 \text{ nm}) / \text{Co} (0.5 \text{ nm})]_7 / (\text{Co}_{50}\text{Fe}_{50})_{80}\text{B}_{20} (1.2 \text{ nm}) / \text{MgO} (t_{\text{MgO}} \text{ nm}) / \text{Co}_{50}\text{Fe}_{50} (1.0 \text{ nm}) / \text{Tb}_{20}\text{Fe}_{80} (20 \text{ nm})$ with $t_{\text{MgO}} =$ (a) 1.6 nm and (b) 1.4 nm. The resistance changes at low and high fields correspond to the switchings of the Co/Pd multilayer and TbFe layer, respectively, which are consistent with the MH loops shown in Fig. 1. Gradual increase of the MR ratio before the switching of Co/Pd multilayer is considered to be due to the insufficient exchange coupling between Co/Pd and CoFeB layers as mentioned

Fig. 1 Hysteresis loops of the MTJ films with (a) $[\text{Pd} / \text{Co}]_7 / \text{MgO} (1.6 \text{ nm}) / \text{Tb}_{20}\text{Fe}_{80}$ and (b) $[\text{Pd} / \text{Co}]_7 / \text{MgO} (1.4 \text{ nm}) / \text{Tb}_{20}\text{Fe}_{80}$.

in Fig. 1. The MR ratios of about (a) 16 %, and (b) 9 % were obtained at a low bias voltage of 40 mV (solid line), and they reduced to about (a) 9 % and (b) 5 %, respectively, when the bias voltage was increased to 400 – 500 mV (dotted line). The MR ratios of the present samples are not sufficient for high density MRAM applications. However, the MR ratio will be enhanced by annealing the sample before the deposition of TbFe to improve (001) orientation of the MgO layer and to crystalize the bottom CoFeB layer. The resistance area products RA of these MTJs were (a) $703 \Omega\mu\text{m}^2$ and (b) $342 \Omega\mu\text{m}^2$, respectively. It was reported the power density of $2 \text{ mW}/\mu\text{m}^2$ is necessary for the TA switching of the TbFe layer¹¹⁻¹³. The power density P generated in the MgO layer by the current pulse is written as $P = V_w^2 / RA$, where V_w is the applied voltage for writing. Under the condition of appropriate V_w , e.g., $0.5 \text{ V} < V_w < 1 \text{ V}$ and $P = 2 \text{ mW}/\mu\text{m}^2$, the MTJ with $125 \Omega\mu\text{m}^2 < RA < 500 \Omega\mu\text{m}^2$ is desired.

Figure 3 shows MgO thickness dependence of RA of MTJs with a stack of $[\text{Pd} (1.0 \text{ nm}) / \text{Co} (0.5 \text{ nm})]_7 / (\text{Co}_{50}\text{Fe}_{50})_{80}\text{B}_{20} (1.2 \text{ nm}) / \text{MgO} (t_{\text{MgO}} \text{ nm}) / \text{Co}_{50}\text{Fe}_{50} (1.0 \text{ nm}) / \text{Tb}_{20}\text{Fe}_{80} (20 \text{ nm})$. The cell size of the MTJs with $t_{\text{MgO}} = 1.6 \text{ nm}$ and 1.4 nm was $2.4 \mu\text{m} \times 2.4 \mu\text{m}$. The RA exponentially decreased with decreasing the MgO thickness and the appropriate RA was obtained at the MgO thickness t_{MgO} around 1.4 nm.

Fig. 2 MR curves of the MTJs with (a) $[\text{Pd} / \text{Co}]_7 / \text{MgO} (1.6 \text{ nm}) / \text{Tb}_{20}\text{Fe}_{80}$ and (b) $[\text{Pd} / \text{Co}]_7 / \text{MgO} (1.4 \text{ nm}) / \text{Tb}_{20}\text{Fe}_{80}$.

Fig. 3 MgO thickness dependence of RA of MTJs with $[\text{Pd} / \text{Co}]_7 / \text{MgO} (t_{\text{MgO}} \text{ nm}) / \text{Tb}_{20}\text{Fe}_{80}$

Figure 4 shows the junction resistance after the application of the switching pulse current under a static external magnetic field H_{ext} . Before the application of the current pulse, a large negative field of -10 kOe was applied to saturate both the Co/Pd reference layer and the TbFe memory layer. Then a positive field of 500 Oe was applied to switch low coercive Co/Pd layer, which makes the MTJ high resistance state. As seen in Fig. 4, under positive external fields of H_{ext} = (a) 1.30 kOe, (b) 0.91 kOe, (c) 0.50 kOe, (d) 0.10 kOe, the MTJ resistances after the application of the current pulse were plotted as a function of the current pulse.

Fig. 4 I - R curves of the MTJ with $[\text{Pd} / \text{Co}]_7 / \text{MgO} (1.4 \text{ nm}) / \text{Tb}_{20}\text{Fe}_{80}$ taken for H_{ext} = (a) 1.30 kOe, (b) 0.91 kOe, (c) 0.50 kOe, and (d) 0.10 kOe

As shown in Fig. 4 (a), up to around 7 mA current pulse, the MTJ kept antiparallel (AP) state (high resistance), and further increase of the current pulse results in the decrease of resistance. Note that the applied field of 1.3 kOe is smaller than the coercivity of TbFe layer (1.5 kOe), and thus the Joule heat generated in the MTJ by applying a current pulse is considered to assist the magnetization reversal of TbFe layer. The gradual decrease of the resistance with increasing the current is probably due to the domain formation in the TbFe layer. With decreasing the static field, the pulse current necessary to the TA switching increased as shown in Fig. 4 (b) ~ (c), and the TA switching was confirmed at a low H_{ext} of 100 Oe as shown in Fig. 4 (d).

Fig. 5 (a) Critical power density P and (b) square of voltage V^2 necessary for TA-switching of MTJs with $[\text{Pd} / \text{Co}]_7 / \text{MgO} (t_{\text{MgO}}) / \text{Tb}_{20}\text{Fe}_{80}$ as a function of an external field H_{ext}

Figure 5 shows (a) critical power density P and (b) square of voltage V^2 necessary to complete the TA switching of MTJs with $[\text{Pd} / \text{Co}]_7 / \text{MgO} / \text{Tb}_{20}\text{Fe}_{80}$ as a function of H_{ext} .

The power density P for TA switching linearly increased with decreasing H_{ext} . The uniaxial anisotropy K_u (or coercivity H_c) of many ferromagnetic materials is known to be proportional to $M_s^2 \sim M_s^3$, where M_s is saturation magnetization^{14), 15)}, and the M_s is considered to be proportional to square root of the temperature according to a simple mean field theory. Therefore, the switching field is considered be proportional to $P \sim P^{1.5}$, since the temperature of TbFe layer will be proportional to P , and this is roughly consistent with the results in Fig. 5. For the MTJ with $t_{\text{MgO}} = 1.6$ nm, the TA switching by applying a power density $2.0 \text{ mW}/\mu\text{m}^2$ was confirmed at $H_{\text{ext}} = 1.8$ kOe. The MTJ with $t_{\text{MgO}} = 1.6$ nm has an RA of $703 \Omega\mu\text{m}^2$, and the applied voltage to generate $2.0 \text{ mW}/\mu\text{m}^2$ reaches 1.2 V (see Fig. 5 (b)). Thus further increase of the power density will result in the breakdown of the MTJ. The decrease of RA is effective to avoid the breakdown as discussed above. For the MTJ with $t_{\text{MgO}} = 1.4$ nm, the TA switching was confirmed under a low $H_{\text{ext}} = 100$ Oe. The power density and the applied voltage for the switching at $H_{\text{ext}} = 100$ Oe was $2.2 \text{ mW}/\mu\text{m}^2$ and 0.9 V, respectively. The power density of $2.2 \text{ mW}/\mu\text{m}^2$ corresponds to the current density of $2.5 \times 10^5 \text{ A}/\text{cm}^2$ for this MTJ. In this experiment, we estimated the power and current densities by applying the current pulse with the duration of 100 msec. The increases of the power and current densities are expected by shortening the pulse width down to 10 nsec as discussed in Ref. 12) and 13). Roughly speaking, $10 \text{ mW}/\mu\text{m}^2$ will be expected for the heating with 10 nsec pulse width from the references. However, the MTJs studied in this paper have top and bottom electrodes dissipating the generated heat at the junction. The suppression of the heat dissipation to the top and bottom electrodes^{16), 17)} will be effective to obtain smaller power and current densities than the values estimated in the present experiments even with the pulse width of 10 nsec which will be necessary for the MRAM application.

4. Summary

Perpendicular magnetized tunnel junctions with TbFe memory layer having a large perpendicular anisotropy and low Curie temperature were fabricated, and TA switching of TbFe layer by a Joule heat generated in the junction was studied. MTJ with MgO 1.4 nm exhibited MR ratio of 9% and resistance area product (RA) of $342 \Omega\mu\text{m}^2$ at low bias voltage of 40 mV. The coercivity of

TbFe was about 1.5 kOe, while the magnetization switching was confirmed at low magnetic field of 100 Oe using the joule heating created by flowing a current pulse through the tunnel junction. The power and current densities necessary to complete the TA switching was $2.2 \text{ mW}/\mu\text{m}^2$ and $2.5 \times 10^5 \text{ A}/\text{cm}^2$, respectively. The power density to heat TbFe for TA switching was almost the same as that in the previous report, and the rather low current density of around $10^5 \text{ A}/\text{cm}^2$ is considered to be attractive for high density MRAMs. This current density will be reduced further by suppressing the heat dissipation to the upper and lower electrodes.

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