Synthetic CoFeB/Ru/NiFe Free Layer on MgO Barrier Layer for Spin Transfer Switching

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Abstract. In order to study the application potential of spin transfer switching in magnetic tunnel junctions (MTJs), a synthetic parallelly coupled layered structure such as a hard CoFeB/Ru/soft NiFe layers deposited on a MgO layer is investigated. The magnetic coupling between the layers is maintained after post-annealing at 300°C, while annealing at 350°C reduces the coupling strength. The observation of spin transfer switching in the junction indicates that parallel-to-antiparallel transition does not occur when the applied current pulse width is in the sub-millisecond range, which is far from the precessional range. This result indicates that spin transfer from NiFe to CoFeB might affect the dynamics of CoFeB magnetization.

1. Introduction
Spin transfer switching in a free layer in magnetoresistive multilayers or magnetic tunnel junctions (MTJs) is being widely studied because this phenomenon has various applications such as in magnetic random access memory (MRAM). Thus far, many attempts have been made to reduce the spin transfer switching current $I_c$. A ferri/ferro coupling structure of synthetic free layer has attracted the attention of many researchers [1–4]. Recently, a reduction in the switching current was achieved by using a free layer consisting of parallel-coupling soft layer and hard layer on an AlO$_x$ barrier layer [5]. It is expected that the soft layer assists the magnetization reversal of the hard layer with a low switching current; however, the mechanism of magnetization reversal is not clear. We have investigated the magnetic properties of a synthetic CoFeB/Ru/NiFe free layer deposited on a MgO layer and have observed spin transfer switching measurement in order to understand the switching mechanism.

2. Experiments
We deposited thin films on a thermally oxidized silicon substrate by dc/rf magnetron sputtering. We prepared MgO(5)/Co$_{40}$Fe$_{40}$B$_{20}$(2)/Ru($d_{Ru}$)/Ni$_{80}$Fe$_{20}$(2)/Ta(10) (in nm) layered structure for magnetic measurement and Ta(5)/Ru(10)/Ir$_{75}$Mn$_{25}$(10)/Co$_{75}$Fe$_{25}$(2)/Ru(0.85)/Co$_{40}$Fe$_{40}$B$_{20}$(3)/Mg(0.4)/wedge MgO(0.2-0.8)/Co$_{40}$Fe$_{40}$B$_{20}$(2)/Ru($d_{Ru}$)/Ni$_{80}$Fe$_{20}$(2)/Ta(10) layered structure for the fabrication of magnetic tunnel junctions. The thickness of the...
Ru layer, $d_{\text{Ru}}$, was varied from 0 nm to 1.4 nm. The magnetic tunnel junctions were fabricated by electron beam lithography and Ar ion milling. The junction size was about 80 nm × 230 nm. We annealed the samples in vacuum ($P < 10^4$ Pa) in a magnetic field of 10 kOe after sample preparation. The magnetic properties were measured using a vibrating sample magnetometer (VSM). For understanding spin transfer switching mechanism, we measured the resistance of the junction by a lock-in technique after applying a gradually increasing pulsed current. The applied current when the resistance changes is defined as the switching current. Rectangular pulse current was injected through a 2-kΩ resistor by a pulse generator. The pulse width was set between 0.01 ms and 100 ms.

3. Results and discussion

We studied the influence of the annealing temperature on the magnetic properties of CoFeB/Ru/NiFe layers. Figure 1(a) shows the dependence of the saturation field ($H_s$) and spin-flip field ($H_{sf}$), which were measured after post-annealing at 300 °C for 1 hour on the thickness of the Ru layer. The evolution of $H_{sf}$ and increase in $H_s$ are the evidence of ferri coupling between the CoFeB and NiFe layers. The hysteresis curves of layers with $d_{\text{Ru}} = 0.4$ nm in Figure 1(b) are shown, for instance. $H_{sf}$ was observed in the case of the layers with Ru thickness ranging from 0.4 nm to 1.0 nm. $H_s$ also increased in the layers with Ru thickness ranging from 0.4 nm to 0.9 nm. This result suggests that annealing at $T_a = 300$ °C kept the synthetic structure of CoFeB/Ru/NiFe. In contrast, $H_{sf}$ was not observed and $H_s$ became smaller for all layers at $T_a = 350$ °C, which indicates the ferri coupling structure was broken.

We fabricated a junction with $d_{\text{Ru}} = 1.2$ nm and carried out annealing at 300 °C for realizing weak parallel coupling with a composite free layer, which have a low switching current as reported before [5]. Figure 2(a) shows the its resistance-magnetic field ($R$-$H$) hysteresis curve of the junction. For carrying out the spin transfer switching measurement, we used a junction with a low resistance and sufficient high magnetoresistance(MR) ratio from the junctions with various resistances and MR ratios because of a wedge MgO layer. The $R$-$H$ curve showed clear resistance jumps and the MR ratio was 51%. Figures 2(b) and (c) are the resistance-current ($R$-$I$) hysteresis curves measured for a current pulse width of 100 ms. In these figures, several transitions observed by performing sequential measurements are shown. The $R$-$I$ curves also showed sharp transitions.

Figure 1. (a) Ru-thickness dependence of saturation field ($H_s$) and spin-flip field ($H_{sf}$) of Co$_{40}$Fe$_{40}$B$_{20}$(2)/Ru($d_{\text{Ru}}$)/Ni$_{80}$Fe$_{20}$(2) (in nm) annealed at $T_a = 300$ °C. (b) Hysteresis curves of Co$_{40}$Fe$_{40}$B$_{20}$(2)/Ru(0.4)/Ni$_{80}$Fe$_{20}$(2) (in nm) annealed at $T_a = 300$ °C and 350 °C.
Figure 2. (a) Resistance-magnetic field ($R$-$H$) curve of junction with free layer of Co$_{40}$Fe$_{40}$B$_{20}$(2)/Ru(1.2)/Ni$_{80}$Fe$_{20}$(2) (in nm) annealed at $T_a = 300$°C. (b) and (c) are the resistance-current ($R$-$I$) curves of the same junction((b): AP-P, (c): P-AP) measured for a current pulse width of 100 ms. Each transition in the $R$-$I$ curves was obtained by performing sequential measurements.

Figure 3. Current pulse width dependence of switching current of the free layer Co$_{40}$Fe$_{40}$B$_{20}$(2)/Ru(1.2)/Ni$_{80}$Fe$_{20}$(2) (in nm) annealed at $T_a = 300$°C. (a) is of the junction shown in Figure 2, and (b) is of another one. The dashed lines are the fitting lines derived by thermal activation model.

with both current polarities. Although switching currents were distributed due to thermal fluctuations, the high and low resistance values were almost the same as those observed in the $R$-$H$ curve. Therefore, it is considered that these transitions can be attributed to magnetization switching caused by the pulsed current.

Figure 3(a) shows the relationship between the spin transfer switching current $I_c$ and pulse width $\tau_p$ of the junction. Antiparallel-to-parallel (AP-P) transitions were observed for all pulse width of our measurement. However, parallel-to-antiparallel (P-AP) transitions could not be
observed at pulse widths less than 0.2 ms. Moreover, near the cutoff pulse width (0.2–0.3 ms), P-AP transitions occurred stochastically. The intrinsic switching current density $j_{00}$ and a thermal durability factor $\Delta \equiv E_b/k_B T$ were obtained using a thermal activation model [6,7];

$$j_c = j_{00} \left[ 1 - \frac{k_B T}{E_b} \ln \left( \frac{\tau_p}{\tau_0} \right) \right]. \quad (1)$$

Here we assumed that the inverse of the attempt frequency $\tau_0$ was 1 ns. The intrinsic switching current density was $j_{00}^{P-AP} = 3.2 \times 10^7$ A/cm$^2$ and $j_{00}^{AP-P} = 3.0 \times 10^7$ A/cm$^2$, and the thermal durability factor was $\Delta^{P-AP} = 54$ and $\Delta^{AP-P} = 40$ for this junction. We also confirmed that the intrinsic switching current density of the junction with the synthetic parallel-coupling free layer was larger than that of the junction with the single CoFeB layer, that is, the reduction in the switching current in junctions with a parallel-coupling free layer, as reported by Yen et al. [5], could not be observed. The discrepancy in both results can be attributed to the difference in the thickness of the CoFeB and NiFe layers. In Figure 3(b), the $I_c-\tau_p$ diagram of another junction with the same structure is shown. Although the values of switching currents for this junction were different from those of the aforementioned junction, possibly owing to the distribution of crystallization of CoFeB by post-annealing, a similar performance in P-AP transitions was observed. In addition, the switching current drastically increased near the cutoff pulse width and deviated from the extrapolation derived by a thermal activation model. Although such upturn in the switching current is also observed in the precessional switching region, it is limited to tens of nanoseconds [6]; therefore, the upturn observed in the present study was independent of precessional switching. These anomalies in the small-pulse-width region indicate that the thermal activation process is dominant during the P-AP transition. If the spin torque did not pass through the interlayer Ru and the magnetizations of NiFe and CoFeB always rotated cooperatively by interlayer coupling, the asymmetry between AP-P and P-AP transition was reduced. Therefore, the result suggests that electrons flowing from NiFe to CoFeB in the P-AP transition measurement might transfer the spin torque and suppress the magnetization reversal of CoFeB.

4. Summary
A synthetic parallel-coupling layered structure consisting of CoFeB/Ru/NiFe layers deposited on a MgO layer was investigated. Magnetic coupling between the synthetic CoFeB/Ru/NiFe layers was maintained after post-annealing at 300°C, while annealing at 350°C reduced the coupling strength. The observation of spin transfer switching indicated that parallel-to-antiparallel transition could not occur when the current pulse width was below the sub-millisecond range. This result indicates that spin transfer from NiFe to CoFeB might influence the dynamics of CoFeB magnetization.

References
[1] Jiang Y, Nozaki T, Abe S, Ochiai T, Hirohata A, Tezuka N and Inomata K 2004 Nat. Mater. 3 361
[2] Jiang Y, Abe S, Ochiai T, Nozaki T, Hirohata A, Tezuka N and Inomata K 2004 Phys. Rev. Lett. 92 167204-1
[3] Hayakawa J, Ikeda S, Lee Y M, Sasaki R, Meguro T, Matsukura F, Takahashi H and Ohno H 2006 Jpn. J. Appl. Phys. 45 L1057
[4] Nakamura S, Haneda S and Morise H 2006 Jpn. J. Appl. Phys. 45 3846
[5] Yen C-T, Chen W-C, Wang D-Y, Lee Y-J, Shen C-T, Yang S-Y, Tsai C-H, Hung C-C, Shen K-H, Tsai M-J and Kao M-J 2008 Appl. Phys. Lett. 93 092504
[6] Koch R H, Katine J A and Sun J Z 2004 Phys. Rev. Lett. 92 088302
[7] Pakala M, Huai Y, Valet T, Ding Y and Diao Z 2005 J. Appl. Phys. 98 056107