Spin-torque induced rf oscillation in magnetic tunnel junctions with an Fe-rich CoFeB free layer

Y. Masugata¹, S. Ishibashi¹, H. Tomita¹, T. Seki¹, T. Nozaki¹, Y. Suzuki¹,², H. Kubota², A. Fukushima², S. Yuasa²
¹Graduate School of Engineering Science, Osaka Univ., 560-8531, Toyonaka, Japan
²Nano-Spintronics Center, AIST, 305-8568 Tsukuba Japan

E-mail: masugata@spin.mp.es.osaka-u.ac.jp

Abstract. A steady magnetization precession induced by spin-torque was studied in magnetic tunnel junctions with an Fe-rich CoFeB free layer under a perpendicular magnetic field. The Fe-rich CoFeB free layer showed a low critical current ($I_c$) for spin-torque induced switching. The low value of $I_c$ for the Fe-rich CoFeB free layer enabled us to observe the spin-torque induced rf oscillation even at a low dc bias current ($I_{dc}$). The oscillation frequency increased with increasing $I_{dc}$, indicating the out-of-plane precessional mode. Owing to the perpendicular magnetic anisotropy in the Fe-rich CoFeB free layer, the large relative angle between the free and pinned layers was achieved under the perpendicular magnetic field. The out-of-plane precession of the magnetization and the large relative angle resulted in the large rf output power of 175 nW.

1. Introduction
Versatile phenomena induced by spin-torque, which originate from the spin angular momentum transfer from conduction electron spins to local spins, [1, 2] have attracted much attention from the fundamental and practical points of view. One of the important phenomena is a steady magnetization precession induced by spin-torque [3-5] because it provides us with potential applications such as a nanometer-sized rf oscillator. The spin-torque oscillator has great advantages: frequency tunability by electric current injection and/or magnetic field, and the narrow generation linewidth of oscillation. These advantages have fascinated us and spin-torque oscillators have extensively been studied using current-perpendicular-to-plane giant magnetoresistance devices, [4, 6-9] point-contact devices, [5, 10-12] and magnetic tunnel junctions (MTJs). [13-19] From the viewpoint of the output power, MTJs with an MgO tunnel barrier are a candidate for the spin-torque oscillator since a huge tunnel magnetoresistance (TMR) ratio of an MgO-MTJ leads to the large rf output power.

Deac et al. [13] investigated the spin-torque induced rf oscillation in the CoFeB / MgO / CoFeB MTJs under the in-plane magnetic field. Although the large rf output power of 140 nW was achieved, the multiple peak structures of the rf spectra implied the existence of several precessional modes. Wada et al. [19] have reported that the application of the magnetic field perpendicular to the plane of the MTJ is an effective to suppress the additional precessional modes since the perpendicular magnetic field leads to a uniform demagnetization field in the nanosized-pillar of the MTJ in comparison with the in-plane magnetic field. However, the output power under the perpendicular magnetic field was reduced to be 26 nW because the the free and pinned layer magnetizations were almost aligned in the perpendicular direction and the precessional mode was out-of-plane, resulting in a small resistance.
change. A recent paper [20] has reported that the Fe-rich CoFeB free layer possesses a perpendicular magnetic anisotropy. This suggests that an Fe-rich CoFeB free layer may be suitable to increase the relative angle between the free and pinned layer magnetizations under the perpendicular magnetic field, and may be useful to obtain large output power.

In this study, we examined the spin-torque induced rf oscillation in MgO-MTJs with an Fe-rich CoFeB free layer. The magnetic field ($H_{\text{ext}}$) and the dc bias current ($I_{\text{dc}}$) dependences of the rf oscillation were investigated by applying the perpendicular magnetic field. The critical current ($I_c$) for the spin-torque switching was also evaluated using the current pulse measurement.

2. Experimental procedure
MTJ films were prepared using sputter-deposition. The stacked structure of the film is SiO$_2$ substrate / buffer layer / PtMn (15 nm) / CoFe (2.5 nm) / Ru (0.85 nm) / CoFeB (3 nm) / MgO (1.2 nm) / CoFeB (2 nm) / capping layer, where the 2-nm-thick CoFeB layer is the free layer and its composition is Co$_{16}$Fe$_{64}$B$_{20}$. This composition is Fe-rich compared with the Co$_{20}$Fe$_{20}$B$_{20}$ free layer that was used in a previous study. [19] The microfabrication was carried out through the use of electron beam lithography, Ar ion milling, and lift-off technique. The designed size of the junction is 50 nm × 150 nm. The magnetoresistance (MR) measurement was performed at room temperature using a conventional two-terminal technique. The frequency-domain measurement was carried out using a spectrum analyzer. The MTJ device was connected to the circuit with a two-terminal rf probe, and $I_{\text{dc}}$ was applied from a dc power source through a bias-Tee. The rf oscillation generates a high frequency voltage output signal due to the time variation of resistance originating from the TMR effect. Output signals amplified by a preamplifier were fed to a spectrum analyzer. All the rf measurements were performed at room temperature. The positive $I_{\text{dc}}$ is defined as the direction of the electron flow from the free layer to the pinned one. The background signal at $I_{\text{dc}} = 0$ mA was subtracted from the measured rf spectra.

3. Results and discussion
Figures 1 (a) and (b) show MR curves measured at the in-plane and perpendicular magnetic fields, respectively. The MR curve measured in the in-plane magnetic field shows that the hysteresis appears in the negative $H_{\text{ext}}$ region and the parallel magnetization alignment is stable at $H_{\text{ext}} = 0$ Oe because of the orange-peel coupling between the free and pinned layers. The resistance at the parallel state is 139 $\Omega$ and the MR ratio is about 70 %. The coercivity of the Fe-rich CoFeB free layer is obtained to be 110 Oe from the in-plane MR curve. Due to the ferromagnetic coupling between the free and pinned layers.

![Figure 1](image-url)  
Figure 1. MR curves for MTJs with a Fe-rich CoFeB free layer. The external magnetic fields were applied in (a) the in-plane and (b) the perpendicular direction to the plane of the MTJs.
layers, the resistance of the sample gradually increases as the perpendicular magnetic field increases to 5 kOe. This increment of the resistance is mainly due to the rotation of the free layer magnetization from the in-plane direction to the perpendicular direction. Further increase of the perpendicular magnetic field leads to the decrease of the resistance, which results from the rotation of the pinned layer magnetization.

In order to evaluate the value of $I_c$ for the Fe-rich CoFeB free layer, the spin-torque induced switching measurement was performed using the current pulse sequence. Figure 2 shows the values of $I_c$ as a function of the pulse duration time, where $H_{\text{ext}} = -100$ Oe was applied in the in-plane direction. Solid squares denote the results for the switching from the parallel to the antiparallel state ($I_c^+$), and solid circles denote those from the antiparallel to the parallel state ($I_c^-$). From the linear fitting to the data, $I_{c0}^+$ and $I_{c0}^-$ were evaluated to be 1.51 mA and -0.85 mA, respectively. The average critical current ($I_{c0}$) was obtained to be 1.18 mA, which corresponds to the critical current density ($J_c$) of $9.1 \times 10^6$ A/cm$^2$. This value is lower than $J_{c0} = 16.1 \times 10^6$ A/cm$^2$ for the Co$_{60}$Fe$_{20}$B$_{20}$ free layer used in a previous study. [19]

Figure 3 shows the peak frequency of the rf spectrum as a function of $H_{\text{ext}}$. The magnetic field was applied perpendicular to the plane of the MTJ. $I_{dc}$ was set to 0.3 mA. The solid line is the fitting results.

Figure 2. Critical current for spin-torque switching ($I_c$) as a function of the pulse duration time. $H_{\text{ext}} = -100$ Oe was applied in the in-plane direction. Solid squares denote the results for the switching from the parallel to the antiparallel state ($I_c^+$), and solid circles denote those from the antiparallel to the parallel state ($I_c^-$).

Figure 3. Peak frequency of the rf spectrum as a function of $H_{\text{ext}}$. The magnetic field was applied perpendicular to the plane of the MTJ. $I_{dc}$ was set to 0.3 mA. The solid line is the fitting results.
switching. At $I_{dc}$ around the value of $I_c$, the linewidth drastically changes, and the peak broadening occurs. This behavior is similar to the previous results. [19] According to a theory for the nonlinear auto-oscillator, [21] the line shape distortion occurs around $I_c$ in the case that the oscillator exhibits the strong nonlinearity. The observed peak broadening indicates the onset of the spin-torque induced rf oscillation with strong nonlinearity. The peak frequency shows discontinuous jumps and the blueshift at $I_{dc} > I_c$, and the output power significantly increases. The blueshift of the peak frequency means that the magnetization precession is the out-of-plane mode. An important point is that the output power reaches up to 175 nW at $I_{dc} = 1.9$ mA, which is much larger than the previous output power in the Co$_{60}$Fe$_{20}$B$_{20}$ free layer under the perpendicular magnetic field. [19] After the calibration of the rf transmission properties of the MTJ and the power loss in the measurement circuit, the output power from the MTJ is evaluated to be 568 nW.

One of the reasons for the enhancement of the output power is the reduction of $I_c$ for the onset of the rf oscillation. The low $I_c$ enables us to apply the large $I_{dc}$ after the onset of the rf oscillation. Another reason is the increase of the relative angle between the free and pinned layer magnetizations. From the MR curve, the relative angle is estimated to be 47.4º at $H_{ext} = 4.5$ kOe. Considering that the free and pinned layer magnetizations are almost aligned in the parallel configuration in a previous study using the Co$_{60}$Fe$_{20}$B$_{20}$ free layer, [19] the relative angle of the present case increases owing to the perpendicular magnetic anisotropy of the Fe-rich CoFeB free layer. Consequently, the increase of the relative angle and the out-of-plane precessional motion of the magnetization lead to the enhancement of the output power. Although the perpendicular magnetic field is useful to achieve the single peak structure in the spectra, the generation linewidths of the spectra are still large (~400MHz). The reason is not clear at present. However, we achieved both the large output power and the spectral shape with a single peak structure by using the perpendicular magnetic field and the MTJ with the Fe-rich CoFeB free layer, which has not been achieved in previous studies [13, 19]. Therefore, the perpendicular magnetic anisotropy of the free layer and the perpendicular magnetic field are keys to develop high power spin-torque oscillators.

**Figure 4.** rf spectra for the various $I_{dc}$ under the perpendicular magnetic field. $H_{ext}$ was fixed at 4.5 kOe.

**Figure 5.** $I_{dc}$ dependence of (a) the linewidth, (b) the peak frequency, and (c) the output power under the perpendicular magnetic field. $H_{ext}$ was fixed at 4.5 kOe.
4. Summary
We obtained the large rf output power in the MTJ with the Fe-rich CoFeB free layer under the perpendicular magnetic field. The output power reached up to 175 nW, which is mainly attributable to the increase of the relative angle and the out-of-plane precessional mode. The present results clearly indicate that the Fe-rich CoFeB layer with the perpendicular magnetic anisotropy is suitable for the free layer of the spin-torque induced rf oscillation in order to achieve the large output power.

Acknowledgments
The authors thank Canon ANELVA Corporation for their cooperation in the device preparation. This work was partly supported by SCOPE (051407005) from MIC and a Grant-in-Aid for Scientific Research in priority area from MEXT.

References
[1] Slonczewski J C 1996 J. Magn. Magn. Mater. 159 L1
[2] Berger L 1996 Phys. Rev. B 54 9353
[3] Tsoi M, Jansen A G M, Bass J, Chiang W-C, Seck M, Tsoi V and Wyder P 1998 Phys. Rev. Lett. 80 4281
[4] Kiselev S I, Sankey J C, Krivorotov I N, Emley N C, Schoelkopf R J, Buhrman R A, and Ralph D C 2003 Nature 425 380
[5] Rippard W H, Pufall M R, Kaka S, Russek S E and Silva T J 2004 Phys. Rev. Lett. 92 027201
[6] Kiselev S I, Sankey J C, Krivorotov I N, Emley N C, Rinkoski M, Perez C, Buhrman R A and Ralph D C 2004 Phys. Rev. Lett. 93 036601
[7] Mistral Q, Kim J V, Devolder T, Crozat P and Chappert C 2006 Appl. Phys. Lett. 88 192507
[8] Bouille O, Cros V, Grollier J, Pereira L G, Deranlot C, Petroff F, Faini G, Barnaš J and Fert A 2007 Nature Phys. 3 492
[9] Seki T, Tomita H, Shiraishi M, Shinjo T and Suzuki Y 2010 Appl. Phys. Exp. 3 033001
[10] Rippard W H, Pufall M R, Kaka S, Silva T J and Russek S E 2004 Phys. Rev. B 70 100406
[11] Kaka S, Rippard W H, Pufall M R, Russek S E, Silva T J and Katine J A 2005 Nature 437 389
[12] Mancoff F B, Rizzo N D, Engel B N and Tehrani S 2005 Nature 437 393
[13] Deac A M, Fukushima A, Kubota H, Maehara H, Suzuki Y, Yuasa S, Nagamine Y, Tsunekawa K, Djayaprawira D D and Watanabe N 2008 Nature Phys. 4 803
[14] A. V. Nazarov, K. Nikolaev, Z. Gao, H. Cho, and D. Song, J. Appl. Phys. 103, 07A503 (2008).
[15] Houssameddine D, Florez S H, Katine J A, Michel J-P, Ebels U, Mauri D, Oztay O, Delaet B, Viala B, Folks L, Terris B D and Cyrille M-C 2008 Appl. Phys. Lett. 93 022505
[16] Kudo K, Nagasawa T, Sato R and Mizushima K 2009 Appl. Phys. Lett. 95 022507
[17] Cornelissen S, Bianchini L, Hrkac G, Op de Beeck M, Lagne L, Kim J V, Devolder T, Crozat P, Chappert C and Schrefl T 2009 Euro. Phys. Lett. 87 57001
[18] Matsumoto R, Fukushima A, Yakushiji K, Yakata S, Nagahama T, Kubota H, Katayama T, Suzuki Y, Ando K, Yuasa S, Georges B, Cros V, Grollier J and Fert A 2009 Phys. Rev. B 80 174405
[19] Wada T, Yamane T, Seki T, Nozaki T, Suzuki Y, Kubota H, Fukushima A, Yuasa S, Maehara H, Nagamine Y, Tsunekawa K, Djayaprawira D D and Watanabe N 2010 Phys. Rev. B 81 104410
[20] Yakata S, Kubota H, Suzuki Y, Yakushiji K, Fukushima A, Yuasa S and Ando K 2009 J. Appl. Phys. 105 07D131
[21] Kim J V, Mistral Q, Chappert C, Tiberkevich V and Slavin A 2008 Phys. Rev. Lett. 100 167201
