Magnetic tunnel junctions (MTJs) are promising devices for next-generation spintronics devices, such as magnetoresistive random-access memory and microwave communication devices. Efficient electrical spin control of MTJs has been intensively investigated, such as spin-transfer torque,1–5 spin–orbit torque,6–11 voltage-controlled magnetic anisotropy,12–17 and Joule-heat-induced spin control.18–28 Joule-heat-induced spin control is broadly divided into the generation of spin current and the manipulation of magnetic parameters. The former are the spin Seebeck effect26,28 and spin Nernst effect.21,22,24,25,27 The latter is the Joule-heat induced change in magnetic anisotropy,19 exchange bias from antiferromagnet,19 Ruderman–Kittel– Kasuya–Yoshida coupling20 and switching field modulation near the compensation temperature of the ferrimagnet.23 The Joule-heat-induced change in magnetic anisotropy has a fast response speed in the gigahertz frequency region. It induces a large spin-torque which realizes various microwave phenomena, such as microwave amplification and emission and the bolometer-level diode effect.29–31 This is because the temperature of the ferromagnetic layer efficiently increases by suppressing heat dissipation owing to the high thermal resistance at the metal-insulator interface.32,33 Moreover, the magnitude of the change in anisotropy by Joule heating, referred to as heat controlled magnetic anisotropy (HCMA), can be enhanced by changing the capping layer structure, which suppresses the heat dissipation along the out-of-plane direction.33 In summary, the improvement of the thermal design of MTJs is significant for efficient spin control utilizing HCMA. However, while the effect on the HCMA of heat dissipation along the out-of-plane direction has been investigated, that along the in-plane direction does not.

In this study, we evaluated the HCMA of MTJs with various diameters using a previous method that employs spin-torque diode measurements30,34,35 and investigated the effect of the in-plane heat dissipation on HCMA. By comparing the experimental results with a simple model of heat dissipation, we evaluated the ratio of the heat current along the in-plane and out-of-plane directions with various MTJ diameters.

A film stack of a buffer | Ir–Mn | Co–Fe | Ru | Co–Fe–B pinned layer [MgO barrier (1 nm)] Fe–B free layer (2 nm) | MgO capping layer (0.7 nm) | metal electrode was deposited on a Si substrate by magnetron sputtering. The MTJ with a MgO | Fe–B | MgO structure has a large Joule-heat-induced magnetic anisotropy change owing to the high interfacial thermal resistance at the Fe–B | MgO interface.29 The magnetization of the Co–Fe–B layer was pinned in the in-plane direction. The films were patterned into MTJs with design diameters of 135, 180, 225, and 300 nm by photolithography. After the etching to fabricate MTJ pillar, MgO | SiO2 was deposited by sputtering. Although we show a completely vertical-shaped MTJ pillar in Fig. 1, in fact, the pillar forms a trapezoid shape such that the top is shallow and the bottom is wide. In addition, the sputtering has low directivity. Therefore, the MgO | SiO2 was deposited on the side of the MTJ pillar too. The deposited MgO thickness on the side of pillar was estimated to be less than 4 nm. The resistance area product (RA) and magnetoresistance (MR) ratios of MTJs are listed in Table I.

Figure 1 shows the measurement setup for magnetic anisotropy utilizing the spin-torque diode technique. Microwaves were applied to the MTJ using a signal generator. The diode voltage was measured using a lock-in amplifier synchronized with a signal generator. We used an attenuator of −20 dB to reduce the intensity of the microwaves. The input microwave power was −30 dBm at the MTJ position. A magnetic field was applied to the MTJs perpendicular to the film plane. A DC voltage was applied from a current source.

Figure 2(a) shows the frequency dependence of the diode voltage measured by the lock-in amplifier under an out-of-plane magnetic field. The diode voltage was subtracted by that at 600 mT to remove the background signal. The design diameter of the MTJ was 180 nm. Peak signals were observed depending on the magnetic field. These are...
ferromagnetic resonance peaks because the peak frequency increases with an increasing magnetic field. Figure 2(b) shows the magnetic field dependence of the resonance frequency. By considering the Kittel formula, the magnetic anisotropy field $H_k$ can be obtained from the horizontal intercept of the linear fitting shown as dashed lines. We calculated $2\mu_0 H_k$ from the width between the positive and negative horizontal intercepts of the fitting. Here, we eliminated plots whose frequency could not be determined because of the small peak intensity and plots that deviate from the linear fitting line because of the unstable magnetization direction near 0 mT. Figure 2(c) shows the DC voltage dependence of perpendicular magnetic anisotropy $K$ evaluated by $K = \frac{1}{2}\mu_0 M_s H_k$. Here, we used the saturation magnetization $M_s = 1300$ kA m$^{-1}$ measured by a vibrating sample magnetometer. The result shows a parabolic voltage dependence, suggesting that the magnetic anisotropy is modulated by Joule heating. The value of HCMA

| Diameter (nm) | RA (Ω μm$^2$) | MR (%) |
|---------------|---------------|--------|
| 135           | 8.0           | 41     |
| 180           | 5.6           | 44     |
| 225           | 5.9           | 39     |
| 300           | 6.5           | 41     |

Table I. RAs and MR ratios of MTJs with various diameters.

Fig. 1. Circuit for spin-torque diode measurement and film stack of MTJs. The external magnetic field was applied along the perpendicular to the film plane.

Fig. 2. (Color online) (a) Spin-torque diode spectra of 180 nm diameter MTJ under various perpendicular magnetic fields without bias voltage. (b) Perpendicular magnetic field dependence of resonance frequency of 180 nm diameter MTJ without bias voltage. Circle and cross plots represent the sweep direction of magnetic field. Dashed lines are the results of linear fitting. $2\mu_0 H_k$ was obtained from the width between the positive and negative horizontal intercepts of the fitting. (c) The DC voltage dependence of the perpendicular magnetic anisotropy energy. The colors and shapes represent the diameter of the MTJs. Filled and open plots represent the sweep direction of bias voltage. The solid lines represent the second-order polynomial fittings.
Fig. 3. (Color online) (a) Dependence of the MTJ design diameter on HCMA. Dots are the experimental results. Solid line represents the fitting results by the heat dissipation model without including the HCMA at the diameter of 135 nm. (b) Design diameter dependence of the ratio of heat current along in-plane and out-of-plane directions. Solid line corresponds to the results without including the HCMA at the diameter of 135 nm.

\[
\frac{\partial K}{\partial p} = k_2 RA \text{ can be obtained from the second-order coefficient of the polynomial fitting curve,} \]

\[
K = k_0 + k_1 V + k_2 V^2. \]

Figure 3(a) shows the design diameter dependence of HCMA. We observed an HCMA magnitude of up to 5.4 \( \mu J \) (Wm\(^{-1}\)), which is the largest HCMA value ever reported. Moreover, we found that the HCMA increased with increasing diameter. This corresponds to the temperature increase in the Fe–B layer. This result suggests that there was heat current generation along the in-plane direction.

We discuss the ratio of the heat current between the in-plane and out-of-plane directions using the following model. By considering the outflow of heat current from Fe–B and inflow by Joule heating, we obtain the following formula:

\[
\Delta P = \left[ \frac{\pi d^2}{4R_{\text{heat,MgObarrier}}} + \frac{\pi d^2}{4R_{\text{heat,MgOcap}}} + \frac{\pi dt}{R_{\text{heat,side}}} \right] \Delta T,
\]

where \( \Delta P \) and \( \Delta T \) represent the power and temperature changes; respectively; \( d \) and \( t \) are the diameter and thickness of Fe–B; respectively; and \( R_{\text{heat,MgObarrier}}, R_{\text{heat,MgOcap}}, \) and \( R_{\text{heat,side}} \) represent the thermal resistance per unit area of the MgO barrier, MgO capping, and side wall of Fe–B, respectively. On the other hand, because the anisotropy change \( \Delta K \) can be written as \( \Delta K = -\kappa \Delta T \) using the temperature change \( \Delta T \) and coefficient \( \kappa \) in the linear response region, the HCMA can be written as

\[
\text{HCMA} = \frac{\Delta K}{\Delta P} \frac{\pi d^2}{4} = \frac{-\kappa R_{\text{heat,OP}}}{1 + R_{\text{heat,OP}} + R_{\text{heat,side}}} (2)
\]

using Eq. (1). Here, we define the thermal resistance per unit area of the heat current along the out-of-plane direction as \( R_{\text{heat,OP}}^{-1} \equiv R_{\text{heat,MgObarrier}}^{-1} + R_{\text{heat,MgOcap}}^{-1} \).

Here, it should be noted that the anisotropy energy of a 135 nm diameter MTJ had a large variation, especially in the negative DC voltage region as shown in Fig. 2(c). It also deviates from the trend of the increase in magnetic anisotropy with decreasing the junction size. In addition, the HCMA deviates from the trend of its size dependence as shown in Fig. 3(a). Therefore, the HCMA result of a 135 nm diameter MTJ was not reliable. These results may be attributed to the damage to the side of the MTJ pillar caused by the fabrication process, such as ion milling, because the smaller MTJ is affected more strongly by the side of the MTJ pillar. The solid line in Fig. 3(a) shows the fitting result without including the result for the 135 nm diameter. From this result, \( R_{\text{heat,OP}}/R_{\text{heat,side}} \) was 37.7 \pm 2.3. Surprisingly, although both the out-of-plane and in-plane surfaces of Fe–B were in contact with MgO, the thermal resistance per unit area of the out-of-plane surface was markedly larger than that of the in-plane surface. This may be attributed to the different surface conditions of the out-of-plane and in-plane surfaces. For example, interface roughness is the possible origin. Generally, the interface of the out-of-plane direction of an MTJ has a flat surface with a roughness of less than 1 nm. On the other hand, the side of an MTJ may have larger roughness because it is patterned by lithography and milled by etching. The roughness increases the surface area of the side of an MTJ pillar, which decreases the thermal resistance. Therefore, the interface roughness may affect the heat current.

Figure 3(b) shows the diameter dependence of the ratio of the heat current along the in-plane and out-of-plane directions \( I_{\text{IP}}/I_{\text{OP}} = (R_{\text{heat,OP}}/R_{\text{heat,side}})^{-1} \). Although the diameter is two orders of magnitude larger than the thickness, the in-plane heat current is larger than the out-of-plane heat current for diameters smaller than 300 nm. This is because, as mentioned above, the ratio of the out-of-plane and in-plane thermal resistances per unit area is markedly large. Our results indicate that the thermal design in the in-plane direction is significant even in the case of a ferromagnetic layer with a high aspect ratio.

In conclusion, we evaluated the HCMA of MTJs with various diameters measured using the spin-torque diode technique. As a consequence, the magnitude of HCMA was obtained up to 5.4 \( \mu J \) (Wm\(^{-1}\)) which is the highest ever reported HCMA value. Furthermore, HCMA increased with an increase in the diameter. By comparing the experimental results and a simple model of heat current, we evaluated the ratio of the heat current along the in-plane and out-of-plane directions. Although the diameter is two orders of magnitude larger than the thickness, the in-plane heat current is larger than the out-of-plane heat current, for diameters smaller than 300 nm. Our results suggest that the improvement of thermal design along not only the out-of-plane direction but also the in-plane direction is significant in heat-driven MTJs.
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1) L. Berger, J. Phys. Chem. Solids. 35, 947 (1974).
2) L. Berger, Phys. Rev. B 54, 9353 (1996).
3) E. B. Myers, D. C. Ralph, J. A. Katine, R. N. Louie, and R. A. Buhrman, Science 285, 867 (1999).
4) J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1 (1996).
5) J.-i. Inoue, G. E. W. Bauer, and L. W. Molenkamp, Phys. Rev. B 70, 041303 (R) (2004).
6) Y. K. Kato, R. C. Myers, A. C. Gossard, and D. D. Awschalom, Science 301, 1348 (2003).
7) S. Murakami, N. Nagaosa, and S. Zhang, Science 301, 1348 (2003).
8) E. I. Rashba, Phys. Rev. B 68, 241315 (2003).
9) J. Schliemann and D. Loss, Phys. Rev. B 69, 165315 (2004).
10) J. Sinova, D. Culcer, Q. Niu, N. A. Sinitsyn, T. Jungwirth, and A. H. MacDonald, Phys. Rev. Lett. 92, 126603 (2004).
11) S. O. Valenzuela and M. Tinkham, Nature 442, 176 (2006).
12) C. G. Duan, J. P. Velev, R. F. Sabirianov, Z. Zhu, J. Chu, S. S. Jaswal, and E. Y. Tsymbal, Phys. Rev. Lett. 101, 137201 (2008).
13) T. Maruyama et al., Nat. Nanotechnol. 4, 158 (2009).
14) K. Nakamura, R. Shimabukuro, Y. Fujiwara, T. Akiyama, T. Ito, and A. J. Freeman, Phys. Rev. Lett. 102, 187201 (2009).
15) M. Tsukikawa and T. Oda, Phys. Rev. Lett. 102, 247203 (2009).
16) M. Weisheit, S. Fähler, A. Marty, Y. Souche, C. Poinsignon, and D. Givord, Science 315, 349 (2007).
17) H. Zhang, M. Richter, K. Koepenik, I. Opahle, F. Tasnádi, and H. Eschrig, New. J. Phys. 11, 043007 (2009).
18) S. Bandiera, R. C. Sousa, M. Marinis de Castro, C. Ducruet, C. Portemont, S. Auffret, L. Vila, I. L. Prejbeanu, B. Rodmacq, and B. Dieny, Appl. Phys. Lett. 99, 202507 (2011).
19) R. S. Beech, J. A. Anderson, A. V. Pohm, and J. M. Daughton, J. Appl. Phys. 87, 6403 (2000).
20) A. Chavent, C. Ducruet, C. Portemont, L. Vila, J. Alvarez-Hérault, R. Sousa, I. L. Prejbeanu, and B. Dieny, Phys. Rev. Appl. 6, 034003 (2016).
21) S.-g. Cheng, Y. Xing, Q.-f. Sun, and X. C. Xie, Phys. Rev. B 78, 045302 (2008).
22) Z. Ren, K. Qian, M. Aldosary, Y. Liu, S. K. Cheung, I. Ng, J. Shi, and Q. Shao, APL Mater. 9, 031117 (2021).
23) T. Seki, I. Sugai, Y. Hasegawa, S. Mitani, and K. Takahashi, Solid State Commun. 150, 496 (2010).
24) P. Sheng, Y. Sakuraba, Y. C. Lau, S. Takahashi, S. Mitani, and M. Hayashi, Sci. Adv. 3, e1701503 (2017).
25) K. Uchida, S. Takahashi, K. Harii, J. Ieda, W. Koshiba, K. Ando, S. Maekawa, and E. Saitoh, Nature 455, 778 (2008).
26) S. Wimmer, D. Ködderitzsch, K. Chadowa, and H. Ebert, Phys. Rev. B 88, 201108(R) (2013).
27) J. Xiao, G. E. W. Bauer, K.-c. Uchida, E. Saitoh, and S. Maekawa, Phys. Rev. B 81, 214418 (2010).
28) M. Goto et al., Nat. Nanotechnol. 14, 40 (2019).
29) M. Goto et al., Nat. Commun. 12, 531 (2021).
30) Y. Yamada et al., Appl. Phys. Lett. 118, 192402 (2021).
31) T. Böhmert, R. Dutra, R. L. Sommer, E. Paz, S. Serrano-Guisan, R. Ferreira, and P. P. Freitas, Phys. Rev. B 95, 104441 (2017).
32) K. Zhang, M. Bachman, M. Czerner, and C. Heiliger, Phys. Rev. Lett. 115, 037203 (2015).
33) R. Okuno et al., J. Phys.:Condens. Matter 32, 384001 (2020).
34) A. A. Tulapurkar, Y. Suzuki, A. Fujikishima, K. Kubota, H. Maehara, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe, and S. Yuasa, Nature 438, 339 (2005).