Heat dissipation due to ferromagnetic resonance in a ferromagnetic metal monitored by electrical resistance measurement

Kazuto Yamanoi, Yuki Yokotani, and Takashi Kimura

Citation: Applied Physics Letters **107**, 182410 (2015); doi: 10.1063/1.4935243
View online: http://dx.doi.org/10.1063/1.4935243
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/107/18?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS 107, 182410 (2015)

Heat dissipation due to ferromagnetic resonance in a ferromagnetic metal monitored by electrical resistance measurement

Kazuto Yamanoi,[1] Yuki Yokotani,[1] and Takashi Kimura[1,2,a)]
[1]Department of Physics, Kyushu University, 6-10-1 Hakozaki, Fukuoka 812-8581, Japan
[2]Research Center for Quantum Nano-Spin Sciences, Kyushu University, 6-10-1 Hakozaki, Fukuoka 812-8581, Japan

(Received 19 August 2015; accepted 25 October 2015; published online 4 November 2015)

The heat dissipation due to the resonant precessional motion of the magnetization in a ferromagnetic metal has been investigated. We demonstrated that the temperature during the ferromagnetic resonance can be simply detected by the electrical resistance measurement of the Cu strip line in contact with the ferromagnetic metal. The temperature change of the Cu strip due to the ferromagnetic resonance was found to exceed 10 K, which significantly affects the spin-current transport. The influence of the thermal conductivity of the substrate on the heating was also investigated. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4935243]

The dynamical motion of the magnetization in the ferromagnetic material under the magnetic field can be well described by a phenomenological Landau-Lifshiz-Gilbert (LLG) equation.[1,2] Application of the high-frequency magnetic field induces the resonant precessional motion of the magnetizations such as the ferromagnetic resonance (FMR)[3–5] and spin-wave (SW) excitation.[6–8] The frequency range of these resonances in the ferromagnetic metal (FM) can be widely tuned from sub-GHz to a few 10 GHz because of a large gyromagnetic ratio γ, where $\gamma/2\pi$ is approximately 29.2 GHz/T. Moreover, various phenomena combined with magnetization dynamics such as spin pumping[9–11] and spin torque precession[12,13] have been found recently. These properties are highly attractive for future applications in nanoelectric and telecommunication devices.[6–8] Especially, since the dynamical spin motion is found to generate the spin current via the spin pumping effect,[11,15,16] considerable attention have been paid to manipulate the magnetization dynamics in the ferromagnets. To utilize these unique spin functionalities in practical applications, the detailed experimental studies on the magnetization dynamics with deepening the understandings are indispensable issues.

So far, the magnetization dynamics have been mainly investigated under the assumption of a small amplitude of the oscillation, in which the magnetization responses can be treated by linearized LLG equation. However, this simplification becomes invalid when the large amplitude of the precessional oscillation is excited.[14] The deviation from the linearized LLG equation is also caused by the extrinsic natures such as the magnetic inhomogeneity and structural defects. Moreover, it should also be noted that the dynamical magnetization motion produces the dissipation because of the existence of the damping term.[1,9–11] This dissipation finally produces the heat through the direct and indirect magnon-phonon interactions. If the heating effect due to the dissipation is non-negligibly large, the saturation magnetization and the phenomenological damping factor will be changed, leading to the modification of the magnetization dynamics. Although the heating effect induced by the FMR is well known as the FMR heating effect,[18] the study on the FMR heating effect has not been investigated intensively. Especially, in the field of spintronics, there are only a few reports about the investigation of the relationship between spin dynamics and heat.[19,20] On the other hand, recently, the interaction between the spin and heat is found to play an important role both for the localized magnetic moment and the spin polarization of conduction electrons.[21–23] Particularly, the spin current can be produced by the temperature gradient across the ferromagnet(F)/nonmagnet(N) interface.[24] Therefore, the spin current due to the FMR heating may be considered in the phenomena observed in the F/N bilayer systems in addition to the spin current induced by the spin pumping.[15–17] Thus, the precise evaluation of the FMR heating in the hybrid nanostructures is indispensable for the fundamental and technological developments of the spin dynamics. In the present paper, we develop a simple detection method for the FMR heating effect in a patterned ferromagnetic structure with the optimized device structure in order to minimize the spurious effects.

Our device consists of a rectangular ferromagnetic wire covered by a thick Cu strip, which plays a role of the wave guide for the microwave. As a ferromagnet, we use a CoFeAl wire, which is simply fabricated by an e-gun evaporation under the base pressure of 10^{-9} Torr.[25] The dimensions for the CoFeAl wire are 2 μm in width, 500 μm in length, and 40 nm in thickness. Here, the anisotropic magnetoresistance (AMR) for the CoFeAl is 0.03% at room temperature, much smaller than the conventional FMs. The Cu wave guide consists of large Cu pads and a narrow strip line. Here, the dimension of the strip line is 4.5 μm in width, 450 μm in length, and 200 nm in thickness. In order to clarify the influence of the heat, we fabricated the samples on two kinds of the substrates with different thermal conductivities. One is a floating-zone (FZ) Si substrate, which is widely utilized for the high-frequency and power devices and has moderate thermal conductivity. The other one is a glass substrate, which is also often used for the high-frequency experiment but has poor thermal conductivity. The temperature

a)t-kimu@phys.kyushu-u.ac.jp

evaluation during the FMR is simply carried out by the electrical resistance measurement of the Cu strip line with the FM wire. Figure 1(b) shows the temperature dependence of the electrical resistivity for our Cu in the range from 10 K to 320 K. The resistance shows almost linear variation in the temperature range from 50 K to 320 K. We extend this linear relation to 400 K in order to estimate the temperature increase from the resistance measurements. We emphasize that the electrical resistivity for the Cu is approximately 2.3 $\mu\Omega$ cm at room temperature, which is approximately 20 times smaller than that for the CoFeAl. This means that the current flowing in the FM layer of the bilayer system is negligibly small because of the large difference in the electrical resistivity and the film thickness. In addition, because of the large size of the Cu pad, the resistance of the pad area, which is less than 0.1 Ω, is negligibly small compared to the Cu strip line. This indicates that we can precisely estimate the resistance of the strip line from the two-terminal measurement.

First, we evaluate the microwave transmission characteristic of the waveguide and the magnetization dynamics for two samples prepared on the different substrates from the reflection measurement (S_{11}) for the Cu strip line using a vector network analyzer.[4,29] Here, the input microwave power is −10 dBm and the external magnetic field is applied along the Cu wire direction in order to fix the precession axis of the magnetization. The spectra for each magnetic field have been obtained by subtracting the background signal measured at the strong magnetic field. Figures 2(a) and 2(b) show the FMR spectra for the CoFeAl fabricated on the FZ-Si and glass substrates, respectively. In both samples, the signal changes due to the FMR were clearly observed. The field dependence of the resonant frequency $f_{\rm res}$ is well reproduced by the Kittel formula described by the following equation:[3,4]

$$f_{\rm res} = \gamma\sqrt{\mu_0 H(\mu_0 H + M_S)}. \quad (1)$$

Here, μ_0 and M_S are the vacuum permeability and the saturation magnetization, respectively. From the fitting of the Kittel's equation, the saturation magnetization can be obtained as 2.2 T, which is a reasonable value compared with previous reports concerning Co-Fe Alloy.[26] Here, we focus on the spectrum shape due to the FMR. The signal change due to the FMR in the glass substrate sample is smaller than that in the FZ-Si substrate. This indicates that the transmission loss of the Cu strip on a glass substrate is worse than that on the FZ-Si substrate, meaning smaller transmission power for the glass substrates sample. In addition, we point out that the resonant signature in the glass-substrate sample is broader that in the FZ-Si substrate. Since the quantitative estimation of the damping constant is not main subject in the present paper, we do not estimate the damping constants for both films. However, from the spectra shown in Fig. 2, we can easily expect that the damping constant for the glass-substrate sample is much larger than that for the FZ-Si-substrate sample. This is because the surface roughness of the glass substrate is relatively large compared to the FZ-Si substrate.[27]

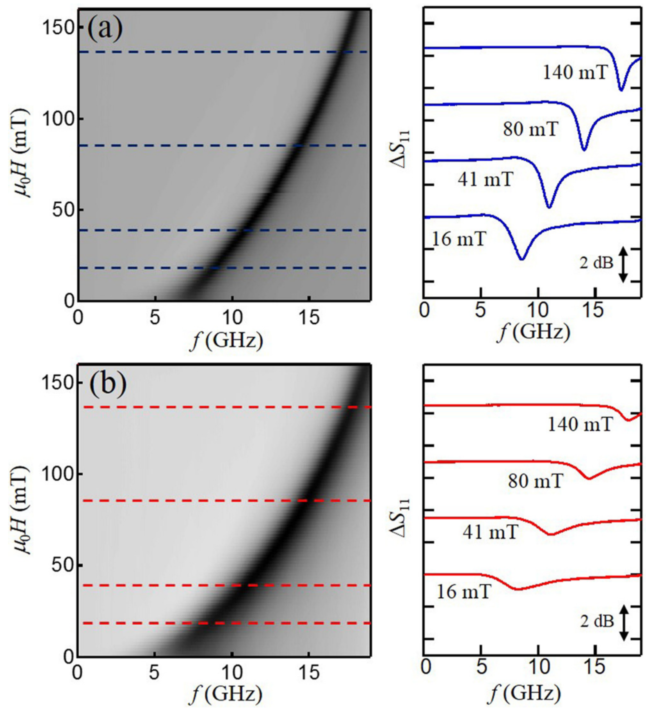

FIG. 2. Image plots for the FMR spectra for (a) FZ-Si substrate sample and (b) glass substrate sample together with the representative spectra for various magnetic fields.

We then measure the electrical resistance of the Cu strip under the microwave irradiation in order to evaluate the temperature during the FMR by using a current-bias low-frequency lock-in detection technique with the bias current of 16 μA. Although the current for the resistance detection flows in the Cu/CoFeAl bilayer system, we can neglect the voltage drop in the FM because of much larger resistance of the CoFeAl. Moreover, since the CoFeAl wire is located underneath the Cu strip line entirely, the Cu strip line should be heated by the FMR almost uniformly. Figures 3(a) and 3(b) show the electrical resistances of the Cu strip on the FZ-Si and the glass substrates, respectively, as a function of the

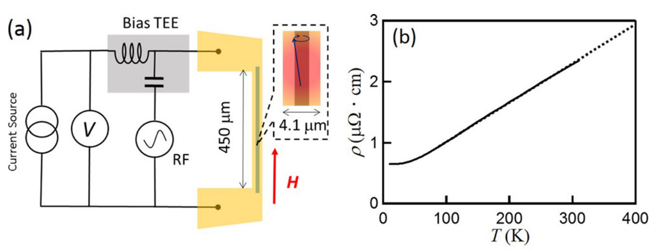

FIG. 1. (a) Circuit diagram for the resistance measurement under the microwave magnetic field application together with the conceptual image of the FMR heating. (b) Temperature dependence of the resistivity for our Cu film.

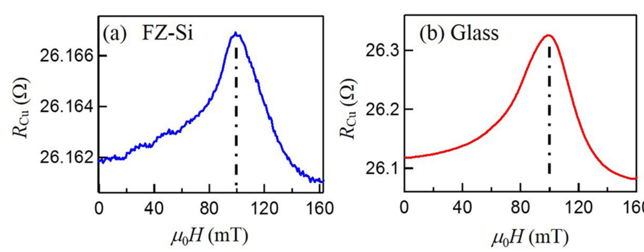

FIG. 3. Field dependences of the electrical resistances for the Cu strip lines on (a) FZ-Si substrate and (b) glass substrate. During the resistance measurements, the microwave signal with the power of 100 mW was superimposed.

external magnetic field. Here, the direction of the magnetic field is parallel to the current, corresponding to the longitudinal configuration. In both samples, we clearly see the rapid increases of the resistance around $H = 98$ mT, which is exactly the same as the magnetic field for the FMR at 16 GHz, as shown in Fig. 3. Therefore, this increase should be related to the FMR. Since the resistance change due to the AMR, which is very small as described above, provides the opposite contribution, we can rule out the spurious effects from the AMR. More importantly, the resistance increase for the glass substrate is roughly 50 times larger than that for the FZ-Si substrate. Thus, we conclude that the main contribution of the observed resistance increase is caused by the FMR heating.[18]

Now, we evaluate the temperature change ΔT due to the FMR. In the present system, since the heat source is the CoFeAl wire, the temperature gradient perpendicular to the CoFeAl/Cu junction should be induced. This perpendicular temperature gradient may give rise to the additional signals such as the anomalous Nernst-Ettingshausen,[28] spin Seebeck,[22] and spin-dependent Seebeck effects.[23] However, since the magnetic field is applied along the strip line (longitudinal configuration), we can exclude the contributions from such spurious effects. Therefore, we assume that the observed resistance change is mainly caused by the change of the Cu resistivity due to the heating.

From the assumption of the linear relationship between the resistance and the temperature shown in Fig. 1(b), we can roughly estimate the temperature of the Cu strip line. For example, in the inset of Fig. 4, since the resistance change is 206 mΩ, ΔT is estimated to be 8 K at the microwave power of 100 mW. Figure 4 shows the summary of the temperature increase due to the FMR, where ΔT as a function of the input microwave power is plotted. ΔT shows almost linear increase with the microwave power below 100 mW, but the slope starts to decrease gradually above 100 mW. This deviation is probably due to the increase in the heat dissipation rate into other parts such as air and substrate. Even in such a large dissipation situation, ΔT reaches at approximately 15 K under

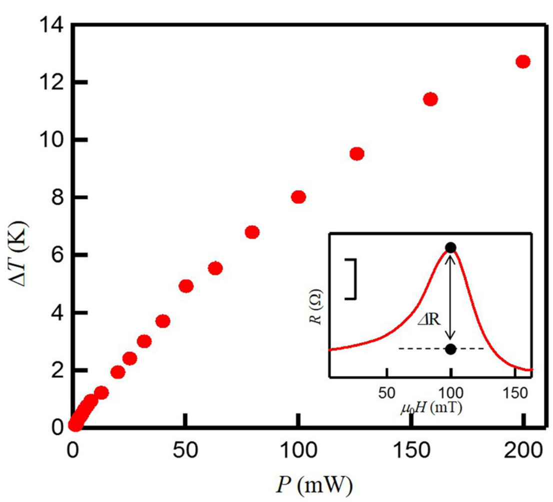

FIG. 4. Temperature change due to the FMR heating of the CoFeAl on the glass substrate as a function of the input microwave power. The inset shows the representative field dependence of the resistance with the definition of ΔR. The scale bar of the inset is 0.1 Ω.

the microwave power of 200 mW. This is sufficiently large for the thermal manipulation of the spin current.[21–23] We also emphasize that the estimated temperature corresponds to the average temperature of the Cu strip line. Since the system is connected to the large Cu pad and the radio-frequency (RF) probe which play roles of the large thermal basses, the huge heat flow into the outside should exist. Moreover, as mentioned before, the temperature distribution in the vicinity of the CoFeAl/Cu interface is inhomogeneous. These indicate that the realistic temperature change of the ferromagnet is much higher than ΔT estimated from the present measurement.

Finally, we discuss about the resistance curve as a function of the external magnetic field. If we carefully see the shape of the resistance curve, the curve slightly shows asymmetric dependence with respect to the resonant field. The reason for the asymmetry in the field dependence of the resistance is not clear at moment. However, since the real part of the magnetic susceptibility shows the anti-symmetric Lorentz curve,[29,30] the origin of the asymmetry should be related to it. One of the possible reasons is the impedance change of the waveguide due to the resonance. We used a RF signal generator as the microwave source in the measurements. Therefore, the input microwave power depends on the impedance of the strip line.[4] Since the inductance of the waveguide reflects the real part of the magnetic susceptibility, the transmission power into the strip line also shows the field dependence similar to the inductance. Another possibility is due to the eddy current loss in the FM strip,[31] which also should reflect the real part of the magnetic susceptibility. These two effects explain the small asymmetry observed in the field-dependence of the resistance qualitatively.

In short, we have developed a relatively simple way to evaluate the heat dissipation due to the magnetization dynamics. We showed that the temperature change due to the FMR can be detected by the electrical resistance change of the Cu strip and found that a nonlinear relationship between the temperature change due to the FMR and the input microwave power. The temperature change due to the FMR is found to reach an approximately 13 K under the microwave power of 200 mW. This is sufficiently a large value for inducing the spin-heat dynamic effects. Considering the fact that our detecting temperature corresponds to the steady-state temperature, we expect that a thermal flow induced by the magnetization dynamics can play a dominant role in the phenomena with the magnetization dynamics.

This work was partially supported by Grant-in-Aid for Scientific Research on Innovative Area, "Nano Spin Conversion Science" (26103002) and for Scientific Research (S)(25220605).

[1]T. L. Gilbert, Phys. Rev. **100**, 1243 (1955).
[2]*Spin Dynamics in Confined Magnetic Structures*, edited by B. Hillebrands and A. Thiaville (Springer, 2006).
[3]C. Kittel, Phys. Rev. **73**, 155 (1948).
[4]T. J. Silva, C. S. Lee, T. M. Crawford, and C. T. Rogers, J. Appl. Phys. **85**, 7849 (1999).
[5]M. V. Costache, S. M. Watts, M. Sladkov, C. H. van der Wal, and B. J. van Wees, Appl. Phys. Lett. **89**, 232115 (2006).
[6]M. P. Kostylev, A. A. Serga, T. Schneider, B. Leven, and B. Hillebrands, Appl. Phys. Lett. **87**, 153501 (2005).

[7]K. Sekiguchi, K. Yamada, S.-M. Seo, K.-J. Lee, D. Chiba, K. Kobayashi, and T. Ono, Phys. Rev. Lett. **108**, 017203 (2012).
[8]K. Yamanoi, S. Yakata, T. Kimura, and T. Manago, Jpn. J. Appl. Phys., Part 1 **52**, 083001 (2013).
[9]S. Mizukami, Y. Ando, and T. Miyazaki, Phys. Rev. B **66**, 104413 (2002).
[10]Y. Tserkovnyak, A. Brataas, and G. E. W. Bauer, Phys. Rev. Lett. **88**, 117601 (2002).
[11]B. Heinrich, Y. Tserkovnyak, G. Woltersdorf, A. Brataas, R. Urban, and G. E. W. Bauer, Phys. Rev. Lett. **90**, 187601 (2003).
[12]S. I. Kiselev, J. C. Sankey, I. N. Krivorotov, N. C. Emley, R. J. Schoelkopf, R. A. Buhrman, and D. C. Ralph, Nature **425**, 380–383 (2003).
[13]M. Tsoi, A. G. M. Jansen, J. Bass, W.-C. Chiang, V. Tsoi, and P. Wyder, Nature **406**, 46–48 (2000).
[14]D. Isaak, *MayergoyzGiorgio BertottiClaudio Serpico Nonlinear Magnetization Dynamics in Nanosystems* (Elsevier, 2008), ISBN: 978-0-08-044316-4.
[15]E. Saitoh, M. Ueda, H. Miyajima, and G. Tatara, Appl. Phys. Lett. **88**, 182509 (2006).
[16]J.-C. Rojas-Snchez, N. Reyren, P. Laczkowski, W. Savero, J.-P. Attan, C. Deranlot, M. Jamet, J.-M. George, L. Vila, and H. Jaffrs, Phys. Rev. Lett. **112**, 106602 (2014).
[17]O. Mosendz, V. Vlaminck, J. E. Pearson, F. Y. Fradin, G. E. W. Bauer, S. D. Bader, and A. Hoffmann, Phys. Rev. B **82**, 214403 (2010).
[18]N. Yoshikawa and T. Kato, J. Phys. D: Appl. Phys. **43**(42), 425403 (2010).
[19]F. L. Bakker, J. Flipse, A. Slachter, D. Wagenaar, and B. J. van Wees, Phys. Rev. Lett. **108**, 167602 (2012).
[20]T. An, V. I. Vasyuchka, K. Uchida, A. V. Chumak, K. Yamaguchi, K. Harii, J. Ohe, M. B. Jungfleisch, Y. Kajiwara, H. Adachi, B. Hillebrands, S. Maekawa, and E. Saitoh, Nat. Mater. **12**, 549–553 (2013).
[21]G. E. W. Bauer, E. Saitoh, and B. J. van Wees, Nat. Mater. **11**, 391–399 (2012).
[22]K. Uchida, S. Takahashi, K. Harii, J. Ieda, W. Koshibae, K. Ando, S. Maekawa, and E. Saitoh, Nature **455**, 778–781 (2008).
[23]A. Slachter, F. L. Bakker, J-P. Adam, and B. J. van Wees, Nat. Phys. **6**, 879–882 (2010).
[24]M. Johnson and R. H. Silsbee, Phys. Rev. B **35**, 4959 (1987).
[25]S. Hu, H. Itoh, and T. Kimura, NPG Asia Mater. **6**, e127 (2014).
[26]C. Bilzer, T. Devolder, J.-V. Kim, G. Counil, C. Chappert, S. Cardoso, and P. P. Freitas, J. Appl. Phys. **100**, 053903 (2006).
[27]S. Mizukami, Y. Ando, and T. Miyazaki, Jpn. J. Appl. Phys., Part 1 **40**, 580 (2001).
[28]S. Y. Huang, X. Fan, D. Qu, Y. P. Chen, W. G. Wang, J. Wu, T. Y. Chen, J. Q. Xiao, and C. L. Chien, Phys. Rev. Lett. **109**, 107204 (2012).
[29]G. Counil, J.-V. Kim, T. Devolder, C. Chappert, K. Shigeto, and Y. Otani, J. Appl. Phys. **95**, 5646 (2004).
[30]A. Azevedo, R. O. Cunha, F. Estrada, O. Alves Santos, J. B. S. Mendes, L. H. Vilela-Leo, R. L. Rodrguez-Surez, and S. M. Rezende, Phys. Rev. B **92**, 024402 (2015).
[31]J. R. Truedson, K. D. McKinstry, P. Kabos, and C. E. Patton, J. Appl. Phys. **74**(4), 2705 (1993).