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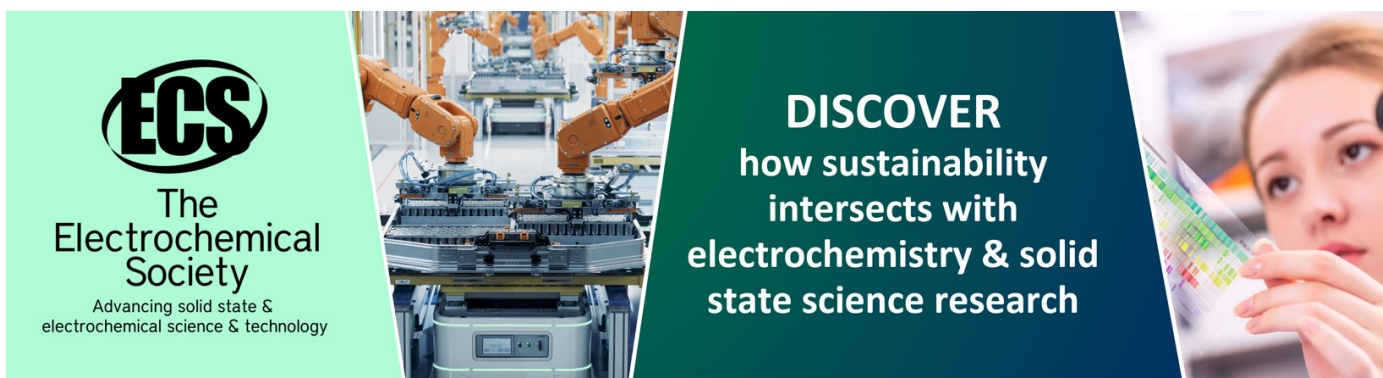
Detection of ferromagnetic resonance in a single-crystalline Fe wire using a rectifying effect

To cite this article: Y Kasatani *et al* 2011 *J. Phys.: Conf. Ser.* **266** 012013

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Detection of ferromagnetic resonance in a single-crystalline Fe wire using a rectifying effect

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Abstract. The broadband ferromagnetic resonance (FMR) of a single-crystalline Fe microwire was measured using a rectifying effect. The experimental result indicates the uniform mode dominates the system. The effective Gilbert damping factor of the Fe wire was estimated by the rectifying effect. A rectifying spectrum is broadened because of the spin wave excitation and the thermal fluctuation as the input power increases.

1. Introduction

The revealing of magnetization dynamics in nanoscale and micronscale artificial ferromagnets is one of the most interesting issues. With the development of the radio frequency (rf) measurement technique, the investigation of the magnetization dynamics in nanoscale and micron-scale patterned magnets has been proceeded [1-10]. For example, the rectifying effect induced by a rf current has been recently applied to detect ferromagnetic resonance (FMR) in the artificial ferromagnetic wire [8].

Because high-quality epitaxial growth method has been established, low-dimensional single-crystalline ferromagnets are available for studying on the magnetization dynamics. Therefore, the Gilbert damping factor has been estimated in the single-crystalline Fe ultrathin film [1,2] and in the single-crystalline Fe strip line [5].

In this paper, the measurement technique for the broadband FMR of a single-crystalline Fe microwire using a rectifying effect is established. We reveal the effect of the thermal fluctuation on the magnetization relaxation caused by Joule heating effect due to a rf current injection.

2. Experimental Preparation

High-quality epitaxial Fe(100)_{bcc} films of 50 nm in thickness were grown in ultrahigh vacuum (UHV) at 100 °C by molecular beam epitaxy (MBE) on MgO(100) substrates, followed by 10 nm-thick protective Au cap at room temperature using MBE in UHV. A Fe wire of 1 μm width was fabricated using e-beam lithography and Ar ion milling. The longitudinal axis of wire was aligned along Fe(100)[011]_{bcc} direction in the plane. A coplanar waveguide (CPW) constructed with Cr (5 nm)/Au (80 nm) were continuously made by the e-beam lithography and the lift-off method. Optical

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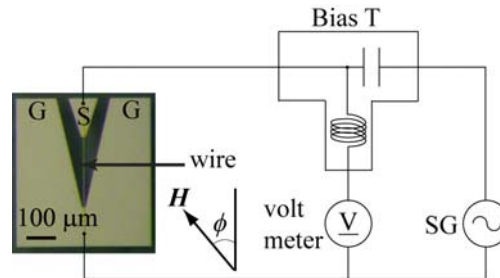


Figure 1. Optical micrograph of a sample and schematic of an electrical measurement circuit.

micrograph of a typical system is shown in figure 1. A ground-signal-ground (GSG)-type microwave probe was connected to the CPW, and the dc voltage difference induced by the rf current was detected via a bias-tee (Bias T) circuit. The rf current was injected into the wire by a signal generator with the frequency range from 500 MHz to 40 GHz. The structural characteristic of the Fe layer was determined by reflection high-energy electron diffraction (RHEED) and out-of-plane thin-film X-ray diffraction (TF-XRD) measurements. The RHEED image of Fe deposited on an MgO(100) substrate (figure 2(a)) showed some spots and streaks from Fe(100)_{bcc}. The out-of-plane TF-XRD result is shown in figure 2(b). These results indicate that the Fe film is epitaxially grown on an MgO(100) substrate with a little strain.

3. Results and Discussion

The external static magnetic field $|\mathbf{H}|$ sweeping from 0 to 2023 Oe was applied in the substrate plane at a tilting angle ϕ from the longitudinal axis of the wire. All FMR spectra were obtained by using the rectifying effect at room temperature.

The rf power dependence of rectifying voltage V spectra for the magnetic field of $|\mathbf{H}| = 2023$ Oe at $\phi = 30^\circ$ are shown in figure 3(a). The resonance frequency ω_k is almost constant against increasing the microwave power. Figure 3(b) shows the differential spectra of rf current power -5 dBm and +17 dBm. The differential rectifying spectra can provide highly-sensitive detection of spin-wave modes excited by the rf current. As seen in figure 3(b), the almost only uniform mode was excited even when the input rf power changed. Therefore, we describe the system with the macrospin model. The macrospin will be treated as an ellipsoid with principal axes along x , y and z and corresponding demagnetizing factors N_x , N_y and N_z . Therefore, the frequency of the uniform-mode spin wave is represented by

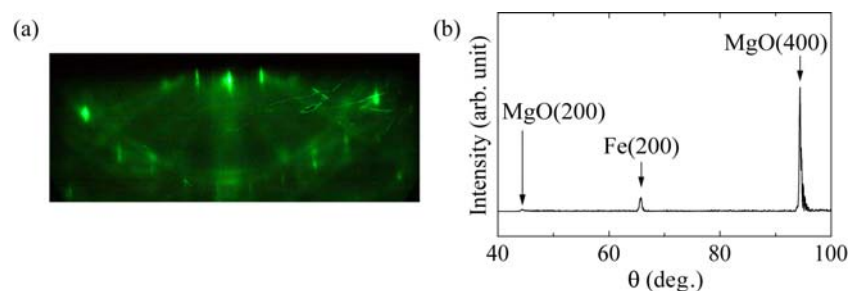


Figure 2. (a) RHEED image of the annealed Fe layer. (b) TF-XRD spectra of a Fe film deposited on an MgO(100) substrate.

$$\omega_k^2 = \gamma^2 H_b' H_c' \quad (1)$$

with

$$H_b' \approx H_{\text{ext}} + M_S (N_y - N_x) \cos 2\phi \quad (2a)$$

and

$$H_c' \approx M_S (N_z - N_x \cos^2 \phi). \quad (2b)$$

Here, H_{ext} , γ and M_S represent the applied external magnetic field, the gyromagnetic ratio and the saturation magnetization, respectively. The rectifying spectrum V is described by

$$V(f) = \frac{C_1(f^2 - f_k^2) + C_2 f^2}{(f^2 - f_k^2)^2 + f^2 \alpha_{\text{eff}}^2 \Delta^2} + V_0, \quad (3)$$

where $f = \omega/2\pi$, $f_k = \omega_k/2\pi$, V_0 , C_1 , C_2 , and α_{eff} are the rf current frequency, resonance frequency, offset voltage, asymmetric and symmetric amplitude coefficients and the effective Gilbert damping factor, respectively[8]. The full width half maximum (FWHM) of FMR spectrum Δ is written by

$$\Delta = \frac{\gamma(H_b' + H_c')}{2\pi}. \quad (4)$$

When we apply Eq. (3) to the measured spectra, we estimate the effective damping constant α_{eff} and the asymmetric and symmetric amplitude coefficients C_1 and C_2 .

The effective Gilbert damping factor α_{eff} is plotted as a function of the rf current power in figure 4. This result indicates that α_{eff} increases with increasing the input rf current power. This is attributable to the heat fluctuation of the magnetization induced by the Joule heating due to the rf current.

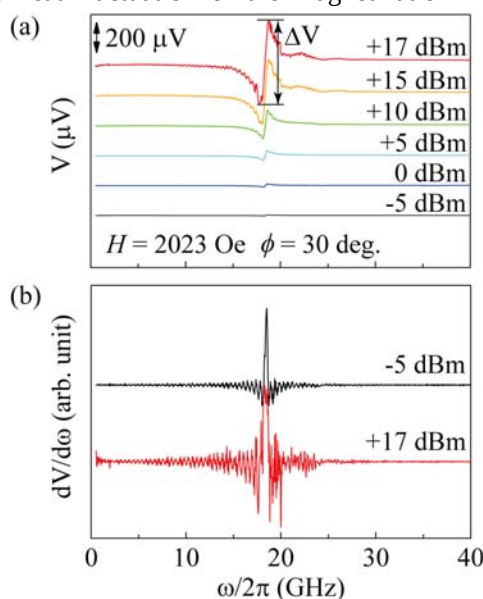


Figure 3. (a) Typical spectra of rectifying voltage V induced by intensity changed rf current under $|\mathbf{H}| = 2023$ Oe at $\phi = 30^\circ$. (b) Differential voltage $dV/d\omega$ plotted as a function of the rf frequency.

Meanwhile, it is reported that the damping factor of the single-crystalline Fe[110] wires of 45-nm in thickness and 80- μm in width is $\alpha = 0.014 \sim 0.016$ in Ref. 5, the damping factor for the single-crystalline Fe(001) film of 30-nm in thickness is $\alpha = 0.003$ in Ref. 2, and in Ref. 11, the damping factor for the epitaxial Fe(001) square dot with 50 nm on a side and 10 ML in thickness is $\alpha \approx 0.02 \sim 0.09$, respectively. It is indicated that the effective damping factor of the single-crystalline Fe decreases with growing the sample size because the boundary condition is extremely important in the magnetization damping process. As the sample size becomes small, as several modes of spin waves come to be excited and the energy dissipation via the excited spin waves increases.

4. Summary

The rectifying measurement in the single-crystalline Fe wire was established. The effective Gilbert damping factor was affected by the size of the sample in terms of the spin wave excitation and influenced by the rf power in terms of the thermal fluctuation.

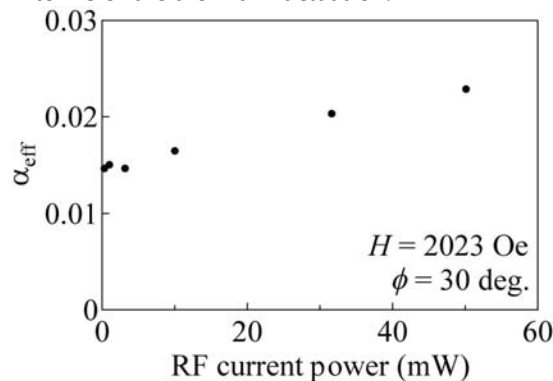


Figure 4. Dependence of the effective Gilbert damping constant on the rf current power under the application of the field of 2023 Oe at 30 degree.

5. Acknowledgements

The present study was partly supported by MEXT Grants-in-Aid for Scientific Research in a Priority Area, a JSPS Grant-in-Aid for Scientific Research, the JST PRESTO program and the JST, CREST.

6. References

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