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Permeability Measurements of Magnetic Thin Film with Microstrip Probe

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A highly sensitive and broadband method of obtaining thin f lm permeability without sample-size limitations was developed based on the change in high-frequency impedance due to the skin effect. A microstrip probe with impedance matching of 50 Ω was fabricated, and placed in proximity to a magnetic thin film. The permeability was optimized with the Newton–Raphson method. The permeability of CoFeB f lm (45 mm × 25 mm and 0.5 μm in thickness) and that of FeCoB/Ru film (50 mm × 40 mm and 0.2 μm in thickness) were evaluated using a permeameter. The measured values were in rough agreement with theoretical values based on the Landau–Lifshitz–Gilbert equation and eddy current generation up to 30 GHz. The proposed method offers promise for measuring the permeability of wafer-sized samples in line because it is not restricted by size limitations.

Key words: microstrip probe, skin effect, thin f lm permeability

1. Introduction

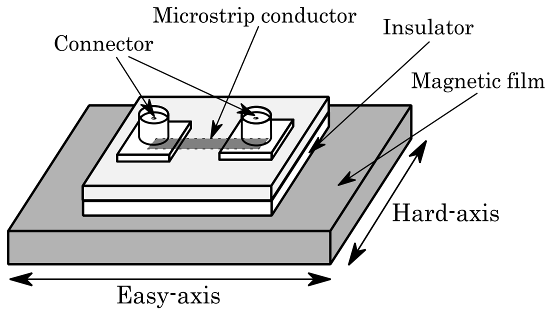
There are many conventional methods of measuring thin f lm permeability[1)–3)]. However, almost all permeameters require a special sample (usually no more than several millimeter wide) because the upper frequency range is limited by the resonance of the pickup coil or the size of the transmission line. Therefore, researchers and engineers must usually cut wafers and specially prepare a sample for permeability evaluation. Thus, many researchers of thin f lm materials as well as manufacturing process engineers would welcome a permeameter which is free from sample–size limitations.

As previously reported, we fabricated a meander–type probe and microstrip–line–type probe and evaluated permeability up to 15 GHz[4)]. This method is advantageous in that it utilizes broadband, is highly sensitive due to utilization of skin effect of magnetic f lm, and is free from sample size limitation and the probe can be scanned to measure permeability distribution. However, the characteristic impedance matching inside the fabricated probe was worsened at the through–hole, which perpendicularly connected the microstrip pattern and the connector, because the probe was handmade. In the present study, we fabricated a new probe whose characteristic impedance was matched to around 50 Ω, including the through–hole. CoFeB f lm and FeCoB/Ru film with high anisotropy f eld were evaluated for demonstration of broadband measurement.

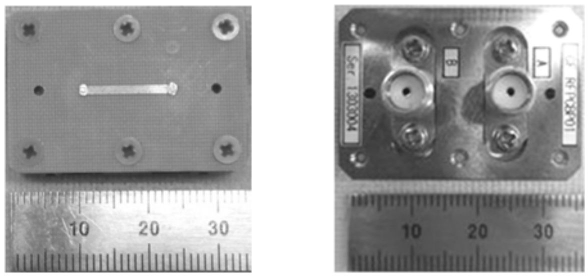
2. Experimental setup

2.1 A new probe and system setup

Fig. 1(a) shows a schematic view of the probe and magnetic film. The probe was placed in proximity of the magnetic f lm. A polyimide f lm about 10 μm thick was set as an insulator between the microstrip probe and magnetic f lm. Coaxial cables were connected to a



(a) Arrangement of probe and magnetic f lm



(b) Photographs of the probe

Fig. 1 Schematic diagram and photograph of the probe.

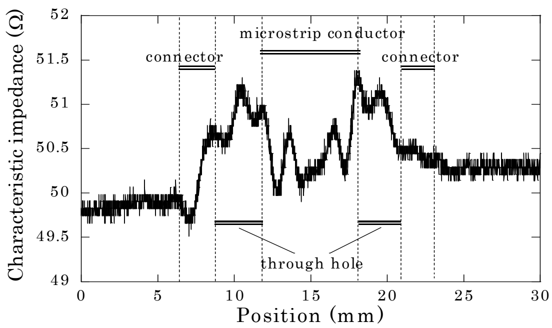


Fig. 2 Characteristic impedance of probe obtained from time-domain reflectometry (TDR) measurements.

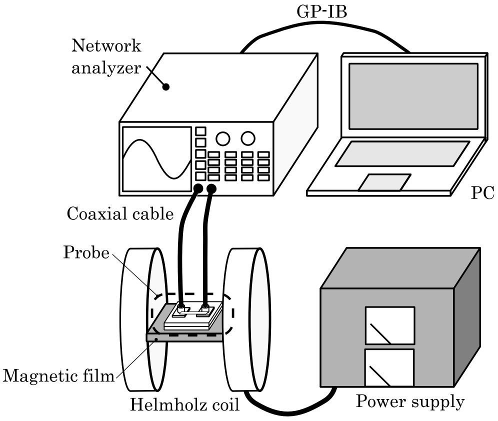


Fig. 3 Schematic of the system setup.

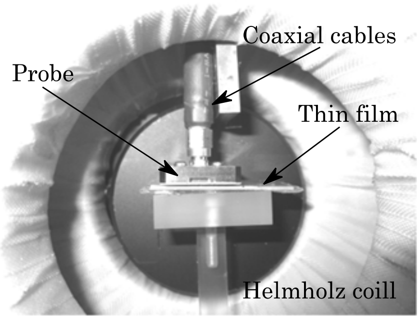


Fig. 4 Photograph of the probe and film.

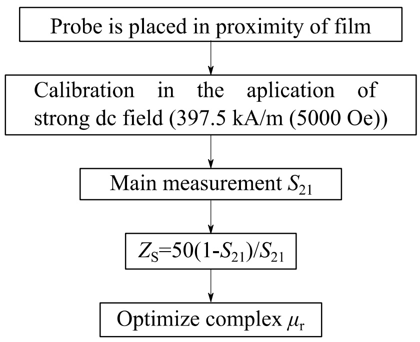


Fig. 5 Flow chart of the permeability measurements.

network analyzer. Fig. 1(b) shows a photograph of the probe. The probe is composed of a straight microstrip conductor (13 mm in length, 1.5 mm in width), two through–holes, and two connectors. The through–holes are connected to the microstrip conductor perpendicularly. The characteristic impedance was designed to be 50 Ω throughout the connectors, the through–holes, and the microstrip conductor. Fig. 2 shows the characteristic impedance of the probe without magnetic film measured by time domain reflectometry (Agilent Technologies 86100A). The characteristic impedance was 49.5–51.5 Ω. Fig. 3 shows the system setup consisting the probe, bias coil, network analyzer (Agilent Technologies 8722ES), a dc power supply (Takasago GPO–60–30), and a personal computer. Fig. 4 shows a photograph of the probe, a magnetic film, a Helmholtz coil, and a micrometer. The spacing between the probe and the film is adjusted by a micrometer. A Fe yoke (cross–sectional area: 50 mm × 80 mm) was

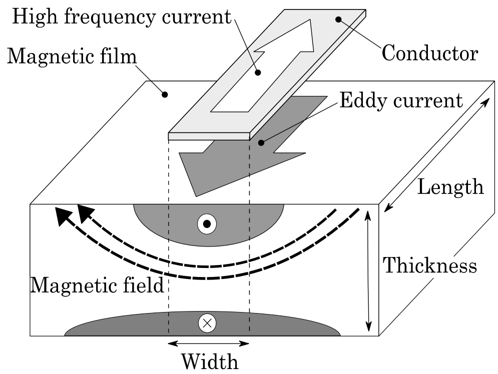


Fig. 6 Schematic of eddy current and magnetic field in a film.

arranged around the bias coil to increase the dc magnetic field. However, the yoke is not represented in Fig. 4 because the probe and film is hidden if the yoke is arranged for the jig.

2.2 Optimization of permeability

Fig. 5 shows a flow chart of this measurement. The complex impedance of the magnetic film is transformed from S_{21} using a network analyzer. S_{21} is first calibrated by the application of a strong dc field (around 397.5 kA/m(5000 Oe)) in the easy–axis direction to saturate the magnetic film as background. Secondly, the S_{21} of the main measurement is obtained without a strong magnetic field. The complex impedance of the magnetic film is then obtained using equation (1).

$$Z_s = 50(1 - S_{21})/S_{21} \quad (1)$$

The effect of resistance of the microstrip conductor, as well as the outer inductance of the magnetic film, can be eliminated. Complex permeability is optimized using the Newton–Raphson method[5] to take the skin effect of the magnetic film into account by using equations (2) and (3).

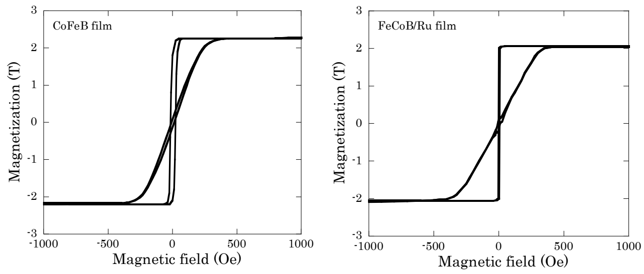
$$Z_s = \frac{k_s \rho l}{2w} coth\left(\frac{k_s t}{2}\right) \quad (2)$$

$$k_s = \frac{(1+j)}{\sqrt{\frac{\rho}{\pi f \mu_r \mu_o}}} \quad (3)$$

where ρ is the resistivity of the film, t is the film thickness, l is the microstripline length, and w is the microstripline width. Fig. 6 shows a schematic diagram of the current and the magnetic field in the film and the microstrip conductor. The high frequency current induces a magnetic field in the width direction of the conductor pattern, and the magnetic field and eddy current are localized in the skin of the magnetic film. The specified permeability in the width direction corresponds to the high frequency impedance, while sacrificing applied magnetic field uniformity. In this paper, CoFeB film[6] and FeCoB/Ru film[7] with a large anisotropy field were evaluated as a demonstration of broadband evaluation.

3. Experimental results

Fig. 7 show MH curves of the films. Fig. 7(a) shows the MH curve of CoFeB film (45 mm × 25 mm, 0.5 μm thick, M_s ≒ 2.2 T, H_k ≒ 260 Oe), (b) shows that of FeCoB/Ru film (50 mm × 40 mm, 0.2 μm thick, M_s ≒ 2.1 T, H_k ≒ 350 Oe). Both films have large anisotropy field and ferromagnetic resonance over 6 GHz. Fig. 8 shows the hard–axis permeability of CoFeB f lm. The film was deposited by Carousel Sputtering[6]. Fig. 8 (a) shows the permeability without a bias f eld, Fig. 8 (b)–(f) show the permeability when bias f elds of 500, 1000, 2500, 3000, and 3500 Oe were applied along the easy axis. Symbols show measured permeability, the dotted lines and the solid lines show the theoretical permeability based on the Landau–Lifshitz–Gilbert equation and eddy current generation[8]. The α (damping factor) of 0.01 and g factor of 2.12 were used to calculate theoretical permeability. The absolute permeability was calibrated by the application of dc magnetic f elds in the direction of the easy axis. The measured permeability roughly corresponds to theoretical permeability up to 30 GHz. Ferromagnetic resonance shifted from 7 to 28 GHz as the dc f eld increased. A sharp change was observed around 31–33 GHz. The limit originated from the ferromagnetic resonance of the magnetic film with a strong bias field of about 5000 Oe. Some errors between the measured and theoretical values were observed around 5 GHz, which may have originated from the capacitive coupling between the microstrip conductor and the magnetic film.



(a) CoFeB film (b) FeCoB/Ru film

Fig. 7 MH-curve of the film sample.

Fig. 9 shows the hard–axis permeability of FeCoB/Ru f lm. Fig. 9(a) shows the permeability without the bias f eld, (b)–(e) show the permeability when bias f elds of 250, 500, 750, and 1000 Oe were applied along the easy axis. A strong dc field of about only 3000 Oe was applied during calibration because the FeCoB/Ru f lm (40 mm × 50 mm) needs a greater gap length between the

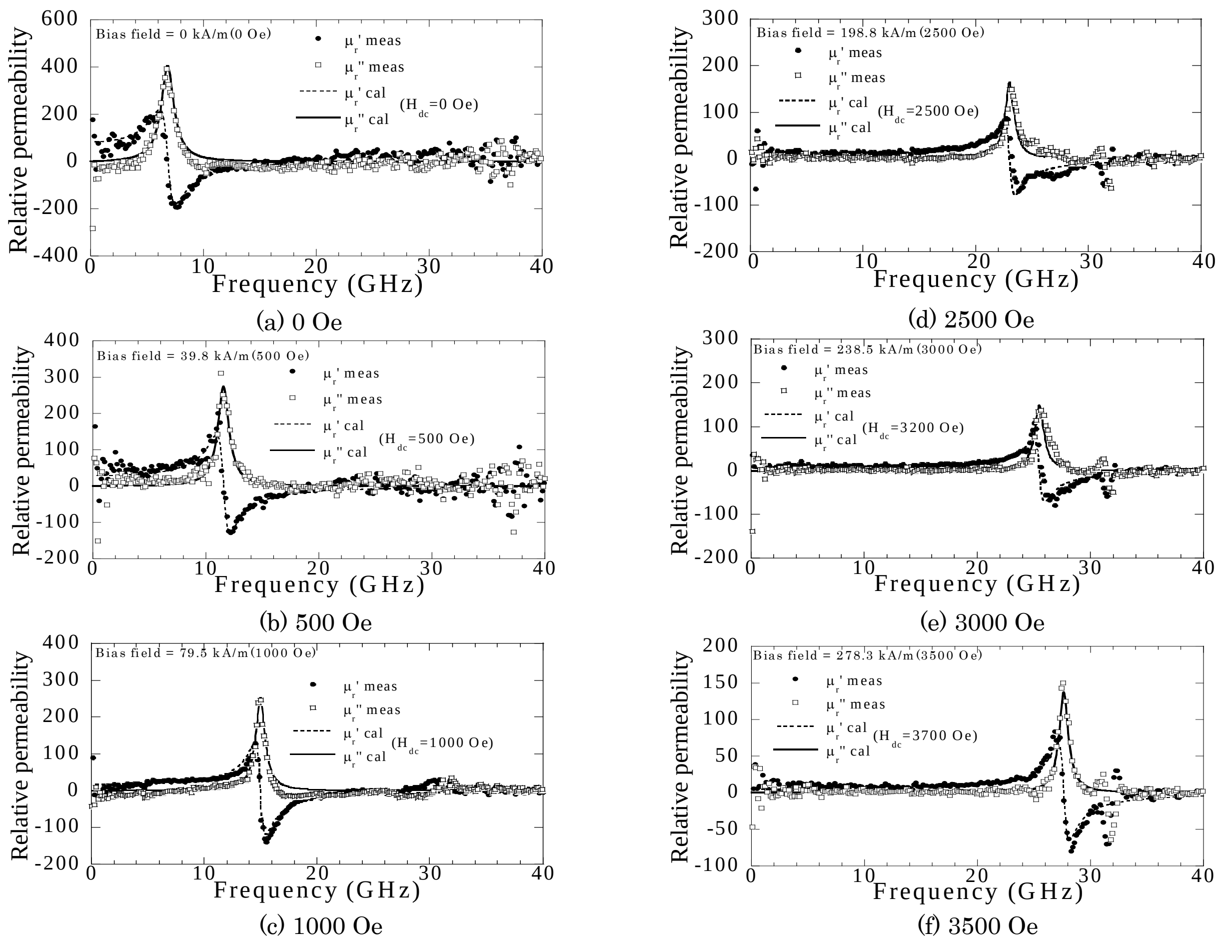
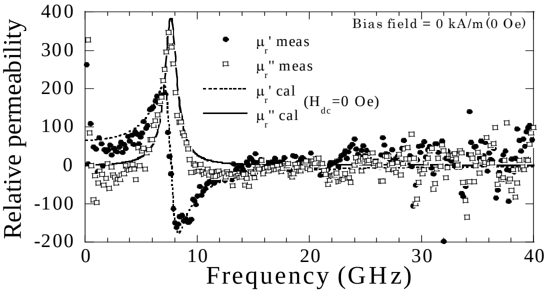
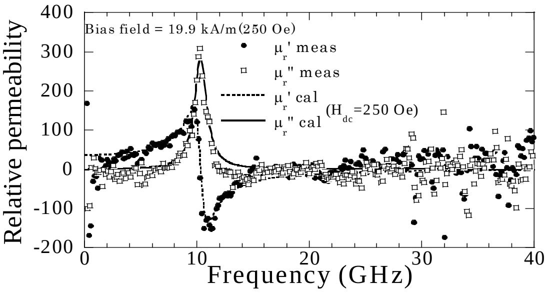


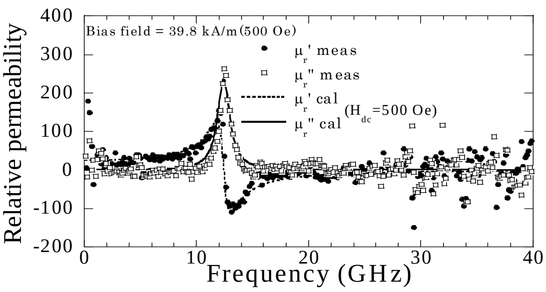
Fig. 8 Permeability of CoFeB f lm (0.5 μm thick). (a) No bias f eld was applied ; (b) Bias f elds of 500 Oe, (c) 1000 Oe, (d) 2500 Oe, (e) 3000 Oe, and (f) 3500 Oe were applied to the easy axis.



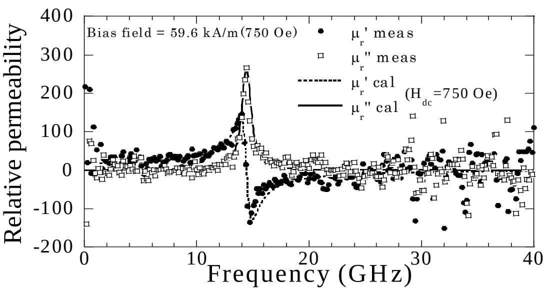
(a) 0 Oe



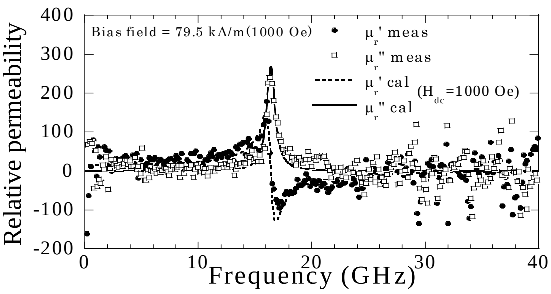
(b) 250 Oe



(c) 500 Oe

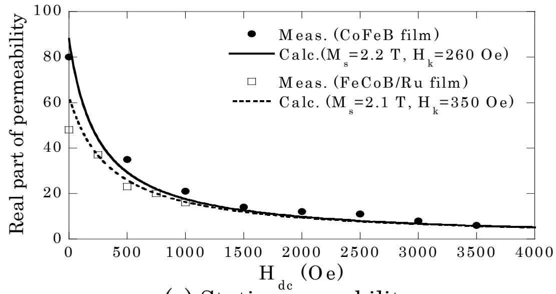


(d) 750 Oe

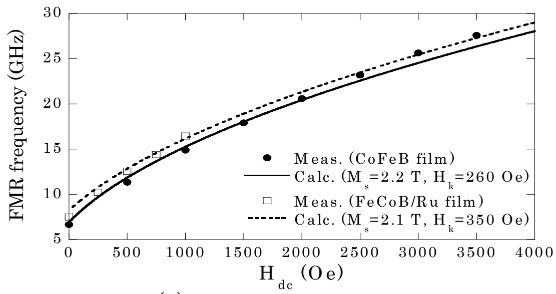


(e) 1000 Oe

Fig. 9 Permeability of FeCoB f lm (0.2 μm thick).
(a) No bias f eld was applied ; (b)–(e) bias f elds of 250, 500, 750, and 1000 Oe were applied to the easy axis.



(a) Static permeability



(b) Resonance frequency

Fig. 10 Static permeability and resonance frequency as a function of Bias field.

magnetic yokes than that of the CoFeB film (45 mm × 25 mm). Measured permeability was roughly corresponded to the theoretical permeability. The permeability of the FeCoB/Ru f lm was noisier than that of the CoFeB film because the FeCoB/Ru f lm (0.2 μm in thickness) was thinner than the CoFeB film (0.5 μm in thickness). Some errors were observed around 5 GHz, which may have originated from the capacitive coupling between the microstrip conductor and magnetic film.

Fig. 10 show (a) static permeability in lower frequency and (b) ferromagnetic resonance (FMR) frequency as a function of bias field. Symbols show measured data of CoFeB film and FeCoB/Ru film. The solid line and the dotted line show the theoretical value based on the Landau–Lifshitz–Gilbert equation and eddy current generation[8]. In Fig. 10(a) and (b), measured static permeability and FMR frequency roughly corresponded to theoretical value. Measured FMR frequency differed from theoretical frequency over 3000 Oe, which may be caused by the non-uniformity of magnetic field inside the yoke.

The proposed method can be used for permeability measurement of wafer–sized samples because the method is free of size limitation of the easy–axis. The measured permeability corresponds to the theoretical permeability in the frequency range up to 30 GHz.

4. Conclusions

1. A broadband and highly accurate method was developed to measure thin f lm permeability using by microstrip type probe. The method is free from sample size limitations.

2. A CoFeB f lm (45 mm × 25 mm and 0.5 μm in thickness) and a FeCoB/Ru film (50 mm × 40 mm and 0.2 μm in thickness) with a high anisotropy f eld was evaluated, and measured permeability was in rough agreement with the theoretical permeability up to 30 GHz.

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