

Modifying factor for determining broadband complex permeability of magnetic thin films

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Abstract: A new method of the modifying factor for determining the broadband complex permeability of magnetic thin films, was proposed. Based on the measurement technology of short-end microstrip line and the new modify factor, a series of FeCo-based magnetic thin films deposited on the oxidized silicon substrates and with an in-plane uniaxial anisotropy were measured in the frequency range of 0.5–5 GHz. The results fit well with the Landau-Lifchitz-Gilbert theory in a broad frequency range.

Key words: magnetic thin films; microwave measurement; complex permeability; microstrip line; high frequency structure simulation

1 Introduction

Magnetic thin films are natural candidates for high-frequency applications, including electromagnetic compatibility, magnetic field sensors, microwave darkroom and wave-absorbing materials [1–2].

FeCo-based magnetic thin films attribute to their high permeability and high loss under microwave frequency to realize broadband absorbing of microwave. Given the usual planar structure of thin films, the ferromagnetic resonance is conveniently characterized by employing the two-port pickup coil type permeameter or the one-port reflection method with microstrip line technology[3–5].

BEKKER et al[6] have developed a one-port permeameter that the complex permeability is deduced from the measured reflection coefficient of a microstrip line. Based on this method, the ferromagnetic resonance of a film with an in-plane uniaxial anisotropy has been deduced in the frequency range of 0.5–5.0 GHz. The modifying factor has been calculated by adjusting the initial permeability at low frequencies determined by the saturation magnetization and the magnetic anisotropy field of thin films.

In this study, a new method of the modifying factor

for determining the broadband complex permeability of magnetic thin films was proposed. The modifying factor, simulated and computed by high frequency structure simulation software, was applied to the measurement of magnetic thin films.

2 Theoretical basis

In the measurement system, a short-ended circuited microstrip line fixture was connected to an Agilent 8722 ES network analyzer. Measurement procedure and data processing were in the three steps as follows. The first step was to obtain measured values of the reflection coefficient $S_{11}^{\text{empty}}(f)$ for an empty microstrip line. Then the measured reflection coefficient $S_{11}^{\text{sub}}(f)$ was obtained when the microstrip line fixture was loaded with the substrate. The measured reflection coefficients $S_{11}^{\text{film}}(f)$ of the microstrip line loaded with the film deposited on the substrate was measured in the third step.

Eventually, the effective permeability of the microstrip line could be finally calculated by

$$\mu_{\text{eff}} = \left[\frac{(l_{\text{sample}} + l_{\text{empty}}) \ln(-S_{11}^{\text{film}}) - l_{\text{empty}} \ln(-S_{11}^{\text{empty}})}{(l_{\text{sample}} + l_{\text{empty}}) \ln(-S_{11}^{\text{sub}}) - l_{\text{empty}} \ln(-S_{11}^{\text{empty}})} \right]^2 \quad (1)$$

where l_{sample} is the substrate length and l_{empty} is the common length of the empty microstrip line sections. The relative permeability of the film with thickness of d was calculated from the relation

$$\mu_r = \frac{\mu_{\text{eff}} - 1}{Kd/h} \quad (2)$$

where μ_{eff} is the effective complex permeability, μ_r is the relative permeability of the magnetic film with thickness of d , $h(0.8 \text{ mm})$ is the inner height between upper line and ground plate, and K is a modifying factor established by a known sample or by adjusting the initial permeability at low frequencies. From the initial permeability at low frequencies determined by the saturation magnetization and the magnetic anisotropy field of magnetic thin films, the modifying factor ($K=2.162$) could be calculated.

There may be discrepancies of the measured values in high frequencies, due to the modifying factor established by adjusting the initial permeability at low frequencies determined by the saturation magnetization and the magnetic anisotropy field of thin films. An improved way to reduce errors in high frequencies was discussed by using not one point but two lines to scale the permeability in this work.

3 New method for modifying factor

A practicable measurement system could be set up by employing a short-ended circuited microstrip line fixture and an Agilent 8722 ES network analyzer. The width (w) of the upper line was 3.9 mm and the height (h) between the upper line and the ground plate was 0.8 mm. The ground plate was made of gold, and the upper line was a layer of copper with the thickness of 30 μm , plated with a piece of material with the thickness of 1 mm. To avoid the resonance in the fixture, the length of the microstrip line (l) was set to be 9 mm[7].

High frequency structure simulator(HFSS), an interactive software package for calculating the electromagnetic behavior of a structure, could simulate the process of a magnetic thin film to scale the modifying factor. Fig.1 shows the model view of the short-ended circuited microstrip line fixture in HFSS.

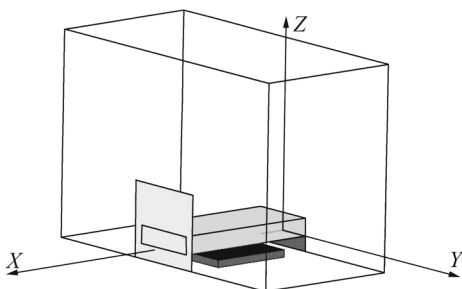


Fig.1 Model view of measurement Jig in software

Smith plot, a 2D polar plot of S -parameters upon which a normalized impedance grid has been superimposed, was created after a swept analysis of the jig model in the frequency range of 0.5–5.0 GHz was made. As shown in Fig.2, the trace in Smith plot indicates it is an inductance branch. The range of phase and amplitude also shows that the jig model is usable and valid.

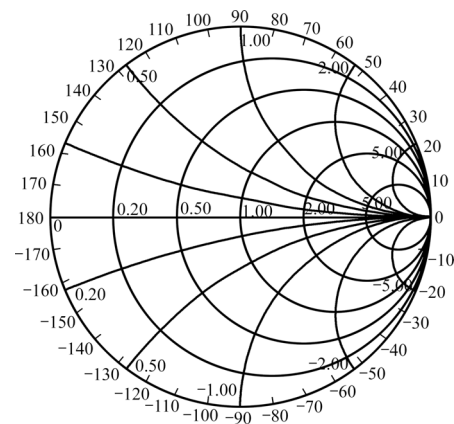


Fig.2 Smith plot of Jig model in HFSS

A FeCo magnetic thin films 200 nm in thickness and known permeability ($\mu=200-j\cdot 0$) placed between the upper microstrip line and the ground plate, were simulated only substrate and films deposited on the substrate were gained. The effective permeability μ_{eff} and then the modifying factor K were calculated by Eqns.(1) and (2), respectively. A simulated diagram of the modifying factor is shown in Fig.3.

Obviously, the modifying factor is a function of frequency. Then the simulation data were introduced into mathematic software, and the value of the modifying factor was fitted and expressed by

$$K(f) = 2.38 - 0.026f^{2.12} \quad (3)$$

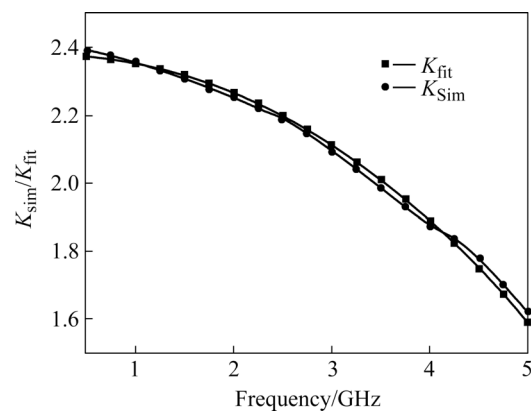


Fig.3 Simulated and fitted curves of modifying factors

Just like the method mentioned above, a magnetic thin film with 200 nm in thickness and known permeability ($\mu=100-j\cdot 0$) was simulated and then a new

modifying factor was gained when the permeability was negative. The fitted expression of the modifying factor is

$$K(f) = 1.38 - 0.026f^{1.25} \quad (4)$$

where $K(f)$, a function of frequency, fits the fact that the broadband permeability is a function of frequency. It is a perfect way to reduce errors in high frequencies to employ Eqn.(3) when $\mu > 0$ and Eqn.(4) when $\mu < 0$, respectively.

4 Results and discussion

A series of FeCo-based magnetic thin films deposited on oxidized silicon substrates and with an in-plane uniaxial anisotropy, were measured in the frequency range of 0.5–5.0 GHz[8].

The experimental complex permeability spectrum of the film ($M_s = 1.29$ T, $H_k = 408$ A/m) is shown in Fig.4. The theoretical permeability spectrum was deduced from the Landau-Lifchitz-Gilbert theory and eddy current dynamic magnetization model[9]:

$$\mu(f) = 1 + \frac{\gamma^2 M_s (M_s + H_k) + j\gamma\alpha f M_s}{\gamma^2 M_s H_k - (1 + \alpha^2)f^2 + j\gamma\alpha f (M_s + 2H_k)} \quad (5)$$

where $\gamma = 2.21 \times 10^5$ m/(A·s) is the gyromagnetic ratio and $\alpha = 0.009$ is the damping parameter.

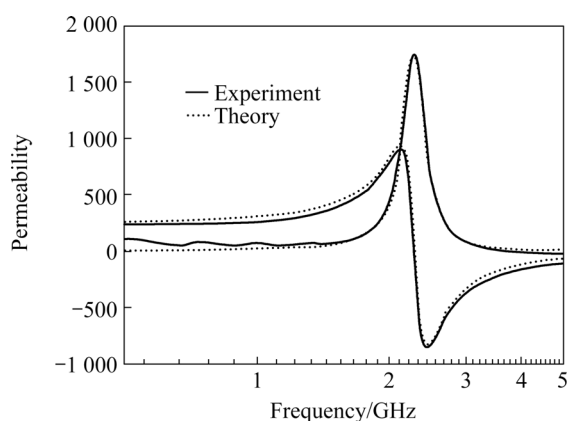


Fig.4 Theoretical and experimental relative permeability of FeCo film with thickness of 200 nm

Due to a marked in-plane uniaxial anisotropy the film could be considered to be uniformly magnetized in one direction so that the Kittel's resonance frequency is valid[10]

$$f_r = \gamma \sqrt{M_s H_k} \approx 2.23 \text{ GHz}.$$

It can be observed from Fig.4 that the experimental values are predominantly in good agreement with the theoretical analytical results. Comparing the experimental relative permeability with the permeability spectrum using one point[6], it is easy to find that this

method can reduce errors in high frequencies effectively by employing two lines to scale the broadband complex permeability of magnetic thin films.

5 Conclusions

1) A short-ended circuited microstrip line fixture for determining the broadband complex permeability of magnetic thin films was applied and the relative permeability was deduced in a better way. The results fit well with the Landau-Lifchitz-Gilbert theory in a broad frequency range.

2) The improved way reduces the errors in high frequencies by using two equations to scale the complex permeability of the magnetic thin film, $K(f) = 2.38 - 0.026f^{2.12}$ and $K(f) = 1.38 - 0.026f^{1.25}$.

3) The method of the modifying factor is put forward for determining the broadband complex permeability of magnetic thin films in the frequency range from 0.5 to 5 GHz.

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