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A new perturbation method for determining the broadband complex permeability of magnetic thin films

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Abstract

In this paper, a new one-port microstrip line permeameter using the perturbation method is presented. A short-ended circuited microstrip line fixture was designed and implemented. Completely new analytical calculation formulas and a two-step measurement procedure were applied to deduce the complex permeability of the material in the frequency range from 100 MHz to 5 GHz. The measured results showed good agreement with the Landau–Lifchitz–Gilbert theory.

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Keywords: Magnetic thin film; Perturbation method; Strip line technique; Broadband complex permeability

1. Introduction

The application of magnetic thin films is becoming more and more extensive with the rapid development of the electromagnetic compatibility, thin-film microwave absorbers and so on. The permeability of the magnetic thin films is a significant parameter for the microwave-absorbing capability, and thus the measurement of the complex permeability of thin films is supposed to be urgent. The main permeability measurement techniques include the pick-up coil technique and the transmission line method [1]. An accurate and reliable result could be provided in the MHz frequency range in the coil technique. When the frequency reaches higher to the GHz range, however, the accuracy decreases due to the dimensional resonance and conductivity effects at high frequency [2]. The usual transmission line broadband measurement method can be divided into two types: the transmission and reflection method (two-port technique) and the reflection method (one-port technique). The equivalent LCR circuit analysis and the equivalent parameter processing in the one-port technique are much simpler, as well as the measurement system and the calibration procedure [3,4].

Bekker et al. [5] developed a one-port strip line permeameter. The complex permeability was deduced from the measured reflection coefficient of a strip line. An analytical calculation procedure with an adaptive error correction was used to deduce the complex permeability of a ferromagnetic film material with an in-plane uniaxial anisotropy in the 0.05–5 GHz frequency range with good accuracy. There may also be discrepancies of the measured values in high frequencies because the proportionality factor is established by adjusting the initial permeability at low frequencies determined by the saturation magnetization and the magnetic anisotropy field of thin films.

In this article, a new measurement method for determining the broadband complex permeability of magnetic thin films was proposed. The magnetic thin film was deposited on oxidized silicon substrates, with an in-plane uniaxial anisotropy. New analytical calculation formulas and a two-step procedure were applied to deduce the complex permeability of the material in the frequency range from 100 MHz to 5 GHz. The energy-dependant coefficient was

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simulated and computed in a new method. The saturation magnetization and the magnetic anisotropy field had not to be measured beforehand. Based on the technology of virtual instrument and the development tool of LabVIEW graphic programming language, an automatic measurement system was established.

2. Measurement principle

The calculation formulas of the measurement method could be deduced according to the perturbation theory of the electromagnetic field. A microstrip line with a length shorter than a quarter of the wavelength was considered to be an inductance coil. The input impedance of the microstrip line changes when the magnetic thin film is introduced into the cavity. Since it is possible to measure the change with high accuracy by a network analyzer, a valuable method for measuring the permeability of the magnetic thin film was provided. Changes of the real part and the imaginary part of the impedance were deduced from the measurement of the reflection coefficient and the complex permeability $\mu = \mu' - \mathrm{j}\mu''$ was obtained.

According to the perturbation theory of electromagnetic field, there is the following expression:

$$\frac{\Delta f}{f_0} = \frac{\int_{v_1} (\mu - 1) \times H^* \times H \,\mathrm{d}v}{\int_{v_2} H^* \times H \,\mathrm{d}v}, \tag{1}$$

where f is the frequency, v_1 and v_2 are the volumes of the thin film and the measurement cavity, respectively, μ is the relative permeability of the thin film, H and H^* are the magnetic field and its conjugation, respectively. k is the magnetic field energy ratio of the magnetic thin film to the cavity, defined as

$$k = \frac{\int_{\text{film}} H^* \times H \,\mathrm{d}v}{\int_{v_0} H^* \times H \,\mathrm{d}v}.$$

Take the real part of the permeability in Eq. (1):

$$\frac{\Delta f}{f_0} = k \times R_{\mathrm{e}}(\mu - 1). \tag{2}$$

When the parameters are related by the following equations:

$$\frac{\Delta f}{f_0} = \frac{\Delta X}{X_0}, \tag{3}$$

where X is the impedance of the microstrip cavity, thus a new expression is obtained

$$\frac{\Delta X}{X_0} = (\mu' - 1) \times k. \tag{4}$$

The real part of the complex permeability of thin films is given by

$$\mu' = \frac{1 + \Delta X}{X_0 \times k}. \tag{5}$$

Meanwhile, the imaginary part of the complex permeability of thin films is given by

$$\frac{1}{Q_{\mathrm{m}}} - \frac{1}{Q} = \mu'' \times k, \tag{6}$$

$$\mu'' = \frac{(1/Q_{\mathrm{m}} - 1/Q)}{k}, \tag{7}$$

where Q is the quality factor and k obtained after simulations and calculations is an energy-dependant coefficient, which is related to the size of the thin film, the field distribution in the cavity and so on. The model of the measurement cavity was established by a finite element method, and the magnetic thin films of linear materials with different known permeability were simulated, respectively. The simulation results were processed in mathematic software and values of k were determined.

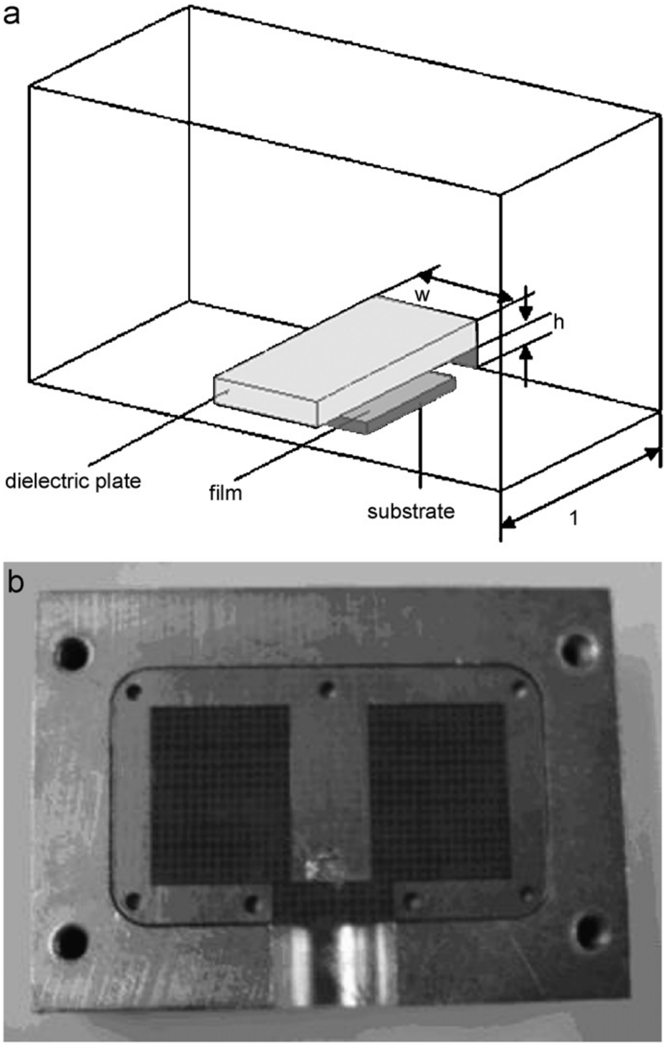

Fig. 1. The design method and fixture of a short-ended circuited microstrip line measurement: (1) design method of the microstrip line fixture and (2) photo of the microstrip line fixture.