Relation between high-frequency properties and direction of anisotropy magnetic field in magnetic thin film for RF inductor applications

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A relation between high-frequency properties, and angle $\theta$ of the easy axis in soft magnetic film and ac applied field was investigated in order to fabricate the film for RF spiral inductor without a localized EMI (Electro-Magnetic Interference). This relationship was measured using a soft CoFeSiO/SiO$_2$ granular multilayer magnetic thin film and simulated by using LLG (Landau-Lifshitz-Gilbert) micromagnetic simulator. The measured and calculated frequency dependence of the film’s complex relative permeability, $\mu'$ and $\mu''$, compared well with 10 % mean error. The real part of complex relative permeability $\mu'$ was dependent on approximately $\sin^2 \theta$. The ferromagnetic resonance (FMR) frequency, $f_r$, and the FMR half-width, $\Delta f_r$, were not dependent on the angle, $\theta$. They were estimated to be 2.54 GHz and 0.3 GHz, respectively. These results are significant for the design of various magnetic thin film spiral inductors in RF integrated circuits without localized EMI.

Index Terms— Magnetic thin film spiral inductor, LLG micromagnetic simulator, Direction of anisotropy magnetic field, CoFeSiO/SiO$_2$ granular multilayer magnetic film, Permeability, FMR frequency.

I. INTRODUCTION

Miniature Radio Frequency (RF) inductors with magnetic thin films are currently under research for use in impedance matching networks and lumped element filters for applications including cellular phones, laptop computers, and various RF communication devices [1]-[4]. Most RF inductors have a spiral and planar design because their inductance densities are typically higher than the densities of meander designs. This is primarily due to the larger positive mutual inductances, therefore, making them suitable for RF integrated circuits. The inductance $L$ and the resistivity $R$ in the RF spiral inductors were affected by the complex permeability $\mu'$ and $\mu''$ in the magnetic thin films, especially. Generally, the magnetic films with uniaxial anisotropic magnetic field in the RF inductors were established such as Fig. 1 [1]-[4]. In this case, an inductance of the area A in Fig. 1 (a) was enhanced by high permeability in the magnetic thin film. On the other hand, the inductance of the area B was equal to that of the air core case, because the permeability $\mu' = \mu_0$ in the magnetic thin film. In addition, it was impossible to suppress cross-talk noise in the area B, so then localized EMI was occurred.

Hence, an RF inductor with 45 degrees of the direction of high-frequency excitation and the hard axis was fabricated such as Fig. 1 (b). In this case, it was possible to obtain high inductance and suppress the cross-talk noise in all areas of the inductor, because all areas had high permeability $\mu'$. However, it was difficult to estimate the complex permeability $\mu'$ and $\mu''$ in the magnetic film by the LLG equation [5] and design the inductors.

In this work, the authors investigated a relation between high-frequency properties and the direction of the anisotropy magnetic field in the magnetic film by experiments and simulations by using LLG micromagnetic simulator.

II. EXPERIMENT

A. Fabrication of magnetic thin film

CoFeSiO/SiO$_2$ granular multilayer films with sharp ferromagnetic resonance (FMR) peak were selected for the fabrication of magnetic thin films. The film was deposited on a silicon wafer using a magnetron sputtering system. The film thickness was controlled to be approximately 400 nm. The thickness of the SiO$_2$ layers was 15 nm. The film was annealed at 450°C for 30 minutes in a nitrogen atmosphere.

Fig. 1. Schematic of (a) conventional and (b) novel RF spiral planar inductors for RF circuits.
magnetic thin film [6]. They were deposited on a surface-
oxidized (100) silicon substrate at room temperature by co-
sputtering Co86Fe20 alloy and SiO2 targets using an inductively
coupled RF sputtering system under a pressure of about 0.2 Pa
of pure Ar gas. During deposition, a magnetic field of about 8
kA/m was applied to the film plane in order to introduce in-
plane uniaxial magnetic anisotropy. The total thickness of the
multilayer films was regulated to be about 50 nm. The granular multilayer films were diced to 4 mm square size by
using a dicer (Disco Corporation; DAD3220).

B. Measurement

The frequency dependence of permeability in the range from
1 MHz to 9 GHz was measured by using a high-frequency
permeameter (Ryowa Electronics Co., Ltd.; PMM-9G1) with
the sample size of 4 mm square size in the granular multilayer
film [7].

III. SIMULATION

A. Micromagnetic simulator

The behavior of magnetic moment of the magnetic thin film
was analyzed by using an LLG Micromagnetics Simulator (by
M. R. Scheinfein) [8]. The behavior of magnetic moment was
calculated on the basis of following basic equations.

$$\frac{dT}{dH} = \frac{\gamma M \times H_{\text{eff}}}{(1 + \alpha^2)}$$

$$H_{\text{eff}} = \left(\frac{E_{\text{s}} + E_{\text{ex}} + E_{\text{cs}}}{2\alpha M}ight)$$

where $M$ is the magnetization, $M_s$ is the saturation
magnetization, $\gamma$ is the gyromagnetic constant, $\alpha$ is the
damping constant, $H_{\text{eff}}$ is the effective magnetic field, $E_{\text{s}}$ is the
uniaxial magnetocrystalline anisotropy energy, $E_{\text{ex}}$ is the
cubic magnetocrystalline anisotropy energy, $E_{\text{cs}}$ is the surface
magnetocrystalline anisotropy energy, $E_s$ is the self-
magnetostatic field energy, $E_t$ is the external field energy, and
$E_{\text{ex}}$ is the exchange energy.

B. Simulation model

In the LLG simulation, as shown in Fig. 3, each parameter
was established according to the experimental results. A model
for simulation with $x$-$y$-$z$ three dimensional coordinate
composed of 1 mm x 1 mm area in $x$-$y$ plane, and thickness $t_p$
of 50 nm in the $z$-axis. The saturation magnetization $M_s$ of
1.44 T and the uniaxial anisotropy field, $H_{\text{ka}}$, of 4.54 kA/m
obtained in the magnetic film were given to the model. The
direction of the uniaxial anisotropy field $H_{\text{ka}}$ was established in the
$x$-$y$ plane. An angle $\theta$ of the direction and y-axis ranged
from $0^\circ$ to $90^\circ$. Namely y-axis was the easy axis when $\theta = 0^\circ$.
On the other hand, y-axis was the hard axis when $\theta = 90^\circ$. The
ac field $H_{\text{ac}}$ with amplitude of 8 A/m was applied in the $y$-axis.
The damping constant $\alpha$ of 0.007 was given to the model [7].

IV. RESULTS AND DISCUSSION

A. Frequency dependence of complex relative permeability

Figure 4 shows the frequency dependence of the complex
relative permeability and the quality factor, $Q$, which were
measured and calculated for the CoFeSiO/SiO2 granular multilayer films at $\theta = 90^\circ$, $60^\circ$, and $45^\circ$. The $Q$ is equivalent
to $\mu'' / \mu''$. From Fig. 4, the calculated result agreed well with
the experimental one. Their mean percent error was estimated
about 10 %. However, the experimental data in the vicinity of the
FMR frequency $f_r$ which is about 2.5 GHz deviate from calculated one. The authors considered that the reason is a
dispersion of the uniaxial anisotropy field in the films and a
measurement error. However, the detailed reason is currently
not clear. Both $f_r$ and $\Delta f_r$ were not dependent on $\theta$. The FMR
half-width $\Delta f_r$ was estimated about 0.3 GHz from the results.
The value is less than half that of generally ferromagnetic
films for high-frequency devices [9], [10]. Therefore, the
CoFeSiO/SiO2 granular multilayer film is expected as the
magnetic thin film for the RF with low loss, because the FMR
loss is small around the FMR frequency.

B. Relation between the angle $\theta$ and complex relative permeability

Figure 5 shows the relation between the angle $\theta$, complex
relative permeability $\mu'$, $\mu''$, and the quality factor $Q$ measured
and calculated for the CoFeSiO/SiO2 granular multilayer films at 1 GHz (a), and 2 GHz (b). The imaginary
part of relative permeability $\mu''$ in Fig. 5 (a) was excluded,
because the data had large measurement error. From Fig. 5,
the experimental data are indeed consistent with calculated
one approximately. The real part of the complex relative permeability $\mu'$ is described by the following equation;

$$\mu'=(\mu_{\text{in}}-1)\sin^2\theta+1$$

where $\mu_{\text{in}}'$ is the real part of complex relative permeability in the
hard axis $\mu''$. The authors considered that this result agrees
with following equation;
Fig. 4. Typical of frequency dependence of complex relative permeability and quality factor measured and calculated for the CoFeSiO/SiO$_2$ granular multilayer films, $\theta = 90^\circ$ (a), $60^\circ$ (b), and $45^\circ$ (c).

Fig. 5. Relation between the angle $\theta$, complex relative permeability $\mu'$, $\mu''$, and quality factor $Q$ which were measured and calculated for the CoFeSiO/SiO$_2$ granular multilayer films at 1 GHz (a), and 2 GHz (b).

$$E_{ku} = K_u \sin^2 \theta$$

where $K_u$ is the anisotropy constant. Hence the uniaxial magnetocrystalline anisotropy energy $E_{ku}$ in the CoFeSiO/SiO$_2$ granular multilayer film is governed mainly.

The quality factor $Q$ is approximately constant in $\theta \geq 45^\circ$ in Fig. 5. On the other hand, $Q$ has the peak in $\theta \approx 20^\circ$ in Fig. 5. These reasons are currently not clear.

V. CONCLUSIONS

The relation between high-frequency properties and the direction of the anisotropy magnetic field in the CoFeSiO/SiO$_2$ granular multilayer magnetic thin films for RF inductor applications were measured and simulated using an LLG micromagnetic simulator. The results obtained are as follows:

1. The measured and calculated frequency dependence of the complex relative permeability for the CoFeSiO/SiO$_2$ granular multilayer films compared well with a mean percent error of 10%.

2. The real part of complex relative permeability, $\mu'$, was approximately dependent on Eq. (3). This result was caused by the uniaxial magnetocrystalline anisotropy energy $E_{ku}$ as Eq. (4).

3. The FMR frequency and the FMR half-width were not dependent on the angle, $\theta$, of the direction of the easy axis and ac applied field. They were estimated to be 2.54 GHz and 0.3 GHz, respectively.

These results are significant for the design of various magnetic thin film spiral inductors in the RF integrated circuits without the localized EMI.

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REFERENCES


