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# Ferrite Magnetic-Anisotropy Field Effects on Inductance and Quality Factor of Planar GHz Inductors

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**Abstract**—Planar gigahertz (GHz) inductors were fabricated based on high crystalline-anisotropy $Zn_{0.13}Co_{0.04}Ni_{0.63}Fe_{2.2}O_4$ (Zn-Co-Ni ferrite) and $Ba_3Co_2Fe_{24}O_{41}$ ($Co_2Z$ hexaferrite) and characterized for inductance ($L$) and quality ($Q$) factor. The planar ferrite inductors show an $L$ of 4.5 nH (Zn-Co-Ni), 5.6 nH (Zn-Co-Ni + low $H_k$ and $f_{FMR}$ $Co_2Z$:), and 4.8 nH (Zn-Co-Ni + high $H_k$ and $f_{FMR}$ $Co_2Z$:) at 2 GHz. The corresponding $L$-densities are 18.0, 22.4, and 19.2 nH/mm$^2$, which are greater than 16.8 nH/mm$^2$ of the air-core inductor. With respect to the $Q$ factor, the air-core and ferrite inductors exhibit $Q$ factors of 6.7 (air-core), 4.8 (Zn-Co-Ni), 2.8 (Zn-Co-Ni + low $H_k$ $Co_2Z$), and 4.0 (Zn-Co-Ni + high $H_k$ $Co_2Z$) at 2 GHz. The $\tan\delta_\mu$ of the ferrites caused a reduction in the $Q$ factor. Nevertheless, the high $H_k$ and $f_{FMR}$ $Co_2Z$ ferrite inductor demonstrates a higher $Q$ factor than that of the low $H_k$ and $f_{FMR}$ $Co_2Z$ inductor. It is, therefore, suggested that high resistivity, anisotropy, magnetization ferrite can produce large $L$ density and $Q$ factor GHz inductors.

## 1. INTRODUCTION

Radio frequency (RF) transceivers with fully integrated circuits, including voltage controlled oscillators, low-noise amplifiers, and frequency filters, are in high demand for mobile electronic devices. In response to this, a large number of inductors are integrated into RF integrated circuits (RFICs). However, the inductors consume a large area of the RFICs, and their quality ($Q$) factors are critical for power management and RF signal processing. Therefore, compact and high $Q$ integrated inductors are required.

Integrated magnetic inductors have been widely investigated. A high-permeability material increases the $L$ and $Q$ factor of inductors by increasing magnetic flux density and decreasing coil resistance and parasitic capacitance [1, 2]. A 2 µm thick CoZrTa magnetic film inductor with relative permeability ($\mu_r$) of about 1000 showed a high $L$ density of 1.3 µH/mm$^2$ and a 28 times increase in $L$ compared to that of the air-core inductor [2]. However, low resistivity ($\rho = 99\,\mu\Omega\cdot$cm) of the CoZrTa film decreased the $Q$ factor below 6 at 1 GHz.

In an effort to address the low $Q$ factor, multilayered magnetic films [3–5] or high-resistivity ferrites ($\rho > 1\,$k$\Omega\cdot$cm) [6–9] were used in integrated inductors to suppress GHz eddy current loss. A FeGaB/$Al_2O_3$ multilayer solenoid inductor showed an $L$-density of 15 nH/mm$^2$ and $Q$ factor of 14 at 1.2 GHz [4]. A $Ni_{0.4}Zn_{0.4}Cu_{0.2}Fe_2O_4$ (Ni-Zn-Cu) ferrite spiral inductor had an $L$-density of 12 nH/mm$^2$ ($L$ of 1.94 nH) and $Q$ factor of 17.2 at 4 GHz, which were increases of about 3.9% and 6.3%, respectively, compared to those of the air-core inductor [9]. It is found that the high-resistivity ferrite is effective in increasing both $L$ and $Q$ factor at GHz frequencies [9, 10]. The $L$ of the ferrite inductor is enhanced by

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the ferrite's magnetic permeability ($\mu_r > 1$). The magnetic loss tangent ($\tan\delta_\mu$) of the ferrite plays a role and causes a decrease in GHz $Q$ factor.

The $Q$ factor of the ferrite inductor can be expressed by the air-core and magnetic-core components in Eq. (1) [13],

$$Q = \frac{\omega L}{R} = \frac{\omega L}{(R_{\mathrm{AC}} + \Delta R)}. \tag{1}$$

The resistance ($R_{\mathrm{AC}}$) of the air-core inductor is mainly attributed to conductor loss from skin-depth effect. The magnetic-core loss ($\Delta R \propto \tan\delta_\mu$) is related to the frequency-dependent loss $\tan\delta_\mu$. The $\tan\delta_\mu$ increases with frequency and becomes considerably large when the operating frequency approaches the ferromagnetic resonance frequency ($f_{FMR}$) of the ferrite. Therefore, a high $f_{FMR}$ ferrite is required, thereby contributing to low-loss characteristics and realizing high $Q$ GHz inductors. According to Eq. (2) [11]

$$f_{FMR} = (\gamma/2\pi)\sqrt{(4\pi M_s H_k)}, \tag{2}$$

$f_{FMR}$ increases with increasing $H_k$, where $H_k$ is the magneto-crystalline anisotropy field, $M_s$ the saturation magnetization, and $\gamma/2\pi$ the gyromagnetic constant (2.8 MHz/Oe). In contrast, ferrite's $\mu_r$ decreases with increasing $f_{FMR}$ by the Snoek law in Eq. (3) [12]

$$(\mu_r - 1)\cdot f_{FMR} = \frac{4}{3}\gamma M_s, \tag{3}$$

and $L$ consequently decreases. Therefore, a high crystalline-anisotropy ferrite inductor needs to be designed in consideration of magnetic parameters, including $H_k$, $M_s$, $\mu_r$, $f_{FMR}$, and $\tan\delta_\mu$.

In this paper, we investigate the relation of $H_k$ to inductor $Q$ factor and report electrical characteristics of high crystalline-anisotropy $Zn_{0.13}Co_{0.04}Ni_{0.63}Fe_{2.2}O_4$ (Zn-Co-Ni ferrite) and $Ba_3Co_2Fe_{24}O_{41}$ ($Co_2Z$ hexaferrite) inductors in comparison to an air-core inductor.

## 2. FUNDAMENTALS OF FERRITE INDUCTOR

### 2.1. Inductance and Quality Factor of a Ferrite Inductor

The $L$ of the ferrite inductor can be given by the sum of the air-core inductance ($L_{\mathrm{AC}}$) and the inductance gain ($\Delta L$) from the high-permeability ferrite in Eq. (4) [13],

$$L = L_{\mathrm{AC}} + \Delta L. \tag{4}$$

$L_{\mathrm{AC}}$ depends primarily on the geometry of a coil structure, including the length, width, and thickness. On the other hand, the gain $\Delta L$ is proportional to magnetic properties and geometry parameters of the ferrite in Eq. (5) [14, 15],

$$\Delta L \approx \mu_0 \mu_{eff} \frac{t_m w_m}{2 l_m}, \tag{5}$$

where

$$\mu_{eff} = \frac{\mu_r}{1 + N_d(\mu_r - 1)},$$

$t_m$, $w_m$, and $l_m$ are the thickness, width, and length of the ferrite, and $N_d$ is the demagnetization factor. Accordingly, the $L$ of the ferrite inductor can be enhanced by the ferrite's magnetic permeability ($\mu_r > 1$) as compared to the air-core ($\mu_r = 1$) inductor.

The $Q$ factor of the ferrite inductor is a function of the alternating current (AC) conductor loss ($R_{\mathrm{AC}}$) and magnetic-core loss ($\Delta R \propto \tan\delta_\mu$) according to Eq. (1). The $R_{\mathrm{AC}}$ can be reduced by the design optimization of inductor coil thickness, width, and length. With respect to the magnetic-core loss, the loss $\tan\delta_\mu$ is expressed by three main contributions in Eq. (6) [16],

$$\tan\delta_\mu = \tan\delta_h + \tan\delta_e + \tan\delta_r, \tag{6}$$

where $\tan\delta_h$ is the hysteresis loss, $\tan\delta_e$ the eddy current loss, and $\tan\delta_r$ the residual loss. For high-resistivity, soft-magnetic ferrites, the $\tan\delta_h$ and $\tan\delta_e$ become neligible. However, the $\tan\delta_r$, which is determined by the domain wall and spin rotational resonances, is predominant [17, 18]. For high $Q$ ferrite inductors, the $\tan\delta_\mu$ associated with the residual loss needs to be minimized.

### 2.2. Permeability Dispersion and Magnetic Loss of Ferrite

Permeability dispersion of a polycrystalline ferrite is associated with the domain wall motion and spin rotation, as given by Eqs. (7) and (8) [19]

$$\mu' = 1 + \frac{K_{DW}\omega_{DW}^2\left(\omega_{DW}^2-\omega^2\right)}{\left(\omega_{DW}^2-\omega^2\right)^2+\beta^2\omega^2} + \frac{K_{sp}\omega_{sp}^2}{\omega_{sp}^2+\omega^2}, \tag{7}$$

$$\mu'' = \frac{K_{DW}\omega_{DW}^2\beta\omega}{\left(\omega_{DW}^2-\omega^2\right)^2+\beta^2\omega^2} + \frac{K_{sp}\omega\omega_{sp}}{\omega_{sp}^2+\omega^2}, \tag{8}$$

where $K_{DW}$ is the static magnetic susceptibility, $\omega_{DW}(= 2\pi f_{DW})$ the resonance frequency, $\beta$ the damping factor of the domain wall motion, $K_{sp}$ the static magnetic susceptibility, and $\omega_{sp}(= 2\pi f_{sp})$ the resonance frequency of the spin rotation. Based on the above equations, the individual loss components (i.e., $\tan\delta_{DW}$ and $\tan\delta_{sp}$) of the ferrite can be obtained by Eqs. (9) and (10), respectively.

$$\tan\delta_{DW} = \left(\frac{K_{DW}\omega_{DW}^2\beta\omega}{\left(\omega_{DW}^2-\omega^2\right)^2+\beta^2\omega^2}\right) \Bigg/ \left(\frac{K_{DW}\omega_{DW}^2\left(\omega_{DW}^2-\omega^2\right)}{\left(\omega_{DW}^2-\omega^2\right)^2+\beta^2\omega^2}\right) = \frac{\beta\omega}{\omega_{DW}^2-\omega^2}. \tag{9}$$

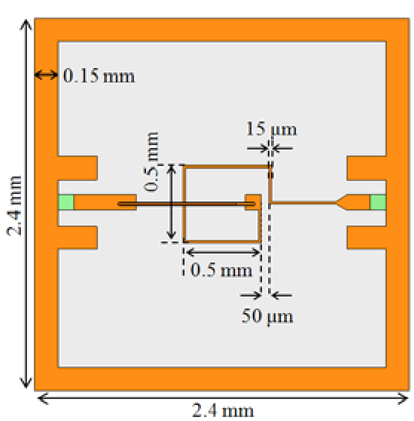
$$\tan\delta_{sp} = \left(\frac{K_{sp}\omega\omega_{sp}}{\omega_{sp}^2+\omega^2}\right) \Big/ \left(\frac{K_{sp}\omega_{sp}^2}{\omega_{sp}^2+\omega^2}\right) = \frac{\omega}{\omega_{sp}}. \tag{10}$$

It is noted that both the loss $\tan\delta_{DW}$ and $\tan\delta_{sp}$ decrease with increasing the resonance frequencies, $\omega_{DW}$ and $\omega_{sp}$. It is known that the domain wall resonance contributes to low-frequency permeability dispersion, while the spin rotational resonance is dominant in high-frequency permeability dispersion [20]. The high-frequency resonance frequency of ferrite, which is referred to as $f_{FMR}$, can be increased with high $H_k$ according to Eq. (2). Therefore, high resistivity, crystalline-anisotropy ferrite is necessary for high $L$-density and $Q$-factor GHz inductors.

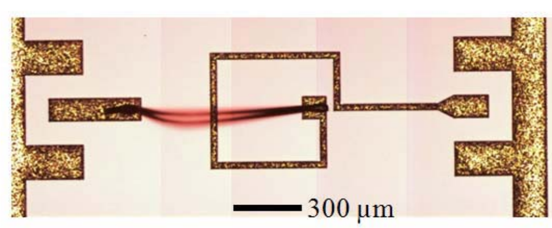
## 3. EXPERIMENT

### 3.1. Inductor Design and Fabrication

A one-turn spiral inductor was designed as shown in Fig. 1(a). The inductor has a coil area of $0.5 \times 0.5\,\text{mm}^2$, width of $15\,\mu\text{m}$, space of $50\,\mu\text{m}$, and thickness of $7\,\mu\text{m}$. A bonding wire was used between the center and outermost pads for an electrical connection. This designed coil structure was

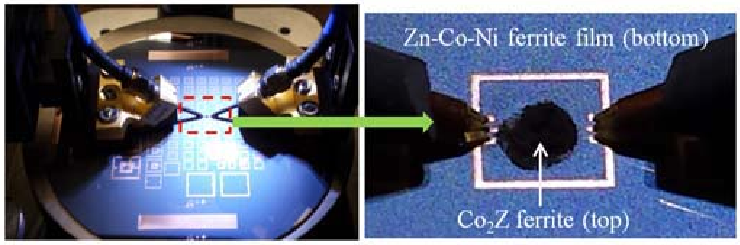


(a)

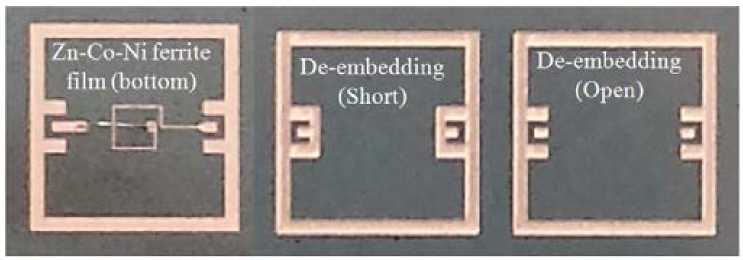


(b)

**Figure 1.** (a) Designed one-turn spiral inductor and (b) optical microscope image of the fabricated air-core inductor.




(a)




(b) (c) (d)

**Figure 2.** Photo-images of (a) embedded-type $Co_2Z$ hexaferrite inductor (bottom Zn-Co-Ni ferrite film + top $Co_2Z$ ferrite particles), (b) bottom-type Zn-Co-Ni ferrite film inductor, and (c) short and (d) open de-embedding structures.

used in simulating inductor performance (using ANSYS HFSS ver. 11) and fabricating air-core and ferrite inductors.

Figure 1(b) shows the air-core inductor that was fabricated on a 0.6 μm thick silicon oxide ($SiO_2$)/600 μm thick Si substrate. The conductivity ($\sigma$) of the Si substrate is 10–100 S/m. Figs. 2(a) and (b) exhibit the fabricated ferrite inductors with two different structures. One is the embedded-type ferrite inductor, where the inductor coil is positioned between the bottom Zn-Co-Ni ferrite film and top $Co_2Z$ hexaferrite particles as shown in Fig. 2(a). The second is the bottom-type ferrite inductor, having the coil formed on the Zn-Co-Ni ferrite film as presented in Fig. 2(b).

To fabricate the inductors, a microfabrication process and sputtering deposition were employed. First, a 2.45 μm thick Zn-Co-Ni ferrite film was deposited on the $SiO_2$/Si substrate, followed by Au (50 nm)/Ti (20 nm) seed layers for use in copper (Cu) coil electroplating. A 10 μm thick photoresist (PR) mold (Microchem KMPR1005) was then photolithographically produced on the Au/Ti layers. A 7 μm thick Cu coil was subsequently deposited by electroplating, followed by PR stripping and ion beam etching (IBE) of the Au/Ti layers for the bottom-type ferrite inductor as shown in Fig. 2(b). A mixture of $Co_2Z$ hexaferrite particles and ethanol was applied on the top of the bottom-type ferrite inductor and dried in air to realize the embedded-type ferrite inductor as presented in Fig. 2(a).

### 3.2. Preparation of High Crystalline-Anisotropy Zn-Co-Ni Ferrite Film and $Co_2Z$ Hexaferrite Particles

The Zn-Co-Ni ferrite film was prepared by the sequential direct current (DC) magnetron sputtering of nickel (Ni), iron (Fe), zinc (Zn), and cobalt (Co) metal targets in a mixture of 75% Ar and 25% $O_2$. During the sputtering deposition, the substrate temperature was held at 850°C, and the working pressure and DC power for each target were 5 mTorr and 250 W (200 W for Zn), respectively. The deposited multilayered oxide films were post-annealed at 850°C for 4 hours in a mixture of 67% Ar and 33% $O_2$ in order to crystallize the films into the Zn-Co-Ni ferrite.

With regard to $Co_2Z$ hexaferrite particles, the solid-state reaction process was used. The detailed process is reported elsewhere [21, 22]. Two different-sized $Co_2Z$ particles were prepared with and without 10-hour ball milling for the embedded-type ferrite inductor.

### 3.3. Measurement

The static magnetic properties and crystalline phases of the Zn-Co-Ni ferrite film and $Co_2Z$ particles were characterized by a vibrating sample magnetometer (MicroSense EV9) and X-ray diffractometer, respectively. A scanning electron microscope (SEM: JEOL 7000) was used to observe the cross-sectional image of the Zn-Co-Ni ferrite film.

To measure inductor electrical characteristics, a vector network analyzer (Agilent N5260A) and GSG probes (Cascade Microtech ACP40-GSG-200) were used. The $L$ and $Q$ factor of the air-core and ferrite inductors were calculated from the measured complex two-port scattering ($S$)-parameters ($S_{11}$, $S_{12}$, $S_{21}$, and $S_{22}$) [23]. The experimental setup for the inductor measurement is shown in Fig. 2(a). The probes were calibrated using the short-open-load-through (SOLT) technique with an impedance standard substrate (Cascade Microtech 101-190). The de-embedding technique [24] was also used to eliminate the parasitic effects of the probe pads and ground structure. The short and open de-embedding structures are shown in Figs. 2(c) and (d), respectively.

## 4. RESULTS AND DISCUSSION

### 4.1. Properties of High Crystalline-Anisotropy Zn-Co-Ni Ferrite Film and $Co_2Z$ Hexaferrite Particles

The measured X-ray diffraction patterns confirm that the Zn-Co-Ni ferrite film (in Fig. 3) and $Co_2Z$ particles (not shown here) are well crystallized into spinel and hexagonal ferrites, respectively. The cross-sectional SEM image in Fig. 4 shows that the Zn-Co-Ni ferrite film has a thickness of 2.45 μm and a smooth and clean surface.

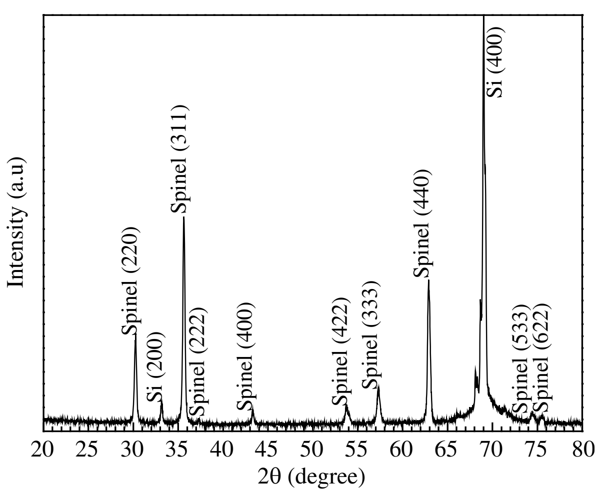



**Figure 3.** X-ray diffraction pattern of the fabricated Zn-Co-Ni ferrite film on silicon substrate.

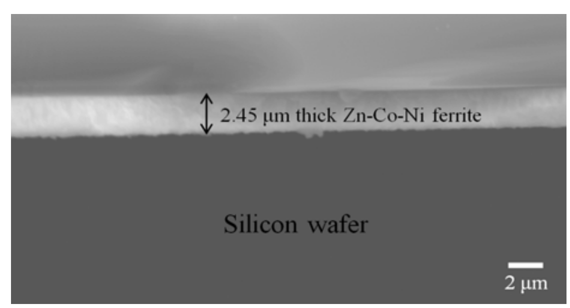



**Figure 4.** Scanning electron microscope (SEM) cross-sectional image of the Zn-Co-Ni ferrite film.

Figure 5 shows the measured magnetic hysteresis loop of the Zn-Co-Ni ferrite film. The saturation magnetization ($M_s$) and coercivity ($H_c$) of the film are 334 emu/cm$^3$ and 178 Oe, respectively. The in-plane $H_k$ of the ferrite film is 420 Oe, which was obtained by the method in [25]. It is noted that the fabricated Zn-Co-Ni ferrite film has higher $M_s$ and $H_k$ than those of low crystalline-anisotropy Ni-Zn-Cu ($M_s = 204$ emu/cm$^3$, $H_k = 401$ Oe) and YIG ($M_s = 94$ emu/cm$^3$, $H_k = 238$ Oe) ferrites [9]. It is, therefore, expected that the $f_{FMR}$ of the Zn-Co-Ni ferrite film increases with high $M_s$ and $H_k$ according to the relation $f_{FMR} = (\gamma/2\pi)(4\pi M_s H_k)^{0.5}$.

The measured magnetic hysteresis loops for the two different-sized $Co_2Z$ hexaferrites are presented in Fig. 6. One is the non-milled $Co_2Z$, while the other is the 10-hour milled $Co_2Z$ particles. The 10-hour milled $Co_2Z$ particles exhibit saturation magnetization ($\sigma_s$) of 49 emu/g and $H_c$ of 168 Oe. On the other

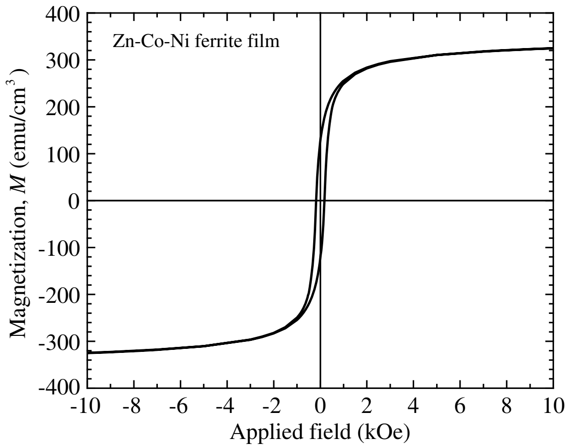



**Figure 5.** Measured magnetic hysteresis loop of the Zn-Co-Ni ferrite film.

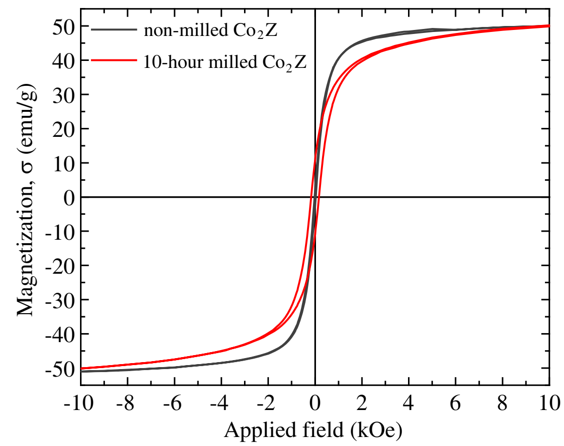



**Figure 6.** Measured magnetic hysteresis loops of the non-milled and 10-hour milled $Co_2Z$ hexaferrite particles.

hand, the non-milled $Co_2Z$ particles show $\sigma_s$ of 50 emu/g and $H_c$ of 23 Oe. The larger $H_c$ of the milled $Co_2Z$ implies a higher $H_k$ than that of the non-milled $Co_2Z$ [21].

With respect to dynamic magnetic properties, we calculated the frequency-dependent complex permeability for the Zn-Co-Ni ferrite film using Eq. (11) and permeability spectra for the $Co_2Z$ hexaferrite particles in order to estimate $\mu_r$, $\tan\delta_\mu$, and $f_{FMR}$. The complex permeability of the ferrite film can be calculated by Eq. (11) [26],

$$\mu(\omega) = 1 + \frac{\gamma 4\pi M_s}{\gamma H_k + j\alpha\omega} \times \left[1 + \frac{\omega^2}{(\gamma H_k + \gamma 4\pi M_s + j\alpha\omega)(\gamma H_k + j\alpha\omega) - \omega^2}\right], \tag{11}$$

where $\omega$ is the angular driving frequency, $\gamma$ the gyromagnetic constant ($1.76 \times 10^7$ rad/Oe·s), and $\alpha$ the damping constant. Thus, the parameters in the calculation include the experimental $M_s$ of 334 emu/cm$^3$, in-plane $H_k$ of 420 Oe, and $\alpha$ of 0.05 [27]. The calculated complex permeability spectra are presented in Fig. 7. The real part of permeability ($\mu'$) is about 14 at 2 GHz. The loss $\tan\delta_\mu$ (at 2 GHz) and $f_{FMR}$ are 0.11 and 3.86 GHz, respectively. The $f_{FMR}$ is determined by the maximum imaginary part of permeability ($\mu''$). It is noted that the large $H_k$ and $M_s$ of the Zn-Co-Ni ferrite film leads to a higher

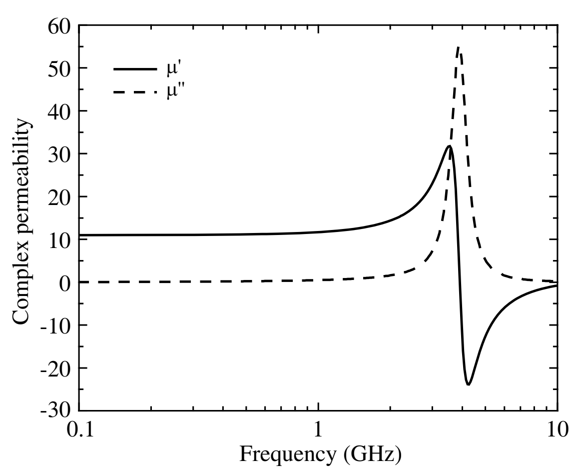



**Figure 7.** Calculated complex permeability of the Zn-Co-Ni ferrite film using the parameters $M_s = 334$ emu/cm$^3$, $H_k = 420$ Oe, and $\alpha = 0.05$.

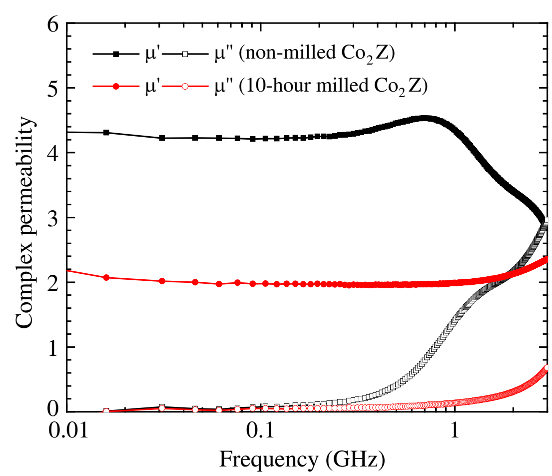



**Figure 8.** Measured complex permeability of the non-milled and 10-hour milled $Co_2Z$ hexaferrites.

$f_{FMR}$ than 0.26 GHz of the Ni-Zn-Cu ferrite and 0.06 GHz of the YIG [9]. The $\mu'$ and $\tan\delta_\mu$ were used in inductor performance simulation.

To measure the frequency-dependent complex permeability of the $Co_2Z$ hexaferrite, the $Co_2Z$ particles were formed into a toroidal ring (inner diameter: 3.2 mm, outer diameter: 7.8 mm) and characterized with an impedance/material analyzer (Agilent E4991). Fig. 8 presents the measured permeability spectra of the non-milled and 10-hour milled $Co_2Z$ hexaferrites. The $\mu'$ at 2 GHz is 3.4 (4.3 at 1 GHz) for the non-milled $Co_2Z$ and 2.1 (2.0 at 1 GHz) for the milled $Co_2Z$. The corresponding loss $\tan\delta_\mu$ are 0.64 (0.3 at 1 GHz) and 0.14 (0.06 at 1 GHz), respectively. It is obvious that the increased $H_k$ of the milled $Co_2Z$ leads to an increase in $f_{FMR}$ (beyond the measured frequency range in Fig. 8) and contributes to an improvement in GHz magnetic loss characteristics.

### 4.2. Electrical Characteristics of High Crystalline-anisotropy Zn-Co-Ni Ferrite Film Inductor

The fabricated ferrite inductors were characterized for $L$ and $Q$ factor in comparison to those of the air-core inductor. Figs. 9(a) and (b) show the measured and simulated $L$ and $Q$ factor of the bottom-type Zn-Co-Ni ferrite film and air-core inductors. The experimental $L$ and $Q$ factor of the inductors are in close agreement with the simulation results. It is noted that the discontinuity in the measured $Q$ factor in Fig. 9(b) is due to a minor measurement error. The measured $L$ of the Zn-Co-Ni ferrite and air-core inductors are 4.5 and 4.2 nH at 2 GHz, respectively. The corresponding $L$ densities are 18.0 and 16.8 nH/mm$^2$. It is found that the Zn-Co-Ni ferrite inductor shows a 7.1% increase in $L$ compared to that of the air-core inductor. The high crystalline-anisotropy Zn-Co-Ni ferrite inductor exhibits a small $L$ increase due to relatively low $\mu_r$.

With respect to the $Q$ factor of the inductors, the Zn-Co-Ni ferrite inductor shows a $Q$ factor of 4.8 at 2 GHz (8.5 at 1 GHz), which is lower than 6.7 (12.5 at 1 GHz) of the air-core inductor. The maximum $Q$ factors are 12.3 at 0.5 GHz for the Zn-Co-Ni ferrite and 14.1 at 0.55 GHz for the air-core inductors. The relatively low $Q$ factor of the ferrite inductor is mainly attributed to $\tan\delta_\mu$ of the Zn-Co-Ni ferrite. The measured inductor characteristics, therefore, indicate that GHz magnetic loss of the ferrite plays a critical role in inductor $Q$ factor. It is also found that the low $Q$ factors of both the air-core and Zn-Co-Ni ferrite inductors were caused by the large substrate loss of the high-conductivity Si substrate ($\sigma$ = 10–100 S/m). However, when we used the low-conductivity Si substrate ($\sigma$ = 0.01 S/m) in inductor performance simulation, the $Q$ factors of the Zn-Co-Ni ferrite and air-core inductors significantly increased to 20.0 and 31.9 at 2 GHz, respectively. The simulation results suggest that the Zn-Co-Ni ferrite film with high $M_s$ of 334 emu/cm$^3$ and $H_k$ of 420 Oe can produce an improved $L$-density, $Q$-factor inductor as compared to the low anisotropy Ni-Zn-Cu ferrite and YIG inductors [9].

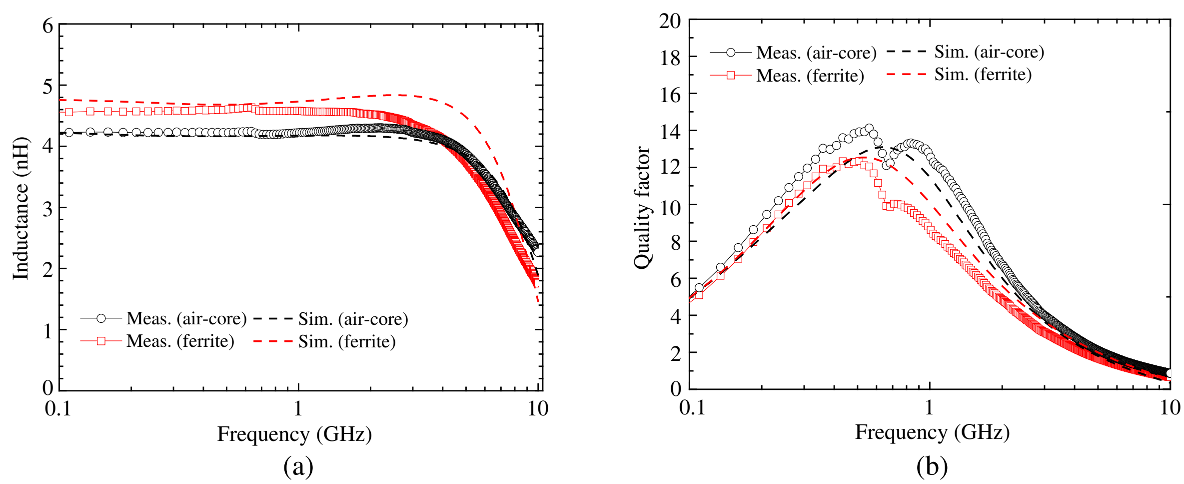



**Figure 9.** Measured and simulated (a) $L$ and (b) $Q$ factor of the air-core and Zn-Co-Ni ferrite film inductors.

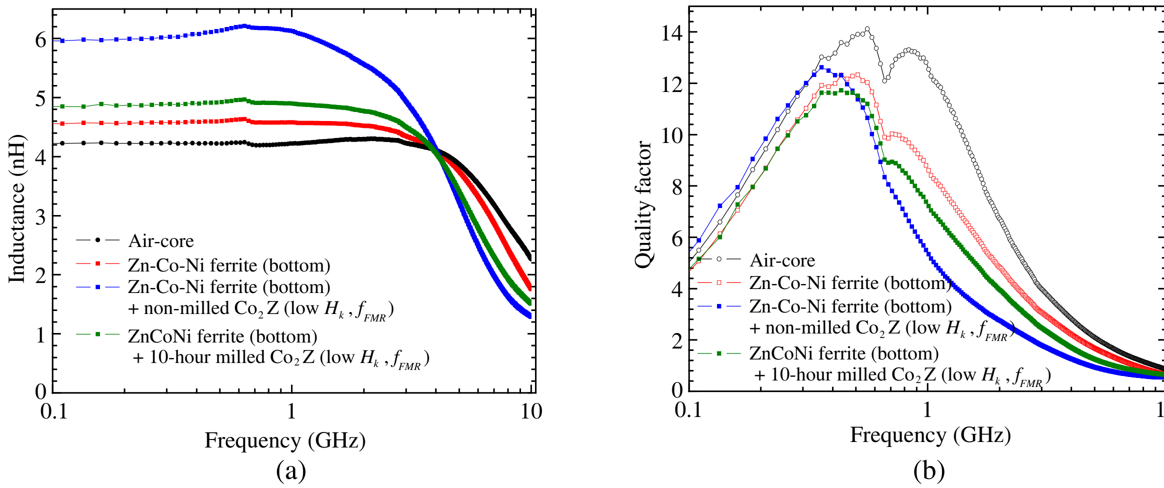



**Figure 10.** Measured (a) $L$ and (b) $Q$ factor of the air-core, Zn-Co-Ni ferrite (bottom), Zn-Co-Ni ferrite (bottom) + non-milled $Co_2Z$ hexaferrite (top), and Zn-Co-Ni ferrite (bottom) + 10-hour milled $Co_2Z$ hexaferrite (top) inductors.

**Table 1.** Measured electrical characteristics of the fabricated air-core and ferrite inductors at 2 GHz.

| At 2 GHz | $L$ (nH) | $L$ increase (%) | $Q$ | Max. $Q$ |
|---|---|---|---|---|
| Air-core | 4.2 | - | 6.7 | 14.1 at 0.55 GHz |
| Zn-Co-Ni ferrite film (bottom) | 4.5 | 7.1 | 4.8 | 12.3 at 0.50 GHz |
| Zn-Co-Ni ferrite film (bottom) + non-milled $Co_2Z$ (low $H_k$ and $f_{FMR}$) | 5.6 | 33.3 | 2.8 | 12.6 at 0.35 GHz |
| Zn-Co-Ni ferrite film (bottom) + 10 h-milled $Co_2Z$ (high $H_k$ and $f_{FMR}$) | 4.8 | 14.3 | 4.0 | 11.7 at 0.43 GHz |

### 4.3. Effect of Dynamic Magnetic Properties of $Co_2Z$ Hexaferrites on $L$ and $Q$ Factor

To further investigate the effect of dynamic magnetic properties on a ferrite inductor's $L$ and $Q$ factor, two-different sized $Co_2Z$ hexaferrites were applied to the bottom-type ferrite inductor as shown in Fig. 2(a). Fig. 10 shows the measured $L$ and $Q$ factor of the embedded-type ferrite inductors, with the coil positioned between the bottom Zn-Co-Ni ferrite film and top $Co_2Z$ hexaferrite particles, in comparison to the electrical characteristics of the air-core and bottom-type Zn-Co-Ni ferrite inductors. The embedded-type ferrite inductors show an $L$ of 5.6 nH (Zn-Co-Ni + non-milled $Co_2Z$: low $H_k$ and $f_{FMR}$) and 4.8 nH (Zn-Co-Ni + 10-hour milled $Co_2Z$: high $H_k$ and $f_{FMR}$) at 2 GHz. These inductances are greater than 4.2 nH of the air-core and 4.5 nH of the Zn-Co-Ni ferrite film inductors. The $L$ of the embedded-type ferrite inductors increase by 33% and 14% compared to the $L$ of the air-core inductor. The corresponding $L$-densities are 22.4 nH/mm$^2$ for the low $H_k$ $Co_2Z$ and 19.2 nH/mm$^2$ for the high $H_k$ $Co_2Z$. The significant increase in $L$ occurs because the $Co_2Z$ hexaferrite enhances magnetic flux density and also reduces leakage magnetic flux. On the other hand, the additional $\tan\delta_\mu$ from the $Co_2Z$ caused a reduction in the $Q$ factor as shown in Fig. 10(b). It is found that the high $H_k$ and $f_{FMR}$ $Co_2Z$ embedded-type inductor demonstrates a higher $Q$ factor of 4.0 at 2 GHz (7.2 at 1 GHz) than 2.8 (5.3 at 1 GHz) of the low $H_k$ and $f_{FMR}$ $Co_2Z$ inductor. Table 1 summarizes the measured characteristics of the fabricated air-core and ferrite inductors.

### 4.4. Relation of Magneto-Crystalline Anisotropy Field, $H_k$ to Inductor $Q$ Factor

The experimental inductor characteristics demonstrate that GH $\tan\delta_\mu$ plays a role in the inductor $Q$ factor, and therefore, the $H_k$ becomes a key magnetic parameter. Inductor performance simulation was carried out to investigate the relation of $H_k$ to inductor $Q$ factor. Fig. 11 shows the dependence of both $f_{FMR}$ and $Q$ factor on $H_k$ at $\mu_{\rm dc}$ of 10, 20, and 30. The relation $\mu_{\rm dc} = 1 + 4\pi M_s/H_k$ and the Eqs. (2) and (11) were used to obtain the $f_{FMR}$ (in Fig. 11) and frequency-dependent $\mu'$ and $\tan\delta_\mu$. The calculated $\mu'$ and $\tan\delta_\mu$ at 2 GHz were then applied in the inductor simulation to determine the $Q$ factor. The designed inductor geometry shown in Fig. 1(a) was used. The Si-substrate had $\sigma$ of 0.01 S/m, and the ferrite film had a thickness of 2.45 µm. As shown in Fig. 11, the $f_{FMR}$ increases with increasing the $H_k$. At $\mu_{\rm dc}$ of 10, the $f_{FMR}$ increases to 5 GHz from less than 2 GHz as the $H_k$ increases from 200 to 600 Oe. The results suggest that the GHz $\tan\delta_\mu$ can decrease with high $H_k$ according to Section 2. The corresponding inductor $Q$ factor at 2 GHz is 37.9 with the $H_k$ of 600 Oe and 3.4 with the $H_k$ of 200 Oe. When the $H_k$ is higher than 400 Oe, the ferrite inductors' $Q$ factors become greater than that of the air-core inductor ($Q$ of 31.9 for the Si $\sigma$ of 0.01 S/m). With respect to the $L$, the simulated $L$ was about 4.4 nH at $\mu_{\rm dc}$ of 10, 4.6 nH at $\mu_{\rm dc}$ of 20, and 4.8 nH at $\mu_{\rm dc}$ of 30. It is, therefore, suggested that the high $H_k$ and $f_{FMR}$ ferrite inductor with a large $M_s$ is desired for high $L$ density and $Q$ factor GHz inductors.

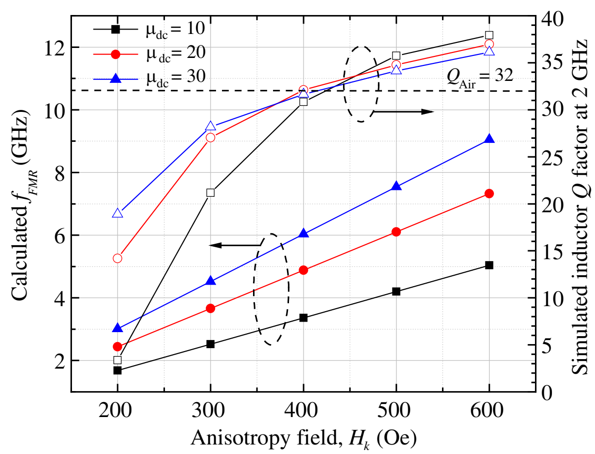



**Figure 11.** Calculated $f_{FMR}$ and simulated inductor $Q$ factor at 2 GHz as a function of $H_k$ at $\mu_{\rm dc}$ of 10, 20, and 30.

Exploring material candidates suggests that exchange-coupled magnets can meet the desired magnetic properties. The coupling of magnetically soft (i.e., high $M_s$ and small $H_k$) and hard (i.e., small $M_s$ and high $H_k$) phases in the exchange-coupled system realizes simultaneously high $M_s$ and large $H_k$. Therefore, future research will focus on exchange-coupled magnetic GHz inductors.

## 5. CONCLUSION

Planar GHz inductors were fabricated based on high crystalline-anisotropy Zn-Co-Ni ferrite and $Co_2Z$ hexaferrite and characterized for $L$ and $Q$ factor. The ferrite inductors show $L$ densities of 18.0 nH/mm$^2$ (Zn-Co-Ni), 22.4 nH/mm$^2$ (Zn-Co-Ni + low $H_k$ and $f_{FMR}$ $Co_2Z$:), and 19.2 nH/mm$^2$ (Zn-Co-Ni + high $H_k$ and $f_{FMR}$ $Co_2Z$:). With respect to the $Q$ factor, the ferrite inductors exhibit $Q$ factors of 4.8 (Zn-Co-Ni), 2.8 (Zn-Co-Ni + low $H_k$ $Co_2Z$), and 4.0 (Zn-Co-Ni + high $H_k$ $Co_2Z$) at 2 GHz. The $L$ densities and $Q$ factors of the ferrite inductors are greater and lower than 16.8 nH/mm$^2$ and 6.7 of the air-core inductor, respectively. The high $H_k$ of Zn-Co-Ni ferrite film and $Co_2Z$ hexaferrite results in increased $f_{FMR}$ and moderate $\mu_r$, but the ferrites' $\tan\delta_\mu$ causes a decrease in the $Q$ factor. Accordingly, $L$ densities and $Q$ factors are trade-off for GHz ferrite inductors. Future research needs to focus on development of low-loss and high-permeability GHz ferrites. In addition, low-temperature fabrication technique is inevitable since the ferrite process temperature is incompatible with complementary metal-oxide-semiconductor (CMOS) processing temperature in contrast to air-core inductors. In conclusion, the simulation and experiment results suggest that high resistivity, crystalline-anisotropy, low loss ferrite along with high $Q$ inductor design can give rise to high $L$ density and $Q$ factor GHz inductors.

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