Magnetic Nano Particles and Thin Films for High Frequency Micro Inductors

by

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A thesis submitted in partial satisfaction of the requirements for the degree of
Doctor of Philosophy
in
Engineering – Mechanical Engineering
in the
Graduate Division
of the
University of California, Berkeley

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Fall 2015
Magnetic Nano Particles and Thin Films for High Frequency Micro Inductors

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Abstract

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The size and performance of integrated circuits have been following Moore’s law to continuously shrink and progress over the past decades while on-chip inductors have seen little advancements. This work proposes several unique approaches in the integrated magnetic cores for high frequency micro inductor developments, including: (1) spherical-shape, anti-oxidizing magnetic nanoparticle composites; (2) sputtered magnetic thin films with magnetization-induced anisotropy; and (3) rectangular-shape magnetic particles with geometry-induced anisotropy. Theoretical and simulation studies have been conducted with experimental demonstrations to validate these concepts.

Chemical syntheses of spherical-shape magnetic FeNi₃ particles of 100 nm in diameter, with and without a thin passivation SiO₂ coating have been investigated. After the integration with micro inductors by a CMOS-compatible process, it is found that the inductance values have increased 20-45% up to 2 GHz for micro inductors after adding the magnetic nanoparticle composites. The quality factors have degraded slightly mainly due to the magnetic losses from large coercivity at about 100 Oe despite of the reduction of eddy current losses in the magnetic nanoparticle composites.

The control of magnetization-induced anisotropy of magnetic thin films by using different magnitudes of sputtering deposition power under an external magnetic field has been studied and characterized. By reducing the sputtering power from 1000 to 150 Watts, the sputtered CoZrTaB thin films have smaller grain size and higher in-plane anisotropy and higher FMR frequency from 1.48 to 2.17 GHz. After the integration the magnetic thin films with stripline inductors, 2.5-3.5 times higher inductances and 2.5-3 times higher Q-factors than those of air-core inductors have been accomplished.

Magnetically aligned, rectangular plate-like structures have been demonstrated for geometry-induced nano magnets in micro inductors. These magnets have been analyzed in theories and simulations with experimental validations to have advantages of particles in low eddy current losses and thin films in magnetic anisotropy for high FMR. After the integration with micro inductors under an external magnetic field, the roll-off frequencies in inductance of micro inductors have reached 4.2 GHz with 10% increase in inductance.
To my family members,

I couldn’t have done this without you.

Thank you for all of your support.
ACKNOWLEDGMENT

Over the past years at Berkeley I received invaluable help and support from a great number of individuals. It is impossible to describe my doctoral study without them, and I am truly fortunate to have the opportunity to work with them. Especially, I would like to thank my advisor, Prof. Liwei Lin, for the guidance and support during the Ph.D. program. I would also like to thank my committee members, Prof. Denis K. Lieu and Prof. Ana C. Arias for their advice and feedback. In addition, I appreciate Dr. Kevin P. O’Brien and Dr. Donald S. Gardner for their mentorship.

I would like to express my deep appreciation and gratitude to my parents, Young Hee Jung and Kwang Byung Koh, for their encouragement and support during my long journey in academia. I would also like to thank my brother, Kisup Koh, for serving parents alone during my absence.

Finally, I would be remiss if I did not acknowledge the innumerable sacrifices from my wife, Mijoo Jeon. I do not have words to express my gratitude for her love and support. I also want to thank my daughter, Surin Koh, who always makes me smile. I could endure hard time because of you. I could not have done this without you, and I appreciate all of your support.
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Chapter 1  Introduction

1.1 Motivation

1.1.1 More than Moore and Migration of Components

Gordon E. Moore’s observation and forecast in the so-called “Moore’s law” has been the roadmap for the semiconductor industry, and the number of transistors in integrated circuits (ICs) has been increased exponentially. It is based on smaller device dimensions for higher circuit density, leading to reduction of manufacturing cost and the increase in chip values. Although the trend following “Moore’s law” has continued for decades, the prediction regarding the limitations of the progresses has been a huge concern as it is approaching the limits of miniaturization at the atomic levels. In that time, another direction called “More than Moore” (MtM) has emerged as another future direction in the semiconductor industry by combining functionalities of ICs and other silicon-based devices for higher values, which do not scale according to "Moore's Law" as
depicted in Figure 1 [1]. Many of the non-digital components might fall into this category. For example, some of these non-digital components have been realized by the printed circuit board (PCB) approaches and recent technology progresses have enabled migrations of non-digital components from PCB to the chip packages in integrated circuits, known as System-in-Package, SiP, or to the microelectronic chips, referred as System-on-Chip, SoC, as shown in Figure 2 [2].

The explosive growth of wireless communication systems has led the demands on the increase in functionality and reductions in size and cost for radio frequency (RF) applications. The reduction in the size of discrete passive components in PCBs is reaching its limit due to the high cost in the assembly of tiny discrete components. For example, a typical mobile phone has hundreds of passive components and only 20 to 40 ICs. The discrete passive components account for 90% of the component count, 80% of the size and 70% of the cost [4]. For miniaturization of electronics systems, it is important to integrate these passive components from the PCB to the wafer-scale IC processes. This will make the continuing reduction in size and cost be possible.

Figure 2 Migration of components in the trend of system integration [2, 3]
1.1.2 Scaling of High Frequency On-chip Inductors

According to the trend of “More than Moore” and the demands for miniaturization of devices, there have been efforts to integrate passive elements including inductors, capacitors, and resistors, which are indispensable in RF systems from PCBs to chip substrates as integrated passive devices (IPDs). The passive elements are fabricated by using standard IC fabrication technologies, and a typical IPD structure is illustrated in Figure 3, with inductors, resistors, and capacitors on the substrate surface.

![Figure 3 Illustration of Integrated Passive Device [3].](image)

The on-chip inductors (IPD inductors) are formed in conductive interconnection layers on the substrate with spiral-shapes due to the planar IC fabrication technologies. Relative to other components, the on-chip inductors occupy a large footprint on a chip area as shown in Figure 4, and it has been a bottleneck in chip miniaturizations. While the transistors have been scaled down based on the Moore’s law, the on-chip inductors have remained the same size for the past decades without technological advancements as compared with the IC technologies as shown in Figure

![Figure 4 A 3.1-9.5 GHz UWB pulse radio receiver [5]. The red dot line shows the area of on-chip inductors.](image)
Figure 5 Comparison of scaling trends between transistors and inductors [6-14]. The size of inductors was calculated as the square root of the footprint.

1.2 Magnetic Materials and Inductors

1.2.1 Soft Magnetic Materials and Magnetic Cores

Magnetic materials (referring to ferromagnetic materials in this thesis) change magnetization ($M$) according to the applied magnetic field ($H$) with remanence ($M_r$) and coercivity ($H_c$) as shown in Figure 6. If a magnetic material is magnetized in a direction with an applied field, the magnetization may not go to zero when the applied field is removed. The magnitude of maintained magnetization without the applied field is called remanence, and it can be reduced to zero by applying a field of opposite direction and is called the coercivity.

Figure 6 A hysteresis loop of magnetic materials showing remanence and coercivity [15].
When an alternating magnetic field is applied to a magnetic material, the magnetization draws a loop of curves called a hysteresis loop, and the phenomenon is called hysteresis. Magnetic materials are classified to soft and hard magnets according to the hysteresis of the materials as shown in Figure 7. The soft magnetic materials exhibit minimal hysteresis with large permeability (the slope at the zero applied magnetic field).

![Figure 7 Classification of magnetic materials and their applications: Soft and hard magnetic materials according to hysteresis loops.](image)

It is desirable to minimize the energy dissipations under the alternating fields for AC electrical applications. For example, magnetic materials have been used as magnetic cores in large-scale inductors to enhance their performances in terms of inductance and quality factor as illustrated in Figure 8.

![Figure 8. Magnetic field from an air-core solenoid coil (left) and a magnetic-core solenoid coil (right) [16].](image)

Inductance represents the voltage generated in conductors due to the changes in the current, and quality factor of an inductor is the ratio between the inductive reactance and resistance at a given
frequency. A magnetic core is a piece of a magnetic material, and it is used to increase the magnetic fields by the high permeability of the material ($\mu_r$). The magnetic material with high permeability generates large amount of magnetic fields induced by an applied magnetic field from the electrical coil as shown in Figure 8. Adding soft magnetic cores to inductors leads to increase inductance ($L$) and quality factor ($Q$) by the large permeability of magnetic materials ($\mu_r$) as shown in the following equations. In other words, it can reduce the size of inductors for a certain level of inductance. Therefore, the magnetic cores have been widely used to fabricate compact inductors and transformers.

For a solenoid coil,

$$L = \mu_0 \mu_r \frac{N^2 A}{l}$$

(1.1)

where $\mu_0$ is the vacuum permeability, $\mu_r$ is the relative permeability of magnetic materials, $N$ is the number of turns, $l$ is the length of the coil, and $A$ is the cross-section area of the solenoid.

$$Q = \frac{2\pi fL}{R}$$

(1.2)

where $f$ is the frequency, $L$ is the inductance, and $R$ is the resistance.

1.2.2 Magnetic Losses and Magnetic Resonance

As mentioned previously, the high permeability of magnetic materials enhances inductance and quality factor in general. However, the quality factor ($Q$) is not always increased by adding the magnetic materials. Although the quality factor ($Q$) is proportional to the inductance ($L$) in Equation (1-2), it is inverse proportional to the resistance $R$.

![Figure 9 Total loss per cycle including hysteresis loss, eddy current loss, and anomalous losses [15].](image)
The resistance comes from the energy losses in magnetic-core inductors with three main sources: hysteresis loss, eddy current loss, and anomalous losses. Hysteresis loss is an energy loss from irreversibility of magnetization in alternating excitations (Figure 7). Eddy current loss is due to the induced currents in a conducting magnet which dissipate the energy as heat. Anomalous loss is from the domain wall motion, nonuniform magnetization and sample inhomogeneity. Figure 9 illustrates these losses and the total loss per cycle including all three mechanisms. Therefore, suppressing the magnetic losses is a key challenge in all magnetic applications.

For high frequency electromagnetic devices, magnetic resonance is the most representative loss factor besides the aforementioned magnetic losses such as hysteresis loss, eddy-current loss, and anomalous losses. In the GHz frequency range, the magnetization process involves magnetization rotation rather than domain-wall motion, and losses are influenced by ferromagnetic resonance. Typically, the ferromagnetic resonance frequency is near 1 GHz such that it is difficult to incorporate magnetic materials as the magnetic cores into GHz frequency inductor applications.

The magnetic losses from the resonance can be presented in terms of a complex permeability ($\mu$). When an external magnetic field with a frequency ($\omega$), $h = h_0 e^{i\omega t}$ is applied to a magnetic material, the induced magnetic flux density, $b = b_0 e^{i(\omega t - \delta)}$, lags behind by a phase angle ($\delta$). The complex permeability $\mu = (b_0 / h_0) e^{-i\delta}$ is expressed as

$$\mu = \mu' - i\mu''$$

(1.3)

where $\mu' = (b_0 / h_0) \cos \delta$ and $\mu'' = (b_0 / h_0) \sin \delta$. The real part gives the component of the complex permeability in phase with the excitation field, and the imaginary part gives the component which lags behind by $\pi / 2$. The loss from the magnetic resonance is proportional to $\mu''$. The real part permeability decreases to zero due to the magnetic resonance loss as shown in Figure 10. As it was mentioned previously, the magnetic resonance frequency is near 1 GHz for most materials, such that it is difficult to use magnetic materials for high frequency electromagnetic devices above 1 GHz as the cores.

Figure 10 Complex permeability showing real and imaginary parts change over frequency.
1.2.3 Magnetic Cores for High Frequency On-chip Inductors

Especially for planar structure inductors, magnetic films have been integrated to inductors for decades, it was well described by V. Korenivski [17]. The first fabrication of magnetic thin-film inductors was attempted by Saleh and Qureshi [18]. They presented magnetic analysis, the use of the fast transverse permeability (excitation along the hard axis), as well as the segmentation of the magnetic film to avoid displacement currents due to the conductor-to-film capacitance. The spiral conductors are sandwiched between Permalloy films on glass substrates, and the inductor was optimized for operation at 10 MHz with 15% inductance enhancement over the air-core value. Soohoo gave a basic magnetic analysis for a magnetically sandwiched spiral and a magnetic core solenoid, and he fabricated a prototype inductor with copper windings wrapped around a Permalloy/glass(Si) substrate, which showed a 700 times enhancement in the specific inductance [19].

Besides the aforementioned frontiers, there have been efforts to fabricate on-chip magnetic inductors and extend their operation frequency range from 1-10 MHz to 100-1000 MHz. Shirae et al. demonstrated various structures including a planar coil embedded in SiO and sandwiched by two Permalloy films [20]. This inductor had resonances at a few tens of MHz due to the distributed coil-to-film capacitance in the structure. An inductance gain up to a factor of 4 at ~100 MHz was obtained by Yamaguchi et al. for Permalloy coated conductor strips [21, 22]. Korenivski and van Dover implemented Cu strips sandwiched with Permalloy and CoNbZr for 7-fold inductance enhancement up to 250 MHz [23]. Viala et al. demonstrated thin film inductors with magnetic films for 135% inductance increase up to 1 GHz [24]. Generally, it is difficult to integrate magnetic materials as the cores for high frequency applications above 1 GHz due to the ferromagnetic resonance frequency, which leads to permeability roll-offs.

1.3 Dissertation Goal and Organization

The goal of this thesis is exploring magnetic materials for possible candidates for magnetic cores operating in the GHz frequency ranges. In the first chapter, the background is described, including the applications of magnetic materials as the cores for on-chip micro inductors; the factors for magnetic materials as magnetic cores for high frequency applications; and the difficulty in using magnetic materials for high frequency applications such as on-chip inductors. In addition, the history of on-chip inductors with magnetic materials is presented.

Chapter 2 describes efforts in using magnetic nanoparticle composites as the magnetic cores to achieve good permeability over the GHz frequency ranges. Theoretical models based on the effective medium approximation are introduced followed by the material preparations and characterizations. Experimental data of micro inductors with magnetic nanoparticle composites are studied and investigated.

Chapter 3 discusses the permeability of a sputtered magnetic thin film with increased FMR frequency by lowering the sputtering power. Theoretical background of magnetic resonance and magnetization induced anisotropy are presented. Quasi-static and dynamic magnetic properties of the film are provided as well as other material properties. Characterizations of inductors with the monolithic integration of the magnetic thin films are presented.
Chapter 4 presents plate-like magnetic structures made of thin rectangular films to result in high FMR frequency. The advantages of plate-like particle composites for high magnetic anisotropy and high FMR frequency are theoretically analyzed. Fabrication and characterization of the plate-like particles are discussed with experimental results. Experiments of inductors with plate-like magnetic particles are reported with extended operation frequency ranges for micro magnetic inductors.
Chapter 2 Magnetic Particle Composites

2.1 Introduction

Magnetic particles have been researched from a wide range of disciplines for applications in magnetic cores [25], electromagnetic wave absorption [26], data storage [27], non-destructive testing [28], magnetically separable catalysis [29], magnetic resonance imaging (MRI) [30], biotechnology/biomedicine [31, 32], and environmental remediation [33]. For AC applications such as magnetic cores and electromagnetic wave absorbers, the modeling and measurement of permeability/susceptibility in frequency domains are explored extensively using various magnetic materials [34-46].

For magnetic cores, soft magnetic composite materials (SMCs) composed of magnetic particles (typically 5-200µm in diameter) and insulation structures have been explored for decades with various materials and processing techniques for good relative permeability in the low frequency ranges (< 0.1 MHz), magnetic saturation, and high electrical resistivity (low eddy current loss). However, SMCs have limited usages in discrete/off-chip inductors due to the requirements of harsh processing conditions such as heat treatments and high pressure compactions.

Magnetic composites without annealing/compaction have found applications in electromagnetic wave absorbers due to the isotropic broadband characteristics from in randomly distributed particles. From that standpoint, the permeability of nanoparticle composites have been studied for high frequency applications above 1 GHz as their permeability can be larger than unity in the GHz frequency range.

Figure 11 A schematic for an inductors with magnetic nanoparticle composites.
Inductors are essential elements in radio frequency (RF) and microwave systems for wireless communication functions, and there has been a demand for high frequency compatible magnetic materials for reducing the size of high frequency on-chip inductors due to their large footprints compared to other components. Since conventional magnetic materials such as thin films and SMCs have permeability drop before 1 GHz due to magnetic losses such as magnetic resonance, eddy-currents and magnetic hysteresis, the magnetic nanoparticle composite is highlighted as magnetic cores for the high frequency (> 1 GHz) inductors as illustrated in Figure 11. In this chapter, magnetic particle composites made of FeNi$_3$ and insulating materials are introduced for high frequency on-chip inductor applications. Modeling and analytical study of the magnetic particle composites, the synthesis processes for the magnetic nanoparticles, and the material characterizations are investigated. Furthermore, on-chip micro inductors are fabricated and integrated with the magnetic nanoparticle composite, and characterized for inductance and quality factor.

2.2 Theoretical Background

2.2.1 Magnetic Resonance and Broadband Permeability

When a magnetic dipole is subjected to a uniform magnetic field $\mathbf{B}$ in the $z$ axis and a transverse high frequency field $\mathbf{b}$ in the $xy$ plane as shown in Figure 12, the magnetic resonance is observed. The magnetic moment $\mathbf{m}$ is associated with the total angular momentum $\hbar \mathbf{J}$, with the gyromagnetic ratio $\gamma$ as:

$$\mathbf{m} = \gamma \hbar \mathbf{J} \quad (2.1)$$

For a macro spin or a giant spin of the magnetic moment $\mathbf{m}$ in the absence of damping, the torque on the magnetic moment $\mathbf{m}$ in the field $\mathbf{B}$ is derived as:

$$\Gamma = \mathbf{m} \times \mathbf{B} \quad (2.2)$$

Since the torque is equal to the change of the total angular momentum, the equation of motion of the magnetic moment $\mathbf{m}$ or the magnetization $\mathbf{M}$ (moment per volume) is derived as:

$$\frac{d\mathbf{m}}{dt} = \gamma (\mathbf{m} \times \mathbf{B}) \quad \text{or} \quad \frac{d\mathbf{M}}{dt} = \gamma (\mathbf{M} \times \mathbf{B}) \quad (2.3)$$

Then, the magnetic moment or the magnetization precesses around the field in $z$ axis as shown in Figure 12 at angular frequency $\omega_0$, which is called the Larmor frequency:

$$\omega_0 = \gamma B \quad (2.4)$$
Figure 12 A magnetic resonance setup with a static field and an alternating field (left) and the precession of magnetic moment in an applied magnetic field (right) [15].

Under the external magnetic field $\mathbf{H} = \mathbf{B}/\mu_0$, the internal magnetic field of the ferromagnetic material can be expressed as $\mathbf{H}_{\text{int}} = \mathbf{H} + \mathbf{H}_d$. The demagnetizing field $\mathbf{H}_d = -\mathbf{NM}$ is assumed diagonal with the demagnetizing factors as shown below:

$$N = \begin{bmatrix}
N_x & 0 & 0 \\
0 & N_y & 0 \\
0 & 0 & N_z
\end{bmatrix} \quad (2.5)$$

On the condition of $b << B$, the magnetization is approximated where $m(t)$ is the small in-plane component.

$$\mathbf{M} \approx M_z \mathbf{e}_z + m(t) \quad (2.6)$$

The magnetization and the demagnetizing field are expresses as:

$$\mathbf{M} = M_x \mathbf{e}_x + M_y \mathbf{e}_y + M_z \mathbf{e}_z \quad (2.7)$$

$$\mathbf{H}_d = -N_x M_x \mathbf{e}_x - N_y M_y \mathbf{e}_y - N_z M_z \mathbf{e}_z \quad (2.8)$$

The internal magnetic field is summation of the external magnetic field and the demagnetizing field.

$$\mathbf{H}_{\text{int}} = (H - N_x M_x)e_x - N_y M_y e_y + (H - N_z M_z)e_z \quad (2.9)$$

According to the equation of motion, the magnetization with the uniform magnetic field $\mathbf{B}$ in the $z$ axis and the transverse high frequency field $\mathbf{b}$ in the $x$ axis can be described as:
For the $m(t)=m_0e^{i\omega t}$, the oscillating component, the above systems of differential equations have solutions when

$$
\begin{vmatrix}
-i\omega & \mu_0\gamma\left(H + (N_y - N_z)M_s\right) \\
-\mu_0\gamma\left(H + (N_x - N_z)M_s\right) & -i\omega
\end{vmatrix} = 0
$$

(2.11)

The above determinant leads to the Kittel equation for the resonant frequency.

$$
\omega_b^2 = \mu_0\gamma^2\left[H + (N_x - N_z)M_s\right]\left[H + (N_y - N_z)M_s\right]
$$

(2.12)

Especially for spherical particles, the demagnetizing factors are

$$
N_x = N_y = N_z = \frac{1}{3}
$$

(2.13)

The ferromagnetic resonance frequency of a sphere particle is proportional to the magnitude of static magnetic field, which is orthogonal to the transverse high frequency magnetic field.

$$
\omega_b = \mu_0\gamma H
$$

(2.14)

The magnetocrystalline anisotropy (energy to align the magnetization in certain axes contributed by crystalline structure and dipole-dipole interactions) also influence the ferromagnetic resonance by adding the anisotropy field $H_a=2K_1/M_s$ to the demagnetizing field in the above expression. For a spherical particle with the $z$ axis as the anisotropy axis, the resonance frequency is described as

$$
\omega_b = \mu_0\gamma\left(H + \frac{2K_1}{M_s}\right)
$$

(2.15)

where $K_1$ is the anisotropy constant and $M_s$ is the saturation magnetization. From the equation, it is possible to observe ferromagnetic resonance without the external magnetic field for a single-domain particle, or a crystal of high-anisotropy material magnetized along $z$ axis.

As it is explained above, the spherical particles have resonance under a small alternating excitation even without a static magnetic field, and the resonance is the most critical energy loss factor, which leads to the reduction in permeability. However, the permeability of magnetic particle composites shows a different behavior in contrast to the magnetic thin films. Typically,
the permeability of the magnetic thin film drops quickly when the frequency is close to the FMR frequency of the magnetic material. On the other hand, the magnetic particle composites show a slow reduction in permeability in the GHz frequency ranges due to the randomly distributed magnitude and direction of magnetic anisotropy as depicted in Figure 13. Each particle is under the influence of the magnetic field including the magnetization of nearby particles, and the magnitude and the direction are randomized in the entire system. A. Sukhova et al. have showed randomly distributed anisotropy axes and anisotropy energies result in a significant broadening of the FMR signal as compared to particles having the same anisotropy presented in Figure 14 [47]. As the simulation work presented, the random distribution of magnetic particles leads to the broad permeability over frequency ranges especially in the GHz ranges.

Figure 13 Typical permeability curve (real part) from a magnetic film with uniaxial anisotropy and a spherical-shape magnetic particle composite made of magnetic particles with random anisotropy.
Figure 14 Simulation results of the mean resonance curves from an assembly of 2000 nanoparticles with randomly distributed anisotropy axes and a Gaussian distribution of anisotropy energies: Absorbed FMR power (arbitrary units) vs. reduced magnetic field for different values of reduced anisotropy $d$, which describe the randomness of anisotropy [47].

2.2.2 Effective Medium Approximation

Based on the random distribution of anisotropy magnitude and direction in magnetic particle composites, analytical or theoretical modeling methods have been used to describe the macroscopic properties of the magnetic particle composites. Effective medium approximation or effective medium theory is developed to produce acceptable approximation describing useful parameters and properties of the composite materials. The average values of the constituents are used as the constituent values can vary due to the inhomogeneous material distributions and the precise calculation of the constituents is impossible. The effective medium approximation gives estimations of the particle composites based on the properties and the relative fraction of the components. Specifically, the effective medium approximation methods are derived from an equivalent dipole representation of the mixture, and the effective macroscopic electromagnetic properties are modeled as an effective dipole moment per unit volume. Among the effective medium approximation methods, the Bruggeman’s model is widely used to estimate permeability in quasistatic regime where the particle diameter is much smaller than incident electromagnetic wavelength [36]. For spherical inclusions, the Bruggeman’s formula is expressed as:

$$\sum_i \delta_i \frac{\mu_i - \mu_e}{\mu_i + (n-1)\mu_e} = 0 \quad (2.16)$$

where $n$ is the Euclidean spatial dimension; $\delta_i$ is the fraction of each component; $\mu_i$ is the permeability of each component; and $\mu_e$ is the effective permeability of the entire system. From the above equation, the effective permeability of the system consists of two components, the magnetic particle and the non-magnetic matrix as:
where $\delta_p$ is the volume fraction of the particle; $\mu_p$ is the permeability of the particular material; and $\mu_m$ is the permeability of the non-magnetic matrix which is the unity. For typical metallic ferromagnetic particles (Fe, Ni, and Co), it is important to consider eddy currents in the quasistatic regime because the eddy currents can contribute to permeability significantly. Rousselle et al. modified the Bruggeman’s model by adding magnetic polarizability of a conducting sphere subjected to a time varying magnetic field [35, 36]. The modified model called the extended Bruggeman approximation and it gives good agreement for experimental data, which have particle concentration 25-50% [37]. The extended Bruggeman approximation is described as:

\[
\delta_p \frac{\mu_p - \mu_e}{\mu_p + 2\mu_e} + (1 - \delta_p) \frac{\mu_m - \mu_e}{\mu_m + 2\mu_e} = 0
\]  

(2.17)

\[
A(a, f, \rho_p, \mu_p) = \frac{2(ka \cos ka - \sin ka)}{\sin ka - ka \cos ka - k^2a^2 \cos ka}
\]  

(2.19)

\[
k = (1 + i) \frac{\pi f \mu_p}{\varepsilon_0 c^2 \rho_p}
\]  

(2.20)

where $a$ is the radius of particle; $f$ is the frequency of incident wave; $\rho_p$ is the resistivity of the particular material; $\varepsilon_0$ is the vacuum permittivity; and $c$ is the speed of light. The effective permeability from the extended Bruggeman approximation is a function of volume fraction, intrinsic permeability of the material, and the function $A$ since the non-magnetic matrix permeability is the unity. The intrinsic permeability is a function of frequency, which is influenced by eddy currents and ferromagnetic resonance in the high frequency range. The eddy current effect is considered in the function of $A$, and the ferromagnetic resonance effect is negligible in the randomly oriented magnetic particle composites due to the broadening of magnetic loss as discussed previously. The function of $A$ is a function of radius, resistivity and intrinsic permeability of the particular material, and frequency. The effective permeability is plotted in the following figures with different volume fraction, intrinsic permeability and diameter of particles. As seen in the following Figures 15 and 16, the variations in the intrinsic permeability and the volume fraction little influence on the roll-off frequency. However, the size of the particles (diameter) has strong influence on the roll-off frequency of the permeability due to the reduction of eddy current losses as seen in Figure 17. Smaller particles lead to have wide frequency bands.
Figure 15 Simulation results showing the permeability versus frequency of spherical particles of different intrinsic permeability and same properties such as diameter (100nm), volume fraction (50%), and the resistivity (1e-8 ohm·m).

Figure 16 Simulation results showing the permeability versus frequency of different volume fraction with same properties of relative permeability (1000), diameter (100nm), and the resistivity (1e-8 ohm·m).
2.3 Magnetic Particle Preparation and Characterization

The previous discussions and simulations support the approach of small magnetic particle composites for good effective permeability in the GHz frequency range. In order to demonstrate the approach experimentally, magnetic particles were mixed with an insulating polymer similar to the soft magnetic composites (SMCs) for the magnetic cores in electromagnetic applications [25]. However, due to the constraints for the back end of line (BEOL) processes, the high-pressure compaction and heat treatment steps are not conducted for the on-chip micro inductor devices.

In the preliminary tests, a commercially available magnetic particle of Permalloy (Ni$_{80}$Fe$_{17}$Mo$_{3}$, NanoAmor) was mixed with a polymer resist (OCG 825 35CS, Fujifilm) as shown in Figure 18. Due to the large surface to volume ratio of the metallic nanoparticles, it was found that the particles without the polymer are oxidized very quickly. For the particle composites with the polymer matrix, there are spaces permeable to the air and humidity. As a result, after the particles were mixed in nitrogen environment at a glove box, the particle composites were oxidized within 48 hours in the air as the color changed from black to brown. The oxidation leading to the change from metal to metal oxide and it could change the magnetic property from ferromagnetic to ferromagnetic to reduce the permeability.

To resolve the issue of oxidation of metallic particles, ferromagnetic materials in native element mineral were searched. Awaruite is a naturally occurring alloy of nickel and iron with a composition from FeNi$_2$ to FeNi$_3$ with strong ferromagnetic property. In this work, chemical synthesis of FeNi$_3$ nanoparticles are implemented, and a SiO$_2$ coating of particles is performed for removing possible conduction paths by the agglomeration of metallic particles via the Stöber process [48]. The nanoparticles are characterized in XRD and TEM, and their ferromagnetic property is characterized in VSM.
2.3.1 Chemical Synthesis

Fe_{x}Ni_{x-1} nanoparticles have been synthesized by chemical reduction of iron ions and nickel ions [49-51]. FeNi$_3$ nanoparticles synthesized via the hydrazine reduction process in aqueous solution at room temperature were based on the aforementioned references. All the reactants, FeCl$_2$·4H$_2$O (98%, Alfa), NiCl$_2$·6H$_2$O (98%, Alfa), hydrazine hydrate (N$_2$H$_4$·H$_2$O, 80%, Aldrich), and NaOH (96%, Aldrich), were of reagent grade and used without further purification. The synthesis processes are described as follows: (1) 0.01 mol FeCl$_2$·4H$_2$O and 0.03 mol NiCl$_2$·6H$_2$O were dissolved into 200mL distilled water with addition of PEG (1.0 g, MW 6000) as a surfactant, (2) Sodium hydroxide (NaOH) was added to the solution and the pH value was controlled in the range 12 ≤ pH ≤ 13, (3) Hydrazine hydrate was added to the suspension. The reaction was continued with stirring for 24 hours at room temperature. Afterwards, the synthesized black FeNi$_3$ nanoparticles were rinsed with deionized water and were dried in air. The SiO$_2$ shell coating process can be conducted to construct the FeNi$_3$-SiO$_2$ core-shell nanoparticles. After dispersing FeNi$_3$ nanoparticles in a mixture of 80 mL of ethanol, 20 mL of deionized water and 0.2 g of tetraethyl orthosilicate (TEOS), 2.0 mL of 20 wt% concentrated ammonia aqueous solution (NH$_3$·H$_2$O) was added with stirring for 24 hours at room temperature. The synthesized FeNi$_3$-SiO$_2$ core-shell nanoparticles were rinsed with deionized water and were dried in air. All processes are illustrated in Figure 19, and Figure 20 shows the actual images of the chemical processes.
2.3.2 Material Identification and Magnetic Properties

The synthesized nanoparticles were observed in SEM and TEM as shown in Figure 21. The diameter of FeNi$_3$ particles is in the range of 100-150nm, and the insulating shell of FeNi$_3$-SiO$_2$ core-shell particles shows 15-20nm in thickness. From the TEM images, it is found that the FeNi$_3$ particles have 2-5nm-thick surface oxidation which prevent further oxidation inside the particles.
As shown in Figure 22, the particles were examined by X-ray powder diffraction (XRD) analysis using Co Kα radiation. The measured data match the library data of FeNi₃ as shown in Figure 23.
The magnetic property of FeNi$_3$ particles was characterized in a vibrating sample magnetometer (VSM). The magnetic moment per mass was plotted in the range from -70000 to 70000 Oe, and the particles showed strong ferromagnetic characteristics with the coercivity of 100 Oe as shown in Figure 24.
2.4 Magnetic Particle Composites for Micro Inductors

2.4.1 Device Fabrication

The FeNi$_3$ magnetic particle composites were integrated with micro inductor structures. Both stripline and spiral inductors were constructed by the microfabrication processes. For closed magnetic flux paths, it is desirable to wrap the entire metal lines in the inductors with the magnetic particle composites. However, it was found that the drop casting process for the particle composites can easily distort the suspended metal lines. Therefore, the particle composites were only placed around the metal lines without filling the bottom to form a closed magnetic loop.

A stripline structure was constructed by a 7μm-thick copper electroplating process on a patterned wafer as illustrated in Figure 25. In Figure 26, the stripline structure is shown with dimensions, and the fabricated stripline, open and short structures for de-embedding are shown in Figure 27. The de-embedding structures were used to remove the undesirable effects from the test fixture. The particle composites were deposited on the specific locations by using a stencil masks. Figure 28 shows the stripline inductor with FeNi$_3$ magnetic particle composites on top of the structure.

Figure 25 Fabrication processes for the stripline inductors made of copper: (a) SiO$_2$ deposition on top of a silicon substrate. (b) Seed-layer copper deposition. (c) Spin coating of photoresist and photolithography for patterning. (d) Electroplating to fill up the opening area from the previous resist patterning. (e) Removal of the resist. (f) Etching away the copper seed layer.
Figure 26 A layout design of a stripline inductor with detailed dimensions.

Figure 27 An optical photo showing fabricated stripline inductors with short and open structures for de-embedding.
The FeNi₃ magnetic particle composites were tested on spiral inductors which were fabricated by a foundry process via National Semiconductor (acquired later by Texas Instruments). The layout of a 3-turn planar spiral inductor is shown with dimensions in Figure 29. The passivation layer on top of the 1μm-thick metallization was etched in a post plasma etching process to expose the spiral inductors. The nanoparticle composites were applied to cover the area of the spiral inductors by using the stencil masking technique. The process flow and the device images are shown in Figure 30.
2.4.2 Inductance and Quality Factor

The inductance and quality factor of the fabricated micro inductors were measured by using a vector network analyzer (VNA). The measurement setup is shown in Figure 31, and the Ground-Signal-Ground (GSG) probes in the probe station are connected to a VNA to measure scattering parameters (s-parameters). After measurements, s-parameters from open and short structures were used in a de-embedding process to extract the results from the device under test (DUT) as other reference works [52-54]. The admittance parameters (y-parameters) were found first, and the inductance and quality factor of the inductors were calculated over frequency by using the equations:

\[ L = \frac{\text{Im}[Y_{11}^{-1}]}{2\pi f} \]  \hspace{1cm} (2.21)

\[ Q = \frac{\text{Im}[Y_{11}^{-1}]}{\text{Re}[Y_{11}^{-1}]} \]  \hspace{1cm} (2.22)
The inductance and quality factor of the stripline inductor composed of two lines of 1200μm long, 30μm wide and 8μm thick copper are plotted in Figure 32. The air-core stripline without magnetic particle composites shows 0.8 nH in inductance up to 4 GHz, and the inductance is increased due to the LC resonance of the stripline composed of metal lines. After the integration of the nanoparticle composites (FeNi₃ magnetic particles) on top of the metal lines, the inductance increases 1 nH up to 4 GHz. From repeated measurements, it was found that the inductance increase is about 25% up to 4 GHz. The peak quality factor of the air-core stripline reaches 15 at 3 GHz; however, the peak quality factor with the magnetic nanoparticle composites only reaches 8 around 1 GHz. Over the tested frequency range, the quality factor of the stripline with magnetic composites shows lower values than the air-core stripline inductors because the energy losses from the magnetic material. Although eddy current losses can be reduced by preventing large current loops in the magnetic core, the large coercivity (100 Oe) of the particle composites can generate large energy losses especially in the high frequency regime.
Figure 32 Measurement and simulation data of the inductance and quality factor from the stripline inductors.

The large coercivity around 100 Oe of the FeNi$_3$ magnetic particle composites, it is difficult to measure permeability values over frequency by using a commercially available tool, permeameter. Therefore, a commercial finite element method solver for electromagnetic structures, High Frequency Structural Simulator (HFSS), was used to evaluate the relative permeability value from the FeNi$_3$ magnetic particle composites. The model was constructed by using the layout dimensions, and the magnetic particle composites in 100$\mu$m thickness same as the thickness of the used stencil mask was located on top of the striplines as shown in Figure 33. The simulated inductance and quality factor match with the measurement data as shown in Figure 32, and the simulated inductance of the stripline with magnetic particle composites matches the measurement
data when the effective permeability of the composite is 4 as plotted as the simulation line in Figure 32. The simulated quality factor showed discrepancy, and it is larger than the measurement data. Due to the unavailability of using a permeameter for the magnetic particle with large coercivity, the simulation was unable to consider hysteresis losses. As a result, the simulated quality factors shows larger values than from the measurement data.

Figure 33 Model structures in the HFSS simulator: (left) an air-core stripline inductor; and (right) a stripline inductor with magnetic nano particle composites on top.

The inductance and quality factor of the 3-turn spiral inductor fabricated by a foundry service are plotted in Figure 34. The 3-turn spiral inductor with outer diameter of 240μm had an 8μm-thick copper line with width of 10μm and spacing of 2μm. The air-core inductor showed 4.5 nH in inductance up to 2 GHz, and the inductance was increased due to the LC resonance induced from the spiral lines. The spiral inductor with FeNi3 magnetic composites on top of the spiral area had inductance of 6.5 nH (45% increase) up to 2 GHz. The inductor with FeNi3-SiO2 core-shell particles had 5.3 nH (20% increase) up to 2 GHz. Due to the increase of inductance values, the LC resonance frequency shifted to lower frequency. The peak of the inductance curves moved to lower frequency as the inductance increases in Figure 34 (a). Regarding the quality factor in Figure 34 (b), the peak quality factor of the air-core spiral reaches 2.75 at 3 GHz. The peak quality factor of the spiral with FeNi3 was 2.5, and the one of spiral with FeNi3-SiO2 was 2.1 as the magnetic material added energy losses. The core-shell particles has a lower volume fraction of the magnetic material, and it leads to less increase in inductance; however, it shows better quality factor since it has less magnetic losses from the magnetic composites. In addition, the performance of the magnetic particle composites on the spiral inductors was tested in 3 months with same results as those shown in Figure 34.
2.5 Conclusion

Magnetic nanoparticle composites were studied as a potential magnetic core in high frequency electromagnetic devices such as micro inductors. Theoretical background for the broadband permeability of spherical nanoparticles with random magnetization was explored. The most widely used approximation of magnetic nanoparticle composites, the extended Bruggeman effective medium approximation, was used to investigate the influences on permeability due to different properties/parameters of magnetic particles for high frequency device applications, such as intrinsic permeability, volume fraction, and diameter of magnetic particles. A natural alloy from
of nickel and iron with the composition of FeNi$_3$ was chosen as the magnetic nanoparticles for studies, and a core-shell structure with SiO$_2$ as the passivation layer was investigated. The magnetic nanoparticles of 100nm in diameter with and without the coatings of SiO$_2$ were synthesized by the chemical processes. The permeability of the magnetic nanoparticle composites in the GHz ranges was validated experimentally with the integration with micro inductors. It is found that the inductance values increased about 20 to 45% in the GHz frequency range after adding the magnetic nanoparticle composites to the micro inductor structures. The quality factors, on the other hand, were degraded mainly due to the magnetic loss from large coercivity despite of the reduction of eddy current losses in the magnetic nanoparticle composites.
Chapter 3 Magnetic Films with Magnetization Induced Anisotropy

3.1 Introduction

Magnetic films have been studied for planar inductors to amplify magnetic flux and produce smaller inductors. Previously, Saleh and Quresh attempted to fabricate magnetic thin-film inductors to increase inductance density (inductance per area), and presented magnetic analyses on the use of fast transverse permeability (excitation along the hard axis) for high frequency magnetic inductor applications [18]. In general, the incorporation of magnetic materials for micro on-chip inductors is limited to the FMR frequency at near 1 GHz. The increase of FMR frequency can be achieved by the increase of the magnetic anisotropy field ($H_k$) according to Kittel’s formula [55]. There have been various efforts toward this goal by exploring material compositions [56-58], deposition conditions (e.g. sputtering power [59], gas [60, 61] and thickness [62]), directional ordering of atoms during depositions [63-65], thermomagnetic treatments [66], multilayer structures with exchange bias [67], and patterning [68].

Among the aforementioned methods of generating magnetic anisotropy, magnetization-induced uniaxial anisotropy resulted from the directional ordering of atoms using magnetic fields during thin film deposition (sputtering [69] and electroplating [70]) in Figure 35 has been utilized for on-chip inductors recently because of the easy integration of magnetic materials with IC processes. Magnetic films with magnetization by the coherent rotation of aligned magnetic moments result in fast response of magnetization and less energy losses from the magnetic hysteresis as compared with films with magnetization by the domain wall motions [71].

In this chapter, magnetization-induced uniaxial anisotropy of sputtered CoZrTaB films under an external magnetic field will be explored for high frequency permeability. Especially, control of the magnetic anisotropy according to grain sizes of sputtered film by changing the sputtering conditions will be discussed, including the change of magnetization-induced anisotropy and the change of ferromagnetic resonance frequency. In addition, the sputtered film under different conditions and resonance frequencies will be integrated with on-chip inductors for improving inductance and quality factor toward device miniaturizations.

![Figure 35 Schematic of magnetization-induced anisotropy during the sputtering process.](image-url)
3.2 Theoretical Background

3.2.1 Landau-Lifshitz-Gilbert Equation and Magnetic Films

The theory of magnetic resonance was introduced based on the classical model in the previous chapter. The magnetic resonance has been explained from the classic field in the vast literature to the quantum mechanical phenomena. The resonant magnetic systems are small quantum objects (ions, electrons, or nuclei with unpaired spin), and they have resonant transitions between quantized Zeeman split energy levels under an external magnetic field as shown in Figure 36 [15].

![Figure 36](image)

Figure 36 Zeeman split energy levels for an electronic system with $S = 1$ [15].

For example, the magnetic moment $m$ of an electron associated with an electronic angular momentum $\hbar S$ can be expressed as [15]:

$$m = \gamma \hbar S$$  \hspace{1cm} (3.1)

The constant of proportionality is the gyromagnetic ratio, $\gamma$, with the unit of Hz/T. The Zeeman interaction $m \cdot B$ under the static field $B$ applied along the z-axis is represented by the Hamiltonian as:

$$H_z = -m \cdot B = -\gamma \hbar B S_z$$  \hspace{1cm} (3.2)

The energy levels are split with eigenvalues:

$$E_i = -\gamma \hbar B M_i \hspace{1cm} M_i = S, S-1, \cdots, -S$$  \hspace{1cm} (3.3)

The energy level difference is represented as: $\Delta E = \gamma \hbar B$, and the magnetic dipole transition between the adjacent energy level can be derived from the radiation of the angular frequency, $\omega_0$, where $\Delta E = \hbar \omega_0$. Therefore, the resonance occurs at
As discussed in the previous chapter, the equation of motion of the magnetic moment $m$ or the magnetization $M$ (moment per volume) under the external magnetic field $B$ is derived as:

$$\frac{dm}{dt} = \gamma (m \times B) \quad \text{or} \quad \frac{dM}{dt} = \gamma (M \times B)$$  \hspace{1cm} (3.5)$$

The precession of the magnetization at frequency $\omega_0 = \gamma B$ stops eventually and must align with the external magnetic field. This process is related to spin-lattice relaxation of the quantum spin system. To represent this macroscopic magnetization, a phenomenological damping term is added to the equation of the motion as represented in Figure 37.

Lev Landau and Evgeny Lifshitz suggested a form as known as Landau-Lifshitz (LL) equation [72]:

$$\frac{dM}{dt} = \gamma M \times B - \gamma \frac{\lambda}{M} M \times M \times B$$  \hspace{1cm} (3.6)$$

where $B$ is the effective field consisted of the external magnetic field, the demagnetizing field, and quantum mechanical effects; $\lambda$ is a phenomenological damping parameter known as Landau damping parameter. From the Landau-Lifshitz equation, T. L. Gilbert replaced the damping term by one depending on the time derivative of the magnetic field, and it is referred to as Landau-Lifshitz-Gilbert (LLG) equation [73]:

$$\frac{dM}{dt} = \gamma M \times B - \alpha \frac{M \times dM}{dt}$$  \hspace{1cm} (3.7)$$
where $\alpha$ is the Gilbert damping parameter. When $\alpha \ll 1$, the two forms are equivalent, and typical values of $\alpha$ are in the range between 0.001 to 0.1. The effect of the damping terms is introducing additional torque terms, which pushes the precessing magnetization spiral towards the direction of the applied field $B$.

The equation of motion without considering the damping term is:

$$\frac{dM_x}{dt} = \gamma B M_y = \gamma \mu_0 H M_y$$
$$\frac{dM_y}{dt} = -\gamma B M_x = -\gamma \mu_0 H M_x$$
$$\frac{dM_z}{dt} = 0$$  \hspace{1cm} (3.8)

After differentiating with respect to time,

$$\frac{d^2 M_x}{dt^2} = \gamma \mu_0 H \frac{dM_y}{dt} = -\gamma^2 \mu_0^2 H^2 M_x = -\omega_0^2 M_x$$
$$\frac{d^2 M_y}{dt^2} = -\gamma \mu_0 H \frac{dM_x}{dt} = \gamma^2 \mu_0^2 H^2 M_y = \omega_0^2 M_y$$
$$\frac{d^2 M_z}{dt^2} = 0$$  \hspace{1cm} (3.9)

The solution is a uniform precession

$$M_x = M_s \sin \theta \exp(i\omega_0 t)$$
$$M_y = M_s \sin \theta \exp\left(i\omega_0 t + \frac{\pi}{2}\right)$$
$$M_z = M_s \cos \theta$$  \hspace{1cm} (3.10)

When the Gilbert damping term is included, the equation of motion is:

$$\frac{dM_x}{dt} = \frac{\omega_0}{1 + \alpha^2} \left(M_y + \alpha \frac{M_y M_z}{M_s}\right)$$
$$\frac{dM_y}{dt} = \frac{\omega_0}{1 + \alpha^2} \left(-M_x + \alpha \frac{M_x M_z}{M_s}\right)$$
$$\frac{dM_z}{dt} = \frac{\omega_0}{1 + \alpha^2} \left(-M_y + \alpha \frac{M_z^2}{M_s}\right)$$  \hspace{1cm} (3.11)

The solution of oscillation is graphically described in Figure 38 [15].
From differentiating the uniform precession without the damping term:

\[
\frac{dM_x}{dt} = i\omega M_y \sin \theta \exp i\omega t + M_y \frac{d\theta}{dt} \cos \theta \exp i\omega t \tag{3.12}
\]

\[
\frac{dM_z}{dt} = \omega M_y + \frac{M_y M_z}{\sin \theta M_x} \frac{d\theta}{dt} \tag{3.13}
\]

Therefore,

\[
\omega = \frac{\omega_0}{1 + \alpha^2} \tag{3.14}
\]

\[
\frac{d\theta}{dt} = \frac{\omega_0}{1 + \alpha^2} \alpha \sin \theta \tag{3.15}
\]

The dynamic behavior from the LLG equation can be solved for study of magnetization in high frequency magnetic field. Since the differential equation describing the change in magnetization is a function of the magnetization itself and the magnetic field, the nonlinear equation is difficult or impossible to solve for the general case. The nonlinear equation can be approximated with assumptions for highly permeable thin films by a linear equation. To solve the LLG equation, the following assumptions were used to lead to a solvable linear equation [74]: (1) the anisotropy field in y-axis is small in comparison with the saturation magnetization \(H_k \ll M_s\); (2) the demagnetizing factor equals 1 in the z-axis \((N_z = 1)\), being defined as parallel with the normal of the thin film in the xy-plane, and is equal to 0 in the x and y axes \((N_x = N_y = 0)\); (3) the damping constant is small \(\alpha \ll 1\); (4) the external field is applied in x-axis and is perpendicularly
to the anisotropy axis in y-axis \( H_{\text{ext}} = h_z \); (5) the applied field is small in comparison with the anisotropy field \( h_x << H_k \); (6) the film is so thin that the eddy currents can be neglected. From the above assumption, the magnetization \( \mathbf{M} \) and the effective field \( \mathbf{H} \) can be described as shown below.

\[
\mathbf{M} = M_x e_x + M_y e_y + M_z e_z = m_x e_x + m_y e_y + m_z e_z \tag{3.16}
\]

The internal magnetic field is the summation of the external magnetic field and the demagnetizing field can be written as:

\[
\mathbf{H} = (h_x - N_x M_x)e_x + (H_k - N_z M_z)e_z + (-N_y m_y)e_y = h_x e_x + H_k e_z - m_y e_y \tag{3.17}
\]

By applying the magnetization and the effective field into the LLG equation, two linear equations can be achieved for \( M_x \) and \( M_z \).

\[
\frac{dM_x}{dt} = \frac{dm_x}{dt} = \gamma \mu_0 (m_x M_z - m_z H_k) - \alpha \frac{dm_z}{dt} \tag{3.18}
\]

\[
\frac{dM_z}{dt} = \frac{dm_z}{dt} = \gamma \mu_0 (m_y M_x - m_x H_k) + \alpha \frac{dm_x}{dt}
\]

For the \( m(t) = m_0 e^{i\omega t} \), the oscillating magnetization in x and z axes, the above systems of differential equations can be written as:

\[
 i\omega m_x = \gamma \mu_0 (m_y M_x - m_x H_k) - i\alpha m_z
\]

\[
 i\omega m_z = \gamma \mu_0 (m_y M_x - m_x H_k) + i\alpha m_x \tag{3.19}
\]

From the two linear equations, the relative permeability \( \mu_r \) in the axis of the excitation (x-axis) can be defined as:

\[
\mu_r = 1 + \frac{m_x}{h_x} = 1 - \frac{\gamma^2 \mu_0 \gamma M_x + H_k + \frac{i\alpha \omega}{\mu_0 \gamma}}{(1 + \alpha^2) \omega^2 - \gamma^2 \mu_0 \gamma H_k (M_x + H_k) - i\alpha \omega \mu_0 (M_x + 2H_k)} \tag{3.20}
\]

The above equation derived from the LLG equation is widely used for magnetic thin films, and the equation provides the magnitude of permeability at low frequency \( \omega \rightarrow 0 \) as:

\[
\mu_r (\omega \rightarrow 0) = 1 + \frac{M_i}{H_k} \tag{3.21}
\]

In addition, the resonance angular frequency \( \omega_r \) is obtained. At the frequency \( \omega_r \), the real part of the above permeability becomes zero.

\[
\omega_r = \gamma \sqrt{M_i H_k} \tag{3.22}
\]
It is same as the Kittel’s equation which is well-known expression for the resonant frequency. Figure 39 shows the above magnitude of permeability at low frequency and the resonance angular frequency in frequency domain.

![Complex permeability of magnetic thin films and Kittel’s expression for low frequency permeability and resonance frequency.](image)

3.2.2 Control of Parameters toward Higher Resonance Frequency

From the solution of the LLG equation for magnetic thin films, it is found that the magnetic resonance frequency depends on the value of saturation magnetization, $M_s$ and anisotropy field, $H_k$. In order to have high resonance frequency, it is important to achieve both large saturation magnetization and anisotropy field. In addition, the control of the anisotropy field is critical since large anisotropy can result in low permeability.

According to collective electron theory of ferromagnetism [15], the exchange energy is minimized if all the electrons have the same spin. Parallel alignment of electron spins in metals increases the band energy used to transfer electrons from the lowest band states. Considering the Fermi energy in the 3d and 4s bands of a ferromagnet in Figure 40, the Fermi energy level $E_F$ is on both 3d and 4s bands. In the 4s band, which is wide in energy with low density of states at $E_F$, energy required to move 4s electrons to the empty state to reverse its spin is higher than the energy gained by the resulting decrease in the exchange energy. In the 3d band, which is narrow in energy with high density of states at $E_F$, a large number of electrons near $E_F$ reduces the band energy required to reverse a spin, and energy gain in the exchange energy dominates. Therefore, a displacement of states in the 3d band is generated with one spin direction relative to states with opposite spin direction as shown in Figure 40, and the exchange interaction is the fundamental of the spontaneous magnetic moment in the ground state.
The Slater–Pauling curve in Figure 41 calculates saturation magnetization as a continuous function of number of the 3d and 4s valence electrons per atom. The curve shows the linear increase in the saturation magnetization from Cr to Fe, and then the linear decrease to zero in magnetization at electron density between Ni and Cu. Compared to measured magnetization, it has good agreement and has been widely used for material selections. As found in the Slater–Pauling curve, the magnetization is a material dependent factor, and there have been experimental efforts to study high frequency permeability from the vast material selections.
Although the saturation magnetization ($M_s$) is depends on the material, the magnetic anisotropy ($H_k$) is controllable in the fabrication process. Magnetic anisotropy in ferromagnets describes the magnetic axis of a sample along a fixed axis or some fixed axes, and the easy and hard axes are defined based on the magnetic anisotropy. The easy axis is the direction inside a sample, along which a small applied magnetic field is sufficient to reach the saturation magnetization. The hard axis is the direction inside a sample, along which a large applied magnetic field is needed to reach the saturation magnetization.

There are three main sources of anisotropy: (1) sample shape, (2) crystal structure, and (3) atomic texture. The shape anisotropy is from the demagnetizing field in a sample as the energy of a sample in its demagnetizing field gives a contribution to the direction of magnetization in the sample. The magnetocrystalline anisotropy is from the crystal structure of a material as the magnetization process is different when the field is applied along the different crystallographic directions. Its origin is in the crystal-field interaction and spin-orbit coupling, or interatomic dipole–dipole interaction. The induced anisotropy arises when an easy direction of magnetization is created by applied stress, or by depositing or annealing a disordered alloy in a magnetic field to create some atomic-scale texture.

In order to reach high magnetic resonance frequency for device applications, there are methods to generate the magnetic anisotropy in magnetic thin films. For example, the magnetization induced uniaxial anisotropy can be generated from the directional ordering of atoms by applying a magnetic field during a thin film deposition process [63-65]. This has been used in standard complementary metal-oxide semiconductor (CMOS) processing. Magnetic thin films with the coherent rotation of aligned magnetic moments by the magnetization induced uniaxial anisotropy can result in fast response of magnetization and less energy losses for high frequency device applications.

3.2.3 Magnetization Induced Anisotropy in Sputtered Films

The magnetization induced anisotropy is uniaxial in a plane, and the coherent magnetization reversal can be described by Stoner-Wohlfarth model, a simple analytical model for hysteresis in magnetic materials [15]. Figure 42 illustrates a uniformly magnetized ellipsoid particle with uniaxial anisotropy under a magnetic field with an angle $\alpha$.

![Figure 42 A Stoner–Wohlfarth particle.](image)
In the absence of an external field, the anisotropy energy of the ellipsoid particle can be approximated as 

\[ E_a \approx K_u \sin^2 \theta, \]

where \( K_u \) is the sum of the all anisotropy assumed to have the same axis. When an external field is applied, the magnetostatic or Zeeman energy applies as \( E_{\text{Zeeman}} = -\mu_0 M H \cos(\alpha - \theta) \). The energy density can be written as the sum of anisotropy energy and Zeeman energy:

\[ E_{\text{total}} = K_u \sin^2 \theta - \mu_0 M H \cos(\alpha - \theta) \tag{3.23} \]

By minimizing \( E_{\text{tot}} \) with respect to \( \theta \), either one or two energy minima can be derived, and the hysteresis arises in the field range where two minima are present. When \( \alpha < 45^\circ \), switching of magnetization is the irreversible jump from one minimum to another, which occurs when \( d^2 E / d\theta^2 = 0 \). The switching field is equal to the coercivity. On the other hand, when \( \alpha > 45^\circ \), the switching field, known as anisotropy field, is larger than coercivity. The hysteresis of a Stoner–Wohlfarth particle is illustrated in Figure 43 [15].

Figure 43 Magnetization curves for the Stoner–Wohlfarth model for various angles \( \alpha \) between the field direction and the easy axis [15].

For the Stoner–Wohlfarth model, the relation between the coercivity and anisotropy field can be analyzed in the following derivation. For easy axis magnetization (\( \alpha = 0^\circ \)), the total energy is:

\[ E_{\text{total}} = K_u \sin^2 \theta - \mu_0 M H \cos \theta \tag{3.24} \]
To find the magnetization angle $\theta$, that minimizes the total energy,

$$\frac{dE}{d\theta} = (2K_u \cos \theta + \mu_0 MH) \sin \theta = 0 \quad (3.25)$$

$$\frac{d^2 E}{d\theta^2} = -2K_u \sin^2 \theta + 2K_u \cos^2 \theta + \mu_0 MH \cos \theta > 0 \quad (3.26)$$

To satisfy the above conditions,

$$\theta = n\pi \quad (n \text{ is integer}) \quad (3.27)$$

$$-\frac{2K_u}{\mu_0 M_s} < H < \frac{2K_u}{\mu_0 M_s} \quad (3.28)$$

The energy will be minimized for all magnetic field between the coercivity, $H_c$.

$$H_c = \frac{2K_u}{\mu_0 M_s} \quad (3.29)$$

For hard axis magnetization ($\alpha = 90^\circ$), the total energy is:

$$E_{total} = K_u \sin^2 \theta - \mu_0 MH \sin \theta \quad (3.30)$$

To find the magnetization angle $\theta$, that minimize the total energy,

$$\frac{dE}{d\theta} = (2K_u \sin \theta - \mu_0 MH) \cos \theta = 0 \quad (3.31)$$

$$\frac{d^2 E}{d\theta^2} = 2K_u \cos^2 \theta - 2K_u \sin^2 \theta + \mu_0 MH \sin \theta > 0 \quad (3.32)$$

To satisfy the above conditions,

$$\theta = \pm \frac{\pi}{2} + n\pi \quad (n \text{ is integer}) \quad (3.33)$$

$$H = \frac{2K_u}{\mu_0 M_s} \quad (3.34)$$

The energy will be minimized when the magnetic field is equal to the following as known as the magnetic anisotropic field, $H_a$. 

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From the aforementioned derivations in the case of uniaxial anisotropy, the magnetic anisotropic field is equal or proportional to magnetic coercivity.

The coercivity, also called the magnetic coercivity, coercive field or coercive force, is a measure of the ability of a ferromagnetic material to withstand an external magnetic field without becoming demagnetized. It has been widely studied in magnetic materials as a fundamental property. Especially, coercivity is known as a function of grain size in a magnetic material in Figure 44 [15]. The different grain structures can be obtained from the melt by rapid quenching, or by annealing an amorphous precursor produced by melt quenching or hydrogen treatment. The sputtering deposition process can act as a physical piling of particular material, and the magnetic coercivity also can be changed by the sputtering process conditions.

![Figure 44 Coercivity versus grain size for a range of soft magnetic materials [15].](image)

3.3 Magnetic Thin Films with Magnetization Induced Anisotropy

3.3.1 Material Preparation

As discussed previously, magnetization-induced uniaxial anisotropy can result from the directional ordering of atoms using magnetic fields during the thin film deposition processes such as sputtering [69] and electroplating [70]. Recently, sputtered cobalt alloys (CoZrTa [75] and
CoZrTaB [76]) have been integrated with on-chip inductors due to their small magnetostriction [77], high resistivity (~100 $\mu\Omega \cdot \text{cm}$), and good thermal stability (up to 400 °C) [78] for monolithic integration with IC processes. Therefore, CoZrTaB (Co-4at%Zr-4at%Ta-8at%B) alloy was chosen in this study for the control of magnetic anisotropy in sputtered films under external magnetic fields for the induced anisotropy.

Figure 45 shows the sputtering setup with the external magnetic field parallel to the 100nm-thick CoZrTaB thin film on a silicon substrate under different sputtering powers of 1000, 700, 300, and 150 Watts. It is found that the magnitudes of the sputtering power affect the grain size, resistivity, magnetic anisotropy, and magnetic resonance frequency of the deposited films while the atomic ratio is maintained from the electron microprobe measurements except for the boron concentration as shown in Table 1.

![Figure 45 Schematic of the magnetization-induced anisotropy for the CoZrTaB thin films by sputtering process deposition.](image)

Table 1 Chemical composition of CoZrTaB thin films measured by electron microprobe analyzer.

<table>
<thead>
<tr>
<th></th>
<th>150 W</th>
<th>300 W</th>
<th>700 W</th>
<th>1000 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td>at%</td>
<td>wt%</td>
<td>at%</td>
<td>wt%</td>
</tr>
<tr>
<td>Co</td>
<td>80.75</td>
<td>90.66</td>
<td>81.28</td>
<td>91.1</td>
</tr>
<tr>
<td>Zr</td>
<td>6.4</td>
<td>4.64</td>
<td>5.7</td>
<td>4.15</td>
</tr>
<tr>
<td>Ta</td>
<td>12.84</td>
<td>4.69</td>
<td>13</td>
<td>4.75</td>
</tr>
</tbody>
</table>

The grain sizes from each sputtering power level were observed in the SEM and AFM images as shown in Figure 46 to Figure 49. As the sputtering power reduces, the average grain size of the deposited thin films reduces from 18.3 to 12.7nm in Figure 50, while the resistivity increases as the result of increased number of grain boundaries from 1.126 to 1.944×10⁻⁶ ($\Omega \cdot \text{m}$) as shown in Figure 51. The deposition rate of CoZrTaB reduces from 1.5nm/sec to 0.26nm/sec due to the reduced sputtering energy as shown in Figure 52.
Figure 46 (a) A SEM image of the CoZrTaB film deposited by using the sputtering power of 1000W (b) An AFM image of the CoZrTaB film deposited by using the sputtering power of 1000W.
Figure 47 (a) A SEM image of the CoZrTaB film deposited by using the sputtering power of 700W (b) An AFM image of the CoZrTaB film deposited by using the sputtering power of 700W.
Figure 48 (a) A SEM image of the CoZrTaB film deposited by using the sputtering power of 300W. (b) An AFM image of the CoZrTaB film deposited by using the sputtering power of 300W.
Figure 49 (a) A SEM image of the CoZrTaB film deposited by using the sputtering power of 150W. (b) An AFM image of the CoZrTaB film deposited by using the sputtering power of 150W.
Figure 50 Sputtering power vs. average grain size of CoZrTaB thin films.

Figure 51 Sputtering power vs. resistivity of CoZrTaB thin films.
3.3.2 Magnetic Property Measurements

From the SEM and AFM observation, it is found that the grain sizes are affected by the sputtering power levels. As discussed in theoretical background, grain size can affect coercivity, while the coercivity and the magnetic anisotropy are equal or proportional in the magnetic material has uniaxial magnetic anisotropy as described by the Stoner-Wohlfarth model. Therefore, it is expected that the changes of sputtering power, and affect the magnetic anisotropy. To verify the hypothesis, the M-H curves from the CoZrTaB films under different sputtering powers of 1000, 700, 300, and 150 Watts were measured in a VSM for the characterizations of their quasi static in-plane magnetic properties. Figures 53(a) and 53(b) show results from the easy axis (parallel to the applied magnetic field) and hard axis (orthogonal to the easy axis), respectively.
Figure 53 Magnetic hysteresis curves with different sputtering powers in VSM measurements for (a) in-plane easy axis, and (b) in-plane hard axis.

When the sputtering power is reduced, the easy axis direction shows increased coercivity from 1.5 to 40 Oe and reduced saturation magnetization from 970 to 786 emu/cm³, while the hard axis direction shows increased magnetic anisotropy field from 22.4 to 50 Oe as shown in Figure 54.
As discussed previously, it is observed that the increased anisotropy field corresponds to the reduction of the apparent grain size of the deposited CoZrTaB films from 18.3 to 12.9nm in the hard axis M-H curves. This implies that smaller grain size leads to larger anisotropy. The increase of the uniaxial in-plane anisotropy from the CoZrTaB films with smaller grains can lead to an increase in the FMR frequency according to the Kittel’s formula for magnetic films.

\[ \omega_r = \gamma \sqrt{M_s H_k} \]  

As expected by the increase of magnetic anisotropy field, the FMR frequency increase has been obtained in the permeability measurement in the frequency domain. Using a permeameter (Ryowa Electronics Co.), permeability measurements versus frequency show a gradual increase in the FMR frequency from 1.48 GHz to 2.17 GHz, as shown in Figures 55 (a) and (b), for the real and imaginary parts, respectively. The increased magnetic anisotropy matches up the decrease of grain size and increase in the FMR frequency. However, the increased anisotropy leads to reduced real values of the permeability along the hard axis as the enhanced stiffness in magnetization makes it more difficult for the magnetic moments to move from the easy to the hard axis following the Snoek’s law [79].
Figure 55 Complex permeability measurements from the permeameter up to 3 GHz for sputtered thin films under different sputtering power levels: (a) real part and (b) imaginary part.

3.4 Magnetic Thin Films for Micro Inductors

3.4.1 Device Fabrication

The CoZrTaB magnetic films have been utilized in the monolithic fabrication of on-chip inductors as illustrated in Figure 56. The process starts with a silicon wafer with a 6 μm-thick
LPCVD silicon dioxide film on top to reduce the silicon substrate losses. A 100 nm-thick CoZrTaB film is then deposited and patterned using a lift-off process. Afterwards, a 100 nm-thick silicon nitride thin film is deposited followed by a 1 μm-thick copper deposition, and patterning is performed by a second lift-off process. A 100 nm-thick silicon nitride film is then deposited and vias are etched using a dry etching process. The second 100 nm-thick CoZrTaB film is deposited and patterned using a third lift-off process. The final structure consists of a 1000 μm-long, 10 μm-wide, and 1 μm-thick stripline copper inductor surrounded with magnetic films with a closed-loop path for the magnetic flux.

(a)

(b)

(c)

Figure 56 Fabrication processes of stripline inductors with CoZrTaB magnetic films

The layout of the stripline inductor is shown in Figure 57, and the fabricated device (top view) is shown in Figure 58, where a 1000 μm-long stripline inductor is covered by CoZrTaB with a magnetic core area of 900×80 μm² serving as the magnetic-core inductor (Figure 58(a)). Two different sputtering power levels (1000W and 300W) have been chosen to deposit the CoZrTaB films which show controlled magnetic anisotropy without significant changes in coercivity in the hard axis of the M-H measurements. In addition, stripline inductors without the integration of the CoZrTaB core (Figure 58(b)) have also been fabricated for comparison purposes.
Figure 57 A layout design of a 1000µm-long stripline inductor with detailed dimensions.

Figure 58 (a) A fabricated stripline inductor with a CoZrTaB magnetic core. (b) A fabricated stripline inductor without the magnetic core (air core) as the reference.
3.4.2 Inductance and Quality Factor

Measurements of the inductor samples are performed by using the GSG probes and the Vector Network Analyzer (VNA). To remove the external effects outside the device under test (DUT), the de-embedding technique has been performed with open and short structures shown in Figure 59, and the de-embedded scattering parameters from the VNA are converted to inductance (L) and quality factor (Q) at each frequency. Stripline inductors with CoZrTaB films as the magnetic cores deposited by the 1000W and 300W sputtering power are tested and compared with a stripline inductor without the integration of the magnetic core (an air-core inductor). Experimental results on the inductance and qualify factor with respect to frequency are plotted in Figure 60(a) and Figure 60(b), respectively. The magnetic-core inductors with CoZrTaB films deposited under the 1000W and 300W sputtering power have shown 3.5 and 2.5 times higher inductances up to 200 and 700 MHz, respectively, than that of the air-core inductor. The inductance value by the 1000W CoZrTaB device is flat at lower frequency, and starts to increase from 200 MHz and drops to the air-core level at 1.5 GHz. On the other hand, the inductance value from the 300W CoZrTaB device starts to increase from 700 MHz and drops to the air-core level at 2 GHz. The Q-factors of the inductors have also increased 3 and 2.5 times, respectively with the peak shifting from 700 MHz to 1 GHz. The magnetic-core inductor with CoZrTaB films deposited under 300W has a higher roll-off frequency than that of the magnetic-core inductor with CoZrTaB films deposited under 1000W due to the elevation of the FMR frequency. To confirm the bandwidth change of stripline inductors due to the FMR frequency shift, inductance curves from a 700µm-long stripline and a 1000µm-long stripline were compared in Figure 61. Two striplines with different length showed roll-off at the same frequency for CoZrTaB films sputtered at 1000W in Figure 61(a) and for CoZrTaB films sputtered at 300W in Figure 61(b).
Figure 60 Measurements of (a) inductance and (b) Q-factor versus frequency of an air-core inductor and two magnetic-core inductors with CoZrTaB films sputtered with 1000W (blue) and 300W (red) of power.
Figure 61 Measurements of inductance versus frequency of a 700μm-long stripline inductor and a 1000μm-long stripline inductor with (a) CoZrTaB films sputtered at 1000W and (b) CoZrTaB films sputtered at 300W.
3.5 Conclusion

The control of magnetization-induced anisotropy on magnetic thin films using different magnitudes of sputtering deposition power under external magnetic fields has been studied and characterized. It is found that the grain size has changed and the resulting in-plane anisotropy has also changed. The deposited CoZrTaB films with smaller sputtering power have produced smaller grain and higher FMR frequency due to the anisotropy change. The magnetic thin films have been integrated with a stripline inductor fabrication process for micro inductors with higher inductance and Q-factor than those of an air-core inductor. The high operation frequency has also been achieved with the increased FMR frequency of CoZrTaB films using lower sputtering power. This work can lead to useful applications in high frequency on-chip inductors towards integrating magnetic materials for chip miniaturization.
Chapter 4 Rectangular Magnetic Particles

4.1 Introduction

Magnetic particles have been studied for applications in electromagnetic components, data storages, and bio/medical applications [80]. These particles are stacked or mixed with media with random distributions of magnetic orientations resulting in large coercivity, large hysteresis losses [81], and broad distribution of magnetic resonance losses in frequency domain [47]. Therefore, the alignment of magnetic orientation is desirable for magnetic anisotropy fields in high magnetic resonance frequency devices [17].

Magnetic resonance occurs when a magnetic moment under a static magnetic field absorbs energy from an oscillating magnetic field at a frequency, which correspond to the energy levels split by the static magnetic field including the anisotropy fields and the demagnetization fields. According to classical electrodynamics, the static magnetic field exerts a torque to the magnetic moment into the direction of the field and induces the Larmor precession describing a cone with respect to the static magnetic field. When the oscillating magnetic field superimposes on the precession, it can attract and repel the moment. However, the oscillating frequency synchronizes with the precession frequency and the magnetic moment absorbs energy from the oscillating field and resonates. Over that frequency, the magnetic moments fail to follow the oscillating field, and it results in rapid decrease or relaxation of the magnetic susceptibility. Since the magnetic resonance is related to the energy split by the static field, the resonance frequency is proportional to the strength of the static field, which can be formed by the alignment of the magnetic moments in the material.

The high demands in performance enhancement and size reduction of inductors for radio frequency integrated circuits (RFICs) have attracted research in the integrated magnetic materials with devices [82]. The integration should enhance the performance of devices without introducing significant side effects, and that is challenging due to inevitable magnetic losses such as magnetic resonance loss, hysteresis loss, and eddy current loss. For this reason, magnetic thin films or multilayer films have been researched for high frequency applications rather than particles or bulky magnetic materials [83]. Thin films are favorable to have higher magnetic resonance frequency than bulk material or spherical particles due to demagnetization fields. In addition, thin films with magnetic anisotropy can have low coercivity and coherent rotation of magnetization along the axis perpendicular to the anisotropy axes, which are advantageous for low hysteresis losses and high frequency operation, respectively.

On the other hand, magnetic thin films should be patterned or deposited in the form of insulated multilayers to reduce eddy current losses at high frequency operations. In terms of reducing eddy current losses, particle composites is more favorable, and various research efforts have been focusing on magnetic particle composites and the integration of magnetic particle composites for high frequency micro inductor applications with high resistivity to reduce eddy current losses [84].

In this chapter, magnetically aligned rectangular plate-like magnetic particles are demonstrated to combine the benefits of magnetic thin films and particles. The plate-like particles having uniaxial in-plane magnetic anisotropy are fabricated by micromachining processes, and these magnets are deposited under an external magnetic field to align them for high magnetic
resonance frequency and lower hysteresis losses than those of spherical particles with low eddy current losses. Figure 62 illustrates the benefits of the rectangular plate-like particles aligned under an external magnetic field as compared with randomly distributed spherical magnetic particles.

![Figure 62 Comparison between spherical particles and rectangular particles for their magnetism.](image)

### 4.2 Theoretical Background

#### 4.2.1 Thin Film Shapes and Magnetic Resonance

The dynamic behavior of the magnetization can be described by the Landau-Lifshitz-Gilbert equation [73], given by

\[
\frac{dM}{dt} = \gamma M \times B - \frac{\alpha}{M} M \times \frac{dM}{dt}
\]  \hspace{1cm} (4.1)

where \(M\) is the magnetization; \(B\) is the effective magnetic field including the external magnetic field, anisotropy field, and demagnetizing field; \(\gamma\) is the gyromagnetic ratio; and \(\alpha\) is the damping constant. Figure 63 shows a specific coordination for the magnetization and excitation axes, and the Landau-Lifshitz-Gilbert model can be solved for the permeability (the degree of magnetization of a material in response to an applied magnetic field) as [68]:

\[
\mu_r = 1 + \frac{m_s}{h_s} = 1 - \frac{\gamma^2 \mu_0^2 M_s \left( M_s + H_k \right) + i\alpha\omega}{\left(1 + \alpha^2\right) \omega^2 - \gamma^2 \mu_0^2 H_k \left( M_s + H_k \right) - i\alpha\gamma \mu_0 \left( M_s + 2H_k \right)}
\]  \hspace{1cm} (4.2)

where \(M_s\) is the saturation magnetization; \(H_k\) is the anisotropy field in z axis; and \(N_x, N_y, N_z\) are the demagnetization shape factors for x, y, z axes, respectively. The susceptibility equation goes through a singularity when the frequency matches with the magnetic resonance frequency. The
magnetic resonance frequency is defined by Kittel expression with the assumption of an infinitesimal damping constant and the magnetization in the z axis [55]:

\[
\omega_k^2 = \mu_0^2 \gamma^2 \left\{ H_k + (N_x - N_z)M_s \right\} \left\{ H_k + (N_y - N_z)M_s \right\}
\]

where \(\mu_0\) is vacuum permeability. The shape factors of bulk materials, spherical-shape particles, and thin films are listed in Table 1 as well as their magnetic resonance frequencies. If all spherical particles are aligned in a particular axis, they should have the same magnetic resonance frequency as bulk materials. Since \(M_s\) is typically higher than \(H_k\), magnetic films should have higher magnetic resonance frequency than particle/bulk magnets in Table 2. Therefore, the rectangular plate-like particles should have high magnetic resonance frequencies for device applications.

Table 2 Summary of magnetic resonance frequencies from different shapes with magnetization in z axis. (Thin film normal is parallel to the x axis.)

<table>
<thead>
<tr>
<th>Shape</th>
<th>(N_x)</th>
<th>(N_y)</th>
<th>(N_z)</th>
<th>(\omega_k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(\mu_0 H_k)</td>
</tr>
<tr>
<td>Sphere</td>
<td>(1/3)</td>
<td>(1/3)</td>
<td>(1/3)</td>
<td>(\mu_0 H_k)</td>
</tr>
<tr>
<td>Thin film</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>(\mu_0 (M_s H_k)^{1/2})</td>
</tr>
</tbody>
</table>

4.2.2 Shape Anisotropy in Rectangular Particles

The demagnetization field in thin films can lead to high magnetic resonance frequency as explained previously, and the rectangular-shape structures are also contribute to the high resonance frequency due to their shape anisotropy. It is investigated here with CoZrTaB as the magnetic material using the software – Object Oriented Micro Magnetic Framework (OOMMF) from the National Institute of Standards and Technology. The magnetization distribution is obtained by the minimization of the total magnetic energy density, which is affected by magnetic dipole exchanges, demagnetization, anisotropy and the applied magnetic field (Zeeman) [85]. The time evolution of the magnetization distribution is determined at each mesh points by solving the Landau-Lifshitz-
Gilbert equation (Eq. 4.1). The simulation starts from the initial state of randomly oriented magnetic moments as shown in Figure 64.

![Figure 64](image)

**Figure 64** A 2×2×0.1μm³ plate-like magnet with randomly distributed magnetization.

The energetically favorable states of magnetic moments in the magnets with different aspect ratio are simulated and shown in Figure 65. It is observed that high aspect ratio micro magnets result in better dipole alignment along the longitudinal axes with less alignment in transverse axes (white areas). The magnetic resonance frequencies from different aspect ratios of micro magnets are simulated. First, an excitation magnetic pulse is applied at the equilibrium state as shown in Figure 66 (a), and the Fast Fourier Transform (FFT) is conducted on the response of the magnetization in time domain in Figure 66 (b). The magnetic resonance frequency is extracted from the frequency domain responses. It is found that the higher aspect ratio magnet result in higher anisotropy and higher magnetic resonance frequency. The permeability of the 1:1 ratio magnet starts to drop near 1 GHz, while the permeability of the 10:1 ratio magnet drops at 4 GHz.

![Figure 65](image)

**Figure 65** Magnets with different aspect ratios (all magnets are 100nm-thick).
Figure 66 (a) Impulse excitation on a magnet at its equilibrium state from a randomly distributed magnetization state and its magnetization responses (red box) (b) Magnetization response signal and sampling for Fast Fourier Transform.
Figure 67 Complex permeability over frequency from the impulse excitation of (a) a 1:1 ratio magnet and (b) a 10:1 ratio magnet.

4.3 Fabrication and Characterization of Rectangular Magnetic Particles

4.3.1 Fabrication Processes

While conventional magnetic particles are manufactured by ball milling or chemical synthesis, the 2D micro magnets are fabricated by microstructuring technology including
photolithography, sputtering deposition, and lift-off. Figure 68 illustrates the fabrication process flow. For the lift-off process, an undercut layer with 400 nm in thickness was coated on a silicon substrate followed by a photoresist layer coating with 500 nm in thickness as shown in Figure 68 (a). Photolithography is then performed to have the 2D rectangle patterns where each rectangle has an area of $10 \times 2 \, \mu m^2$. After a development process, the mushroom shapes shown in Figure 68 (b) are achieved. A 100 nm-thick magnetic film is deposited on top of the whole area, and the magnetic film can cover the mushroom heads as shown in Figure 68 (c). Unlike the general lift-off process, the metal patterns on the photoresist (which are disposed in the general lift-off process) are collected in polymer/solvent mixture. After cleaning the polymer residue in the mixture, the patterned particles are mixed with ethanol. Finally, the rectangular plate-like particles are drop casted on a target substrate under an external magnetic field as shown in Figure 68 (d).

![Figure 68 Fabrication processes for the rectangular plate-like particles. (a) Spin coating for the bilayer of the photoresist layer and the undercut layer (b) Bilayer patterns by photolithography. (c) Sputtering deposition of a 100nm-thick magnetic film. (d) Lift-off and drop-casting onto the target substrate.](image)

Figure 69 shows SEM images of the structures after fabrication steps. The mushroom shapes structure is constructed by the bilayer photolithography as shown in Figure 69 (a) and the 30 degree tilted view in Figure 69 (b). After the lift-off of the particles, the patterned wafer is shown in Figure 69 (c). Figure 69 (d) shows an individual magnet with a rectangle area of $10 \times 2 \, \mu m^2$. The low sidewalls around the rectangle prevents the warpage of the 100 nm-thick sputtered magnetic film since it acts like a guide ring. The 2D micro magnets were drop casted onto a target substrate without an external magnetic field, and the magnets are randomly placed as shown in Figure 70. By applying an external magnetic field with a magnitude of 0.2 T, the magnets are rotated and
aligned along the direction of the external field as shown in Figure 71. In addition, structures with different aspect ratios are fabricated and drop casted under an external magnetic field as shown in Figure 72.

Figure 69 SEM images of (a) a cross sectional view of the bilayer patterns with mushroom shapes; (b) a 30 degree tilted view of the bilayer patterns; (c) patterns after the lift-off process; and (d) a 10×2 μm² single particle after the drop casting process.

Figure 70 Optical (left) and SEM (right) images of drop casted CoZrTaB rectangular magnets under no applied external magnetic fields.
Figure 71 Optical (left) and SEM (right) images of drop casted CoZrTaB rectangular magnets with different concentrations under an applied external magnetic field in the vertical direction.
Figure 72 SEM images of drop casted CoZrTaB rectangular magnets with different aspect ratios: (a) 1:1, (b) 3:1, and (c) 5:1, under an external magnetic field in the vertical direction.
4.3.2 Magnetic Property Characterization

The rectangular magnets have been drop casted on a target substrate, and tested with Vibrating Sample Magnetometer (VSM) for magnetic property characterizations. To verify the anisotropy, a 100nm-thick Supermalloy (Ni:Fe:Cu:Mo = 77:14:5:4) thin film has been deposited and tested as the reference in Figure 73 (a) with the isotropic characteristics in plane. On the other hand, the rectangular-shape particles made of Supermalloy and drop-casted under an applied external magnetic field have showed in-plane anisotropy in the magnetization curves as shown in Figure 73 (b). The M-H curve has gradually changed its slope probably due to the slight misalignment of particles. From the slope at applied zero fields, the anisotropy field is estimated as 200 Oe.

CoZrTaB has also been used to fabricate rectangular-shape magnetic particles. From the previous chapter, CoZrTaB films deposited under the sputtering power of 1000 W has the anisotropy field around 22 Oe. Rectangular particles made of the same magnetic films have been drop casted under an external magnetic field for VSM characterizations as shown in Figures 74, 75, and 76. Rectangle patterns with 2 µm gaps have also been tested as the reference of perfect alignments. For the 5:1 aspect ratio rectangular particles, the M-H loop in Figure 74 (a) shows the anisotropy field is approximately 300 Oe estimated from the slope at the zero field. The estimation is validated from the M-H loop of 5:1 rectangle patterns in Figure 74 (b), which is directly patterned without the misalignment shown in drop casted particles. The 3:1 aspect ratio rectangles shows the M-H loops from drop casted particles (Figure 75 (a)) and patterns (Figure 75 (b)), and the results are same as the M-H loops from 5:1 aspect ratio. It can be the saturation of shape anisotropy. However, the M-H loop for the 1:1 aspect ratio rectangular particles and patterns shows the isotropic behavior in the M-H curves. From the above measurements, it is concluded that the magnetization-induced anisotropy has little impact in micro magnets while the shape anisotropy has dominant effects.
Figure 73 (a) An isotropic M-H loop from a thin film made of Supermalloy (Ni:Fe:Cu:Mo = 77:14:5:4). (b) Anisotropic M-H curves of rectangular plate-like particles made of Supermalloy in easy and hard axes.
Figure 74 Anisotropic M-H curves of rectangular plate-like particles made of CoZrTaB with 5:1 aspect ratio in (a) particles and (b) patterned arrays.
Figure 75 Anisotropic M-H curves of rectangular plate-like particles made of CoZrTaB with 3:1 aspect ratio in (a) particles and (b) patterned arrays.
Figure 76 Isotropic M-H curves of rectangular plate-like particles made of CoZrTaB with 1:1 aspect ratio in (a) particles and (b) patterned arrays.
4.4 Rectangular Magnetic Particles for Micro Inductors

4.4.1 Device Fabrication

The CoZrTaB rectangular magnetic particles with aspect ratio of 5:1 and 3:1 have been fabricated as explained in the previous section. To test the effect of particles, 4 different micro inductor device configurations have been fabricated as shown in Figure 77: (a) copper only, (b) bottom magnetic thin films with patterns, (c) top magnetic particles, and (d) top magnetic particles and bottom magnetic thin film patterns. A copper stripline inductor has been fabricated with the cross section shown in Figure 77 (a). (The fabrication processes are the same as one in Chapter 3.) Figure 77 (b) shows the stripline with 100nm- thick CoZrTaB rectangle pattern arrays with 2µm gaps under the copper layer (the patterns are shown in Figures 74 (b) and 75 (b)), and the cross sectional view. Figure 77 (c) shows the stripline micro inductor is covered with the rectangular particles on top with the cross sectional view. Figure 77 (d) shows the combination of the magnetic particles on top and the magnetic thin film pattern arrays under the copper line.

Figure 77 Four different configurations of micro inductors with magnetic films and particles: (a) copper only; (b) with 100nm-thick bottom magnetic thin film with isolation patterns; (c) covered with top magnetic particles; (d) with 100nm-thick bottom magnetic thin film with isolation patterns and covered with top magnetic particles.
4.4.2 Inductance and Quality Factor

Measurements of the micro inductors with four different configurations are performed by using the GSG probes and the Vector Network Analyzer (VNA). De-embedding processes using open and short structures (detail in Chapter 3) can remove the external effects outside the device under test (DUT), and the de-embedded scattering parameters from the VNA are converted to inductance \((L)\) and quality factor \((Q)\). The 3:1 aspect ratio particles and patterns have been tested with the stripline micro inductors as shown in Figure 78, and the results of 5:1 aspect ratio particles are shown in Figure 79. The results the 3:1 and 5:1 particles and patterns of show little difference in inductance and quality factor due to the little difference in the magnetic properties in the M-H loops between the two different aspect ratio. In addition, the magnetic thin film pattern arrays with either 3:1 or 5:1 aspect ratio in Figures 78 or 79, respectively, show no improvement in inductance and quality factor due to the large magnetoresistance from 2 μm gaps between the patterns. On the other hand, the stripline micro inductors with rectangular particles on top (with or without the bottom magnetic thin film patterns) configurations show 10% enhancement in inductance. Due to the increase in anisotropy field from 22 Oe to 300 Oe, the FMR frequency can shift 3.7 times higher under assumption that the magnetization is conserved. The thin CoZrTaB films have measured values of the FMR frequency at 1.6 GHz in Chapter 3 such that the estimated FMR frequency of the rectangular particles is 5.9 GHz. Experimentally, the roll-off frequencies in inductance of both experiments are about 4.2 GHz. Compared with the roll-off frequency in a stripline with the CoZrTaB film in Chapter 3, the bandwidth of operation frequency increases 3 GHz due to the high magnetic anisotropy in rectangular particles.
Figure 78 Measurements of (a) inductance and (b) Q-factor versus frequency of the four different micro inductors: a stripline inductor without magnetic materials (Cu only), an inductor with rectangular particles of 3:1 aspect ratio on top (Top), an inductor with the magnetic thin films with 3:1 aspect ratio pattern arrays under the copper layer (Bottom), and the combination for Top and Bottom (Top+Bottom).
Figure 79 Measurements of (a) inductance and (b) Q-factor versus frequency of the four different micro inductors: a stripline inductor without magnetic materials (Cu only), an inductor with rectangular particles of 5:1 aspect ratio on top (Top), an inductor with the magnetic thin films with 5:1 aspect ratio pattern arrays under the copper layer (Bottom), and the combination fo Top and Bottom (Top+Bottom).
4.5 Conclusion

Magnetically aligned, rectangular plate-like structures have been demonstrated as promising materials for high frequency magnetic devices. These magnetic structures have been analyzed in theories and simulations, and realized by using microfabrication technologies. The shape induced anisotropy has been validated experimentally. The assembly of the rectangular-shape magnetic structures under an external magnetic field has been utilized to the fabrication of micro inductors to enhance their inductance and high frequency applications with successful experimental verifications. The rectangular-shape micro magnets, which have the advantages of particles (low eddy current losses) and thin films (magnetic anisotropy for high FMR) in higher frequency performances, can open up a new class in utilizing magnetic particle composites for high frequency device applications.
Chapter 5  Summary and Future Works

5.1 Summary

Over the past decades, the semiconductor industry has used “Moore’s Law” as the roadmap to guide long-term research and development in digital regime. In recent years, modern electronics have challenged another direction as “More than Moore” to enable non-digital functions on chips for higher value systems. As one of the most basic passive element in circuitry, inductors are natural components for various applications in the “More than Moore” domain such as in analog circuits and signal processing for various communication systems. While the size and performance of transistors have been constantly and continuously advancing, on-chip inductors have seen little advancement in size reduction and performance. Clearly, the development of on-chip inductors has been lagging and transformative innovations are in need to catch up with the transistor developments. Since most IC industries and academia have been concentrating on shrinking the size of transistors and neglected the development of on-chip inductors, this work propose and demonstrates unique approaches to address on-chip micro inductor developments. Specifically, key investigations have made contributions in the following area: (1) anti-oxidizing magnetic nanoparticle composites for broadband permeability; (2) control of FMR frequency of sputtered magnetic thin films with magnetization-induced anisotropy; and (3) rectangular-shape magnetic particles with shape anisotropy for high frequency applications.

In the demonstration of anti-oxidizing magnetic nanoparticle composites for broadband permeability, FeNi$_3$ nanoparticles synthesized by chemical solution processes have been characterized with confirmation on their stability in air. Additional SiO$_2$ coating performed on the nanoparticles to reduce the impact of eddy current losses in high frequency magnetic applications. Theses magnetic particles have been drop casted on micromachined on-chip inductors by using the screen printing process with stencil masks. Experimental results show that these on-chip inductors have increased inductance up to 45% with operation frequency up to 3 GHz, while the quality factor have been maintained up to 1 GHz.

The power levels in the sputtering deposition process for the CoZrTaB thin films under an external magnetic field have been investigated as a possible direction to improve high frequency properties of magnetic materials. It is found that lower sputtering power can result in smaller grain size and higher magnetic anisotropy. Specifically, the increases of magnetic anisotropy and FMR frequency have been confirmed by using VSM and permeameter characterizations, respectively. Furthermore, the increase of inductance density and the widening of operation bandwidth toward higher frequency up to 2 GHz have been demonstrated by using micro stripline inductors surrounded by the CoZrTaB thin films.
Micromagnetic simulations and demonstrations of rectangular plate-like particles have been performed for high frequency magnetic applications. Magnetism of rectangular micro magnets with different aspect ratios has been studied and shape anisotropy has been derived. Experimentally, micromachining technologies have been used to construct thin rectangular magnets. The increase of magnetic anisotropy more than 10 times has been achieved from the thin rectangular particles as compared with thin films. By incorporating the rectangular magnetic particles with the micro inductors, it is found that the operation bandwidth of a stripline micro inductor with the addition of rectangular CoZrTaB particles can go up to 4 GHz.

5.2 Future Works

Most of the current magnetic materials follows Snoek’s limit, and the magnitude of permeability (real part) is inversely proportional to the magnetic resonance frequency. As such, the increase of operation bandwidth toward high frequency inevitably leads to low permeability (real part). Rectangular plate-like magnetic particles demonstrated in this study have shown the increase of operation frequency up to 4 GHz; however, the increase of inductance density has been only 10%. The low increase in inductance comes from low magnitude of permeability (real part), and it is generally bounded in Snoek’s limit.

In a paper published by R. P. Cowburn, different shape of magnetic thin films with thickness in the nanometer range can lead to good DC permeability [86]. It is believed that the nano structures in the single domain state with well-controlled anisotropy and low hysteresis can lead to high permeability of over 1000. The large permeability values are unique in nanoscale particles and patterns as possible direction for the following future work.

Simulations have been conducted for the single domain nanostructures using the micromagnetic simulation tool (OOMMF) for the CoZrTaB materials with results summarized in Figures 80 and 81. In general, magnetic thin films thicker than 30nm will results in vortex phase, and thinner magnets may show single domain states without the formation of vortex of magnetization as shown in Figure 80, which is in favor of high FMR frequency. The magnetization response against an impulse has been simulated, and it was found that both the magnitude of permeability (real part) and magnetic resonance frequency increase as shown in Figure 81 when the magnetic film thickness is reduced from 50nm to 10nm. As such, experimental demonstrations of thin magnetic films with single state magnetic particles will be further studied in the future for high frequency magnetic responses in fundamental science and possible practical applications.
Figure 80 Different magnetization configurations calculated in various sizes and thicknesses. Flower (F) and buckle (B) states are considered as the single domain state against the vortex states (V).

Figure 81 Complex permeability over frequency from the impulse excitation of a 200×200×10 nm³ magnet (red) and a 200×200×50 nm³ magnet (blue): (a) real part and (b) imaginary part.
References


