# 1

## Nanomagnetic Materials and Structures, and their Applicationsin Integrated RF and Power Modules

P. Markondeya  $\text{Raj}^{^{\star}},$  Dibyajat Mishra, Himani Sharma, Madhavan Swaminathan and Rao Tummala

3D Systems Packaging Research Center, Georgia Institute of Technology, Atlanta, GA, USA  $^{\rm +} \rm Corresponding author$ 

## Outline

Introduction	. 2
Nanomagnetic structures and properties	4
Applications of nanomagnetic structures	11
Summary	23
References	23

### Introduction

Electronic system miniaturization with higher performance, lower cost and enhanced reliability is primarily enabled by four building blocks:1) Nanoscale ICs, and their thinning and stacking as 3D IC (Integrated Circuits) 2.) Interposers or packages that enable ultra-high wiring densities at low-cost, and 3.) Fine pitch and high-reliability device-package interconnections, 4.) Functional integration with other system components such as passive components and thermal structures. The advances in active system components to nanoscale device dimensions and thicknesses of 30 microns resulted in dramatic advances in multifunctional mobile and computing products over the past two decades. The pioneering advances towards 3D interposers and packages with high-density throughvias and ultrashort interconnections has begun to successfully address the interconnect challenges of emerging systems in the last two years. What will become critical in the future is a system integration strategy that benefits from this ultrathin and ultrahigh performance packages, but goes beyond interconnection technologies to include system components such as RF (Radio Frequency) and digital passives along with active components to form ultrathin and high-performance modules and sub-systems. The primary examples of passive components are inductors, capacitors, resistors, circulators, isolators, EMI isolation structures, antennas etc. that support the active components to perform various functions in power and RF modules such as voltage conversion, noise suppression, amplification, filtering etc. A new set of thinfilm component passive component technologies is needed to overcome the limitations of today's passive components to enable this module integration. These passive component applications themselves can create or impact an annual 50 Billion dollar industry playing a major role in the 5 Trillion dollar electronics industry of the future. These are broadly classified as power and RF passive components.

The operating voltages and power levels are becoming increasingly varied with more diversity of functionality coming from a variety of devices, working at different voltage levels to serve a variety of heterogeneous functions. Emerging high-performance ICs contain different elements with varying voltage requirements even within the same chip. Hence multiple power converters in conjunction with decoupling capacitors, each requiring several passive components, are used to create stable power-supply. A typical power convertor consists of an active network that works in conjunction with power storage components, such as capacitors and inductors, to perform the voltage conversion. Three types of power modules are currently pursued by leading-edge industry and academia: 1.)on-chip passives, overlaid or integrated in CMOS (Complimentary Metal Oxide Semiconductor) using IC or wafer-level packaging infrastructure, focusing on trench capacitors or thinfilm magnetic devices on active silicon, 2.) package-integrated modules with embedded active power ICs and passive components, using embedded multichip packages or fan-out wafer-level packages, thinfilm passives on silicon, organic or copper carriers with thermal vias for efficient cooling and 3.) discrete power components that are SMT-assembled onto board. While active components have been migrating to sub-32 nanometer CMOS-scaling, combined with 3D stackedarchitectures, the power components, that are critical for power conversion, are still at microscale in structure providing low storage density per unit volume, and milli-scale in component size, thus, making them the bulkiest components in a mobile system. The high volumetric density and low losses with nanomagnetics provide unparalleled opportunities for thin and integrated power components.

The need for advanced passive components is also critical for microwave or RF modules. The industry trend is towards the heterogeneous integration of systems. Such a system is expected to support wireless communication for mobility through the integration of several standards such as

Bluetooth, WLAN and WIMAX, support high-speed computing, and in some cases also support sensing for security and healthcare functions. However, multiband RF modules impose a number of stringent system requirements, including high linearity, wide frequency bands that are very closely spaced, and much higher power efficiency than current 3G networks [1]. These system specifications translate to a number of disruptive device and module packaging technologies that include a) 10x increase in active and passive component densities, b) an order of magnitude reduction in form factor, cost and power consumption, and c) higher reliability in spite of anticipated and increased thermal loads. The primary goal of all the new technologies is to reduce size (area and height), increase performance and reduce cost. The main challenges to system integration and miniaturization arise from the power and RF components that typically outnumber the active components by more than 10-to-1. These challenges are at two levels, one at the individual component level and the other at the subsystem or module functionality level.



#### FIGURE 1.1



Current leading-edge RF passives are mostly based on either low-temperature co-fired ceramics (LTCC) or low-cost organic substrates. The LTCC (low-temperature cofired ceramic) substrates provide the best loss and quality factor at GHz frequencies for RF interconnections and embedded RF passives, but cannot meet the thickness and cost needs for future smart mobile devices. Traditional organic substrates, fabricated on large panels using low-cost glass-epoxy laminates do not have the required RF characteristics. However, they can be fabricated with advanced dielectrics such as liquid crystal polymers (LCP) and fluoropolymers to achieve the desired RF properties which results in high cost and inability to shrink lithographic dimensions with the tight tolerances required for multi-band LTE and mm-wave applications. Organic substrates also have challenges in achieving fine-pitch chip-level interconnections with high reliability due to the TCE mismatch to Si and GaAs RF ICs. Silicon substrates are not a viable option for RF modules due to their high electrical loss arising from its semi-conducting nature of silicon and high cost due to high wafer fab costs.

Nanomagnetics provide unique opportunities to address the fundamental limitations of traditional electronic materials in meeting the requirements for miniaturization of RF and power components, as integrated modules and sub-systems, while simultaneously enhancing their performance. This is schematically illustrated in Figure 1.1. The chapter describes applications of nanomagnetics for

highly integrated ultrathin power and RF modules in mobile (smartphone) and high-performance (computing) applications. These applications will be classified into:

- a) Power and RF inductors,
- b) Non-reciprocal structures,
- c) Antennas,
- d) Electromagnetic Interference Isolation (EMI) structures.

## Nanomagnetic structures and properties

The key magnetic properties for both power and RF passive components are permeability, magnetic loss tangent and frequency-stability. Ferrites, ferrite composites or metal composites are the most common magnetic materials used for thin-film passive power components today. However, they face fundamental limitations in achieving the required properties and processability for future applications, as described in Section 3 in more detail. Magnetic materials that comprise of nanoscale metal structures in an amorphous or insulating matrix provide unique opportunities to address these fundamental limitations of microscale magnetic materials. These are briefly illustrated in Figure 1.2, and described in detail in this section.

The magnetic properties of an assembly of small grains depend strongly on the counterplay of local magnetic anisotropy energy and ferromagnetic exchange energy. For large grains, the magnetization follows the easy magnetic directions in the single grains and multiple domains are formed within the grains. The magnetization process is determined by the magneto-crystalline anisotropy,  $K_1$ , of the crystallites. As the particle size is reduced down to the nanoscale, the particle size and exchange length converge, allowing for single domain states to stabilize. However, the ferromagnetic exchange interaction between the grains forces the magnetic moments to align parallel, thus, impeding the magnetization to follow the easy directions of each individual grain. As a consequence, the effective anisotropy for the magnetic behavior is an average over several grains and, thus, reduced in magnitude. Therefore, higher permeability can be achieved in magnetic nanocomposites by reducing the particle size and the separation between the neighboring metal particles down to the nanoscale, which leads to magnetic exchange coupling phenomena [2, 3]. For example, Co- or Fe-based nanocomposites show much higher permeability at microwave frequencies than those obtained from the bulk Co or Fe metal or their microscale composites. Because of the nanosized metal particles, the eddy currents produced within the particle are also negligibly small, leading to much lower loss for nanocomposites, compared to that of conventional microsized ferrites and powder materials.



#### FIGURE 1.2

Schematic of magnetic nanocomposites and their benefits

The transition from multi-domain to single domain becomes very apparent when one considers the coercivity as a function of particle sizes [4]. As can be seen, the critical size of particles for single domain formation corresponds to a peak in coercivity, below which there is a drastic reduction in coercivity. Brown [5] has calculated the critical radius ( $R_{c1}$ ) of the single domain according to the micromagnetics principle:

$$R_{c1} = \frac{3.6055}{M_s} \left(\frac{K}{\mu_0}\right) \qquad \text{Equation 1}$$

where  $M_{s}$ , K and  $\mu_0$  are saturation magnetization, magnetocrystalline anisotropy and vacuum permeability, respectively. An assembly of single-domain ferromagnetic particles without interaction among particles usually possesses high  $H_c$  and low permeability, due to the large magnetoanisotropy and demagnetization effect of individual particles. To achieve superior properties, single-domain particles are needed, however with low  $H_c$ . This special behavior can be understood by the exchange coupling among particles described by Herzer [6].

*Herzer model*: When particle size (D) along with the distance (S) between particles is smaller than the exchange length (L<sub>ex</sub>), the exchange coupling takes place, which forces the magnetizations of particles to be aligned parallel, therefore, leading to a cancellation of the magnetic anisotropy of individual particles. The exchange coupling interaction, which leads to magnetic ordering within a grain, extends out to the neighboring environments within a characteristic distance,  $I_{ex}$  which is ~20-30 nm for Fe or Co [7, 8]. The exchange interaction in nanocomposites also leads to the cancellation of magnetic anisotropy of individual particles and the demagnetizing effect, leading to higher permeability and lower coercivity. As a result, the average anisotropy (K) of the film and hence the coercivity H<sub>c</sub> reduces considerably.

Herzer analyzed the scaling behaviors of the magnetocrystalline anisotropy energy density of nanocrystalline materials based on the random anisotropy model (RAM) [9]. The critical scale, called the exchange length, below which this averaging mechanism takes place is given by

$$L_{ex} = \sqrt{\left(\frac{A}{K}\right)}$$
 Equation 2

where  $L_{ex}$  is the exchange length, A and  $K_1$  are the exchange constant and magnetocrystalline anisotropy constant, respectively. Due to exchange coupling, the effective anisotropy constant  $K_{eff}$  due to averaging can be expressed as

$$K_{eff} = \frac{K_1}{\sqrt{N}}$$
 Equation 3

where N is the number of exchange coupled grains within the volume of  $L_{ex}^{3}$  with grain size D given by

$$N = (\frac{L_{ex}}{D})^3$$
 Equation 4

The magnetic properties such as coercivity ( $H_c$ ) and permeability ( $\mu$ ) are a function of the magnetocrystalline anisotropy constant of the material. Coercivity ( $H_c$ ) varies linearly with the magnetocrystalline anisotropy constant (K). Permeability ( $\mu$ ) is inversely proportional to K. From these equations it can be seen that a large N will result in  $K_{eff}$ <K and hence effectively decreases  $H_c$  and increases the magnetic permeability. Thus, the excellent soft magnetic properties of nanocrystalline magnetic materials is explained with the phenomenon of exchange coupling.



#### FIGURE 1.3

Variation of coercivity with particle size [10]

**Losses in magnetic materials:** Metal composites having micro- and sub-microscale fillers suffer from high losses beyond a few MHz [11, 12] from hysteresis, domain-wall and eddy-current losses. The eddy current losses in metal-nanocomposites are a strong function of the particle size, particle conductivity and the frequency. They are represented as [13-15]:

$$\frac{\mu''}{\mu'} = \frac{2\pi\mu_0\mu_r D^2 f}{3\Omega}$$
 Equation 5

 $\Omega$  is the particle resistivity, D is the particle size,  $\mu_r$  is the relative permeability, and f is the frequency. The eddy current losses are directly proportional to the particle size and are therefore higher for microscale particles [11] compared to nanoparticles. A linear change in  $\mu''/(\mu')^2$  with frequency is an indication of eddy current loss. The frequency ( $F_{EC}$ ) above which the eddy current losses dominate is estimated using the equation [11]:

$$F_{EC} = \frac{4\rho}{\pi\mu_o(1+X)D^2}$$
 Equation 6

where  $\rho$  is the conductivity and X is the magnetic susceptibility [11]. Estimated  $F_{EC}$  for 100 nm particles is much more than 10 GHz, again indicating that eddy currents are not dominant. Ramprasad's analysis [16] also predicts that the eddy currents do not contribute to net losses at microwave frequencies when the particle size is ~100 nm.

The losses from domain wall resonance become prominent when multidomains are present within the particles, and are usually dominant at 1-250 MHz frequencies for microsized ferrites and metallic nanoparticles [17, 18]. The frequency ( $F_{DW}$ ) where the domain wall losses dominate is given as [11]:

$$F_{DW} = \sqrt{\frac{2\delta(n+1)}{3\pi(1+X)D}} \frac{\gamma J_s}{2\pi\mu_o} \qquad \text{Equation 7}$$

where  $\delta$  is the domain wall thickness,  $\gamma$  is the gyromagnetic ratio,  $D_d$  is the domain spacing or domain size, n is the number of domains in a particle with diameter D,  $\mu_o$  is the permeability of free space, X is the susceptibility of the material,  $J_s$  is the saturation polarization. A simplified equation is also used for estimating the domain wall resonance [19].

$$\frac{\omega_{DW}}{\gamma} = M_s \sqrt{\frac{4\pi\delta}{D_d}}$$
 Equation 8

where  $\omega_{DW}$  is the domain wall resonance frequency and  $M_s$  is the saturation magnetization. The domain wall thickness is dependent on the exchange constant (A) and the magnetic anisotropy energy (K). The domain size varies as the particle dimensions. Finer particles show domain wall resonance at higher frequencies. In case of larger microscale particles, domain wall resonances leads to magnetic losses at lower frequencies, while these losses are absent in single-domain finer nanoparticles.

**Frequency stability from FMR:** The electron magnetic moment in a ferromagnet precesses about the direction of the magnetic field, and energy is absorbed strongly from the RF transverse field when the RF frequency is equal to the precession frequency [20]. A transmitted field shows a dip at the ferromagnetic resonance frequency due to the coupling of the microwave energy to the magnetic spin system. The transverse magnetic susceptibilities are very large because of the high magnetization in ferromagnetic moments. For an anisotropic material, this resonance frequency is given by:

$$\frac{\omega_{FMR}}{\gamma} = \sqrt{(4\pi M_s + H)H}$$
 Equation 9

H is the applied field or the anisotropy field  $H_k$ ,  $M_s$  is the saturation magnetization and  $\gamma$  is the gyromagnetic ratio (2.31 x  $10^8$  m/kAs). For materials with uniaxial anisotropy, the inherent frequency-stability and magnetic loss is governed by the saturation magnetization ( $M_s$ ) and field anisotropy ( $H_k$ ) when eddy current and hysteresis losses are not significant. For nanocomposites, the FMR is related to the effective field anisotropy, and is represented as [21]:

$$\frac{\omega_{FMR}}{\gamma} = H_{eff}$$
 Equation 10

where  $F_{res}$  (FMR) is the resonance frequency,  $\gamma$  is the gyromagnetic ratio and  $H_{eff}$  is the effective field anisotropy. The frequency stability for metal-nanocomposites is in multi GHz range. The FMR is estimated to reach 4 GHz for cobalt or iron nanocomposites while that for nickel is 2 GHz. Iron ( $\alpha$ -Fe) nanoparticles are shown to have higher FMR and lower losses when coated with Fe<sub>3</sub>B instead of a direct oxide passivation such as Y<sub>2</sub>O<sub>3</sub>[22]. The Fe<sub>3</sub>B coating with higher anisotropy field increased the FMR to 6 GHz compared to that of Y<sub>2</sub>O<sub>3</sub>-coated iron which was only in the range of 2-3 GHz. However, the peak broadening creates high losses even at lower frequencies [23].

There is a tradeoff between high permeability levels and operation at high frequencies according to Snoek's limit [24].

$$(\mu_r - 1)F_{res} = \left(\frac{\gamma}{3\pi} 4\pi M_s\right)$$
 Equation 11

For soft magnetic thin films with uniform uniaxial in-plane anisotropies, a modified law, known as Acher's limit, is applicable:

$$(\mu_r - 1)F_{res}^2 = (\frac{\gamma}{2\pi} 4\pi M_s)^2 \qquad \text{Equation 12}$$

Where  $F_0$  is the FMR frequency and  $\gamma$  is the gyromagnetic factor. Thus, a high saturation magnetization ( $4\pi M_s$ ) ensures high permeability at elevated frequencies of operation.

Polymer nanocomposites loaded with metal nanoparticles also show enhancement in permittivity with higher metal-filler content. The additional polarization, which is strongly frequency-dependent, occurs because of the charge redistribution at the metal-polymer interfaces that creates electric dipoles. Permittivities of ~10 are typically seen in metal-polymer nanocomposites in the 1-5 GHz range with oxide-passivated nanoscale particles [15] [25-27]. Permittivity models suggest that the particle conductivity, size and permittivity of the medium surrounding the nanoparticles influence the dielectric relaxation frequency. Beyond the relaxation frequency, the permittivity of the nanocomposite approaches that of the matrix.



#### FIGURE 1.4

FMR as a function of aspect ratio and saturation magnetization [28]

**One-dimensional nanostructures**: Anisotropic one-dimensional nanostructures based on nickel or cobalt nanowires or filaments have been modeled, designed and fabricated to overcome the limitations of isotropic nanocomposites. The FMR increases with aspect ratio as shown in a theoretical analysis by Nam et al. [28] and shown in Figure 1.4.For composites consisting of nanowires with both shape and crystal anisotropy, the FMR is proportional to the net field anisotropy, which also includes the dipolar interactions. When the magnetocrystalline axis is parallel to the wire axis, FMR is as given by [29]:

$$\frac{\omega_{FMR}}{\gamma} = H + 2 \pi M_s - 6 \mu M_s P + H_u$$
 Equation 13

 $M_s$  saturation magnetization,  $2\pi M_s$  is the shape anisotropy,  $-6\pi M_s P$  refers to the dipolar interaction, P is the volume fraction,  $H_u$  is the crystal anisotropy. When the magnetocrystalline axis is perpendicular to the wire axis, FMR is as given by:

$$\left(\frac{\omega_{FMR}}{\gamma}\right)^2 = (H + 2\pi M_s - 6\mu M_s P + H_u) \times (H + 2\pi M_s - 6\mu M_s P)$$
 Equation 14

The FMR as a function of applied field in different angles to the nanowire orientation is shown in Figure 1.5. Nanowires with strong shape and crystal anisotropy are expected to have frequency stability in GHz range. The diagonal and off-diagonal components of the permeability can be expressed as a function of frequency, saturation magnetization ( $M_s$ ) and the strength of the applied field ( $H_{ex}$ ) as:

$$\mu = 1 + \frac{\omega_m(\omega_r + i\omega\alpha)}{(\omega_r + i\omega\alpha)^2 - \omega^2} \qquad \kappa = \frac{\omega_m\omega}{(\omega_r + i\omega\alpha)^2 - \omega^2}$$
Equation 15

with  $\omega_m = \gamma Ms$ ,  $\omega_r = \gamma H_{ex} + \omega_m/2$ ,  $M_s$  is the saturation magnetization,  $H_{ex}$  is the applied static magnetic field which includes the crystal and shape anisotropy, and the exchange coupling,  $\gamma$  is the absolute value of the gyromagnetic ratio,  $\alpha$  is the dimensionless dampening coefficient. Nanowire composites with crystallographically oriented cobalt of high magnetocrystalline field anisotropy showed suppressed loss and enhanced frequency stability till 5 GHz [30, 31].





FMR as a function of applied field in nickel nanowire composites [29].

**Two-dimensional nanostructures:** The frequency stability in bulk metal and microscale composites, and suppression in eddy current losses can be enhanced with two-dimensional structures. Two types of nanocomposites will be briefly described in this category: 1.) Nanoflake composites and 2.) Layered nanomagnetic structures. Studies on NiFe alloy flake-polymer nanocomposites showed permeabilities of 5-10 with losses of above 0.1 at 1 GHz [32]. In another study by Yang et al., oriented flake-shaped Fe alloy particles mixed in a paraffin matrix showed a permeability of 8 at 100 MHz and 3.9 upto 2 GHz [33]. Oriented ferrite films with hard-axis in the direct perpendicular to the film plane are also shown to enhance frequency stability [34].

Nanolaminate structures that are designed to have strong exchange coupling at the interfaces are expected to have high FMR and permeability, according to the equations:

$$\frac{\omega_{FMR}}{\gamma} = \sqrt{4\pi \left(\frac{M_s}{\mu_o} + H_k + H_{ex}\right)(H_k + H_{ex})}$$
Equation 16  
$$H_{ex} = \frac{J_{ex}}{t_f M_s}$$
Equation 17

where  $H_k$  is the field anisotropy,  $H_{ex}$  is the exchange energy at the interfaces,  $J_{ex}$  is the exchange energy,  $t_f$  is the thickness of the ferromagnetic film and Ms is the saturation magnetization. The thickness of the ferromagnetic layer is used to control the FMR at the expense of the permeability, in a study by Sonehara et al. [35]. Chai et al. [36] has shown that nanolaminates with  $(Co_{96} Zr_4/Cu)_n$ multilayers have higher frequency stability than predicted by Acher's limit, stated in Equation (12), because of the negative interface anisotropy. Similar to Equation (16), they state the frequency stability as:

$$\frac{\omega_{FMR}}{\gamma} = \sqrt{\left(4\pi M_s - 2 \frac{2K_u}{tM_s}\right)(H_k)}$$
 Equation 18

Where t is the thickness of a single magnetic layer,  $K_u$  is the negative interface anisotropy constant. Utilization of nanolaminates to optimize frequency stability and permeability is a promising avenue for RF applications in multi GHz range.

## **Applications of nanomagnetic structures**

Nanomagnetic materials can impact the size and performance of several components in power and RF modules. An integrated electronic module with various applications for magnetic nanomaterials is shown in Figure 1.1. The applications are classified into inductors, antennas and EMI isolation structures, and are described in detail below.

#### Power and RF inductors

Design and fabrication of high-density inductors for power-supply applications are limited by the availability of magnetic materials that form the core of the inductors. Unlike RF inductors which mostly depend on low-loss dielectric materials, power inductors require magnetic cores with high permeability and high saturation magnetization, along with low-loss, for achieving high power-handling capability and power-conversion efficiency. Ferrite-based inductors have been the most dominant since 1980s. However, recent trends show that novel materials such as microcomposites and laminated metal structures have improved performance. Nanomagnetics further enhance the inductance density while retaining GHz stability (for RF), low losses and high current-handling. The key nanomagnetic structural attributes that leads to these advantages will be described, along with suggestions for future R&D to realize the promise of nanomagnetics.

#### Material property requirements for magnetic inductor cores

Magnetic inductors for power and RF applications with standard planar toroid and solenoid designs are modeled using simple analytical equations. The classical model predicts that the inductance of the solenoid inductor is enhanced by the relative permeability ( $\mu_r$ ) of the magnetic core material [37]:

$$L_{solenoid} = \frac{t_m w_m N^2 \mu_r \mu_0}{l_m}$$
 Equation 19

where N is the number of coil turns, and  $w_m$ ,  $t_m$  and  $l_m$  are the width, the thickness, and the length of the magnetic core, respectively. If a high-permeability material is incorporated into an inductor without producing extra losses, a substantially higher inductance can be obtained without increasing the size of the device.

The inductance of a toroid inductor is given as:

$$L = \frac{\mu_o \mu_r A_c N^2}{l_c} = \frac{N^2}{R}$$
 Equation 20

Where  $I_c$  is the length of the core,  $A_c$  is the cross-section area of the core, R is the reluctance, and N refers to the number of turns.

To achieve the target inductance, it is important to maximize the number of turns while enhancing the permeability. However, enhancing the inductance density limits the quality factor in two ways: 1) Increasing the number of turns raises the magnetic field inside the core and consequently increases the core hysteresis losses. They also saturate the inductor at lower DC currents and, therefore, degrade the permeability, and 2) Resistance increases with higher number of turns and thereby raises the joule-heating losses. The quality factor of the inductor, in its simplistic form considers only the second factor, and is defined as:

 $Q = \frac{\omega L}{Resistance} = \frac{\omega \mu_o \mu_r N^2 A_c A_w}{2\rho W l_c}$  Equation 21

where  $A_w$  is the cross-sectional area of the conductor,  $\omega$  is the radian frequency, 2W is the length of the coil per turn, and  $\rho$  is the resistivity of the conductor material. Increasing the number of turns compromises the Q by increasing the length of the coil that increases the resistance.

The DC current saturation is described by the equation:

$$I_{sat} = B_{sat} \frac{l_c}{N\mu_o\mu_r}$$
 Equation 22

where  $B_{sat}$  refers to the saturation flux density and  $I_c$  is the length of the core. Increase in the inductance density by increasing the number of turns saturates the inductor at lower DC currents as seen from Equation (22). The inductor has to be designed such that the DC magnetization field is within the saturation field of the material, referred to as  $B_{sat}/(\mu_o \mu_r)$  or  $H_k$ , the field anisotropy. By creating magnetic anisotropy,  $H_k$  can be dramatically increased in the hard axis for higher current-handling, however, at the expense of permeability.

The inductor size requirements can also be reduced by orders of magnitude by increasing the operation frequency [38]. However, at high frequencies, permeability decreases and the losses increase. Main magnetic loss mechanisms that need to be considered include: (a) hysteresis loss [39]; (b) eddy current loss [40]. The area inside the magnetic hysteresis loop corresponds to the energy loss per cycle, and the hysteresis power loss is proportional to the loop area. Hence a small coercivity ( $H_c$ ) is required to minimize the loop area, and in turn, the hysteresis loss. The eddy current losses are inversely proportional to the electrical resistivity of the magnetic material.

In summary, the requirements for the material used as the magnetic core in high-frequency inductors are:

- High permeability
- High saturation magnetization  $(4\pi M_s)$
- High uniaxial anisotropy field (H<sub>k</sub>)
- Low coercivity (soft magnetic materials)
- Sufficiently high resistivity to reduce eddy current losses

**Ferrites:** Even though ferromagnetism, which results in high permeability and high saturation, is prevalent in metals such as Co, Fe and Ni, they are not suitable for high-frequency applications in bulk form because of their high conductivity leading to eddy current losses. Ferrites are based on oxides of these metals with higher electrical resistivity and thereby more suitable for power

inductor applications. Spinel ferrites (e.g., NiFe<sub>2</sub>O<sub>4</sub>, Mn-Zn- and Ni-Zn-ferrites) are extensively used in power converters because of their low losses than metal cores, resulting in high Q factors at moderate frequencies of 100 kHz to 1 MHz [41, 42]. However, for emerging high frequency consumer applications, ferrites suffer from several major disadvantages, including: 1)low saturation magnetization,  $4\pi M_s < 3000$ G limiting the power density of the converters; This fundamentally limits the ability of ferrites in achieving a combination of high permeability and low magnetic losses at high frequencies, 2) low Curie temperature, (for Mn-Zn-ferrites, T<sub>c</sub>< 300°C; for Ni-Zn-ferrite, T<sub>c</sub><  $400^{\circ}$ C), thus the current densities and operating temperatures have to be restricted to control the inductor losses and stability; 3) low initial permeability; and 4) poor frequency response of magnetic properties due to their strong relaxation behavior. These limitations lead to millimeter size components and make ferrites unsuitable for emerging applications. In addition, traditional high-frequency magnetic materials such as ferrites also suffer from high process temperatures, thus making them incompatible in integrating into Si CMOS wafers or organic substrates.

**Microcomposites:** Metal-polymer composites have high resistivity which results in lower eddy current losses. In addition, microcomposites are more attractive for power-inductor cores because of their easier processing as toroids using powder compaction techniques. These composites constitute of metallic magnetic particles that are coated (or separated) by an insulating phase. Such magnetic powders in polymer paste form are commercially available from various vendors [43]. Examples of these include iron powder and permalloy powder, which show permeabilities of 10-100 in the low MHz frequency range. These materials show insufficient permeabilities and unstable properties beyond 10 MHz, which is their major limitation. Furthermore, the magnetic properties of these degrade even under mild magnetization force (e.g. 10% drop in permeability for 10 Oe) indicating lower power-handling capability.

**Metal Laminates:** To overcome the metal-based limitations, magnetic cores made of sequentially deposited alternate layers of metal-polymer or metal-oxide structures have been designed to achieve higher permeability with higher power-handling capabilities than microcomposites. Laminated, low-profile magnetic cores with micron scale laminations of high-permeability metallic alloys have been demonstrated with higher power-handling ( $\geq 1W$ ) [44]. Various processes such as mechanical laminations made by hot pressing [45] or horizontal laminations using electroplating have been demonstrated. The electroplated laminate process involves core fabrication by sequential electroplating of permalloy and a sacrificial layer, followed by the etching of sacrificial layer, to achieve micron-level laminations that cannot be attained using a mechanical process. This process does not require the expensive vacuum steps involved in sputtering [46]. The laminations are very thin compared to the skin-depth and break the electrical path for eddy currents, leading to very low loss compared to a bulk core.

**Emerging Magnetic Nanomaterials:** Nanoscale magnetic materials are emerging to enhance the volumetric density and overcome the challenges with microscale materials. These nanoengineered materials include nanogranular and core-shell nanocomposite magnetic materials. The nanogranular materials consist of randomly-deposited nanograins of magnetic metals or alloys in a ceramic matrix commonly prepared by sputtering transition elements or alloys in the presence of gases such as O<sub>2</sub> and N<sub>2</sub>. The core-shell nanocomposite materials are typically prepared with either nanosized magnetic particles deposited on insulating spherical cores (micrometer sized) of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, etc., or by oxidizing magnetic nanoparticles of transition elements to create an insulating shell around the particles.

**Nanostructured, but microscale materials:** Reducing the structural correlation length of solids to nanoscale brings about dramatic changes in their physical properties as described in Section 2. Magnetic softening in ferromagnetic nanostructures is one of the examples of such size effects. The first nanostructured magnetic material invented Yoshizawa et al. from Hitachi Metals Laboratory [47] created strong enthusiasm in soft magnetic nanostructures. Most of the nc alloys are prepared by partial devitrification of an amorphous precursor. The so-called Finemet with a nominal composition  $Fe_{73.5}Si_xB_{22.5-x}Nb_3Cu_1$  (with usually x = 13.5 or 16.5 at%) consists of Fe-Si BCC crystallites, with 10-14 nm average diameter, embedded in the residual amorphous matrix. The nanocrystallization process is based on the overlapping action of nucleating (especially Cu) and grain-growth inhibiting element (Nb, with larger atomic diameter than iron). The soft magnetic properties of nanocrystalline materials has been explained with the phenomenon of magnetic exchange coupling by Herzer's model [6].

Stable permeability in a large frequency range can be accomplished in Finemet based nanocrystalline alloys by transverse induced anisotropy in ribbons that overcome the demagnetizing effect in powdered nc alloys. Owing to the brittleness of nanostructured Finemet alloys, powders down to 20 microns can easily be produced by grinding the ribbon samples. Since the amorphous phase is strongly stabilized by the nanocrystallization, the nanostructure is not appreciably changed. The flake-shaped particles are molded in resin [48, 49] or solder glass [50] under pressure with eventual field orientation of the flakes. The magnetic properties are related to the air-gap distribution and can be controlled by both the flake size and the compacting pressure with very good reproducibility. The largest permeability (6000) is obtained after hot-pressing of large flakes (1 mm) with 5% solder glass, but this results in a low cut-off frequency (10 kHz). In contrast, the smallest permeability (ranging from 7 to10) is obtained after cold pressing of 20 micron flakes with 50% resin having the highest cut-off frequency (100 MHz). Figure 1.6 shows the frequency dependent permeability of Finemet powder cores and stress annealed ribbons. The frequency limit of permeability is not only due to eddy currents related to skin depth but also due to domain wall resonance and ferromagnetic resonance (FMR).

Certain brittle and metastable intermetallic compounds can be prepared by planar flow casting and then grinding the ribbon into powder, preserving its nanostructure obtained from rapid quenching. For example, silicon-rich iron ribbons can be crushed into micro-sized particles with nanocrystalline structure. Special interest is devoted to Fe<sub>2</sub>Si, which exhibits a high resistivity of 220 m $\Omega$ cm, due to its highly disordered B2 metastable nanostructure (grain size~50 nm). The magnetic polarization is relatively low, 0.6 T, but sufficient in high-frequency applications. An appreciable permeability of 250 is maintained up to 10MHz [11]



#### FIGURE 1.6

Frequency-dependent permeability of Finemet powder composite cores and stress-annealed ribbons[11]

**Nanoparticle composites** in polymer matrices are also synthesized via chemical synthesis routes to improve frequency stability and reduce losses compared to their microstructured counterparts [8,51-55]. The techniques successfully applied for the preparation of the above mentioned granular and core-shell nanocomposites are: reducing from metal oxides, hydrothermal precipitation, sol-gel processing of Fe–SiO<sub>2</sub> [51], Ni–SiO<sub>2</sub> [52], Fe–Al<sub>2</sub>O<sub>3</sub> [10], ball-milling of FeCo–SiO<sub>2</sub> [53], Fe–SiO<sub>2</sub> wet-chemistry method [54, 55], etc. Co-SiO<sub>2</sub> or Ni-SiO<sub>2</sub> nanocomposite samples, for example, are reported to have a permeability of 15 and a flat-frequency response up to 1 GHz, much higher than that of microsized NiFe<sub>2</sub>O<sub>4</sub> [56-58] which is in 10-100 MHz range. Permeability as high as 30 was also reported from Permalloy-(Ni<sub>47</sub>Fe<sub>53</sub>) encapsulated with Ni–Zn ferrite. These systems showed magnetic relaxation at 1 GHz.



#### FIGURE 1.7

3D Inductor structures with sputtered nanolaminates [59, 60]

**Sputtered nanogranular granular films** consisting of ferromagnetic metallic nanoparticles distributed uniformly in an insulator matrix, have attracted much attention because of their excellent soft magnetic properties operating in the high-frequency range (up to GHz). These films take the advantages of high permeability ( $\mu$ ) of magnetic metals and the high resistivity ( $\rho$ ) of insulators, making high  $\mu$  and high  $\rho$  possible in the same material. The critical factor leading to good soft magnetic properties in these materials is the exchange coupling between magnetic nanoparticles which can be explained by extending the Herzer model to such materials. Nano Fe-M-O (M = Hf, Zr, Si, Al or rare-earth metal element) thin films have been successfully demonstrated via co-sputtering or atomic deposition. These are nanocomposites composed of (<10nm) magnetic

16

nanoparticles surrounded by an amorphous insulator. The  $\mu$ ' for Fe- and Co-based nanocomposites thin films can be as large as 500 and with essentially flat frequency response even above 0.1 GHz [61, 62], which is significantly better than the magnetic properties of conventional ferrite and powder materials. Nanogranular CoZrO ferromagnetic thin films have been reported by Sullivan et al.as integrated core material for high-frequency microinductor structures upto 1GHz [63]. Magnetic cores with sputtered high-resistivity alloys such as Co–Zr–T, Co–Hf–Ta–Pd, Co-Zr-Nb can marginally increase the frequency-stability and Quality factor. Inductors displaying 0.05-0.15  $\mu$ H/mm<sup>2</sup> at 1-2 MHz [64-66] are reported with such cores. However, one issue to be resolved with this material is the small processing window for depositing high-performance material repeatedly.

**Nanolaminates:** Inductors with nanolaminates show much higher inductance density at above 100 MHz, higher frequency stability and Quality factor. Nanolaminates with spiral coils showed inductance densities of up to  $2.0 \,\mu$ H/mm<sup>2</sup> at 500-1000 MHz, higher than the state-of-the-art. Their work demonstrated that nanolaminates can increase the roll-off frequency from 300-800 MHz. The sputtered nanolaminates core layers are integrated into a continuous 3D structure with closed magnetic circuit and metal coils to achieve high inductance density. These inductors take advantage of the uniaxial magnetocrystalline anisotropy in the magnetic core surrounding the spiral inductor coils [67]. However, the power-handling with these inductors is limited unless the inductor thickness is increased to several microns. The geometry requirements make the sputtered inductor-core process very expensive.

#### Nanomagnetic antennas

Amongst the RF components, antenna is still considered a major barrier to system miniaturization because the antenna performance is directly dependent on its physical size [68]. In order to decrease the antenna size, it has to be surrounded by a material with either high permittivity ( $\epsilon$ ) or permeability ( $\mu$ ), which would shorten the wavelength by square root of  $1/\mu\epsilon$  [69, 70] and lead to miniaturized designs as shown in Figure 1.8. Over the past decade, the materials employed in high-frequency planar antennas were mostly confined to thick film LTCC [71, 72] owing to their low loss, stable properties, and partial integration capability, although the end-systems with these technologies are still bulky and costly. Polymer dielectrics, on the other hand, provide the benefits of low-cost manufacturing and total integration capabilities with the rest of the polymer-based systems. However, traditional organic materials such as epoxies have high electrical losses at high frequencies while low-loss organics have low permittivity and no magnetic properties. These limitations lead to large component designs, and also make it extremely difficult to build integrated high-performance front-end modules [73, 74].



#### FIGURE 1.8

Antenna miniaturization and performance enhancement with nanomagnetic dielectrics

Magneto-dielectric materials can also potentially lead to a dramatic reduction in antenna size because of their combined effect of high permittivity and permeability. Compared to traditional polymer dielectrics, increases in the permeability and permittivity by 4X in magnetic nanocomposites can reduce the antenna dimensions by a factor of 4, resulting in significant miniaturization of antenna. By tuning the material formulations, the materials can be designed to have lower permittivity:permeability ratio so as to have good impedance match with that of free space [75]. The antenna bandwidth on such magnetic substrates will therefore be wider than that with the high-permittivity dielectric substrates [76-78] that provide the same miniaturization just from the permittivity. The high permeability suppresses back-scattering and improves the radiation efficiency, resulting in further performance enhancement.

The magneto-dielectric properties required, but not totally achieved to date, are low electrical-loss and, stable permeability and permittivity in the gigahertz frequency range. One group of materials, named as artificial magneto-dielectrics, has been proposed to emulate the characteristics of the magneto-dielectric materials. These materials are constructed by the stacking and periodic placement of embedded circuits in a dielectric host medium. For instance, the embedded-circuit building blocks proposed by Buell et al. [79] are periodic spiral inductors, while similar behavior has also been reported in Maslovski et al. [80] using stacked-ring resonators, and using fractal Hilbert cells as the embedded circuits [81]. Recent advances in material synthesis and design have increased the hope for new magneto-dielectric materials for antenna and other electromagnetic structure miniaturization.

Materials with inherently high permittivity and permeability are better suited as magneto-dielectric antenna substrates [82]. Recent study showed stable properties in nanocomposites from ferrite nanoparticles, with permeabilities of 5-10 till 15 GHz [83]. Compounds based on BaO,  $Fe_2O_3$  and other oxides (MO, M = Co, Ni etc.) with hexagonal structures are more suited for high-frequency applications [84]. Hexaferrites and their nanocomposites with glass and polymer were also characterized for antennas. Co2Z hexaferrites showed a permeability of ~10 at 300-400 MHz [85]. Permeability of ~2 with a loss of 0.03 has been shown with ferrite-glass nanocomposites with a frequency-stability of upto 2-3 GHz [86].

Magnetic materials that comprise of nanoscale metal particles in an amorphous matrix provide unique opportunities to address the fundamental limitations of microscale magneto-dielectric materials. Higher permeability and frequency-stability can be achieved in magnetic nanocomposites by reducing the particle size and the separation between the neighboring metal particles down to the nanoscale, which leads to magnetic exchange coupling phenomena [2, 3]. Such behavior is mostly seen in sputtered films which cannot be deposited to adequate thickness (200-500 microns) that is required for antennas. Nanoparticle composites can be printed to such thicknesses but do not show such high permeability as sputtered films although they have improved frequency stability and lower loss compared to their microstructured counterparts [15, 69, 87-90]. By careful optimization of nanocomposite structure, low loss with a permittivity of 7-8 and permeability of ~2 has been achieved with metal-polymer nanocomposites [91]. Such a nanocomposite shows about 70-80% reduction in antenna size compared to material with nonmagnetic dielectrics.

Anisotropic one-dimensional nanostructures based on nickel or cobalt nanowires or filaments have been studied to overcome the limitations of isotropic nanocomposites. Nanowire composites with crystallographically oriented cobalt of high magnetocrystalline field anisotropy showed a permeability of 3.5 and loss of 0.045 till 4.5 GHz [30, 31]. A brief summary of microwave properties of magnetodielectrics is compiled elsewhere [91].

#### Nonreciprocal and tunable nanomagnetic devices

Non-reciprocal devices have asymmetric device characteristics. The most common example is a circulator. In this three-port device, the insertion loss is low when signal enters Port 1 and leaves Port 2, but high in the reverse direction. The signal entering Port 2 is, therefore, redirected to Port 3. The RF energy only moves in a specific rotary motion as shown in Figure 1.9. Circulators are widely used in RF front-end modules, where the incoming signal from antenna goes to the low-noise amplifier (LNA) path and not the power amplifier (PA), while only the outgoing signal from the PA goes to the antenna. Other similar examples of nonreciprocal components include phase-shifters, delay lines, isolators, power limiters, switches etc. The recent emergence of multiband wireless modules is also driving new RF architectures that need nonreciprocal components in smartphone applications.



FIGURE 1.9 Circulator as an example for non-reciprocal device [92]

The performance of nonreciprocal devices is strongly dependent on the anisotropy of the permeability tensor, and linewidth of FMR, which is a measure of the dampening in the relaxation process. Ferrites, when combined with rare-earth elements, change their crystal structure from spinel to garnet form with low FMR linewidths and low dielectric losses [93]. These materials also have low dielectric constants, and are therefore widely used in nonreciprocal devices. Because of their low saturation magnetization, it can be seen from Equation (9) that ferrites require an external magnetic field to create high FMR. The external biasing field is provided by a permanent magnet. Hence, they are difficult to be integrated into planar devices.

Recent advances in hexaferrites with inherently high FMR provide unique solutions that can successfully address the limitation of garnets [94, 95]. Hexaferrites are ferrites with hexagonal crystal structure that have high uniaxial magnetic anisotropy leading to high FMR, along with low FMR linewidths. Under suitable processing conditions, these devices can be self-biased to achieve higher FMR frequency and lower linewidth without the need for external magnets. The emergence of multiferroic materials will further enhance the tunability of microwave passives, giving rise to reconfigurable bandwidths.

Metal-based magnetic materials can enhance FMR further because of their inherently high Ms. However, in order to retain the frequency-stability, these materials need to be synthesized as nanocomposites in an insulating matrix. Nanowire composites are widely investigated as nextgeneration microwave devices because they have high magnetic field anisotropy from the combined effects of shape and crystal anisotropies [31]. This high anisotropy makes them selfbiased and still retain high FMR and low linewidth without the need of external magnetic field. The anisotropies are also tuned to give dual FMR characteristics that lead to potential new applications. Further, these materials can be fabricated using simple electrochemical plating routes without any process-compatibility issues with standard packaging substrates. This technology can be easily extended to other applications such as phase-shifters, inductors and EMI absorbers (described in Section 3.4) [96].





Variety of nanowire composites have been fabricated and characterized recently. An example of FMR signal for a nanowire composite illustrates this phenomenon in Figure 1.10 [92]. Cobalt nanowire composites in polycarbonate templates showed a self-biased FMR of 26 GHz. The high insertion losses in these materials are attributed to the polymer host matrix. By studying the

dielectric loss of nanowire composites as a function of nanowire loading, Saib et al. concluded that the nanowires are not a major contributor to the dielectric loss [97]. Figure 1.11 shows the dielectric loss of nanowire composites. Efforts are ongoing to further reduce the dielectric loss by replacing the polycarbonate template with an alumina template. By replacing the polycarbonate template, the insertion losses were reduced to -6 dB. A high return loss of 35 dB is also seen in the reverse direction. Isolator devices were demonstrated by loading the microstrip lines with such nanowire composites [92].





#### EMI isolation structures

The industry is moving towards heterogeneous integration of electronic systems that combine multiband wireless functions with high-speed digital computing. The market demand for portable, ultraminiaturized and thin products has led to the evolution of 3D packaging of digital, memory, RF and sensor dies and packages. A major problem in such highly integrated systems is Electromagnetic Interference (EMI), which causes significant noise coupling between the digital and RF dies.

EMI in integrated systems can occur in two directions, horizontal direction through the substrate and along the vertical direction between stacked dies, as shown in Figure 1.12. A major internal source of coupling along the horizontal direction is through the power delivery network. The timevarying current flowing through the digital circuits can cause the excitation of EM waves which behave as noise. This noise generated by the high-speed digital circuits can couple through the power distribution network (PDN) and transfer to sensitive RF circuits, degrading the functionality of these noise-sensitive RF circuits. This noise can be mitigated using several approaches such as decoupling capacitors, RF chokes, Electromagnetic Bandgap (EBG) structures.

EBGs are periodic structures with a repeating unit cell, in which the propagation of electromagnetic waves is forbidden in certain frequency bands. In these EBG structures, the constructive and destructive interference of electromagnetic waves results in transmission and reflection bands [99] creating a specific bandgap response. EBGs provide isolation levels of -100dB or better for unwanted electromagnetic mode transmission and radiation in microwave and millimeter waves in an area of 1 cm<sup>2</sup> [100, 101]. An example of an EBG structure is shown in Figure 1.13. For a particular

bandgap response, the size of EBG scales with the wavelength of the electromagnetic radiation, which, in turn, is determined by the electromagnetic properties of the medium such as permittivity, permeability and loss tangents. Using polymer nanocomposite dielectrics with high permittivity and permeability will therefore scale down EBGs. Miniaturization of EBGs is achieved by incorporating magnetic fillers in the polymer to simultaneously increase permittivity and permeability, as described in the section on "Nanomagnetic antennas".



#### FIGURE 1.12

Noise coupling and isolation need in integrated system packages

The vertical noise coupling between the RF and Digital die has been identified as another major bottleneck in 3D integration. EBGs in its present form, however, cannot be applied to isolate stacked dies to minimize vertical noise coupling. Nanomagnetics provide the ability to design and create unique Electromagnetic Interference (EMI) isolation thinfilm structures instead of the bulky ferrite beads and traditional EBGs. The structure, composition and magnetic anisotropy in films can be designed to create EMI isolation in the target frequency band. The FMR can be used as the loss generation mechanism whereby the noise in the power delivery network can be absorbed by the magnetic film. The FMR frequency can be controlled by the structure, composition and magnetocrystalline orientation of the magnetic films and hence can be varied depending on the frequency range over which isolation is required. FMR can also be controlled in magnetic nanocomposites by changing the magnetic particle chemistry, size and conductivity. Unlike EBGs, nanomagnetics also suppress noise in the vertical direction to create EMI isolation in devices that are located one above the other in a 3D package.



#### FIGURE 1.13 EBGs to suppress noise propagation in power-ground planes

Using the property of FMR, the magnetic films can be used to absorb energy in a direction that is orthogonal to the magnetization direction [102]. The tuning of the absorption frequency can be achieved with: 1) Magnetic alloy selection (Figure 1.15), 2) Magnetocrystalline and shape anisotropy, 3) Nanolayered or nanoarray structures, 4.) Nanocomposite structures. FMR noise absorption peaks can also be tuned by applying external fields.

**Tunability with magnetic alloy selection**: Magnetic resonance frequencies increase conversely with magnetization. Ferrites are characterized by relatively low saturation magnetization (4  $\pi$ M<sub>s</sub>\_<5 kG), with operating frequencies below 100 MHz. The frequency range is increased with ferromagnetic materials because of their high saturation magnetization (4 $\pi$  M<sub>s</sub>< 21.5 kG). The total internal field can be increased by enhancing the exchange coupling between the magnetic spins. This is accomplished by modulating the interatomic distances with alloying. In a recent study, extensive material magnetization and FMR data of various iron, nickel and cobalt alloys were obtained [103]. Based on the data, it was shown that zero-field FMR can be as high as 20 GHz by choosing the appropriate FeNiCo ternary alloy system as shown in Figure 1.14 [104].



#### FIGURE 1.14

Tuning absorption with alloy composition [104]

**Tunability with magnetocrystalline and shape anisotropy:** Isotropic permalloy suffers from a low magnetic anisotropy field ( $H_k$ , 2–6 Oe) and consequently low ferromagnetic resonance frequency (~ 100 MHz) since FMR is proportional to the square root of  $H_k$ . The overall magnetic anisotropy and the resonant frequency has been enhanced up to above 5.0 GHz by controlling the texture inside the films. The orientation of the magnetic moments can be made in-plane or out-of-plane based on film growth conditions and appropriate choice of the growth substrate [105].

**Nanolayered or nanoarrayed structures:** The line width of FMR (measure of FMR broadening) is a critical parameter that determines the bandwidth or the frequency range at which the film can absorb noise. Line width is enhanced by stacking layers of metal and insulator which increase the dampening factor by changing the magnetic coupling between the alternate magnetic layers. Stress in the film can also be engineered to increase the damping factor and broaden the noise absorption frequency [106]. The absorption is also engineered with high aspect ratio nanomagnetic arrays [107, 108].

**Tunability with nanocomposite structures:** The FMR with particle nanocomposites can be tuned between 100 -2000 MHz depending on the particle size which determines the field anisotropy. With coarser particles that have multiple domains within the particle, the loss mechanisms are also created by domain wall resonance. For example, 100 nm nickel composites show high microwave absorption at 200 MHz while 25 nm nanocomposites show similar absorption at 1000 MHz, while materials such as cobalt with high field anisotropy can create high absorption 2 GHz range.

## Summary

Magnetic materials at nanoscale can achieve high permeability with low coercivity and loss while retaining stability at high frequencies. Further, by invoking shape and crystal anisotropy, anisotropic properties can be achieved for applications in nonreciprocal components. This unique combination of properties provides several opportunities to overcome the fundamental limitations of traditional magnetic materials such as microscale ferrites and metal composites. The impact of nanomagnetics can be seen in several applications such as antennas, high-density inductors with high Q at high frequencies, circulators, isolators and EMI isolation. This new class of nanomagnetic materials can thus transform today's bulky discrete components into integrated thinfilms, resulting in simultaneous size reduction and performance enhancements.

## References

- 1. Li Y, Zhu R, Prikhodko D, Tkachenko Y: LTE power amplifier module design: challenges and trends. In: Solid-State and Integrated Circuit Technology (ICSICT), 2010 10th IEEE International Conference on: 2010: IEEE; 2010: 192-195.
- Hayakawa Y, Makino A, Fujimori H, Inoue A: High resistive nanocrystalline Fe-MO (M= Hf, Zr, rare-earth metals) soft magnetic films for high-frequency applications. Journal of applied physics 1997, 81(8):3747-3752.
- 3. Ohnuma S, Fujimori H, Masumoto T, Xiong X, Ping D, Hono K: FeCo–Zr–O nanogranular soft-magnetic thin films with a high magnetic flux density. Applied physics letters 2003, 82(6):946-948.
- 4. Wen T, Krishnan KM: Cobalt-based magnetic nanocomposites: fabrication, fundamentals and applications. Journal of Physics D: Applied Physics 2011, 44:393001.
- 5. Xiaolin Y, Chengli R: High frequency properties of Ni<sub>75</sub>Fe<sub>25</sub>-SiO<sub>2</sub>granular thin films with very high resistivity. Materials Letters 2007, 61(3):908-911.
- 6. Herzer G: Grain size dependence of coercivity and permeability in nanocrystalline ferromagnets. Magnetics, IEEE Transactions on 1990, 26(5):1397-1402.
- 7. Herzer G: Soft magnetic nanocrystalline materials. Scripta Metallurgica et Materialia 1995, 33(10):1741-1756.
- 8. Zhao Y, Ni C, Kruczynski D, Zhang X, Xiao JQ: Exchange-coupled soft magnetic FeNi-SiO<sub>2</sub> nanocomposite. The Journal of Physical Chemistry B 2004, 108(12):3691-3693.
- 9. Alben R, Becker J, Chi M: Random anisotropy in amorphous ferromagnets. Journal of applied physics 1978, 49(3):1653-1658.
- 10. Santos A, Ardisson J, Viegas A, Schmidt J, Persiano A, Macedo W: Structure and magnetism of granular Fe–Al<sub>2</sub>O<sub>3</sub>. Journal of magnetism and magnetic materials 2001, 226:1861-1863.

- 11. Mazaleyrat F, Varga L: Ferromagnetic nanocomposites. Journal of magnetism and magnetic materials 2000, 215:253-259.
- 12. Gramatyka P, Nowosielski R, Sakiewicz P: Magnetic properties of polymer bonded nanocrystalline powder. Journal of Achievements in Materials and Manufacturing Engineering 2007, 20:115-118.
- 13. Li Y, Li G: Physics of ferrites. Science, Beijing 1978:335.
- 14. Liao S: Ferromagnetic Physics. Science, Beijing 1992:17-81.
- 15. Lu B, Dong X, Huang H, Zhang X, Zhu X, Lei J, Sun J: Microwave absorption properties of the core/shell-type iron and nickel nanoparticles. Journal of magnetism and magnetic materials 2008, 320(6):1106-1111.
- 16. Ramprasad R, Zurcher P, Petras M, Miller M, Renaud P: Magnetic properties of metallic ferromagnetic nanoparticle composites. Journal of Applied Physics 2004, 96(1):519.
- 17. Wu M, Zhang Y, Hui S, Xiao T, Ge S, Hines W, Budnick J, Taylor G: Microwave magnetic properties of Co50/(SiO<sub>2</sub>) 50 nanoparticles. Applied Physics Letters 2002, 80(23):4404-4406.
- 18. Abshinova MA, Lopatin AV, Kazantseva NE, Vilčáková J, Sáha P: Correlation between the microstructure and the electromagnetic properties of carbonyl iron filled polymer composites. Composites part A: Applied science and manufacturing 2007, 38(12):2471-2485.
- 19. Obol M, Vittoria C: Microwave permeability of Y-type hexaferrites in zero field. Journal of applied physics 2003, 94(6):4013-4017.
- 20. Kittel C, McEuen P: Introduction to solid state physics, vol. 7: Wiley New York; 1996.
- 21. Kittel C: On the theory of ferromagnetic resonance absorption. Physical Review 1948, 73(2):155.
- 22. Liu JR, Itoh M, Machida K-i: Electromagnetic wave absorption properties of  $\alpha$ -Fe/Fe<sub>3</sub>B/Y<sub>2</sub>O<sub>3</sub> nanocomposites in gigahertz range. Applied physics letters 2003, 83(19):4017-4019.
- 23. Raj PM, Sharma H, Samtani S, Mishra D, Nair V, Tummala R: Magnetic losses in metal nanoparticle-insulator nanocomposites. Journal of Materials Science: Materials in Electronics 2013, 24(9):3448-3455.
- 24. Snoek J: Dispersion and absorption in magnetic ferrites at frequencies above one Mc/s. Physica 1948, 14(4):207-217.
- 25. Bonincontro A, Cametti C, Di Biasio A: Effect of volume ion polarisations on Maxwell-Wagner dielectric dispersions. Journal of Physics D: Applied Physics 1980, 13(8):1529.
- 26. Tsangaris G, Psarras G, Kouloumbi N: Evaluation of dielectric behaviour of particulate composites consisting of polymeric matrix and conductive filler. Materials science and technology 1996, 12(7):533-538.
- 27. Youngs I, Bowler N, Lymer K, Hussain S: Dielectric relaxation in metal-coated particles: the dramatic role of nano-scale coatings. Journal of Physics D: Applied Physics 2005, 38(2):188.
- 28. Nam B, Choa YH, Oh ST, Lee SK, Kim KH: Broadband RF Noise Suppression by Magnetic Nanowire-Filled Composite Films. Magnetics, IEEE Transactions on 2009, 45(6):2777-2780.
- 29. Sharma M, Pathak S, Sharma M: FMR Measurements of Magnetic Nanostructures. Ferromagnetic Resonance–Theory and Applications 2013:93.
- 30. Kou X, Fan X, Zhu H, Cao R, Xiao JQ: Microwave Permeability and Tunable Ferromagnetic Resonance in Cobalt Nanowire Arrays. Magnetics, IEEE Transactions on 2010, 46(5):1143-1146.

- 31. Darques M, Spiegel J, De la Torre Medina J, Huynen I, Piraux L: Ferromagnetic nanowireloaded membranes for microwave electronics. Journal of magnetism and magnetic materials 2009, 321(14):2055-2065.
- 32. Shirakata Y, Hidaka N, Ishitsuka M, Teramoto A, Ohmi T: High permeability and low loss Ni–Fe composite material for high-frequency applications. Magnetics, IEEE Transactions on 2008, 44(9):2100-2106.
- 33. Yang W, Qiao L, Wei J, Zhang Z, Wang T, Li F: Microwave permeability of flake-shaped FeCuNbSiB particle composite with rotational orientation. Journal of applied physics 2010, 107(3):033913-033915.
- 34. Guo D, Zhang Z, Lin M, Fan X, Chai G, Xu Y, Xue D: Ni–Zn ferrite films with high resonance frequency in the gigahertz range deposited by magnetron sputtering at room temperature. Journal of Physics D: Applied Physics 2009, 42(12):125006.
- 35. Sonehara M, Sugiyama T, Ishikawa T, Inagaki K, Sato T, Yamasawa K, Miura Y: Relation between microwave complex permeability and ferromagnetic Fe-Si layer thickness in Mn-Ir/Fe-Si exchange-coupled film. Magnetics, IEEE Transactions on 2006, 42(10):2984-2986.
- 36. Chai G, Xue D, Fan X, Li X, Guo D: Extending the Snoek's limit of single layer film in (Co96Zr4/Cu) n multilayers. Applied Physics Letters 2008, 93(15):152516.
- 37. C.J.Kaiser: The Inductor Handbook: CJ Publisher; April 1996.
- 38. Lotfi AW, Wilkowski MA: Issues and advances in high-frequency magnetics for switching power supplies. Proceedings of the IEEE 2001, 89(6):833-845.
- 39. Lee DW, Li L, Wang SX, Lu J, Wong CP, Bhattacharya SK, Papapolymerou J: Embedded Passives. 2009:459-502.
- 40. Van de Riet E, Roozeboom F: Ferromagnetic resonance and eddy currents in highpermeable thin films. Journal of applied physics 1997, 81:350.
- 41. C.W.Chen: Magnetism and Metallurgy of Soft Magnetic Materials, vol. XV. New York: North Holland Publishing Company; 1977.
- 42. Wijn JSaHPJ: Ferrites. Holland: Philips; 1959.
- 43. Application guide Inductor design for switched mode power supplies.
- 44. Park JW, Cros F, Allen MG: Planar spiral inductors with multilayer micrometer-scale laminated cores for compact-packaging power converter applications. Magnetics, IEEE Transactions on 2004, 40(4):2020-2022.
- 45. Park JW: Core lamination technology for micromachined power inductive components. 2004.
- 46. Park JW, Allen MG: Ultralow-profile micromachined power inductors with highly laminated Ni/Fe cores: application to low-megahertz DC-DC converters. Magnetics, IEEE Transactions on 2003, 39(5):3184-3186.
- 47. Yoshizawa Y, Oguma S, Yamauchi K: New Fe-based soft magnetic alloys composed of ultrafine grain structure. Journal of applied physics 1988, 64(10):6044-6046.
- 48. Leger V, Ramiarinjaona C, Barrue R, Lebourgeois R: Composite magnetic materials based on nanocrystalline powders for middle-and high-frequency applications up to 1MHz. Journal of magnetism and magnetic materials 1999, 191(1):169-173.
- 49. Müller M, Novy A, Brunner M, Hilzinger R: Powder composite cores of nanocrystalline soft magnetic FeSiB-CuNb alloys. Journal of magnetism and magnetic materials 1999, 196:357-358.
- 50. Nuetzel D, Rieger G, Wecker J, Petzold J, Mueller M: Nanocrystalline soft magnetic composite-cores with ideal orientation of the powder-flakes. Journal of magnetism and magnetic materials 1999, 196:327-329.

- 51. Xiao G, Chien C: Temperature dependence of spontaneous magnetization of ultrafine Fe particles in Fe-SiO2 granular solids. Journal of applied physics 1987, 61(8):3308-3310.
- 52. Takahashi R, Sato S, Sodesawa T, Suzuki M, Ichikuni N: Ni/SiO<sub>2</sub> prepared by sol-gel process using citric acid. Microporous and mesoporous materials 2003, 66(2-3):197-208.
- 53. Ennas G, Marongiu G, Marras S, Piccaluga G: Mechanochemical route for the synthesis of cobalt ferrite–silica and iron–cobalt alloy–silica nanocomposites. Journal of Nanoparticle Research 2004, 6(1):99-105.
- 54. Giri AK, De Julian C, Gonzalez J: Coercivity of Fe-SiO<sub>2</sub> nanocomposite materials prepared by ball milling. Journal of applied physics 1994, 76(10):6573-6575.
- 55. Kim D, Ohnishi M, Matsushita N, Abe M: Magnetic cores usable in gigahertz range: permalloy/Ni-Zn ferrite microcomposite made by low-temperature wet process. Magnetics, IEEE Transactions on 2003, 39(5):3181-3183.
- 56. Sato H, Kitakami O, Sakurai T, Shimada Y, Otani Y, Fukamichi K: Structure and magnetism of hcp-Co fine particles. Journal of applied physics 1997, 81:1858.
- 57. Zhan Y, Wang S, Xiao D, Budnick J, Hines W: Nanocomposite Co/SiO<sub>2</sub> soft magnetic materials. Magnetics, IEEE Transactions on 2001, 37(4):2275-2277.
- 58. Tang N, Zhong W, Liu W, Jiang H, Wu X, Du Y: Synthesis and complex permeability of Ni/SiO<sub>2</sub> nanocomposite. Nanotechnology 2004, 15:1756.
- 59. Gardner DS, Schrom G, Hazucha P, Paillet F, Karnik T, Borkar S, Hallstein R, Dambrauskas T, Hill C, Linde C et al: Integrated on-chip inductors using magnetic material (invited). Journal of Applied Physics 2008, 103(7):07E927.
- 60. Mathuna S, O'Donnell T, Wang N, Rinne K: Magnetics on silicon: an enabling technology for power supply on chip. Power Electronics, IEEE Transactions on 2005, 20(3):585-592.
- 61. Hayakawa Y, Makino A, Fujimori H, Inoue A: High resistive nanocrystalline Fe-MO (M= Hf, Zr, rare-earth metals) soft magnetic films for high-frequency applications. Journal of Applied Physics 1997, 81:3747.
- 62. Fujimori H: Structure and 100MHz soft magnetic properties in multilayers and granular thin films. Scripta Metallurgica et Materialia 1995, 33(10-11):1625-1636.
- 63. Sullivan CR, Sanders SR: Microfabrication process for high-frequency power-conversion transformers. In: 1995: IEEE; 1995: 658-664 vol. 652.
- 64. Mino M, Tsukamoto K, Yanagisawa K, Tago A, Yachi T: A compact buck-converter using a thin-film inductor. In: 1996: IEEE; 1996: 422-426 vol. 421.
- 65. Sugahara S, Edo M, Sato T, Yamasawa K: The optimum chip size of a thin film reactor for a high-efficiency operation of a micro DC-DC converter. In: 1998: IEEE; 1998: 1499-1503 vol. 1492.
- 66. Mathuna SCO, O'Donnell T, Wang N, Rinne K: Magnetics on silicon: an enabling technology for power supply on chip. Power Electronics, IEEE Transactions on 2005, 20(3):585-592.
- 67. Gardner DS, Schrom G, Paillet F, Jamieson B, Karnik T, Borkar S: Review of on-chip inductor structures with magnetic films. Magnetics, IEEE Transactions on 2009, 45(10):4760-4766.
- 68. Yang G-M, Xing X, Daigle A, Liu M, Obi O, Wang J, Naishadham K, Sun NX: Electronically tunable miniaturized antennas on magnetoelectric substrates with enhanced performance. Magnetics, IEEE Transactions on 2008, 44(11):3091-3094.
- 69. Martin LJ, Ooi S, Staiculescu D, Hill MD, Wong C, Tentzeris MM: Effect of Permittivity and Permeability of a Flexible Magnetic Composite Material on the Performance and Miniaturization Capability of Planar Antennas for RFID and Wearable Wireless Applications. Components and Packaging Technologies, IEEE Transactions on 2009, 32(4):849-858.

- Altunyurt N, Swaminathan M, Raj PM, Nair V: Antenna miniaturization using magnetodielectric substrates. In: Electronic Components and Technology Conference, 2009 ECTC 2009 59th: 2009: IEEE; 2009: 801-808.
- 71. Dernovsek O, Eberstein M, Schiller W, Naeini A, Preu G, Wersing W: LTCC glass-ceramic composites for microwave application. Journal of the European Ceramic Society 2001, 21(10):1693-1697.
- 72. Ghosh I, Hilgers A, Schlenker T, Porath R: Ceramic microwave antennas for mobile applications. Journal of the European Ceramic Society 2001, 21(15):2621-2628.
- 73. Altunyurt N, Rieske R, Swaminathan M, Sundaram V: Conformal antennas on liquid crystalline polymer based rigid-flex substrates integrated with the front-end module. Advanced Packaging, IEEE Transactions on 2009, 32(4):797-808.
- 74. Nikolaou S, Bairavasubramanian R, Lugo Jr C, Carrasquillo I, Thompson DC, Ponchak GE, Papapolymerou J, Tentzeris MM: Pattern and frequency reconfigurable annular slot antenna using PIN diodes. Antennas and Propagation, IEEE Transactions on 2006, 54(2):439-448.
- 75. Mosallaei H, Sarabandi K: Magneto-dielectrics in electromagnetics: Concept and applications. Antennas and Propagation, IEEE Transactions on 2004, 52(6):1558-1567.
- 76. Liu Y, Wang Y, Yang R: On study of a new patch antenna with macromolecule magnetic substrate. In: Antennas, Propagation and EM Theory, 2003 Proceedings 2003 6th International SYmposium on: 2003: IEEE; 2003: 116-119.
- 77. Zhan Y, Wang S, Xiao D, Budnick J, Hines W: Nanocomposite Co/SiO<sub>2</sub>soft magnetic materials. Magnetics, IEEE Transactions on 2002, 37(4):2275-2277.
- Fechine PBA, Távora A, Kretly L, Almeida AFL, Santos MRP, Freire FNA, Sombra ASB: Microstrip antenna on a high dielectric constant substrate: BaTiO<sub>3</sub> (BTO)-CaCu<sub>3</sub>Ti<sub>4</sub>O<sub>12</sub> (CCTO) composite screen-printed thick films. Journal of electronic materials 2006, 35(10):1848-1856.
- 79. Buell K, Mosallaei H, Sarabandi K: A substrate for small patch antennas providing tunable miniaturization factors. Microwave Theory and Techniques, IEEE Transactions on 2006, 54(1):135-146.
- 80. Maslovski SI, Ikonen PM, Kolmakov I, Tretyakov SA, Kaunisto M: Artificial magnetic materials based on the new magnetic particle: Metasolenoid. Progress In Electromagnetics Research 2005, 54:61-81.
- 81. Yousefi L, Ramahi OM: Miniaturized wideband antenna using engineered magnetic materials with multi-resonator inclusions. In: Antennas and Propagation Society International Symposium, 2007 IEEE: 2007: IEEE; 2007: 1885-1888.
- 82. Collin R: Foundations for microwave engineering, 1966. In.: McGraw-Hill.
- 83. Bayrakdar H: Complex permittivity, complex permeability and microwave absorption properties of ferrite–paraffin polymer composites. Journal of magnetism and magnetic materials 2011, 323(14):1882-1885.
- 84. Rozanov K, Li Z, Chen L, Koledintseva M: Microwave permeability of Co<sub>2</sub>Z composites. Journal of applied physics 2005, 97(1):013905-013905-013907.
- Bae S, Hong Y, Lee J, Jalli J, Abo G, Lyle A, Nam I, Seong W, Kum J, Park S: New Synthetic Route of Z-Type (Ba<sub>3</sub>Co<sub>2</sub>Fe<sub>24</sub>O<sub>41</sub>) Hexaferrite Particles. Magnetics, IEEE Transactions on 2009, 45(6):2557-2560.
- Lee J, Hong Y-K, Bae S, Jalli J, Abo GS, Park J, Seong W-M, Park S-H, Ahn W-K: Low loss Co<sub>2</sub>Z (Ba<sub>3</sub>Co<sub>2</sub>Fe<sub>24</sub>O<sub>41</sub>)–glass composite for gigahertz antenna application. Journal of Applied Physics 2011, 109(7):07E530.

- 87. Tang N, Zhong W, Wu X, Jiang H, Liu W, Du Y: Synthesis and complex permeability of Co/SiO<sub>2</sub>nanocomposites. Materials Letters 2005, 59(14):1723-1726.
- 88. Peng K, Zhou L, Hu A, Tang Y, Li D: Synthesis and magnetic properties of Ni–SiO<sub>2</sub> nanocomposites. Materials Chemistry and Physics 2008, 111(1):34-37.
- 89. Liu W, Zhong W, Jiang H, Tang N, Wu X, Du Y: Highly stable alumina-coated iron nanocomposites synthesized by wet chemistry method. Surface and Coatings Technology 2006, 200(16):5170-5174.
- 90. Zhan Y, Wang S, Xiao D, Budnick J, Hines W: Nanocomposite Co/SiO<sub>2</sub> soft magnetic materials. Magnetics, IEEE Transactions on 2001, 37(4):2275-2277.
- 91. Guo Y, Chia M, Chen Z: Miniature built-in multiband antennas for mobile handsets. Antennas and Propagation, IEEE Transactions on 2004, 52(8):1936-1944.
- 92. Darques M, De la Torre Medina J, Piraux L, Cagnon L, Huynen I: Microwave circulator based on ferromagnetic nanowires in an alumina template. Nanotechnology 2010, 21(14):145208.
- 93. www.mmgca.com: Data sheet for Ni-Zn ferrite
- 94. Harris VG, Geiler A, Chen Y, Yoon SD, Wu M, Yang A, Chen Z, He P, Parimi PV, Zuo X: Recent advances in processing and applications of microwave ferrites. Journal of Magnetism and Magnetic Materials 2009, 321(14):2035-2047.
- 95. Pardavi-Horvath M: Microwave applications of soft ferrites. Journal of Magnetism and Magnetic Materials 2000, 215:171-183.
- 96. Maslovski S, Ikonen P, Kolmakov I, Tretyakov S, Kaunisto M: Artificial magnetic materials based on the new magnetic particle: Metasolenoid. Progress In Electromagnetics Research 2005, 54:61-81.
- 97. Saib A, Darques M, Piraux L, Vanhoenacker-Janvier D, Huynen I: Unbiased microwave circulator based on ferromagnetic nanowires arrays of tunable magnetization state. Journal of Physics D: Applied Physics 2005, 38(16):2759.
- Spiegel J, de la Torre J, Darques M, Piraux L, Huynen I: Permittivity model for ferromagnetic nanowired substrates. Microwave and Wireless Components Letters, IEEE 2007, 17(7):492-494.
- 99. Joannopoulos JD, Meade R, Winn JN: Photonic crystal: Modeling the flow of light. In.: Princeton University Press., Princeton, NJ; 1995.
- 100. Chen ZN, Yang N, Wang YY, Chia M: A novel compact electromagnetic bandgap (embg) structure and its application for antenna duplexer. In: Radio and Wireless Conference, 2002 RAWCON 2002 IEEE: 2002: IEEE; 2002: 71-74.
- 101. Yang L, Fan M, Chen F, She J, Feng Z: A novel compact electromagnetic-bandgap (EBG) structure and its applications for microwave circuits. Microwave Theory and Techniques, IEEE Transactions on 2005, 53(1):183-190.
- 102. Abothu IR, Hwang JH, Iyer MK, Pulugurtha MR, Swaminathan M, Tummala R: Ferroelectrics and ferromagnetics for noise isolation in integrated circuits, packaging, and system architectures. In.: Google Patents; 2011.
- 103. Kim KH, Ohnuma S, Yamaguchi M: RF integrated noise suppressor using soft magnetic films. Magnetics, IEEE Transactions on 2004, 40(4):2838-2840.
- 104. Encinas-Oropesa A, Demand M, Piraux L, Ebels U, Huynen I: Effect of dipolar interactions on the ferromagnetic resonance properties in arrays of magnetic nanowires. Journal of Applied Physics 2001, 89(11):6704-6706.
- 105. Kuanr B, Malkinski L, Camley R, Celinski Z, Kabos P: Iron and Permalloy based magnetic monolithic tunable microwave devices. Journal of applied physics 2003, 93(10):8591-8593.

- 106. Xu F, Zhang X, Ma Y, Phuoc N, Chen X, Ong C: Influence of Cu underlayer on the high-frequency magnetic characteristics of as-sputtered FeCoSiN granular thin films. Journal of Physics D: Applied Physics 2009, 42(1):015002.
- 107. Zhuang Y, Vroubel M, Rejaei B, Burghartz J, Attenborough K: Shape-induced ultrahigh magnetic anisotropy and ferromagnetic resonance frequency of micropatterned thin Permalloy films. Journal of Applied Physics 2006, 99(8):08C705-708C705-703.
- 108. Malkinski LM, Yu M, Vovk AY, Scherer II DJ, Spinu L, Zhou W, Whittenburg S, Davis Z, Jung J-S: Microwave absorption of patterned arrays of nanosized magnetic stripes with different aspect ratios. Journal of Applied Physics 2007, 101(9):09J110.