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Magnetic Nanoferrites for RF CMOS: Enabling 5G and Beyond

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Emergence of 5G

From connected thermostats to self-driving vehicles, advanced connectivity is transforming our lives while saving energy and reducing pollution, thus making living more sustainable. This is the hallmark of the Internet of things (IoT). But the full extent of IoT possibilities is yet to be realized. One of the key foundational technologies that will serve as the core architecture for future capabilities is 5G—the 5th generation telecommunication systems. Unlike its predecessors, 5G is going to be a new heterogeneous ecosystem that includes integration of 4G, Wi-Fi, millimeter waves, and other wireless access technologies, utilizing bandwidths from various frequency bands ranging from <4 GHz to 100 GHz.[1] Different usage scenarios demand different capabilities that can be attained in different frequency bands. As per the International Telecommunication Union (ITU), three main usage scenarios are envisaged to expand and support a diverse array of applications for International Mobile Telecommunications (IMT) 2020 and beyond, namely: 1) enhanced mobile broadband; 2) massive machine-type communications; and 3) ultra-reliable and low latency communications (as illustrated in Fig. 1), along with the key performance indicators (KPIs) associated with them.[2] The taming of this spectrum is considered essential to achieving the 5G vision of a truly connected world.

RF CMOS: Requirements and Key Challenges

The focus of this article is mainly on two of the proposed frequency bands, centered around 6 GHz and 28 GHz, which are designated for connected vehicles and indoor hotspot applications, respectively. Demanding KPIs of various applications call for innovation in radio frequency integrated circuit (RFIC) design. For example, for the connected vehicles in urban grids and highways, high mobility (>300 km/h), high reliability and low latency (≤1 ms) are essential. Lower latency can be achieved by bringing circuit components in a mixed-signal chip closer to one another. However, the physical proximity of the electromagnetic (EM) noise aggressor, viz., digital components, and the victim, viz., analog components, at such high frequencies may lead to serious electromagnetic interference which, in turn, may degrade the reliability of the devices and the systems.[3,4] This is of serious concern in designing the RF CMOS circuit layout that uses all frequency bands related to 5G. Therefore, to continue miniaturization of radio frequency integrated circuits while maintaining high reliability, either a novel circuit design approach should be adopted or an on-chip EM noise suppressor must be used.

Besides electromagnetic compatibility issues, progress in bringing analog, digital, and RF circuits on one chip—commonly known as system-on-chip (SoC)—is hindered greatly due to a crucial passive component—the inductor. Inductors are widely used in RF integrated circuits. They are essential components of low-noise amplifiers (LNA), power amplifiers (PA), oscillators, filters, etc. But, often, they are the largest components in the circuit, costing more than 50% of chip-area. Apart from "chip real estate," their large footprint results in a large parasitic capacitance at high frequencies which, in turn, degrades the quality factor and reduces the self-resonance frequency. The need of the hour is to obtain an inductor with high inductance density and high quality factor in the aforesaid frequency bands.

Various attempts have been made to enhance the quality factor of integrated inductors on silicon by optimizing coil design, controlling substrate losses, using patterned ground shields, etc., with significant success.[5,6] However, it is understood that, to keep up with the technology scaling, on-chip inductors may not be practical to use beyond 10 GHz.[5] Distributed passive elements like transmission lines are suggested for the use at frequencies ≫10 GHz. But the length of such distributed elements can be prohibitive for their integration on-chip below 30 GHz.

Integration of ferromagnetic and high-ε materials has thus become essential for frequencies of 10-30 GHz—some of the key frequency bands for 5G applications. Therefore, to continue with the miniaturization of RFICs and to move towards SoC solutions, on-chip integration of magnetic materials is necessary and that can pave way for high performance on-chip inductors for the frequency bands above 10 GHz, and thus can fulfill the promise of SoC and IoT. Magnetic materials have played a significant role in achieving efficient high frequency devices since the middle of the last century. Changing requirements over the years have sparked innovation in materials science and processing technology. At present, the requirement is to

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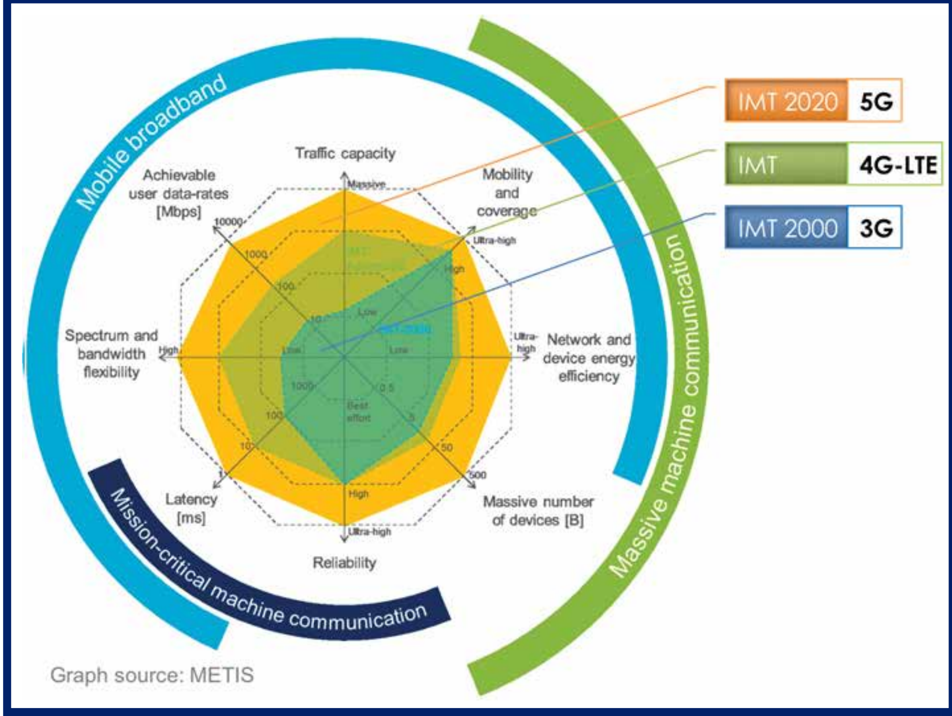

Graph source: METIS

Fig. 1. *Proposed key performance indicators of upcoming 5G technology.*

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obtain a suitable, integrated magnetic film on Si-CMOS chip. So, for clarity, the discussion henceforth will be confined to such an on-chip integrated magnetic film and its two applications—as an inductor core and as an EM noise suppressor.

A suitably chosen integrated film can serve both the purposes—tackling electromagnetic compatibility issues and enhancing the performance of on-chip passives. It is, however, to be noted that the governing principle of the suppression of electromagnetic interference using a magnetic film is different from the principle behind the enhancement of inductance of a coil with a magnetic core, even though both are related to the permeability of the magnetic medium.

When subjected to a high frequency magnetic field (several kHz or higher), the permeability of a magnetic material can be expressed as a complex quantity ($\mu = \mu' - j\mu''$), considering that the magnetic dipoles of the material exhibit a delayed response that results in a loss. In general, μ' represents the ability of the material to confine magnetic flux, while the μ'' describes magnetic losses. μ' assumes a constant value at lower frequencies and begins to drop below zero beyond a cut-off frequency, known as the ferromagnetic resonance frequency (f_{FMR}), and has a direct influence on the inductance of a coil having the said material as the core. On the other hand, the driving idea of noise suppressors is the remediation of RF magnetic field, which is the strongest near the interconnects, by placing nearby a material that has large μ'' at that RF frequency.

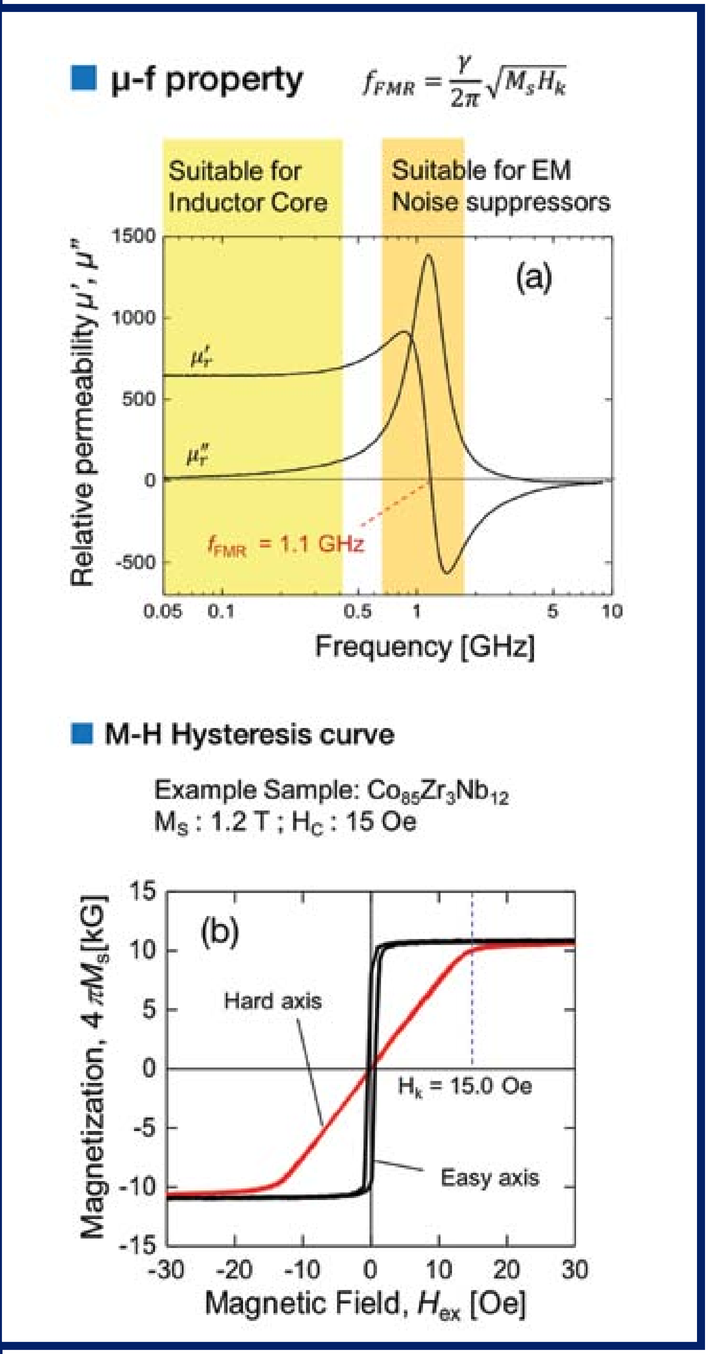

Fig. 2. *(a) Schematic drawing of frequency dispersion of complex permeability, highlighting the appropriate frequency ranges for inductor and noise-suppressor applications. Amorphous CoZrNb thin film is chosen as an example (Ref. Yamaguchi, et al.,[13]). (b) Magnetic hysteresis curve of the same film.*

The frequency dispersion of complex permeability of a magnetic material (amorphous ferromagnetic CoZrNb thin film, chosen as an example) is shown schematically in Fig. 2, highlighting the usage scenarios of the same as either an inductor core or an EM noise suppressor. Every magnetic film typically exhibits similar characteristics—high μ' at low frequency and the highest μ'' at f_{FMR}. Magnetic materials are characterized by these three parameters—μ', μ'', and f_{FMR}. Therefore, a given material can be utilized as an EM noise suppressor if the noise frequency is close to the f_{FMR}, whereas the same material can be used as inductor core at a frequency range well below f_{FMR} where the loss component is negligible. In other words, for a given frequency of application, a single material cannot serve both the purposes simultaneously.

Why Ferrites?

Ferromagnetic metal-alloy-based materials are very popular and are being used extensively both as EM noise suppressors and inductor core, especially in the frequency bands below 2 GHz.[7-13] However, owing to their low electrical resistivity, eddy current losses are extremely high in the GHz range. Furthermore, with the ferromagnetic resonance frequency below 5 GHz in most of them, they can neither be used as inductor core nor as EM noise suppressor in the frequency band in between between 5 GHz and ~30 GHz. Ferromagnetic resonance frequency depends on the magnetic anisotropy present in the material and can be expressed as follows, assuming spherical particles:

$$f_{FMR} = \frac{\gamma}{2\pi} H_a$$

where γ is the gyromagnetic constant and H_a is the effective magnetic anisotropy field, which is the sum of magnetocrystalline anisotropy, shape anisotropy, stress anisotropy. Being amorphous in nature, metal-alloy-based ferromagnetic films possess no magnetocrystalline anisotropy, and thus, exhibits very low anisotropy and FMR frequency. As a result, the focus is now on magnetic oxides, such as spinel ferrites, hexaferrites, and garnets as alternative to ferromagnetic metal-alloys to succeed in the above-specified frequency band—in the realm of 5G.[14-17]

Ferrite materials are unique because they belong to the family of insulating oxides that are magnetic—possessing moderate permeability, very high magnetic anisotropy, moderate-to-high permittivity, and low losses up to a few tens of GHz. Spinel ferrites (structural formula: AB_2O_4, such as $NiFe_2O_4$, Fe_3O_4, $Mn_xZn_{1-x}Fe_2O_4$, etc.) and garnets (structural formula: $A_3B_5O_{12}$, such as $Y_3Fe_5O_{12}$, $Y_3Ga_xFe_{5-x}O_{12}$, etc.) have cubic crystal structure with close-packed oxygen lattices, whereas the hexaferrites can exist with several hexagonal close-packed structural variations, such as M, Y, W, X, Z, U, in which the metal and oxygen stoichiometry are different.[14-17] The possibility of innumerable combinations of metal substitution in them allows fine-tuning of their properties as per requirement. However, the real technological challenge is to deposit thin films of such complex oxides on the Si-CMOS chip. Unlike amorphous metal-alloy films, ferrites and garnets should be well-crystallised to exhibit their magnetic characteristics. High-temperature annealing is often necessary to achieve desired crystalline quality.

CMOS Integration of Ferrite Film: Issues and Solutions

Given that magnetic films are typically integrated at the back-end of CMOS fabrication steps, use of processing temperature above 400 °C is untenable, as it makes the whole device fabrication process CMOS-incompatible.[18,19] On the other hand, a low-temperature process often leads to inadequately crystallised ferrite films, resulting in inferior magnetic properties and weak adherence, thus limiting their practical usefulness. Printing/pasting a composite layer of pre-processed ferrite powder in a polymer matrix can certainly be a low-temperature CMOS-compatible process.[20,21] But, the effective permeability of the composite layer can become untenable due to the presence of polymer material. Therefore, the focus should be on a continuous, dense ferrite film to obtain the best result. In a nutshell, the challenge is to obtain on silicon chips, below 400 °C, a well-adhering ferrite film, having the FMR frequency in the range 5 ~ 30 GHz.

Among ferrites, hexaferrites possess high magnetocrystalline anisotropy and thus exhibit FMR at frequencies ranging from a few GHz to several tens of GHz, making them perfectly suited for applications in the desired frequency band. However, the formation of hexagonal ferrites requires annealing above 1000 °C, making them inapt for on-chip integration.[17] Development of a low-temperature hexaferrite deposition method can offer invaluable freedom in choosing appropriate magnetic materials for appropriate applications. Despite having a little lower magnetocrystalline anisotropy than hexaferrites, spinel ferrites can be deposited at a temperature compatible with CMOS processing by various soft-chemical deposition routes, such as spin-spraying,[22-24] microemulsion technique,[25,26] sonochemical method,[27] and microwave solvothermal technique[28-30] to name a few, in addition to physical routes like pulsed laser deposition (PLD)[31] and alternating target laser ablation deposition (ATLAD).[32]

Among low-temperature spinel ferrite deposition processes, the spin spraying technique provides well-crystallized ferrite layers at sub-100 °C.[22-24] However, the formation of ferrite demands sequential spraying of reaction- and oxidizing-solutions, both of which may corrode exposed Cu-wirings of on-chip circuit elements, such as inductors or transmission lines. Furthermore, a substrate pretreatment is advised to achieve required adherence.[24] On the other hand, despite the capability of depositing an epitaxial quality film at low-temperature, methods like pulsed laser deposition (PLD) and alternating target laser ablation deposition (ATLAD) are limited to being valuable research tools because of low deposition rates and small substrate size.[15]

Due to their symmetric cubic crystal structure, spinel ferrites possess moderate magnetocrystalline anisotropies that result in ferromagnetic resonance at frequencies below 10 GHz. Therefore, pushing the f_{FMR} of the spinel ferrites towards 30 GHz has become an added challenge.

Tailoring FMR: A Low-Temperature Non-Equilibrium Approach

The origin of magnetism in ferrites is the exchange energy between spins of neighboring metallic ions that are aligned antiparallel to each other in their lowest energy configuration. As the distance between two metal ions is too large in ferrites to support a direct exchange, unlike in most magnetic metals, the exchange interaction in ferrites is mediated by lattice oxygen which resides between two cations—known as superexchange.[33] The strength of such superexchange depends on three factors—distance, direction, and the superexchange interaction angle. It is, therefore, easy to surmise that substitution of a lattice cation by a foreign cation of different size and electronegativity would alter the crystal symmetry and, consequently, the magnetic characteristics of ferrites.[14,34]

Crystal symmetry can be broken by inducing oxygen vacancies, too. Zuo, et al.,[31] and Yang, et al.,[32] revealed that oxygen partial pressure-mediated far-from-equilibrium distribution of cations in Mn- and Cu-ferrite film systems, deposited by PLD and ATLAD respectively, increases magnetic anisotropy from ~20 Oe to >1000 Oe, thus extending the applicability of spinel ferrites to a higher frequency than is normally associated with them. Now the question is: can we induce a far-from-equilibrium distribution of cation and/or break in crystal symmetry through a soft-chemical method? A rapid synthesis of nanocrystalline ferrite could be the answer.

In this context, microwave-assisted deposition technique (MADT)—a rapid, sub-200 °C, and "far-from-equilibrium" solution-based film deposition method, wherein the precursors decompose and react to form the desired composition under the influence of microwave irradiation—has established itself as an excellent choice for depositing nanocrystalline spinel ferrite films on silicon chips.[35-38] An example of the zinc ferrite thin film deposition process steps along with the description of the microwave reactor is schematically shown in Fig. 3. It is to be noted that the formation of oxide nanocrystals and their characteristics depend largely on the reaction mechanism, which is governed by microwave dielectric heating. Therefore, the choice of precursor material and solvent system is extremely important to attain the desired result. There are some excellent review articles[28-30,39-41] which discuss microwave-assisted synthesis of oxide nanoparticles in great depth.

Furthermore, zinc ferrite nanocrystallites prepared by microwave-assisted synthesis display an unusually high degree of inversion, with ~50% of the lattice zinc atoms out of their equilibrium positions in the crystal structure.[42] Such a high degree of crystallographic inversion can alter the crystal symmetry as well as the spin structure, and may thereby induce a higher anisotropy and an enhanced f_{FMR} as a consequence. Although it is in its infancy, this approach can be an excellent way to modulate ferromagnetic resonance frequency of spinel ferrites via the soft-chemical route.

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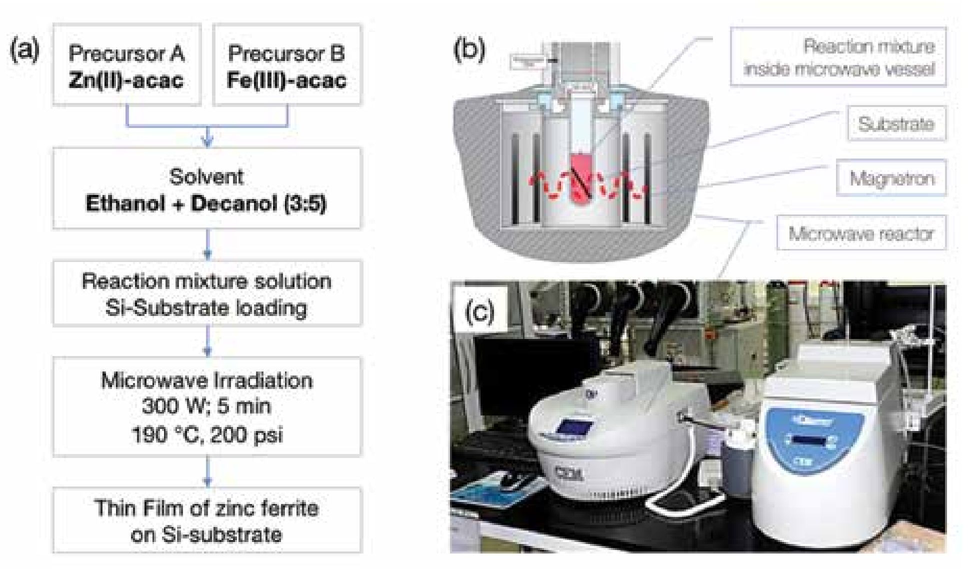

Fig. 3. *(a) Processing steps for zinc ferrite thin film deposition by microwave-assisted deposition technique (MADT); (b) Schematic cross-section view of the microwave-reactor used for MADT; (c) A photograph of that bench-top deposition system.*

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On-Chip Ferrite-Core Inductors and Noise-Suppressors

A recent article described the deposition of a partially inverted zinc ferrite film with excellent soft magnetic characteristics, i.e., saturation magnetization of ~130 emu/cc and coercivity of ~120 Oe directly on a Si-CMOS integrated circuit by MADT.[38] The CMOS compatibility of the deposition process was also demonstrated by comparing the I_D-V_D and I_D-V_G characteristics of a MOSFET before and after exposing it to microwave-assisted processing. In addition to producing a strongly adherent, uniform, and nonporous film, the said deposition technique offers conformal coating on any exposed surface of irregular geometric shape. In a separate article, such a conformal coating on screw-shaped silica-based micro-propellers was demonstrated.[43] A wide variety of thicknesses were obtained, ranging from a few hundred nm to several tens of microns.[44]

The partially inverted zinc ferrite composite thin film, deposited by MADT, showed FMR frequency above 30 GHz, with negligible FMR loss below 15 GHz. Therefore, this film exhibits perfect characteristics to be used as inductor core in the frequency range up to 15 GHz and as an EM noise suppressor around 30 GHz. Up to 20 % enhancement of inductance was reported with a film 1 µm in thickness—making it the best on-chip ferrite-core inductor with the highest inductance density (750 nH/mm^2) at 5 GHz. Furthermore, 13% enhancement in inductance density and 25% enhancement in the quality factor was demonstrated at 10 GHz, staking claim to be the highest-density (450 nH/mm^2) inductor at that frequency.[37,38] The quality factor of these inductors could not be enhanced much by depositing the ferrite film only on top of the inductor coil. Moreover, it is proven theoretically that inductance can be increased only by 100% by depositing a magnetic film on just on one side of the coil.[7] To harness the best effect of magnetic film, a complete magnetic path, i.e., complete encapsulation of the coil is necessary. By utilizing the ability of MADT to deposit ferrite film conformally, three-sides of the on-chip coil are covered by zinc ferrite thin film in a single step. The resulting coil structure is demonstrated both schematically and with SEM images in Fig. 4. An enhancement of Q-factor by 78% is achieved, as shown in Fig. 4e. It is to be noted that the magnetic path is, nevertheless, not closed. A very large increase of inductance and inductance density can be achieved if the coil can be fabricated on a ferrite layer instead of the interlayer dielectric.

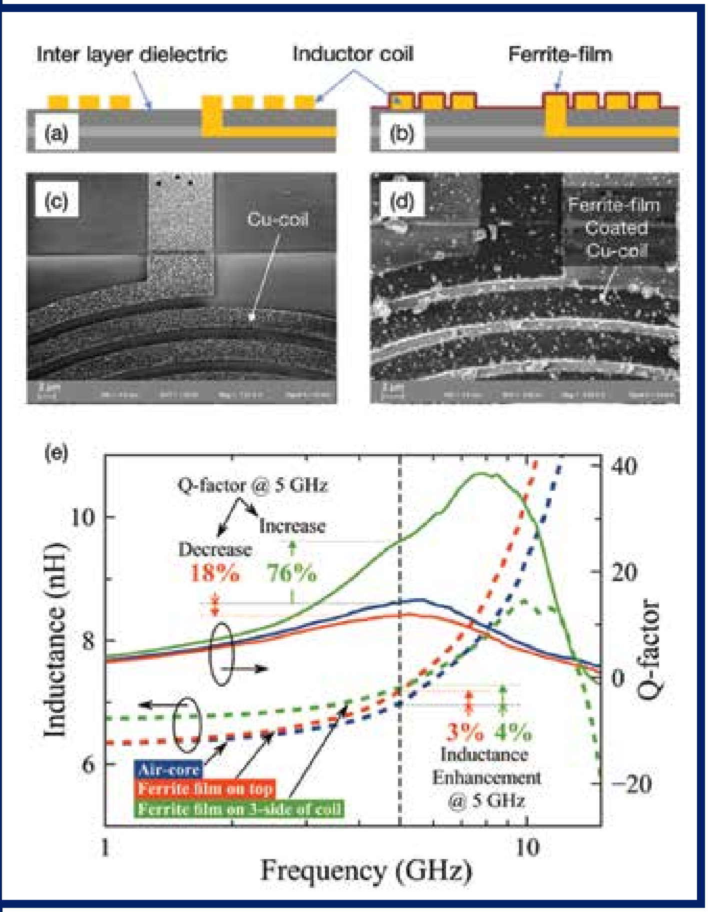

Fig. 4. *Ferrite-coated on-chip inductor and its measurements; schematic drawing of inductor coil on a Si-CMOS chip (a) with passivation removed from 3-sides of the coil, and (b) with zinc ferrite thin (250 nm) film coated conformally; (c) and (d) show the SEM images of the coil before and after ferrite coating; (e) Measured inductance and Q-factor of the on-chip inductance with ferrite film deposited only on top (in red) and surrounding 3-sides of the coil (in green).*

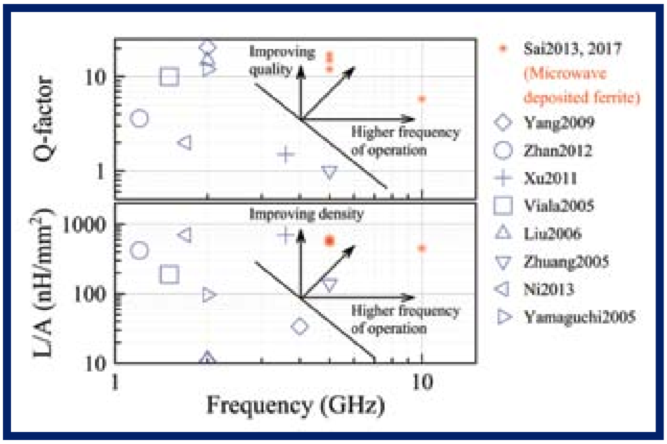

Fig. 5. *State-of-the-art of ferrite-core inductors operating at GHz frequency, highlighting the results with zinc ferrite composite film deposited by MADT.*

There is a serious dearth of on-chip ferrite-core inductors now. Most of the ongoing research is still in the sphere of the research laboratory. There is rapidly growing interest in taking such inductors to the market by the year 2020 to meet the demands of 5G systems. In Fig. 5, the reported ferrite-core inductors are compared with the microwave-deposited ferrite-core on-chip inductors. The superiority of the microwave deposition approach is evident as it forms a bridge between the best of two aspects—high quality coil fabrication by IC technology and positive effect of the ferrite-core.

The electromagnetic noise suppression effectiveness of the ferrite film can be shown by depositing the film on a coplanar waveguide, followed by measuring the power loss ratio in the film.[13] As mentioned before, it has been demonstrated that 400 nm-thick films of partially inverted zinc ferrite exhibit FMR frequency around 30 GHz.[38] Therefore, the film can be suitable for EM noise suppression in the frequency band ~30 GHz. In Fig. 6, the ratio of loss power to input power to an on-chip CPW structure, coated with partially inverted zinc ferrite, is demonstrated. It is found that up to 20% of EM noise power can be dissipated by the ferrite film. This is well below the requirement of the industry at present. However, this has been the first and only demonstration of EM noise suppression at 30 GHz by an on-chip ferrite film.

Closing Remarks and Outlook

The technological shift towards higher frequency for the looming 5G systems brings countless challenges, thus providing boundless opportunities to innovate, so as to meet the demanding specifications of high frequency integrated circuits. Innovation is essential at all levels, from circuit design to device fabrication to system packaging. The role of functional materials, especially magnetic oxides such as ferrites, are going to be the most critical ever for integrated devices. Development of CMOS-compatible low-temperature deposition of ferrite films and the integration of such a deposition method into the

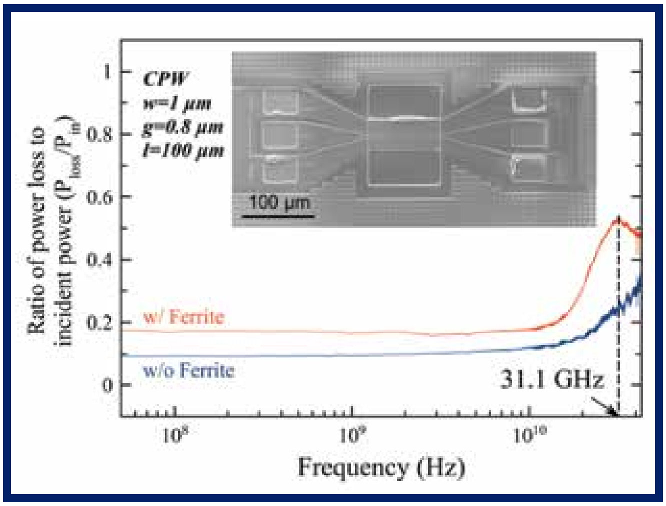

Fig. 6. *Demonstration of EM noise suppression at ~30 GHz, achieved by partially inverted zinc ferrite composite thin film deposited by MADT (Sai, et al., article under review).*

semiconductor processing technology is the immediate necessity. Being the most suitable magnetic material in the frequency bands ranging from a few GHz to several hundreds of GHz, hexagonal ferrites and their stoichiometric derivatives hold the key to the realization of the full potential of high frequency magnetics in the years to come. Therefore, a serious effort is necessary to deposit hexaferrite films in a CMOS-compatible way. Microwave-irradiation-assisted, solution-based, non-equilibrium spinel ferrite deposition technique offers an excellent approach towards CMOS-compatible and scalable ferrite film deposition. However, it is still in its infancy and demands extensive research to attain industry-scale reliability and control over material properties.

Besides nanoferrite film deposition, accurate measurement of magnetic characteristics at several tens of GHz is also extremely challenging. Development of permeability measurement systems with high sensitivity is also imperative. Above all, an interdisciplinary approach combining the wisdom of RF engineers, semiconductor technologists, material scientists, physicist, and chemists together is the way forward.

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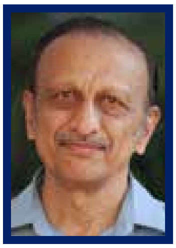

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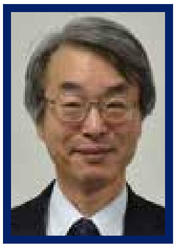

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