CMOS-Compatible and Scalable Deposition of Nanocrystalline Zinc Ferrite Thin Film to Improve Inductance Density of Integrated RF Inductor

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Development towards the combination of miniaturization and improved functionality of RFIC has been stalled due to the lack of high-performance integrated inductors. To meet this challenge, integration of magnetic material with high permeability as well as low conductivity is a must. Ferrite films are excellent candidates for RF devices due to their low cost, high resistivity, and low eddy current losses. Unlike its bulk counterpart, nanocrystalline zinc ferrite, because of partial inversion in the spinel structure, exhibits novel magnetic properties suitable for RF applications. However, most scalable ferrite film deposition processes require either high temperature or expensive equipment or both. We report a novel low temperature $(< 200^{\circ}\mathrm{C})$ solution-based deposition process for obtaining high quality, polycrystalline zinc ferrite thin films (ZFTF) on Si (100) and on CMOS-foundry-fabricated spiral inductor structures, rapidly, using safe solvents and precursors. An enhancement of up to 20% at 5 GHz in the inductance of a fabricated device was achieved due to the deposited ZFTF. Substantial inductance enhancement requires sufficiently thick films and our reported process is capable of depositing smooth, uniform films as thick as $\sim 20\ \mu\mathrm{m}$ just by altering the solution composition. The method is capable of depositing film conformally on a surface with complex geometry. As it requires neither a vacuum system nor any post-deposition processing, the method reported here has a low thermal budget, making it compatible with modern CMOS process flow.

***Index Terms*—CMOS-compatible, deposition, film, RF inductor, zinc ferrite.**

I. Introduction

AN important aspect of the development of RF-CMOS integrated circuits is the design and fabrication of the inductor element through a process that is compatible with modern CMOS fabrication. It is essential to shift from traditional air-core inductor to one with a magnetic-core to enhance the inductance per unit area so as to save significant chip real estate, which could then be utilized to meet the ever-increasing demand for functionality. It is also equally essential to shift from permalloy and other amorphous alloys to ferrites and hexaferrites as the core material because of their very high electrical resistivity so as to keep losses in check, a criterion that cannot be compromised on in GHz frequency applications [1]. This is viable, however, only if the integration of the magnetic core (film), particularly a ferrite film, is fully compatible with the CMOS fabrication process. Various approaches have been taken to meet this requirement, including investigations of employing layers of ferrite materials to envelop the inductor loop [2]–[6]. However, the deposition of thin films of ferrites, whether by PVD or CVD, usually calls for the deposited ferrite layer to be annealed at an elevated temperature to crystallize the layer so that its magnetic characteristics are appropriate for the optimum performance of the circuit element. Such annealing is incompatible with CMOS process flow required for aggressive device geometries, as the inductor element is added after the active semiconductor circuit is processed, and any exposure of the processed circuit to elevated temperatures risks disturbing precise doping profiles employed.

What is called for is a low-temperature process for the deposition of a ferrite layer on top of the patterned inductor element—a layer of thickness such that most of the fringe field is encapsulated—while ensuring that the layer comprises crystallites of uniform size that leads to uniform magnetic behaviour. Recognizing the difficulty of meeting the various stringent requirements, it has recently been remarked that such a goal is impossible to meet [7].

We report here the development of a CMOS-compatible, microwave-assisted chemical reaction process in the solution medium, which allows the deposition of adherent thin film of nanostructured zinc ferrite which, due to partial inversion of the spinel structure, becomes ferrimagnetic. The process has been utilized to fabricate inductors on foundry-fabricated CMOS circuits, demonstrating clearly the enhancement of inductance at gigahertz frequencies, achieved by covering the inductor loop with a ferrite layer deposited by the microwave-assisted process.

II. Experimental

The microwave-assisted zinc ferrite $(\mathrm{ZnFe_2O_4})$ thin film (ZFTF) deposition process involves several process parameters including the choice of reactants and their concentrations, solvents, surfactants, microwave power, and the mode of the applied microwave field. Each of them affects the morphology and thickness of the film. The hallmark of this deposition process is that a substrate immersed in the solution is coated rapidly and uniformly with ZFTF, while a precipitate of ZF is also formed. The process was optimized using Si (100) as substrate. A typical optimized recipe that yields a 500 nm-thick film is described here briefly.

β-diketonate complexes of Fe and Zn, namely, Fe(III)acetylacetonate $(\mathrm{Fe(acac)_3})$ and Zn(II)acetylacetonate $(\mathrm{Zn(acac)_2})$,

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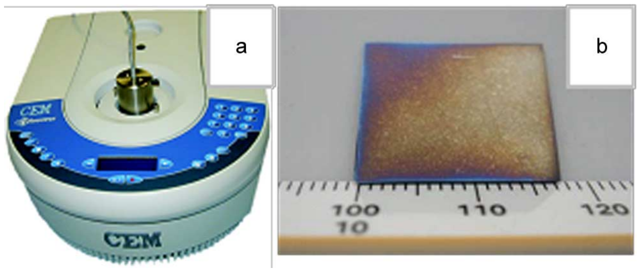

Fig. 1. (a) Single-mode microwave reactor. (b) Optical micrograph of the deposited zinc ferrite film on a Si (100), illustrating uniformity and large area coating capability.

were used in the synthesis. AR-grade ethanol, 1-decanol were utilized as solvents. Solutions of 1 mmol of Zn $(acac)_2$ and 2 mmol of $Fe(acac)_3$ in 40 ml of alcoholic solution (1-decanol:ethanol::5:3) were transferred to the reaction vessel. A p-type Si (100) piece (2 cm $\times$ 2 cm) was cleaned by the RCA cleaning protocol and immersed in the solution in the vessel. This reaction mixture was irradiated in a single-mode microwave reactor (CEM Corp., USA, 2.45 GHz, 300 W), shown in Fig. 1(a), for 10 min, yielding a visibly uniform coating (Fig. 1(b)) on the substrate as well as a small amount of precipitate at the bottom of the vessel. The solid precipitate was separated by centrifugation and recovered, whereas the coated silicon substrate was cleaned by ultrasonication in acetone and ethanol for 5 minutes. The temperature of the reaction mixture was found not to exceed $190^\circ C$ during microwave irradiation.

III. Results and Discussion

The film comprises very small crystallites as observed by the SEM (Fig. 2(b)). The XRD pattern (Fig. 2(a)) of the film is indexable to the zinc ferrite spinel structure (PCPDF No. 82-1049), confirming the formation of phase-pure zinc ferrite. The broad XRD peaks confirm that the oxide is nanocrystalline. X-ray photoelectron spectroscopy (XPS) analysis was performed to identify the presence of Fe^{2+}, a signature of Fe_3O_4, if any, as it is difficult to resolve its XRD and SAED patterns from those of $ZnFe_2O_4$. The presence of principal peak of Fe $2p_{3/2}$ at 711.54 eV and a satellite peak at 719.86 eV, as shown in Fig. 3(a), confirms that *only* Fe^{3+} is present. The distribution of Zn^{2+} in the lattice can be extracted from an analysis of the Zn $2p_{3/2}$ photoelectron peak. XPS of ZFTF prepared by the microwave-assisted deposition technique (MADT) shows a peak at 1022.1 eV (Fig. 3(b)), which can be resolved into two major peaks cantered at 1021.7 eV and 1022.7 eV, with FWHM of 1.3 eV and 1.2 eV, respectively. This is evidence that, in ZFTF, Zn^{2+} occupies both tetrahedral and octahedral sites, leading to a partially inverted spinel structure [8]. Such partial inversion is probably a result of the rapid, far-from-equilibrium nature of the process and the high nucleation density caused by the uniform microwave field acting on the reaction mixture [9]. Thus, it is apparent from XPS analysis that the presence of Fe^{2+} on the surface of ZFTF is improbable. Taken together, XRD and XPS indicate that spinel zinc ferrite prepared by the rapid MADT is partially inverted. This means that the presence of magnetic Fe^{3+} on both the 'A' and 'B' sites of the spinel

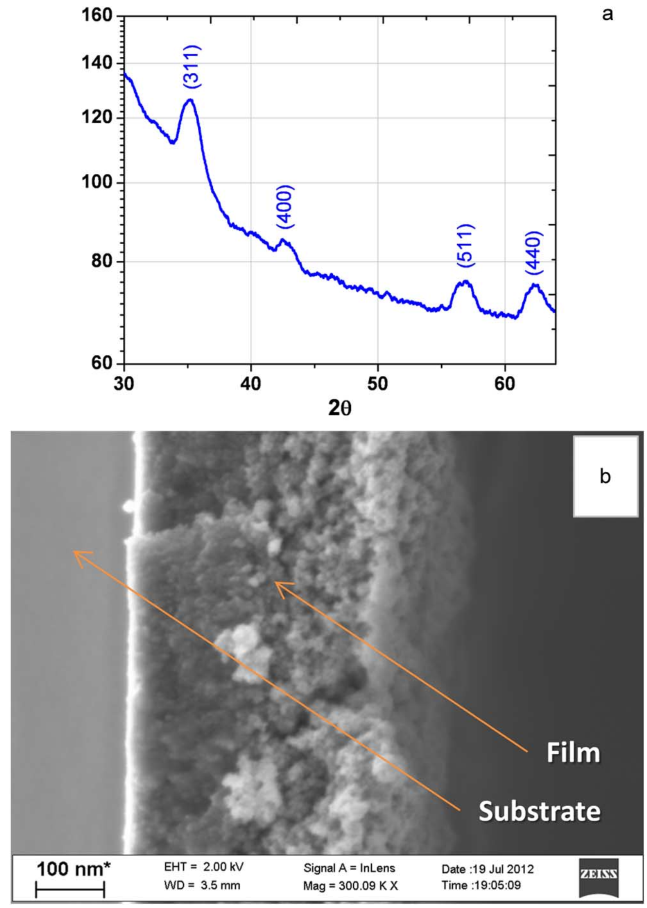

Fig. 2. (a) XRD pattern of the ZFTF. (b) Cross-sectional SEM image of a 400 nm-thick ZFTF, revealing the presence of very small ($<\sim$5 nm) crystallites.

structure enables the strong A-B exchange interaction and a significant magnetic moment [10].

The other features of the microwave-assisted deposition technique are its ability to coat large areas ($\sim 1'' \times 1''$) at a high rate ($\sim 1\ \mu m/min$), with compositional uniformity throughout. In the RF inductor, the magnetic layer must not only be deposited between metal inductor lines but also on the top and side walls of the metal. Thus, a very conformal coating process is required. The MADT appears to provide this, as illustrated by the coverage of the fine features on the unpolished (rough) back side of the Si (100) wafer (Fig. 4). It is seen that the many uneven, but deep, micrometric features are very conformally covered by nanocrystalline ferrite. [As it is immersed in the solution, both sides of a substrate are coated in the MADT.] The SEM images of Fig. 5 show the blanket deposition of semi-transparent ZFTF on an inductor coil. These features make the MADT appropriate for integration of zinc ferrite into the RF inductor structure.

An inductor was designed along with its de-embedding pads and the design was sent to a commercial 130 nm CMOS process foundry for the fabrication of the on-chip inductor. The motivation for opting for a commercial foundry over a home-made device is to avoid the process variability that might interfere with the RF measurement, as well as to test the credibility of the MADT with a real CMOS device. The unpackaged die was tested with single-port network analyzer to obtain their s-parameters before the ZFTF deposition. The unpackaged die was

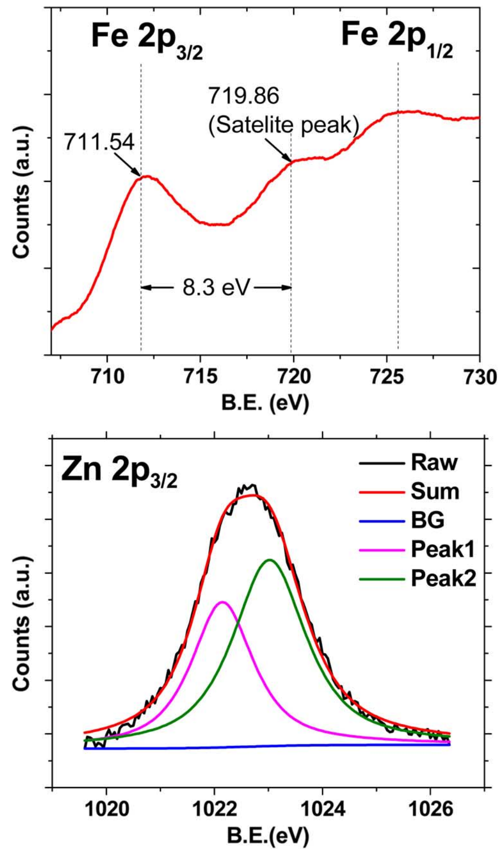

Fig. 3. X-ray photoelectron spectra of (a) Fe 2p and (b) Zn $2p_{3/2}$. In Fe 2p spectra presence of satellite peak confirms the absence of Fe^{2+} and the splitting of Zn $2p_{3/2}$ confirms the partially inverted structure of the ZFTF.

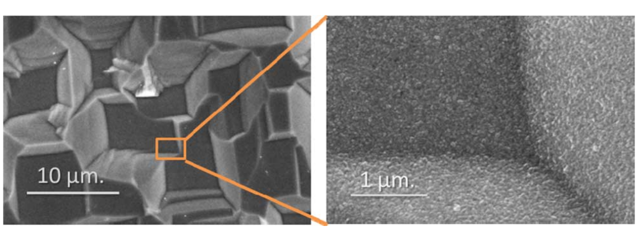

Fig. 4. SEM micrograph of ZFTF the deposited on the back side of the Si (100) substrate, demonstrating the conformal nature of the deposition process.

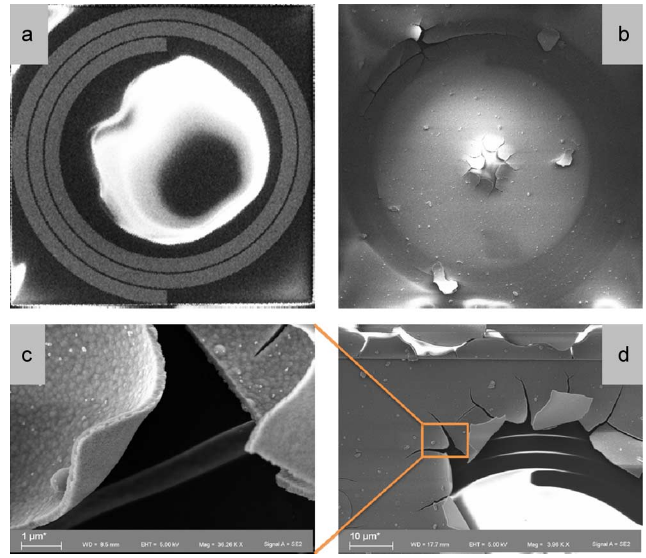

Fig. 5. SEM image of the inductor structure (a) before deposition; (b) after deposition; (c) and (d) demonstrating the morphology and the uniformity of the film deposited on the inductor structure. (The film was deliberately peeled-off for characterization).

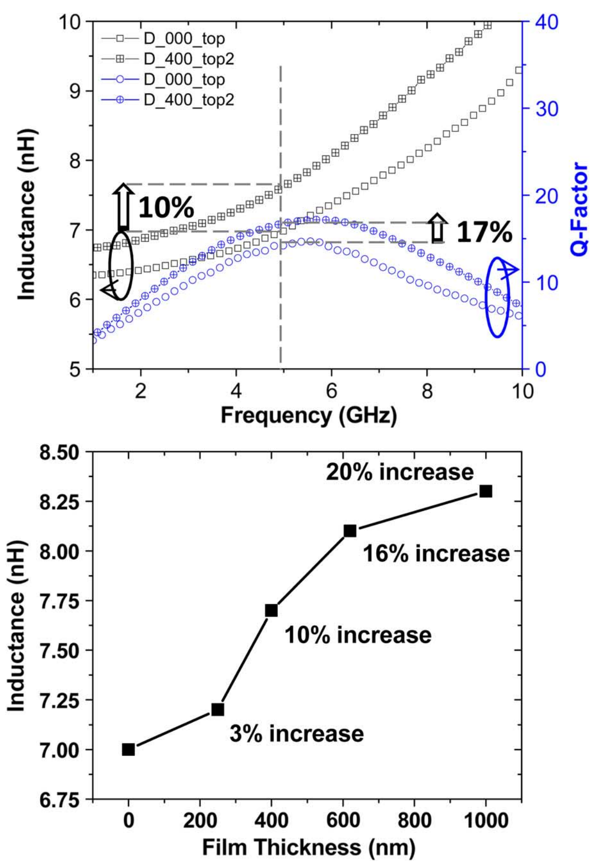

Fig. 6. (top) Frequency-dependent plot of inductance and Q-factor of the on-chip RF spiral inductor with ZFTF of 400 nm deposited on top, yielding a 10% enhancement of inductance at 5 GHz; (bottom) Plot shows the increase of inductance and thus inductance density with various thickness of ZFTF deposited on top of the inductor.

then glued on to a $(1'' \times 1'')$ Si (100) wafer and submerged in the solution and exposed to microwave radiation. Upon the application of 300 W of power, the solution temperature rose to nearly 190°C, and the pressure in the vessel touched ~200 psi. The coated die was characterized again with the network analyzer. The s-parameters obtained were then processed to extract the inductance value. An enhancement of the inductance by up to 20%, at 5 GHz, is observed by just depositing ZFTF of different thicknesses on the top of the inductor, as shown in Fig. 6. The quality factor (Q-factor) of the inductor is also found enhanced. It is evident that the thickness of the film has significant impact on the enhancement of inductance, which in turn improves inductance density. Inductance per unit area is enhanced by 20% to 680 nH/mm^2, which is among the highest reported to date [11]. The ferromagnetic resonance frequency (f_{FMR}) is greater than 10 GHz, though it decreases slightly because of the eddy current loss related to the complex permeability of the magnetic thin film and due to inverse proportionality of f_{FMR} to the inductance. Through encapsulation of the inductor coil both at the top and the bottom, a much higher (up to a factor of $\mu_{\rm r}$) enhancement of inductance can be achieved [12].

The choice of stable, reactive, and safely-handled metal-organic precursors and common alcohols as solvents was made judiciously, in order to provide a process that is convenient and CMOS-compatible. Furthermore, not only is the processing temperature low $(< 200^{\circ}{\rm C})$, but the resulting ZFTF requires no post-deposition annealing either, making it a very low thermal budget process. As such, a scaled-up MADT can be incorporated into the CMOS process flow easily.

IV. Conclusion

Inductors for RF-CMOS require a magnetic core material with high real permeability $(\mu_{\rm r}')$ and low complex permeability $(\mu_{\rm r}'')$ to be integrated onto it in a CMOS-compatible manner. Ferrites are considered the fittest materials in this context. In this effort, a novel, CMOS-compatible microwave-assisted deposition technique has been developed, which enables the deposition of nanostructured zinc ferrite thin films. Partial inversion in the spinel structure makes the ferrite magnetic, enhancing inductance of an on-chip inductor up to 20% which, in turn, also enhances the inductance per unit area by 20%. The technique can be extended to other ferrites, whose properties can be tailored by "tuning" the deposition parameters.

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