Invited paper

GHz magnetic film inductors

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Abstract

Use of magnetic films for miniaturization of planar inductors operating at ultra-high frequencies is reviewed. Materials and design aspects determining the efficiency of the devices are analyzed. Mechanisms involved in magnetic dissipation and their role in limiting the device operation frequency range and quality factor are discussed. Typical inductor geometries are considered. A magnetically sandwiched strip inductor is argued to hold a promise for GHz applications. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

An increasing demand for small-size/light-weight communication products has been motivating research on monolithic integration of radio components and systems, such as GHz-range transceivers. The fundamental electronic component least compatible with silicon integration is the inductor, which is required for implementation of filters, oscillators and matching networks. The dominating integrated inductor design is an air-core spiral. Due to a parasitic coupling with the conductive silicon integrated spirals perform poorly, with quality factors $Q \approx 3$ being usual. The planar spiral geometry is far from being solenoidal and the inductance does not scale efficiently with the number of turns. That is why typical spirals consume large amounts of chip area compared to other on-chip components. Use of magnetic films as flux-amplifying components yields smaller inductors. Designs exist with most of the flux contained within the magnetic films, which reduces unwanted losses in the silicon.

After summarizing the current state of research in the field in the next section, we discuss the materials and design issues involved in developing efficient magnetic film inductors. We then continue with analyzing a specific implementation, a magnetically sandwiched strip inductor, giving extra attention to magnetic dissipation in the structure.

2. Background

The first attempts at fabrication of magnetic thin-film inductors date back at least 30 yr. Saleh and Qureshi [1] discuss a square spiral deposited on glass, in which the conductor turns are sandwiched between two Permalloy films, $\sim 0.3 \mu m$ thick. The inductor was optimized for operation at 10 MHz and showed a quality factor $Q \approx 18$ with a $\sim 15\%$ inductance enhancement over the free-space value. Although the demonstrated gain in the specific inductance was not very convincing, the presented magnetic analysis, the use of the fast transverse permeability (excitation field along the hard axis), as well as the segmentation of the magnetic film to avoid displacement currents due to the distributed conductor-to-film capacitance, are still very relevant for high-frequency magnetic inductor design. Soohoo [2] brought the subject of integrated inductors to the attention of the magnetism community. He gave a basic magnetic analysis for a magnetically sandwiched spiral and a magnetic film core solenoid. He also presented a prototype inductor with copper film windings 'wrapped' around a Permalloy film/glass(Si) substrate, which showed a $\sim 700$-fold increment in inductance.
enhancement in the specific inductance (no $Q$ or frequency range provided).

Over the last 10–15 yr there have been a number of efforts to fabricate an efficient IC-compatible magnetic inductor and extend its operating frequency range from 1–10 MHz to 100–1000 MHz. Without giving a complete literature survey we will briefly discuss the results that we believe are representative of the current status in the field. Shirae and co-workers have implemented a number of structures, starting with planar coils imbeded in SiO and sandwiched between two Permalloy films [3]. This design did not yield an efficient inductor ($Q \sim 1$) and the resonances at a few tens of MHz were attributed to the distributed coil/SiO/film capacitance in the structure. Going from magnetically sandwiched planar coils to magnetically sandwiched conductor strips (Py/Cu/Py tri-layers) patterned into planar coils was found to improve the high-frequency characteristics of the devices: $Q \gg 3$ at $\sim 100$ MHz. The gain in the specific inductance due to the magnetic cladding was however ‘too small’ [4]. In this regard the importance of flux closures at the edges of the conductor (which we call below ‘flanges’) was pointed out [5]. A gain in inductance up to a factor of 4 with $Q \approx 2$–3 at $\sim 100$ MHz was obtained by Yamaguchi et al. [6,7] for Permalloy-coated conductor strips, with and without magnetic closures at the edges, formed into meanders and spirals. Korenivski and van Dover [8] have studied Cu strips sandwiched with Permalloy and Co–Nb–Zr, with and without flanges at the edges. Up to 7-fold inductance enhancements over the air-core value (100 nH/cm linear inductance density) with $Q \leq 2$ at $f \leq 250$ MHz were observed for 10–50 µm strips. Another geometry, a solenoid, was studied by Shirakawa and co-workers, who have demonstrated $\sim$ 10-fold inductance gains with $Q = 10$–15 at $f = 10$–100 MHz for planar solenoids with laminated amorphous magnetic cores [9,10]. Two recent papers discuss the use of Fe–Ta–N and high resistance Fe–Al–O in planar inductors. The design, however, was chosen such that in one case the frequency range was limited to about 20 MHz [11] and in the other the gain in inductance was only 8.6% [12].

The most common approach to model magnetic film inductors is to use equivalent magnetic circuits. In this the inductance is obtained from the DC reluctance of the magnetic circuit, and the frequency dependence comes from assuming the same permeability as that of a magnetic film with eddy currents in a uniform in-plane AC field (see e.g. Ref. [13]). Such approach (with some modifications, see Section 5) can be appropriate for certain geometries, however it can be quite inadequate for others, especially those with air gaps since it neglects flux leakage and fringing. A more robust approach is the so-called transmission-line models, which were first introduced for recording heads [14,15] and later extended to generic inductor designs [8,16,17]. Here Maxwell’s equations are solved for the structure under consideration, which permits a consistent treatment of air gaps. The model for magnetically coated strips has been extended to explicitly take into account eddy currents in the films [18,19]. Another approach, using current images, was employed by Roshen to analyze planar circular spirals on or sandwiched in magnetic (insulating and having isotropic permeability) films [20]. This technique, however, is not straightforward to apply to other inductor geometries.

We would like to briefly mention a related application area, inductors and transformers for power circuits typically used at 1–10 MHz. Extensive literature exists on magnetic reluctance and eddy current analysis for soft magnetic alloy and ferrite core devices (see e.g. Refs. [21,22] and references therein). However, differing design requirements for GHz applications, such as issues related to ferro-magnetic resonance (FMR) in films and severe complications caused by capacitive couplings in structures with insulations, prevent one from directly transferring the existing techniques to the design of GHz inductors.

3. Materials

3.1. Material requirements

There are two basic requirements to magnetic materials for use in inductors: large lossless permeability in the operating frequency range, and process compatibility with integrated designs. The first requirement can be subdivided into the following items:

- high saturation magnetization. This is a precondition for high permeability. Most, if not all, of the designs are expected to employ the transverse (hard axis) permeability in films of uniaxial anisotropy, which is directly proportional to $M_s$: $\mu \approx 4\pi M_s/H_k$, $H_k$ is the anisotropy field;
- controllable anisotropy, probably in the range $H_k = 10$–50 Oe. For higher $H_k$ the permeability is reduced (see above). For lower $H_k$ the FMR frequency is too low for use at UHF: $f_{FMR} \approx \gamma \sqrt{4\pi M_s H_k}$, $\gamma$ is the gyromagnetic ratio. At FMR the permeability is mostly imaginary, which would make an inductor into a resistor;
- small FMR linewidth. This is commonly defined as the half-width at half-maximum in the bell-shaped imaginary part of the permeability. In a system without dissipation the line is infinitely narrow. In a real system it can be rather broad due to various dissipation processes, such as spin–lattice relaxation, non-uniform magnetization modes (spin-waves), eddy currents;
- high resistivity. Eddy currents is one of the many dissipation channels. However, in widely used soft
magnetic alloys screening often dominates as a magnetic loss mechanism;

- single domain state, for low magnetic loss as well as for reproducibility. Variations in inductance caused by changes in the domain pattern of the (soft) films will most likely be unacceptable in a commercial product;
- low magnetostriction is preferable, since the fabrication process may result in stress in the films leading to stress-induced anisotropy, limiting the permeability.

The highest impact for integrated inductors is seen in scaling down CMOS or BiCMOS RF ICs. Process compatibility in this respect would mean the ability to fabricate the material on various ‘imperfect’ substrates (polycrystalline or amorphous insulation or metallization layers, SiO, Al, etc.), and a restricted process temperature required for other on-chip components, preferably room temperature.

3.2. Integrated ferrites

Ferrites and other oxides are attractive for one reason, their high resistivity. Other properties of ferrites are disadvantageous compared with those of soft magnetic alloys. The saturation magnetization is a factor of 5 lower. Generally, the anisotropy in oxides is much more sensitive to growth conditions and is harder to control. The simple and robust method of growing soft uniaxial alloy films in a biasing field is not available with ferrites. Epitaxial garnets are known to have the smallest FMR linewidths among the magnetic materials. However, their low saturation magnetization (10 times lower than that in alloys) and especially the need for single-crystalline lattice-matched substrates, disfavors garnets for use in integrated inductors. Polycrystalline ferrite films prepared at relatively low temperature have relatively large FMR linewidths. Exchange biasing of ferrite films for achieving a single-domain remnant state, though has been demonstrated, is less straightforward than with alloy films. It should be emphasized once again that the high resistivity of ferrites is a big advantage, and this alone warrants research on integrating ferrite films into Si-based IC technology.

A common method to prepare ferrite cores for power inductors and transformers is to use a pre-fabricated ferrite powder, mix it with a polymer by ball mill rotation, spin cast or screen print it on a substrate, and finally cure the resulting paste at a few hundred °C [23] up to 800°C [24]. Typical permeability obtained by this method $\mu = 20–30$, sustainable up to $\sim 10$ MHz [23].

NiZn-ferrite films produced on glass substrates by a low-temperature ($T < 100°C$) plating technique, having $4\pi M_s \approx 6$ kG and a large anisotropy perpendicular to the plane, for use in microwave non-reciprocal devices have been reported [25]. This technique is very promising and it would be interesting to see if the method can be used to produce ferrite films with properties required in a GHz inductor (see Section 3.1).

Sputtering and pulsed laser deposition have been used to fabricate ferrite films. Typically sputtered as-deposited films are highly disordered or amorphous [26], and exhibit poor magnetic properties, even spin-glass behavior [27]. The films often require a post-deposition annealing at up to 1000°C. Pulsed laser deposition of high-quality (Mn, Zn)Fe-ferrite films, having bulk magnetic properties, was achieved at 400–600°C by a careful selection of buffer layers [28]. Also exchange biasing has been demonstrated in ferrite bilayers [29].

We have mentioned only a few characteristic examples from the large amount of research done on fabrication of ferrite films. It will be interesting to follow the developments in this area. At present, however, there appears to be no readily available techniques for fabrication of ferrites having the desired properties for use in GHz inductors and compatible with the Si IC-based processes. In this respect the situation is quite different with soft magnetic alloys.

3.3. Soft magnetic metal-alloy films

Soft magnetic alloy films can be prepared by a variety of deposition techniques practically on any surface in various multilayer configurations at low/room temperature. Permalloy as the core material has dominated the field of planar inductive devices for decades. Its relatively low saturation magnetization (\( \sim 10 \) kG) and resistivity (20–40 $\mu$Ω cm), however, often make the material too lossy to be used at above $\sim 100$ MHz. Recent success in fabrication of a number of alloy systems with high $M_s$ (15–20 kG) and high resistivity (in excess of 100 $\mu$Ω cm) gives a large choice to a designer of UHF inductors. Polycrystalline nitrides (e.g., Fe–N and its derivatives [30,31]), amorphous alloys (FeBSi, CoNbZr, etc.), granular oxygen/nitrogen containing films (such as reactivly sputtered Fe(Co)AlO(N) [32] are all well suited for use at $\sim 0.1–1$ GHz, and in fact have already been tested in planar inductors [10–12]. Taking note of the fact that process-compatible materials with desirable magnetic properties are available, in what follows we concentrate on discussing the design issues for inductors based on soft magnetic metal-alloy films, rather than ferrites, the issues that are important for producing a magnetic film inductor attractive enough to challenge the square spiral in RF ICs.

4. Design

A thorough analysis of all possible inductor designs is beyond the scope of this paper. For details the reader is referred to the literature cited in Section 2. Here, we list and briefly argue the advantages and disadvantages, in
author’s view, with the common inductor designs for the GHz range. One of the designs is then discussed in some detail in the following section.

4.1. Sandwiched spiral/meander

As mentioned in Section 2, there have been numerous attempts to produce an efficient inductor, which would have a noticeable inductance gain over the air-core value and operate close to 1 GHz, by sandwiching planar coils with magnetic films. The main advantage of this geometry is:

- a well-developed integrated fabrication process exists.

The main disadvantages are:

- the spiral is a compromise between the need for a planar layout and a solenoid, hence not very efficient magnetically. It is more efficient than the meander (having negative mutual inductance between neighboring conductor strips), though, and often justifies adding an extra metallization level;
- insulation is required when coils are sandwiched between conductive magnetic films. This introduces a distributed coil-to-film capacitance, which is strongly geometry dependent and is recognized to be a limitation for operation at ~ 1 GHz;
- the above sandwich magnetic structure contains relatively large air gaps, which is undesirable from the basic magnetic circuit analysis point of view;
- use of the ‘fast’ hard-axis (rotational) permeability and not the easy-axis (switching) permeability is much preferred. In this regard biasing the magnetic films sandwiching the spiral is not straightforward since the field of, say, a square spiral is bi-axial. A solution to magnetically cover one-half of the coil [1] is available, though at the expense of reducing the magnetic volume by ~ 50%.
- planar coils produce large out-of-plane fields, which in turn produce in-plane eddy currents in magnetic films. In-plane patterning of films can be a remedy, though of questionable efficiency, since at ~ 1 GHz the scale for segmentation may be small enough to cause magnetostatic problems.

4.2. Planar solenoid

A planar solenoid can be formed by plating/patterning the lower conductor layer, covering it with polyimide or SiO, depositing the magnetic core of desired geometry with another layer of polyimide/SiO, arranging for metal via contacts and finally plating/patterning the top conductor layer. The advantages with this geometry are:

- biasing the magnetic core is straightforward;
- most of the field produced by the solenoid is in the plane of the core, so eddy currents can be controlled by varying the thickness of the core (lamination if necessary).

The disadvantages are:

- large distributed capacitance in the structure;
- relatively complex structure with multiple via contacts, which may add up to a high resistance of the coil and lead to low Q. It is important to note that the inductors used at ~ 1 GHz are often of only several nH, the value that can be realized with a magnetic core solenoid having a single turn. Such single-turn solenoid can then rightfully be called a sandwich strip inductor.

4.3. Sandwich strip

A sandwich strip inductor is a thin film multilayer having a conductor strip, typically made of Al or Cu, 0.1–1 µm thick, 10–50 µm wide and ~ 1 mm long, sandwiched between two magnetic films, with optional insulation layers between the conductor and the magnetic films. In addition, flux closure can be achieved by incorporating magnetic flanges at the edges of the strip, flux-linking the magnetic films. Two common sandwich strip geometries, with and without flanges, are depicted in Fig. 2 of Ref. [8]. A short narrow strip, having a 5–10 fold inductance enhancement over the air-core value, can substitute a typical RF spiral, thus releasing a lot of real estate. If needed, longer strips can assume a spiral or a meander layout to achieve large inductances. The structure has the following advantages:

- simple in fabrication;
- biasing the magnetic films is straightforward;
- the field is concentrated in the magnetic films. The external field is in the plane of the substrate, therefore, a reduced dissipation in Si is expected;
- the field produced by a strip in the magnetic films is mostly in plane, so eddy currents can be controlled by varying the thickness of the films;
- no insulation is required, since the difference in the conductivity between Al(Cu) and currently available high-resistivity soft alloys is ~ 10². This eliminates the unwanted capacitance.

Disadvantages:

- flanges are desirable for magnetic efficiency. Incorporating flanges adds additional fabrication steps and is typically done by making the top magnetic film somewhat wider to cover the conductor strip. The process can result in some additional stress in the magnetic film at the edges and, hence, anisotropy. This problem, however, is routinely dealt with in making, for example, writing heads in magnetic recording.
5. Sandwich strip inductors based on soft magnetic alloy films

5.1. DC magnetic analysis

The simplest to implement is a magnetic/conductor/magnetic sandwich inductor, in which the layers are grown on top of one another and all have the same width. This design does not require any additional lithography steps compared to a bare conductor strip, which is extremely attractive from the fabrication point of view. Magnetic efficiency, however, is compromised, since the absence of flux closure at the edges of the strip limits the maximum achievable inductance. It is interesting to note that, despite the apparent simplicity of this inductor design, typically a good knowledge of the materials parameters involved, and the many attempts to implement it, we still do not know (cannot predict) its limits as related to the inductance gain, $Q$ and frequency range, even for a stand-alone lumped element without interference from the substrate or other on-chip components. One of the reasons is the lacking attention to the basic magnetic circuit analysis.

Let us assume for the moment that the frequency is sufficiently low and the resistivity of the magnetic layers is sufficiently large so the current is contained within the conductor. The field produced by a strip conductor is along the width of the magnetic films. It is then tempting to take the magnetic reluctance of the structure as being a sum of the reluctances of the magnetic films and some (often arbitrarily chosen) air reluctances at the edges, as though there were present magnetic shorts made of air [3,13]. This approach neglects entirely flux leakage through the conductor, and, in fact, can be in error by an order of magnitude. Solving Maxwell’s equations for this sandwich geometry [8] shows that the fringing flux is negligible (infinite flange reluctance), the in-plane flux decays toward the edge over a characteristic length

$$\lambda = \sqrt{\frac{\mu_m t_m c}{2}},$$

where $t_m, t_c$ are the thickness of the magnetic film and conductor. The leakage flux (perpendicular to the plane of the conductor) increases toward the edge.

The inductance due to the magnetic films as a function of the inductor parameters is

$$L = \frac{\mu_m l}{2w} \left(1 - \frac{2\lambda}{w} \tanh \frac{w}{2\lambda}\right).$$

(1)

where $w$ and $l$ are the width and length of the strip, $\mu = \mu_0 \mu_r$. This function peaks for a specific combination of the parameters. For example, it has a maximum at a certain width with other values fixed. This maximum, i.e., the potential inductance gain, is easy to miss if approximate equivalent circuit models are used.

The structure with flanges is much more straightforward to analyze, since the reluctance of the flange is small compared to that of air and flux leakage is negligible. Eq. (1) reduces to

$$L = \frac{\mu_m l}{2w},$$

(2)

which is also the inverse of the reluctance of the two magnetic films in series. This is true, however, as long as the permeability of the flange is high enough. If the fabrication results in a reduced permeability of the flanges (due to, for example, high stress at the height gradients), then again one may have to properly treat leakage of flux across the conductor.

5.2. Eddy currents

The above DC magnetic analysis gives the upper limit for the inductance, neglecting various sources of magnetic loss encountered at high frequencies. Losses due to eddy currents often dominate the overall magnetic loss in metallic magnets. These can be taken into account in a rather simple way (neglecting the external flux), at least for the flanged structure, by using in the expression for the DC inductance (say Eq. (2)), the permeability of a magnetic film with eddy currents subjected to a uniform AC field [13]. Two problems arise, however. If the driving current is confined to the conductor, i.e., there is no contact between the conductor and magnetic films, then the excitation is ‘one-sided’ as opposed to uniform, and an appropriate correction to the penetration depth has to be made. This alters the impedance significantly. Secondly, for structures without insulation the current distribution over the cross section changes continuously with frequency. At a sufficiently high frequency the current will flow in a thin screening layer at the outer magnetic surface, and not in the conductor, as the simple model must assume. These effects can be taken into account explicitly by solving (analytically) a time-dependent electromagnetic model [18,19], including a consistent treatment of the external flux. The model shows that the structure without insulation is to be preferred, and that the maximum efficiency is achieved in the regime of partial screening. Up to 10-fold inductance gains at $\sim 1$ GHz with $Q \sim 10$ can be predicted.

The problem of a sandwich without flanges with eddy currents (with an explicit time dependence) has not been solved up to date. Due to the flux leakage the problem is inherently two dimensional, as opposed to that for the flanged sandwich where a reduction to 1-D is adequate. Analysis of the external flux, which can constitute an appreciable portion of the total flux and therefore has to be treated accurately, is not trivial in this 2-D geometry. Crowding of the leakage field (out-of-plane) at the edges of the strip is expected to induce large in-the-plane eddy currents in the conductor, which may in fact be the main factor degrading the frequency response of the device. This is in contrast to the flanged layout where screening
of the in-plane field in the magnetic films limits the frequency range of the inductor.

5.3. Spin dynamics and relaxation

Eddy currents is one of the many dissipation mechanisms found in magnetic materials, by which the excitation is eventually transferred into heat. Another known loss factor is the so-called FMR loss, already mentioned in Section 3.1, which is due to spin motion specific to ordered magnetic media. This can be roughly divided into direct relaxation to the lattice and indirect relaxation via excitation of non-uniform magnetization modes (spin waves) [33]. Needless to say that the response of the spin system and screening by eddy currents in a conducting ferromagnetic film are always coupled. The treatment presented in Section 5.2 is an approximation, which only would cover the frequency range well below the FMR. To obtain this limit a high anisotropy would be required (to push the FMR frequency well above the operating frequency), with the result of a proportionally reduced permeability. In reality devices will likely operate in a partial screening/FMR regime, as that is where the efficiency is maximum (inductive reactance and Q are proportional to the permeability and frequency). Modeling such devices requires a coherent treatment of spin dynamics and relaxation.

Almeida and Mills [34] have examined the influence of the finite conductivity on spin waves (of which the uniform mode, FMR, is the lowest lying mode) in metallic ferromagnetic films. Spin precession was found to induce eddy currents which damp the spin waves and renormalize their dispersion law. The theory was extended to magnetic sandwiches [35]. Two branches in the magnetostatic spin-wave (MSW) spectrum were found. The finite conductivity of the magnetic layers significantly affects the dispersion law for these branches, mostly contributing to the imaginary part of the MSW frequencies (dissipation). ‘Intrinsic’ damping is usually treated phenomenologically through the introduction of a relaxation time (damping constant), which can have components related to, e.g., magnetoelastic [33] or magnon scattering [36].

6. Prospects

An efficient magnetic film inductor with an appreciable inductance gain over the air-core value, operating at ~1 GHz is yet to be developed. In this respect a magnetic/conductor/magnetic sandwich is argued to be promising. In order to be used in electronic circuits, magnetic inductors have to be accompanied by a reliable receipt for computing their impedance, $Z(\omega)$, as a function of the physical parameters of the inductor. This work is still in progress even for a relatively simple structure of a magnetic sandwich. The advances will have to come from a better understanding of dissipation in layered magnetic systems [37].

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