Integrated High Frequency RF Inductors with Nano/micro Patterned Ferromagnetic Cores

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ABSTRACT

Integrated solenoid inductors with high operating frequency and low loss have been demonstrated by using nano-/micro- size granular Ni_{80}Fe_{20} cores. The Ni_{80}Fe_{20} films were deposited by electroplating on three types of seed layer, Cr, Ti, and Ti covered by TiN under a magnetic field ~ 80 mT to align the magnetization. The Ni_{80}Fe_{20} film on Ti seed layer exhibits a large amount mostly disconnected islands with maximum diameter < 1.6 µm. By using the granular Ni_{80}Fe_{20} layer as the magnetic core, the inductors show high operating frequency >6.5 GHz and high cut-off frequency >20 GHz. Systematically optimizing the device’s geometrical parameters, a high inductance per area >0.20 µH/mm², and a high quality factor >4.5 have been reached.

Keywords: RF, ferromagnetic, micro-patterning, inductor, integration

1 INTRODUCTION

 Developing high performance and small volume of on-chip inductive RF/microwave components like inductors is crucial for the cost-effective RF/BiCMOS and RF/CMOS technologies [1]. Considerable efforts are underway to develop on-chip inductors with ferromagnetic (FM) cores having a high inductance per area (IPA) with a sufficiently high maximum quality factor (Q_{max}), a high operating frequency (f_{Q_{max}}) (where the quality factor Q reaches its maximum), and a high cut-off frequency (f_{cut-off}) that is related to the ferromagnetic resonance (FMR) frequency [2]-[4]. However, the FM core’s high conductivity deteriorates the device performance at RF/Microwave frequencies manifested by the low Q_{max}, f_{Q_{max}}, and f_{cut-off}, even the principal superior solenoid-type inductors have been exploited [4]. Reduction of the effective FM film conductivity and thus of eddy currents, while maintaining a sufficiently high permeability and FMR, can be achieved by nano/micro-size patterning of the FM film. Recently, nano-granular FM films with low conductivity δ<10^5 S/m has been reported by using multiple-target sputtering techniques [5]. In IC processing, however, a more cost-effective deposition method is more preferable.

Fig.1 Plain view photograph (a), and cross-sectional sketch (b) of a 4-turn Ni_{80}Fe_{20}-core solenoid inductor. “In” and “Out” in (b) denote the direction towards inside and outside of the plane, respectively. Ni_{80}Fe_{20} films (thickness indicated above) have been deposited by means of electroplating on three different kinds of seed layer, i.e. α—seed: 100nm Ti, β—seed: 100nm Ti covered by 10 nm TiN, γ—seed 100 nm Cr.

In this paper, we present a novel low-cost method to obtain nano/micro structured Ni_{80}Fe_{20} film by electroplating in combination with an optimized seed layer. A series of on-chip solenoid inductors with Ni_{80}Fe_{20} films on three types of seed layer were fabricated and compared. By optimizing the design of the devices, high f_{Q_{max}} (>6.5 GHz), and high f_{cut-off} (>20 GHz) have been obtained on inductors with the granular Ni_{80}Fe_{20} core.

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The process of integrated solenoid inductors with Ni80Fe20 core has been described in [4]. Fig. 1 shows a 4-turn solenoid inductor, as an example. Three types of seed layer 100 nm Ti (D-seed), 100 nm Ti/10 nm TiN (E-seed), and 100 nm Cr (J-seed) have been deposited by magnetron DC sputtering. The core Ni80Fe20 films with thickness of 1.0 μm (D-core), 0.4 μm (E-core), and 0.5 μm (J-core) have been deposited by electroplating on D-seed, E-seed and J-seed, respectively. DC magnetic field ~ 80 mT has been applied during the electroplating to align the magnetization along the y-axis. The D-core with Ti-seed exhibits a nano/micro pattern of mostly disconnected NiFe grains with a maximum diameter of D ~ 1.6 μm (Fig. 2(a); α-seed). The β-core (Fig. 2(a); β-core) and γ-core (Fig. 2(a); γ-core) are homogeneously continuous films. The β-core, however, shows a much rough surface than the γ-core.

Fig. 2 Micrograph of surface morphology of electroplated Ni80Fe20 films on the three kinds of seed layer described in Fig. 1: (a) α-seed, (b) β-seed, (c) γ-seed. Mostly isolated grains with the maximum diameter less than 1.6 μm have been achieved with the α-seed by properly optimizing the seed layer and its deposition condition, together with the plating condition of Ni80Fe20 film.

Fig. 3 Comparison of normalized inductance versus frequency of 20-turn 1000×500 μm² solenoid coils with the three magnetic cores. The decay of inductance results from the limits by the FMR, the eddy current loss, and the LC-resonance. The #α1 exhibits the highest drop-off frequency.

2 FABRICATION

The process of integrated solenoid inductors with Ni80Fe20 core has been described in [4]. Fig. 1 shows a 4-turn solenoid inductor, as an example. Three types of seed layer 100 nm Ti (α-seed), 100 nm Ti/10 nm TiN (β-seed), and 100 nm Cr (γ-seed) have been deposited by magnetron DC sputtering. The core Ni80Fe20 films with thickness of 1.0 μm (α-core), 0.4 μm (β-core), and 0.5 μm (γ-core) have been deposited by electroplating on α-seed, β-seed and γ-seed, respectively. DC magnetic field ~ 80 mT has been applied during the electroplating to align the magnetization along the γ-axis. The α-core with Ti-seed exhibits a

3 RESULTS AND DISCUSSIONS

Table I: Geometrical structure parameters of solenoid inductors with Ni80Fe20 core. Here $L_{FM}$ and $W_{FM}$ denote the width of the Ni80Fe20 core (Fig. 1). $W_{L}$ and $S_{L}$ denote the line width and spacing of the coil. $W_{S}$ and $n$ are the spacing between the FM-core and the via connections, and the number of turns, respectively. Core denotes the type of core: α - 1.0 μm Ni80Fe20/100 nm Ti, β - 0.4 μm Ni80Fe20/100 nm Ti/10 nm TiN, γ - 0.5 μm Ni80Fe20/100 nm Cr.

<table>
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<th>Core</th>
<th>$W_{FM}$ (μm)</th>
<th>$L_{FM}$ (μm)</th>
<th>$W_{L}$ (μm)</th>
<th>$S_{L}$ (μm)</th>
<th>$W_{S}$ (μm)</th>
<th>$n$</th>
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<th>1000</th>
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<th>30</th>
<th>10</th>
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relates to the ferromagnetic resonance frequency (FMR), and the eddy current flowing in the magnetic core at radio frequency. Below the FMR, the real part of permeability is positive and the device with magnetic core shows inductor characteristic. Above the FMR, however, the real part of permeability becomes negative and the device behaves as a capacitor. Therefore, the inductor with magnetic core can only work below the FMR. The grains in α-core have arbitrary shape and size, which leads to a non-uniform randomly orientated magnetization (NUROM), owing to their large magnetic shape anisotropy. The NUROM causes an extraordinarily broad FMR peak, as a result, there is no clear FMR peak on both the real and imaginary part of permeability of the α-core, which are proved by extraction of permeability based on the method described in [7]. Due to the absence of FMR, the #α1 has much less impact from the FMR compared to #β1 and #γ1. The NUROM also causes a generally low permeability of the α-core (around 10 from 1GHz to 10 GHz), which consequently weak the eddy current effects. The skin depth δFM of the α-core becomes larger than the β- and γ- core’s. In addition, the calculation in Fig.4 points out that nano-/micro- patterning of the magnetic core into isolated islands can effectively eliminate the eddy current effect, demonstrated by the constant ratio between μ_eff (permeability considering eddy current effect) and μ_FM (permeability without considering eddy current effect), when the skin depth is larger than the island size. Furthermore, because of the low permeability and smaller inductance, the LC resonance frequency of #α1 is higher than that of #β1 and #γ1. Due to the combined effects of less impact from the FMR, weaker eddy current effect, and higher LC resonance frequency, the drop-off frequency of #α1 is higher.

![Diagram](image_url)

**Fig.4** (a) Model of configuration of the granular film (α-core) shown in Fig.2 (a). The granular grains are simplified to a number (N) of spheres with radius R. (b) Calculation of the ratio of permeability with (μ_eff) and without (μ_FM) considering the eddy current loss. As R approach to the skin depth δFM, the eddy current loss become significant by manifest itself from the decrease and increase of the real and imaginary μ, respectively. The filling factor in the calculation is set to 1.

Inductance and quality factor of three 4-turn α-core inductors #α2, #α3, and #α4 as a function of frequency are shown in Fig.5. The f(Q_max) of #α2, #α3, and #α4 stay almost constant, while the WFM and the track capacitance has a 4-fold increase. This means the f(Q_max) is independent on the geometrical size of the devices and does not originate from the LC resonance, but mainly determined by the μ_eff of the Nio80Fe20 core. The LC resonance frequencies of #α2, #α3, and #α4 have been estimated above 20 GHz.

Compared to the control device with SiO2 dummy core, #α2 has a more than 40% increase of inductance from 0.1 GHz to 10 GHz. This indicates the high permeability of the α-core in spite of the granularity. As discussed above, the nano/micro granular Nio80Fe20 film α-core has advantages over the β- and γ- cores typically in high frequency applications. The device operating frequencies f(Q_max) have been reached above 5 GHz by using the developed nano/micro granular Ni80Fe20 film, while the cut-off frequencies have been shifted above 20 GHz.

![Graph](image_url)

**Fig.5** Inductances and quality factors versus frequency of 4-turn α-core inductors, (a) #α2: 30×60μm², (b) #α3: 60×60μm², (c) #α4: 120×60μm². The device operating frequencies f(Q_max) have been shifted above 5 GHz by using the developed nano/micro granular Ni80Fe20 film, while the cut-off frequencies have been shifted above 20 GHz.
the cut-off frequencies are well above 20 GHz (out of the measurement range of our equipment). The inductance of the devices increases when their size increases, for example from 0.65nH (\( \#D_2 \)) to 1.05nH (\( \#D_4 \)) at 1 GHz by \(~60\%\), however, the density of inductance IPA and the maximum quality factor decrease. Apparently, there exists an optimized design of device to tailor the device’s inductance, the quality factor, and the inductance per area.

Systematic design optimization of inductors has been carried out by varying \( LF_{M} \), \( W_{M} \), \( WL \), \( SL \), and \( n \). The inductance per area (IPA), the maximum quality factor \( Q_{\text{max}} \), and the operating frequency \( f(Q_{\text{max}}) \) are compared as a function of \( L(Q_{\text{max}}) \) (the value of inductance where Q shows the maximum), shown in Fig. 6. The Magnetic Region marks the domain, within which the devices’ performance is mainly dependent on the magnetic properties of the core film, while in the LC-Region, the devices’ performance depends on both the magnetic core and the structural LC-resonance. Generally, devices in the Magnetic Region have higher IPA, \( Q_{\text{max}} \), and \( f(Q_{\text{max}}) \) than those in the LC-Region. Additionally, in the Magnetic Region, IPA and \( Q_{\text{max}} \) are favorable to the small size devices and are traded against the device dimension, while the \( f(Q_{\text{max}}) \) exhibits a maximum at \( L(Q_{\text{max}}) \sim 1.0 \) nH. The trade-off between IPA, \( Q_{\text{max}} \), and \( f(Q_{\text{max}}) \) indicates how the full potential of FM films can be exploited by proper design of the solenoid coil and optimum micro/nano patterning of the FM core. After optimizing the design, the inductors with \( IPA > 0.20 \) \( \mu \)H/mm\(^2\), \( Q_{\text{max}} > 4.5 \) and \( f(Q_{\text{max}}) > 6.5 \) GHz have been achieved (Fig.6).

4 SUMMARY

A novel nano/micro patterned Ni\textsubscript{80}Fe\textsubscript{20} film, formed by using cost-effective electroplating on a Ti seed layer, has been demonstrated for RF applications. Optimum FM-core inductor characteristics can be achieved through a trade-off of IPA, \( Q_{\text{max}} \), and \( f(Q_{\text{max}}) \), in combination with an appropriate micro/nano patterning of the FM film in order to reduce the effective conductivity and thus eddy currents in the FM film. Inductors with \( IPA > 0.20 \) \( \mu \)H/mm\(^2\), \( Q_{\text{max}} > 4.5 \) and \( f(Q_{\text{max}}) > 6.5 \) GHz have been achieved.

REFERENCES


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