Two-Port Type Ferromagnetic RF Integrated Inductor

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Abstract — Two-port type rf integrated inductor with on-top magnetic layer was fabricated. Equivalent circuit analysis of the ferromagnetic RF integrated inductor was performed for the first time. Structure of the possible equivalent circuit is proposed. Parasitic capacitance of the ferromagnetic film is negligibly small if the film is applied slits. Ferromagnetic $Co_{85}Nb_{12}Zr_3$ film with slits effectively enhanced the inductance up to 5 GHz.

I. INTRODUCTION

Many efforts have been done to improve the quality factor, Q and to miniaturize the size of RF integrated inductors fabricated on a Si wafer. A way to develop a high-Q integrated inductor is to reduce the wiring losses by utilizing a thick and low-resistivity metal [1],[2]. It is also worth trying to employ high-resistivity semiconductor substrate or to form a cavity beneath the coil to reduce the eddy currents in the substrate [3]. Stacked coil was also tried to save the coil area and to increase the mutual inductance but the coil resistance was doubled. Thus it is not easy to achieve high-Q and size reduction simultaneously.

A new solution to this problem is to apply ferromagnetic thin films to the RF integrated inductor. The original idea is to enhance the number of magnetic flux associated with the coil current and accordingly to enhance the inductance and quality factor of the inductor.

We have pioneered this idea and demonstrated an on-top type ferromagnetic inductor for 1 GHz range that was applied a ferromagnetic film on top of an integrated spiral [4],[5]. A sandwich type ferromagnetic RF integrated inductor for a 2GHz application was also demonstrated [6]. The cloth structure [7] and the double-bar structure [8] have also been discussed by another research groups.

Currently, the soft ferromagnetic materials for the GHz-range application are available only in the sputter-deposited form and they are conductive still. i.e. The magnetic film can be an electrode of a parasitic capacitance which may arise an additional LC resonance in the frequency range of the application interest.

Therefore the parasitic impedance is discussed in this work based on the equivalent circuit analysis of the two-port type integrated RF spiral inductors with on-top magnetic thin film structure.

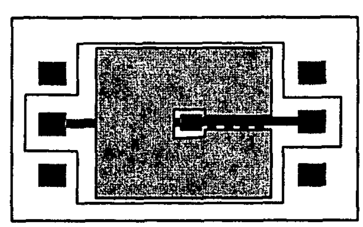
II. STRUCTURE AND DESIGN

Fig. 1 shows the structure of the fabricated on-top type RF integrated inductor. The coil is made of a 2.6 μm thick copper with width w_c=12 μm and spacing d_c= 10 μm. The outer size of the spiral is 393x393 μm^2. The 0.1 μm thick amorphous $Co_{85}Nb_{12}Zr_3$ (at%) soft ferromagnetic film was sputter deposited on top of the spiral with the 3.2 μm thick spun-coat polyiimde layer in between. The hard axis of magnetization of the ferromagnetic film was along the vertical direction in Fig. 1(b), where the magnetization process is governed by the spin rotation and is with high permeability in the RF range.

A portion of the magnetic film was removed from the spiral center to the right hand side pad in order to provide a space for the lead-out line, which is in the right angle to the hard axis of magnetization. The magnetization process at the removed portion is based on the domain wall movements and the walls cannot follow the RF field. Accordingly the permeability in this direction is very low. Therefore, the removal of the magnetic film does not degrade the performance of the inductors.

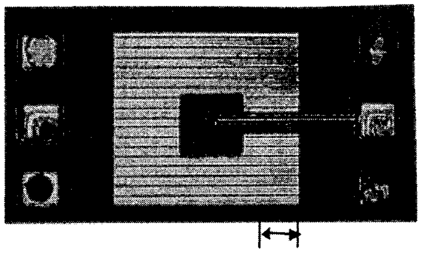
Fig. 2 shows the fabrication inductors. The substrate was 600 μm-thick (100) oriented n-type Si with resistivity of

(a) Top view

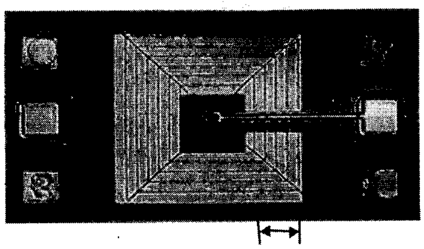


(b) Top view

Fig. 1 Two-port and on-top type ferromagnetic RF integrated spiral inductor.

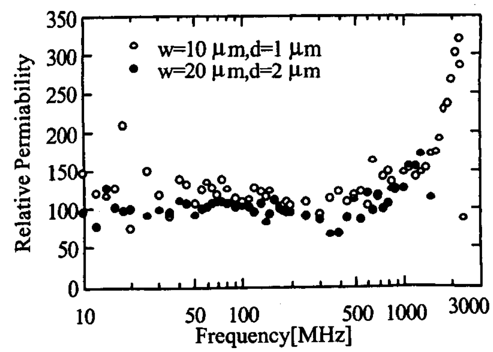


(a) Parallel bar pattern

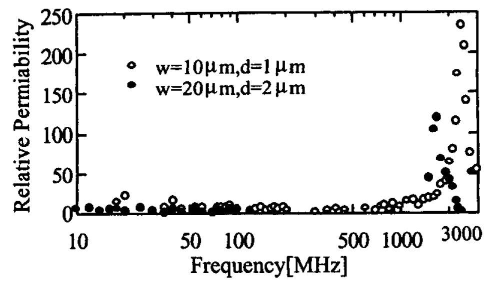


(b) Orthogonal bar

Fig. 2 Fabricated inductors



(a) Real Part



(b) Imaginary Part

Fig. 3 High frequency permeability. *w is the width of the patterned film and d is the spacing between the patterned films.*

higher than 500 Ωcm. The coil was defined by a lift-off process with the rf-sputter deposited Cu sandwiched by the top and bottom 5 nm-thick Ti layers to improve the adhesion. Next, a 4 μm-thick polyimide layer was provided with surface planarization. Then the $Co_{85}Nb_{12}Zr_3$ magnetic film was rf-sputter deposited to the thickness of 0.1 μm. The magnetic film was applied narrow slits to enhance the ferromagnetic resonance (FMR) frequency [5] by ion milling. The total processes were completed with the lift-off process of the lead-out line.

III. MAGNETIC MATERIAL DESCRIPTION

The amorphous $Co_{85}Nb_{12}Nb_3$ soft magnetic film has the saturation magnetization, M_s, of 1.0 Tesla with resistivity of 1.2×10^{-8} Ωm. Its saturation magnetostriction is less than +1 ppm. The anisotropy field, H_k, is 400-800 A/m (5-10 Oe) and the intrinsic relative permeability was 500-1000. Accordingly the FMR frequency is below 1GHz. Note that the FMR frequency is proportional to the square root of the product of M_s and H_k.

The application of narrow slits along the easy axis direction introduces demagnetizing field when the magnetic field is applied along the hard axis. This effectively enhances the anisotropy field, H_k, and accordingly the FMR frequency, as shown in Fig. 3.

IV. EQUIVALENT CIRCUIT

Fig. 4 shows the known equivalent circuit of the RF integrated air-core inductor. The main inductance, L_s, is in series with the resistance, R_s, representing the wiring loss of the coil portion. This leg is in parallel with the line-to-line parasitic capacitance, C_s, which includes the capacitance between the coil and the lead-out line. The capacitances, C1 and C2, lie between the coil and the doped-Si layer. Then the grounding parasitics are shown by C_{21}, C_{22}, R_1 and R_2.

In Fig. 5(a), the physical structure of the on-top type RF ferromagnetic integrated inductor is depicted. There are parasitic capacitances, C_{cm1} and C_{cm2}, between the magnetic film and the coil. Such capacitances are also between the magnetic film and the ground, C_{gm1} and C_{gm2}. The grounding capacitances should be associated with parallel resistance, R_{gm1} and R_{gm2}, which correspond to the eddy current losses in Si.

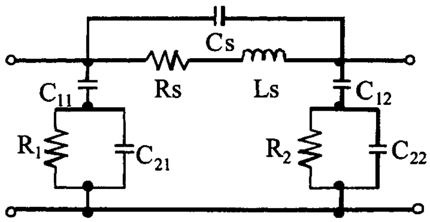
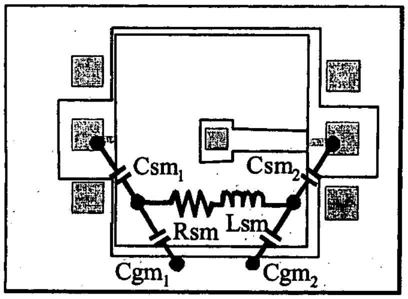
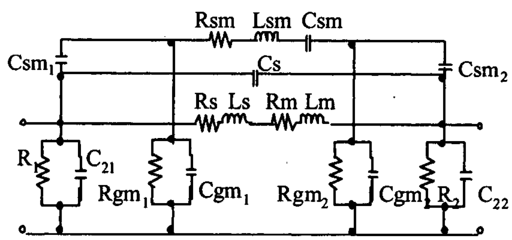


Fig. 4 Equivalent circuit of an RF air-core inductor.



(a) Physical structure



(b) Possible equivalent circuit

Fig. 5 Equivalent circuit consideration of the on-top type ferromagnetic RF integrated inductor

The displacement current goes into the magnetic film through the C_{cm1} and C_{cm2}. Then the displacement current meets the impedance of magnetic film represented by L_{sm} and R_{sm}. A capacitance, C_{sm}, should be added in series to L_{sm} and R_{sm} if the magnetic film is applied slits.

These considerations are summarized in Fig. 5(b). The main contribution of magnetic film is represented by the inductance, L_m, and the loss resistance, R_m, which are in series to the leg of the air-core inductance.

In this work, we discuss the equivalent circuit up to 5GHz. Therefore Fig. 5(b) can be reduced to a certain degree.

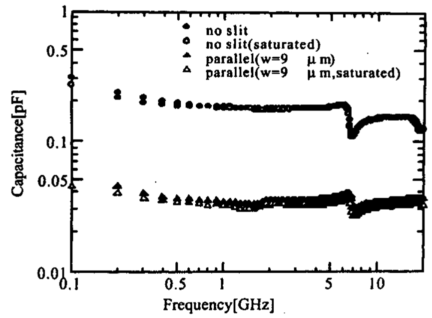


Fig. 6 Capacitance between the coil and magnetic film

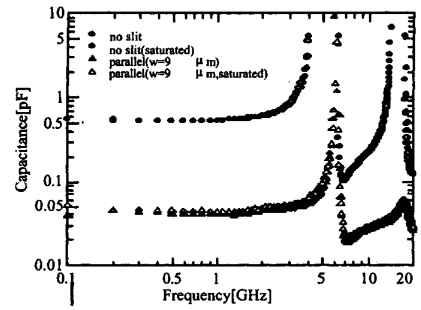


Fig. 7 Capacitance between the ground plane and magnetic film.

V. Parasitic Capacitance of Magnetic Film

Fig. 6 shows the measured capacitance between the coil and the magnetic film. The measurement was with a G-S type wafer probe (GGB Industries Inc., Model 40-A) connected to the coil pad and the magnetic film. If the magnetic film is not applied slits, the capacitance was a constant of 0.2 pF up to 6GHz. This value was not changed when the film was magnetically saturated. This means that $C_{sm1}+C_{sm2}\tilde{}$ 0.2pF.

It is interesting that the capacitance of the slit-film inductor was only 0.035 pF up to 6GHz. This is because the capacitors were divided into small segments and they were in the series connection.

Fig. 7 shows the measured capacitance between the coil and the magnetic film. The measured result showed similar tendency as Fig. 6. Again here, the capacitance of the slit-film inductor was much smaller than the non-slit inductor. Based on this result, tt will be approximated hereafter that the leg of C_{sm}, L_{sm} and R_{sm} is open.

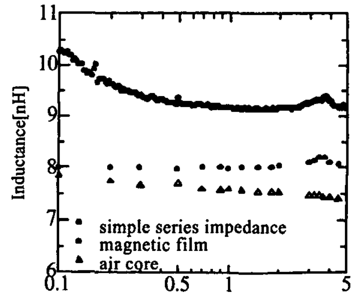


Fig. 8 Analyzed inductance of the ferromagnetic RF integrated inductor.

These results show that the application of narrow slits to the magnetic film is useful to reduce parasitic capacitance associated with the magnetic film. This finding is quite important because the parasitic capacitance has been the only possible disadvantage of introducing ferromagnetic material to the RF integrated inductor.

VI. Parameter Acquisition

Firstly, the s_{11}, s_{21}, s_{12} and s_{22} parameters of an inductor without magnetic film were measured by a network analyzer (HP 8720D) to determine the parameters shown in Fig. 4. Here the C_{11} and C_{21} were neglected because our substrate has not the doped layer. The capacitance, C_s, was also neglected because there was not a resonance associated with the C_s up to 5 GHz range.

Then the s-parameters of the ferromagnetic RF integrated inductor were measured to determine all the parameters shown in Fig. 5(b). It was assumed that all the air core parameters, Ls, Rs, C21, C22, R1 and R2 do not change in the ferromagnetic inductor.

Fig. 8 shows the analyzed inductance of the ferromagnetic RF integrated inductor, as a representative result of the equivalent circuit analysis. It is seen magnetic film effectively enhance the inductance up to 5GHz, which is ever high frequency

At 1 GHz, the analyzed parameters were L_s=7.57 nH, L_m=0.39 nH, R_s=11.2 Ω, R_m=20.8 Ω, C_{21}=0.129 pF, C_{22}=0.088 pF, R_1=8834 Ω, R_2=8771 Ω, C_{gm1}=0.004 pF, C_{gm2}=-0.009 pF, R_{gm1}=3300 Ω and R_{gm2}=28600 Ω.

VII. Conclusion

Two-port type RF integrated inductor with on-top magnetic layer was fabricated. Equivalent circuit analysis of the ferromagnetic RF integrated inductor was performed for the first time. Structure of the possible equivalent circuit is proposed. Parasitic capacitance of the ferromagnetic film is negligibly small if the film is applied slits. Ferromagnetic $Co_{85}Nb_{12}Zr_3$ film with slits effectively enhanced the inductance up to 5 GHz.

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