SANDWICH TYPE FERROMAGNETIC RF INTEGRATED INDUCTOR

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ABSTRACT

First microfabrication of a sandwich type ferromagnetic RF integrated spiral inductor at 2 GHz range is demonstrated. The two ferromagnetic CoNbZr films sandwich the spiral to enhance the number of magnetic flux linkage across the coil current. The inductance, L, of 7.9 nH and the qualify factor, Q, of 12.7 were obtained for a 200 μm x 400 μm size 4-turn rectangular spiral at f=2GHz. The inductance was better than that of an air core of the same coil size by 19 %, and the Q was better by 23%.

INTRODUCTION

A high-quality factor (Q) and miniature RF integrated inductor has been discussed [1]-[3] for an RF electronic circuitry. A new approach in this work is to apply ferromagnetic thin films to the inductor. The original idea is to enhance the number of magnetic flux associated with the coil current by using the ferromagnetic films.

Our first trial was the on-top type ferro-magnetic inductor for 1 GHz range that was simply applied a ferromagnetic film on top of an integrated spiral [4],[5]. The performance obtained for a four-turn square spiral of a 377 x 377 μm^2 area CoNbZr soft ferromagnetic film with AlSi coil material was L=7.6 nH, R= 6.8 Ω and Q=7.1 at 1 GHz. This published work had demonstrated that ferromagnetic film was useful at 1 GHz range to enhance the inductance without any degradation of the quality factor. The rate of the inductance enhancement, however, was only 12 % of the conventional air-core spiral of the same size.

In this work, a new sandwich type ferro-magnetic RF integrated inductor for a 2GHz application was microfabricated having an improved Q and an inductance per unit area.

STRUCTURE AND DESIGN

Currently, the magnetic films for the RF inductor in a GHz range is available only by sputter-deposition. Each film has uni-axial anisotropy with the easy axis of magnetization oriented along a certain direction in the film plane. In the RF range, permeability is generally high only along the hard axis of magnetization which is in the right angle to the easy axis. Therefore hard axis excitation effectively increase the number of magnetic flux associated with the coil current and accordingly the inductance of the inductor.

The rectangular coil shape employed in this work is preferable for such an uni-axial magnetic film because the magnetic film area for the hard axis excitation is larger than that of a square spiral and a round spiral.

Fig. 1 shows the outlook of the fabricated a 200 x 400 μm size spiral inductor. Two ferromagnetic

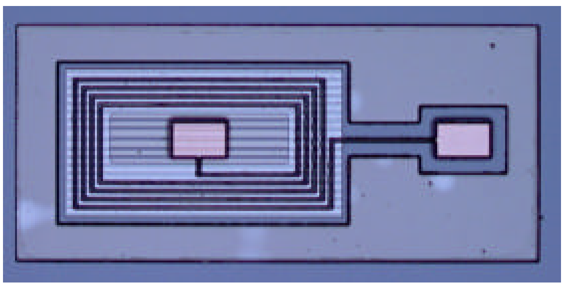


Fig. 1 Outlook of the fabricated sandwich-type ferromagnetic RF integrated inductor (200 x 400 μm^2).

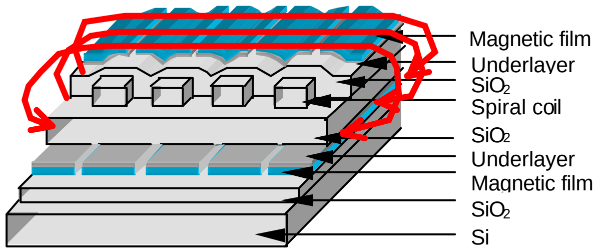
$Co_{85}Nb_{12}Zr_3$ amorphous films sandwich the spiral with SiO_2 insulator in between. The hard axis of magnetization is in the vertical direction of the figure. Magnetic field from the coil current is applied to the hard axis direction at the top and bottom legs of the spiral, which contributes to enhance the number of magnetic flux. On the other hand, the magnetic field at the left and right legs of the spiral is applied along easy axis direction. Here, the number of magnetic flux remains unchanged.

In detail, the magnetic films are applied narrow slits along the length direction of the spiral as shown in Fig. 2(a). These slits or the magnetic wire array structure increase the demagnetizing field along the flux path and therefore effective anisotropy field, Hk, increases. This greatly helps to enhance the ferromagnetic resonance (FMR) frequency of the magnetic film and to make a broad bandwidth inductor [6].

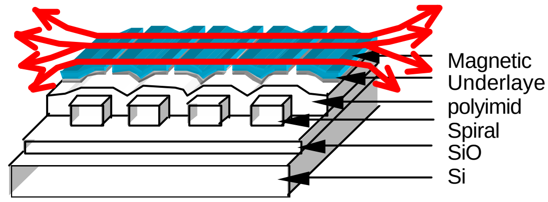
As compared with the on-top type inductor shown in Fig. 2(b), the sandwich type is advantageous as;

(a) Number of magnetic flux linkage across the coil current is larger. Therefore inductance and quality factor are enhanced.

(b) Leakage magnetic flux is smaller. Therefore electromagnetic interference (EMI) to the integrated circuits should be insignificant.



(a) Sandwich type



(b) On-top type

Fig. 2 Two types of ferromagnetic RF integrated inductors.

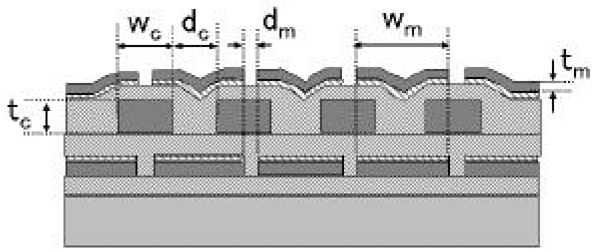


Fig. 3 Cross sectional view of the sandwich type inductor.

(c) Eddy current losses in substrate should be smaller because of low level leakage flux.

Table I Specifications and characteristics of the fabricated ferromagnetic RF integrated inductors.

	1GHz			2GHz		
(Unit: μm)	L(nH)	R(Ω)	Q	L(nH)	R(Ω)	Q
Sandwich type						
air(w_c=8,d_c=3,t_c=3)(Cu)	6.2	5.1	7.8	6. 7	8.2	10.3
no slit	9.1(+47%)	13.1	4.5(-43%)	6.1(-7.9%)	47.0	1.6(-84%)
w_m=9,d_m=2,t_m=0.1	6.9(+10%)	5.7	7.6(-2.2%)	8.1(+21%)	10.6	9.6(-6.7%)
w_m=8,d_m=3,t_m=0.1	6.9(+7.2%)	5.4	7.9(+0.5%)	7.8(+17%)	7.8	12.6(22%)
w_m=7,d_m=4,t_m=0.1	6.8(+8.3%)	5.1	8.5(+8.3%)	**7.9(+19%)**	**7.9**	**12.7(+23%)**
On-top type						
air(w_c=11,d_c=11,t_c=2.7)(Al-Si)	6.6	6.9	6.2	7.4	15.7	5.9
w_m=10.25,d_m=0.75,t_m=0.1	**7.4(+11%)**	**7.5**	**6.3(+2.0%)**	8.6(+17%)	20.8	5.2(-12%)
w_m=9.5,d_m=1.5,t_m=0.1	7.3(+10%)	7.6	6.2(+0.1%)	**8.3(+12%)**	**18.5**	**5.6(-5.8%)**

In the cross sectional view of Fig. 3, t_c is the coil thickness, w_c the coil width, d_c the coil spacing, t_m the magnetic film thickness, w_m the slitted magnetic wire width and d_m the magnetic film wire spacing. The dimensions of fabricated inductors are listed in the left-most column in Table I. Each coil has four turns with 3 μm thick, 8 μm wide and 3 μm spacing. Magnetic film wire thickness is also a constant of 0.1 μm. The wire width and spacing were changed so that the permeability and FMR frequency vary. The on-top type inductors are listed in Table I for

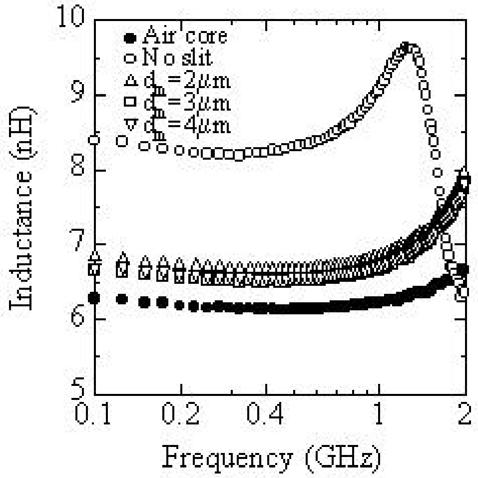
These processes can be completed as the post-Si processes. This is a great feature to integrate ferromagnetic inductors.

RF CHARACTERISTICS

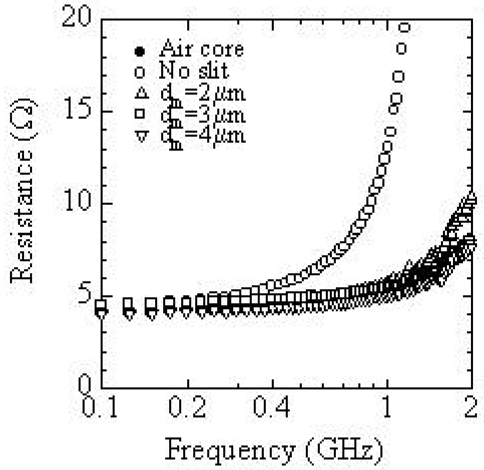
Fig. 4 shows measured high frequency characteristics of the sandwich inductors. A wafer probe (GGB Industries, Picoprobe Model-10) and a network analyzer (HP 8720D) were used to extract the impedance parameters. Major results at 1 GHz and 2 GHz are summarized in Table I. The reference air core exhibited L=6.8 nH and Q=10.3 at 2 GHz.

In Fig. 4(a), the inductance of each ferromagnetic inductor was higher than the air core inductance. In the low frequency range, the inductor with no-slit ferromagnetic film showed the highest inductance, achieving L=9.1 nH at 1 GHz. The value obtained was higher than the air core's by 47 %. This is because of high permeability of the no-slit ferromagnetic film. With raising the drive frequency, however, the inductance degraded because of the low FMR frequency of the no-slit ferromagnetic film. The influence of the FMR is also seen as the increase of resistance in Fig. 4(b) and the degradation of the quality factor in Fig. 4(c).

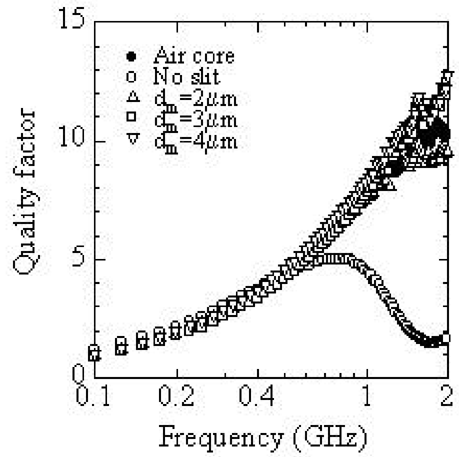
The ferromagnetic inductors with micro wire array film structure exhibited as high quality factor as the air core up to 2 GHz. The best performance was



(a) Inductance



(b) Resistance



(c) Quality factor

Fig. 4 Measured electric characteristics.

L=7.9 nH and Q=12.7 at 2 GHz obtained for the ferromagnetic wire width of 7 μm and its spacing of 4 μm. The inductance was higher by 19 % and the quality factor was better by 23 % as the air core.

In the case of the on-top type inductors, quality factor was maxim between 1 GHz and 2 GHz, and the value obtained was less than 8. Therefore the sandwich type inductors are advantageous against the on-top type inductor on the quality factor achieved and the bandwidth. This is because; (a) Design of slit work was optimized for the 2 GHz band, (b) Number of magnetic flux per unit area was larger, and (c) Stray capacitance might be smaller.

Further improvement should be possible by optimizing the magnetic film thickness with optimum slit work, terminating the top and the bottom magnetic layers at their edges, and employing a magnetic film with higher anisotropy field and higher saturation magnetization.

CONCLUSION

First microfabrication of a sandwich type ferromagnetic RF integrated spiral inductor at 2 GHz range is demonstrated. The two ferromagnetic CoNbZr films sandwich the spiral to enhance the number of magnetic flux linkage across the coil current. The inductance of 7.9 nH and the qualify factor of 12.7 were obtained for a 200 μm x 400 μm size 4-turn rectangular spiral at f=2 GHz. The inductance was better than that of an air core of the same coil size by 19 %, and the quality factor was better by 23%.

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