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Microfabrication and characteristics of magnetic thin-film inductors in the ultrahigh frequency region

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Thin-film inductors for 1 GHz-drive mobile communication handset application has been demonstrated. This is the possible practical application of soft magnetic films in 1 GHz range. $Fe_{61}Al_{13}O_{26}$ with $M_s = 1.2$ T, $\rho = 500$ $\mu\Omega$ cm, $f_r = 2$ GHz were used for the inductors. $L = 7.6$ nH, $R = 6.5$ Ω, and $Q = 7.4$ were obtained at 1 GHz in a 370 μm$\times$370 μm square four turn spiral of line/space=11 μm/11 μm covered with 0.1-μm-thick slitted $Fe_{61}Al_{13}O_{26}$ film with Cr underlayer. The L was increased over the flux saturated inductor by 8.6% without any degrade of quality factor. [S0021-8979(99)05811-9]

I. INTRODUCTION

Recent growing need for mobile communication handsets is pushing forward new requirements of further miniaturization and lower insertion losses for inductive components installed in monolithic microwave integrated circuits (MMICs) of the handsets. Some early works to meet this requirement have been done by using air core spirals.[1,2] Also, possible magnetic materials[3,4] and analytical simulation for 1 GHz drive magnetic thin-film inductors[5] have been reported. Real microfabrication of the inductors, however, have not been reported yet.

Here we microfabricated magnetic thin-film inductors usable for an radio frequency (rf) front-end receiver's impedance matcher in a 1 GHz-drive mobile communication handsets. The work covers material development, three dimensional finate element method simulation, microfabrication processes being compatible with currently used semiconductor processes, and measurement techniques.

II. INDUCTORS AND THEIR MEASUREMENT TECHNIQUES

Figure 1 shows the structure of the fabricated magnetic thin-film inductors, showing that a magnetic thin film simply covers the top of a spiral coil fabricated on a Si wafer. The magnetic film and the spiral are insulated by polyimide film. It is known that magnetic film of this structure contributes only up to 100% enhancement of air-core inductance.[6] This structure, nevertheless, has been chosen because the 50% enhancement of the air-core inductance should be enough for industrial applications. Magnetic film is either with or without slits as shown in Figs. 1(b) and 1(c). The role of slits is to reduce eddy current losses. Dimensions of the inductors are listed in Table I. Difference between the group 1 and 2 is the number of turns of the spiral.

The fabrication process is as follows: A (100) oriented n-type Si wafer with as high resistivity as 500 Ω cm was used for the processing substrate in order to reduce eddy current losses in the substrate. A 1.4 μm thick SiO_2 film was formed firstly by wet thermal oxidation and then by atmospheric-pressure chemical vapor deposition on the wafer surface. This is to reduce eddy current losses in Si substrate by providing a reasonably large spacing between the spiral and the Si substrate. Second, a 2.6–3.0-μm thick

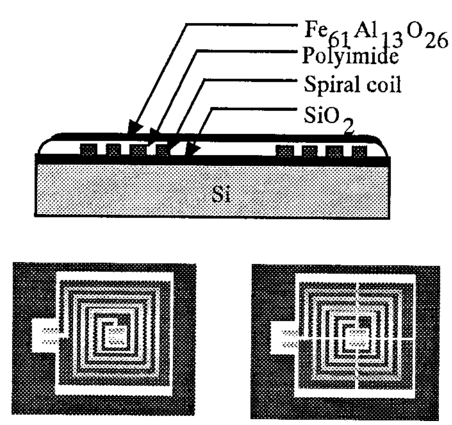

FIG. 1. Structure of the fabricated magnetic thin-film inductors: (a) cross sectional view, (b) slitless inductor, (c) slitted inductor.

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TABLE I. Dimensions of fabricated thin-film inductors.

Group			1	2
Coil	Number of turns		4	5
	Width	μm	11.0	11.0
	Spacing	μm	11.0	11.0
	Thickness	μm	2.6–3.0	2.6–3.0
	Area	μm^2	337×337	381×381
Magnetic thin film	Thickness	μm	0.1	0.1, 0.5
	slit width	μm	10.0	⋯
Substrate	thickness	μm	600	600

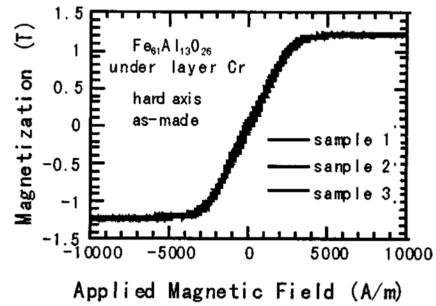

FIG. 3. M–H curves of 0.1 μm thick $Fe_{61}Al_{13}O_{26}$ film deposited on soda glass substrate.

Al–Si layer was rf-sputter deposited on SiO_2 and then wet etched into four turn spiral with line/space=11 μm/11 μm. After spin coating 3.5-μm-thick photosensitive polyimide insulator, 0.1-μm-thick Fe–Al–O film was rf-sputter deposited and etched by ion milling. All these processes can be done after finishing the normal semiconductor MMIC processes.

A wafer probe (Cascade Microtech, Picoprobe GT-1000) and a network analyzer (HP8720D) were used to measure impedance $Z_r = R + jX$ of the inductors at a 100 MHz–2 GHz frequency range. The impedance is given by using s_{11} of the reflection coefficient of scattering matrix as

$$Z_r = R + jX = Z_0(1 + s_{11})/(1 - s_{11}), \tag{1}$$

where Z_0 is characteristic impedance of the transmission line. Our measurement system has $Z_0 = 50\,\Omega$. The value L of inductance is obtained by dividing reactance X by angular frequency ω ($L = X/\omega$) so far as X is positive.

As shown in Fig. 2, the measurement is without bonding wire,[7] which eliminates stray impedance and signal delay time between the probe tip and the inductor. These improves measurement accuracy especially beyond 300 MHz range.

Evaluation of the fabricated inductors were based on the comparison of L, R, and quality factor, Q, between normally measured state (normal inductor) and flux saturated state (flux saturated inductor) which was realized with an application of dc 500 Oe field by using two magnets.

III. Fe–Al–O GRANULAR HIGH RESISTIVITY FILM

Material development to avoid excess loss generation at 1 GHz range is a point of this work. The Fe–Al–O granular film[8,9] consisting of fine grains of Fe and oxides of chemically active elements were used because of high resistivity and high ferromagnetic resonance (FMR) frequency. It has been reported, however, that easy axis orientation of the Fe–Al–O film is radial from the film center due to microscopic shape anisotropy associated with the granular structure.[3,10] This matters much for batch fabrication of thin-film inductors.

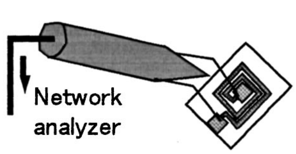

FIG. 2. Wafer probe connection to the inductors.

An inclined film-substrate holder (arranged 30° angle to targets) was employed and thin Cr film was used as an underlayer for the Fe–Al–O film in order to settle this problem. In Fig. 3, the coercive force became reproducible and went down to 0.5 Oe at lowest. If without the Cr underlayer, the coercive force of five different samples was up to 12.5 Oe. The Cr underlayer might have controlled initial growth layer, but the details are still unknown.

The Landau–Lifshits–Gilbert equation gives FMR frequency, f_r, of single domain magnetic thin film along hard axis as[11]

$$f_r = (\gamma/2\pi)(H_k M_s/\mu_0)^{1/2}, \tag{2}$$

where, γ is gyro magnetic constant. The relation between the FMR frequency and the resistivity of 2-μm-thick Fe–Al–O film is summarized in Fig. 4. Measured values of anisotropy field and saturation magnetization were used to obtain FMR frequency. Resistivity was measured by the four terminal method.

In Fig. 4, there is a trade-off correlation between resistivity and FMR frequency. A three-dimensional electromagnetic field simulation was performed to fix this trade-off problem and clarified the necessity of high resistivity at least 500 $\mu\Omega$ cm if $\mu_r = 300$. The simulation also revealed the magnetic film should be thinner than 0.1 μm in order to avoid electromagnetic field reflection at the film surface. In addition, the FMR frequency should be higher than 2 GHz in order to avoid excessive loss generation at 1 GHz. Therefore, $Fe_{61}Al_{13}O_{26}$ with $M_s = 1.2$ T, $\rho = 500$ $\mu\Omega$ cm, $f_r = 2$ GHz was used for the inductors.

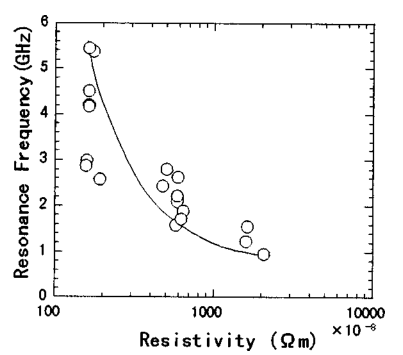

FIG. 4. Relation between the FMR frequency and the resistivity of 2-μm-thick Fe–Al–O film.

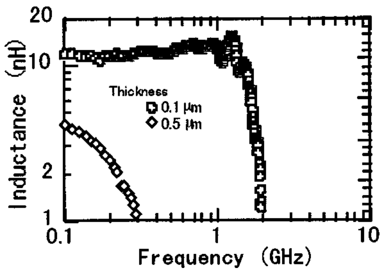

FIG. 5. Frequency characteristics of slitless normal inductors (group 2).

IV. HIGH FREQUENCY CHARACTERISTICS OF FABRICATED INDUCTORS

Figure 5 shows the frequency characteristics of slitless normal inductors with different magnetic film thickness. If the Fe–Al–O film is 0.5 μm thick, the inductance dropped down at below 500 MHz. On the other hand, the 0.1-μm-thick Fe–Al–O film exhibited a flat frequency profile up over 1 GHz, as simulated in the previous section. The Fe–Al–O thickness will be always 0.1 μm hereafter.

Figure 6 compares the high frequency characteristics of the fabricated inductors whose magnetic film has no Cr underlayer. The slitless normal inductor showed inductance of 7.2 nH, which is enhanced by 6% from 6.8 nH of the flux saturated inductor's at 1 GHz. Besides, the resistance became larger from 6.2 to 7.5 Ω. The slits on magnetic film effectively reduced the resistance, but still larger than the flux saturated inductor's.

In Fig. 7, the resistance at 1 GHz of normal inductors became much smaller by using a Cr underlayer. Comparing with Fig. 6, the resistance of normal slitless inductor decreased from 10.4 to 7.2 Ω (31%) at 1 GHz. This is because of eddy current suppression by the slits. Inductance was not degraded by using the slits.

Figure 8 compares the quality factor of the inductors. Effects of the Cr underlayer and slits are again clear over the bare polyimide finished inductor, where the quality factor was enhanced from 4.3 to 7.4. The quality factor of the normal slitted inductor with a Cr underlayer was as high as the flux saturated inductor at 1 GHz.

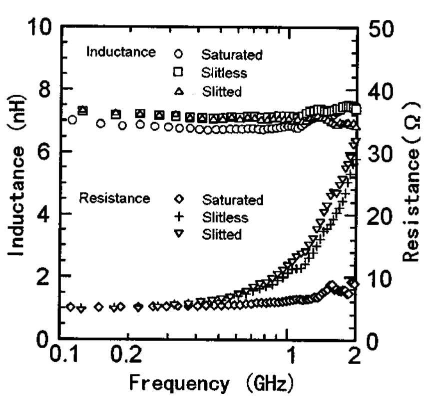

FIG. 6. Frequency characteristics of the inductors without a Cr underlayer (group 1).

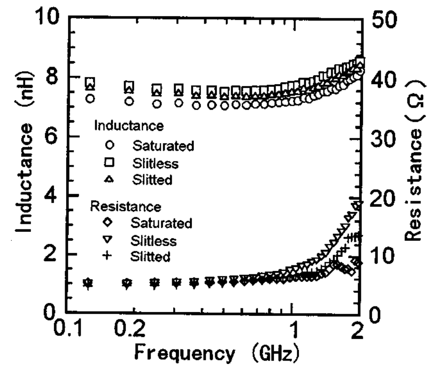

FIG. 7. Frequency characteristics of the inductors with a Cr underlayer (group 1).

V. CONCLUSION

Thin-film inductors for GHz-drive mobile communication handset application has been demonstrated for the first time. This is possible practical application of soft magnetic films in 1 GHz range.

(1) Soft magnetic granular films with as high resistivity as 500 $\mu\Omega$ cm is required for this application if $\mu_r = 300$.

(2) $Fe_{61}Al_{13}O_{26}$ with $M_s = 1.2$ T, $\rho = 500$ $\mu\Omega$ cm, $f_r = 2$ GHz were used for the inductors.

(3) Using a Cr underlayer, easy axis orientation of $Fe_{61}Al_{13}O_{26}$ film was well aligned and coercive force went down to 0.5 Oe. The Cr underlayer also drew resistance of the inductors down and therefore improved quality factor.

(4) A 0.1-μm-thick $Fe_{61}Al_{13}O_{26}$ film was useful to enhance inductance at 1 GHz while a 0.5-μm-thick $Fe_{61}Al_{13}O_{26}$ film was useless because of eddy current generation and electromagnetic field reflection at the film surface.

(5) $L = 7.6$ nH, $R = 6.5\,\Omega$, and $Q = 7.4$ was obtained at 1 GHz in a 370 μm×370 μm square four turn spiral of line/space=11 μm/11 μm covered with 0.1-μm-thick slitted $Fe_{61}Al_{13}O_{26}$ film with a Cr underlayer. The L was advantageous over the flux saturated inductor by 8.6% without any degrade of the quality factor.

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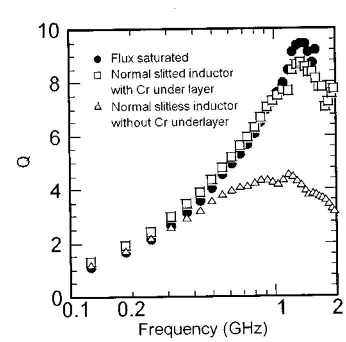

FIG. 8. Quality factor of the inductors (group 1).

[1] J. N. Burghartz, K. A. Jenkins, and M. Soyuer, IEEE Electron Device Lett. **17**, 428 (1996).
[2] J. Y.-C. Chang, A. A. Abidi, and M. Gaitan, IEEE Electron Device Lett. **14**, 246 (1993).
[3] K. Kato, W. D. Li, O. Kitakami, and Y. Shimada, J. Magn. Soc. Jpn. **21**, 423 (1997).
[4] E. J. Yun, W. Win, and R. M. Walser, IEEE Trans. Magn. **32**, 4535 (1996).
[5] V. Korenivski and R. B. van Dover, IEEE Trans. Magn. **34**, 1375 (1998).
[6] W. A. Roshen, IEEE Trans. Magn. **26**, 270 (1990).
[7] M. Yamaguchi, Y. Takahashi, K. I. Arai, and S. Kikuchi, J. Magn. Soc. Jpn. **22**, 861 (1997).
[8] W. D. Li, O. Kitakami, Y. Shimada, K. Ishiyama, and K. I. Arai, J. Magn. Soc. Jpn. **20**, 461 (1996).
[9] W. D. Li, K. Kato, O. Kitakami, and Y. Shimada, J. Magn. Soc. Jpn. **22**, 449 (1998).
[10] S. Ohnuma, N. Kobayashi, T. Masumoto, and H. Fujimori, J. Magn. Soc. Jpn. **22**, 441 (1998).
[11] L. Landau and E. Lifshitz, Phys. Z. Sowjetunion **8**, 153 (1935).