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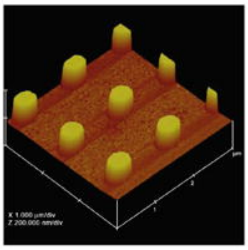

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Accelarated Publication

Increasing the thin film inductance by using soft magnetic $Co_{92}Zr_8$ as conductor

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A B S T R A C T

Planar-type thin-film inductor has been fabricated using $Co_{92}Zr_8$ soft magnetic thin film with high permeability as conductor. The inductance of the $Co_{92}Zr_8$ inductor is about five times more than that of the Cu inductor at frequency 60 MHz. At the same time, the dissipation of thin-film inductor using $Co_{92}Zr_8$ is similar with that of the Cu inductor. This result presents a novel method for increasing the inductance of thin-film inductor with simple technical process.

1. Introduction

At present, devices in electronic system towards 'small, thin and precision' are following the development of the information technology [1]. Planar inductor is one of the essential passive components in the circuitry of the latest electronic products [2], e.g., in notebook computers, camcorders, pagers, cellular phones, and etc. Therefore, it has been attended extensively by the scholars to improve the inductor performance at high frequency.

Two-dimensional inductors are usually used at traditional micromachine because of the predominant compatibility with semiconductor. So, the integration of small size inductors with high inductance and high quality factor into RF-circuits on silicon becomes an important challenge. To some extent, the inductor performance has been improved by optimizing structure, geometric parameters and technical process [3–8]. In order to improve the inductance, it is common to cover the magnetic material under and upon the conductors of these thin-film inductors. But these inductors have problems such as high dissipation, high cost and complex process. In this work, thin-film inductor has directly been fabricated using $Co_{92}Zr_8$ soft magnetic material for conductor. Because of the high permeability of $Co_{92}Zr_8$, the magnetic flux of $Co_{92}Zr_8$ thin-film inductor has greatly been enhanced. Following, the inductance of $Co_{92}Zr_8$ thin-film inductor has been greatly improved. And, those shortages, as stated in the above, are largely avoided.

2. Experiment

Two meander-type thin-film inductors were fabricated using $Co_{92}Zr_8$ soft magnetic material and Cu for the conductors. In order to simplify the equivalent-circuit model and analyze the inductor performance, the structure of these inductors is very simple, as shown in Fig. 1a and b for plain and cross-sectional view, respectively. The parameters of the two inductors are the same with the line width $w = 1.50$ mm and space $d = 2.75$ mm. The thicknesses of conductor and SiO_2 are 200 nm and 800 nm, respectively. The SiO_2 underlay layer was formed by wet thermal oxidation on the (1 1 1)-oriented Si substrates surface. The SiO_2 is prepared to reduce eddy current losses in Si substrate by providing a reasonably large spacing between the inductor and the Si substrate. The Cu and $Co_{92}Zr_8$ soft magnetic thin films were prepared by radio frequency (rf) sputtering onto $10 \times 10 \times 0.42$ mm^3 SiO_2/Si substrates attached to a water-cooling system with background pressure lower than 5×10^{-5} Pa [9–11]. A Cu target, 70 mm in diameter and 3 mm in thickness, was used to deposit Cu layers. And a Co target, same size as Cu target, on which Zr chips were placed in a regular manner, was used to deposit $Co_{92}Zr_8$ layers. During sputtering, an Ar flow rate of 20 SCCM (SCCM denotes cubic centimeters per minute at STP) was needed to maintain an Ar pressure of 0.15 Pa, and the rf power density was 1.7 W/cm^2.

Thicknesses of these thin films were measured by a Vecco Dektak 8 setback instrument. The static magnetic properties are obtained by magnetic hysteresis loop measured by vibrating sample magnetometer (Lakeshore model 7304). The permeability spectrum were carried out with a PNA E8363B vector network analyzer using the microstrip method from 100 MHz to 8 GHz with sample

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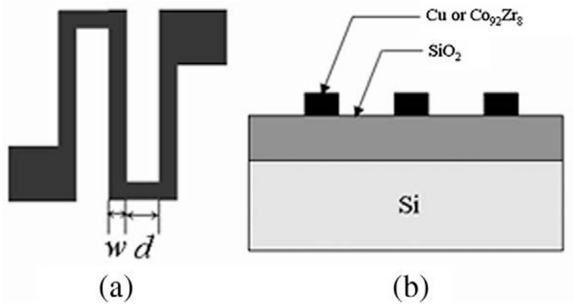

Fig. 1. Structure of fabricated thin-film inductors: (a) top view, (b) cross-sectional.

($5 \times 5 \times 0.42$ mm^3) positioned in the middle of strip line with inner height 0.8 mm between upper line and ground plate, width of upper line 3.94 mm, length 9 mm [12]. The impedance-frequency characteristics were measured by an Agilent 4294A impedance measuring equipment.

3. Result and Discussion

Fig. 2a shows hysteresis loop for the $Co_{92}Zr_8$ thin film. From the *M–H* loop we found that $Co_{92}Zr_8$ thin film had well in-plane uniaxial anisotropy. The coercive force of easy axis and hard axis are both lower than 0.203 kA/m. The anisotropy field H_k was 2.4 kA/m. The saturation magnetization $\mu_0 M_s$ was 1.2 T. It means that the relative initial permeability of $Co_{92}Zr_8$ was high according to $M_s/H_k + 1 = \mu'$, and the loss is also low. The high permeability $Co_{92}Zr_8$ soft magnetic thin film was adopted to satisfy the extending of magnetic flux of thin-film inductor. From Fig. 2b, it can clearly be seen that the solid part of relative permeability of $Co_{92}Zr_8$ is $\mu_r' = 400$, which is about 400 times than Cu below 1 GHz. And the resonance frequency of the $Co_{92}Zr_8$ soft magnetic thin film is $f_r = 1.7$ GHz. Therefore, employing $Co_{92}Zr_8$ to prepare inductor may obtain better inductor properties with high inductance and low dissipation.

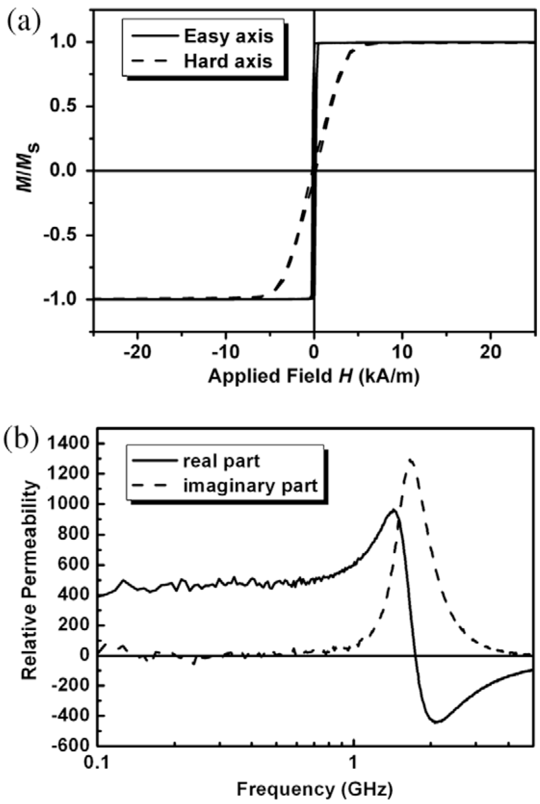

Fig. 2. (a) Hysteresis loop and (b) frequency dependences of the real and imaginary components of the relative permeability for $Co_{92}Zr_8$ soft magnetic thin film.

Fig. 3 shows the well-known equivalent-circuit model of miniature RF chip inductors suggested by Ahn and Allen [13], Yue and Wong [14] and Kim et al. [15]. In this model, *R* accounts for the metal resistance that symbolizes the energy loss due to the skin effect in the metal coils, *C* represents the stray capacitance between the wound coils, and *L* stands for the total inductance of the meander-type thin-film inductor. Therefore, the impendence equation can be described as follows (1)

$$Z = \frac{R(1 - 2\omega^2 Lc)}{(1 - \omega^2 Lc)^2 + (R\omega C)^2} + j\frac{\omega(L - \omega^2 L^2 C + R^2 C)}{(1 - \omega^2 LC)^2 + (R\omega C)^2} \tag{1}$$

where ω is angular frequency. The resistances of the Cu and $Co_{92}Zr_8$ inductors are 33 and 170 Ω, respectively. The inductance–frequency and capacitance–frequency characteristics can be derived from Eq. (1) and the performance–frequency characteristics, as shown in Fig. 4.

Fig. 4a shows the typical inductance–frequency (*L–f*) characteristics obtained from two different planar inductors. The solid and dashed lines represent the inductances of the $Co_{92}Zr_8$ and Cu inductors, respectively. From Fig. 4a, it can be seen that the inductance of the $Co_{92}Zr_8$ inductor is 5.0 μH, which is enhanced by five times from 1.0 μH of the Cu inductor at 60 MHz. The main reason of this result is that the $Co_{92}Zr_8$ soft magnetic material has the high permeability when frequency from 1 to 110 MHz, therefore, the magnetic flux of the $Co_{92}Zr_8$ thin-film inductor is greatly enhanced compared with the Cu thin-film inductor. To illustrate this result, we take straight conductor for example. Self-inductance of thin-film inductors with rectangular cross sections can be expressed by [16]

$$L = 0.002l\{\ln[2l/(w+d)] + 0.25049 + [(w+d)/3l] + \mu'\mu_0/4\} \tag{2}$$

where *L* is the inductance in microhenries, *l* is the conductor length, *w* and *d* are the rectangular dimensions of the cross section, μ_0 and μ' are the permeability of the vacuum and the dielectric relative, respectively. The total inductance for the $Co_{92}Zr_8$ meander-type thin-film inductors includes self-inductance and mutual inductance. The relative permeability of the $Co_{92}Zr_8$ thin film and Cu are 400 and 1, respectively. So, the self-inductance of the $Co_{92}Zr_8$ inductor is much higher than that of the Cu inductor. And then, the total inductance of the $Co_{92}Zr_8$ meander-type thin-film inductors is much higher than that of the Cu inductor, as shown in Fig. 4a.

Fig. 4b shows the typical capacitance–frequency (*C–f*) characteristics obtained from two different planar inductors. The solid and dashed lines represent the capacitances of the $Co_{92}Zr_8$ and Cu inductors, respectively. From the measured results of inductors, it is found that these capacitances of the $Co_{92}Zr_8$ and Cu inductors are approximately the same with the increasing frequency. It is

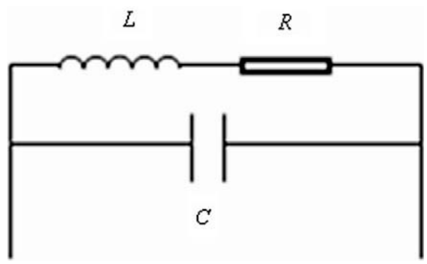

Fig. 3. Equivalent circuit of the RF chip inductor used to analyze circuit parameters.

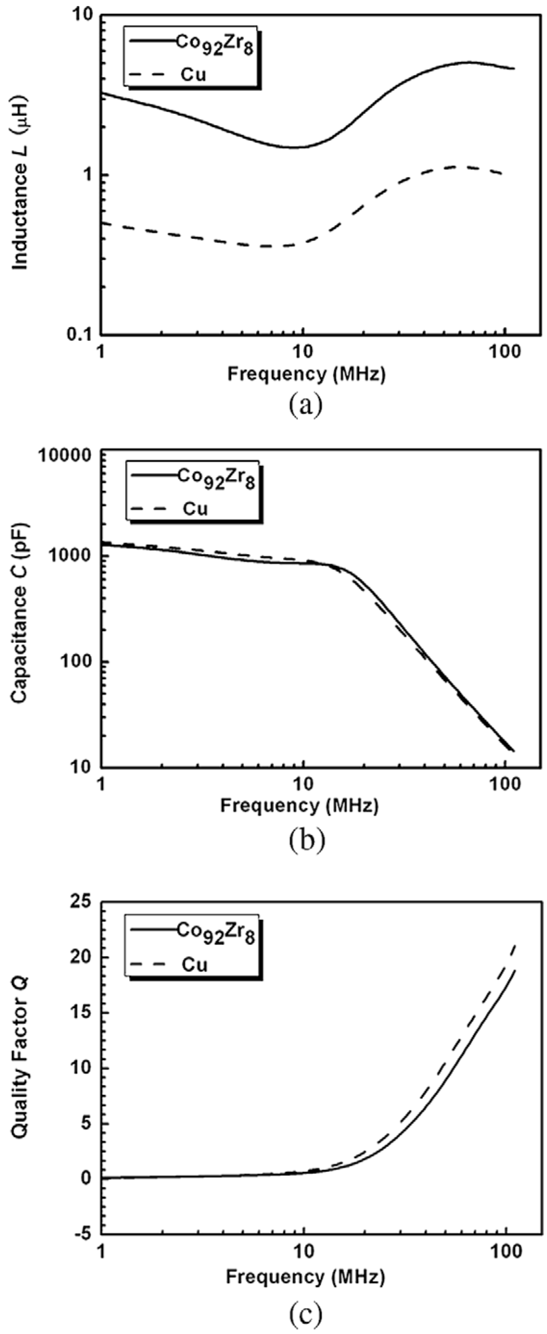

Fig. 4. Frequency dependences of (a) the inductance, (b) the capacitance, (c) the quality factor for the $Co_{92}Zr_8$ and Cu inductors

known that a capacitance can be described by $C \propto \epsilon S/d$, here, ϵ is the dielectric constant, S is the coil areas, and d is the distance between the coils. Because the two inductors have the same dielectric constant, coil areas and distance, the capacitances of the two inductors are approximately the same.

The typical quality factor-frequency (Q–f) characteristics of the thin-film inductors are shown in Fig. 4c. The solid and dashed lines represent the quality factors of the $Co_{92}Zr_8$ and Cu inductors, respectively. The quality factor of the inductors increases with increasing frequency. The quality factor of an inductor can be expressed as $Q=\omega L/R$ [17], here, ω is angular frequency, L stands for the total inductance, and R accounts for the metal resistance. From the Fig. 4c, it is shown that the quality factor of the Cu inductor is a little bit larger than that of the $Co_{92}Zr_8$ inductor. And The Q accounts for the stored magnetic energy and the ohmic loss in the resistance.

From Fig. 4, it can clearly be seen that the capacitance and quality factor of the inductor using $Co_{92}Zr_8$ soft magnetic material are approximately the same as that of the inductor using Cu, however, these little changes can be negligible with respect to the range of the increased inductance. In a word, the high-performance inductor is obtained, which has high inductance, high quality factor and low parasitic capacitance.

4. Conclusion

The $Co_{92}Zr_8$ thin-film inductor has been fabricated by using $Co_{92}Zr_8$ as conductor in compatibility with standard Si technology. From the measured results, the inductance of the $Co_{92}Zr_8$ inductor is about five times more than that of the Cu inductor at frequency 60 MHz, because the $Co_{92}Zr_8$ inductor has high magnetic flux with high permeability of $Co_{92}Zr_8$. The $Co_{92}Zr_8$ inductor compared with inductors in previous studies has a very good inductor performance with high inductance, high quality factor and low parasitic capacitance. Therefore, such an inductor has potential applications in MEMS and standard CMOS IC.

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