Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.556-557

P2-5

Grating Metal Structure with Low-K BCB and Electroplated Copper for High-Q Spiral Inductors

Sung-Ku Yeo, Seong-Ho Shin, Ju-Hyang Lee and Young-Se Kwon

Department of Electrical Engineering and Computer Science, KAIST,
373-1 Guseong-dong Yuseong-gu, Daejeon 305-701, Republic of Korea
Phone: +82-42-869-5421 Fax.: +82-42-869-8021 E-mail: dennis@kaist.ac.kr

1. Introduction

On-Chip high-Q Inductor is one of the most important elements in the microwave front-end modules, voltage controlled oscillators (VCOs), low-noise amplifiers (LNAs) and filters for impedance matching in power amplifiers [1].

In the past, many high-performance inductors on Si substrate have been proposed. But these inductors exhibit poor Q-factor due to the severe substrate loss of the standard grade silicon substrate and the ohmic loss of the aluminum thin-film [2]. Therefore, higher conductivity metal layers such as copper to reduce losses of the metal and low- loss substrate such as glass, quartz, sapphire and HRS (High Resistivity Silicon) to reduce losses in the substrate at high frequency are used. Also there is an approach to reduce substrate coupling loss by inserting a low-loss, low-K dielectric layer such as BCB (Benzocyclobutene) between inductor metal and substrate [3].

Nowadays, many approaches were proposed to reduce inductor's metal loss. The loss in the metal lines comes from the metal resistivity and the skin effect [4]. Aluminum is gradually replaced by copper and thickness of the inductor metal lines is increased to minimize resistive loss. The skin effect limits the effective conductive cross-sectional area of the metal lines [5]. Hence, there is a limitation of improvement of the inductor's Q-factor in spite of the increment of metal thickness. Metal loss is primarily caused by a series resistance, which is induced by the skin effect, ground effect and current crowding effect [6]. Therefore, if the skin effect and current crowding resistance are reduced, we can increase Q-factor of the spiral inductors.

In this paper, we are proposing to reduce metal ohmic loss of the inductor metal lines and to enhance Q-Factor by making grating metal structure with low-K BCB and electroplated copper.

2. Experiments

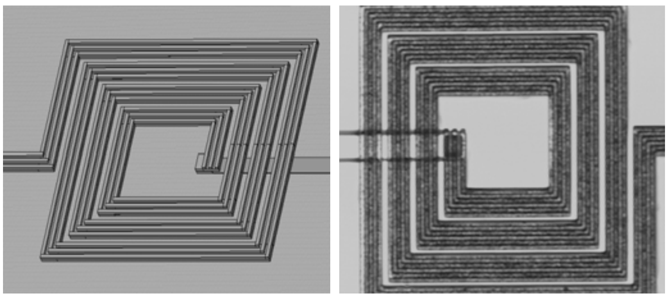
Table I shows geometrical dimensions of the fabricated grating spiral inductors. Figure.1 gives pictures of the proposed grating spiral inductor, which is made by BCB dielectric and electroplated copper process. Grating metal structure is fabricated by the additional photolithography and copper plating process, after the second metal plating process is completed.

The inductors were fabricated on a p-type high resistivity silicon substrate with a resistivity of 3kΩ·cm. First 2-μm-thick metal was fabricated by copper plating. And a 4-μm-thick BCB layer was formed with 3000 rpm spinning speed. BCB via holes(18~24μm) were opened on the Cu strips for contact with second metal. After curing the BCB dielectric at 250°C, a Ti-W (300 Å thick) and Au seed layer (500 Å thick) were sputtered by DC sputter.

Table I
Listed dimensions of the fabricated grating spiral inductors

parameters	Inductor
N(Number of turns)	1.5~4.5
Width(μm)	20
Spacing(μm)	10
Inner Radius(μm)	120
Metal thickness(μm)	2/3/3(1st/2nd/3rd)
Grating Width/Spacing(μm)	4/4

Then, photoresist (AZ4330) layer was coated and inductor pattern was defined. The copper metallization was done by copper electroplating and via was filled with copper metal. Grating metal structure was fabricated by additional photolithography and copper electroplating. To avoid the oxidation of the Cu layer, a thin layer of Ni/Au cap can be electroplated on top of Cu. Finally, the photoresist and Ti-W /Au seed layers were removed by chemical stripping and metal etching. Our entire grating inductor process is carried out with low temperature (below 250℃) to be compatible with standard backend CMOS process.



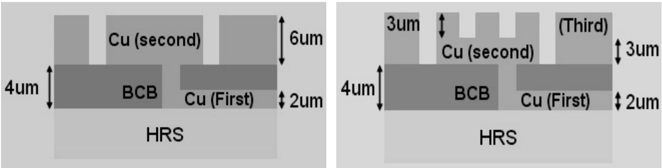
(a) (b)

Fig. 1 Pictures of inductor with grating metal structure
(a) 3-D structure of the grating inductor
(b) CCD photograph of the grating inductors

3. Results and Discussion

Two types of inductors, the reference spiral inductors (2nd, 6μm) and grating metal structure spiral inductors (2nd/3rd, 3/3 μm), are compared to show the effect of grating metal structure. The schematics of each inductor are shown in Fig.

2. On-wafer measurement of inductors was conducted using a network analyzer HP8720C and cascade Micro-tech GSG 150 probes.



(a) (b)

Fig. 2 Schematic cross-sectional diagrams of the fabricated spiral inductors
(a) Normal metal line(2^{nd}, 6㎛) spiral inductor, (b) Grating metal structure spiral inductor($2^{nd}/3^{rd}$, 3/3㎛)

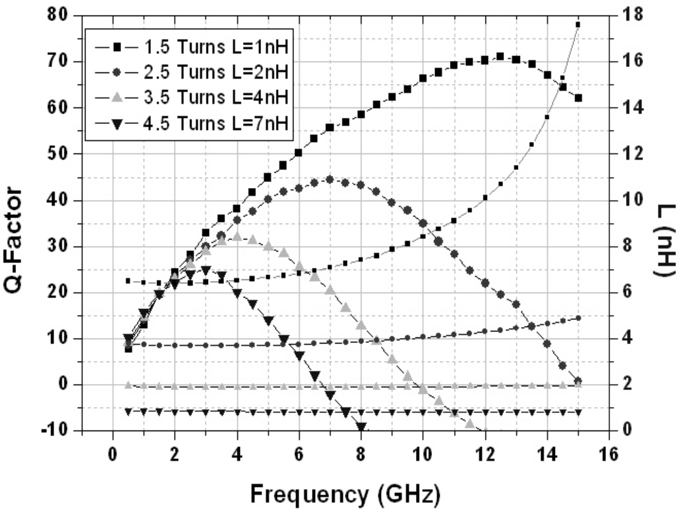


Fig. 3 Measured quality-factors and inductance values with different turns (1.5~4.5 turns)

Fig. 3 shows measured Q-factors of the grating structure spiral inductors. The Q-factor and inductance (L) were derived from the following equations.

$$Q_{ind} = -\frac{\mathrm{Im}\{Y11\}}{\mathrm{Re}\{Y11\}} \quad (1), \quad L_s(f) = \mathrm{Im}(-\frac{1}{Y21})/2\pi f \quad (2)$$

Table II shows that Qmax values are 72, 45, 32, 25 for grating spiral inductor's turns (1.5~4.5), while inductance values are 7, 4, 2, 1nH, respectively. The Q-factors are better than those of conventional on-chip spiral inductors because of low-K BCB, copper electroplating, and grating metal structure.

Table II
Measured values of the fabricated grating spiral inductors

Turns	1.5	2.5	3.5	4.5
Qmax	72	45	32	25
L(nH)	1	2	4	7
f-resonance(GHz)	12.5	7	4	3

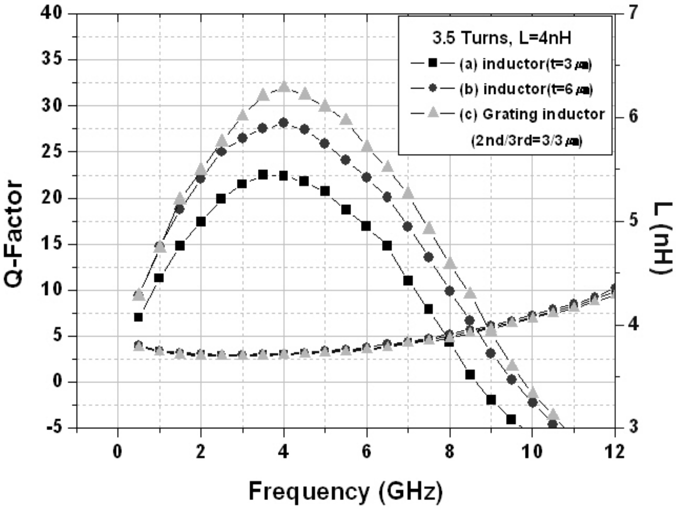


Fig. 4 Comparison of different inductors which are (a) Spiral inductor(2^{nd}, 3㎛), (b) Spiral inductor(2^{nd}, 6㎛), and (c) Grating metal structure spiral inductor($2^{nd}/3^{rd}$, 3/3㎛)

Fig. 4 shows that the Qmax value of the (c) grating metal structure inductor improves by 15% compared to the (b) inductor (2^{nd}, 6㎛) and improves by 45% compared to the (a) inductor (2^{nd}, 3㎛), while the inductance values of three compared inductors are identical. Enhancement of the Qmax value is primarily caused by the increased effective areas of the inductor's metal line, which decrease the skin effect and the current crowding effect. Actually, effective areas increase of 23% occurs between (c) grating metal structure inductor and (b) normal inductor (2^{nd}, 6㎛).

4. Conclusions

In this paper, the grating metal structure spiral inductor has been proposed and fabricated using low-K BCB and electroplated copper. The proposed inductor's Q-factor is between 25 and 72 while inductance values range from 1 to 7nH. By using simple electroplating technique, effective areas of the inductor metal lines have been increased and Q-factor values have been enhanced by 15% when compared with normal structure inductor that has a same metal thickness.

References

[1] Chiaming Alex Chang et. al., IEEE Transaction On Microwave Theory And Techniques, Vol.52, No.5, MAY (2004)
[2] Joachim N. Burghartz and Behzad Rejaei et. al., IEEE Transaction On Electron Devices, Vol.50, No.3, MARCH (2003)
[3] Xiao Huo, Kevin J. Chen and Philip C.H. Chan et. al., IEEE Electron Device Letters, Vol. 23 No. 9, SEPTEMBER (2002)
[4] Matthias Peter, Heiko Hein, Frank Oehler, Peter Baureis, IEEE MTT-S Digest 2001-2004 (2002)
[5] Ban-Leong Ooi, Dao-Xian Xu, Pang-Shyan Kooi, andFu-Jiang Lin, IEEE Transaction On Microwave Theory And Technique , Vol. 50, No. 9, SEPTEMBER (2002)
[6] W.B.Kuhn and N.M.Ibrahim et. al., IEEE Microwave Theory and Techniques, 49, 1, 31-39, (2001)