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Method for Extracting RF Characteristics of CMOS-MEMS Inductors

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1. Introduction

Improving the performance of on-chip inductors is the key to reducing the size and power consumption of RF CMOS circuits [1]. A promising way to improve the performance is to fabricate thick air-suspended inductors above a CMOS LSI [2]. We have achieved the fabrication of such inductors through the fusion of CMOS and MEMS technologies [3].

In the development of CMOS-MEMS inductors, analyzing the loss factors of the inductors is important for obtaining high performance. For the analysis, a new method for extracting RF characteristics of CMOS-MEMS inductors is required to investigate the influence of the skin effect in thick interconnections and the influence of a lossy CMOS substrate at high frequencies.

In this paper, we first explain the structure of our CMOS-MEMS inductors. Then, a new extraction method is proposed. Finally, an analysis of inductor losses is demonstrated by using the method.

2. CMOS-MEMS Inductor

A structure of the CMOS-MEMS inductor is shown in Fig. 1 [3]. The inductor is suspended above a CMOS LSI and has thick interconnections. In addition, the inductor is sealed with a film for protection by using spin-coating film transfer and hot-pressing technology [4].

The losses in the inductor are caused by interconnect resistance, and magnetic and capacitive coupling with the CMOS substrate. The resistance of the thick interconnections at high frequencies is affected by surface current distribution due to the skin effect. Thus, extracting this effect is important for CMOS-MEMS inductors. In addition, the suspension reduces parasitic capacitances and increases the self-resonant frequency, so an extraction method applicable to a wide frequency range is required.

3. Extraction Method

A flow of the proposed extraction method is shown in Fig. 2. It features (i) skin-effect extraction by means of the measurement of coplanar transmission line and (ii) wide-frequency applicability through the use of T-shaped inductor model.

First, S parameters of an inductor and a coplanar transmission line are measured with a network analyzer. Next, the influence of pad parasitic capacitance is removed by using a de-embedding technique. Then, impedances of a T-shaped circuit are calculated. The T-shaped circuit can be used in a wider frequency range than a conventional π-shaped circuit [5], so it is suitable for CMOS-MEMS inductors. Then, model parameters of the T-shaped inductor model, which is shown in Fig. 3, are extracted. The model takes into account the effects of interconnect resistance and capacitive and magnetic coupling with a CMOS substrate. We designed the model so that each model parameter can be determined without using parameter fitting techniques in order to suppress deviation from actual electrical characteristics. In the extraction process, the skin effect included in the interconnect resistance is extracted by exploiting the measurement results for the coplanar transmission line, which is formed on a low-loss substrate to measure the skin effect accurately. Finally, AC circuit simulation is carried out using the T-shaped inductor model, which allows us to analyze inductor losses by calculating power dissipation at each resistor.

4. Results and Discussion

Figure 4 and Table 1 show the extracted model parameters of the T-shaped inductor model. The extracted inductance up to 10 GHz is approximately consistent with the calculated one, indicating that the extraction method provides appropriate parameters. The increase of the interconnect resistance at high frequencies was successfully extracted by using the coplanar transmission line.

The analyzed loss factors of the inductor are shown in Fig. 5. The dominant loss factors are the interconnect resistance at 1 GHz and magnetic coupling at 10 GHz. The loss due to capacitive coupling is much smaller than the other losses. These results indicate that the proposed method enables the analysis of loss factors in CMOS-MEMS inductors.

5. Summary

An extraction method featuring skin-effect extraction and a T-shaped inductor model is proposed. The characteristics of a CMOS-MEMS inductor were extracted by using the method, revealing the loss factors in the inductor. Therefore, the proposed method is suitable for the analysis of CMOS-MEMS inductors.

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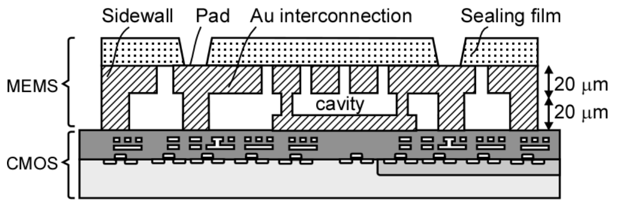

Fig. 1. Cross-sectional schematic of a CMOS-MEMS inductor.

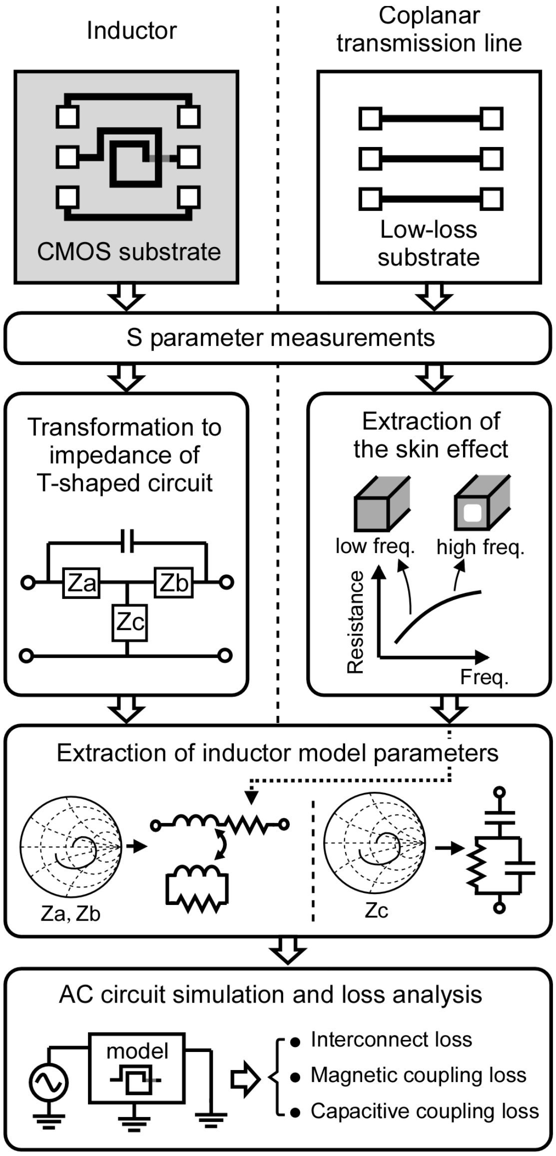

Fig. 2. Flow for extracting RF characteristics of CMOS-MEMS inductors. The S parameters of an inductor and a coplanar transmission line are measured and translated to a T-shaped inductor model for analysis.

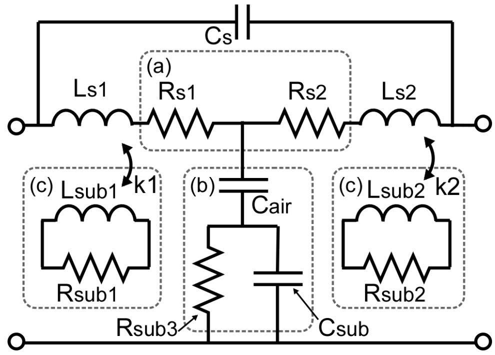

Fig. 3. Schematic diagram of the T-shaped inductor model. The model includes the effects of (a) interconnect resistance, (b) capacitive coupling, and (c) magnetic coupling with a CMOS substrate.

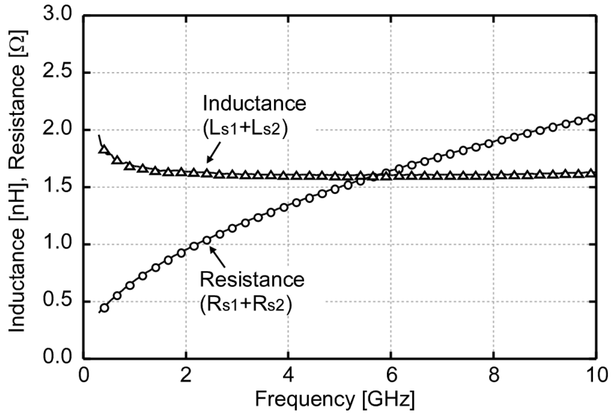

Fig. 4. Extracted inductance and interconnect resistance of the CMOS-MEMS inductor. The increase of the resistance at high frequencies is extracted from the measurement results for the coplanar transmission line.

Table. 1. Extracted model parameters of the CMOS-MEMS inductor at 1 GHz and 10 GHz.

	(k1+k2)/2	Cair	Csub	Cs
1 GHz	0.44	211 fF	103 fF	25 fF
10 GHz	0.54	211 fF	78 fF	25 fF

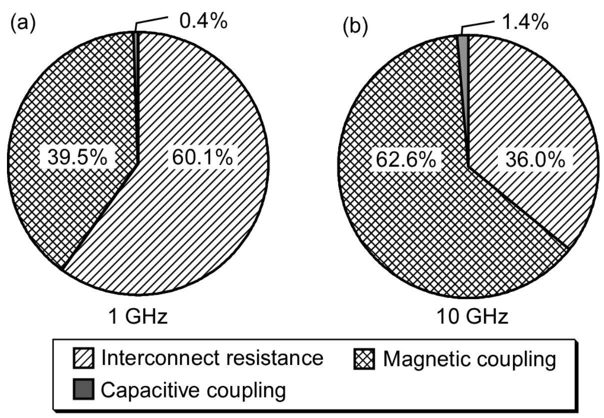

Fig. 5. Analyzed loss factors of the CMOS-MEMS inductor at (a) 1 GHz and (b) 10 GHz.