Encapsulation of the Micromachined Air-Suspended Inductors

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***Abstract*—We have proposed and investigated encapsulation of air-suspended microstructures, especially for micromachined inductors in silicon radio frequency integrated circuits (RF ICs), providing a practical solution for covering up structural weakness to shock/vibration and accommodating package processes. As an encapsulating agent, two materials have been studied; polydimethylsiloxane (PDMS) for examining possible structural deformation when spin-coated, and benzocyclobutene (BCB) for measuring possible electrical performance degradation due to the finite dielectric constant. According to the experiments, no structural deformation has been observed after PDMS is spin-coated. After encapsulated by BCB, the maximum 20% degradation of integrated inductor Q-factor has been observed.**

I. Introduction

The inductor has been used as a key component in most RF IC's, such as voltage-controlled oscillators (VCO), low-noise amplifiers (LNA), power amplifiers, and so on. Nevertheless, integrated inductors fabricated by conventional IC processes have suffered from large ohmic and substrate losses (resulting in low *Q*-factors below 15) due to thin metal film and intimate contact with lossy silicon substrate, respectively. Recently, several researches employing thick metal and suspended inductor structure have been done using thick-metal surface micromachining technology [1], [2]. However, most frequently-asked questions have been about the suspended structure, such as the structural weakness to shock and vibration and how to package safely[3]. Therefore, in this work, we have proposed and investigated an encapsulation method for placing the suspended structure firmly in the encapsulant, providing a solution for those questions. Also, we have investigated possible *Q*-factor degradation due to the higher dielectric constant of encapsulant than that of air.

II Fabrication

Fig.1 shows the cross-sectional process flow for fabricating air-suspended inductors, which was reported previously [4], adding up with the final step of encapsulation proposed in this work. The process steps up to Fig. 1(h) were developed for fabricating thick-enough (>10μm) metal line, suspended with a sufficient air-gap (>50μm), for substantially reducing metal ohmic and substrate losses to achieve high *Q*-factors (>30). Standard silicon substrates of 1~30Ω·cm in resistivity covered with 1μm and 7μm SiO_2 have been used in this work. When considering the encapsulant for packaging of air-suspended inductors, the encapsulant must have a low dielectric constant and low process cost and visibility for observing the deformation of structure after encapsulant is molded. Polydimethylsiloxane (PDMS) can be a good solution as encapsulant due to low dielectric constant (2.65) and low price and spin- coatable, and transparent characteristics for observing of a deformation of inductors

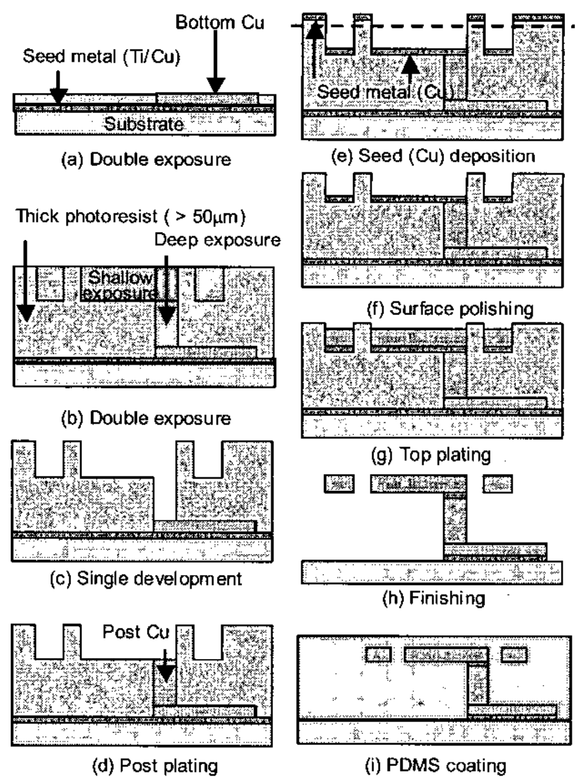

Fig. 1: Cross-sectional view of the fabrication process

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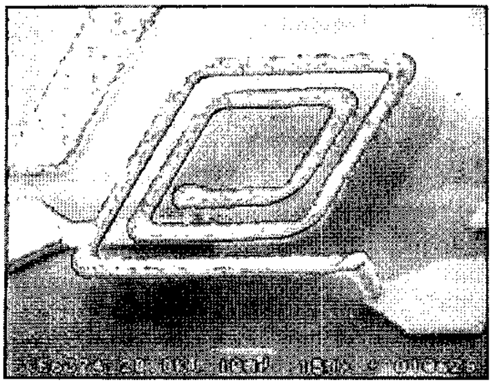
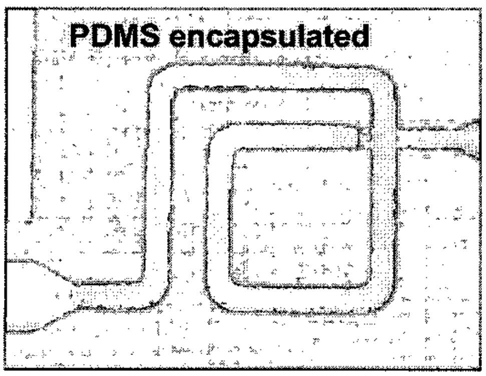
after encapsulated. After releasing the air-suspended inductor, PDMS is spin-coated with 500rpm, 30sec conditions on the substrate and cured at 100°C for 60min.



(a)Air-suspended inductor



(b) PDMS coated inductor

Fig.2 Photographs of fabricated inductors

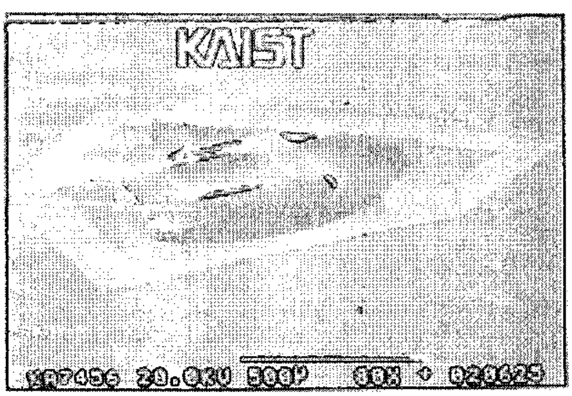
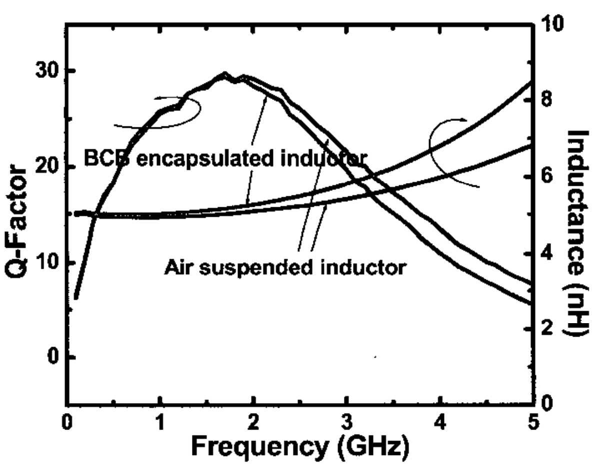


Fig.3 Photograph of BCB encapsulated inductor with 3 turn

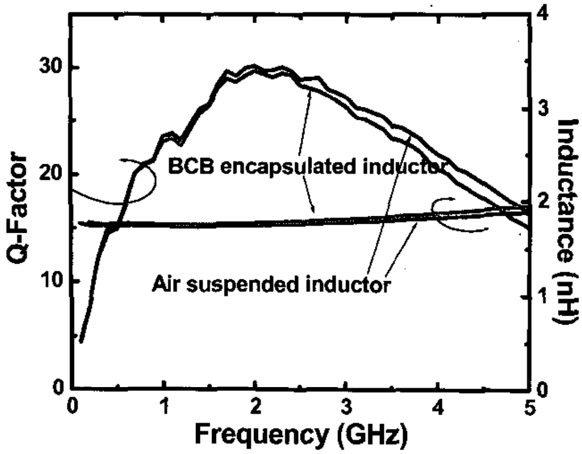
Fig. 2(a) and 2(b) show the fabricated air-suspended and PDMS-coated inductors, respectively. The metal width, thickness and suspension height were 30μm, 10μm, and 50μm, respectively. As can be seen in Fig. 2b, no structural deformation has been observed in the whole 4 inch wafer after encapsulation. In order to investigate inductor performance variation after encapsulation, we have used a BCB material as an encapsulant since it has been widely used in RF/microwave applications [5]. At this time, benzocyclobutene (BCB) is dropped on the air-suspended inductor to accommodate probe accessing and it is cured at 150°C for 60min. Fig. 3 shows the suspended and BCB-encapsulated inductors.

III MEASUREMENT AND DISCUSSION

The on-wafer RF measurement has been performed using an HP 8510C network analyzer, coplanar GSG probes, a Cascade microwave probe station, and a CS-5 calibration kit. The small pad(20μm×35μm) for measurement is used so that de-embedding is not carried out. Fig.4 shows the measured inductance and Q-factor of the inductor on silicon substrate with 1μm oxide at a few GHz frequency ranges before and after the BCB encapsulation. As can be seen in Fig. 4, there has been negligible change of inductance and Q-factor by the encapsulation. This can be explained using the conventional inductor model shown in Fig. 5(a) and the schematic cross-sectional view of the BCB-encapsulated inductor in Fig. 5(b). The BCB encapsulation mainly changes (increases) capacitance between the inductor and the substrate, which are C_{ox1} and C_{ox2} in Fig. 5(a). Each capacitance consists of the capacitances originated from the bottom line and the



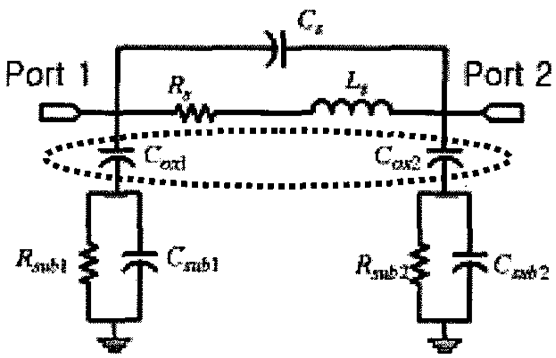
(a) 1 turn inductor



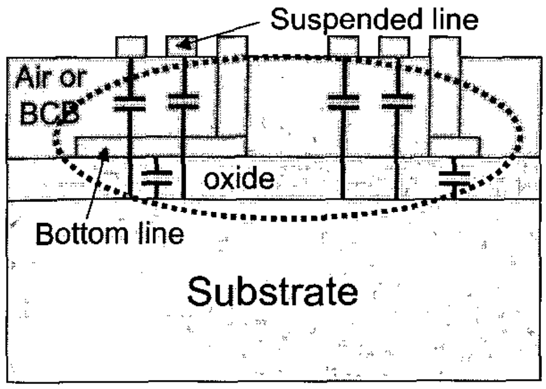
(b) 3turn inductor

Fig.4. Measured data of air suspended and BCB encapsulated inductors with 1 turn and 3 turn

suspended line, as shown in Fig. 5(b). Since the BCB encapsulation can only change capacitance from the suspended line, where the change is not efficient compared with the dominant capacitance from the bottom line due to the thin (1μm) oxide layer, the overall capacitance change becomes not much to affect the inductor performance. This has been verified with the EM simulation using HFSS, as shown in Fig. 6. The simulated structure was 1-turned inductor shown in Fig. 4(a). The simulated result is very similar to the measured result shown in Fig. 4(a). If the thicker oxide layer between the bottom line and the substrate is used for reducing a capacitance from the bottom line, the effect by BCB encapsulation to Q-factor can be emphasized. Fig. 7 shows the simulated results with the same structure shown in Fig. 6 differentiating the oxide thickness (7μm). The effect of the BCB encapsulation can be seen more clearly.

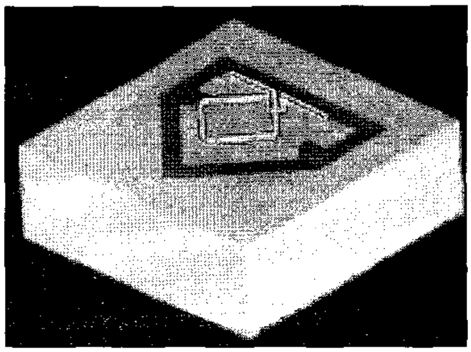


(a) Equivalent circuit

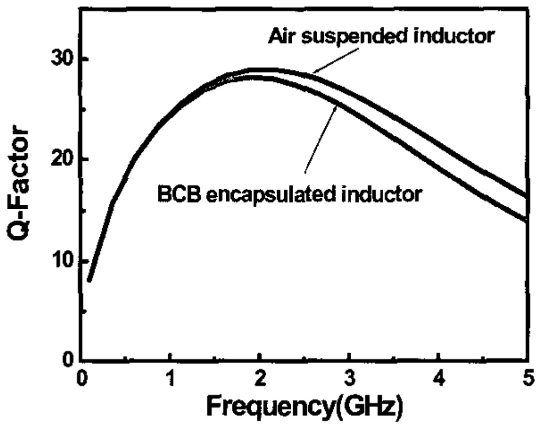


(b) Cross sectional view

Fig. 5 : Equivalent circuit and cross sectional view of inductor



(a) Simulation structures



(b) simulated data

Fig.6 : Simulated data from HFSS,EM simulator and simulated structure

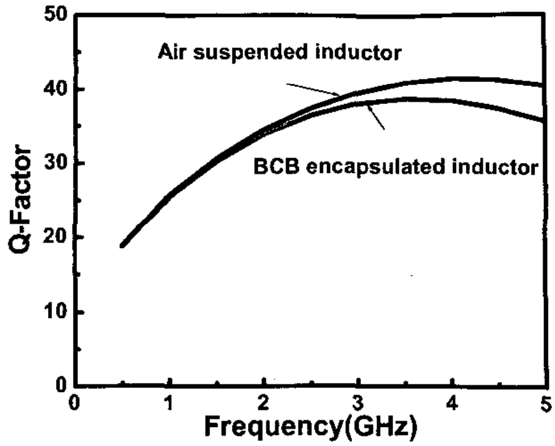


Fig. 7 : Simulated data from HFSS, EM simulator with 7μm oxide

Fig. 8 shows the Q-factor variation of the 3-turned inductor on 7μm oxide after BCB encapsulation. The results are fairly different from those observed from the inductors on 1μm oxide. As shown in Fig.8, the Q-peak frequency and maximum Q-factor is enhanced compared with Fig.4(b). This is due to small capacitance between bottom line and substrate. By the BCB encapsulation, the Q-peak frequency is shifted from 4.1GHz to 3.3GHz and the maximum Q-factor is decreased from 55 to 47. About 20% degradations of Q-peak frequency and maximum Q-factor have been observed due to encapsulation. The amount of the degradation can show that it is reasonable

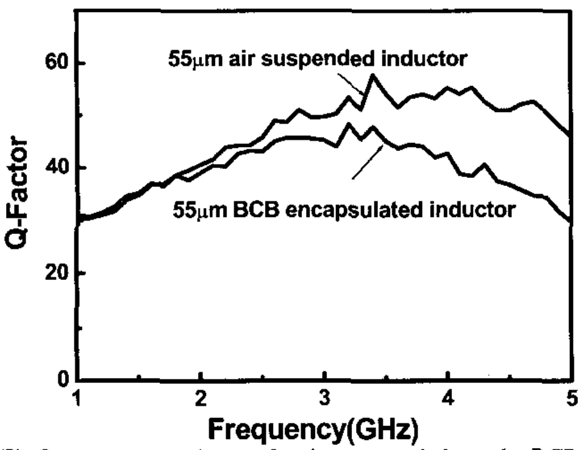


Fig.8: Measured data of air suspended and BCB encapsulated inductors with 3 turn on silicon substrate with 7μm oxide

to employ the encapsulation technique to protect the suspended inductor without severe affection in inductance and Q-factor.

V. CONCLUSION

In this work, we have successfully shown that post-release encapsulation can be a good and practical solution for the mechanical reliability and package issues of the air-suspended inductors. Also the performance degradation by encapsulation has been verified with experimental results.

ACKNOWLEDGEMENTS

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