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High-Q Resonator on Thin-Film Substrate for mm-wave System-on-Package (SOP)

Sangsub Song and Kwang-seok Seo

Seoul National University, School of Electrical Engineering and Computer Science
San 56-1 Shillim-dong Kwanak-gu Seoul 151-742, Republic of Korea
Phone: +82-2-877-0298, Fax: +82-2-887-6575, E-mail: insss79@snu.ac.kr

1. Introduction

Conventional high-Q resonators with metallic rectangular or cylindrical waveguides are heavy in weight, costly to manufacture, and difficult to integrate with monolithic integrated circuits. To solve these problems, there has been an increasing effort to develop high-Q cavity resonators using bulk micromachining of silicon [1]-[3].

However, for integrating the resonator into the mm-wave module, more intelligent packaging technology is needed. This paper presents novel high-Q resonator structure for mm-wave SOP technology. For the resonator, a silicon cavity was fabricated with silicon wet-etching process and integrated on a thin-film substrate with coplanar waveguide (CPW) lines by means of flip-chip bonding. And the silicon cavity has a groove structure on the opposite side of the CPW feed line to avoid the unwanted detuning effect. The CPW line on the thin-film substrate can make it possible to realize the silicon cavity resonator with very simple coupling structure.

In the following sections, the proposed resonator is analyzed and demonstrated. The unloaded Q of the fabricated resonator is measured and computed.

2. Cavity Resonator Design

A 1-port 60-GHz resonator was designed to verify the novel high-Q resonator structure. Fig. 1 shows overview of the proposed resonator.

The resonator's dimension is determined by the corresponding resonance frequency from

$$f_{101} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad (1)$$

for the TE_{101} dominant mode, where a, b, and d are the width, height, and length of the cavity, respectively, and m=l=1, n=0 are the indexes for the 101 mode. Considering the slop of cavity wall (54.75°) and the height of flip-chip bumps, the cavity's top side dimension (3785 μm x 3785 μm) was determined for 60-GHz resonance frequency.

The silicon cavity is enclosed with the metal plane on the top side of the thin-film substrate suitable for mm-wave SOP. The thin-film substrate consists of a 30-μm-thick BCB layer over a lossy silicon substrate (20 Ω·cm), Si-bumps, and flip-chip bumps. Here, the lossy silicon substrate is used to suppress parasitic substrate modes between CPW lines and a bottom metal plane below the substrate. More information on the thin-film substrate with flip-chip technology was presented in [4].

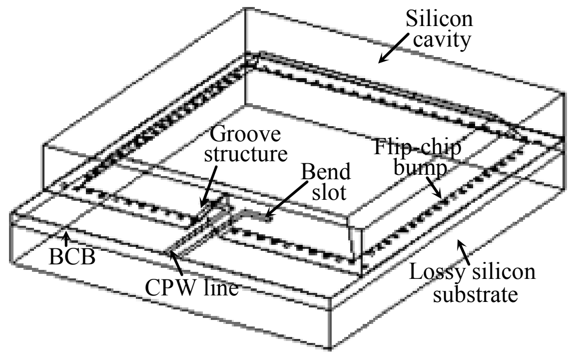

Fig. 1. Schematic overview of the proposed resonator.

Electromagnetic wave coupling with the cavity resonator is achieved from the CPW line formed on top side of thin-film substrate. The coupling between the cavity and the CPW line is achieved via each bend slot on the CPW line as shown in Fig. 2. The CPW line is ended with a short circuit. This guarantees maximum current at the slot and optimum magnetic coupling. Full-wave field simulation was performed to optimize the size of the slot as well as the cavity dimension with the groove structure.

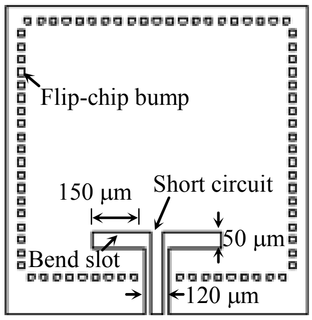

Fig. 2. Geometry of the thin-film substrate for coupling with the resonator.

3. Fabrication

The cavity was fabricated by silicon micromachining techniques. A silicon wafer <100> was wet-etched in a 45 % KOH solution at 80 °C until a depth of 380 μm was achieved. A 1000 Å SiN_x was used as a mask. At the same time, the groove structure in the silicon cavity was formed on the opposite side of the CPW feed line. However, the groove structure with two convex corners is not apparent since the etching of convex corners in anisotropic wet-etching leads to a deformation of the edges due to corner undercutting [5]. Therefore, to protect concave corners, compensation lines were introduced at concave corners. The groove structure can be predicted since the concave corner shape after wet-etching is determined by compensation lines and wet-etching condition. And the silicon cavity was electroplated with 5-μm-thick gold. The cavity was then flip-chip bonded on the thin-film substrate with Au/Sn flip-chip bump. After flip-chip bonding, the height of the flip-chip bump was about 5 μm. Fig. 3 shows the fabricated silicon cavity, thin-film substrate, and resonator.

It is worthwhile to mention that the fabrication process for the silicon cavity involves only single silicon wafer with one mask level, and major processing techniques required are silicon wet-etching and electroplating. And the high-Q resonator can be realized and packaged just as the silicon cavity is flip-chip mounted on the substrate with the CPW line. This means that the fabrication process is very simple and the high-Q resonator can be easily integrated into mm-wave SOP modules.

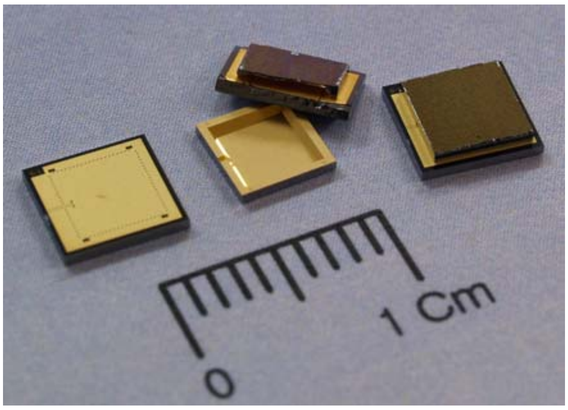

Fig. 3. Fabricated silicon cavity, thin-film substrate, and resonator.

4. Results and Discussion

A return loss and real-imaginary plot of the measured *S*-parameters from the fabricated resonators are shown in Fig. 4 and Fig. 5, respectively. The data was processed to obtain the unloaded *Q* of the resonators using the critical points method [6]. In this method, the *S*-parameters are converted to input impedance and plotted on the real-imaginary plane. Two critical points are marked as f_1 and f_2, which are the maximum and minimum reactance points, respectively. From these frequencies, the unloaded *Q* factor, Q_u, can be found with

$$Q_u \approx \frac{f_1 + f_2}{2|f_1 - f_2|} \qquad (2)$$

Using the above definitions and the measured results, Q_u of the proposed resonator is found to be about 750 with 60.04 GHz resonance frequency. The measured results are very similar with the simulated results from full-wave field simulation.

5. Conclusions

A novel high-Q resonator structure, which is compatible with mm-wave SOP technology, has been proposed. This scheme enables that the high-Q resonator for mm-wave SOP can be realized and packaged just as the silicon cavity is flip-chip mounted on the substrate with the CPW line. The 1-port 60 GHz resonator was fabricated to demonstrate this technology and excellent results have been achieved. As the measured Q_u of the fabricated resonator are about 750 with 60.04 GHz resonance frequency, these results are very close with the expected results from full-wave field simulation.

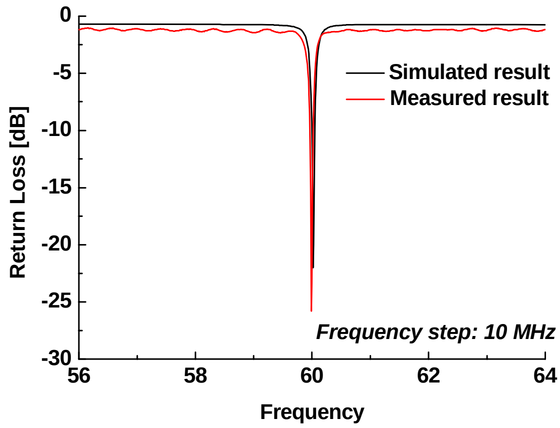

Fig. 4. Measured and simulated return loss for the resonator.

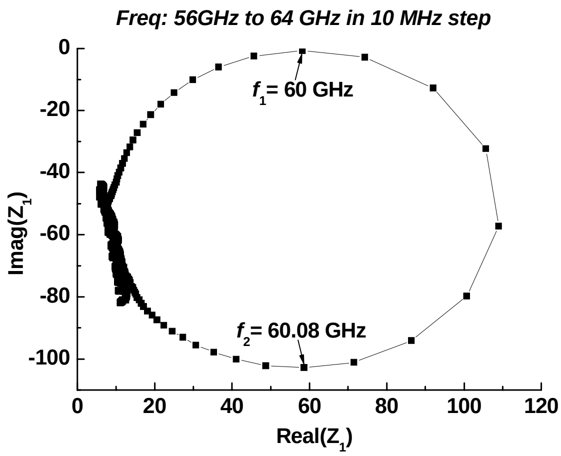

Fig. 5.Measured real-imaginary plot for the fabricated resonator

Acknowledgements

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