Motional Resistance Issue of TSV-Based Resonator Device and Its Improvement With a Concave Cu TSV Structural Design

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***Abstract*— Motional resistance of TSV-based resonator devices with 3D integration techniques is investigated at the operating oscillating mode. Even with well-developed TSV and device fabrication, the motional resistance issue of the TSV-based resonator device is found due to the poor connected Ag paste. The corresponding solution is demonstrated by a modified concave Cu TSVs structure. This modified concave Cu TSV design shows the excellent device characteristics and no visible gaps between the Cu TSVs and resonator devices to insure a good electrical connection.**

***Index Terms*— Three-dimensional (3D) integration, concave through silicon via (TSV), motional resistance.**

I. INTRODUCTION

THREE-DIMENSIONAL (3D) integration technology has received generally acknowledgement as the probable solution for next semiconductor generation. The fact comes from that this technology performs the potential to make a breakthrough in the limit of traditional 2D scaling and provides a platform for multifunctional integration. This technology scheme possesses the advantages such as small form factor, high performance, the great capability for heterogeneous integration and low power consumption [1]–[3]. Furthermore, 3D integration is the candidate to facilitate the concept of “More than Moore” making the possible connection between different materials, substrates, and functional blocks [4], [5].

TSV-based resonator device has been proposed using Si packaging technologies, Cu TSVs and metal hermetic sealing bonding [6]. Several advantages of TSV-based resonator device are revealed including easy of scaling down, wafer level process and compatible with semiconductor industries. This advanced TSV-based resonator device uses Si cap and metal hermetic sealing bonding, but not metal lid to protect the active area of resonator and avoid mechanical attack, contamination and moisture. In addition, Ag paste, which connects quartz blank and Cu TSV, can reduce and absorb the thermal stress near Cu TSV surface due to its flexibility [7]. However, relation between electrical performances such as motional and this advanced process scheme is not studied yet. In this letter, we investigate the issues of motional resistance and demonstrate a novel Cu TSV with concave structure design. The electrical and frequency characteristics of TSV-based resonator device are realized and improved simultaneously with concave Cu TSVs structure.

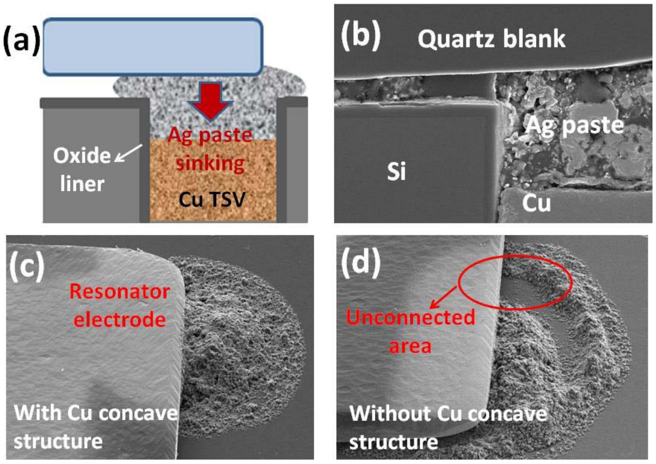

Fig. 1. (a) Schematic of concave Cu TSV structure; (b) SEM cross-sectional image view of concave Cu TSV structure; (c) SEM image of TSV-based resonator device with concave Cu TSV structure; (d) SEM image of TSV-based resonator device without concave Cu TSV structure.

II. PROCESS AND INTEGRATION DEMONSTRATION

The schematic diagram and SEM cross-sectional image of concave Cu TSVs connecting crystal resonator device below and Ag paste above are shown in Figs. 1(a)–(b). Cu TSVs with the diameter of 100 μm and the depth of 250 μm are formed by deep reactive-ion etching (DRIE) Bosch process, 1-μm plasma enhanced chemical vapor deposition (PECVD) oxide liner deposition, sputtering TiN/Cu barrier/seed layer deposition, and Cu electrochemical deposition (ECD) to fill holes. After Cu ECD fabrication, the overfilling Cu must be grinded and polished until the oxide liner is exposed. In order to fabricate the concave Cu TSVs, the top side of Cu TSVs is etched back by a mixture of piranha solution (H_2O_2:H_2SO_4=1:1, by volume) for approximately 10 second. Afterwards, 200-μm-diameter Ag paste is applied

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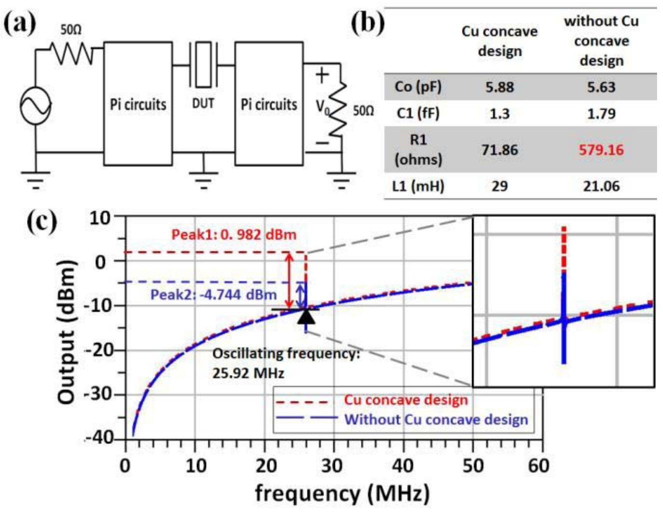

	Cu concave design	without Cu concave design
Co (pF)	5.88	5.63
C1 (fF)	1.3	1.79
R1 (ohms)	71.86	579.16
L1 (mH)	29	21.06

Fig. 2. (a) Vector network analyzer with pi circuits; (b) measured results of TSV-based resonator device with and without concave Cu TSV structure; (c) the response output versus frequency of two TSV-based resonator devices.

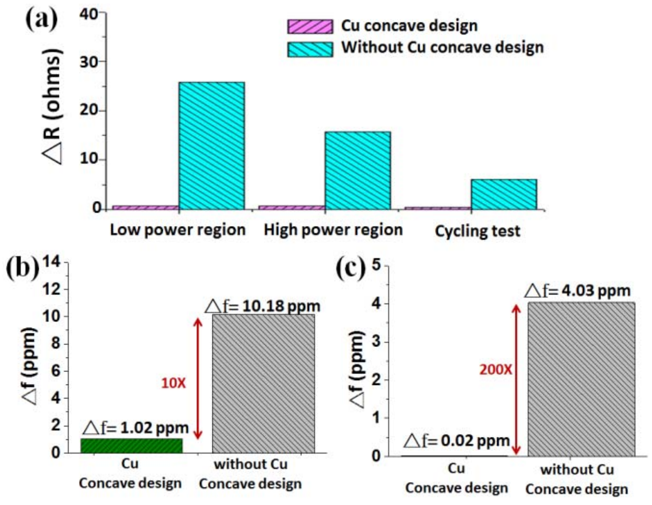

Fig. 3. (a) The range of motional resistance for low, high frequency and a cycling test; (b) the range of oscillating frequency for with and without concave Cu TSV structure; (c) stability of oscillating frequency for with and without concave Cu TSV structure.

on concave Cu TSV to attach quartz blank and then cured at 200 °C for 2hr in vacuum, as shown in Fig. 1(c). On the other hand, for Cu TSV structure without the concave, the collapsed Ag paste is found owing to the fluidic Ag paste collapsed between Cu TSV and crystal resonator, and the larger value of motional resistance is detected. The issue of motional resistance is caused by the bad (partial) connection between the collapsed Ag pasted and resonator electrode in Fig. 1(d). Consequently, a good connected Ag paste between resonator electrode and Cu TSV is important to ensure the electrical integrity in this research.

Based on the above integration scheme, TSV-based resonator devices using concave Cu TSVs are successfully fabricated with the connection of the electrical signal inside the resonator device.

III. ELECTRICAL AND OSCILLATING FREQUENCY INVESTIGATION OF TSV-BASED RESONATOR DEVICES

Fig. 2(a) shows the vector network analyzer with pi circuits for measurement of conventional and TSV-based crystal resonator devices. Experimental results in Fig. 2(b) display the components of Butterworth-Van Dyke equivalent circuit [8], including C_1, L_1, R_1 and C_0 of TSV-based resonator device with and without concave Cu TSV structure. The quartz blanks of both Cu TSV structures connect with resonator devices, so the components of electrical parameter and oscillating frequency can be measured by vector network analyzer. However, the issue of a large motional resistance related to the collapsed Ag paste appears in TSV-based resonator devices. The frequency response is also influenced due to poor motional resistance and the recognition rate of oscillating frequency decreases compared to the device with concave Cu TSV. The output peak value of frequency response drops down from 0.982 dBm to −4.744 dBm at same oscillating frequency of 25.92 MHz, as shown in Fig. 2(c).

IV. RELIABILITY INVESTIGATION AND DEVICE CHARACTERISTICS

Considering the stability characteristics of TSV-based resonator devices, the range ($\Delta X = X_{max.} - X_{min.}$) and the stability characteristics of motional resistance and oscillating frequency are considered for evaluating the whole device characteristics with and without concave Cu TSV structure. Since all the measured results from different samples with and without concave Cu TSV structure are in the same order on the motional resistance and oscillating frequency, Figure 3(a)–(c) demonstrate performance comparisons of two samples with and without concave Cu TSV structure.

The range of motional resistance ($\Delta R = R_{max.} - R_{min.}$) is evaluated to measure value variation under different power regions, as well as the qualified resistance stability after a cycling test with drive power of 100 μW. The measured results show a smaller value of variation with designed concave Cu TSV structure and the one without concave has unstable large values, as shown in Fig. 3(a).

In addition, the reliability of frequency is considered. With the concave Cu TSV structure, the range of oscillating frequency demonstrates the excellent results, which are less than 1 ppm in Fig. 3(b), as well as the great stability of oscillating frequency after a cycling test in Fig. 3(c). Conversely, Cu TSV structure without concave has extremely poor range and stability due to the collapsed Ag paste causing the bad electrical connection.

In general, the oscillation frequency depends on the load capacitance, as shown in formula (1) [8]. In order to realize the frequency change with the variation of load capacitance, the parallel-loaded capacitance (from 1 pF to 30 pF) of TSV-based resonator device is considered in Fig. 4(a).

$$f_L = f_s\sqrt{1 + \frac{C_1}{C_0 + C_L}}; \quad fs = \frac{1}{2\pi}\sqrt{\frac{1}{L_1 C_1}} \dots\dots\dots\dots \quad (1)$$

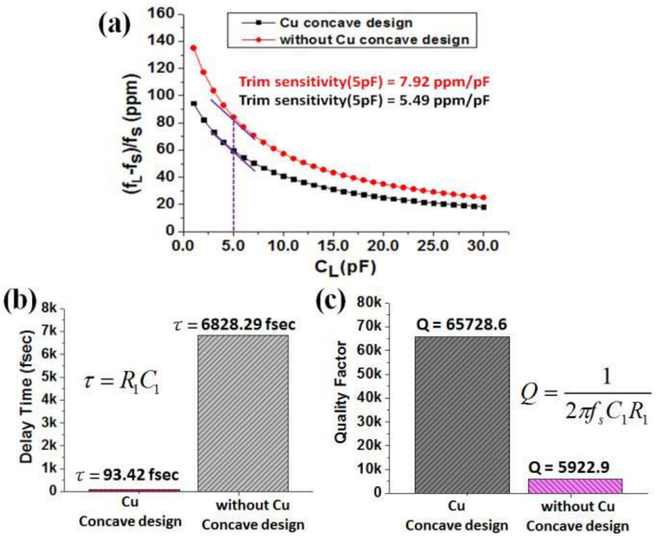

Fig. 4. (a) Frequency change versus variation of parallel-loaded capacitance; (b) delay time of TSV-based resonator device for with and without designed concave Cu TSV; (c) quality factor of TSV-based resonator device for with and without designed concave Cu TSV.

In addition, since the variation of loaded resonance frequency is important, the trim sensitivity of frequency oscillating device has to be specified by formula (2) [8]:

$$Trim\ sensitivity = \frac{-C_1}{2(C_0 + C_L)^2} \ldots\ldots.. \quad (2)$$

Values of trim sensitivity at 5 pF are 5.49 and 7.92 ppm/pF for resonator devices with and without concave Cu TSV, respectively. The results show that the device without designed concave Cu TSV structure is influenced easily by the same load capacitance. Consequently, the TSV-based resonator device with designed concave Cu TSV is hardly affected by external floating capacitance, which is unwanted, and demonstrates a steady frequency characteristic relatively.

In Figs. 4(b)–(c), the delay time and quality factor of TSV-based resonator device with and without concave Cu TSV are clearly improved. For the delay time, the motional resistances of two designs show a large difference due to the connection quality of TSV and Ag paste, while their motional capacitances are almost the same. As a result, the major effect of delay time is the different motional resistance between Cu and non-Cu concave design. Overall, TSV-based resonator device using concave Cu TSV structure indeed has the better electrical, frequency stability and device characteristics than those of the one without the concave Cu TSV structure.

V. CONCLUSION

In this letter, the concave Cu TSV structure design is proved to reach excellent electrical and frequency performances and characterizations. We have investigated design and characterization of both TSV-based resonator devices with and without concave Cu TSV structure. The concave Cu TSV structure design can solve the issue of motional resistance caused by the collapsed Ag paste before following cured process. This design further demonstrates the potential of TSV-based resonator devices for future advanced products.

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