Millimeter-wave transmission line with through-silicon via for RF-MEMS devices

Shinpei Ogawa^{1a)}, Takeshi Yuasa², Yoshio Fujii¹,
Yukihiro Tahara², and Hiroshi Fukumoto¹

¹ Advanced Technology R&D Center, Mitsubishi Electric Co.,
8-1-1 Tsukaguchi-Honmachi, Amagasaki, Hyogo 661-8661, Japan

² Information Technology R&D Center, Mitsubishi Electric Co.,
5-1-1 Ofuna, Kamakura 247-8501, Japan

a) Ogawa.Shimpei@eb.MitsubishiElectric.co.jp

Abstract: We designed and fabricated a low-loss transmission line structure with through-silicon vias (TSVs) for use in the millimeter-wave region for three-dimensional packaging of radio frequency microelectromechanical system devices. High-frequency simulations were used to determine the optimum transmission line structure. A transformer was employed to compensate for the impedance mismatch between the TSVs and the coplanar waveguide. The proposed structure was fabricated using a combination of surface micromachining and the molten solder ejection method. The electrical properties of the TSVs and the transmission line were measured, and a low insertion loss of 0.7 dB at 80 GHz was achieved.

Keywords: TSV, RF-MEMS, packaging, millimeter-wave

Classification: Micro- or nano-electromechanical systems

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1 Introduction

There has been growing interest in radio frequency microelectromechanical system (RF-MEMS) devices [1, 2] for use in automotive radar systems at millimeter wavelengths [3]. By vertically integrating and stacking silicon-based devices such as RF-MEMS switches [4], MEMS antennas [5, 6] and MEMS phase shifters [3], the size and cost of such radar systems are expected to decrease.

Integration of MEMS devices requires hermetic packages to protect them from contamination, and electrical interconnections must be made between the packaged MEMS devices and external circuits or devices. There are many methods for achieving wafer level hermetic packaging [7], including direct bonding [8], anodic bonding [9] and intermediate-layer bonding [10]. The type of interconnection used is of crucial importance for maximizing the device performance and minimizing the chip size. Although buried feedthroughs and wire bonds have the advantage of utilizing conventional silicon processes, the disturbance produced by the seal ring and the long electrical wiring path cause serious degradation of the high-frequency performance. For this reason, through-silicon vias (TSVs) offer advantages for RF and millimeter-wave applications, due to their shorter

path and minimal inductance [11, 12, 13]. They are also compatible with both surface mounting and vertical 3D chip stacking approaches, which result in a high device density and more compact packaging. Various methods for fabricating TSVs have been developed [14], such as Cu electroplating [15, 16, 17], bottom-up Cu electroplating [18] and molten solder filling [19]. Because of its low resistivity, Cu is an attractive filling material. However, the difference in transmission loss between Cu and solder is negligible in the short path of a TSV, because of the skin depth effect at high frequencies.

We previously proposed a molten solder ejection method (MSEM) for fabrication of TSVs and for hermetic packaging [20, 21], and demonstrated an RF-MEMS switch that used low-loss TSVs and operated at 15 GHz [4]. In the MSEM, solder droplets of various diameters are ejected with a high positional accuracy from a specially designed ejection head. It can be used in a wide range of packaging applications, such as production of sealing rings for vacuum packaging, formation of fine-pitch micro solder bumps for vertical interconnects, and filling of via holes to form TSVs. Using this technique, TSVs can be fabricated without the need for chemical mechanical polishing, which is a necessary step when Cu electroplating is used.

At higher frequencies such as the 80-GHz band, in order to realize a 3D low-loss transmission line, it is extremely important both to compensate for impedance mismatching at the TSV, which connects the upper and lower planar signal lines, and to prevent radiation loss in the capping and device layers. Some approaches for producing impedance-matched components have been proposed, such as a shift-aligned ground-signal-ground TSV configuration [22] and a coaxial TSV structure [23]. However, the former still suffers from large losses of about 1.8 dB in the 80-GHz band, and the latter requires a complex fabrication procedure that leads to high costs.

In the present study, we propose a transmission line structure with TSVs produced by the MSEM that uses an impedance matching transformer as a basic component for 3D packaging. The application of such a structure to millimeter-wave RF-MEMS devices, especially automotive radar devices, is investigated.

2 Design

Figure 1(a) shows the concept of the proposed transmission line structure. The signal line consists of a coplanar waveguide (CPW1) as an input or output port, a signal TSV (SIG-TSV), CPW2, a transformer (Trans) and CPW3. The capping layer is bonded to the device layer using solder bumps. All ground (GND) planes in both layers are connected by ground TSVs (GND-TSVs), which prevents radiation loss in the substrates.

The basic components for vertical interconnection are SIG-TSV, CPW2 and Trans. The length of CPW1 is variable depending on the layout, and this component may not always be present because SIG-TSV may be connected by a solder bump to another SIG-TSV or a signal line in the connected package in order to realize the shortest electrical path. CPW3 is the line that directly connects to the mounted RF-MEMS device, and its length is also variable.

We investigated the performance of the low-loss interconnection

Fig. 1. TSV structure for 3D packaging of RF-MEMS devices. Schematic diagrams of (a) overall TSV structure, (b) GND-TSVs and cavity, (c) CPW1 and SIG-TSV, and (d) CPW2 and transformer. (e) Calculated insertion and return losses for CPW1, SIG-TSV and CPW2.

structure indicated by the dotted rectangle in Fig. 1(a) using the High Frequency Structure Simulator (HFSS) from ANSYS. Figures 1(b)–(d) show schematic diagrams of the designed structure. CPW2, Trans and CPW3 are set at the bottom of the cavity in order to reduce the chip size. The thickness and resistivity of the Si wafer are $300\ \mu\text{m}$ and $20\ \text{k}\Omega\cdot\text{cm}$, respectively. Figure 1(b) shows the aligned GND-TSVs and the solder bumps, which act to shield the transmission line. The diameter of both the TSV and solder bumps is $150\ \mu\text{m}$. The $400\text{-}\mu\text{m}$ -pitch GND-TSVs are aligned along both sides of the transmission line in order to prevent parallel plate radiation. The spacing between the two lines of GND-TSVs is $600\ \mu\text{m}$. All GND parts are electrically interconnected. The depth and width of the cavity for forming the CPWs are 150 and $350\ \mu\text{m}$, respectively. Figure 1(c)

shows CPW1 and SIG-TSV. The width of CPW1 is $135\text{ }\mu\text{m}$ and its distance from the coplanar GND is $110\text{ }\mu\text{m}$, resulting in a characteristic impedance of $50\text{ }\Omega$.

Figure 1(d) shows SIG-TSV, CPW2 and Trans. The sidewalls of the cavity are metalized and act as a ground for CPW2 and Trans. The width and length of CPW2 are 100 and $95\text{ }\mu\text{m}$, respectively, resulting in a characteristic impedance of $50\text{ }\Omega$. Trans is inserted between CPW2 and CPW3, where the impedance mismatch occurs. The length and width of Trans are 160 and $302.5\text{ }\mu\text{m}$, respectively, in order to adjust the combined impedance of CPW1, TSV and CPW2 to the value of $50\text{ }\Omega$ for CPW3.

To investigate the electrical characteristics of the proposed structure, it is useful to carry out the calculations for just a single CPW1/SIG-TSV/CPW2/Trans structure, since the overall structure is symmetric. To allow a direct comparison between the simulation and experimental results, CPW1 is assigned a length of $800\text{ }\mu\text{m}$, since this is the length of the input probe port in the fabricated device. In the simulation model, a wave port is used for CPW1 and Trans. The wave port for Trans has a normalized impedance of $50\text{ }\Omega$, which matches that of a transmission line such as CPW3 in the actual structure.

Figure 1(e) shows the calculated insertion and return losses at 80 GHz . A low insertion loss of 0.12 dB and a return loss of less than -30 dB were achieved by using the GND-TSVs and Trans. This insertion loss is superior to that previously reported for a shift-aligned TSV structure fabricated using MSEM [22]. The -20 dB impedance bandwidth extends from 75 to 85 GHz . This performance is sufficiently high for application of the proposed structure to general hermetic packaging of RF-MEMS devices and automotive radar systems operating in the 80-GHz band. The dimensions of Trans and the width of the cavity are 160×302.5 and $350\text{ }\mu\text{m}$, respectively, which makes the structure very compact compared to conventional packaging approaches.

3 Fabrication

Figure 2(a) shows the fabrication procedure for the transmission lines and TSVs: (i) A $300\text{-}\mu\text{m}$ -thick Si wafer with a resistivity of $20\text{ k}\Omega\cdot\text{cm}$ is prepared. A cavity with a depth of $150\text{ }\mu\text{m}$ is formed by inductively coupled plasma-reactive ion etching (ICP-RIE). (ii) Cu ($0.05\text{ }\mu\text{m}$) is sputtered as a seed layer. Ni/Au layers ($2.0/1.0\text{ }\mu\text{m}$ thick) are formed by electrolytic plating on the signal line, the sidewalls of the cavity, the capping layers of the via holes and the pads of the solder bumps. The seed layer is etched using ion beam etching (IBE). (iii) Cr/AlSi layers ($0.05/0.5\text{ }\mu\text{m}$ thick) are sputtered and patterned by IBE to form the GND part and expose the pads of the solder bumps. The figure shows a cross section of the capping layers of the via holes. (iv) The via holes are formed using ICP-RIE. Ni/Au layers ($2.0/0.5\text{ }\mu\text{m}$ thick) are sputtered to metalize the inner walls of the via holes in order to improve the solder wetting properties. The metal layers on the surface are then peeled off. The via holes are filled with molten solder (Sn-Ag) droplets using MSEM [6]. The solder droplets are $45\text{ }\mu\text{m}$ in diameter and the ejection rate is 200 drops/s . The wafer is placed on a heating stage which is maintained at a temperature of 210°C . (v) Cr/Ni/AlSi layers ($0.05/2.0/0.5\text{ }\mu\text{m}$ thick) are sputtered and patterned by IBE to form the

Fig. 2. Schematic diagram of process used to fabricate transmission line structure with TSVs using MSEM.

GND and CPW1. (vi) A second Si wafer is prepared. Cr/Ni/Au layers ($0.05/2.0/0.5\ \mu\text{m}$ thick) are sputtered and patterned by IBE to form the capping layers of the via holes and the pads of the solder bumps. (vii) A TSV is formed using the same procedure as in (v). (viii) Cr/Ni/AlSi layers ($0.05/2.0/0.5\ \mu\text{m}$ thick) are sputtered and patterned by IBE to form the GND part. (ix) Cr/AlSi layers ($0.05/0.5\ \mu\text{m}$ thick) are sputtered and patterned by IBE to form the GND part and expose the pads of the solder bumps. (x) The two wafers are bonded together on the heating stage using solder bumps produced by MSEM.

The fabricated waveguide structure consists of two symmetric sets of CPW1/TSV/CPW2/Trans structures, connected by two CPW3 lines. This symmetry allows the characteristics of a single set to be determined, so that the results can be compared with those of the simulation. Based on the HFSS results, the length and width of CPW3 were set to 70 and $450\ \mu\text{m}$, respectively, in order to obtain a characteristic impedance of $50\ \Omega$. In an actual device application, the CPW3 length would vary depending on the connected RF-MEMS device.

Figures 3(a), 3(b) and 3(c) show an optical reflection image of CPW1, a scanning electron microscopy (SEM) image of the signal line, which consists of SIG-TSV, CPW2, Trans and CPW3 on the bottom of the cavity, and an X-ray image of the transmission line structure, respectively. From the X-ray image, it can be seen that no voids are present in the TSVs. Although the probe port was optimized for the GND-SIG-GND configuration of the probe used for the measurements, the HFSS simulations confirmed that any

Fig. 3. (a) Optical reflection image of CPW1 and TSV (b) SEM image of transmission line on cavity of device layer (c) X-ray image of 3D transmission line structure.

differences in shape to the CPW1 used in the calculation model had a negligible impact on the results. The images in Fig. 3 verify that a transmission line with TSVs between the wafers can be successfully fabricated using surface micromachining and MSEM.

4 Measurements

The S-parameters were measured using through-reflect-line (TRL) calibration, and the results are shown in Fig. 4. At 80 GHz, the insertion and return losses are about 1.4 and -20 dB, respectively. Since this corresponds to two sets of CPW1/TSV/CPW2/Trans/CPW3 structures, the insertion loss for

Fig. 4. Measured insertion and return losses for developed structure.

a single set is about 0.7 dB. The differences between the calculation and measurement results are attributed to the structural non-uniformities caused mainly by surface roughness at the side and bottom of the cavity. Further improvements can therefore be made to the fabrication process in order to enhance the performance of the proposed structure. Nevertheless, a -10 dB impedance bandwidth of <70 to 83 GHz is achieved.

These results indicate that the proposed TSV structure with an impedance matching transformer fabricated using MSEM can successfully provide a low-loss interconnection between RF-MEMS devices and exterior circuits operating in the millimeter-wave region, and is expected to be especially useful for automotive radars.

5 Conclusion

A millimeter-wave transmission line with TSVs and impedance-matching transformers was designed and fabricated. Its structure was optimized using high-frequency simulations at 80 GHz, and fabrication was carried out using surface micromachining and MSEM. Based on the measured S-parameters, the insertion loss for a single TSV set was about 0.7 dB at 80 GHz.

Although the measured loss is larger than the simulated result due to structural non-uniformities introduced during fabrication, this loss value is superior to that for a shift-aligned impedance matching structure. In addition, a -10 dB impedance bandwidth of <70 to 83 GHz was achieved. The size of the impedance matching component is $160 \times 302.5 \mu\text{m}$. The minimum length and width of the proposed 3D interconnection are 547.5 and $900 \mu\text{m}$, respectively, including the SIG-TSVs, GND-TSVs and impedance matching components. These dimensions are small in comparison to those for conventional packages.

These results clearly demonstrate that the proposed structure produced using MSEM is highly promising for achieving low-loss, low-cost 3D interconnections for compact automotive radar devices operating in the millimeter-wave region.

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