

Low-Cost and Reliable Packaging Technology for Stacked MCP with MEMS and Control IC Chips

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Abstract

This paper reports a wafer-level package (WLP) encapsulation and a stacked multi-chip package (MCP) for electrostatically actuated MEMS variable capacitor and control IC chips. Since the MEMS capacitor needs to be operated in dry atmosphere, we developed the WLP encapsulation structure with four thin-film layers fabricated by conventional back-end-of-the-line (BEOL) LSI technologies. Furthermore, since a MEMS chip is actuated by a control IC chip that provides high voltage, we developed the stacked MCP to integrate the MEMS chip and the control IC chip. In order to handle relatively fragile WLP encapsulation, the stacked MCP process was optimized. The stacked MCP has 4.5×4.5 mm size and 0.8 mm thickness, which is the thinnest package for stacked MEMS and IC chips. Normal operation of the MEMS variable capacitor in the stacked MCP confirmed up to 85%RH after reliability tests, i.e. temperature cycling, accelerated moisture resistance, and moisture/reflow sensitivity.

Key words: MEMS capacitor, wafer-level package, stacked multi-chip package.

Introduction

Since MEMS devices, such as various sensors and radio frequency (RF) actuators [1]-[2], consist of movable parts and need to be operated in vacuum or controlled atmosphere, the conventional packaging techniques for LSI cannot be applied [3]. Therefore, expensive silicon or glass cap [4]-[6] had to be used for the conventional MEMS packages, making it difficult to reduce the package size and the assembly cost.

Figure 1 shows an SEM view of the electrostatically actuated MEMS variable capacitor [7]. The MEMS consists of two kinds of pair electrode: one pair is the capacitor electrodes, and the other pair is the actuation electrodes. In addition, each pair of electrodes consists of a fixed lower electrode and a movable upper electrode. These movable upper electrodes are connected by dielectric material. If the actuation voltage is added between the actuation electrodes, the distances between electrodes are changed by electrostatic attractive force. Thus, the

capacitances between them are also changed. For instance, if the voltage is not added, the distance is wide (pull-out) and the capacitance is low, and if the voltage is added, the distance is narrow (pull-in) and the capacitance is high.

However, if the pull-in voltage is added for a long time in humid atmosphere, the charging effect occurs in a dielectric film on the electrodes. The charging effect is characterized by the voltage shift that can be derived by measuring the C-V hysteresis curve after applying the pull-in voltage [8].

Figure 2 shows the voltage shift versus relative humidity and total pull-in time [9]. The result shows that the higher humidity makes the voltage shift faster. Thus, the MEMS capacitor needs to be operated in dry atmosphere. Furthermore, it is known that the movable electrodes vibrate if a MEMS capacitor is operated in vacuum atmosphere [10]. Therefore, the operation atmosphere needs to be an atmospheric pressure. To address these issues, we had developed the WLP encapsulation with hybrid thin film

fabricated by standard BEOL technologies. It is low cost and has high reliability.

Since the MEMS capacitor needs an actuation voltage, the control IC chip was developed to provide high voltage to the MEMS [7]. Therefore, use of the MEMS capacitor via the control IC does not require preparation of a high-voltage source. This control IC chip is convenient for integration with the MEMS chip. Therefore, we developed the stacked MCP that is easy to use for many customers. However, a conventional packaging process for LSI cannot be applied to the WLP encapsulation, because the WLP encapsulation, fabricated with thin-film layers, is fragile. Therefore, the stacked MCP process needs to be optimized.

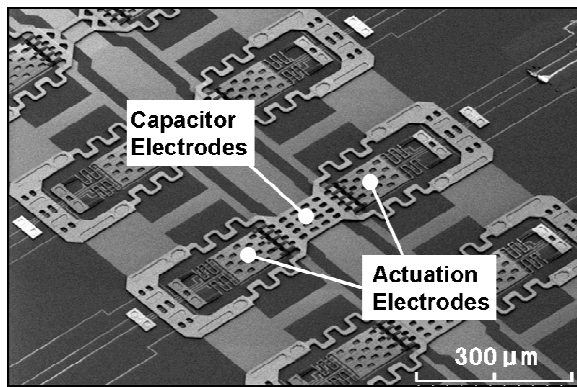


Figure 1: SEM view of RF MEMS variable capacitor.

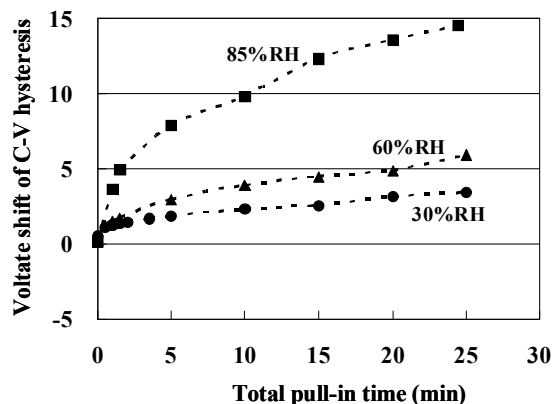


Figure 2: The voltage shift of C-V hysteresis measured at 30 °C as a function of relative humidity.

Package Design Concepts

When considering the MEMS package, there are two essential requirements. The first concerns the atmosphere surrounding the MEMS. The movable parts, such as electrodes, need to be encapsulated in dry atmosphere at approximately atmospheric pressure. As mentioned above, it is essential to prevent vibration and the charging effect of electrodes. The second requirement concerns integrating the MEMS chip with the control IC chip. As mentioned above, the control IC chip provides actuation voltage to the MEMS capacitor. Therefore, we developed the WLP encapsulation to meet the first requirement and the stacked MCP to meet the second one.

Figure 3 shows a schematic view of our WLP encapsulation structure. This encapsulation structure consists of four layers. The first layer is the cap layer made of SiO₂; it makes a cavity for the movable parts of the MEMS capacitor. The second layer is the plug layer made of polymer; it plugs holes on the first layer. The third layer is the moisture barrier layer made of SiN; it blocks the moisture. The fourth layer is the protective layer formed in the polymer; it protects the entire encapsulation against the subsequent MCP processes such as wafer grinding. Figure 4 shows an optical microscope image of a hybrid thin-film hermetic encapsulation. We had fabricated various kinds of encapsulation; one of these features large size caps (1480×1080μm). As well as encapsulating the large or multiple MEMS elements enabling high capacitance, it reduces the chip size. Figure 5 shows the shift of voltage as a function of relative humidity comparing with and without the WLP encapsulation. The results show that the WLP encapsulation is effective for protecting the MEMS capacitor against external moisture.

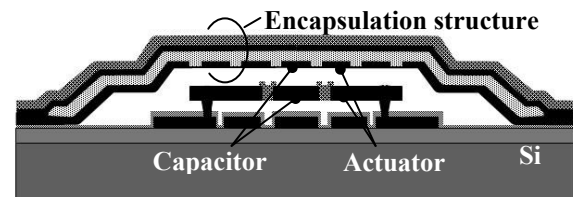


Figure 3: Schematic view of WLP encapsulation.

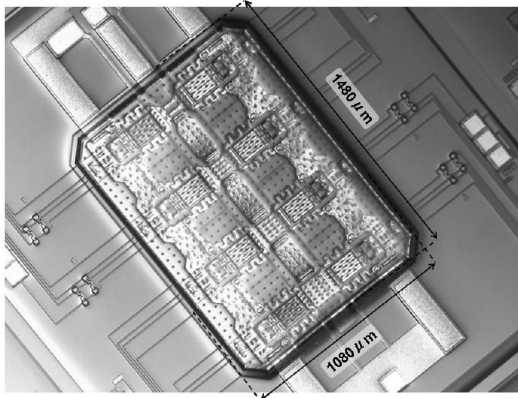


Figure 4: Optical microscope of a large WLP encapsulation.

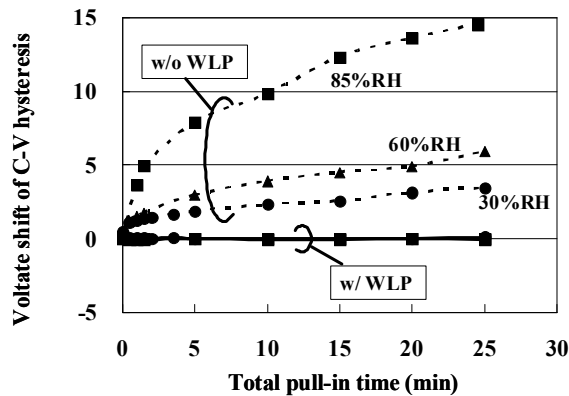


Figure 5: The Voltage shift of C-V hysteresis measured at 30 °C as a function of relative humidity comparing with and without the WLP encapsulation.

Next, when considering an MCP, care must be exercised concerning the package's electrical properties, such as inductance, capacitance, and resistance. In particular, the package inductance needs to be low, because large inductance results in low resonant frequency of the MEMS capacitor. When using the MEMS capacitor in a low-frequency application such as a tunable antenna module for a mobile TV device, the required inductance for the package is about 1nH.

Certainly, a chip scale package or a system-on-a-chip is suitable for reducing the package inductance. But these packages are difficult to integrate with the MEMS chip with the control IC chip. Furthermore, since the outer I/O pitch is small, these are inconvenient for general users. Therefore, we developed the stacked MCP shown in Figure 6. Since an inductance is relatively large owing to bonding wire, substrate, and I/O ball, we estimate the package

inductance beforehand. Figure 7 shows the electrical simulation model for the stacked MCP. The simulation result of inductance is about 0.7nH, which is sufficient for our purpose.

A BT-substrate is used to ensure consistency with Pb-free process. The control IC chip is attached on the BT-substrate by a die attach film (DAF), and the MEMS chip is stacked on the control IC chip by a DAF. Each chip is electrically connected to the substrate by Au wire. The chip-assembled side of the substrate is covered with epoxy-based resin. Some Pb-free solder balls are attached on the opposite surface for I/O terminals. Since the ball pitch is 0.5mm, reflow-mounting on a printed circuit board is easy. This stacked MCP has the merits of user-friendliness, small size, and low cost.

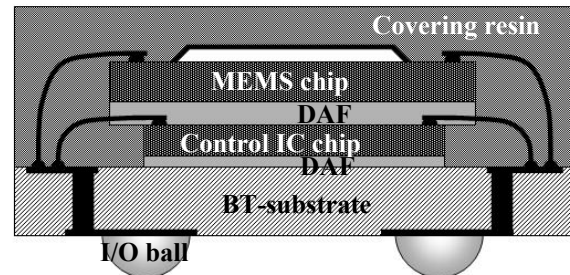


Figure 6: Schematic view of the stacked MCP.

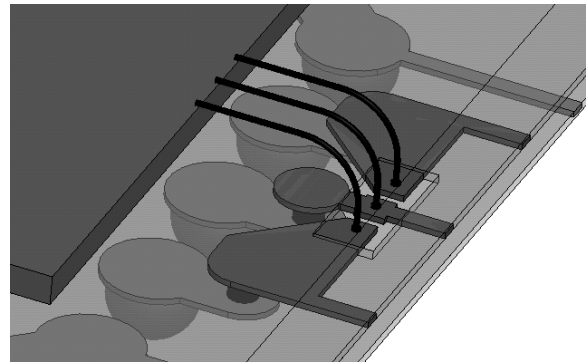


Figure 7: Electrical simulation model for the stacked MCP.

WLP Fabrication Process

Figure 8 shows the schematic process flow of a hybrid thin-film hermetic encapsulation that we have developed as the WLP. First, on the MEMS device (Figure 8a), 8μm-thick polymer layer is coated, cured and patterned as a sacrificial layer (Figure 8b). Then a 3μm-thick SiO cap layer is formed by PE-CVD at 250 °C, and holes are opened by the conventional photolithography and dry etching processes (Figure 8c). Next, the sacrificial layer is removed through

these holes by the dry ash process (Figure 8d). Then, another polymer layer is coated, cured and patterned on the SiO layer, and the holes on the SiO layer are plugged by this polymer (Figure 8e). The aperture ratio such as hole size and pitch is optimized for the removal performance and the deformation of first layer. Next, the SiN layer is formed by PE-CVD at 250 °C. It is essential to prevent moisture from penetrating the encapsulation (Figure 8f). Finally, a third polymer layer is coated, cured and patterned as a protective layer (Figure 8g).

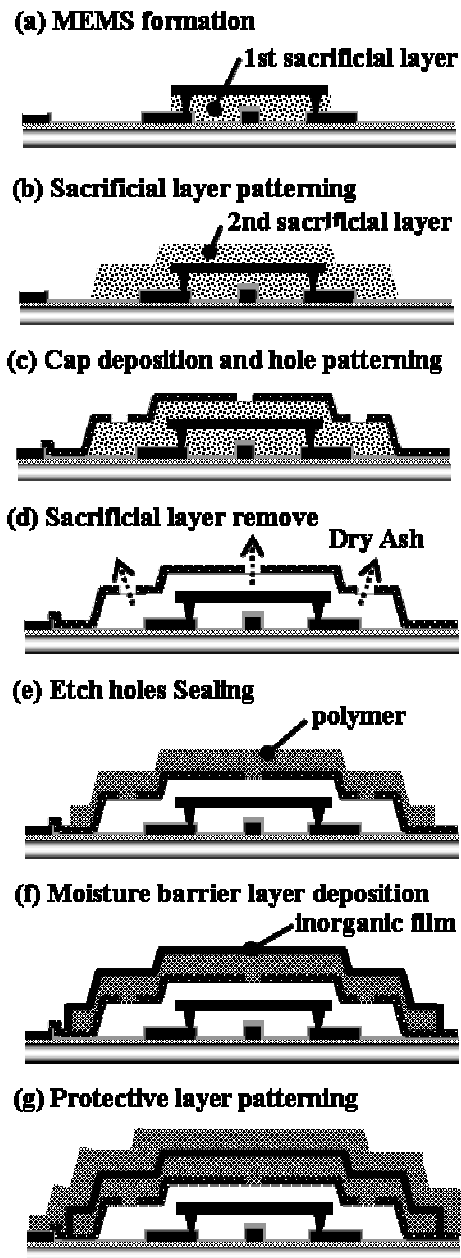


Figure 8: Schematic of fabrication flow of WLP encapsulation.

MCP Fabrication Process

Figure 9 shows the schematic process flow of the stacked MCP following WLP process. First, a control IC wafer is thinned by wafer grinding process, pasted with DAF on wafer backside surface, and divided into chips by wafer dicing process. Conventional methods are applicable for these processes. Then, a MEMS wafer (Figure 9a) is also thinned, pasted (Figure 9b), and divided into dies (Figure 9c). In the case of the MEMS wafer, the WLP encapsulation is broken by using a conventional grinding tape. Therefore, it is necessary to use a soft and thick grinding tape. This point should be noted.

Next, a control IC chip is attached on the substrate with DAF and electrically connected to the substrate with Au wire (Figure 9d). As shown in Figure 10, the substrate has 16 units divided into a package. The number of units can be increased to reduce the assembly cost. Figure 11 shows an optical microscope view after assembling the control IC chip.

Similarly, the MEMS chip is stacked on the control IC chip and electrically connected to the substrate with Au wire (Figure 9e). Since there is a swell of WLP encapsulation on the surface of the MEMS chip, a vacuum chucking tool for handling the MEMS chip needs to be designed to avoid it. Figure 12 shows an optical microscope view after assembling the MEMS chip. The design of all bonding wires for the control IC chip and the MEMS chip is such that they do not cross one another.

Next, the epoxy base resin is coated and cured on the entire surface of the substrate on which the chips are assembled (Figure 9f). In this process, an injection molding method is frequently used in a conventional packaging process, but it is not applicable for the WLP encapsulation, because the molding pressure breaks it. Therefore, we apply the vacuum printing method for this process. The printing pressure is sufficiently low to prevent WLP encapsulation from breaking. Furthermore, since the environmental pressure in printing is low, voids are not generated even in a narrow gap with this process. Next, this covering resin is thinned and flattened by the grinding method (Figure 9g). The total thickness of the substrate and the covering resin is 0.55mm.

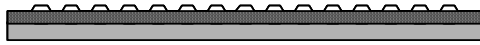
Finally, the substrate, which is covered with resin, is divided into packages by the dicing method, and then, some Pb-free balls are attached as the outer I/O terminals by the reflow-soldering method (Figure 9h).

Figure 13 shows the ball side view of the finished MCP. The package size is 4.5×4.5mm, and the package thickness is less than 0.8mm including ball-height. This package is one of the thinnest package for stacked MEMS and IC chips.

(a) MEMS wafer with WLP encapsulation



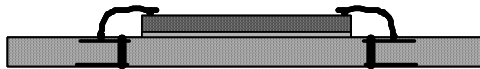
(b) Thinning wafer by grinding, and paste DAF to back side



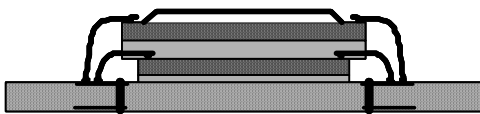
(c) Divide into chip by dicing



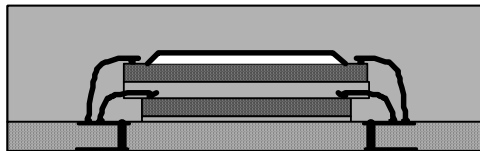
(d) Control IC chip mount and wire bonding



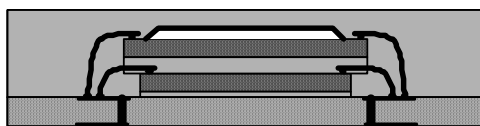
(e) MEMS chip mount and wire bonding



(f) Make cover layer by vacuum printing method



(g) Thinning and flattening of cover layer



(h) Divide into package and ball mount

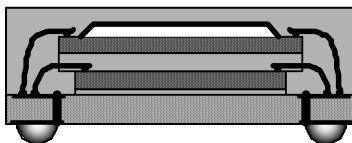


Figure 9: Schematic of fabrication flow of stacked MCP.

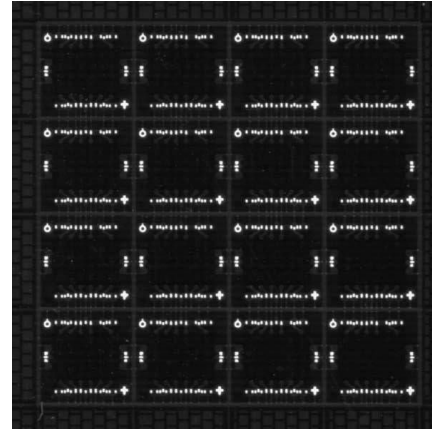


Figure 10: Top view of the substrate.

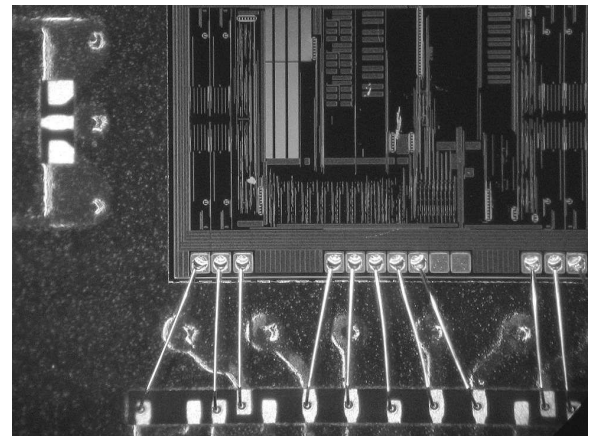


Figure 11: Top view after assembling the control IC chip.

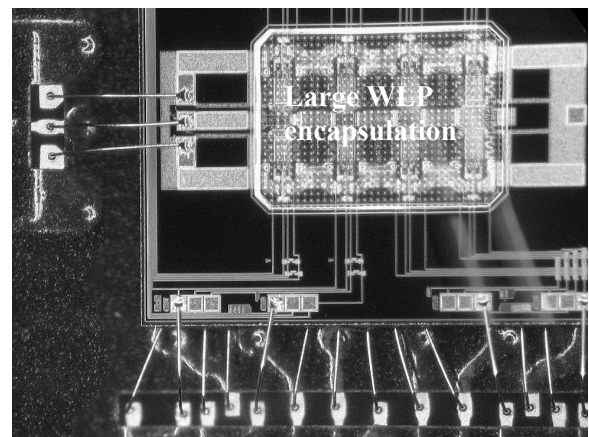


Figure 12: Top view after assembling the MEMS chip.

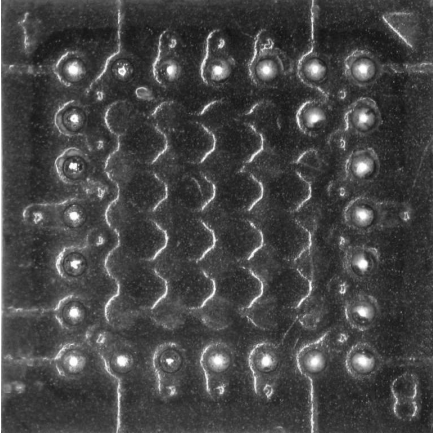


Figure 13: Ball side view of finished MCP.

Fabrication Results

Figure 14 shows the cross-sectional view of the stacked MCP including the WLP encapsulation. Neither crack nor void exists in any component or at structural boundaries. Figure 15 shows the cross-sectional view of the WLP encapsulation in the stacked MCP, and Figure 16 shows a close-up image of it. According to these images, neither distortion nor crack exists on the WLP encapsulation.

In addition, to confirm whether crack exists on the WLP, the encapsulation is examined by a microscope following the dissolving of the covering resin by acid. Figure 17 shows the top view of WLP encapsulation after dissolving the covering resin. It shows that no crack exists on the WLP encapsulation.

The moisture-proof property is examined by measuring the shift of voltage in humid atmosphere. Figure 21 shows the results for several humidity values and pull-in times. Since the shift of voltage does not occur in the test range (85%RH, 25min), it is proved that this package is effective for enduring moisture.

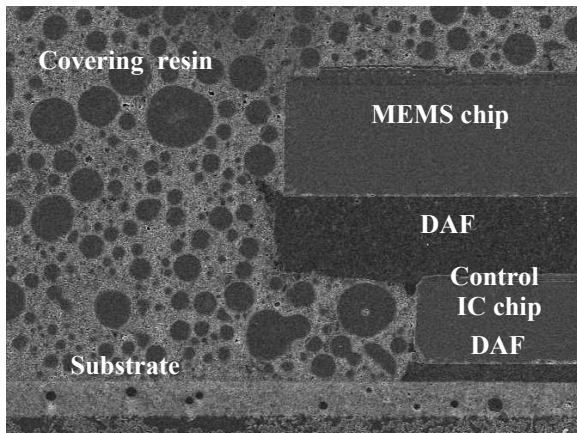


Figure 14: Cross-sectional view of stacked MCP.

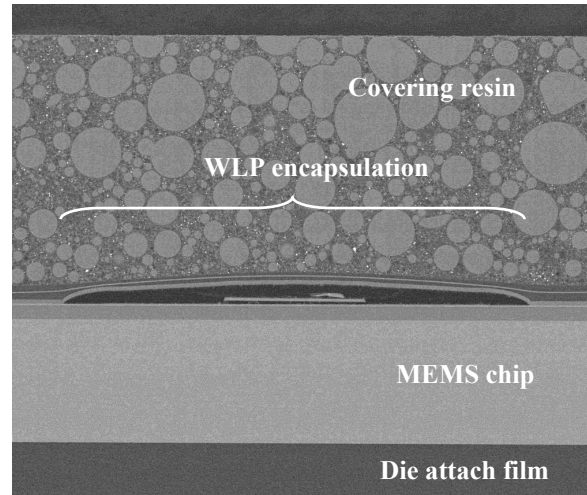


Figure 15 Cross-sectional view of WLP encapsulation.

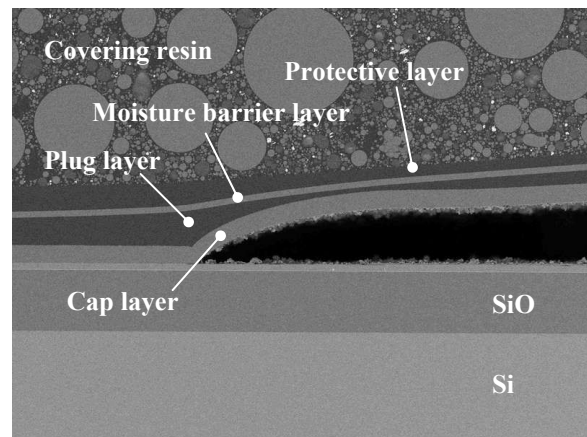


Figure 16: Cross-sectional view of WLP encapsulation's shoulder area.

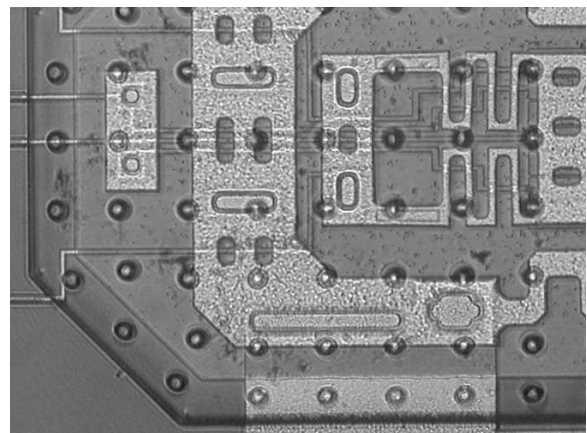


Figure 17: Top view of WLP encapsulation's shoulder area after dissolving the covering resin.

Reliability Test Results

Reliability tests are conducted for the stacked MCP. Test items are temperature cycling, accelerated moisture resistance, and moisture/reflow sensitivity. The test conditions are shown in Table 1.

Table 1: Reliability tests conditions.

Test Item	Condition
Temperature Cycling	-55 °C / 125 °C, 100 cycle
Accelerated Moisture Resistance	110 °C, 85%RH, 1.2atm, 168hr
Moisture/Reflow Sensitivity	moisture absorption 30 °C, 70%RH, 196hr reflow : 3times , max260 °C

Following the reliability tests, an examination was performed with the same method as that mentioned above, namely, observation of the cross-section, observation of the top view after dissolving covering resin, and measurement of the shift of voltage. Figures 18-20 show the observation results after reliability tests. Each figure shows the cross-sectional view of the WLP encapsulation and the top view of the WLP encapsulation after dissolving the covering resin by acid. Both observation results show neither distortion nor crack exist on WLP encapsulation, and the entire MCP structure is mechanically stable against these reliability tests.

The shift of voltage is also measured in 30°C, 85%RH condition as shown in Figure 21. The shift of voltage does not occur up to 25min (total pull-in time), which means the encapsulation structure is hermetically stable against these reliability tests.

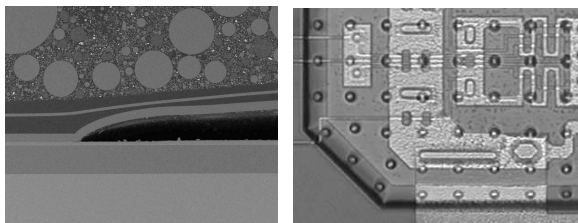


Figure 18: Examination results after temperature cycling test.

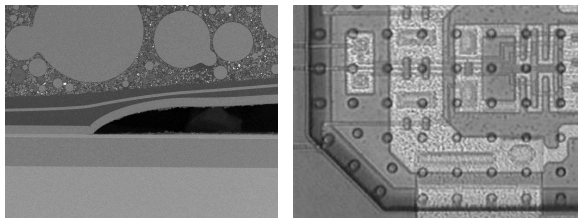


Figure 19: Examination results after accelerated moisture resistance test.

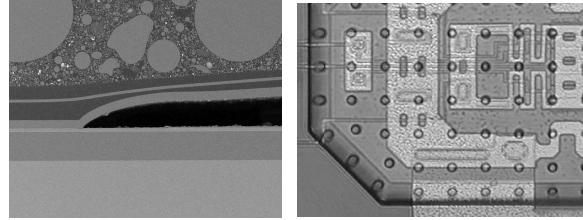


Figure 20: Examination results after moisture/reflow sensitivity test.

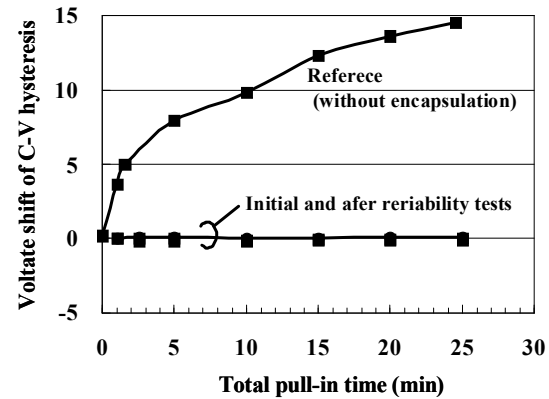


Figure 21: The voltage shift of C-V hysteresis for Initial and after reliability tests comparing stacked MCP and without encapsulation at 30 °C / 85%RH.

Conclusions

In this paper, we presented the WLP encapsulation and the stacked MCP for the electrostatically actuated MEMS variable capacitor and the control IC chip.

We had developed the WLP encapsulation in which the inner atmosphere is dry and approximately atmospheric pressure. This WLP encapsulation consists of four thin-film layers and is effective for protecting the MEMS device from external moisture. Since conventional BEOL process and materials are applicable to fabrication of the WLP encapsulation, it is easy to reduce the chip size and chip cost. We had fabricated the large (1480×1080μm) encapsulation for large MEMS. Furthermore, we had developed the stacked MCP to integrate the MEMS chip and the control IC chip. The fabrication process of the stacked MCP is based on a conventional packaging process, but some processes needed to be optimized to handle the fragile WLP encapsulation. For instance, a backside-grinding process of a MEMS wafer needs soft and thick backside-grinding tape, and the vacuum printing method is required for the covering process for the entire package. The developed package is a small (4.5×4.5mm) and thin (0.8mm-thick) MCP, which is one of the thinnest package for stacked

MEMS and IC chips.

We examined the reliability of the stacked MCP, including the WLP encapsulation, by reliability tests, namely, temperature cycling, accelerated moisture resistance, and moisture/reflow sensitivity. The results of them show that neither voids nor cracks exist in the stacked MCP. We confirmed the normal operation of the MEMS variable capacitor up to 85%RH.

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