Gas permeable protection caps for wafer level chip scale packaging (WLCSP) of MEMS environmental sensors

Ole Behrmann
MEMS Applications
Fraunhofer-Institute for Silicon Technology ISIT
Itzehoe, Germany
ole.behrmann@isit.fraunhofer.de

Thomas Lisec
MEMS Applications
Fraunhofer-Institute for Silicon Technology ISIT
Itzehoe, Germany
thomas.lisec@isit.fraunhofer.de

Finn Klingbeil
MEMS Applications
Fraunhofer-Institute for Silicon Technology ISIT
Itzehoe, Germany
finn.klingbeil@isit.fraunhofer.de

Niklas Kyoushi
MEMS Applications
Fraunhofer-Institute for Silicon Technology ISIT
Itzehoe, Germany
niklas.kyoushi@isit.fraunhofer.de

Björn Gojdka
MEMS Applications
Fraunhofer-Institute for Silicon Technology ISIT
Itzehoe, Germany
bjoern.gojdka@isit.fraunhofer.de

This work presents new porous environmental protection caps designed for wafer level chip scale packaging (WLCSP) of MEMS environmental sensors. The caps consist of gas-permeable microstructures formed from loose aluminum oxide powder solidified by a ceramic thin film, grown using atomic layer deposition (ALD). For the first time, the full process flow of the proposed approach is demonstrated by manufacture of the cap wafer followed by substrate bonding using glass-frit technology. By analyzing the influence of the caps on the response time of MEMS humidity sensors, this study proves the viability of the proposed packaging technology. In addition, the ability to further functionalize the porous caps is demonstrated by the deposition of a superhydrophobic polymer thin film by chemical vapor deposition.

Keywords - Sensor, MEMS, Gas Sensor, Pressure Sensor, Cap, Package, Wafer Level Package, Humidity Sensor, Chip Scale Package

I. INTRODUCTION

This work builds upon the previously reported "PowderMEMS" fabrication process, used for creating three-dimensional porous microstructures in MEMS applications [1–3]. MEMS environmental sensors require protection from dust, condensing moisture, and mechanical damage during operation while maintaining gas exchange with the environment [4–6]. Typically, this protection involves mounting the sensor die on a lead-frame and then over molding it to create an open cavity above the sensing area. For humidity sensors, a gas-permeable hydrophobic polymer membrane seals this cavity, while pressure sensors use a filter element or gel-like substance.

In this study, we introduce a novel concept for simultaneously capping multiple MEMS environmental sensors through a single wafer-bonding step. Leveraging the unique PowderMEMS technology, we create gas-permeable porous microstructures within a silicon wafer (Figure 1(a)). This cap wafer is then bonded to the MEMS device wafer, and the capped sensors are released using standard wafer dicing techniques (Figure 1(b)). To demonstrate the efficacy of this approach, we compare the output signals of capped and uncapped MEMS humidity sensors at the chip level.

PowderMEMS structures can possess pore sizes ranging from tens of nanometers to several micrometers. Their significant internal surface areas offer the advantage of functionalizing with thin films to achieve specific surface properties. By employing particles with a mean size in the micrometer range, we can create micron-sized pores that facilitate rapid gas exchange while still allowing the deposition of functionalization layers without the risk of

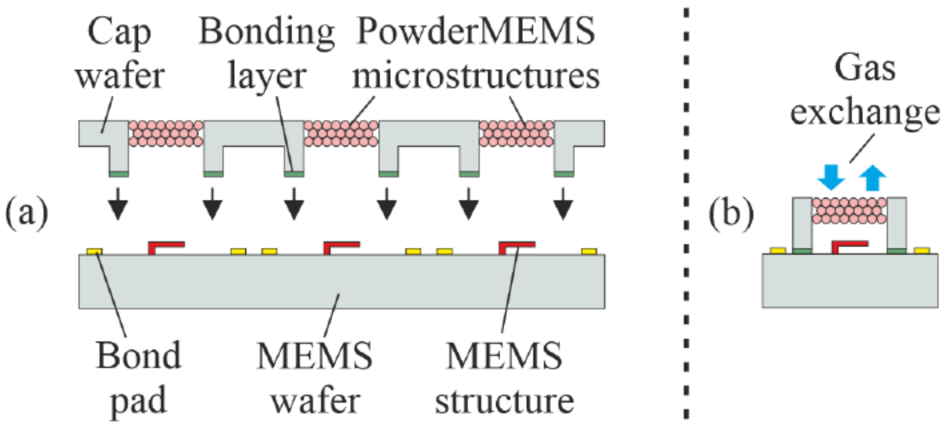

Figure 1: (a) PowderMEMS Cap- and MEMS-wafers before bonding. (b) Chip scale package (CSP) after bonding and dicing.

clogging.

Nevertheless, the presence of pores in PowderMEMS structures also results in high hydrophilicity, which is undesirable for environmental protection caps meant to shield the encapsulated MEMS from condensing moisture. To address this limitation, we investigate the hydrophobation of PowderMEMS cap structures through the deposition of Parylene C polymer thin films.

II. Materials and Methods

A. PowderMEMS

In Figure 2, an overview of the PowderMEMS process is presented, demonstrating the creation of porous micro-structures within 200 mm silicon wafers with a thickness of 725 µm. The process begins with standard lithography to pattern a photoresist, serving as a mask for the subsequent deep reactive ion etching (DRIE) of 400 µm cavities using SPTS Pegasus equipment (Figure 2(a)).

Subsequently, loose Al_2O_3 particles with a mean diameter of 7 µm (D_{50}) are carefully deposited into these etched cavities (Figure 2(b)). The next step involves subjecting the wafers to 750 cycles of binary low-temperature (75 °C) atomic layer deposition (ALD). This ALD process utilizes trimethyl-aluminum (TMA) and water as precursors, resulting in the growth of a 75 nm thick Al_2O_3 layer on both the powder and other exposed surfaces (Figure 2(c)).

This ALD layer facilitates the agglomeration of the previously loose powder, transforming it into mechanically rigid porous microstructures. Notably, the porous micro-structures also become mechanically connected to the interior surfaces of the microcavities due to the ALD layer.

Following this, the wafers are inverted, and standard lithography is employed to pattern a second soft mask on the backside. In a subsequent step, another DRIE process is performed, removing the remaining silicon from the backside. The ALD layer at the bottom of the cavities acts as an etch-stop during this process (Figure 2(d)).

Finally, a final Reactive Ion Etching (RIE) step using Applied Materials P5000 equipment is carried out to eliminate the bottom ALD layer and enable gas flow through the porous structures.

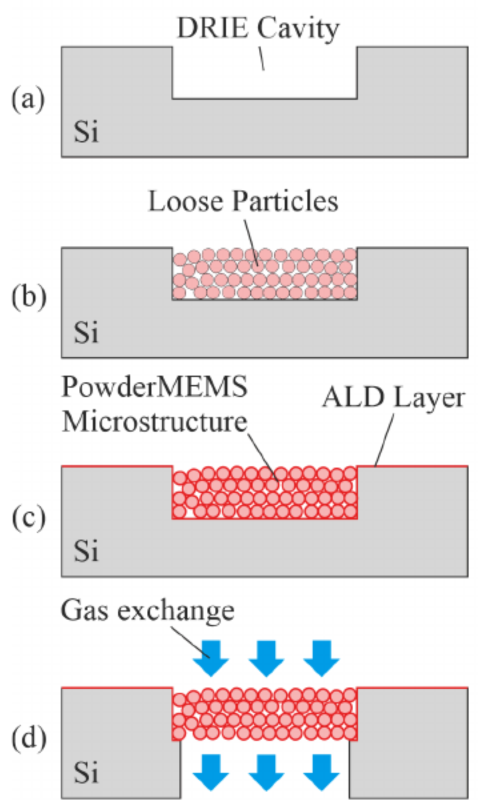

Figure 2: Major steps of the PowderMEMS Process.

B. Substrate bonding

The PowderMEMS cap wafer is bonded to a second 200 mm substrate using a standard glass-frit process. To facilitate visual inspection of the bond seams, a Borofloat 33 glass wafer is chosen as the second substrate. In brief, glass-frit paste is screen printed onto the glass wafer. The glass wafer is then heated in an oven to remove the polymeric binder from the glass-frit paste. After alignment of the two wafers on a bond aligner (Süss BA8), glass-frit substrate bonding is performed in a substrate bond tool at 425 °C (Süss SB8).

C. CVD

Parylene C was applied onto the embedded porous micro-structures using a conventional chemical vapor deposition (CVD) procedure. 1.08 g of the Parylene C precursor di-para-xylylene were evaporated under vacuum conditions and allowed to polymerize on the chips resulting in a film thickness of about 200 nm. The substrates were kept at room-temperature.

D. Measurement setup

The cap arrays were diced into individual caps, which were subsequently hand-mounted onto the inlet port of a commercial MEMS humidity sensor (SHT-35, Sensirion, Switzerland) using silicone glue. To conduct the measurements, a sensor enhanced with a PowderMEMS cap, and an unmodified reference sensor were both connected in parallel to a USB-interface (SEK-SensorBridge, Sensirion, Switzerland). Throughout the measurements, both sensors remained in close proximity to each other.

III. Results and Discussion

A. PowderMEMS processing

The proposed caps were successfully manufactured, as showcased in Figure 3. The 200 mm wafer features embedded PowderMEMS membranes of various geometries.

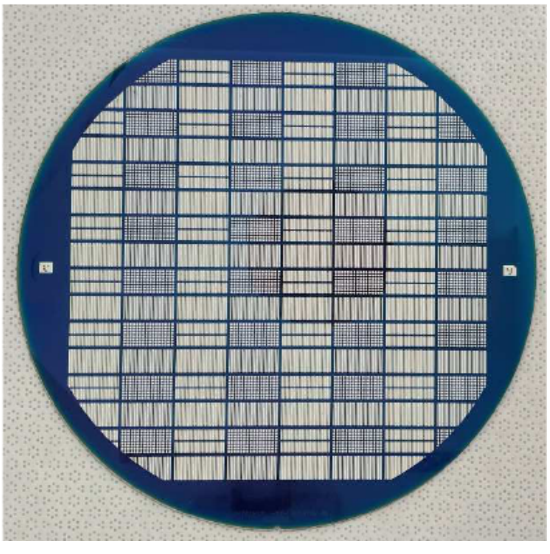

Figure 3: Top view of a 200 mm PowderMEMS cap wafer

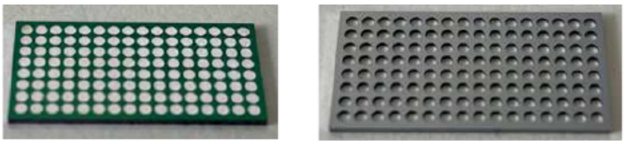

Figure 4: Top (left) and bottom (right) view of an 8x16 array of PowderMEMS environmental protection caps.

For further investigation, circular structures with a diameter of 1 mm were selected. For a more detailed view, Figure 4 exhibits an 8x16 cap array from both the top and bottom angles, providing insight into the precise positioning of PowderMEMS structures within vertical silicon channels.

B. Substrate bonding

Substrate bonding was successfully performed, and no defects were observed on the PowderMEMS cap wafer. Figure 5 gives an overview of the backside of the bonded wafer stack. The glass-frit bond seams are visible through the transparent Borofloat 33 wafer. Visual inspection confirmed the success of the substrate bonding process.

C. Hydrophobation

In Figure 6, the wetting characteristics of the PowderMEMS microstructures are depicted both before and after the process of hydrophobation. In the initial state (Figure 6, left), the structures exhibit easy wetting, causing water droplets to be drawn into them. However, following the hydrophobation by Parylene C deposition (Figure 6, right), the structures become impermeable to water. Instead of penetrating the surface, water forms a droplet with a contact angle exceeding 120°, providing clear evidence of the successful hydrophobation process. Finally, the caps were immersed in water at a depth of 1 meter for a duration of 30 minutes and no water ingress was observed.

D. Humidity sensor performance

In this experiment, both a modified humidity sensor (Figure 7) and an unmodified sensor were subjected to repeated exposure to humid air (Figure 8). Notably, the performance of the modified sensor closely mirrored that of the unmodified sensor. This outcome indicates that the PowderMEMS structure's µm-sized pores facilitate rapid gas exchange, and the proposed approach has minimal impact on the sensor's response time constant.

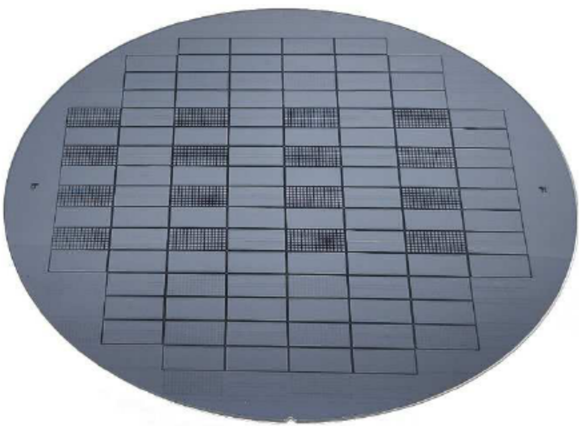

Figure 5: Bottom view through the glass wafer. The glass-frit bond seams are visible.

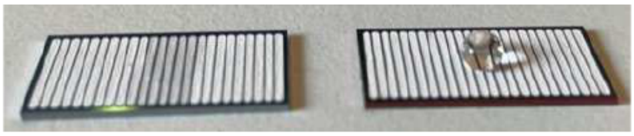

Figure 6: Wetting behavior of the porous microstructures before (left) and after (right) hydrophobation.

IV. Summary and Outlook

This study showcases the fundamental production process and capabilities of PowderMEMS environmental protection caps designed for MEMS gas and pressure sensors. The successful fabrication of these caps on 200 mm Si-wafers was demonstrated, followed by full wafer substrate bonding.

In addition, hydrophobation by deposition of Parylene C thin films was performed on single caps. These caps were then mounted on commercial MEMS humidity sensors and their influence on the sensor response time constant was evaluated. The change in sensor time constants was found to be only very minor. These results demonstrate the validity of the proposed wafer-level packaging approach. Finally, the hydrophobic caps were immersed in water at a depth of 1 meter for a duration of 30 minutes after which no water ingress was observed. In further work, environmental testing towards long term stability of the caps according to industrial standards such as IPxx and AEC-Q100 is planned. Additionally novel concepts for the integration of catalytic materials for the removal of interfering gases will be explored.

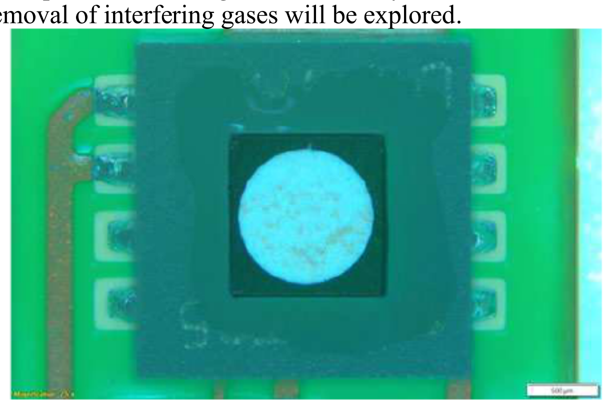

Figure 7: Micrograph of a single cap assembled on a commercial MEMS humidity sensor (SHT-35, Sensirion).

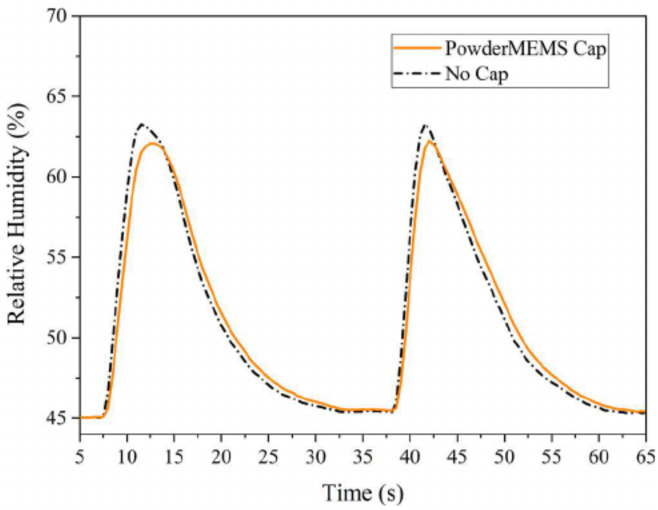

Figure 8: Performance of a commercial MEMS humidity sensor modified with a 400 µm thick gas permeable PowderMEMS environmental protection cap (solid line) compared to an unmodified sensor (dotted line).

ACKNOWLEDGMENT

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