A LOW COST WAFER-LEVEL MEMS PACKAGING TECHNOLOGY

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ABSTRACT

This paper presents a low-cost low-temperature packaging technique for wafer-level encapsulation of MEMS devices fabricated on any arbitrary substrate. The packaging process presented here does not involve wafer bonding and can be applied to a wide variety of MEMS devices after their fabrication sequence is completed. Our technique utilizes thermal decomposition of a sacrificial polymeric material through a polymer overcoat cap, and can be applied to both surface and bulk micromachined structures. Encapsulation of high-Q silicon-on-insulator resonators, and thick silicon gyroscopes and accelerometers are presented.

I. INTRODUCTION

Wafer-level packaging represents a challenging and costly task in microsystem manufacturing [1]. Several techniques have been reported for wafer-level packaging of MEMS devices, including a variety of wafer bonding [2-6] and sacrificial-film-based [7,8] methods. Most of the reported techniques are either costly (require wafer bonding, lapping, and cap formation), require high-temperature, or are device-specific.

This work reports on a low-cost wafer-level packaging process that is applicable to both surface and bulk-micromachined structures, after their fabrication is completed. Our technique is based on thermal decomposition of a polymeric sacrificial material, Unity 2000 (Promerus, LLC) [9,10], through a spin-coated *solid* polymer overcoat, Avatrel (Promerus, LLC) that covers the microstructure. The sacrificial material undergoes thermolytic degradation in a nitrogen-purged oven to create an air cavity on top of the movable parts of the device. The main advantages of our technique are:

(1) Low-temperature process, suitable for packaging of MEMS and CMOS devices that are sensitive to high temperature and thermally-induced residual stress.
(2) Low-cost polymer-based packaging that does not require wafer to wafer bonding.
(3) Thermal decomposition of sacrificial material is used instead of wet etching, which is fast, reliable, structurally benign, and stiction-less.
(4) The thickness of the sacrificial material and the polymer overcoat can be arbitrarily chosen based on the device size and application.

Both the sacrificial material (Unity) and the polymer overcoat (Avatrel) can be made photo-sensitive. A layer of metal can be sputtered on top of the overcoat to realize hermetic sealing of the MEMS device. The edges of the polymer overcoat can be tailored to have smooth transition to accommodate metal evaporation/sputtering/plating.

This general approach to MEMS packaging is cost-effective and can be carried out in batch or wafer form using common processing facilities.

II. PACKAGING PROCESS FLOW

Packaging via Patterning (PVP)

The first method is more suitable for surface micromachined devices such as SOI resonators. Figure 1(a) shows the packaging process sequence, referred to as packaging via patterning (PVP). The photo-definable sacrificial material Unity 2000P [9] is first spin-coated and soft-baked. The Unity polymer is then patterned using Deep UV exposure (248nm), followed by bake-developing at 110°C to decompose the exposed area. The patterned sacrificial material is covered by a negative-tone photo-definable polymer overcoat, Avatrel. After the encapsulation, the bond pads are opened via patterning of the Avatrel. The sacrificial material under the overcoat that covers the MEMS structure is then thermally decomposed at 200-300°C to create an air-cavity. This is the highest temperature step in this process. The by-products of thermal decomposition can easily permeate through the polymer overcoat. Ultimately, an aluminum layer can be sputtered and patterned to hermetically seal the encapsulated MEMS device.

Packaging via Dispensing (PVD)

The second sequence, referred to as packaging via dispensing (PVD), is described in Fig. 1(b) and is used to package bulk micromachined structures with wide and deep cavities and/or fragile elements. In this method, the sacrificial material (which does not have to be photo-definable) can be applied by a syringe-dispensing tool with adjustable droplet size (0.5 mm to 1 cm) to cover the cavity. Upon soft-baking, the Unity becomes solid and will support the released MEMS structure in the proceeding step. The sacrificial material is then overcoated using Avatrel, and the process sequence continues similar to PVP. A final metallization step can enable a hermetically sealed package. The PVD is especially suitable for MEMS devices with delicate components that can break during spin coating of the sacrificial material; examples are MEMS accelerometers and gyroscopes, and RF MEMS tunable capacitors and contact switches.

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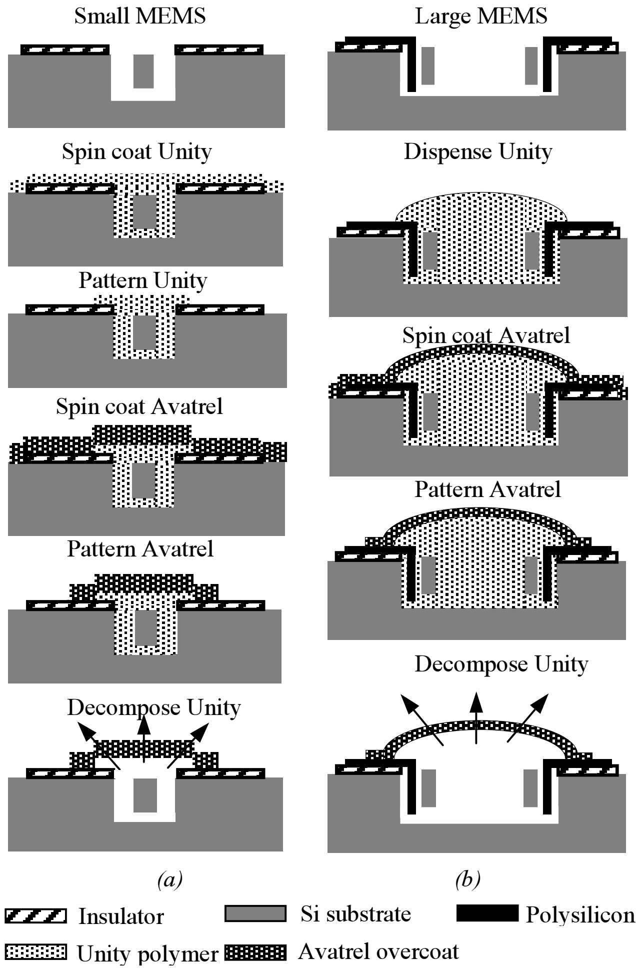

Figure1: Packaging process sequence for: (a)PVP, (b) PVD.

III. IMPLEMENTATION

The feasibility of applying both PVP and PVD methods to package MEMS devices has been successfully verified. A 15μm thick 2.6MHz SOI beam resonator (released) with 1μm gap spacing shown in Fig. 2(a) was packaged via PVP. Narrow trenches were etched down to the buried oxide to define the shape of the resonator and the sense/drive pads, followed by the removal of the buried oxide in HF solution. Figure 2(b) shows the picture of the resonator after PVP. Figure 2(c) shows another packaged resonator, after DC sputtering of gold to hermetically seal the device. In this device, the Avatrel overcoat was extended on top of isolation trenches. Figure 2(d) shows the cross section of a broken packaged resonator, showing a 15μm tall, 80μm wide cavity under a 20μm thick Avatrel cap.

A packaged resonator was tested at wafer-level inside a vacuum probe station. A DC polarization voltage in the range of 70-80V was applied while the electrodes were directly connected to the network analyzer. Figure 3(a) and (b) show the frequency response of the resonator in vacuum before and after packaging. The high *Q* factor of ~5000 did not change for this device, proving that thermal decomposition of the Unity sacrificial material after packaging does not affect the performance of the device.

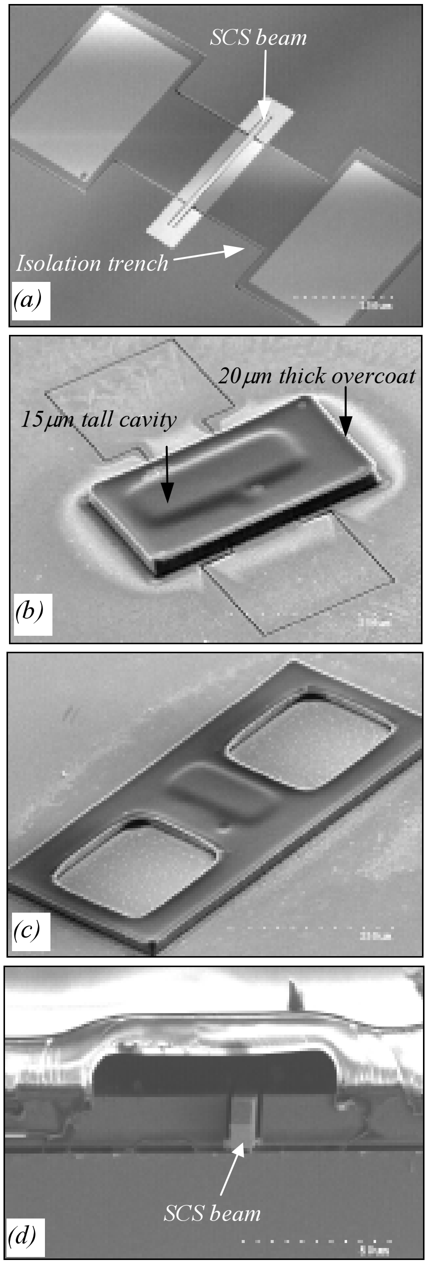

Figure 2: SOI beam resonator; a) before PVP, b) after PVP, c) after metallization, d) cross section of the cavity, the beam resonator, and the Avatrel cap.

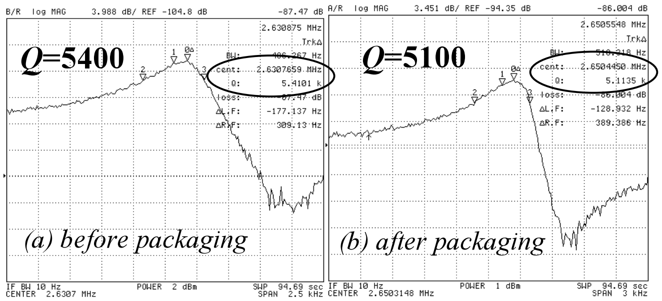

Figure 3: Frequency response of the 2.6MHz SCS beam resonator before and after packaging via PVP technique in vacuum.

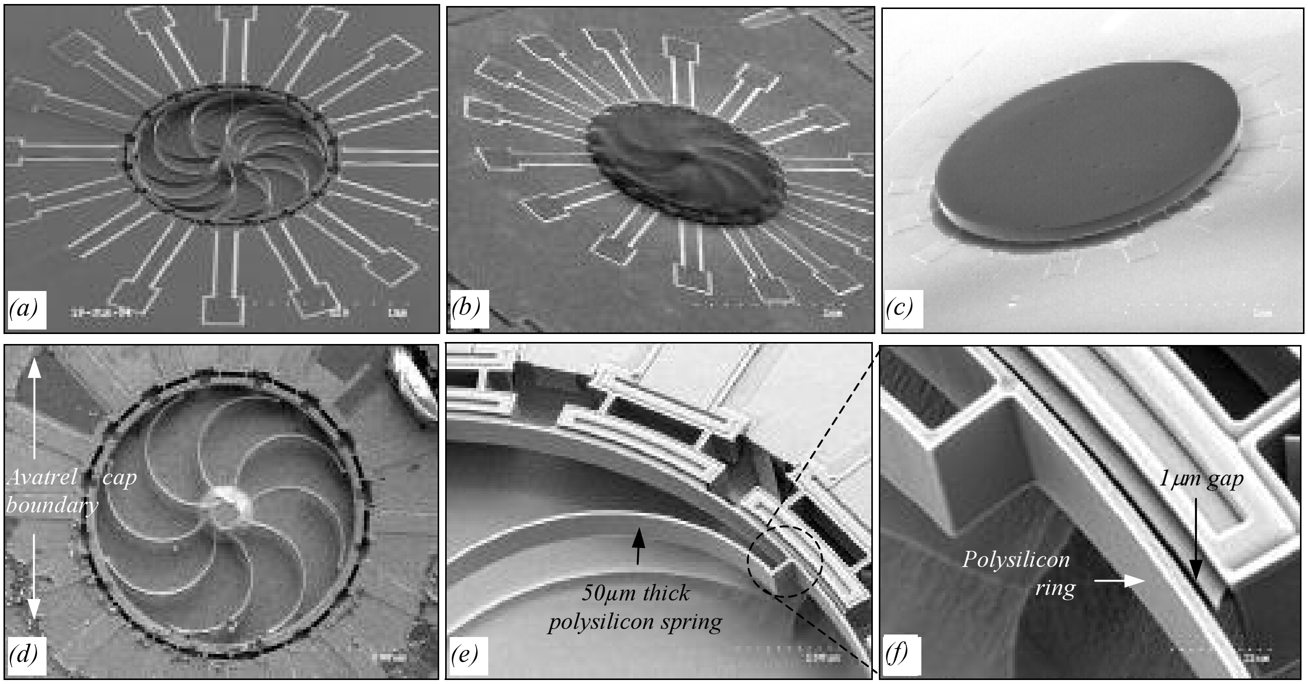

Figure 4: a) HARPSS Polysilicon ring gyroscope, b) after dispensing Unity, c) after encapsulation with Avatrel and thermal decomposition, d) after breaking the Avatrel cap, e, f) close-up views, showing clean and intact device structure.

In order to evaluate the PVD method, a 50μm thick polysilicon HARPSS ring gyroscope with 1μm gap and 200μm deep cavity was fabricated, as shown in Fig. 4(a) [11, 12]. HARPSS sequence starts with patterning the nitride anchors and defining the trench. A thin layer of sacrificial oxide is deposited to uniformly cover the trench sidewalls and define the capacitive gap in between the SCS and polysilicon electrodes. Trenches are refilled with doped polysilicon to form the ring, springs, and the electrodes. Finally, the sensor is released in a DRIE tool, followed by removing the sacrificial oxide in HF solution. Figure 4(b) shows the same device after manual dispensing of the sacrificial material. Figure 4(c) is the view of the device after forming a thick (120μm) overcoat cap and decomposing the sacrificial material from inside the cavity. Figure 4.d shows the device after breaking the 2mm wide Avatrel capsule, confirming a very clean cavity and intact device structure (device is free to vibrate).

The close-up view of the electrodes, the 1μm capacitive gap, and the 4μm wide polysilicon ring and support springs are shown in Fig. 4(e) and 4(f). This clearly shows that the sacrificial material can be decomposed through a very thick overcoat to create a stiff cap. It takes a few hours in room temperature before the air molecules can outgas through the Avatrel cap inside a vacuum chamber and the structure can start to resonate with high *Q*-factor.

HARPSS technology has been used to fabricate a 50μm thick lateral silicon accelerometer. Figure 5(a) shows an 1.8mm×1.5mm accelerometer, encapsulated using the PVD method. The movable SCS electrodes and proof mass with release holes are supported by four SCS springs (440μm long, 6μm wide) at each corner. The stationary polysilicon electrodes with stiffeners are anchored on top of silicon nitride. The movable electrodes consist of 460μm long, 50μm wide perforated SCS beams.

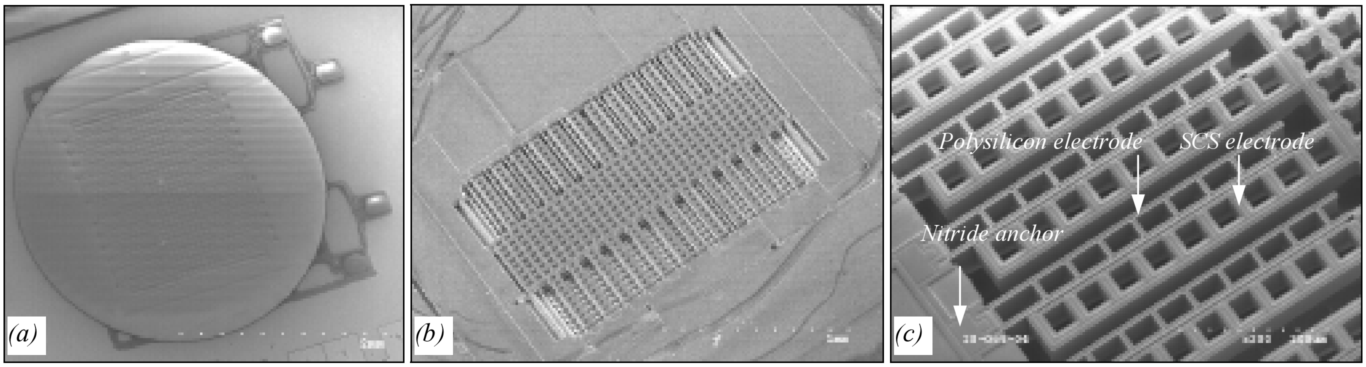

Figure 5: (a) packaged HARPSS SCS accelerometer using PVD technique, (b) same device after breaking the Avatrel cap, some of electrodes are broken during removal of the cap, (c) close-up view of the electrodes, anchors and mass after breaking the cap.

The total capacitive area of the HARPSS accelerometer is about 0.5mm^2, so any tiny residue left during the packaging sequence inside the 1μm capacitive gap can stop the large proof mass from moving. Figure 5(b) shows the same accelerometer after breaking the 120μm thick overcoat. The accelerometer electrodes are free of any sacrificial material residues, as verified in Fig. 5(c). The single-sided static sensitivity of the accelerometer was measured, to be 0.27pF/g and the estimated Mechanical Noise Equivalent Acceleration (MNEA) of the sensor is ~5μg/√Hz in a 10Hz bandwidth.

Compared to the packaging techniques that use inorganic thin-films to cover the sacrificial material, Avatrel overcoat has three main advantages:

(1) It is possible to create thick (up to 500μm) and pinhole-free encapsulation layer over large-area MEMS structures, which is very difficult (if not impossible) to achieve by Chemical Vapor Deposition (CVD) of inorganic films.

(2) Avatrel can be spin-coated at room temperature without inducing any thermal stress on the sacrificial material or the MEMS device.

(3) Avatrel is photo-definable and can be patterned without extra photoresist processing. Avatrel is transparent to visible light, and can withstand temperatures as high as 350°C without considerable deformation.

IV. CONCLUSION

A low-cost low-temperature packaging technique for wafer-level encapsulation of MEMS devices fabricated on silicon substrate is presented. The packaging process does not involve wafer bonding or wet etching of sacrificial thin-films. It utilizes decomposing a sacrificial material through a dielectric polymer overcoat, and has been successfully applied to encapsulate surface/bulk micromachined structures; SCS beam resonators on SOI substrate, HARPSS silicon gyroscopes and accelerometers. For the 2.6MHz SCS beam resonators, a quality factor of about 5000 was measured before and after encapsulation by direct probing to wafer in a vacuum probe station.

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