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Robust Pop-Up Shape Encapsulation Using Dual-Sealing

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***Abstract*— This letter presents pop-up-shaped (having a spherical top shape) thin film encapsulation (TFE) using two-step sealing method. The first sealing step seals the etch holes in the cap layer, whereas the second step provides the shape. A pop-up shape with 2.4-μm upward deformation is demonstrated using a negative pressure difference between the two sealing layers—0.5-μm SiN at 1100 mTorr followed by 3-μm SiO_2 at 390 mTorr on an aluminum nitride cap encapsulating 800-μm × 800-μm size cavities. Besides a deeper cavity, the pop-up shape has smaller downward deformation of the cap layer due to its sturdy design. The increase in the robustness of TFE with pop-up radius is verified through finite element method simulations and theoretical calculation. [2013-0341]**

***Index Terms*— Thin film encapsulation, packaging, microelectromechanical system (MEMS), release time, robustness packaging.**

I. Introduction

Packaging of microelectromechanical system (MEMS) devices such as RF-MEMS switch [1], MEMS resonator [2], MEMS based filter and oscillator [3] is essential to protect their fragile structure from the harsh environment and provide ambience for their reliable operation [4]. Thin Film Encapsulation (TFE) is an attractive alternate technique to the wafer bonding due to possible reduction of overall thickness of the final MEMS device [4], [5], reduction of collective area of the packaged device and low cost from elimination of the cap wafer [6]–[8]. However, TFE has a drawback of downward deformation of thin cap layer due to its lower strength against external pressure after the sealing process. Various approaches have been reported to improve the robustness of the TFE against external pressure in the literature. Mele et al. [7] proposed strengthening of cap layer by creating columns to support it and improve its spring constant to reduce its downward deformation. However, this arrangement cannot be universally applied for all kinds of MEMS devices, particularly, for bigger MEMS devices. Shimooka et al. [8] used additional thick polymer sealing layer to improve spring constant of the cap layer and reduce downward deformation of the cap layer. However, the additional polymer layer increases unnecessary topography of the final device which may increase residual stress. Also proper handling of polymer is needed. In this letter, pop-up shape TFE formation was proposed to avoid the limitation on MEMS device design and unnecessary topography of final encapsulation. This letter presents formation of pop-up shape TFE, means change in shape of TFE top from flat (fig 1(a)) to spherical shape (fig 1(d)), by simple dual sealing process. This enhances robustness of TFE.

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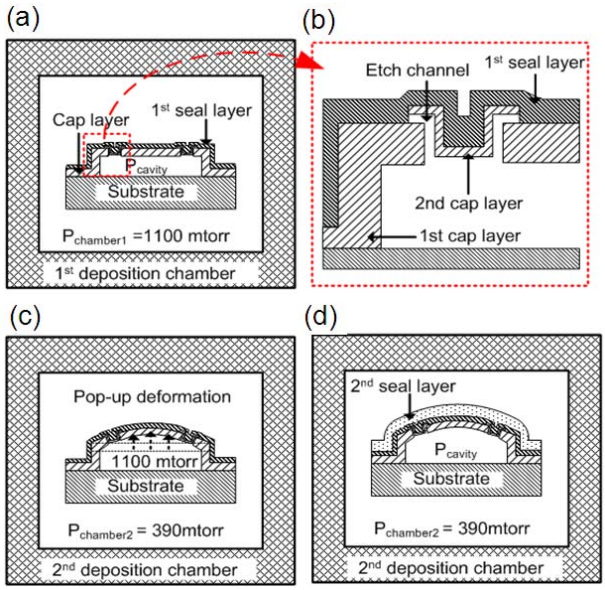


Fig. 1. Schematic diagram of pop-up shape TFE using double sealing process. (a) TFE after 1st thin sealing at relatively high pressure. (b) Enlarged view of TFE near etch channel. (c) Pop-up deformation of TFE during low pressure deposition. (d) Final pop-up shape TFE after 2nd sealing layer deposition.

II. Concept and Fabrication

Figure 1 shows schematic diagram of the proposed method for realizing the pop-up shape TFE. In order to achieve the pop-up shape TFE, first a thin film is deposited at higher pressure (Fig. 1 (a, b)) to just seal the cap (called as first sealing layer) followed by a thick layer deposition at lower pressure (Fig. 1(c, d)) (called as second sealing layer). The higher pressure inside the sealed cavity relative to deposition chamber pressure during the second sealing layer deposition results in an upward deformation of the thin encapsulation as shown in Fig. 1 (c). As the second sealing layer is thicker than first sealing layer, pop-up shape of cap layer remain sustained as shown in Fig. 1(d). The second sealing layer was designed to be thicker to obtain the higher spring constant for the cap layer and to improve the hermetic performance of TFE. This technique helps in realizing large size and deeper cavities for encapsulating of MEMS devices using thin sacrificial layer.

The dual cap layer scheme for fabrication of TFE as shown in Fig. 1(b) is demonstrated in our previous work on 8” silicon wafers [6]. In this work, sealing process is modified to achieve pop-up shape TFE. Following are the process steps followed for fabrication of pop-up shape TFE: (1) Wafer cleaning (2) Deposition and patterning of 3 μm thick Plasma Enhanced Chemical Vapor Deposition (PECVD) SiO_2 as a first sacrificial layer. This defines the cavity for the MEMS device. The thickness of the sacrificial layer partially defines the depth of the cavity (3) deposition and patterning

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TABLE I
SUMMARY OF THE FEM SIMULATION USING ANSYS© FOR DOWNWARD DEFORMATION FOR DIFFERENT MEMBRANE SHAPES AND APPLIED PRESSURES

	Material (Young's Modulus) [GPa]	Applied Pressure [Pa]	Dimension (center high of pop-up cap layer) [μm]	Deformation of cap layer [μm]	Shape of cap layer Simulation image
Simulation 1 (Circular membrane)	AlN (345)	1 x10⁴	Φ 800 x 4 (0)	5.9	
			Φ 800 x 4 (6)	3.5	
			Φ 800 x 4 (12)	1.3	
Simulation 2 (Square membrane)	AlN (345)	94	200 x 200 x 1	0.006	
			400 x 400 x 1	0.10	
			800 x 800 x 1	1.21	
		142	200 x 200 x 1	0.01	
			400 x 400 x 1	0.15	
			800 x 800 x 1	1.82	
	SiO_2 (70)	94	200 x 200 x 1	0.03	
			400 x 400 x 1	0.53	
			800 x 800 x 1	6.05	
			200 x 200 x 2	0.003	
			400 x 400 x 2	0.06	
			800 x 800 x 2	1.00	

of 0.5 μm first AlN cap layer (4) deposition and patterning of second SiO_2 sacrificial layer (5) deposition and patterning of second AlN cap layer of 0.5 μm (6) Etching of sacrificial oxide using VHF via etched holes in cap layer (8) deposition of 0.5 μm thick low stress SiN layer at 1100 mTorr to seal etch holes. The pressure inside the encapsulated cavity is decided by deposition pressure of the first sealing layer. (9) Finally, second sealing layer of 3 μm thick oxide is deposited at 390 mTorr. During the second sealing layer deposition, the cap layer deforms upward in pop-up shape as the pressure inside the encapsulated cavity is higher than the deposition pressure. These two dielectric sealing layers are considered for demonstration because they can be deposited at relatively different pressures. Thicknesses used for sealing layers are optimum for pop-up formation and sealing. However other materials can also be used for sealing.

III. SIMULATION AND CALCULATION RESULTS

In order to check possible pop-up shape formation under applied pressure Finite Element Method (FEM) simulation was carried out on square membranes without considering etch holes using ANSYS© Software. Three different sizes (200, 400 and 800 μm) of cavities and two different thicknesses of cap layer (1 and 2 μm) were considered for the simulation to check the pop-up height deformation at the center of the cap layer under the pressure difference. SiO_2 and AlN were considered as membrane materials to check the effect of the Young's modulus on the pop-up height. Table 1 provides summary of these results obtained in simulation. Figure 2 shows that the pop-up height of TFE increases dramatically with increase of encapsulation size. On the other hand, pop-up height decreases with increase of encapsulation thickness.

Point to be noted is that the dimension of encapsulation (cavity to be sealed) is critical in realizing the pop-up shape TFE using dual sealing process. In general, size of encapsulation layer will be determined by the size of MEMS devices. Therefore, thickness control of the encapsulation is easier choice for pop-up realization. One more important factor is to choose apt materials for encapsulation. For example, when Silicon dioxide (with Young's modulus of 70 GPa [10]) is used for encapsulation instead of AlN (with Young's modulus of 345 GPa [10]), 5 times larger deformation is obtained in the center of the cavity under the same pressure.

Figure 3 shows FEM simulation results of downward deformation for pop-up shape cap structure at the center of the encapsulation.

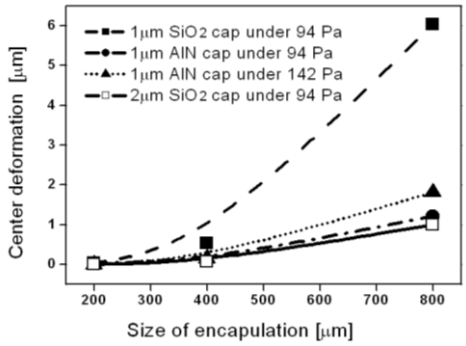


Fig. 2. FEM simulation results of pop-up shape TFE formation as a function of size and thickness of encapsulation, applied pressure and different material.

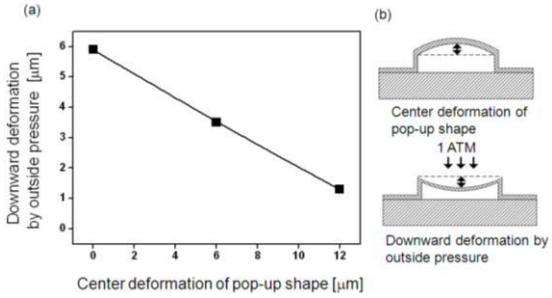


Fig. 3. (a) FEM simulation results of downward deformation as a function of pop-up height for 4 μm thick and 800 μm diameter AlN membrane against 1 atm pressure (b) schematic diagram of membrane, top; pop-up shape, down; downward deformed membrane due to 1 atm applied pressure.

The parameters used in simulations such as size, applied pressure and several pop-up heights, summarized in Table 1. Three different pop-up heights were considered in the simulation.

The downward deformation of the cap layer is found to decrease from 6 μm to 1.3 μm when pop-up height increased from 0 μm to 12 μm for a 4 μm thick AlN encapsulation layer on top of 800 μm (diameter) circular cavity when 1 atm external pressure is applied. The decreased downward deformation of TFE against external pressure with increased cap curvature infers that controlling curvature of encapsulation in pop-up shape is excellent way to enhance robustness of the TFE against external pressure.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4(a) and 4(b) show surface profiler images of 800 μm $\times$ 800 μm size encapsulation with and without additional sealing process step, respectively. One step sealing, obtained by deposition of 3 μm PECVD oxide, results in 5.1 μm deep cavity as shown in Fig. 4(a). An additional 2.1 μm pop-up deformation could be because of residual stress between AlN and SiO_2 encapsulation layers. The control of the pop-up shape deformation could thus be possible by controlling the stress of the encapsulation. Further work to check the deformation due to stress will be carried out in near future.

On the other hand, two level sealing process (first sealing using 0.5 μm of SiN at 1100 mTorr and second sealing using 3 μm of SiO_2 at 390 mTorr) help in achieving the cavity depth of 7.5 μm as shown in Figure 4(b) which is 2.4 μm deeper than the TFE sealed using single step sealing process. This shows that the 2.4 μm height of pop-up shape cap layer is due to pressure difference of 710 mTorr (94.66 pa) between two sealing steps.

The theoretical calculation was carried out using equation (1) [9] to validate the experimental results of the pop-up shape deformation

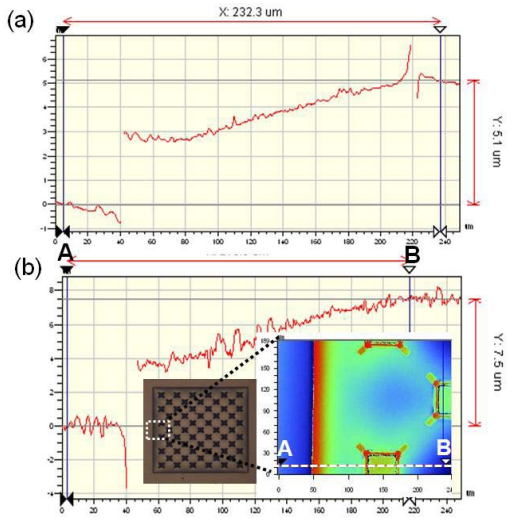


Fig. 4. Surface profiler images of 800 μm × 800 μm size encapsulation after (a) double sealing (1st SiN sealing @ 1100 mTorr, 2nd SiO_2 sealing @ 390 mTorr) (b) single SiO_2 sealing process.

for 800 μm × 800 μm × (0.5 μm AlN + 0.5 μm SiN) encapsulation layer.

$$W_0 = \frac{1}{66}\frac{a_{M^4}}{d_{M^3}}\frac{1-v_{M^2}}{E_M}\Delta P \tag{1}$$

The applied pressure (Δp) was decided to be 94.66 Pa, which is pressure difference between depositions pressures used in TFE demonstration. The thickness of the encapsulation (d_M) was 1 μm (0.5 μm AlN cap layer + 0.5 μm SiN as a first sealing layer). The Young's modulus (E_M) of the composite film was considered to be 252.5 GPa which was calculated by the equation (2) using following formula.

$$E_{composite} = \frac{(E_{SIN} \times t_{SIN}) + (E_{AIN} \times t_{AIN})}{t_{SIN} \times t_{AIN}}. \tag{2}$$

The Young's modulus of SiN and AlN were considered 170 GPa [10] and 345 GPa, respectively, for this calculation. The Poisson ratio (v_M) of the composite film was considered to be 0.25. The maximum upward deformation for 94.66 Pa from this calculation is 1.83 μm which favorably matches with experimental value of 2.4 μm. The difference between experimental and simulation results can be owed to two factors: (1) no etch holes were considered in the membrane for the calculation and, (2) Material properties for the calculation may be different from actual material properties in the experiment. Soft materials with low Young's modulus should be more suitable for this proposed technique for highly curled MEMS devices.

V. Conclusion

In this letter, the dual sealing technique was proposed and demonstrated for achieving pop-up shape TFE. This pop-up shape improves robustness of TFE by solving the main issue of downward deformation which can cause damage to MEMS devices. In proposed technique, sealing was done in two steps: (i) the first thin sealing of 0.5 μm thick SiN at relatively high pressure of 1100 mTorr and (ii) second thick sealing of 3 μm thick SiO_2 at relatively low pressure of 390 mTorr. The cavity depth of encapsulation was increased by 2.4 um with pressure difference of 710mTorr. Much deeper cavities can also be achieved by using appropriate cap materials and deposition techniques. Even deeper cavities can be obtained by using soft materials for cap and sealing layers and deposition methods.

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