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A Robust Thin-Film Wafer-Level Packaging Approach for MEMS Devices

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Abstract—**Micro-electromechanical systems (MEMS) devices are extremely sensitive to their environment, especially at the wafer level, until they are packaged in final form. The harsh back-end (BE) operations that the MEMS devices have to endure include dicing, pick-and-place, wire bonding, and molding. During these processing steps, the MEMS device is exposed to particles and contaminants. Therefore, protection at an early stage is a fundamental requirement.**

We describe a silicon nitride thin-film capping, which is processed using a sacrificial layer technique only with front-end technology. This approach is suitable for mass production of MEMS devices, owing to the fact that it is more cost-effective when compared to other approaches such as wafer-to-wafer bonding and die-to-wafer bonding.

A bulk acoustic wave (BAW) resonator that finds application in the radio frequency (RF) front end, for example, in cell phones, is taken as a MEMS vehicle for our work. It is an example of an extremely sensitive MEMS device, because the resonance frequency shifts significantly when additional mass is accidentally deposited on its surface. The thickness of the silicon nitride capping that is required to withstand all the BE steps, in particular transfer molding, is estimated using simple analytical calculations and finite element model (FEM) simulations. The pressure acting on the thin film capping and the thermal load during molding are included in the FEM model. Using this, the minimum thickness required for the capping is determined. We prove that a BAW resonator capped with silicon nitride at the wafer level can be wafer-thinned, diced, wire bonded, and molded without major degradation in performance.

Keywords—**Thin-film capping, front-end technology, BAW resonator, back-end operations**

Introduction

Micro-electromechanical systems (MEMS) devices are extremely sensitive to their environment, especially at the wafer level, until they are packaged in final form. Therefore, protection at an early stage is a fundamental requirement. To date, a few approaches to cap MEMS devices at the wafer level have been investigated and implemented, known as *0-level packaging* [1] routes. They fall under three broad categories, namely, wafer-to-wafer capping, die-to-wafer bonding, and wafer-level thin film capping [2]. Wafer-to-wafer capping is cost-intensive, requiring one full wafer with a processed microcavity to cap the MEMS device wafer by means of a suitable bonding technique [3]. In addition to this, the wafer-to-wafer capping requires design modifications in the MEMS wafer to account for the bond pad openings and seal rings, thereby demanding additional footprint on the MEMS device wafer. Die-to-wafer bonding involves picking and placing individual silicon or glass dice onto the MEMS die-on-wafer. This operation contributes to the total packaging cost significantly. Both of the above mentioned approaches add significant thickness to the MEMS device.

In our work, we investigate a thin film silicon nitride capping route, processed at the wafer level. A BAW resonator has been taken as a MEMS vehicle to show the feasibility of this front-end (FE) technology. Its advantages over the above-mentioned capping approaches are:

1. A high volume production can be achieved using standard IC processing techniques.
2. As the cap takes the footprint of the device, device density can be significantly increased.
3. When manufactured in FE technology, standard back-end facilities can be used and no investments are necessary.

A BAW resonator exploits the thickness-extensional mode of vibration of a piezoelectric thin film. This thin film is sandwiched between a pair of metal electrodes. The BAW resonator used for the current work consists of aluminum nitride (AlN) piezoelectric dielectric and platinum (Pt) top and bottom electrodes. To contain the acoustic vibrations in the device, an acoustic mirror stack is constructed beneath the bottom electrode. The top electrode is open to air. A simplified schematic is illustrated in Fig. 1. BAW resonators find applications in the radio frequency (RF) front-ends, for example, in cell phones [4]

There are three crucial challenges faced by the BAW resonators for them to be successful products in the marketplace:

1. The accidental deposition of any additional mass shifts the operating resonance frequency, posing a crucial limitation; the mass loading impairs the devices' electrical functionality.
2. One other challenge in the emerging BAW business is to package the devices in an extremely cost-effective way. For a very similar class of devices, called the surface acoustic wave (SAW), ceramic packaging is usually adopted to package the device. It is, in principle; possible to use this

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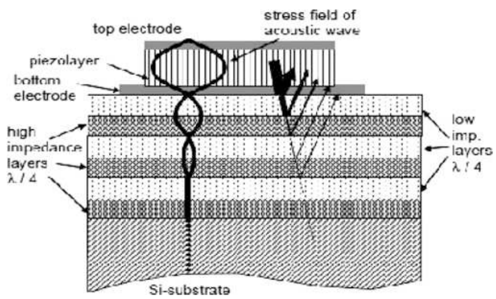

Fig. 1. A solidly mounted BAW resonator, the different functional layers that form the active device: the top and bottom electrodes, the piezoelectric layer sandwiched between them, and the reflector stack beneath the active device.

type of packaging for BAW devices, but it is not the cost optimum.

3. The wafer-level capped BAW resonator must survive the BE processing (including, e.g., 80 bar molding pressure). In addition to this, the critical requirement of mechanical robustness to survive the standard disc sawing with water jet and the pressure load due to injection molding is a challenge when it comes to package-level reliability of the BAW device.

The organization of this paper is as follows. The Work Model section presents the work model linked to different entities, leading to the goal of this work. The Process Flow section describes the process flow to achieve thin-film silicon nitride capping using FE technology [5]. In the Mechanical Simulations section, analytical calculations are used to determine the thickness of silicon nitride required to withstand a molding pressure of 80 bar. Extending this further, numerical simulations, using COMSOL finite element model (FEM) [6] are performed to determine the impact of thermo mechanical loading on the silicon nitride cap during the transfer molding process. Including the above-mentioned loading conditions, the minimum thickness of silicon nitride required is determined and optimized. The Design Layout section describes the design study by means of design of experiments and the choice of a specific capping design based on electrical results. In the Construction Analysis section, the results of failure analyses after transfer molding are presented. The next section presents the results of electrical analyses. Finally, a few important conclusions are drawn.

Work Model

The flow chart in Fig. 2 illustrates the different entities that are linked to each other to come to an effective and reliable capping route. Starting with a set of specifications, the process flow is investigated.

Process flow involves carrying out a number of test experiments to demonstrate the feasibility of the capping process devised. *Design layout* involves the study of two types of design variations in the capping route. *Mechanical simulations* consist of determining the required thickness of the capping considering the mechanical load of 80 bar and a thermal excursion that takes place during the process of molding. In *Electrical analysis*, measurements are done by probing the top and bottom electrodes at the contact points (bond pads) to excite

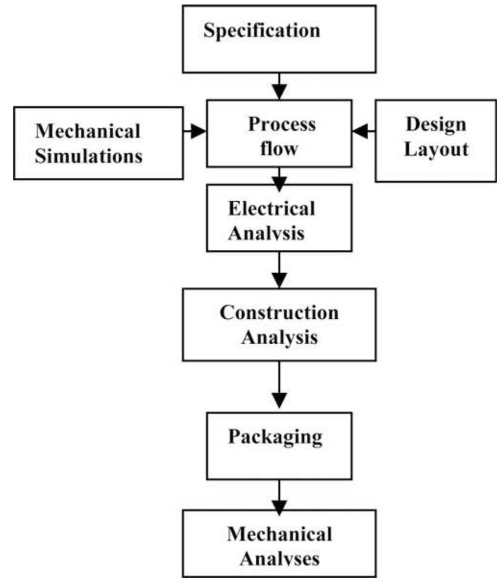

Fig. 2. Project flow: The flow diagram illustrates the different sub parts of the work, phasing it at different levels, starting from specification and ending with the finish.

the resonator and measure the antiresonance frequency (F_a). This is done at three different stages: First, just after processing the resonator device, to tune the resonance frequency; second, after the tuning is finalized; and third, after the wafer-level capping to determine the shifts in F_a. This basically demonstrates the electrical functionality of the resonator. *Construction analysis* involves demonstrating the feasibility of the capping route. *Packaging* consists of molding the capped BAW die in a standard plastic package. The chosen package can be of two different types, the substrate type or the lead frame type. In our work, we have chosen the substrate type, where the die is glued to a laminate; electrical connections are defined and the die is molded using a standard molding process.

Finally, a Mechanical analysis is carried out to determine the impact of molding on the capping.

Process Flow

The active region consists of the aluminum nitride piezoelectric (AlN). The top electrode is platinum (Pt), and the bottom electrode is titanium tungsten/aluminum (TiW/Al). The bond pad region consists of aluminum (Al) as the contacting metal, on top of a very thin layer of titanium nitride (TiN). Both the bond pad and the active device are completely covered with silicon nitride to protect the resonator. The silicon nitride in the active area, on top of the resonator, is selectively etched to tune the resonance frequency.

Fig. 3 illustrates the steps in the process flow. The micro-cap starts with the deposition and patterning of the sacrificial layer on top of the BAW resonator. A thin layer of silicon nitride is then deposited by plasma enhanced chemical vapor deposition (PECVD). In order to release the resonator, release holes are defined and patterned on this silicon nitride. Finally, a thick silicon nitride is deposited by PECVD to seal these release holes.

Mechanical Simulations

The purpose of the mechanical simulations is to determine the required thickness of the capping layer.

Starting with a simplified assumption, as illustrated in Fig. 4, that the capping is a square plate that is clamped at the edges, the deformation of the plate due to an applied load can be calculated with the well-known Timoshenko equation for a square plate [6], given by,

$$y = \frac{0.0138 \cdot q}{E} \times \left(\frac{l^4}{t^3}\right)$$

where y (m) is the deflection of the plate, E (Pa) is the elastic modulus of the plate, l (m) is the length of the plate, t (m) is the thickness of the plate, and q (Pa) is the applied pressure.

Simulations are performed in COMSOL after benchmarking the numerical simulation with the known analytical expression. The type of finite element and the mesh is chosen based on the compromise between the solver accuracy and speed. The required material properties are supplied to the model. The boundary conditions and the load are applied and the deflection of the structure is determined. The process of molding takes place at a temperature of 175°C in addition to the 80 bar pressure load acting on the capping due to the injection pressure of the molding [7]. Therefore, in addition to the mechanical load, the loading due to temperature excursion is also considered. By subjecting the result of the deformed model to a temperature ramp down from 175 to 25°C, this additional influence on the deflection of the capping was determined.

In a very crude form, not considering the visco-elastic properties of the molding compound, the loading due to molding can be broken down into two parts. The stepwise parametric model is illustrated in Fig. 5.

At step 1 the 80 bar pressure is applied, with the temperature fixed at 175°C. In step 2, the temperature is ramped down linearly from 175 to 25°C.

The model used for simulation is illustrated in Fig. 6. We assume that there are two cavities next to each other separated by 80 μm. The simulation model used is a 2D FEM in COMSOL[8]. Material properties are chosen as indicated in Table I [9]. The deformation is plotted at the end of load step 2 and still has a load of 80 bar as presented in Fig. 7. It is seen that the deformation of the silicon nitride cap does not exceed the maximum deformation of 0.83 μm in the simulated model.

It is concluded that, for a 225 × 225 μm^2 footprint that is typical of a BAW resonator used in the design of the capping, a 9 μm thick silicon nitride film would result in a deformation of 0.78 μm, under the impact of 80 bar pressure and temperature

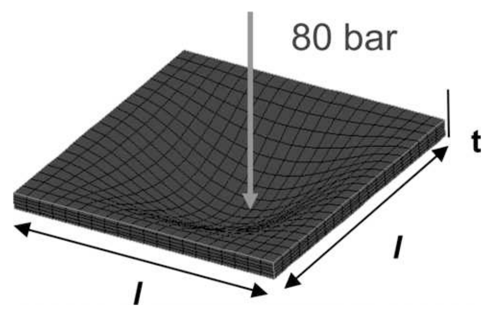

Fig. 4. Square plate with span l and thickness *t* subjected to a surface load, clamped at the edges, the load is the pressure due to molding, which is typically 80 bar in a standard molding process.

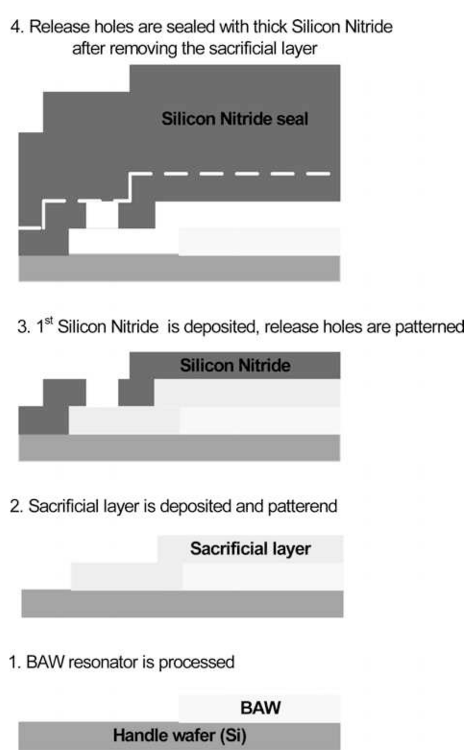

Fig. 3. Process flow. Sequence of steps up to silicon nitride sealing.

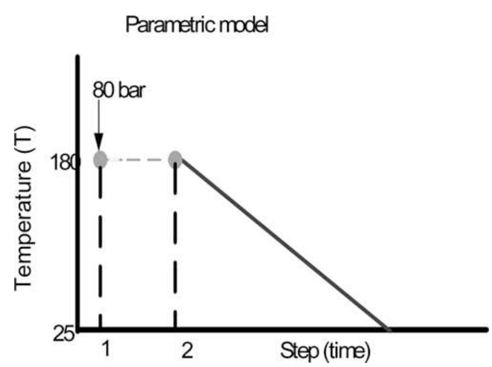

Fig. 5. Stepwise parametric model to include the thermo mechanical load on the silicon nitride thin film capping.

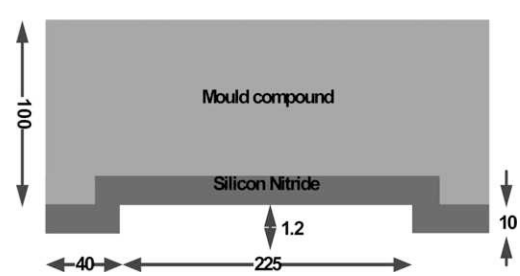

Fig. 6. 2D model implementation for the load case illustrated by the stepwise parametric model, simulated in COMSOL FEM (all dimensions are in μm).

Table I
Material properties used in simulations

Material	Young's modulus, E [GPa]	Poisson's ratio	CTE [ppm /K]
Silicon nitride	180	0.23	3.0
Mold compound	20	0.2	10

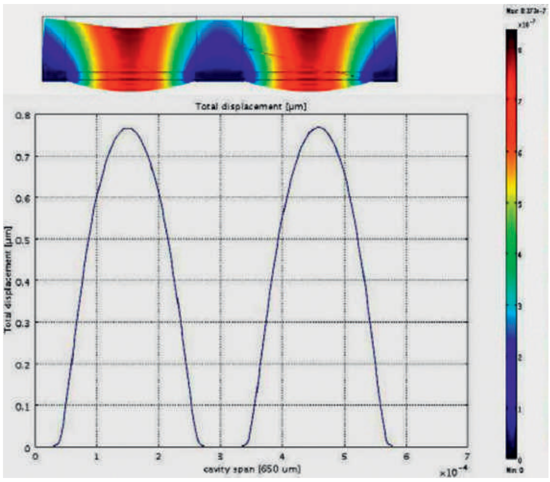

Fig. 7. 2D deformation plot of two micro cavities separated by a distance of 80 μm. From the deformation profile, the deformation is found to be below the maximum deformation of 0.84 μm. The downward cap deformation as seen in the simulation in the top picture is plotted on the positive y axis.

excursion during the molding process. This indicates that the cavity would survive the molding conditions.

Design Layout

In the design study, two different types were considered: the default design, *Type A*, in which the release holes for the removal of the sacrificial layer are placed around edge of the resonator, and the other, *Type B*, in which the release holes are located on top of the resonator. The distance from the resonator to the release holes, *d,* and the release hole size, *CS* are varied. Fig. 8 schematically represents the design variation. In the Electrical Analyses section, the relevance of the design variations is discussed.

Construction Analysis

Construction analysis was done using a focused ion beam (FIB) at the cavity edge to to inspect the cavity with the air gap. Fig. 9 shows the scanning electron microscope (SEM) picture of the cavity at the resonator edge.

From the analysis it can be concluded that the cavity on top of the resonator is intact and only slightly bent down, leaving sufficient room for the BAW device to resonate.

Electrical Analyses

After demonstrating the feasibility of realizing a silicon nitride cap on BAW resonators at the wafer level, the resonators are probed to check the electrical functionality after wafer-level capping. The parameter of interest is the antiresonance

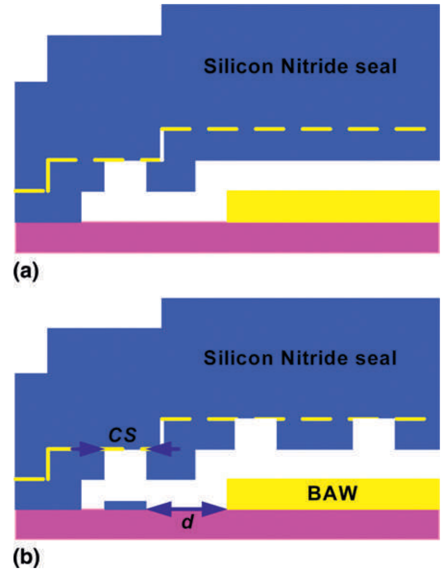

Fig. 8. Design layout variations. (a) Type A: Release holes around the resonator. (b) Type B: Release holes on top and around the resonator, *d*, and *CS* are varied.

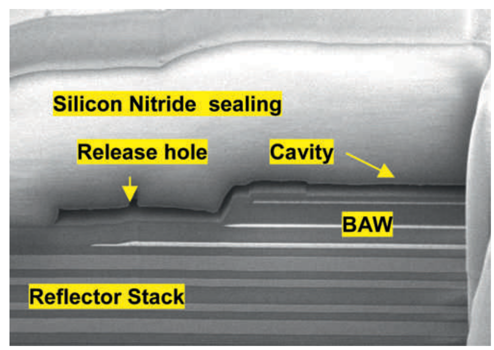

Fig. 9. SEM picture showing the air cavity with silicon nitride sealing the release hole is shown, at the edge of the BAW resonator.

frequency, F_a, because it can be measured more accurately than the resonance frequency and because it is also measured after processing the BAW resonator on wafer. After the wafer-level capping is finished, once again, F_a is measured on the same set of samples.

For the default layout, *Type A*, the mean frequency shift is 1.0 MHz (standard deviation of 0.35 MHz). During the deposition, the silicon nitride sealing material does not reach the active area 6 μm away. For *Type B*, the mean frequency shift is 7.0 MHz. This is rather high. Fig. 10 illustrates the measured shift in F_a for yield up processing condition, for *Type A* design layouts. The best case, namely, the yield up drying step, is taken among the other process variations, such as the default: 150 + 400°C anneal after the sacrificial layer removal, yield up drying step; and the critical drying after sacrificial layer removal. The best results are obtained for the higher anneal temperature of 400°C after sacrificial layer removal. The drying process seems less critical and there is no difference between Marangoni drying and normal spin drying. The results of the electrical analysis are illustrated in Fig. 10. The shift in F_a is independent of the distance d of the release hole from the resonator edge. Therefore the distance d of 6 μm is the optimum in the design.

For the default design, *Type A*, the shift in F_a is dependent on the size of the release holes, amounting to 3.4 MHz. This indicates that the silicon nitride sealing layer reaches the active area of the resonator.

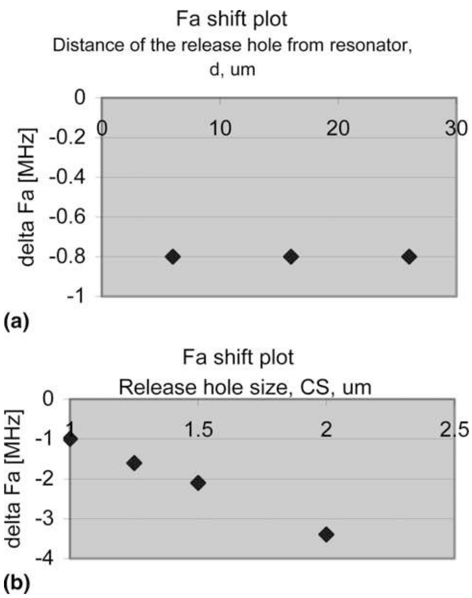

Fig. 10. Frequency shift plot for Type A design, as a function of (a) device to etch hole distance, *d*; (b) etch hole size, CS, at a fixed etch hole distance *d*.

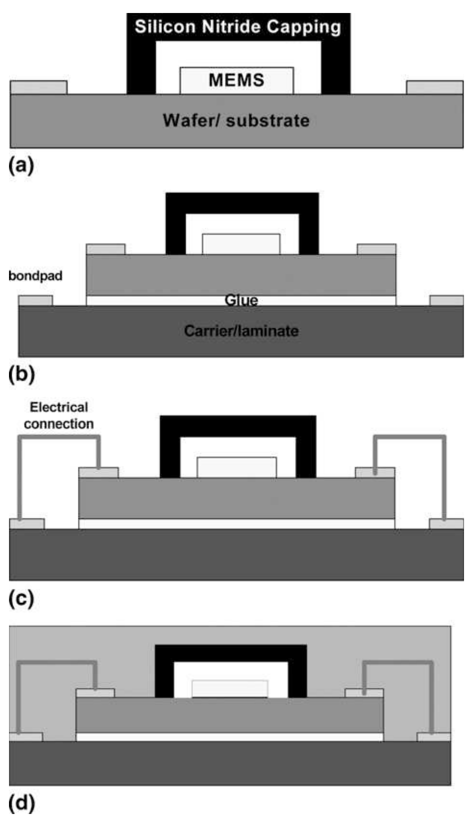

Fig. 11. Process steps from wafer-level capping to molding. (a) Wafer-level capped BAW after back grinding and dicing. (b) Die, attached to the laminate after back grinding the wafer. (c) Wire bonding is done. (d) Finally, molding is performed.

Packaging and Mechanical Analysis

Just after wafer-level capping, the BAW resonators are present on the silicon wafer and they must be singulated by dicing the wafer. Diamond blade dicing, which is the industry standard, is used for dicing. Visual inspection with an optical microscope is done for every operation to monitor the effect of that particular step on the capped BAW resonators. Fig. 11 illustrates the sequence of BE steps until molding. After die attach with a conducting glue, 84-1LMIS [10] and a cure step of 150°C for 1 h, wire bonding with gold wire of diameter 25 µm is done. Finally, molding is performed.

The optical microscope images in Fig. 12 show that the silicon nitride capping survives the wafer back grinding step (from 525 down to 250 µm), die-attach, curing, and wire bonding steps. In Fig. 13, a SEM picture of the BAW resonator edge

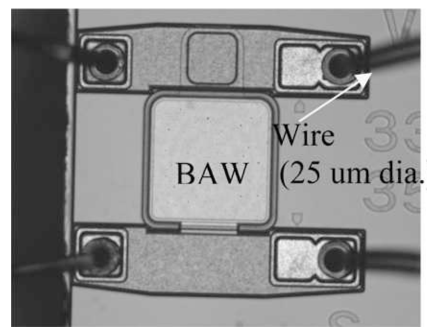

Fig. 12. Optical microscope image of the BAW resonator (top view) capped with silicon nitride, after wafer back grinding, die-attach, and wire bonding.

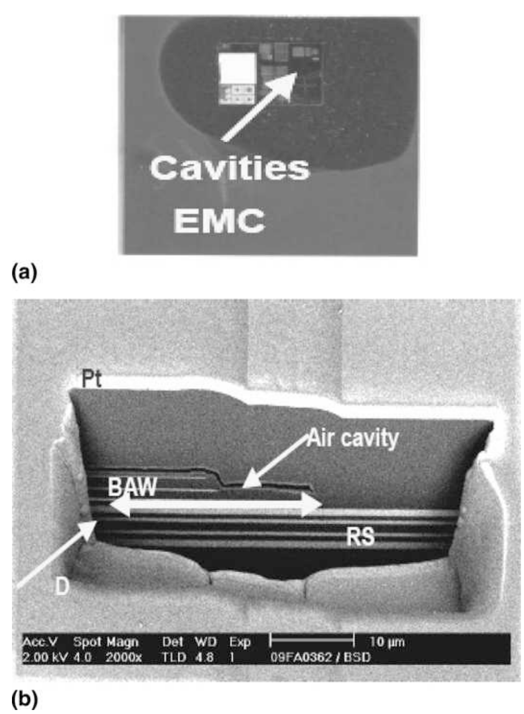

Fig. 13. (a) Silicon nitride cap after the EMC is decapsulated. (b) A functional silicon nitride capping at the BAW resonator edge, after the standard back-end operations, reflector stack (RS), BAW resonator active are visible, D is the direction of view. Platinum (Pt) is the topmost coating.

is presented. This is done after decapsulating the epoxy mold compound (EMC) by a standard decapsulation process, and the cross-section is made using FIB. The region of the silicon nitride capped BAW resonator where the EMC is decapsulated is also shown.

Conclusions

We have successfully demonstrated the feasibility of a silicon nitride capping using the FE technology for capping MEMS devices, using a BAW device as a vehicle.

The following are concluded from the electrical analysis.

1. Resonators of *Type A* design (default) show a frequency shift not greater than 1.0 MHz. This is believed not to be due to mass loading by silicon nitride sealing material, because the shift is independent of the distance *d* from the release holes to the resonator edge. Therefore, it is believed to have come from the packaging. With increasing release hole size, the frequency shift increases. This implies that the silicon nitride sealing material reaches the resonator active area. Since the shifts is (expected to be) constant, it can be take into account with the tuning of the resonator during wafer processing.
2. Resonators of *Type B* design show frequency shifts of at least 7.0 MHz due to deposition of the silicon nitride sealing material on the BAW resonator. For increasing release hole dimensions, the shifts become larger.

From the mechanical analyses, it is concluded that:

1. The silicon nitride capping survives all standard BE operations up to final packaging.
2. The capping is robust enough to withstand the molding pressure of 80 bar.

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