A New Approach to Wafer Level Thin-Film Encapsulation for RF-MEMS

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Abstract. The paper will discuss in detail a new fabrication process developed for the encapsulation of RF-MEMS switches. A shell covering the unreleased switch is created with two layers of PECVD silicon nitride patterned with holes and separated by an aluminum layer which is removed at the end of the shell fabrication sequence. The cavity beneath the shell is then made free burning by oxygen plasma the sacrificial photoresist spacer covering the switch.

The mechanical design of the shell and the optimization of the film parameters are reported and discussed. The shell is then covered with a sealing polymer that should not penetrate into the holes. In order to achieve this result a special design for the hole pattern is presented.

1. Introduction

One of the limits to full exploitation of the potentialities of RF-MEMS switches is the lack of a low-cost packaging system. The requirements of such a package are quite demanding: it must protect the switch from mechanical damage and contaminants, add minimal RF losses and maintain the performances of the switch or circuit. A suitable package should also be low cost, require little additional space and be easy to incorporate in the microwave integrated circuit. It must be hermetic, because MEMS RF components are particularly sensitive to contaminants and humidity, and for this reason the ideal package atmosphere is dry nitrogen or similar inert gases. The usual approach to packaging uses conventional techniques which results in high costs. On the other hand, wafer level packaging techniques include normally wafer bonding schemes and a sealing ring around the switch that increases the switch footprint, while the temperature sensitivity of these devices requires metal-based low temperature solders which can introduce high RF-losses.

In this contribution a thin-film encapsulation scheme is proposed as packaging methodology. This technique is low cost and has a high level of integrated circuit compatibility. Instead of bonding the MEMS wafer on a separate wafer with caps, an open cage-like structure is build around the switch. This is done exploiting standard wafer processing techniques and requires moderate temperatures (200-250°C) [1].

In this type of approach a sacrificial photoresist is deposited above the (unreleased) switch, and then covered with a dielectric to form the shells. Convenient holes are then etched on the dielectric in order to form a release channel. In similar approaches found in the literature [1]-[2], the sacrificial layer is then plasma etched and the cavity sealed with a convenient polymer. The final sealing is however the most critical part of the process because the encapsulant polymer viscosity, the diameter of the holes, the chemical affinity between polymer and cage and the mechanical stiffness of the cage itself play an important role in determining the yield of the process and the final performance of the packaged device. It is then important to find a hole design solution to reduce or prevent polymer wicking through the cage holes keeping in mind that the reduction of hole dimensions is limited by lithographic resolution. In this paper a particular solution to this problem is addressed, that in principle can avoid any wicking phenomena, and produce reliable polymer sealing without compromising the underlying switch functioning.

2. Encapsulation Design Concept

In this section a particular fabrication scheme is presented in order to build a better performing cage structure above the switching devices. The basic idea is to build the shell with two different layers of PECVD silicon nitride with a thin sacrificial layer of aluminum in between them. In all three layers holes are etched but with only a slight superposition between them. When finally the thin aluminum layer is removed, no direct superposition between holes of the two nitride layers is left. This allows the plasma removal of the sacrificial photoresist but inhibits the sealing polymer wicking through the cage holes. A process section for this particular scheme is presented in Fig. 1, while a top view of the holes 2D distribution is reported in Fig. 2. The shell shape is square or rectangular, with side dimensions varying from 500 to 1000 μm. The hole dimensions are 8×8 μm on the two nitride layers, and 6×6 μm on the sacrificial aluminum layer. The free cavity height is determined by the sacrificial spacer height, that is about 3 μm above the device, assuming negligible resist planarization.

In addition a detailed study of parameters influencing the stiffness of the cage material has been planned and performed in order to obtain a more robust shell, which can resist to the sealing polymer spinning process without collapsing on the bottom of the cavity and/or deteriorating the switch performances.

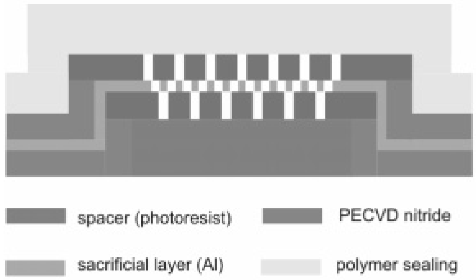


Fig. 1. Encapsulation process scheme.

Improvement of silicon nitride mechanical stiffness can be achieved by controlling its residual stress properties, because the bending spring constant of the shell is strongly depending on its residual stress value. This task involves an evaluation of the stress properties of the PECVD nitride building material as a function of its deposition parameters, and it is reported in detail in the next experimental section.

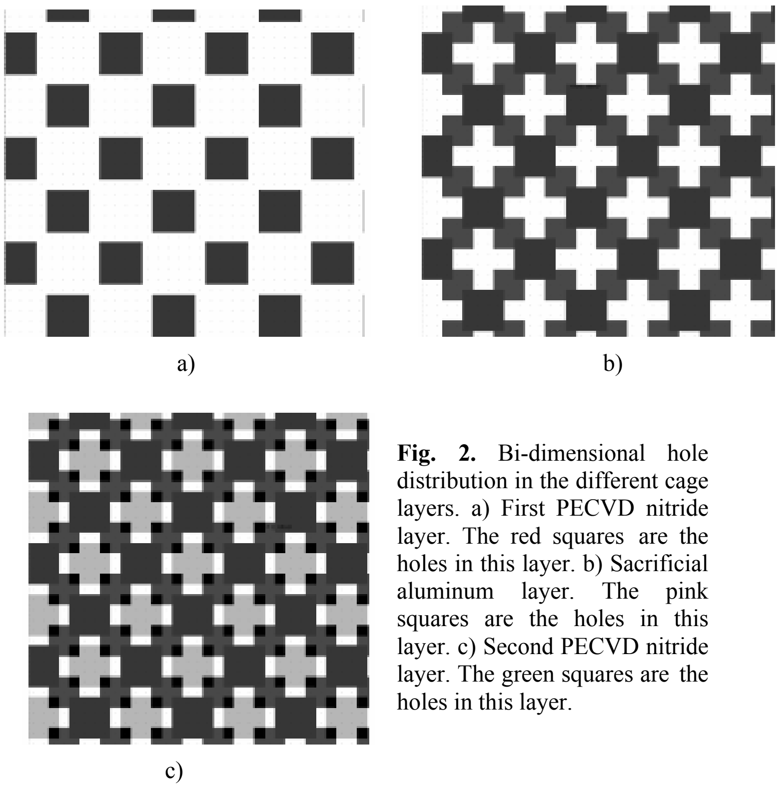


Fig. 2. Bi-dimensional hole distribution in the different cage layers. a) First PECVD nitride layer. The red squares are the holes in this layer. b) Sacrificial aluminum layer. The pink squares are the holes in this layer. c) Second PECVD nitride layer. The green squares are the holes in this layer.

3. Experimental

The thin film encapsulating shells have been fabricated above structured wafers where the complete FBK switch fabrication process [3] has been performed, with exclusion of the final release process in oxygen plasma. The basic switch process includes 8 mask levels, and will not be reported here, while other 5 mask levels are required for the shells. Above the unreleased switches a 3-micron thick photoresist has been deposited, patterned and baked at 250°C, to define the cage dimensions and to act as shell sacrificial layer.

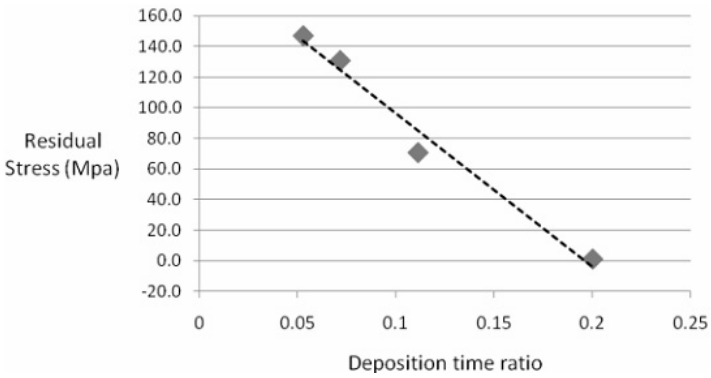


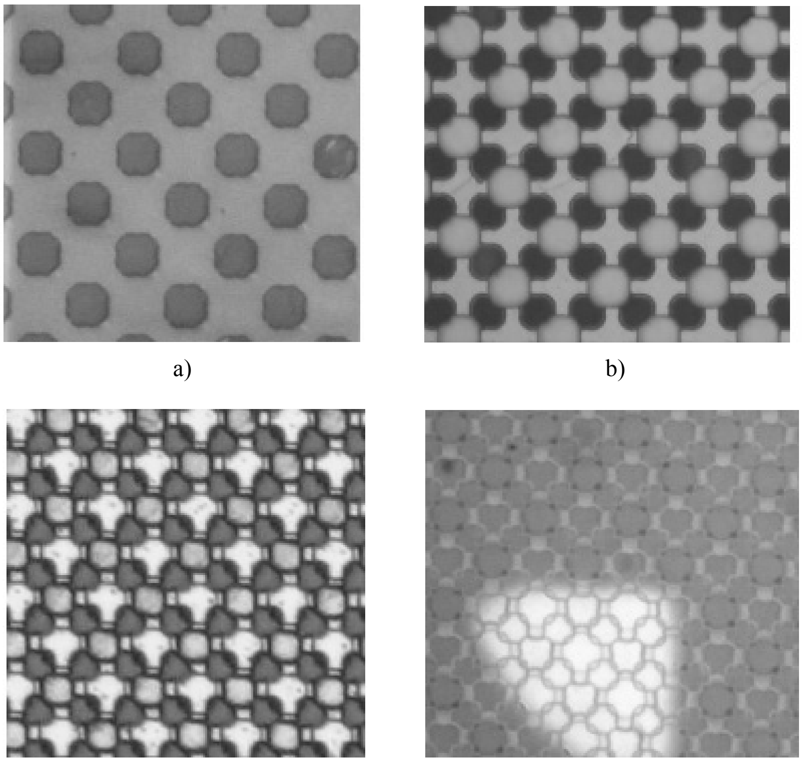
Fig. 3. Silicon Nitride multilayer residual stress variation as a function of deposition time ratio of two basic recipes with stress of -800 Mpa (recipe 1) and 580 MPa (recipe 2).

Preliminary characterization of PECVD silicon nitride residual stress has been obtained depositing at 200°C more than 100 alternating thin layers of silicon nitride having very different stress values. The stress values of the single recipes are -800 MPa (compressive) and 580 MPa (tensile), and are obtained varying the relative compositional parameters of the PECVD gases [4], together with the plasma frequency. Their relative thicknesses can be changed by varying the deposition times [4], and the variation of this parameter allows a continuous variation in average residual stress approximately from zero to 150 MPa as reported in Fig. 3. The residual stress values have been obtained on blank test wafers using the Stoney wafer curvature method.

The more convenient value for nitride stress have been estimated to be around 100-120 MPa (tensile). This value should increase mechanical stiffness but avoids the risk of cracking and should cause only limited deformation of the underlying silicon wafer.

After the characterization 1.5 μm of PECVD nitride with this stress value were deposited, patterned with holes and dry etched (Fig 3a). Then a 500 nm aluminum layer was deposited above the nitride layer, and again patterned with holes and wet etched (Fig. 3b).

A second PECVD nitride layer with the same thickness and deposition parameters of the first one was finally deposited, patterned and etched, as shown in Fig. 3c. From Fig. 3 it can be seen how the lithographic limitations affect the hole shape, but the resolution and the alignment are enough to ensure the correct superposition of the patterned holes. The hole opening on the nitride layers has been performed with some care, since the dry etching rate is sensibly lower in the hole structures than on large areas or blank wafers.



a) b)

c) d)

Fig. 3. Pictures of holes distribution at different process stages: a) First PECVD nitride layer. b) Sacrificial aluminum layer. The dark areas are the holes in this layer. c) Second PECVD nitride layer. The holes in this layer are centered on the cyan crosses, while the light green squares correspond to the holes in the first nitride layer. d) Final released structure. The light area is an underlying aluminum pattern.

At this point the removal of the sacrificial aluminum layer has been performed by wet etch. This process step has the purpose to create a lateral release channel between the holes of the two nitride layers, since the two hole patterns are not overlapping.

Finally the burning of the shell sacrificial layer was performed, leaving free the underneath cavity. This is accomplished with a oxygen plasma asher, and the process is planned to be long enough to burn also the switch spacer and free the movable membrane. A detail of a released shell is reported in Fig. 3d, where it can be noted that the cage is completely transparent and the underlying structure is clearly visible. This last characteristic is even more evident looking at Fig. 4, where an entire (still unreleased) switch included in the nitride shell is reported in the picture.

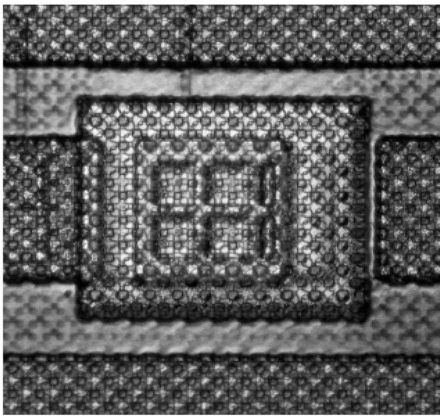


Fig. 4. Cantilever switch included in the nitride cage.

After release of the sacrificial photoresist the free cavity has been tested for its mechanical resistance to external loading by means of a mechanical profilometer equipped with a tip diameter of 2µm. An example of the results of these tests is shown in Fig. 5, where it can be noted that the mechanical resistance is quite good. In addition it has been found that deformations are completely reversible, that is no cracking or irreversible damage has been detected. The holes in the cage profiles are due to some misalignement between the holes and the tip scan.

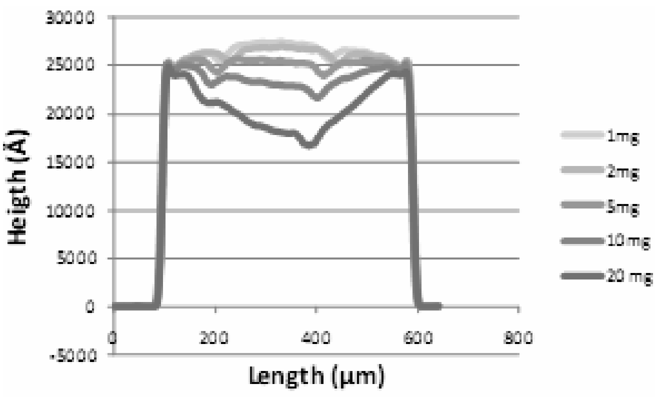


Fig. 5. Load test of a 500 µm wide released nitride shell.

At present, the final covering with a sealing polymer is still under development. Different options are currently under investigation, like polyimide, SU8 and BCB. From the mechanical and structural point of view, the modified cage structure is supposed to work as it was defined at design level. The specific polymer properties may however play an important role in determining the final outcome of this approach, because the capillary forces could allow the polymer to penetrate to some extent through the interstitial channels. In this case the nitride surface affinity and the sealing polymer surface tension may turn out to be important, and the polymer viscosity as well.

4. Conclusion

A new design approach to thin film encapsulation for RF-MEMS devices has been proposed. The main feature consists in the superposition of two different cover layers with holes not directly superimposed. The feasibility of this concept has been practically demonstrated building encapsulating nitride cages above FBK switch wafers.

The cages show good mechanical resistance and no damage of the underlying devices has been detected. The final details of this process and its full validation are still under development and testing.

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