MEMS integration strategies at Léti.

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Abstract

With an always growing penetration in different mass markets, MEMS are now facing a maturity period, with high constraints for manufacturing simplification and processes standardization in order to lower both costs and time-to-market. This paper gives an overview of some key enabling technologies developed at Léti, in light of these observations, to satisfy such manufacturing and cost constraints:
-A description of a generic technology mixing MEMS and NEMS sized parts allowing to manufacture different kinds of MEMS (inertial, pressure, magnetometers…) with a substantial gain in MEMS surface area for an unchanged level of performances.
-A presentation of MEMS specific Wafer level packaging technologies leading to significant cost reductions.

Keywords: MEMS integration technologies, M&NEMS, Thin Film Packaging.

1) Introduction

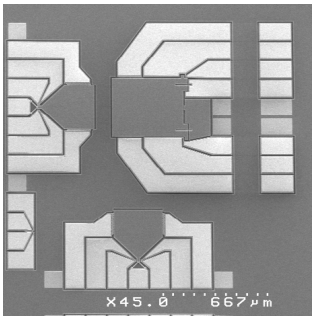
MEMS (MicroElectroMechanical Systems) are more and more used in a wide range of applications. Already available in automotive or industrial applications, they have also entered new markets in consumer applications, with the associated high constraints of cost and miniaturization. With typically a 5 to 15% cost reduction expected each year for these components, there is a strong need of optimization both in terms of miniaturization and packaging. These two improvements axis have been widely investigated at Léti.

2) Miniaturization of Microsystems

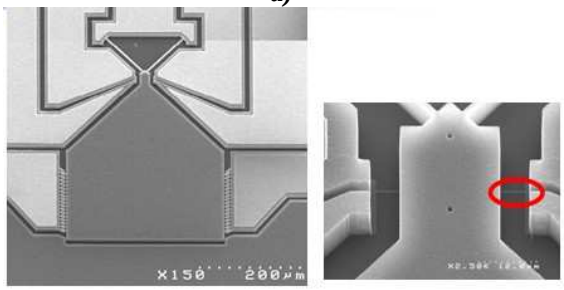
Efficient miniaturization has a two fold interest depending on the foreseen applications, allowing either a gain in MEMS surface area for an unchanged level of performances, or an increase in performances for the same surface area. However, size reduction has major impacts on inertial sensor performances, which are the warhorse of MEMS in consumer markets. Indeed, the reduction of the seismic mass affects the sensitivity, and reduces the nominal capacitance. In turn, the signal to noise ratio (SNR) is reduced. To overcome these limitations, a new design and a new detection mode have been investigated, giving birth to the M&NEMS concept. The basic idea is to combine on a same device a thick MEMS layer for the inertial mass with a thin and narrow NEMS part as suspended strain gauge. The principles of this innovative technology have been described in details in previous papers [1] [2], and only the main items to point out are summarized below:

- The use of a piezo resistive or resonant nano-gauge allows high efficiency of the transduction thanks to high stress concentration effect (very small cross-section of the silicon nanowire gauge) , and a lever arm effect achieved by appropriate design.
- In-plane and out-of-plane detections are easily achieved on the same wafer as well as co-integration of multi-sensors (accelerometer, gyroscope, magnetometer and pressure sensor)
- Differential measurements allows minimization of thermal drift and non linear behaviour.

This ease of design allied with a significant gain in MEMS surface area for similar performances makes this technology very suitable for multi axis inertial sensors. This has been demonstrated using a four step approach. In a first step, 3D accelerometers have been integrated in a single chip. Figure 1 shows an example of 3 axis accelerometer base on M&NEMS technology, with a magnification of the X/Y unit and of the associated nano-gauges. The typical dimensions of sensitive elements are below 0.4mm² per axis.



a)



x/y accelerometer

b)

Figures 1: a) 3 axis accelerometer base on M&NEMS technology b) magnification of the X/Y unit and of the associated nano-gauges.

In a second step, similar developments have been made to achieve 3 axis gyro. The device integrates one sensitive element per axis (avoiding cross sensitivity) using differential detection in open loop mode (no need matched frequencies - process control relaxed) with only rough vacuum required (no getter needed). This new concept of gyroscope, that used nano-gauges for the Coriolis force detection, has typical dimensions below 0.7mm² per axis.

Next step has consisted to integrate on the same chip 3 axis accelerometer and 3 axis gyro with a total footprint below 3.5 mm².

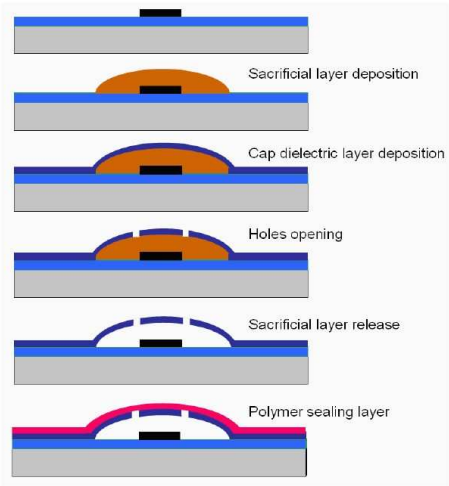
The next step towards the ultimate goal of a full 9 axis IMU (Inertial Measurement Unit) has consisted to demonstrate the interest of the M&NEMS technology for compass application in earth's magnetic field, with maximum resolutions below 10nT/√Hz. This has required to embed magnetic layers into the sensing masses with two perpendicular magnetization directions on the same chip. Ref [2]-[3] describes the validated technical solutions developed to get these goals using either hard magnetic materials or coupled ferro/antiferro thin layers. These very recent validations of the functional reliability by qualitative tests under magnetic fields are concluding the demonstration phase of the technical bricks needed to build a full 9 axis IMU for personal navigation applications, using M&NEMS technology.

3) Efficient low cost packaging for Microsystems

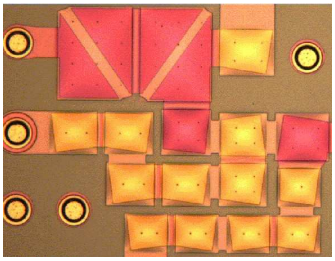
Low cost packaging technologies developed for integrated circuits cannot be directly applied to MEMS because they contain fragile movable parts and need to operate in a specific atmosphere (vacuum, inert gas…). For example, die sawing or injection molding process of plastic package will cause damage to movable parts if they are not protected. Today, the greatest part of the MEMS cost comes from the packaging which must be adapted for each device. To solve this problem, wafer level packaging (WLP) technologies were developed to protect the devices by a cap and to enable dicing and assembly using standard techniques such as plastic molding.

Reviews of some MEMS packaging challenges and technologies can be found in [4] and [5]. One of the most promising technology is Thin Film Packaging (TFP), a low cost technology consisting to build closed cavities above the devices with surface-micromachining techniques. As TFP uses standard IC technologies and consumes less die area, it should offer a lower system cost than wafer bonding packaging. Moreover, it does not require wafer to wafer alignment and backside process technologies, which are not common in IC fabs. Another advantage is the electrical feedthrough which is easier than with wafer bonding, as the different layers are etched at the contact pads during or at the end of the process.

As TFP involves thin layers, mechanical stiffness of the encapsulation is a critical issue. Today, TFP technologies developed worldwide comply with the mechanical constraints related to grinding, handling and sawing steps. But the main hurdle remains the harsh final overmolding step, with high temperature and pressure process (about 100 bars, up to 200°C), inducing challenging thermo mechanical constraints. In light of these observations, Léti has developed an improved TFP (Thin Film Packaging) Technology called TFPR (TFP Reinforcement), using a specific stress-free thick copper layer to reinforce its standard 3-mask TFP process schematically described and illustrated in figures 2 a-b.



a)



b)

Figures 2: a) Standard Léti Thin film packaging process b) SEM of a BAW filter with different cavities sizes.

This technology is now routinely done in CEA/Léti 200mm line dedicated to MEMS with validated design rules (minimum distance between two membranes less than 20µm and the cap size can be less than 10µm greater than the device active area width). It offers substantial advantages such as a very small area consumption compared to wafer-bonding packaging techniques (which require substantial surfaces for seal rings), as well as capability to deal with very different sizes of packages on a same chip.

The TFPR initial assessment of compatibility with molding has been validated first on tests structures [6]-[10], with a bottom electrode on the base substrate and a top electrode under the cap, allowing to detect the collapse of the TFP through the short circuit measured between the electrodes. Test structures with 200µm and 500µm wide caps have been fabricated and assembled in SOP package. TFPR fully withstands the harsh conditions with pressures between 75 and 100 bars, and temperature about 185°C during the molding step. These results have been confirmed by SEM characterizations where no mechanical degradation of the caps is observed: cavities remain still several micrometers high, after molding, as shown on figure Fig. 3.

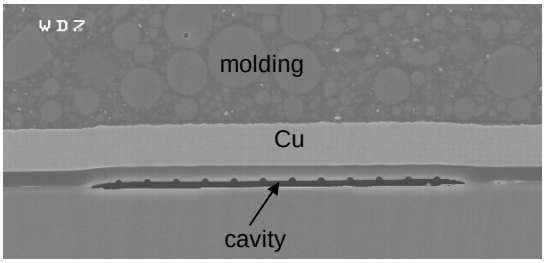


Fig. 3. SEM view of a cap cross section

Next step has consisted to validate the TFPR on real microcomponents such as switches and BAW resonators. A BAW resonator is an excellent device to proof the robustness of the package because any material in contact with the active area would act as a loading layer and result in a significant decrease of the resonance frequencies. TFPR was performed on BAW resonators, with caps reinforced by 25µm-thick electroplated copper (Fig. 4). Then, they were assembled on SOP packages. After wirebonding, overmolding was performed directly on the reinforced caps. In this case the molding conditions were 185°C – 100bar.

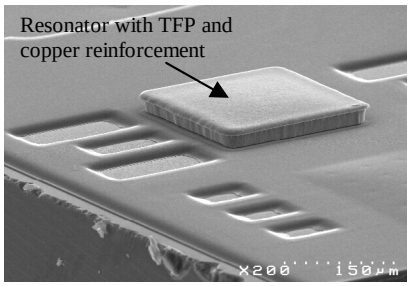


Fig. 4. BAW resonator with TFP after Cu reinforcement

RF measurements performed on these devices have shown typical performances for this particular BAW resonator design. The parameters extracted for the BAW resonator lead to a resonant frequency of 2.134 GHz, an effective coupling coefficient of 5.4% and Q-factor at series resonant frequency of 1200. Tens of devices were tested and all the resonators presented the same electrical characteristics. Figure 5 shows the comparison

between a complete RLC model of the test board extracted around the BAW operation frequency at 2 GHz and the corresponding measurements.

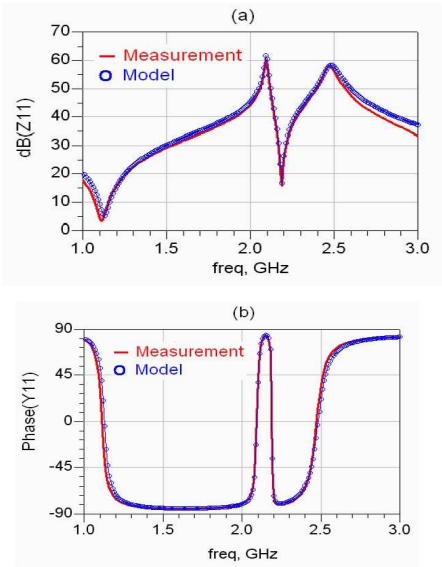


Fig 5: Measurements vs RLC model for encapsulated BAW resonator on its test board

Finally, the global cost of this new technology has been evaluated and compared to competing technologies (such as Si cap-polymer bonding and Si cap with TSV-eutectic bonding) in the present configuration of encapsulated BAW. Evaluations were based on a cost model taking into account the global process (die area, yields…), process flows (equipments CoO, operator time, consumables,…), as well as the clean room environment (HU, depreciation, footprint, production capacities…). Results are summarized in Fig. 6. It is seen that, although a little bit costly than the standard TFP, the improved TFPR remains a very competitive technology.

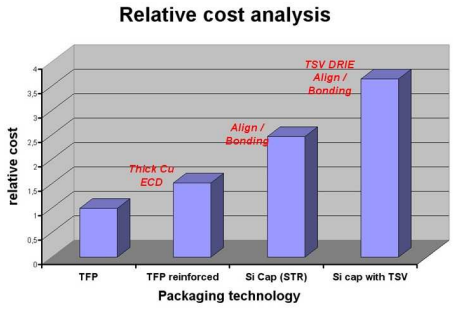


Fig 6: relative cost analysis of packaging technologies for encapsulated BAW. Most expensive process steps of each technology are indicated in red for each packaging scheme.

4) Conclusions

We have presented the latest developments performed at Léti for MEMS miniaturization and cost optimization. First, it has been shown that a generic technology, mixing a thick MEMS layer for the sensing mass with a thin and narrow NEMS part as suspended strain gauge, allows to integrate on a same chip different 3 axis sensors. Experimental demonstrators of accelerometers, gyros, and compass have been manufactured in the 200mm Léti MEMS line, paving the way to the next generation of 9/10 axis IMU.

Second, a specific optimized thin film packaging process for MEMS has been developed and validated on real RF components. Once so encapsulated, MEMS can endure low cost standard packaging techniques used for ICs. Thus, they can be assembled with other circuits and encapsulated in one chip. We have also evaluated the cost of this technology and shown that it was very competitive compared to standard technologies based on Si caps which are presently used.

These two enabling technologies are today perfectly controlled and patented by Léti and can be licensed to a large panel of end-users, involved in manufacturing of inertial MEMS, resonators and actuators.

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