

Implementation of Wafer Level Packaging KOZ using SU-8 as Dielectric for the Merging of WLFO to Microfluidic and Biomedical Applications

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Abstract

Due to its versatility for high density, heterogeneous integration, Wafer Level Fan Out (WLFO) packaging has recently seen a tremendous growth in a broad array of applications, from telecommunications and automotive, to optical and environmental sensing, while addressing the challenges of the next big wave of the Internet of Things (IoT). In this context, WLFO is continuously being challenged to include new families of MEMS/NEMS/MOEMS sensors, low thermal budget devices and biochips with microfluidics for biomedical applications.

Recent developments in WLFO technology by NANIMUM [1] demonstrated the implementation of a keep-out-zone (KOZ) mechanism intended to 1st) protect sensitive sensor areas during the backend processing of WLFO wafers and 2nd) create open zones on the Re-Distribution Layers (RDL). This way, the KOZ mechanism provides a physical, direct path from the embedded device to the environment. This is a necessary feature for environment sensing (e.g., pressure) or to create optical paths free of dielectric and protected from the harsh chemistry steps of the WLFO process.

This paper describes new developments on KOZ, implemented with SU-8 photoresist as a WLFO dielectric, whose application is a novelty in the WLFO platform. The use of SU-8 and the KOZ with it, addresses some gaps of the current WLFO technology towards the integration of chips with bio-sensitive areas and sensors with low thermal budget. Due to its well-known bio-compatibility and inert behavior, SU-8 can be used as a neutral dielectric to be in direct contact to target fluids (e.g., sera, blood). Also, due to its low curing temperature, SU-8 allows a very low temperature WLFO process and thus the embedding of temperature-limited devices that have been outside the WLFO realm, for example, magneto-resistive or magnetic-spin sensor chips, which degrades its performance above 160°C. More interestingly, SU-8 exhibits a particular non-conformal behavior, which creates very smooth surfaces even over the mildly rough mold compound area of a fan-out package. Adding to this, SU-8 is readily available in the market in a wide range of thicknesses, spanning from 0.5 µm to >100 µm, and further allowing multiple spin coatings to build thick layers. Thus, SU-8 can provide smooth and deep enough channels for microfluidic flow over the chip sensing areas and, at the same time, provide the necessary layer thickness discrimination for the KOZ mechanism. Combining these features, the SU-8 layers in WLFO can play the triple role of 1) RDL dielectric insulation, 2) KOZ mechanism and 3) embedded microfluidic channels as part of the RDL.

In summary, besides the unprecedented use of SU-8 in WLFO packaging, KOZ implementation on SU-8 provides a true, attainable bridge between WLFO and integrated microfluidic applications, for biosensing and biomedical applications in general. Outlooking the potentialities of such a merge, a Fan-Out package can embed several chips interconnected by RDL lines, as it currently allows, and also connected by microfluidic channel for multi-point, multi-function biosensing, constituting a true Lab-on-Package, cost-effective solution. Instead of building all sensing areas and microfluidic channels over a large silicon (Si) chip, this solution builds the feed-in, feed-out areas of the microfluidic channel over the inexpensive fan-out area, minimizing the sensing chip area, with the consequent front-end cost reduction.

Key words

WLFO, MEMS, biosensors/microfluidics, KOZ, SU-8

I. Introduction

The increasing growth of high volume applications such as ‘wearable electronics’ and ‘Internet of Things’ (IoT) has given MEMS and sensor ICs a prominent role in the sensors and semiconductors markets. See Figure 1. Also, MEMS and sensors have a broad span of applications in the biomedical field.

Wafer Level Fan-Out (WLFO) is a packaging technology that is very quickly expanding and becoming more and more versatile as it rapidly adapts to more devices and technologies. This expansion is not only due to its versatility but also due to the ability to offer multi-functional and heterogeneous integration which permits significant size reductions at low cost.

Initially, fan-out wafer-level packaging (FOWLP) was not intended to integrate MEMS not only because of the materials it uses, but mainly due to its fabrication processes. Part of the efforts to adapt the technology is described in the ‘Implementation of Keep-Out Zones to Protect Sensor Areas During Back-end Processing in Wafer Level Packaging Technology’ also developed by the authors of this piece, where it describes how to adjust the technology to accommodate open zones in the package to provide a physical, direct path to the environment which was not previously established.

2015-2021 MEMS market forecast in US\$B
(Source: Status of the MEMS Industry 2016, May 2016, Yole Développement)

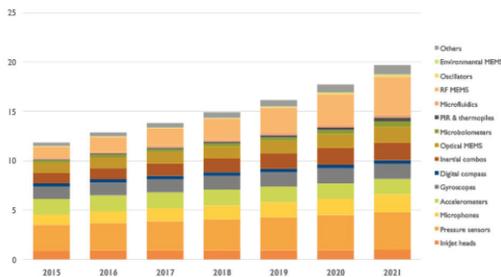


Figure 1: MEMS market forecast (source: Yole).

A bigger challenge was presented to WLFO with the introduction of biosensors/microfluidics. Microfluidic technologies have developed extensively in recent years and will continue to grow (Figure 2) since they have brought many advantages in diagnostic and other biomedical applications: small sample volume, reduced processing time and cost, small systems and near patient technologies [1]. Also, the target applications for these types of devices are very extensive having great impact on the analysis and diagnostic approaches offering very fast and low-cost solutions [1].

In the present work, WLFO was used to integrate MEMS and keep open areas, but the package structural materials had to be biocompatible to the fluids to be tested in the final application – meaning package materials had to be inert to the substance under test to give an accurate reading for the analysis being made.

In this study, SU-8 material was introduced to WLFO as a way to overcome some of the limitations of current WLFO dielectrics: (1) unknown biocompatibility and (2) require high temperature processing. This material was one of the first and obvious choices since it is extensively used in microfluidic and biomedical fields, and its biocompatibility is fully proven. What was yet to be proven

was its applicability on WLFO and KOZ solution, which was successfully accomplished in this work.

Seeking the next killer application
Microfluidics industry products revenue since 2000 (in M\$)
(Source: Status of the Microfluidics Industry 2017, May 2017, Yole Développement)

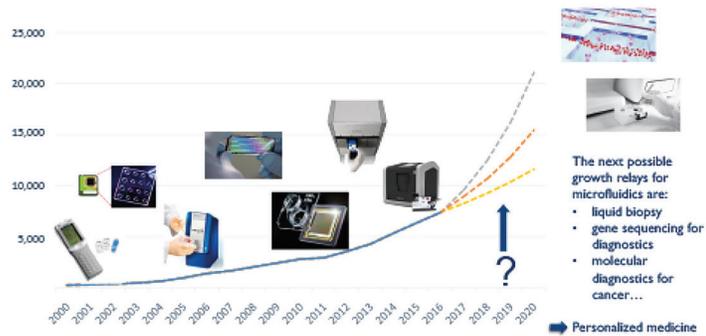


Figure 2: Microfluidic applications growth forecast. From microfluidic devices like manufactured chips, delivery tools, and dispensers, microfluidic-based products (i.e., diagnostic tests with reagents, vaccines, and cartridges) are provided to end-users, offering numerous possibilities [2].

II. WLFO and Keep-Out Zone Implementation

WLFO has experienced vast growth in a number of different applications such as automotive, telecommunications and now IoT and wearables. Its versatility allows R&D engineers to continuously procure solutions to integrate more types of devices by challenging its processes and materials. With the integration of MEMS in WLFO portfolio, a prominent gap was identified: the need to leave open areas in the device after packaged. Keep-out zone was one of those solutions.

This development is thoroughly described in [3] where it explains how KOZ is based on thickness discrimination: a very thin layer of dielectric is deposited covering the active and KOZ area except for the vias, and then subsequent layers leave the KOZ area free in a way that it is protected by the first layer throughout the whole process until it is etched away in the end. As this process is not selective, the last layer of dielectric functions as a mask, being thicker than necessary when coated so that when the KOZ is opened, the latest is also etched to its target thickness (Figure 3).

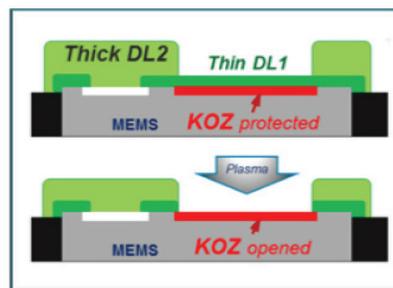


Figure 3: KOZ process.

In this first development, the main constraints for material selection was: 1) thickness range compatibility; 2) compatibility to the chemistries used in production; and 3) curing temperature compatibility to FOWLP technol-

ogy [3]. The introduction of biosensors/microfluidic applications brought a few extra limitations such as:

- Biocompatibility – package materials should be inert to tested fluids
- Thermal budget – WLFO has processes above 200°C, which, in some applications, is simply not compatible

Such restrictions limited the selection of dielectric materials that would comply. With this, SU-8 dielectric material was the obvious choice, since it is widely used in the fabrication of MEMS, as well as bio-MEMS/microfluidics due to its proven biocompatibility. Additionally, it cures at 150°C, fulfilling the requirements of thermal sensitive components. SU-8 has had unprecedented testing as a structural dielectric for the redistribution layers on 300-mm fan-out wafers and in a KOZ building, since it also offers several ranges of thicknesses that conform with the technology.

III. SU-8

SU-8 was first designed for the microelectronics industry and it is currently highly used in the fabrication of microfluidics structures, as well as in MEMS and bio-MEMS because it is high biocompatibility and highly inert [5]. The main common positive and negative aspects are:

- | | | |
|-----|-------------------|---|
| (1) | Advantages | <ul style="list-style-type: none"> → Biocompatible → Wide range of thicknesses, from 0.5 μm upwards → High thermal and chemical resistance → Good mechanical properties that make it suitable as a structural material → Low hard bake curing temperature, $\approx 150^\circ\text{C}$ → Low UV absorption (up to thicknesses of 2 mm) → Allows the coating of thick layers (up to 500 μm) on a single spin coater with multiple spin coatings → Widely used in the industry with abundant literature on processing and process settings |
| (2) | Challenges | <ul style="list-style-type: none"> → Thermal mismatch between SU-8 and common substrates such as glass or Si, which creates stress and may cause film cracking → Unknown behavior in WLFO wafers, where heterogeneous materials and surfaces coexist. → Higher absorption coefficients at shorter wavelengths and, as a result, using a broadband light source tends to cause over-exposure at the surface and underexposure at the bottom [4, 6] |

SU-8 is a negative photoresist consisting of monomers, a photo-initiator salt and an organic solvent (cyclopentanone). When exposed to UV radiation, a photoacid is formed that opens the epoxide rings, which then react with neutral epoxy groups upon heating, resulting in a cross-linked polymer network of high mechanical strength and thermal stability [4, 6].

Compared to standard materials used in this industry, SU-8 has slightly different processing since its cross-linking starts at UV radiation and therefore requires a heating step to ignite the polymerization. The scheme in Figure 4 describes the main steps in the lithography process, highlighting post exposure bake (PEB) as a new process step, compared to standard dielectrics used in the industry, e.g., polyimide (PI) or polybenzoxazole (PBO) materials [4].

SU-8 is extensively used in the industry and there are numerous studies on the best set of processing settings. Several grades of SU-8 were tested with different viscosities. The main outputs assessed in this study were thickness uniformity, resolution and thermal stress behavior since this type of material is prone to crack and is more sensitive to thermal curing [4, 6], see Figure 5.

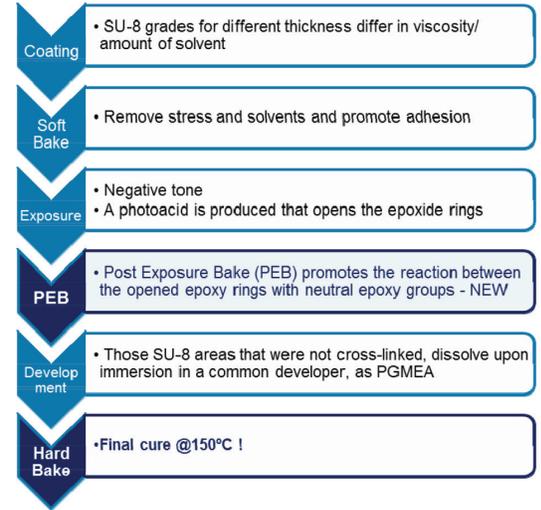


Figure 4: SU-8 lithography process flow [4].

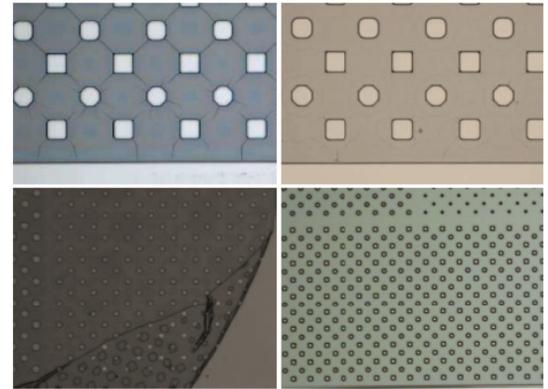


Figure 5: SU-8 lithography on Si wafer. Top images: SU-8 is prone to crack due to insufficient exposure or thermal stress induced during bake. Left picture was processed with lower dosage. In the right exposure, settings were adjusted. Bottom images: Examples of delamination due to insufficient exposure and resolution loss due to overexposure found during setup [4].

IV. Experimental Results

First tests were to set the target parameters for each viscosity, using as reference the supplier data sheet. The main outputs were thickness uniformity and thickness target compliance, process ability, and thermal stress response looking at crack incidence. After the lithography process, the approach shows promising results: the SU-8 dielectric compatibility to KOZ solution is verified.

Good uniformity was observed across the 300-mm wafer (Figure 6) and no significant uniformity differences were observed between different thickness/viscosities grades.

With thermal stress, the higher the viscosity, the more sensitive the material. It was verified that this effect could be handled and minimized by making slight adjustments

to the bakes: soft bake and post-exposure bake. Also, higher exposure doses showed great impact on thermal stability as well, as mentioned before. The thermal stress effect is visible in the form of wrinkles/cracks on the surface of the dielectric and it is further increased when the substrate surface underneath has topography or irregularities to it (Figure 7).

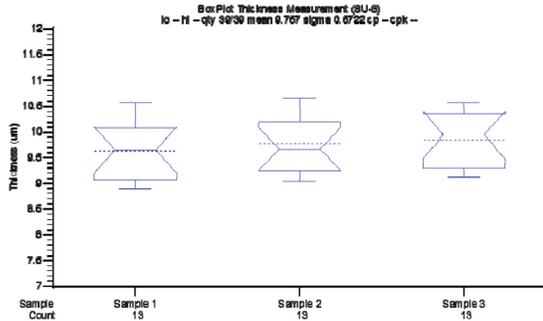


Figure 6: SU-8 thickness measurements on first 300-mm samples.

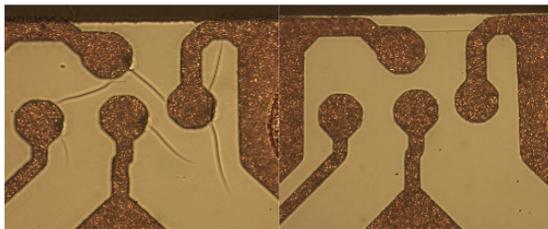


Figure 7: SU-8 lithography in fan-out wafers. SU-8 is disposed to cracking under the wrong parameters at exposure and baking steps. Left picture: lower dosage. Right exposure: adjusted settings. The RDL lines underneath also play a significant role on increasing the film stress, with smooth contours inducing lower stress.

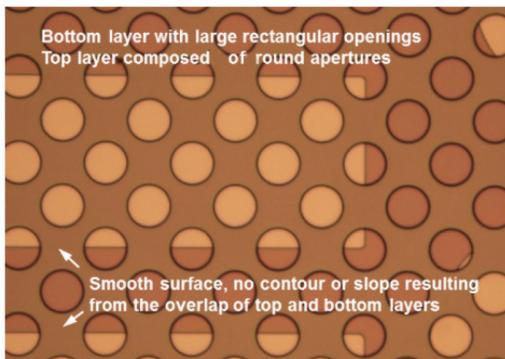


Figure 8: Non-conformal behavior of SU-8.

Figure 8 displays the inspection results of the SU-8 lithography setup, using the same exact parameters and masks, except for the dosage. It is clear that higher dosage deflects the stress of the film. However, it should be taken into account that higher dosages sacrifice resolution. Tests are ongoing to understand the full relevancy of the fissures observed on the underexposed SU-8 surface: their depth and how they behave under stress. Still, preliminary results are very positive, showing a very viable and suitable solution.

Besides the lower curing temperature and lower wafer warping that comes with the use of SU-8, another important advantage seen is its non-conformal behavior, which

makes it very interesting in WLFO. This not only ensures full coverage of die edges at the mold compound interface (a “stand-off”, i.e., the rising of dies above the mold compound level, is always a reality in WLFO technology), but also smooths the die-mold compound slope for the subsequent layers, reducing topography bumps. Figure 8 and Figure 9 provide visual results. Also, the non-conformity greatly helps automatic inspection, as the “lens” effect the dielectric causes around topography bumps practically vanishes (see Figure 10).

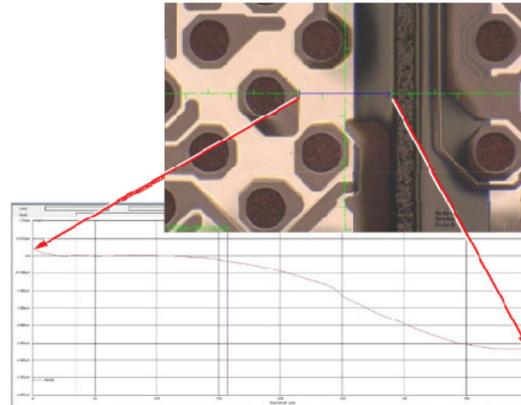


Figure 9: Profile of conformational behavior of SU-8, greatly smoothing the slope at the die edge (“stand-off”).

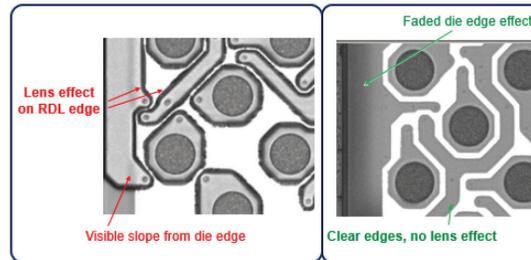


Figure 10: Left image: AOI image from standard dielectric in which conformational behavior creates a “lens” effect at the edges of trace/lines, with negative impact on the inspection (e.g., PD); Right image: AOI of package with SU-8 showing very much reduced optical ‘lens’ effect.

A. KOZ

The particular sensor used in these developments required the constructions of a keep-out zone: the area in the active part of the chip that first needs to be protected against the aggressive chemical and mechanical steps of the packaging processes, and then needs to be exposed to the environment at the end of the wafer processing. This particular feature is quite common in components such as a bio detector or environmental sensor, since they must have a direct path to the exterior for direct contact to air or to the target liquid, and the sensing area must not be contaminated during WLFO process or else the analysis will be compromised.

The KOZ mechanism, originally developed with other materials, was again proven in this vehicle using SU-8. One big advantage of SU-8 is that it has several series that differ in the casting solvent used. In each series, there are grades that vary in solvent quantity and final target thickness after coating – the higher the percentage of solvent, the thinner they can get. SU-8 can go as thin as 1-2 μm to have hundreds of microns with single and multicoatings [6].

KOZ uses a thick/thin discrimination strategy: the 1st layer being a very thin dielectric layer, then the RDL stack applies a much thicker top layer to mask the 1st thin layer. At the end of the process, the wafer is plasma etched and, given the thickness difference, the first layer is quickly removed, exposing the KOZ area without damaging the top layer.

Due to the topographical nature of WLFO since dies and mold compound are not at the same level depending on die size, there is die stand-off since the die surface is in a plane higher than the mold compound. In the standard WLFO configuration, a die stand-off is easily absorbed, but as the 1st layer thickness is below $3\mu\text{m}$, it does not fully cover the die edge. KOZ is designed so that it includes a DL1 boost layer, as explained in [3], which is coated on top of the KOZ layer, but with openings in the KOZ area.

With the wide range of thicknesses that it offers, SU-8 is the perfect candidate for this. Three SU-8 grades were chosen that fit the layers below:

- KOZ layer ($1\text{-}2.5\ \mu\text{m}$)
- DL1 boost layer ($5\text{-}7\ \mu\text{m}$)
- Top layer ($10\text{-}20\ \mu\text{m}$)

Early tests for proof of concept were very successful: SU-8 exhibited good O_2 plasma etching response, with complete removal of the thin KOZ layer (L1) and no visible damage to the top layer (L2) (see Figure 11).

Both L1 and L2 have similar response to O_2 with comparable etch-rates (see Figure 12). At $0.8\ \mu\text{m}/\text{min}$, it is a satisfactory rate.

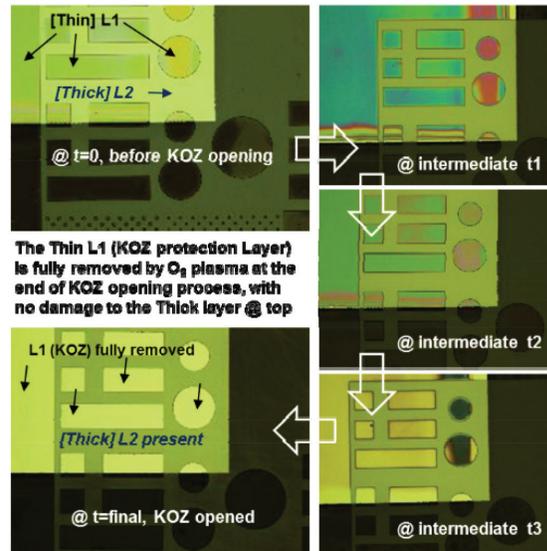


Figure 11: KOZ on SU-8 on WLFO: KOZ protection layer (L1) removed without damage to top layer (L2) after O_2 plasma etching, proving KOZ concept on SU-8.

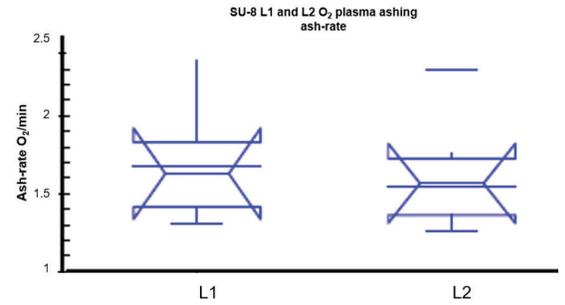


Figure 12: Average etch-rate of $0.8/\text{min}$ on both SU-8 grades tested.

B. Demonstrator results and discussion

Figure 13 shows the first temperature-sensitive magneto-resistive chip for bio-sensing applications with the package developed at NANIMUM, where the fluidic channel crossing over the sensitive area of the chip (KOZ) is visible. The chip was developed by Magnomics and wafer level packaged at NANIMUM in a low-temperature WLFO process.

SU-8 is greatly suited for this application, not only due to its biocompatibility, but also to its non-conformal behavior as it lessens topography concerns being especially advantageous for microfluids. Also, it is proven to be very well adapted to KOZ, since it has good etch rates and can sustain long etching steps without damage.

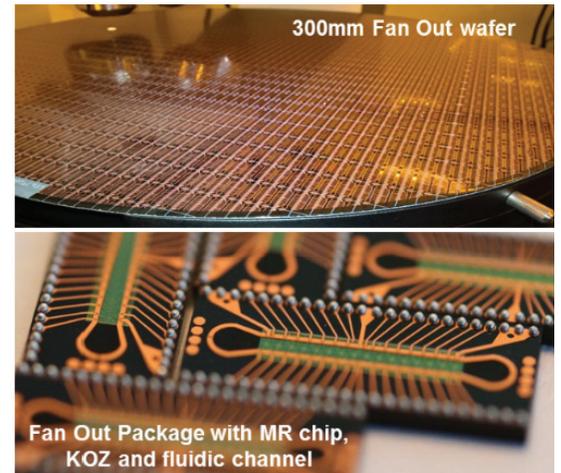


Figure 13 – First biosensor prototype. Top: 300-mm fan-out wafer. Bottom: individual components, where the fluidic channel crossing over the sensing chip is visible.

The successful merge of WLFO and biosensors using microfluidic channels is highly valuable considering both front-end and back-end perspectives. WLFO is especially well suited for microfluidic applications, since the fluid channel can extend outside the chip, utilizing the inexpensive fan-out area of the package. In this particular case, the microfluidic channel is much longer than the chip itself, and the chip represents only 16% of the package area. This is a tremendous cost saving on the biochip, because the use of a smaller chip increases by one order of magnitude the number of chips in a front-end wafer. On the back-end perspective, from a market standpoint, it is possible to include thermally-sensitive components, opening WLFO to a new field of applications and potential growth areas.

Further tests are to be done to prove volume production capability of WLFO process with the SU-8 material. Nevertheless, the results shown are very promising.

V. Conclusion

Very positive work was previously performed to allow the introduction of MEMS and sensors in WLFO with the development of KOZ. In this work, further advances were made to integrate bio-sensor/microfluidic devices in WLFO with the unprecedented introduction of SU-8.

These very promising results using SU-8 as structural and dielectric material in WLFO offer additional process and market advantages, since it provides a true, attainable bridge between WLFO and integrated microfluidic applications, for biosensing and biomedical applications in general.

VI. Acknowledgment

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