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PRODUCTIZATION CHALLENGES OF ACOUSTIC MEMS SENSORS AND ACTUATORS

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ABSTRACT[*]

Silicon-based MEMS technologies for acoustic transducers are mature, widely available and have enabled a strong industry for consumer and niche markets while fulfilling the More-than-Moore promise. Nevertheless, mass production faces continuous innovation, manufacturability and testing challenges that prevent a higher market implantation of proof-of-concept acoustic MEMS devices. In response to these challenges, this paper discusses new integration trends involving the hybrid integration of polymeric materials into the flow of MEMS manufacturing. New test and modeling methodologies to address corresponding performance and data handling challenges are also discussed in this paper.

Keywords: *polymer acoustic MEMS, wafer temporary bonding, thin wafer handling, non-ideal MEMS modeling, manufacturing of acoustic MEMS devices.*

1. INTRODUCTION

Nowadays, majority of micro electromechanical system (MEMS) devices in industrial production have leveraged on pure silicon-based processes. More recently, thin-film piezoelectric materials have enabled a whole new range of miniaturized acoustic MEMS devices, from microphones to speakers, from audio to ultrasound bands, and to serve a wide variety of consumer and industrial applications. While conventional sets of materials and silicon-based processes used in these devices demonstrate proof-of-concept feasibility and functionality, performance for industrialization and mass production is not yet there. To address performance practical implementation issues, recent trends in acoustic MEMS device development have seen increasing efforts in polymeric materials integration (moving on from pure-silicon processes to heterogeneous polymer-MEMS materials) [1-5]. Nevertheless, and while polymers bring in a whole new range of convenient mechanical properties that enable new and competitive applications, it also poses new challenges to micromachining and wafer handing for mass production environments. In the following sections, we compare techniques for polymer film transfer as well as properties crucial for manufacturability and device reliability, which involve crucial temporary bonding and debonding processes, to enable safe and reliable processing of thin wafers. We highlight advantages and disadvantages of state-of-the-art techniques like thermal slide-off, UV and IR laser debonding.

Stress control and tunability is another key challenge faced by MEMS devices, which greatly impact manufacturability and device performance. In Section 4 we discuss the impact of stress performance and methods to carry out stress control to accomplish specific performance goals. Finally, Section 5 proposes a brief discussion on testing challenges associated with non-linear and non-ideal behavior of MEMS devices, and handling, analysis and postprocessing of large amount of test data required in production.

2. POLYMER INTEGRATION TO MEMS PROCESS FLOW

2.1 Polymer film and challenges

Figure 1 shows an example process of an acoustic MEMS device integrating a polymer layer and more *conventional* stacked structure and micromachining techniques. Polymer

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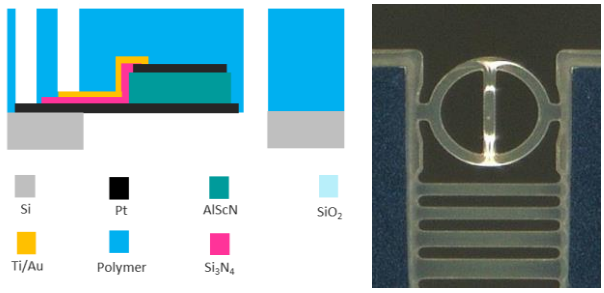


a. b.

Figure 1. Example process of an acoustic MEMS device integrating polymer: (a) Schematic of a cross section; (b) realization o of a polymer-based piezo cantilever and Guckel ring stress test structures

integration in the flow of acoustic MEMS devices is challenging as polymers are usually sensitive to temperature. Requirements involve thick layers that are usually in the range of a 10-100 µm, and that require coating of the polymer on a micromachined surface with high aspect ratio features and finally patterning of the thick polymer layer should be achieved while keeping reachable critical dimensions (CD) as low as possible and side walls as vertical as possible. In the following sections, we discuss the best coating techniques and polymer materials candidate for MEMS integration.

2.2 Polymer selection and coating technique

Specifications and constraints were given for the polymer. This polymer needed to be patterned with a required CD of 10 µm, a minimum reachable aspect ratio of 1, a Young's Modulus higher than 3 GPa, a glass transition temperature (Tg) >150°C, a total thickness of 45 µm. Coating should be conformal on a substrate with surface features consisting in steps of 1 to 4 µm and aspect ratio below 1. And lastly all processes need to be compatible with mass production.

2.3 Polymer dry film

Different coating techniques can be used to realize the dry film, including spin coating, dip coating, spray coating, lamination and vacuum bonding. Among all the different coating techniques, thick layers are mostly coated using dip coating, lamination or vacuum bonding. In general, only lamination and vacuum bonding are mostly used with batch processes. In the end, we selected vacuum bonding to perform conformal coating and potentially reduce the number of trapped air bubbles between the substrate and the polymer. Vacuum bonding is performed with polymer dry films. For this process we selected a 45 µm SU8-based dry-film from Nippon with an expected Young's Modulus of 3.5 GPa and Tg of 280°C. This polymer dry film is a negative photoresist.

2.4 Dry film adhesion and patterning

After substrate plasma O_2 treatment and dry-film vacuum bonding with the EVG 520IS bonder we processed the dry-film using post bonding bake, then UV-exposure, post exposure baking and development using PGMEA. Hard bake was finally performed in an oven at 170°C for at least 80 min. First trials demonstrated vertical sidewalls -see **Figure 2.**

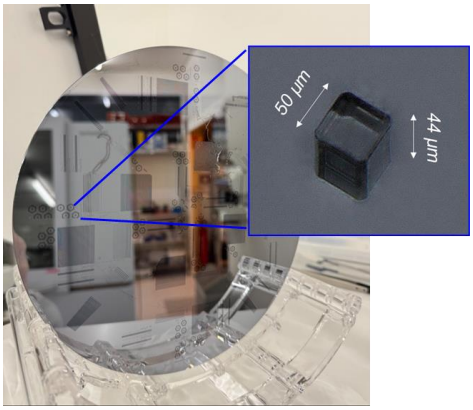
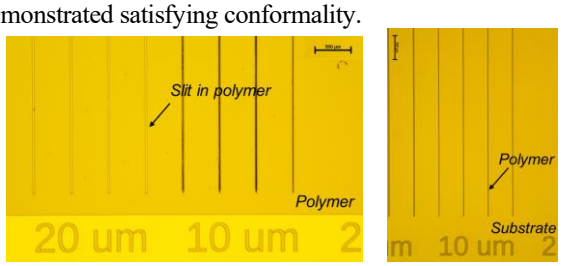


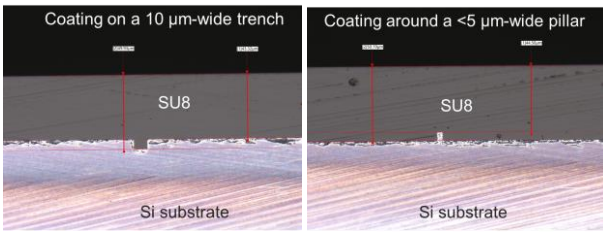
Figure 2. Bird's eye view of a patterned polymer square on 200mm wafer for sidewall characterization.

Error! Reference source not found.3 shows a successful i mplementation example, which reaches a maximum aspect ratio of 2.25 in polymer (**Error! Reference source not f ound.**3a), and a minimum CD of 10 µm see **Error! Reference source not found.**b. On the other hand, **Figure 4** shows test structures with conformal coating on steps with a width of 10 µm and depth of 5 µm were also validated as well as conformal coating of pillars down to a width and height of 5 µm. No trapped air bubbles were noticeable near the patterned features in the silicon substrate. The coating demonstrated satisfying conformality.



a. b.

Figure 3. Optical microscope images of: (a) patterned slits in polymer (AR 2.25); (b) Polymer lines with CD 10um.



a. b.

Figure 4. Cross section images of a. polymer coating and the silicon substrate with a trench, b. polymer coating and the silicon substrate with a pillar.

2.4.1 Adhesion test and Mechanical Properties

To be noted that the substate was coated with a 100 nm-thick SiO_xN_y layer, as for the final device, thus we performed a pull-off adhesion test using a Zwick/Roell Z2.5 apparatus to validate adhesion of the polymer film on the substrate, see **Figure 5**.

Adhesion loss, delamination occurred at ~ 0.31 MPa between the dolly and the double-sided tape used to fix the sample. The 3M LSE-160WF double-sided tape has a theoretical pull-off adhesion limit at 0.47 MPa. We failed to de-bond the polymer layer from its substrate and concluded to a satisfying adhesion of the polymer to the SiO_xN_y layer. The reduced Young's Modulus of the SU-8-based dry-film was measured using the FT-104 Femto-Indenter from Femtotools. We obtain a reduced modulus equal to 5.3 GPa, meaning a Young's Modulus of 4.8 GPa assuming for dry film a poisson coefficient, ν, close to 0.32 [6].

We measured the Young's Modulus, *E*, 137 % higher than

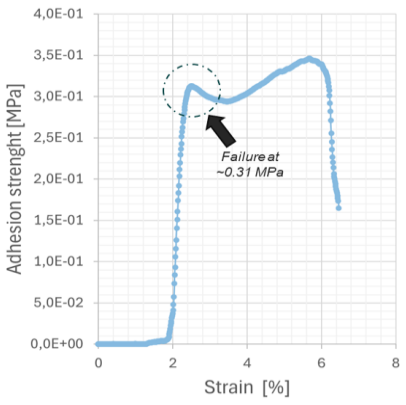


Figure 5. Pull-off test showing dry film adhesion strength vs strain.

what was expected from the datasheets. The discrepancy still needs to be investigated and could be attributed to different characterization techniques and scale between this work and the dry-film manufacturer. However, a higher Young's Modulus than expected is beneficial for the final MEMS device as E > 3 GPa leading to a stiffer structure.

Using our FT-104 Femto-Indenter, we performed continuous stiffness measurement (CSM) nanoindentation from ambient temperature up to 200°C and observed a drop of around 35% of the storage Young's Modulus at 170°C, thus we could assume a Tg close to 170°C which is higher than 150°C, but lower than expected from datasheet. Finally, we measured relatively low residual tensile stress in the blanked polymer layer close to 27 MPa. Ultimately, we selected the dry film polymer from datasheets provided by the manufacturer, development of the processing recipes was performed, and we confirmed its mechanical properties and productization. The next step will be grinding and polishing the silicon substrate to obtain small form factor and thin devices. More details are given in the next section.

3. THIN WAFER HANDLING AND PROCESSING

3.1 Why is temporary bonding needed?

Current mainstream in industrial applications requires miniaturized and cost-effective solutions. Thus, the demand for thin and ultrathin wafers is growing. Temporary bonding is a crucial process that enables safe and reliable processing of thin or to-be-thinned wafers [7, 8]. Thin wafers are very fragile, and as a result chips and cracks can easily occur. Thus, the final yield is at a high risk since these wafers should pass through processing steps like lithography, etching, deposition and others. The industry seeks reliable batch solutions in temporary bonding and debonding that ensures repeatability and high productivity at reasonable cost [9].

3.2 Temporary bonding technologies

A first technique involves direct bonding of MEMS device wafers and a carrier wafer using a special Temporary Bonding Material (TBM) [10] as shown in Figure 5(I). This material is an organic thermoplastic or thermoset adhesive spin coated on a carrier or device MEMS wafer. This process is suitable for simple chemical release debonding. A more complex process combines TBM with a thin Layer Release Material (LRM) [11, 12], intended for UV or IR debonding process -see Figure 5(II).

Typically, the bonding step occurs via thermocompression in vacuum or, in some cases, using UV radiation. The TBM is selected tailored to the intended application considering ease of coating, shorten processing time and simplified cleaning. Ideally, it is applied using single coat step ensuring uniform, void free and low stress interface between carrier and device MEMS wafer. The thickness should be enough to cover all topography on device MEMS wafer. The adhesive should be compatible with the intended thermal budget for subsequent process steps. The choice of carrier wafer is based on the target debonding process and CTE match with the device MEMS wafer to minimize induced thermomechanical stress. For example, silicon carrier is a perfect match for silicon device MEMS wafer. However, the technique such as UV laser debonding is not an option in this case since it requires transparent carriers such as glass.

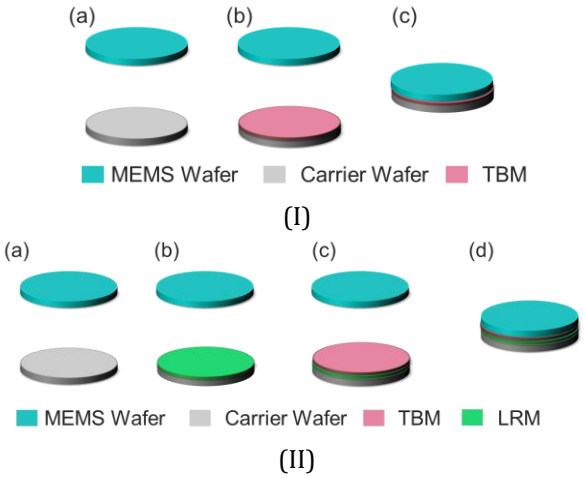


Figure 5. Temporary bonding process designed for: (I) chemical release debonding or thermal slide off; (II) UV or IR laser debonding.

3.3 Chemical release debonding

The chemical release debonding is established and reliable technique for temporary bonded wafers. The temporarily bonded stack is placed in a solvent bath to separate carrier and device MEMS wafer, and then a second bath is used to clean off any remaining adhesive. One can expect an approximate throughput of 25 wafers per debonding cycle that can be up to 4 hours. The main advantage of this technique is low induced stress. However, this technique is comparably slow and, in the end, expensive for high volume production. This pushes industry to develop new temporary bonding materials and corresponding processes.

3.4 Thermal slide-off debonding

In case of thermal slide off debonding, the wafer stack is heated up and separated by sliding wafers apart as Figure 6 illustrates. There is a trade-off between temperature, mechanical force and sliding rate. The maximum throughput is higher, up to 15 wafers per hour. Unfortunately, the stress induced by this debonding technique can be critical for fragile MEMS devices, limiting total yield.

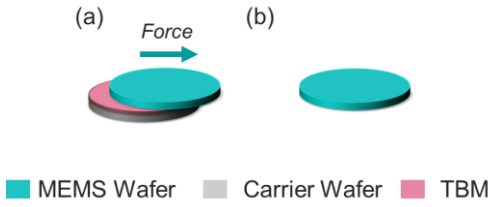


Figure 6. Thermal slide-off debonding process.

3.5 Laser debonding

Laser debonding technique offers high throughput up to 50 wafers per hour and low induced stress that is required to maximize yield in case of sensitive MEMS devices. This technique requires a special inorganic LRM layer [11, 12] that has high absorbance at specific wavelengths in UV (254 nm, 308 nm, 355 nm) or IR (1064 nm) band. This material is decomposed due to photochemical or photothermal effects leaving almost no residues. These residues can be later cleaned using oxygen plasma or an oxidizing solvent. After laser exposure happens, the temporary bonded stack can be separated with almost no force that is a great advantage for fragile structures. Figure 7 illustrates a simple laser debonding process involving (a) laser rastering and heating of the LRM layer; (b) wafers separation; (c) TBM removal.

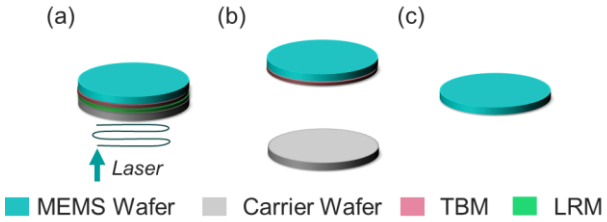


Figure 7. UV or IR laser debonding process.

4. STRESS TUNING FOR ACOUSTIC PERFORMANCE AND MANUFACTURABILITY

4.1 Why is stress control needed?

Stress becomes an important factor for acoustic performance, as it impacts both the geometry, the small and large signal performance and functionality, and the long-term reliability of the device. Geometric parameters include residual deflection of a cantilevered structure, or mismatch of deflections in arrays, buckling, and offsetting of key layout features. Functionality is also affected as losses, electrical, dielectric and piezoelectric performance rely on stress. This has direct consequences on key figures of merit of the device like sensitivity, SNR, resonance frequencies, and electromechanical coupling coefficients, among others. On the other hand, it is worth clarifying that stress is, rather than a problem, a physical situation intrinsic to stacked-layer devices. Also, that stress engineering problems become visible when MEMS manufacturing leave the early R&D proof-of-concept phase, typically done on small wafers, and move to large 200mm wafer format. Therefore, there is a need to tune stress to the performance goals of the MEMS device. This is discussed in the next paragraphs.

4.2 Stress tunability in c-axis textured piezoelectric AlScN thin films

The stress in polycrystalline and textured thin films can be controlled by adjusting various factors. These factors include both extrinsic and intrinsic components. Extrinsic stress is primarily influenced by the processing temperature, known as thermal stress. Intrinsic stress is more complex and arises from the kinetics of film growth, grain boundary densification, and the generation of point defects in the bulk. Chason *et al.* [13] have proposed a kinetic model for stress, which describes *total stress* as the sum of three components, namely growth-related stress, grain boundary energetics-related stress, and bulk energetics-related stress. This model suggests that by controlling the RF bias power of the tools carrying out physical deposition or growth of the acoustic MEMS layers and that affects the kinetic energy of incoming ions, one can manipulate all three components of stress.

As an example, we deposit scandium-doped aluminum nitride (AlScN), a piezoelectric thin-film that we use as active transducer layer of the acoustic MEMS device. Deposition is carried out by physical vapor deposition (PVD) using an industrial cluster tool Cluster 200E from Evatec. In our work, we tune the residual stress of c-axis textured AlScN films by applying an RF bias power to the chuck during deposition. The RF bias power varies from 50 W to 250 W, which leads to a linear increase in compressive stress with increasing power. The residual stress was measured using a Toho Stress measurement system, which employs Stoney's equation to relate the wafer curvature to the film stress [14]. The standard Stoney's equation used is:

$$\sigma = \frac{E \times t_s^2}{(1-\nu) \times t_f}\left[\frac{1}{R_f} - \frac{1}{R_s}\right] \qquad (1)$$

Where E and ν are the Young's modulus and Poisson's ratio of the substrate, t_s and t_f are the thicknesses of the substrate and film, and R_f and R_s are the radii of curvature after and before film deposition, respectively. Our experimental results show that for 500 nm thick Al0.64Sc0.36N films on Pt/AlN/Si100 electrodes, the average biaxial compressive residual stress is linearly dependent on the applied RF bias power. After laser exposure happened, temporary bonded stacks can be separated with almost no force that is a great advantage for fragile structures.

The plot in Figure 5 shows how stress control is a function of RF bias power. Selected bias point is defined by the target value defined by the application and stack of layers in the acoustic MEMS device.

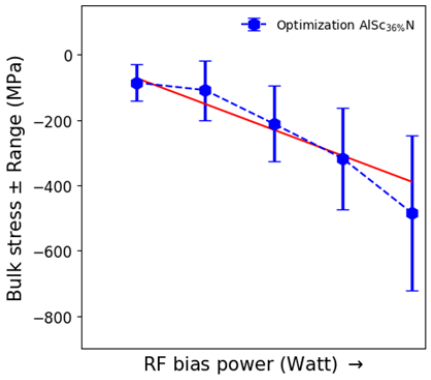


Figure 5. Dependence of RF power chuck bias to the residual stress of the AlScN thin film deposited on a 200 mm silicon wafer.

5. FEW WORDS ABOUT TESTING CHALLENGES

Testing of MEMS devices in the production environment poses several challenges. First of all, foundry setup is typically prepared for pure electrical testing, while MEMS devices generally require multi-physical domain environment. Adapting fab resources away from conventional *e-test* (electrical testing) is far from trivial.

This issue has direct impact in the cost of final application, as MEMS yield has to be characterized, modeled and improved at reasonable cost. Later stages of production will involve singulation of MEMS devices and testing them either integrated with electronic components in a module, or as stand-alone chips. Then, events such as crosstalk due to acoustic waves interfering in the data acquisition, robustness of die bonding using flexible glues, or even clamping losses will affect performance. A fully manufacturable flow will need test methodologies that integrate seamlessly in the manufacturing setup of standard foundries.

6. CONCLUSION

This paper has reported on relevant technologies needed for industrialization and successful inception of MEMS technologies in markets, namely polymeric dry film integration, handling of thin wafers as part of flow, MEMS stack stress management and tuning, and testing methodologies. Dry film integration enables new applications and performance of acoustic devices. MEMS wafer temporary bonding to carrier wafers in turn enables polymer processing, while debonding enables final MEMS device release for acoustic performance. Batch testing finally enables new wafer sorting methodologies.

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