

Improvements in MEMS gyroscope production as a result of using in situ, aligned, current-limited anodic bonding

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Abstract

Control of the bonding process is important in the high volume manufacture of MEMS gyroscope. This paper reports on the use of in situ, aligned, current-limited anodic bonding to enable the required device throughput and control of the bonding process. Statistical analysis of stress-sensitive output parameters of the gyroscope is used to quantify the benefits of different bonding procedures. Current limiting is shown to improve device-to-device reproducibility and the in situ capability of the combined aligner–bonder equipment enables high-throughput manufacturing and yield improvements. Cycle times for the aligned anodic bond process were reduced from 40 to 20 min, and wafer bow reduced by 20%. This reduction in wafer bow translated directly into improved device performance and reproducibility.

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1. Introduction

Wafer bonding [1] is a key process technology for MEMS devices, and control of the bonding process can be critical for the high volume production of MEMS devices. This is especially true for stress-sensitive sensors such as MEMS gyroscopes for which process-induced bow in the glass can cause changes in the resonant behavior of sensitive, silicon micromachined beams. In addition, it is important that the bonding process has a high-throughput consistent with the device production rate.

MEMS gyroscopes [2,3] are complex microstructures and their performance is highly sensitive to manufacturing tolerances. Critical performance parameters can be defined for monitoring device behavior and these are useful for indicating the degree of control that the wafer foundry has over the manufacturing process.

In this paper we report on the manufacturing of an inductively based, anodically bonded [4] MEMS gyroscope

(Fig. 1), and in particular the improvements in device performance and reproducibility that have been achieved through the use of in situ, alignment/current-limited anodic bonding of the sensitive and intricate micromachined silicon structure to the glass support wafer.

Current limiting can produce better process control during anodic bonding than the traditional voltage-limited technique. There are two reasons for this:

- Limiting of the current prevents in situ localised heating at the silicon–glass interface which can occur when the voltage is initially switched on in a non-current limited process.

The peak current (Fig. 2) can be several tens milliampere (for 100 mm wafers) and if the voltage is ~1 kV then several tens Watt can be dissipated in these areas.

However, because of the non-perfect flatness of the wafers, the silicon and glass will initially only be in intimate contact at selective points and the current will initially be concentrated here. The Joule heating that occurs can result in parts of the bond interface being at a higher temperature than the intended wafer temperature,

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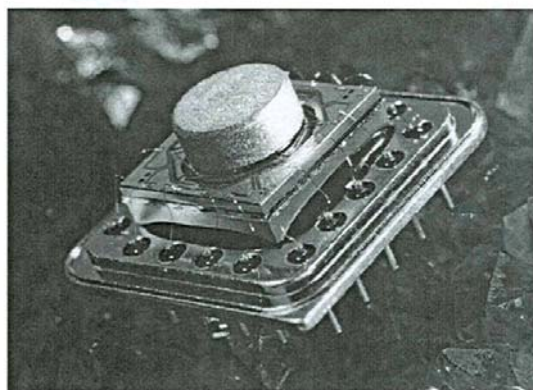


Fig. 1. Inductively based MEMS gyroscope.

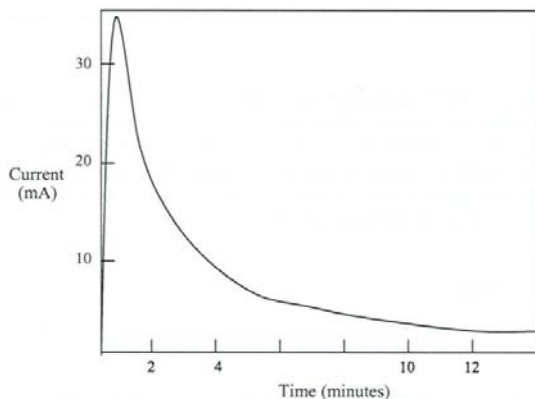


Fig. 2. Typical current shape vs. time for voltage-limited anodic bonding.

as set by thermocouples in the wafer chucks. The variations in local temperature at the time that the two wafers become bonded can result in stress variations caused by the local differences in the differential thermal contraction during cooling of the bonded wafers, and different (temperature-dependent) diffusion profiles of the various mobile ions in the glass [5].

With current-limited bonding the voltage is initially very low and then increases gradually as the bond progresses (Fig. 3) and the bond area increases thereby providing better control over temperature uniformity and hence device-to-device reproducibility.

- (b) At the beginning of the bonding process the glass is relatively highly conductive and the large current and voltage can cause localised electrical breakdown that can adversely affect yield. When using current-limited bonding however there is a much-reduced tendency to cause voltage breakdown in the glass. The reason for this is that as the bond progresses a depletion layer [6,7] is generated in the glass and this increases in depth as time progresses. The much higher resistivity of this layer can support higher voltage. The elimination of localised breakdown results in higher device yields.

2. Product evaluation

The equipment used for performing the bonding experiments was an AML 402 Wafer Bonding Platform. This has the following features:

- Purpose-built bonding system.
- Low cost of ownership.
- In situ alignment.
- Flexible parameter controls (current limiting, independent upper/lower temperature control, etc.).

The in situ alignment capability is beneficial in a production environment as it avoids a single root toolset and eliminates possible alignment issues when using transfer tools between aligners and bonders. Importantly the in situ capability also facilitates alignment under full process conditions, i.e. at bonding temperature and pressure (vacuum). This enables better process control.

In this work, the AML aligner/bonder was evaluated [8] under full production conditions in a high volume MEMS gyroscope manufacturing line, with regards to process control, utilising the current limiting capability of the system.

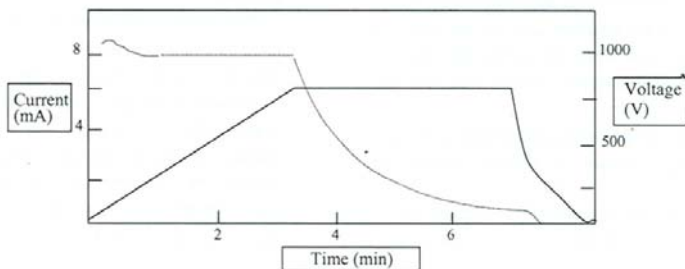


Fig. 3. Typical current and voltage traces for current-limited anodic bonding.

The production targets were as follows (to match process transfer specifications):

- Bond time = <40 min
- Wafer bow = <70 μm
- Alignment = <10 μm

The procedure used to determine the impact of this novel type of in situ, aligned bonding was to fabricate a batch of wafers and to further process these bonded wafers to produce fully packaged gyroscopes. These devices were then analysed by measuring key output parameters that are highly sensitive to packaging stress. Because the anodic bond between the glass and the silicon is used to anchor the sensitive microstructure used to measure the Coriolis force, variations in bond characteristics are expected to show up as stress-induced variation in the stability of this measurement. Comparisons were then made between the devices made using voltage- and current-limited bonding. Further comparisons were then done using the AML 402 as-installed, and then an upgraded machine which specifically addresses fast bond cycling to satisfy the high-throughput, gyroscope manufacturing requirements, yet still maintains the close control of the bonding process to produce device stability and reproducibility.

A bonding temperature of 370 °C was selected as this provided a sufficiently strong bond within the required process time although at this temperature we were initially unable to achieve the required wafer bow parameter with the standard, voltage-limited process.

3. Results

The initial alignment accuracy achieved was <10 μm (~6–8) using in situ alignment (this was limited by the nature of the alignment marks and not by the machine capability and therefore could be improved on by optimising the alignment marks).

Further trials were run using 100 mm wafers utilising the current limiting facility available on the AML 402 bonding system.

The following data taken from the trials shows that a significant improvement in wafer bow was achieved (at a bond temperature of 370 °C) exceeding the <70 μm wafer bow requirement by limiting the current flow during the bond cycle to 8 mA.

Temperature = 370 °C, $V = 600$ V, $I = 8$ mA.

- Max wafer bow = 60 μm
- Mean = 41.6 μm

Temperature = 370 °C, $V = 600$ V, $I = 40$ mA (note that with this high value for the current limit, the process effectively runs under voltage-limited conditions).

- Max wafer bow = 86 μm
- Mean = 74.6 μm

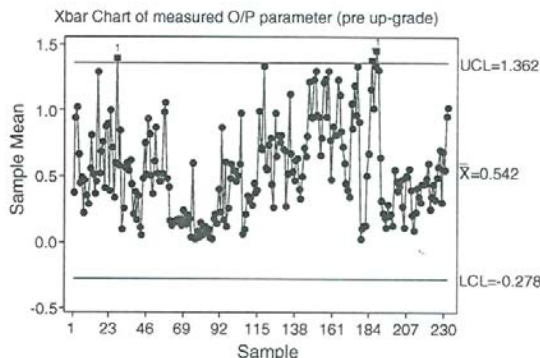


Fig. 4. Variation in device bias parameter before upgrade.

As can be seen, a reduction in wafer bow >20% was achieved with an 8 mA limit in comparison to the 40 mA limit. Figs. 4 and 5 show the improvement in the gyroscope bias monitoring parameters for the two sets of conditions. The sample mean value was 16% lower, which immediately translates into improved performance, and the device-to-device reproducibility was significantly improved. The reproducibility is better shown in Figs. 6 and 7.

C_p is a potential capability index defined as the ratio of the specification spread—Upper set limit (USL) to lower set limit (LSL) to the process spread. Basically the C_p value shows statistically how many times the process spread fits within the process specifications limits.

C_{pk} is a potential capability index defined as the ratio of (USL—process mean) or (Process mean—LSL) whichever is the smallest.

The C_{pk} value shows whereabouts within the specification window the process spread fits, with a value ≥ 1 showing that it is within, but right on the specification limits. Therefore, statistically a C_{pk} value of >1.3 is an industry standard to demonstrate process control with a low probability of producing out of specification devices.

Fig. 6 indicates that the process yield when using standard voltage-limited anodic bonding was very poor, with a C_{pk}

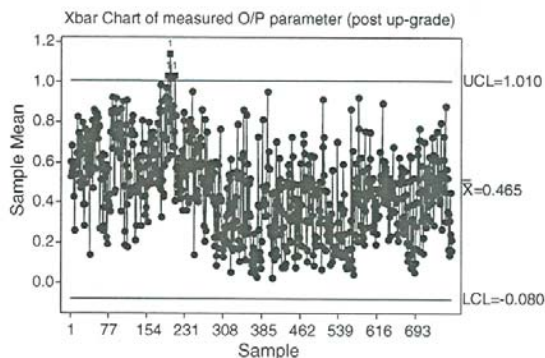


Fig. 5. Variation in device bias parameter after upgrade.

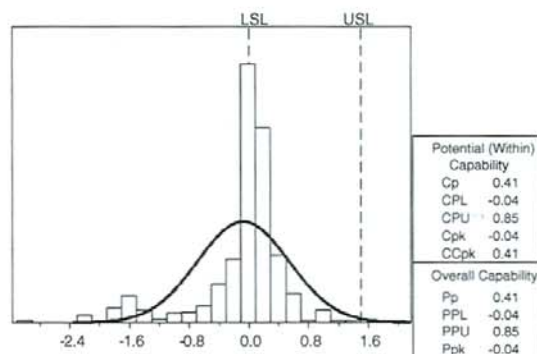


Fig. 6. Process capability for bias parameter without current limiting. The Y-axis scale is number of units produced (arbitrary); the X-axis scale is an electrical parameter of the devices (V). The potential capability and overall capability lists statistical process control values calculated from the bias parameter data set. See also Figs. 7 and 11.

value of -0.04 . The change to current-limited anodic bonding produced significant improvements with a C_{pk} value of 0.47 being achieved. Although still a long way from the target value of 1.3 , it can be seen from Fig. 7 that the majority of devices were now within acceptable limits.

Having demonstrated significantly improved process control and device-to-device reproducibility, an upgrade was performed on the aligner-bonder machine in order to improve the device throughput. C_p and C_{pk} were again used to monitor the process control. The upgrade consisted of the following changes:

- Upgraded platens (material changed from stainless steel to molybdenum which has a higher thermal conductivity and lower heat capacity material).
- Improved platen (i.e. wafer chuck) flatness (from 10 to $5 \mu\text{m}$).
- Faster heating/cooling (higher wattage quartz halogen bulbs).
- Higher temperature capability (improved thermal efficiency of the platens enabled the maximum operating temperature of the platens to be increased from 450 to 560°C).

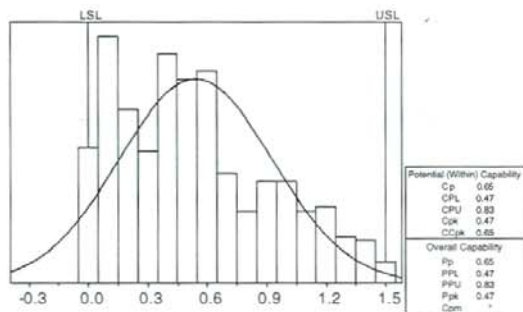


Fig. 7. Process capability for bias parameter with current limiting.

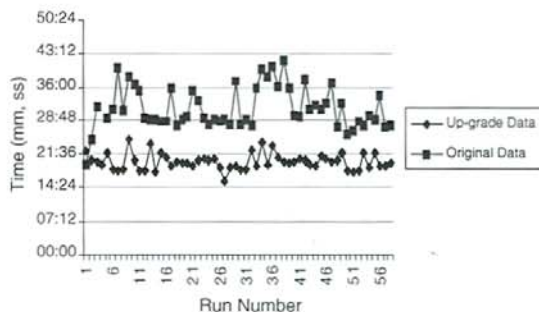


Fig. 8. Effect of upgrade on overall process time (throughput).

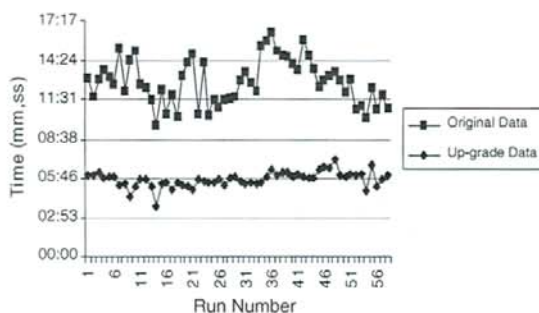


Fig. 9. Effect of upgrade on bond time.

The combined effect of the new platens and higher wattage reduced the heating time from room temperature to 400°C to <10 min (was >20 min previously) and from 200 to 400°C to <5 min (was ~ 13 min previously).

Figs. 8–10 show the effect of the upgrade on system throughput, bond time, and control of the integrated charge (i.e. the total charge transferred during the anodising process that forms the chemical bond/hermetic seal between the glass and the silicon). Significant improvements were observed in all cases with an overall cycle time of ~ 20 min now being achieved. Significantly, as demonstrated in Fig. 11 (compared with the earlier Fig. 7), this faster throughput

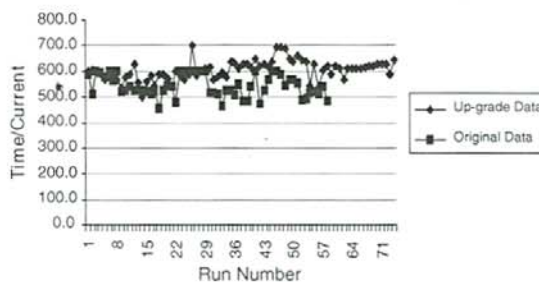


Fig. 10. Effect of upgrade on the control of the integrated charge.

