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Improved throughput and process stability for glass and silicon wafer bonding in the production of MEMS devices

Abstract

The throughput and performance of wafer bonding tools can play a key role in determining the cost of assembly and packaging of MEMS and other microsytems devices. A series of upgrades have been made to a wafer bonding tool in order to raise throughput without compromising performance. The improved system was tested during the anodic bonding of glass to silicon for the production of MEMS gyro rate sensors. Throughput was increased as a result of faster heating and cooling cycles. The stability of various process parameters was also found to be improved. As a result, the standard deviation of a measured output parameter of the completed MEMS gyros was significantly lowered. Process capability was higher, leading to more finished parts falling within specification.

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Introduction

MEMS and other microsystems technologies have shown great promise, but have yet to realize their full commercial potential. Expensive and poorly performing packaging is one of the key reasons for the slow uptake of such technologies, typically accounting for between 30% and 80% of the cost of a microsystem [1] and a significant proportion of device failures.

Anodic bonding of glass to silicon [2-4] is used in packaging finished devices and in the construction of the devices themselves. This is usually done under vacuum to reduce the incidence of particles and voids at the bond interface and involves the application of a high voltage to induce a region of high electric field strength at the interface. This brings the wafers into intimate contact and an anodic reaction between oxygen ions from the glass and the silicon creates a strong oxidation bond between the materials [5].

The throughput of the bonding tool is a key factor in the cost of producing MEMS devices, while the stability and reproducibility of the process has implications for the production yield.

This paper describes the improvements to wafer throughput and process stability that resulted from a program to develop a high-performance flexible bonding tool, the Applied Microengineering AML402.

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Methodology

The AML402 bonder contains two platens onto which the wafers to be bonded can be mounted. For anodic bonding of glass to silicon, the silicon is placed on the lower platen and the glass is held onto the upper platen by a spring-loaded knife edge. This pushes the glass wafer against two rigid stops on the opposite side of the platen. The wafers are mounted in pre-alignment such that their alignment marks coincide with each other and also with two view ports in the chamber lid.

The bonding tool features an alignment system that enables the wafers to be brought into high accuracy alignment in-situ. This removes the need for a costly separate wafer alignment system and lowers the probability of misalignment during the transfer to the bonding tool and subsequent set-up for bonding. Details of the alignment system and its performance are discussed elsewhere [6].

When the wafers are in place, the chamber lid is closed and the pump down begins. Once a pressure of 10^{-3} mbar is reached, wafer heating can begin. This is done using halogen bulbs mounted below the platens. During the heating phase, the wafer alignment can also begin. The wafer alignment marks are viewed using two CCD cameras mounted above the viewports. The lower platen is moveable in the x, y, z, and θ directions. The lower wafer is brought into alignment with the upper wafer using the x, y, θ manipulator and then the two are brought into contact using the hydraulic z-drive until the required contact force has been applied.

The bonding voltage, current and time depend on the area to be bonded and the glass type and thickness. The bonding voltage is determined by a current limit that is set by the operator. A low current will result in a slow bonding process, but if the applied voltage is initially set too high then electrical breakdown of the glass can occur. The bond completion is indicated by monitoring the level of accumulated charge and/or elapsed time and/or residual bond current.

Specific changes to the tool were made as follows:

- The stainless steel platens were replaced with platens machined from molybdenum. This improved the thermal conductivity of the platens, giving a faster time to bonding temperature and more uniform bonding temperature across the wafers.
- The 55W halogen bulbs behind each platen were replaced with 100W bulbs. This increased the maximum available bonding temperature and the heating rate.
- The underside of the lid surrounding the viewports was metallized with gold. This acts as a heat shield for reflecting wasted heat back into the chamber, resulting in quicker warm up time and, coupled with the higher power bulbs, an increase in the maximum bonding temperature to 560°C.

The performance of the modified tool was tested in the bonding of 4 inch Pyrex borosilicate glass wafers to silicon as part of the process for manufacturing silicon MEMS gyro rate sensors. Once the optimum bonding conditions were established for this application, the bonding process was monitored using statistical process control (SPC) of the tool's parameters and correlating these to aspects of device performance that are known to be affected by stresses experienced during processing. The SPC charts were also compared with those from the tool before the modification program was undertaken.

Results and discussion

Table 1 gives the performance parameters of the previous generation of bonding systems, the targeted improvements and the final outcomes of the development program.

The most obvious improvement when using the new system was the great decrease in the total bonding cycle time. For the 4 inch glass to silicon wafer bonding process employed for gyro rate sensor production the cycle time fell from ~30 mins to ~20 mins per wafer. This dramatic improvement is attributed to the redesigned platens and higher wattage heaters which decreased the heating time between room temperature and 400°C to 9 mins from

Parameter	Initial	Target	Final
Max. bond temperature (°C)	450	550	560
Max. bond force (kN)	1	2	2
Anodic voltage (kV)	2.5	2.5	2.5
Particulates (cm^{-2})	0.1	0.05	0.02
Max. wafer stack (mm)	6.5	10	10
Platen temp. uniformity (%)	+/-5	+/-3.5	+/-3
Cooling rate (°C/min)	3	Upgrade	<30
Platen flatness (μm)	25	5	10

Table 1. Performance parameters of existing bonding system, target and actual performance of the modified system.

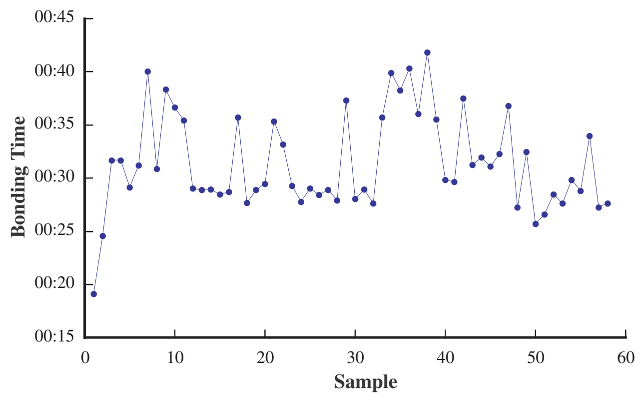

Figure 1a. A plot of process time before the modifications to the bonder.

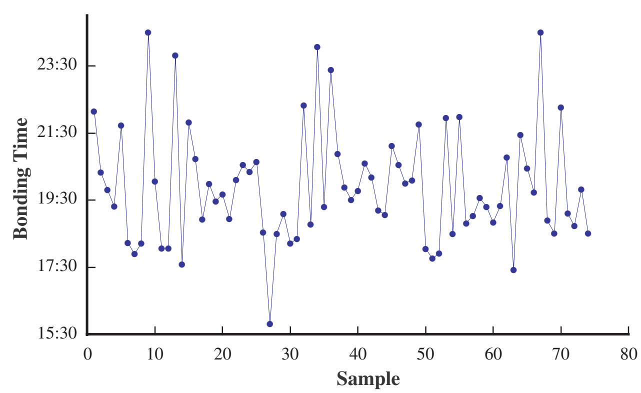

Figure 1b. A plot of the process time after modification of the bonder. In addition to a decrease in the process time, the variation has also been reduced.

about 20 mins previously. In addition to reducing the total cycle time, the statistical data in Figures 1a and 1b also show that the process time is more stable, with less scatter observed in the process time after the modifications.

Moreover, the statistics gathered on other parameters including chamber base pressure, integrated charge, and bonding time also showed greater stability after the modifications. Figures 2 and 3 show charts for the variation of integrated charge and bonding time before and after the modification program. In Figure 2a, the termination of the bonding process was determined by the reaching of an accumulated charge value of 600 mAs or after a specified time, whichever was reached first.

The post-upgrade integrated charge also has a higher average value. This is thought to be because of increased contact area at the start of the bond as a result of the redesigned platens being flatter (5 µm compared with 20 µm previously). A larger contact area enables the bond to start over a larger area, rather than at a few points where the platen and glass are in intimate contact. In this latter case, a number of bond fronts develop which grow outward and may leave voids where they intersect. Also, a large initial contact area enables more current to flow when the glass is at its most conductive, resulting in a higher charge transfer.

The improvements in the stability of the process parameters were seen to correlate to improvements in the stability of a measured output parameter for the finished gyro rate sensors. Figures 4a and 4b show the pre- and post-upgrade statistical process control (SPC) charts for a measured output parameter with the upper and lower control limits for the parameter marked on the charts.

Analysis of the statistical data from the gyros before and after the modifications reveals that the standard deviation is significantly lower at 0.26 post-upgrade, compared with 0.30 pre-upgrade. As would be expected, the process capability (Cpk) also improves from a value of 0.47 pre-upgrade to 0.6 post-upgrade. This translates into a larger number of finished parts performing to specification, enhancing the yield and lowering the cost of production.

Conclusions

The performance of the AML402 wafer bonder has been tested in the anodic bonding of 4 inch Pyrex borosilicate glass and silicon wafers for the manufacture of MEMS gyro rate sensors and has been demonstrated to produce better control of the bonding process and to reduce the cycle time, resulting in a better yield and reduced manufacturing costs compared with an earlier version of the bonder.

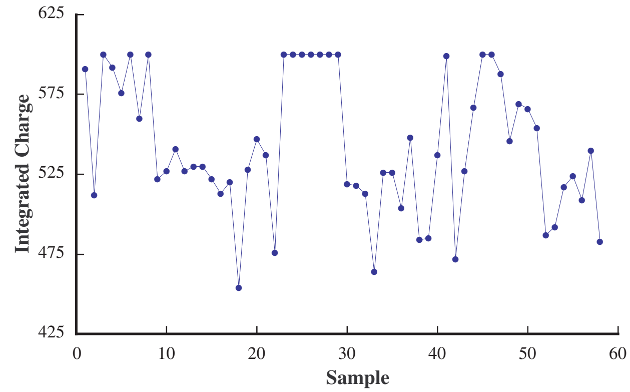

Figure 2a. Integrated charge for the glass-silicon bonding process before the tool was upgraded.

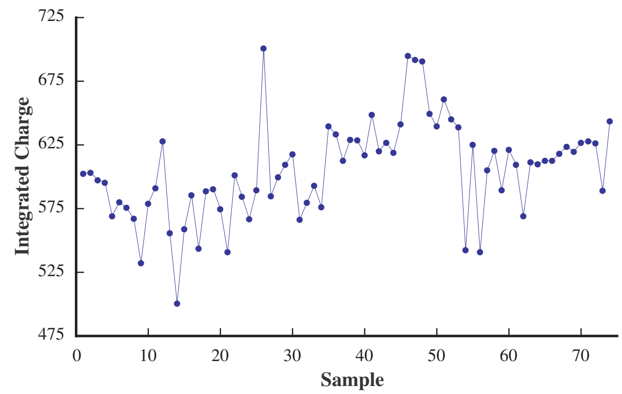

Figure 2b. Integrated charge for the glass-silicon bonding process after the tool was upgraded, showing a reduction in variation and a higher average charge compared with Figure 2a.

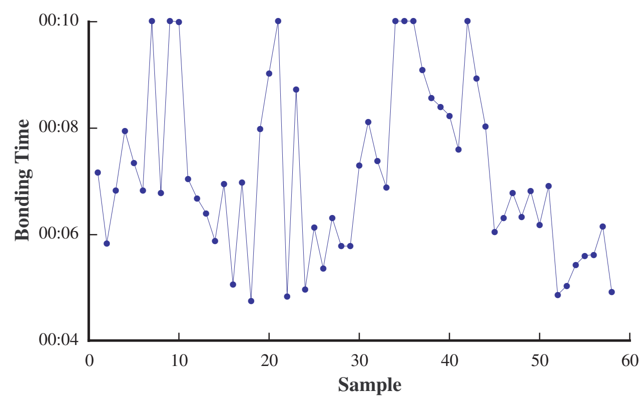

Figure 3a. The bonding time before the modifications were made to the tool.

Improvements to the rate of heating and cooling led to an increase in wafer throughput from 2 to 3 wafers/hr. The stability of process parameters such as integrated charge, bond time and overall process cycle time was seen to improve. This correlated directly to an improvement in the standard deviation of a measured output parameter for the completed MEMS gyros, raising Cpk from 0.47 to 0.6. The overall improvements lead to better yields and lower costs of production for MEMS devices.

References

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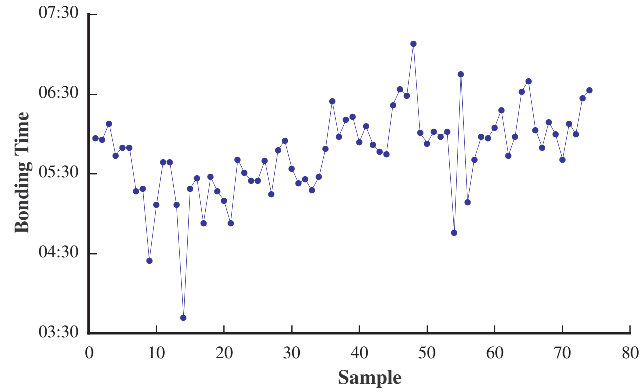

Figure 3b. The bonding time after the modifications, showing a reduction in scatter compared to Figure 3a.

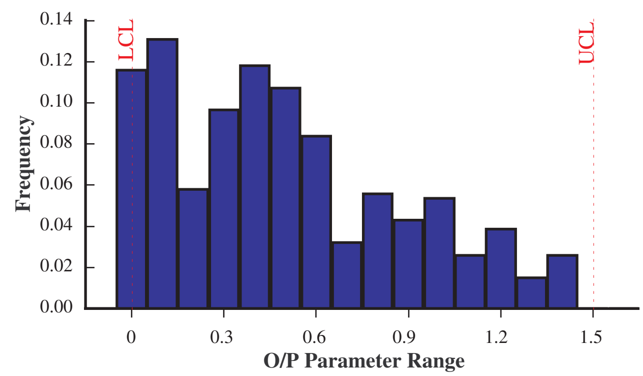

Figure 4a. A measured output parameter for the MEMS gyro before the tool modifications. Upper and lower control limits are marked.

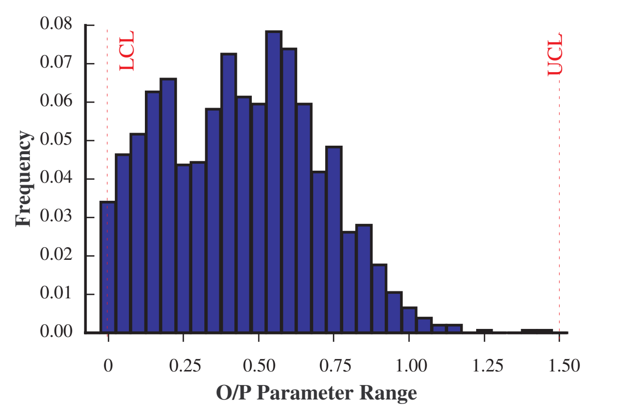

Figure 4b. The same output parameter as figure 4a measured in devices produced using the modified tool. There is less scatter in the results.