FABRICATION AND HERMETICITY TESTING OF A GLASS-SILICON PACKAGE FORMED USING LOCALIZED ALUMINUM/SILICON-TO-GLASS BONDING

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ABSTRACT

A hermetic package based on localized aluminum/silicon-to-glass bonding has been successfully demonstrated. Less than 0.2 MPa contact pressure with 46mA current input for two parallel 3.5µm wide polysilicon microheaters can achieve a strong and reliable bond in 7 minutes. Accelerated testing in an autoclave shows some packages survive more than 200 hours at 3 atm, 100%RH and 128°C. Premature failure has been attributed to some unbonded regions on the failed samples. The bonding yield and reliability has been improved by increasing bonding time and applied pressure. Devices using this process have lasted for more than 320 hours under accelerated conditions. The packaging technology is being applied to vacuum encapsulation of resonant devices.

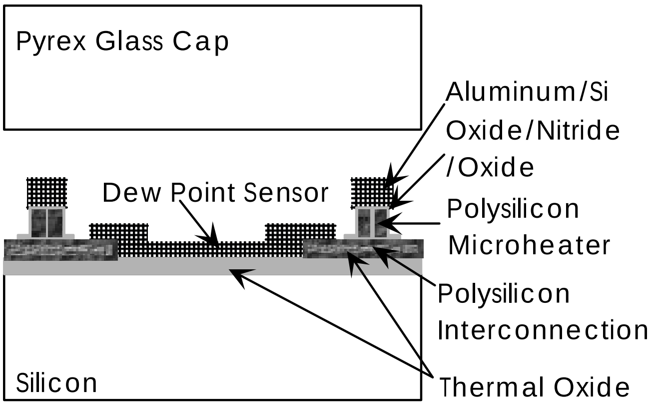
INTRODUCTION

Hermetic packaging is a critical requirement for integrated circuit and MEMS (Micro-electromechanical Systems) applications. The package should protect devices not only from the hostile external environment for longer lifetime, but also from contaminants for better performance **[1-3]**. In the past few years, several approaches have been proposed for the fabrication of a hermetic seal **[4-7]**. In these approaches, a common method to encapsulate MEMS devices utilizes capsules that are bonded to the MEMS substrate. This kind of post-packaging approach provides lower cost and more flexible process design. However, in order to acquire a good bond many of these techniques require a high temperature, which is incompatible with a low temperature needed to reduce the thermal stress on the package and the substrate. Previously, we reported various types of localized bonding schemes, including eutectic and fusion **[8]**, intermediate layer soldering **[9]** and CVD bonding **[10]**. All of these bonding techniques have demonstrated a high-quality bond needed for packaging without exposing the MEMS devices to a high-temperature environment.

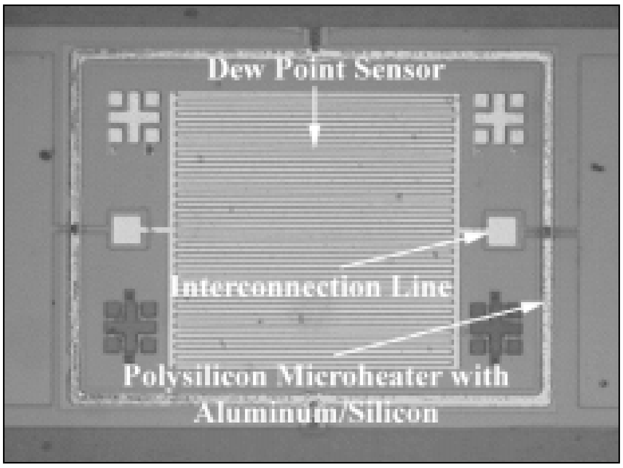
In many hermetic packaging technologies, glass is generally chosen as a protection cap because it is mechanically robust, chemically stable, and transparent to the light which is suitable for bio or optical MEMS applications **[11,12]**. Metal joints have been utilized in IC and MEMS assembly for many years and generally provide lower permeability to moisture than other materials like ceramic and epoxy, and are desirable for hermetic MEMS packaging **[13]**. Although we have already demonstrated glass-to-silicon bonding using localized heating of indium solder, the weak mechanical strength of indium **[9]** has made it inappropriate for some micropackaging applications. In this paper, we present a new bonding scheme based on aluminum/silicon-to-glass solder bonding, apply this technique to the development of a hermetic package for MEMS, and provide test results and techniques to improve the reliability and hermeticity of the package. Because aluminum is a CMOS compatible material and has superior mechanical properties, it is our belief that this hermetic packaging technology will be very useful in other MEMS applications.

DEVICE STRUCTURE

Figure 1(a) shows the schematic diagram of the hermetic package based on localized aluminum/silicon-to-glass bonding. The structure consists of polysilicon interconnect lines, which transfer signals from the sealed inside cavity of the package to the outside world, an on-chip polysilicon microheater, and the bonding material, which in this case is aluminum/silicon. The fabrication processes follows our previous report on localized solder bonding with a built-in aluminum-based dew point sensor **[9]**. After forming the polysilicon interconnect line and microheater, an oxide (1000Å)/nitride (500Å)/oxide (1000Å) sandwich layer is grown on top of polysilicon microheater for electrical insulation. In order to prepare the aluminum/silicon-to-glass bonding system for packaging, which has a higher bonding temperature above 700°C than indium solder, the sandwich dielectric insulation layer is needed to effectively prevent aluminum solder diffusion. Without the insulator, aluminum diffusion will cause electrical current going along the solder instead of the poly-silicon microheater during bonding. After depositing the dielectric layer, aluminum (2µm) and polysilicon (5000Å) are deposited and patterned. A Pyrex glass capsule is placed on top of the device substrate. In initial experiments, bonding is achieved under an applied pressure of 0.1 MPa and a current input of 92 mA. In about 5 minutes, the localized aluminum/ silicon-to-glass bond is completed. Figure 1(b) shows an optical micrograph of a sealed dew point sensor observed through the glass package.



(a)



(b)

Figure 1: Schematic diagram of the hermetic package fabricated by localized aluminum/Si-to-glass bonding: (a) cross section of the package; (b) optical photograph of the hermetic package seen through the glass capsule.

The bonding temperature is controlled by the polysilicon microheater whose temperature is monitored by assuming a linear dependence of resistivity on temperature **[8]**. According to a two dimensional heat transfer simulation by using FEA (Finite Element Analysis), the temperature of aluminum/silicon solder is • 90% of the microheater temperature due to the heat conduction loss to the electrical insulation layer. For example, it was found that a 46mA current input can make the microheater, designed as two parallel 3.5μm wide, 2μm thick phosphorus-doped polysilicon lines with $7.5 \times 10^{19}/cm^3$ dopant concentration and 2μm spacing, rise to 780°C which indicates the bonding temperature is around 700°C.

EXPERIMENTAL RESULTS

One of the advantages in using localized solder bonding to packaging devices is that there is no need for a planarization process. In **[9]**, we reported indium solder reflowing to overcome the surface topography which is created by the electrical interconnection of a sealed device. The principle can also be applied in aluminum/silicon-to-glass bonding system. Figure 2 shows a SEM photograph of the microheater and bond region after aluminum is deposited. A good surface coverage after localized heating to reflow the aluminum/silicon solder can be seen in Fig. 3(a). In addition, the 2μm spacing between two parallel polysilicon lines is filled up by solder as shown in the cross sectional SEM of the microheater in Fig. 3(b).

The package has been subjected to two kinds of tests: (1) a gross leak test in IPA (Isopropanol Alcohol), and (2) an accelerated test in an autoclave **[14]**. Because IPA has better wetability than water, it can more easily penetrate small openings, and is more suitable for gross tests. Figures 4 and 5 show a package before and after immersing it into IPA. As evident from the contrast difference that is due to different refraction indeces from air to IPA in these two photographs, IPA cannot penetrate the aluminum/silicon-to-glass bond. The gross IPA test is useful in screening devices for the accelerated test.

Accelerated testing is then performed in an autoclave on devices that passed the IPA immersion test. Hermeticity was tested using interdigitated patterns that operate as dew point sensors. Interdigitated dew point sensors have been widely used for lifetime testing of hermetic packages **[11,15]**. The operating principle is based on the large resistance change between closely spaced interdigitated electrodes of the sensor. Once moisture condenses on the whole surface of electrodes, the capacitance between these electrodes will increase because the relative dielectric constant changes from dry air (ε_r=1) to water (ε_r=80). Moreover, water has higher electrical conductivity than dry air. Therefore, the total impedance of the dew point sensor will decrease when moisture enters and condenses inside the package. Fig. 6(a) shows the drastic impedance and phase change for the dew point sensor after about 30 hours test. This is accompanied by moisture condensation inside the sensor as shown in Fig. 6(b).

In the first series of tests, a total of 11 packages are tested in the autoclave under the same bonding conditions, as illustrated in Fig. 7. Six of these packages failed almost immediately after insertion into the autoclave, two failed after 30 hours, two failed after 120 hours, and one failed after 200 hours in the autoclave. In order to determine failure mechanisms,

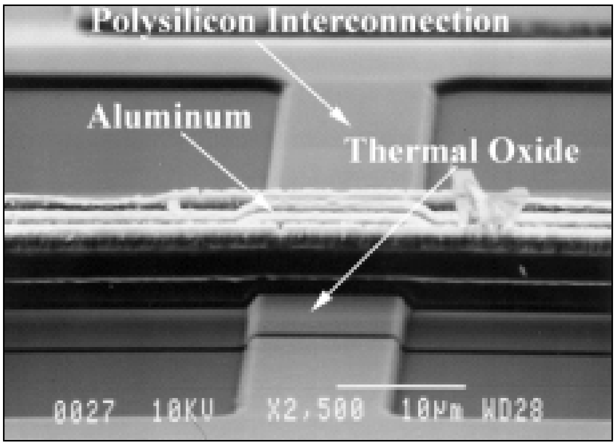
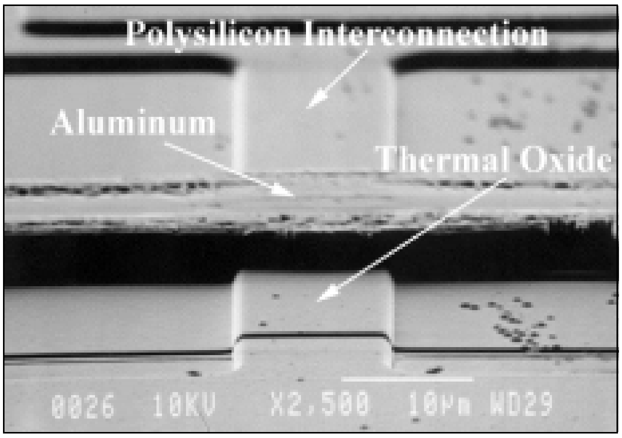
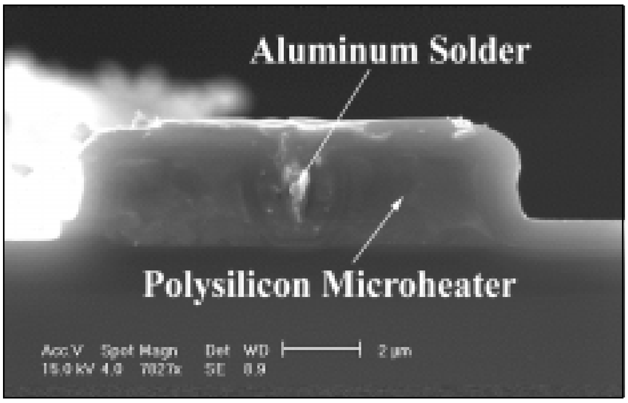


Figure 2: A close view SEM on the silicon substrate before reflowing. The step up of aluminum/Si solder is caused by the underneath polysilicon interconnect line.



(a)



(b)

Figure 3: Close-up SEM of the polysilicon micrheater after reflowing. Very good step coverage is achieved. (a) top view; and (b) cross sectional view.

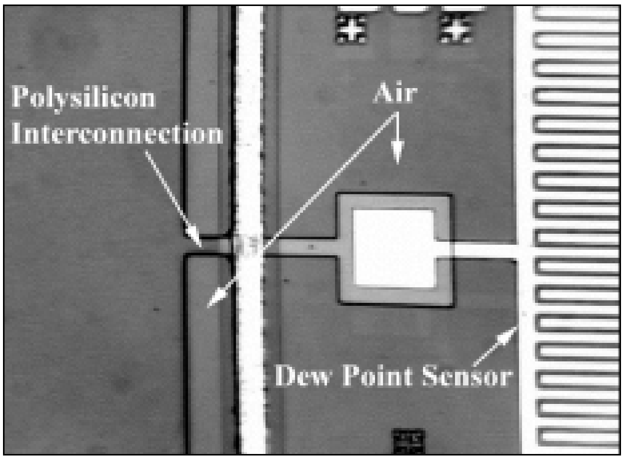


Figure 4: Photograph showing the packaged dew point sensor before immersing into IPA.

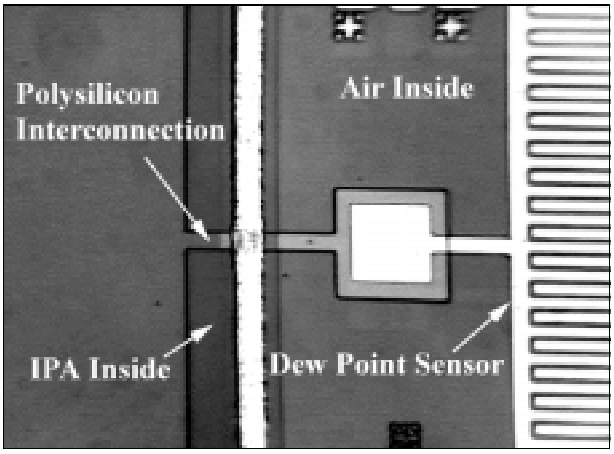
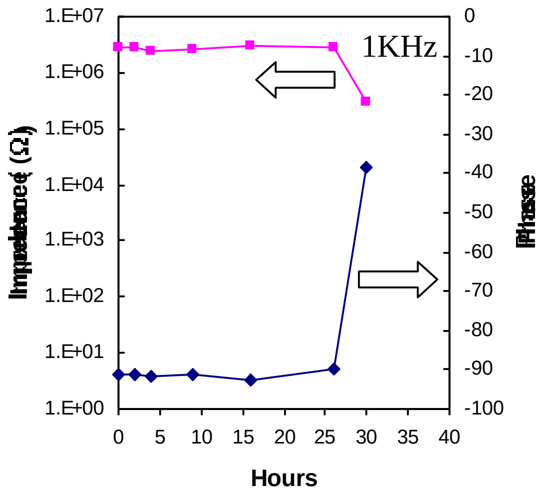


Figure 5: Photograph showing the packaged dew point sensor after immersing into IPA. The brightness difference indicates IPA was not able to penetrate through the bonding area.

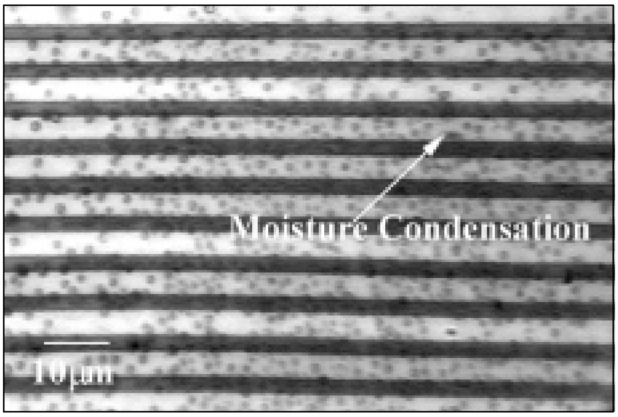
the glass package was forcefully removed from the silicon substrate and the bonding region was examined. Figures 8 and 9 show the device and the cap substrates, respectively. It is observed that in many regions, either the glass or the microheater with its underneath silicon substrate is stripped and attached onto the other substrate, indicating a strong bond. However, when the bonding process is not conducted correctly, as shown on the right bottom corner of Fig. 9 and the enlarged view in Fig. 10, moisture can diffuse into the package. In the package that lasted 200 hours, the unbonded region is much smaller, and almost undetectable.

DISCUSSION

Aluminum/silicon-to-glass bonding has been investigated in our group **[16]**. The strong bonding for



(a)



(b)

Figure 6: Results from the autoclave test. (a) after 30 hours, a drastic change is measured. (b) moisture condensation is found on the sensor.

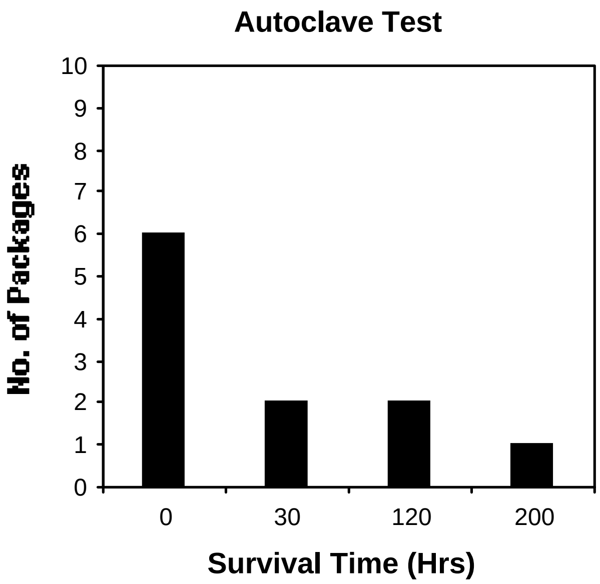


Figure 7: Statistical test results of autoclave test. These devices had all passed the IPA leakage test.

hermetic sealing relies on the formation of aluminum oxide and silicon precipitate while aluminum solder reacts with silicon dioxide under high temperature environment. According to the broken interface of glass and silicon substrate, the bonding strength is higher than the failure strength of Pyrex glass or silicon which is about 10MPa **[17]**. Such a strong bond is very suitable for packaging. In the previous autoclave test results, the unbonded region is identified as a major leakage path for moisture diffusion. Since the bonding quality of aluminum/silicon-to-glass is determined by the interface reaction of aluminum-to-glass, which depends on bonding temperature and time, another 11 packages are re-fabricated and subjected to the autoclave test.

In this second set of devices, all of eleven new packages are produced by increasing the bonding time and contact pressure, which are changed from 5 minutes to 7.5 minutes and from 0.1MPa to 0.2MPa respectively. Increasing the contact pressure and bonding time ensure that aluminum solder intimately contacts and totally reacts with the glass substrate. Fig. 11 shows the autoclave test results for this set of devices. Only one package failed immediately after insertion into the autoclave, three failed after 10 hours, three failed after 30 hours, one failed after 80 hours and three have survived more than 320 hours and are still under test. Even though some improvement has been obtained, it is evident that some devices still fail prematurely. Because raising the bonding temperature instead of time can also improve bonding quality, there are still many ways to improve bonding yield and quality. These other techniques are being studied.

Based on Weibull distribution approximation which is a common statistical theory to calculate the mean time to failure (MTTF) of packages **[18]**, it is found that the MTTF of total 22 glass-silicon packages formed using aluminum/silicon-to-glass bonding is only about 32 hours. Though this value is higher than published MTTF of epoxy-molded packages which is about 8 hours only under 1 atm, 100%RH, and 130°C environment, it is still much lower than we expected, especially for a metal seal. As mentioned, no unbonded regions can be found on the packages once they survive for more than 200 hours. Therefore, the failure mechanism should be different and needs to be identified. Moreover, MTTF is estimated by statistical methods, and the pressure effect of autoclave on the hermeticity test is still unknown. Using more devices for the test will provide more accurate MTTF and help us further understand the reliability of this packaging technology.

CONCLUSION

Aluminum/silicon-to-glass bonding based on localized heating technique has been successfully developed and

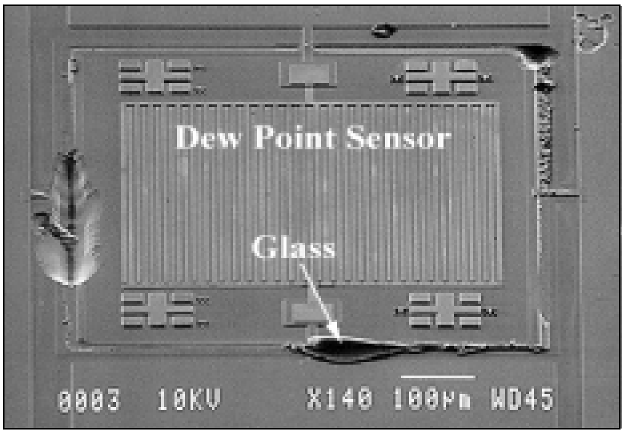


Figure 8: SEM micrograph of the device substrate after breaking the encapsulation.

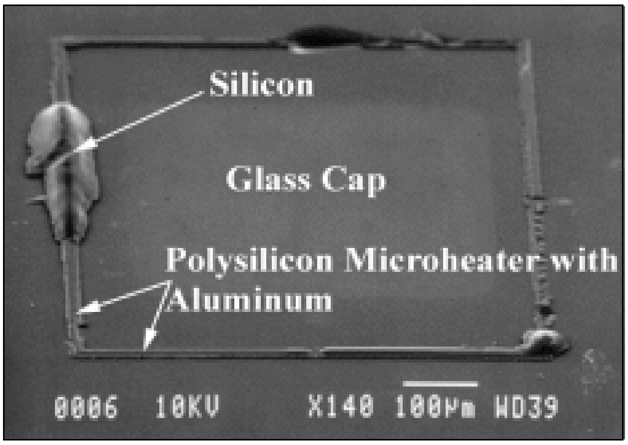


Figure 9: SEM micrograph of the glass substrate after breaking the encapsulation. The polysilicon microheater with aluminum solder is removed from silicon and attached to the glass cap.

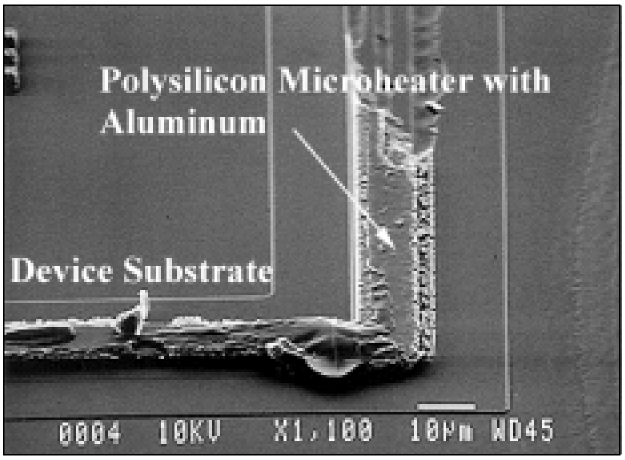


Figure 10: Close view SEM micrograph on the device substrate. There is some area which has weak formation of aluminum/Si-to-glass bond and is the leakage path for moisture.

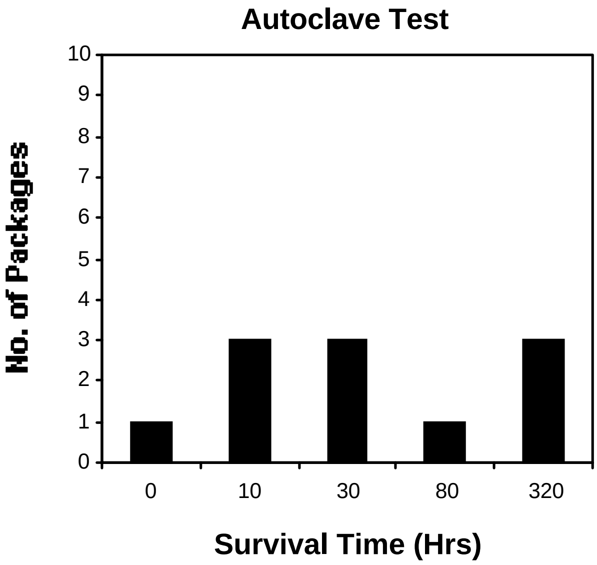


Figure 11: Statistical autoclave test results of another 11 packages produced by increasing bonding time and pressure. These devices had passed IPA leakage test.

applied for hermetic packaging. The surface step created by electrical interconnect feedthrough lines can be planarized by reflowing aluminum/silicon solder for bonding without affecting the performance of the packaged sensor. Under 700°C for about 5 minutes, aluminum can react with glass to form aluminum oxide and silicon precipitate. The formation of the composite provides more than 10MPa bonding strength and good hermeticity. An autoclave test shows some packages can survive more than 300 hours under a harsh environment at 3 atm, 100%RH and 128°C. Non-uniform bonding has been identified as the main failure mechanism to hermetic seal. Experimental results also indicate that bonding quality can be improved by increasing bonding temperature, time and applied pressure to provide intimate contact between aluminum and glass.

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