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Residual Stress and Deformation Analysis of Anodic Bonded Multi-layer of Glass and Aluminum*

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Abstract

The bonding of glass wafer to aluminum foils in multi-layer assemblies was made by the common anodic bonding process. The bonding was performed at temperatures in the range 350-450 ℃ and with an applied voltage in the range 400-700 V under a pressure of 0.05 MPa. Residual stress and deformation in samples of two-layer (aluminum/glass) and three-layer (glass/aluminum/glass) were analyzed by nonlinear finite element simulation software MARC. The stress and strain varying with cooling time were obtained. The analyzed results show that deformation of the three-layer sample is significantly smaller than that of the two-layer sample, because of the symmetric structure of the three-layer sample. This has an important advantage in MEMS fabrication. The maximum equivalent stresses locate in the transition layer in both samples, which will become weakness in bonded sample.

Keywords: Anodic bonding, MEMS, Aluminum, Glass, Residual Stress, Finite element

1. Introduction

As one of the most important bonding methods in microelectromechanical systems (MEMS), the anodic bonding is widely used in bonding of mechanical or electrical components, sealing of micro-instrument and microstructure. In order to reach the requirements of the more complicated circuit and micro-electrical devices, a lot of combining structure of multi-layer of the glass to metal is applied to actual products, for example, the silicon/glass/silicon anodic bonding through the double processes using alternating current was done by Despont [1], which can be used in the microscopy with minimum electron beam. Nimkar [2] designed and developed the fabrication technique for an enhanced surface heat sink to document one-dimensional pool boiling heat transfer data. The heat sink was designed to simulate a multi-chip module, and symmetry was used to create silicon/glass and aluminum/glass bonds. The five-layer sample (silicon/glass/aluminum/glass/silicon) was bonded by using four times anodic bonding processes. Using the anodic bonding, the electrical valve consisting of four-layer wafer was accomplished by Huff and Epstein [3,4].

In the previous investigations on anodic bonding of glass-metal layers, multi-layer of silicon, aluminum or silicon nitride was prepared by sputtering or physical vapor deposition techniques instead of study of the mechanical property of the multi-layer wafer [5-9]. In the present paper, the bonding of multi-layer glass-metal was made by the common anodic bonding process. The residual stress and deformation of multi-layer aluminum and glass were analyzed by

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nonlinear finite element simulation software MARC. The results show the residual deformation in three-layer sample is significantly smaller than that in two-layer sample. The symmetric structure in the three-layer sample resulted in the smaller strain, which has an important advantage in MEMS fabrication.

2. Experimental materials and method

Glass wafers, Pyrex 7740 (obtained from Corning Corporation), were used in the present work. Their chemical composition is given as (wt.%) 80.9 SiO_2, 12.7 B_2O_3, 2.3 Al_2O_3, and 4.0 Na_2O. The roughness of the glass wafers (Ra) is less than 0.1 μm and their thermal expansion coefficient is 2.8×10^{-6} °C^{-1}. The aluminum foil (99.997% pure, obtained from Alfa Aesar, Ward Hill, MA) are 0.02 mm thick and have a thermal expansion coefficient of about 25.6×10^{-6} °C^{-1}. The transition layer of the interfaces of glass/aluminum was considered to be a film of $3Al_2O_3\cdot2SiO_2$.The bonding parameters: voltages in the range 400-700 V and temperatures in the range 350-450 ℃, and time within 15 min, in all cases. At the end of each experiment, the sample was cooled to room temperature at a rate of 1 °$C\cdot s^{-1}$. The glass wafers and aluminum foil were cut into pieces with dimensions of 10×10 ×0.4 mm and 10×10×0.02 mm, respectively.

Before each experiment, the foil and wafers were cleaned ultrasonically in methanol and acetone, and then dried with hot air. A schematic of the apparatus used in this investigation is shown in Fig. 1. The three-layer sample of glass/aluminum/glass was positioned on the bonding platform inside the bonding oven in such a way that the aluminum film was electrically connected to the anode and the two glass wafers connected to the cathode. A low pressure of 0.05 MPa was exerted between the anode and the cathode. When the temperature in the oven reaches a targeted value, a voltage was applied and the resulting current was recorded by a digital load cell (Mettler Corporation). The samples were then cleaned with HCl solution in order to remove the alkali salt on the surface of the glass.

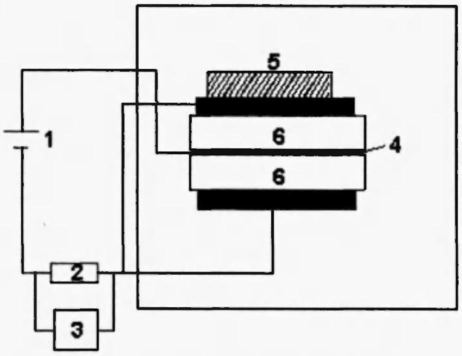


Figure 1. A schematic of the anodic bonding apparatus of three-layer glass/aluminum/glass sample; 1. D.C power supply, 2. Resistance, 3. Current recorder, 4. Aluminum, 5. Pressure controller, and 6. Glass.

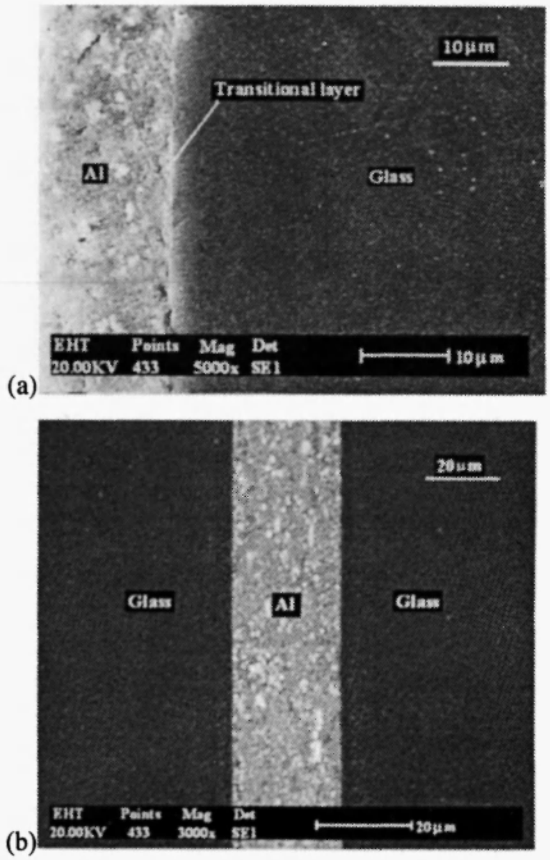


Figure 2. Microstructure of sample bonded with 600 V at 450 °C for 15 min: (a) two-layer sample (aluminum/glass) (b) three-layer sample (glass/aluminum/glass).

Microstructure and back-scattered electron (BSE) SEM image of the two-layer sample (aluminum/glass) and the three-layer sample (glass/aluminum/glass) bonded with 600 V at 450 °C for 15 min are shown in Fig. 2a and 2b.

Figure 2 shows the establishment of good contact between the glass and aluminum and the absence of porosity at the chosen magnification. There are no cracks, pores, or gaps at the two interfaces between the glass and aluminum. The transition layer of the interfaces of glass/aluminum was considered to be a film of $3Al_2O_3{\cdot}2SiO_2$ [10-11].

3. Finite element models and parameters

Analysis of the residual stress and strain in the bonded samples was made by nonlinear finite element simulation software MARC. In the models, aluminum acted as an elastic-plastic material, and others were elastic materials. The dimensions of the samples used in models are: aluminum foil, 2.0×2.0×0.02 mm; glass wafer, 2.0×2.0×0.4 mm. Their thermal-mechanical parameters of the samples for simulation are given in Table 1. Finite element models of the sample are shown in Fig. 3. Because of the symmetry of the sample structure, a quarter of each sample was analyzed. The element type was eight-node hexahedron. The origin of coordinates was at the bottom center of the bonded sample, OO′, the centerline, OAA′O′ and OCC′O, symmetric plane. The symmetrical temperature and mechanical boundary condition were applied. The fixed-displacement boundary condition was used at node O′. The cooling boundary conditions of upper, lower face and side face were applied. The transition layer was considered to be a film of $3Al_2O_3{\cdot}2SiO_2$. The results of two-layer bonded sample (aluminum/glass) were compared with those of three-layer sample (glass/aluminum/glass). In the process of cooling from 450 °C to room temperature, some calculations were made.

Table 1 The thermal-mechanical parameters for simulation

	Yong's modulus of elasticity/ Pa	Poisson ratio	Density Kg/m^3	Coefficient of thermal expansion K^{-1}	Heat conductivity W/(m·K)	Specific heat J/(kg·K)
Glass	6.275×10^{10}	0.2	2230	$3.2\sim3.9\times10^{-6}$	1.55	840
$3Al_2O_3{\bullet}2SiO_2$	3.7×10^{11}	0.22	3900	6.5×10^{-6}	31	880
Al	6.8×10^{10}	0.31	2700	2.56×10^{-5}	237	900~999

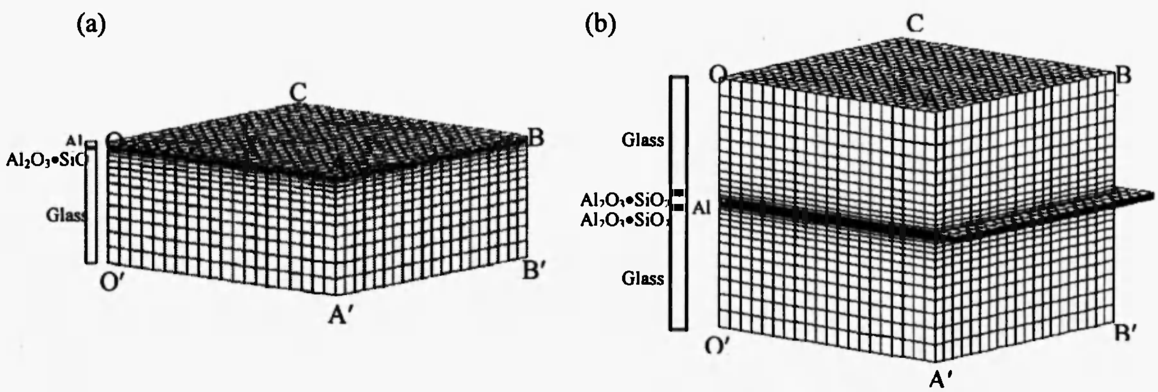


Figure 3. Finite element models of: (a) aluminium/glass sample (b) glass/aluminium/glass sample.

4. Finite element analysis

4.1. Entire deformation of samples

Figure 4a and 4b show the deformation color bands of two-layer sample (aluminum/glass) and three-layer sample (glass/aluminum/glass) respectively. The original shapes of samples are shown in Fig. 4 with black frame. In Fig. 4a, the bonded samples curved towards the aluminum layer with 0.175% maximum deformation. Fig. 4b depicts the deformation of three-layer bonded sample, with 0.00418% maximum deformation. It can be seen that the deformation of the sample is much smaller than that of the two-layer sample, because of the symmetry of the three-layer structure. This has an important advantage in MEMS fabrication.

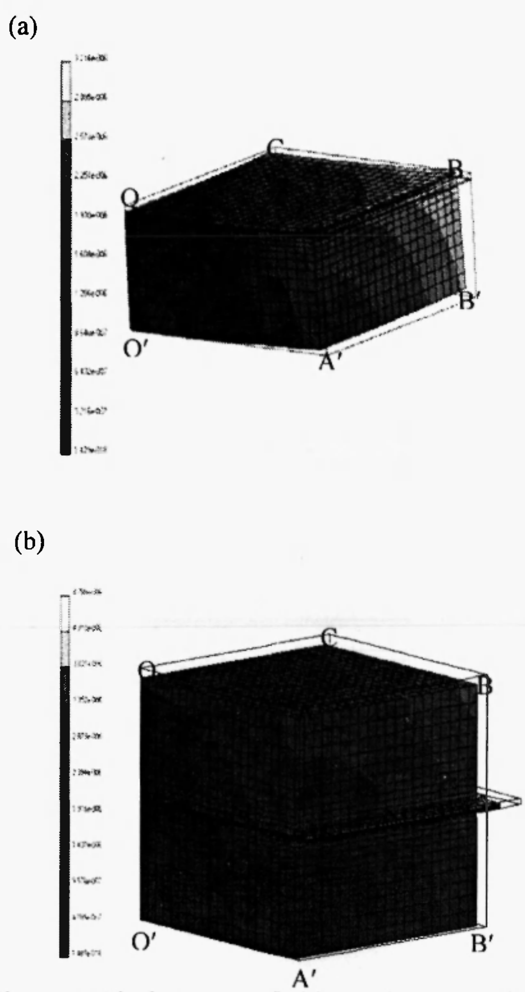


Figure 4. Displacement of: (a) two-layer sample (aluminum/glass) (b) three-layer sample (glass/aluminum/glass).

4.2. Equivalent stress

Because of different thermal-expansion coefficients of these materials, the shrinkage of the model is uneven during cooling processes. Therefore, the residual stress and strain will happen after cooling. Furthermore, the thermal expansion coefficient of aluminum is much larger than that of other materials, and the yield strength of aluminum is much smaller than that of other materials. Plastic deformation may take place in the Aluminum. So aluminum is used as the elastic-plastic material in models, with other materials as the elastic material.

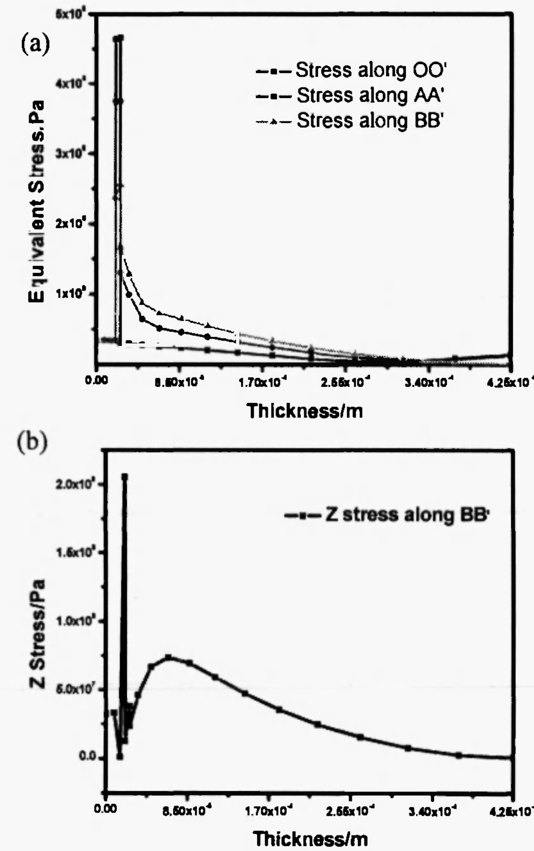


Figure 5. Stress in the two-layer model (aluminum/glass): (a) equivalent stress (b) Z-stress along BB′.

Figure 5 shows the equivalent stress (Fig. 5a) and Z-stress (Fig. 5b) along the thickness of representative location in the sample. In Fig. 5a, the maximum stress locates at the interface between aluminum and the transition layer, the value of which was 466 MPa. Fig. 5b shows Z-stress along BB′ which becomes tensile stress and the value of which was 205 MPa. Fig. 6a shows the equivalent stress (Fig. 6a) and Z-stress (Fig. 6b) along the thickness of representative location in the three-layer sample. It can be seen that the equivalent stress distribution in three-layer sample is symmetric. The equivalent stress of transition layer is much larger than that in other areas of the sample. The maximum value is 597 MPa. Fig. 6b shows Z-stress along BB′ which becomes compressed stress and the value of which was 265 MPa.

From Fig. 5a and Fig. 6a, it can be seen that plastic deformation occurs in aluminum during cooling. By comparing the results of the equivalent stress of two-layer with that of three-layer models, it can be found that the equivalent stress of three-layer sample is larger than that of two-layer sample due to increasing restriction. But at the edge of sample, three-layer sample presents compressed stress, and two-layer sample presents tensile stress.

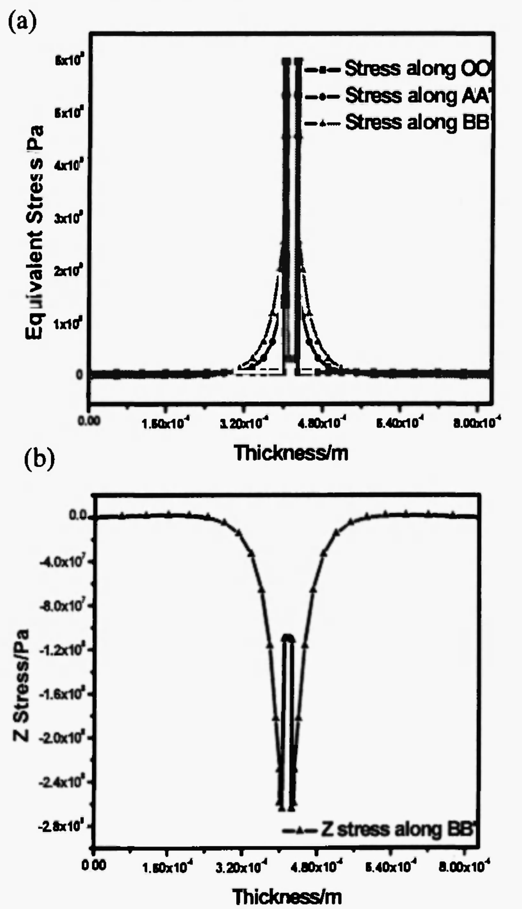


Figure 6. Stress in the three-layer model (glass/aluminum/glass): (a) equivalent stress (b) Z-stress along BB′.

4.3. Equivalent strain

Figure 7 shows the equivalent strain along the thickness of representative location in the samples. In Fig. 7a, it can be seen that the maximum strain, 3.47×10^{-2}, locates at the aluminum layer close to transition layer, and the minimum strain locates at the glass, with a value of 2.34×10^{-2}. Strain in the centerline area is larger than that of edge area. The Fig. 7b shows that the equivalent strain distribution in three-layer is symmetric. The maximum strain occurred at the middle aluminum layer, with the value of 2.42×10^{-2}. By comparing Fig. 7a with Fig. 7b, it can be concluded that the maximum equivalent strain in three-layer model is smaller than that of the two-layer model.

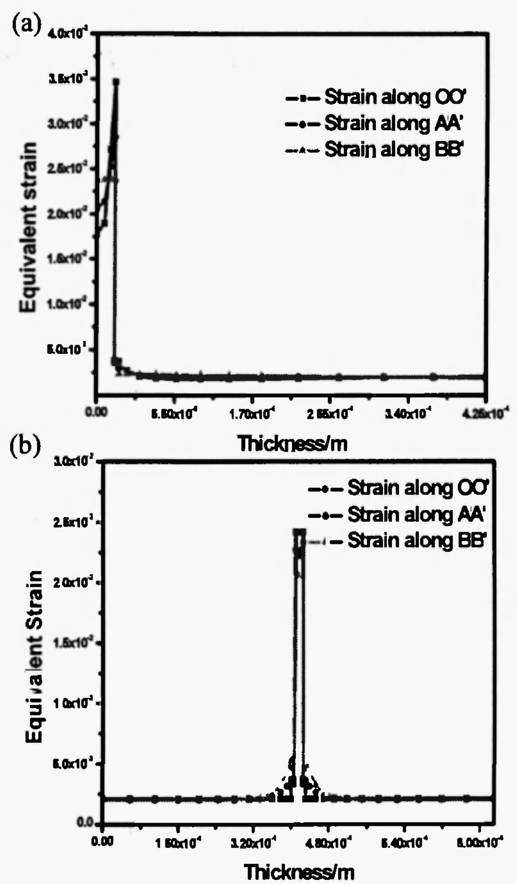


Figure 7. Equivalent strain in: (a) two-layer model (aluminum/glass) (b) three-layer model. (glass/aluminum/glass)

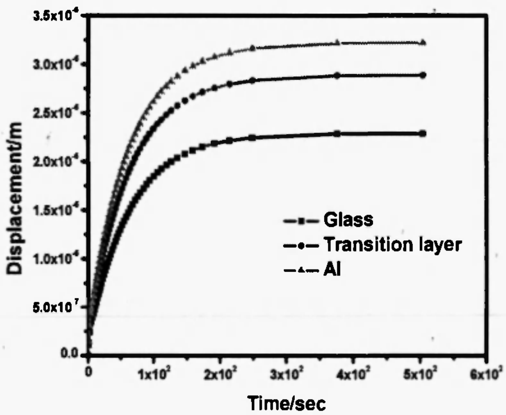
4.4. Parameters variation with cooling time

Figure 8 shows that the deformation pattern along BB′ is the same in two models.

Deformation of materials is gradually increasing with the increasing cooling time. However, displacement along BB′ decreases in turn.

The equivalent stress *vs.* time along BB′ is the same in two models, shown in Fig. 9a and Fig. 9b. Equivalent stress of the transition layer and glass increases with the increasing cooling time, but equivalent stress of aluminum holds constant after yield strength. By comparing Fig. 9a with Fig. 9b, it can be seen that the maximum equivalent stress always occur in the transition layer, which will be weakness area in the bonded sample.

(a)



(b)

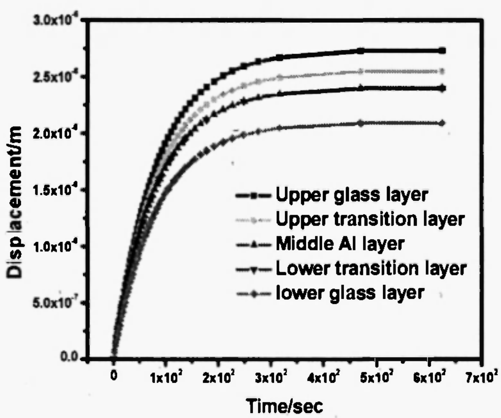
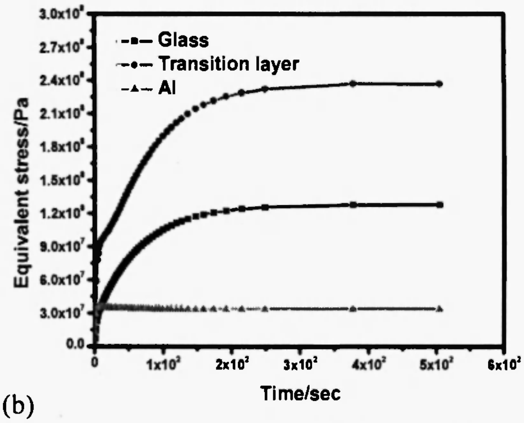


Figure 8. Displacement vs. time along BB′ in: (a) two-layer model (aluminum/glass) (b) three-layer

(a)



(b)

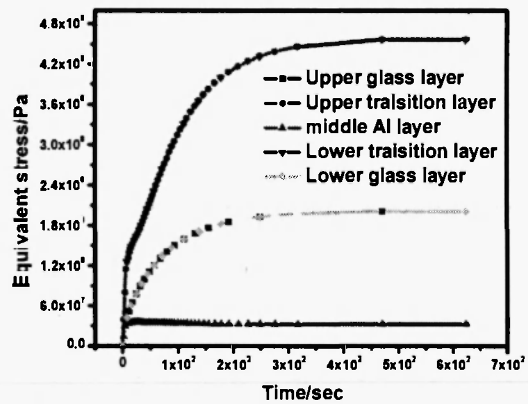


Figure 9. Equivalent stress vs. time along BB′ in:
(a) two-layer model (aluminum/glass)
(b) three-layer model (glass/aluminum/glass)

model (glass/aluminum/glass)

5. Conclusion

(1) Three-layer sample of glass wafers and aluminum foil was successfully bonded by the anodic bonding process. The bonding was achieved at temperatures in the range 350-450 °C and with an applied voltage in the range 400-700 V. A low pressure of 0.05 MPa was applied during the process of bonding.

(2) The analyzed results show that the deformation and equivalent strain in the three-layer sample are significantly smaller than that in the two-layer sample. The symmetric structure in the three-layer sample resulted in the smaller strain, which has an

important advantage in MEMS fabrication.

(3) The maximum equivalent stress of three-layer sample is larger than that of two-layer sample due to increasing restriction, but at the edge of sample, three-layer sample presents compressed stress, and two-layer sample presents tensile stress.

(4) The maximum equivalent stress occurs in the transition layer in both models, which will become weakness area in bonded sample.

Acknowledgments

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