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Pressure and Field-Assisted Bonding of Glass to Aluminum†

Yoshiaki ARATA*, Akira OHMORI**, Saburo SANO*** and Ikuo OKAMOTO*

Abstract

Bonding of aluminum to glass was done by a new bonding method applied a DC voltage under a external pressure. In this method which was named pressure and field-assisted bonding the external pressure plays remarkable roles making easily intimate contact at the glass-metal interface and enabling the metal ions to penetrate easily into the glass. Under higher pressure the bonding can be achieved even at a lower temperature with a lower applied voltage. Moreover, effects of the external pressure and other factors on the bonding were discussed.

KEY WORDS: (Pressure) (Field-Assisted Bonding) (Glass) (Aluminum)

1. Introduction

Recently, we have paid remarkable attentions to ceramics for their useful characters. Many methods of bonding ceramics to metals also have been undertaken for the applications of ceramics[1]. Field-assisted bonding is a method to make a bonding of metals to glass and other insulators at a temperature applied a DC current. The bonding of metals to glass[2],[3] and β-alumina has been done[4]. In this work, a new bonding method which permits the bonding at the lower temperature under the lower applied voltage is described. In this method, a external pressure is applied during field-assisted bonding. The external pressure plays a remarkable role in achieving the bonding and it was named pressure and field-assisted bonding (PFA bonding). The pressure makes the sound contact at the glass-metal interface and enables metal ions to penetrate easily into the glass, so that the bonding is achieved easily at the lower temperature under the lower applied voltage in contrast with field-assisted bonding, in which the external pressure is not applied. In addition, it was acknowledged that the amount of electricity during the bonding was an important factor controlling the bonding. When a certain amount of electricity at a bonding temperature was given, the bonding was achieved. The total amount of electricity required for bonding, changed with Na_2O amount contained in glass.

2. Experimental Procedure

2.1 Materials and specimens

Chemical compositions of glasses used in this study are shown in **Table 1**. No. 1 is a commercial plate glass and No. 2 to No. 5 are four kinds of SiO_2-CaO-MgO-Na_2O system glasses containing various amounts of Na_2O (5 to 20 mol%). Glasses were machined in size 9 × 10 × 3 mm, and both surfaces were finished by polishing with #1500 emery paper.

Table 1 Chemical compositions of glasses used

No	Chemical compositions (mol%)						
	SiO_2	CaO	MgO	Na_2O	Al_2O_3	ZrO_2	As_2O_3
1	72	8	4	15	1	-	-
2	65	20	10	5	1	1	1
3	60	20	10	10	1	1	1
4	55	20	10	15	1	1	1
5	50	20	10	20	1	1	1

*Al_2O_3, ZrO_2 and As_2O_3 were added as dorpant

As the metal, aluminum plate (A1100, 2 mm in thickness) was used mainly. Aluminum plate was cut in size 20 × 20 mm for an anode. A surface directly contacted with the glass was finished with #1500 emery paper. Aluminum wire (1 mm in diameter), aluminum foil (35μm in thickness), silver plate were also used as anode metals.

2.2 Testing apparatus

Figure 1 shows the bonding apparatus used in this study and the assembly for bonding. The bonding apparatus consists of a Mo electric resistant heater, a system for vacuum and a system for pressing. All experiments in this study were done in vacuum of 5×10^{-5} Torr. Specimens for bonding were degreased in acetone with a ultrasonic cleaner. Lead wires and a CA thermocouple were percussion-welded to the specimens and then they were equipped as shown in Fig. 1 (b). After the assembly was heated to a required temperature at the rate of 50°C/

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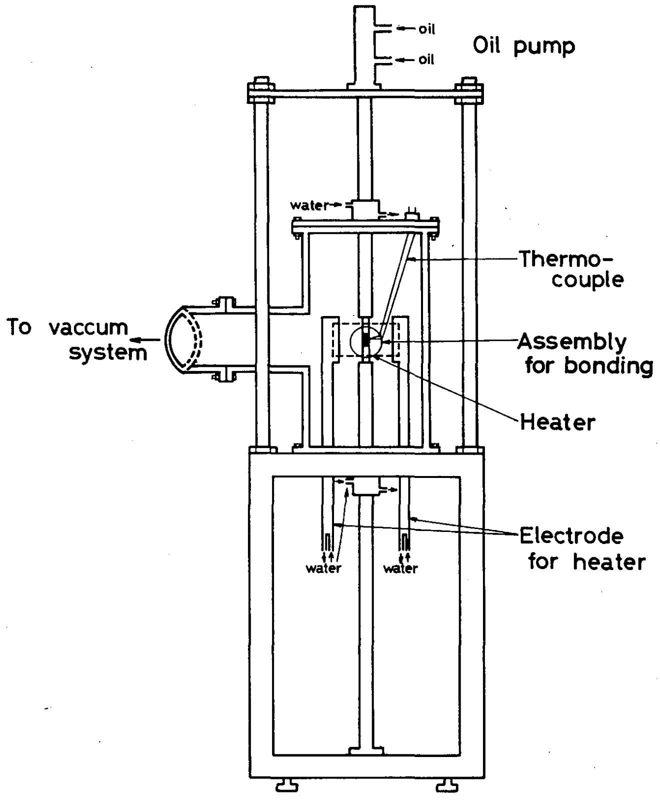
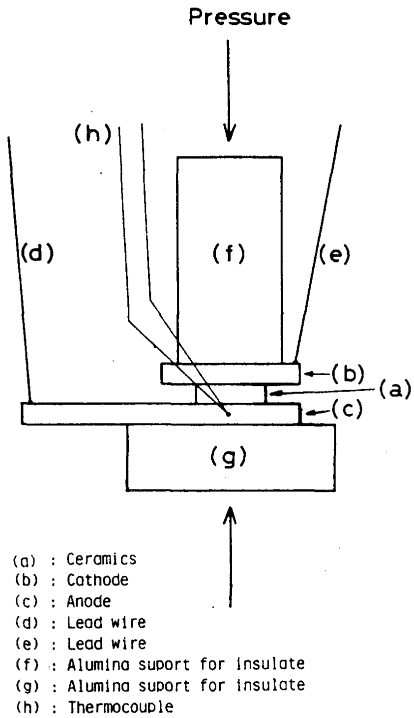


(a)



(b)

Fig. 1 Schematic diagram of apparatus and assembly for bonding

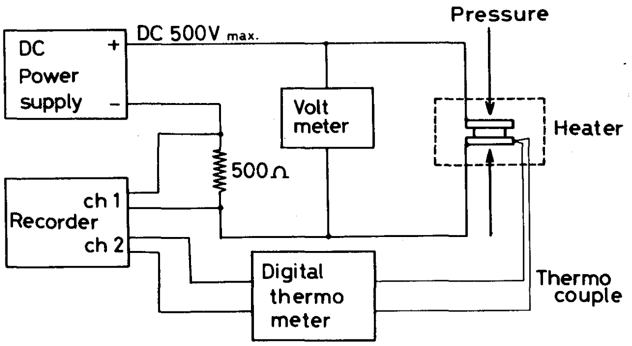


Fig. 2 Test circuit for bonding

min under a external pressure, a DC voltage was applied with a circuit as shown in **Fig. 2**. After bonding, the assembly was cooled with the rate of 10°C/min. The cross sections of the bonding specimens were inspected by EDX analysis.

3. Results and Discussion

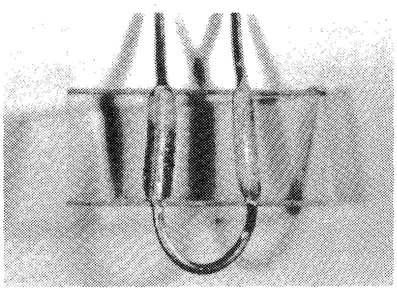
3.1 Preliminary investigation for bonding of glass to aluminum

Figure 3 shows the appearances of bonded specimens of commercial plate glass to aluminum wire (a) aluminum foil (b) and aluminum plate (c)(d). As shown in (a), (b) and (c) in Fig. 3, bonding was achieved at the glass-anode metal interface under the external pressure of 7 kg/cm^2 at 400°C for 10 min with a voltage of 200 V, but as shown in (d) bonding at 300°C didn't occur. For such bonding of glass to aluminum wire and aluminum foil, sound joints were obtained, but for aluminum plate a crack was seen in the glass. It may be caused by the difference of the expansion coefficient between the glass ($\approx 8 \times 10^{-6}$) and the aluminum ($\approx 3 \times 10^{-5}$). During the cooling, the residual stress rised in glass and it caused the crack, when aluminum plate was thick and the residual stress was too large. However, cracks were not observed after bonding when a wire or a foil was used and the bonding was not achieved for a plate (Fig. 3 (d)).

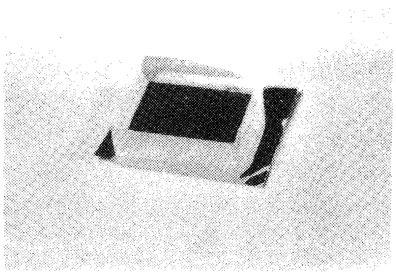
Bonding strength was measured for the sound joint of commercial glass to aluminum wire as above mentioned, and the joint was fractured on the aluminum wire part at the load of 3 kg. Therefore, the bonding were evaluated by the occurrence of the crack in the glass, because the joint was sound when the crack occurred in the glass.

3.2 Effect of external pressure on bonding

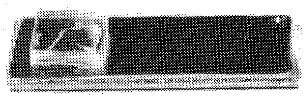
In field-assisted bonding a dielectric polarization occurred at the glass-metal interface[2),3)]. The authors



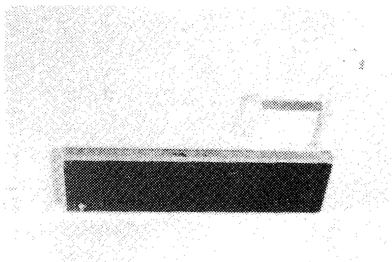
(a) Glass/Al wire



(b) Glass/Al foil



(c) Glass/Al plate (bonded)



(d) Glass/Al plate (Non-bonded)

Fig. 3 Appearances of joints made by pressure and field-assisted bonding

adopted the external pressure during the bonding, and some experiments of field-assisted bonding were done under a variety of external pressures. The authors named this new bonding method, which done under both external pressure and electric field, pressure and field-assisted bonding (PFA bonding). Results are shown in **Table 2**. As shown in the table the external pressures are 0.3 kg/cm^2 and 7 kg/cm^2 respectively for experiments in No. 1 and No. 3 and other conditions are same. In the case of the external pressure of 7.0 kg/cm^2 (No. 3) the bonding was possible, but under the external pressure of 0.3 kg/cm^2 (No.1) the bonding was not achieved. Under the external pressure of 0.3 kg/cm^2 the bonding was achieved at the higher temperature of 550°C (No. 2) Under the external pressure of 7 kg/cm^2, the bonding was achieved at a lower temperature of 400°C with voltage of 100 V (No. 4). These results indicate that under the external pressure the bonding could be obtained under milder conditions such as lower temperature, lower applied voltage in contrast with field-assisted bonding without external pressure.

3.3 Influences of applied voltage and bonding time

Figure 4 shows the effect of the bonding temperature

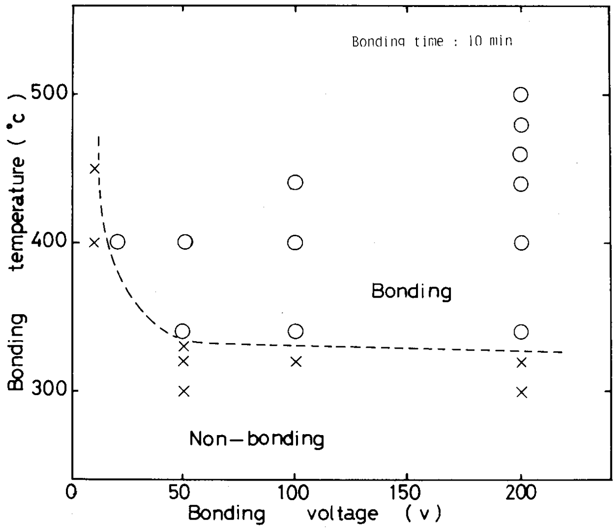


Fig. 4 Effect of applied voltage on bonding of commercial plate glass and aluminum plate

Table 2 Effect of external pressure on bonding of commercial plate glass and aluminum plate

No.	Bonding conditions: Pressure (kg/cm^2)	Temp. (°C)	Voltage (V)	Time (min.)	Current (μA)	Amount of electricity (mC)	Bonding observed
1	0.3	500	200	10	13- 34	16	No
2	0.3	550	200	10	80-500	84	Yes
3	7.0	500	200	10	33-200	35	Yes
4	7.0	400	100	10	2- 10	5	Yes

and the applied voltage on bonding of commercial plate glass to aluminum plate, using 7 kg/cm^2 external pressure and the bonding time of 10 min. The relation between the bonding temperature and the bonding time for bonding of commercial plate glass to aluminum plate under 7.0 kg/cm^2 external pressure with applied voltage of 200 V is shown in **Fig. 5**. From both figures, it was shown

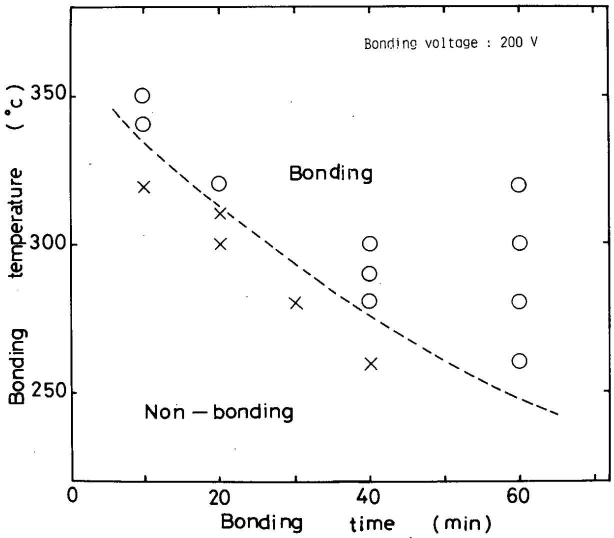


Fig. 5 Effect of bonding time on bonding of commercial plate glass and aluminum plate

that as the applied voltage or the bonding time increased the temperature at which the bonding is possible, decreased. Both figures show that the bonding under the higher pressure is achieved at lower temperature under lower applied voltage where the bonding is impossible under the lower pressure of 0.3 kg/cm^2. These facts indicate that in PFA bonding of 7 kg/cm^2 pressure, the external pressure plays a important role controlling the bonding of glass and aluminum.

3.4 Effect of amount of electricity on bonding

It is important in field-assisted bonding that the positive ion (Na^+) in the glass moves towards the cathode and the region adjacent to the anode becomes deplated of Na^+[2]. In PFA bonding, also the formation of the region is important, and the amount of electricity given during bonding may influence greatly the bonding. The effect of the amount of electricity on the bonding of glass to aluminum is shown in **Fig. 6**, which is given from the data in Fig. 4.

From this figure, the bonding for 10 min is possible when the current flow becomes above a certain value even if the applied voltage changes to 200 V. This fact may indicate that the bonding occurs, when the width of the Na^+ ion deplated region becomes a certain value after a constant amount of electricity was given.

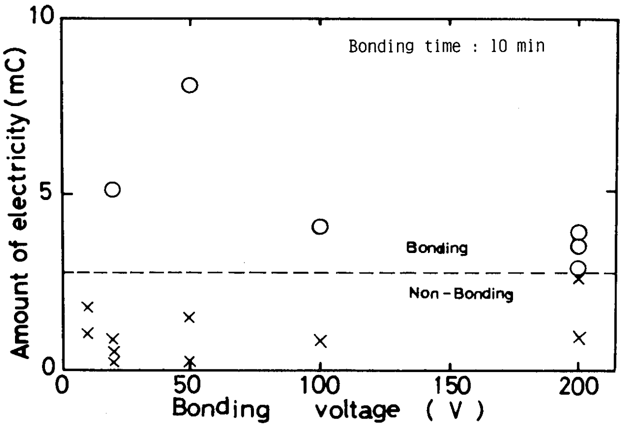


Fig. 6 Effect of amount of electricity on bonding of commercial plate glass and aluminum plate

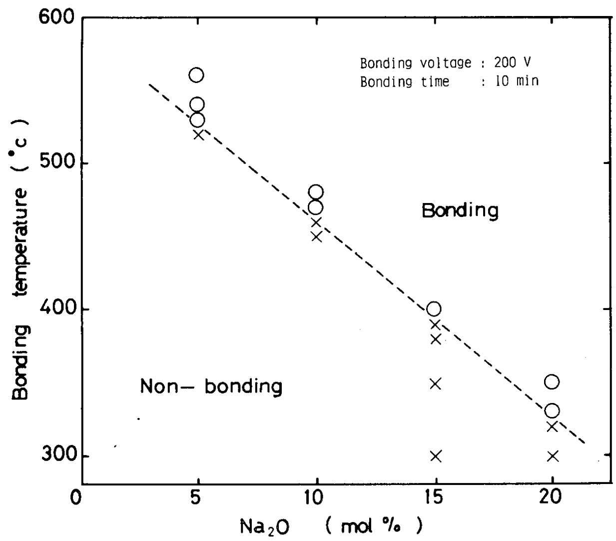


Fig. 7 Effect of Na_2O concentration in glass on bonding

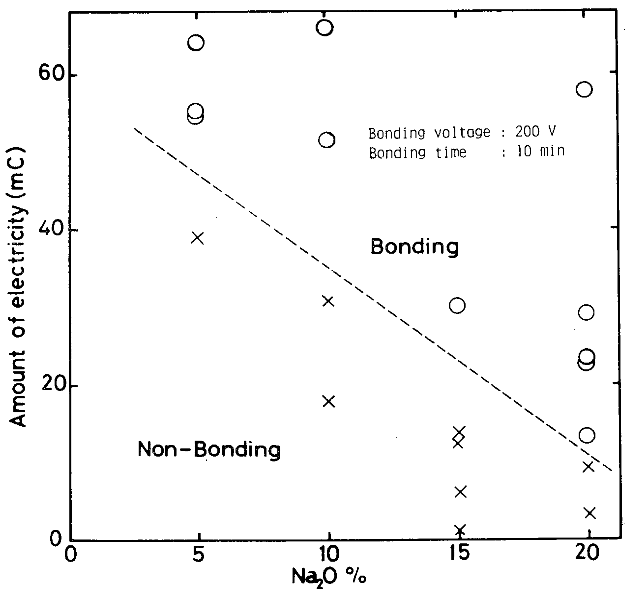


Fig. 8 Effect of amount of electricity on bonding of various glasses to aluminum plate

Next, the effect of the amount of Na_2O in glass on the PFA bonding was examined with the voltage of 200 V for 10 min. The results are shown in **Fig. 7**. From this figure, the temperature at which bonding is possible, decreases, as the amount of Na_2O in glass increases. This means that the amount of electricity decreases with the increase of Na_2O amount as shown in **Fig. 8**. It shows that the Na^+ ion deplated region, which is necessary for bonding, forms easily with lower current flow, when the amount of Na_2O in glass is much.

3.5 Electron microprobe studies of bonding part

In order to know the composition profiles of the bonding interface at the anode, EDX analysis was done for the cross section of the bond joints. The results are shown in **Fig. 9** for bonding of glass to aluminum plate and silver plate. The bonding conditions are shown in **Table 3**. Despite the bonding of shorter time with the voltage of 200V for Ag, the amount of electricity is about 1000 times as much as for Al. For both metals, and metal ions penetrated into the Na^+ deplated zone. However, the deplated region was wider for Ag than for Al. From these results, the PFA bonding is formed due to mutual diffusion of Na^+ and metal ion. The easiness of the mutual diffusion may depend on the nature of metal or metal ion.

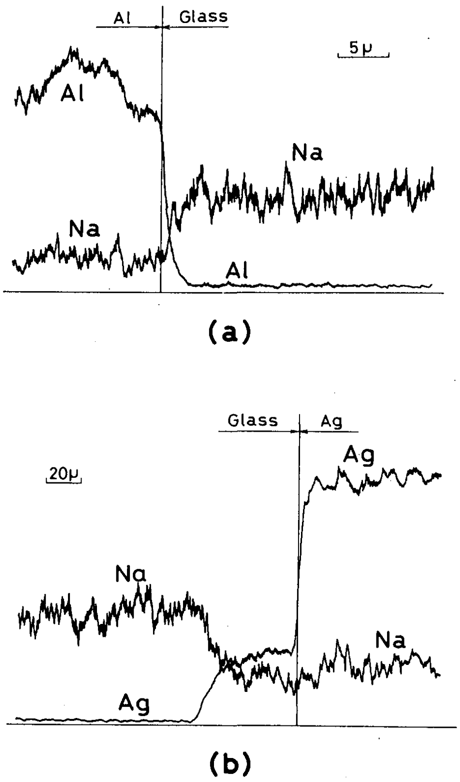


Fig. 9 Results of EDX line analysis at glass-anode metal interface after bonding of commercial plate glass to (a) aluminum plate and (b) silver plate

3.6 Mechanism of pressure and field-assisted bonding.

Under an applied electric field in conventional field-assisted bonding, a dielectric polarization occurs at the glass-metal interface, where the electrostatic force arises. The attractive force (P)[3] can be given by

$$P = \frac{1}{2}\epsilon\epsilon_0 E^2 \qquad (1)$$

where ϵ is the relative dielectric constant of glass, ϵ_0 is the dielectric constant in vacuum and E is the electric field applied at glass-metal interface. E is given by $E = V/\delta$, where V is the voltage across the dielectric region and δ is the width of the dielectric region. For a given applied voltage V:

$$P = \frac{1}{2}\,\frac{\epsilon\epsilon_0 V^2}{\delta} \qquad (2)$$

The relation between P and V is given in **Fig. 10** from eq-(2), where ϵ and ϵ_0 were estimated 10 and 8.85×10^{-2} ($F{\cdot}m^{-1}$), respectively. The dotted line in this figure shows the value of external pressure of 7 Kg/cm^2 used in this experiment. In PFA bonding, the external pressure was added to the bonding interface besides the electrostatic force arising under an applied field.

During field assisted bonding, the current changes usually with time as follows; the current has a maximum value at a certain time and decays slowly with the lapse of time.

Under such higher pressure, the maximum current was given with a high value at shorter time by achieving the intimate contact at the interface. However, the current flow is not easy and higher temperature and voltage are

Table 3 Bonding conditions and results of bonding joints used for EDX shown in Fig. 9

Anode metals	Bonding conditions				Current	Amount of electricity	Bonding observed
	Pressure (kg/cm^2)	Temp. (°C)	Voltage (V)	Time (min.)	(μA)	(mC)	
Ag	7.0	500	200	7	1850-18550	3480	Yes
Al	7.0	400	200	40	3- 27	10	Yes

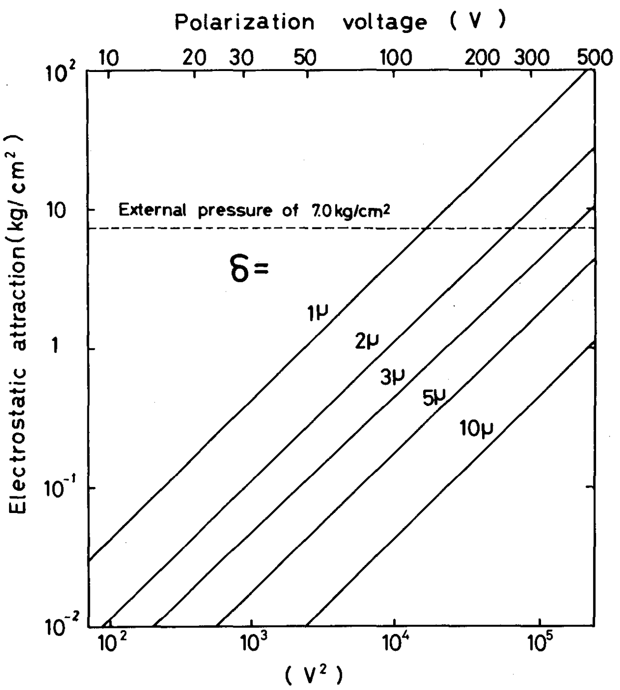


Fig. 10 Relation between applied voltage and electrostatic attraction caused by electrical polarization

necessary to achieve the intimate contact as the width of gap between metal and glass is big without a external pressure.

Moreover, when the Na^+ ion deplated zone was formed after intimate contact, the attraction force decreased with the increase of the zone as shown in **Fig. 10**. As above mentioned, in PFA bonding, the external pressure is applied continually despite the increase of Na^+ ion deplated region, so the diffusion of metal ion to the region becomes easy and the bond forms easily even at lower temperature with a lower voltage. For experiment with silver anode, the current increases within the period of bonding by contrast with aluminum anode. This fact shows that Al^+ ion has a lower mobility in Na^+ ion deplated zone than Ag^+ ion, which moves similarly as Na^+ ion. Therefore, the Na^+ ion deplated zone was filled with Ag^+ ion.

4. Conclusion

By pressure and field-assisted process the bonding of aluminum to glass was achieved at lower temperature with lower applied voltage. The effects of the external pressure were shown as follows;

(1) making intimate contact at the metal-glass interface in addition to the electrostatic attraction caused by applying a DC voltage.

(2) enabling the metal ions to penetrate easily into the glass.

In addition, it was seen the total amount of electricity during the bonding related strongly to the bonding. When a certain amount of electricity was obtained with a voltage the bonding was achieved.

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