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Experimental Analysis on the Anodic Bonding with Evaporated Glass Layer

Woo-Beom Choi [0], Byeong-Kwon Ju, Yun-Hi Lee, Seong-Jae Jeong*, Nam-Yang Lee*, Ken-Ha Koh*, M.R.Haskard**, Man-Young Sung***, Myung-Hwan Oh

Division of Electronics and Information Technology, Korea Institute of Science and Technology, 130-650, P.O.Box 131, Cheongryang, Seoul, Korea
* Information Display Research Institute, Orion Electric Co.,
** Microelectronics Centre, Univ. of South Australia, S.A., 5098, Australia
***Department of Electrical Engineering, Korea Univ., Sungbuk-Ku, Seoul, Korea

Abstract

We have performed silicon-to-silicon anodic bonding using glass layer deposited by electron beam evaporation. Wafers can be bonded at 135 ℃ with an applied voltage of $35V_{DC}$, which enables application of this technique to the vacuum packaging of microelectronic devices, because its bonding temperature and voltage are low. From the experimental results, we have found that the evaporated glass layer more than 1 μ m thick was suitable for anodic bonding. The role of sodium ions for anodic bonding was also investigated by theoretical bonding mechanism and experimental inspection.

I. Introduction

Silicon-to-silicon anodic bonding has become one of the important technologies in the fabrication of micromachining. There are many bonding techniques which have been used for bonding a transducer to a substrate or for the final seal in hermetic packages such as silicon fusion bonding [1], eutectic bonding [2], electrostatic bonding [3,4] etc.. Especially, anodic bonding is a very promising technique because it does not suffer from high temperature or hydrophilic cleaning. Mostly, sputtered Pyrex glass has been used for this method since 1972 [5]. But anodic bonding by sputtered glass layer has the disadvantage of very low deposition rate. Pyrex glass layer can be evaporated with high deposition rate and small surface roughness.

II. Experimental

The glass layer was deposited on n-type silicon wafers by electron beam evaporation at substrate temperature of 200℃. Corning #7740 glass was used as a source material of electron beam evaporation. From Auger electron spectroscopy(AES) analysis, the compositions of evaporated glass film were compared with the bulk glass. Table 1 shows that the evaporated glass film is nearly same as the composition of bulk Pyrex #7740 glass. Whereas, the sputter-coated Pyrex #7740 glass is commonly silicon rich. The deposition rates were up to 50Å/sec. The surface roughness of evaporated glass layers was within 100Å peak to peak. Evaporated glass layers with thickness ranging from 0.4μm to 2.5μm were used for this study. 10×10×0.5 mm n-type silicon chips and 15×15×0.5 mm silicon chips with evaporated glass layer were used. The assemblies were placed on the specially designed field-assisted bonding equipment(Fig. 1). Anodic bonding was performed at temperature of 135-160℃ with an electrostatic voltage of $35\text{-}55V_{DC}$. A negative voltage was applied to the silicon wafer with evaporated glass layer for 10 min., and the bonding current was recorded by SMU(HP237 source and measurement unit).

Element / Material	Si(%)	O(%)	B(%)
Evaporating source	23.70	68.56	7.74
Evaporated glass film	25.90	69.69	4.41

Table 1. Comparison of the composition of evaporated glass with bulk glass.

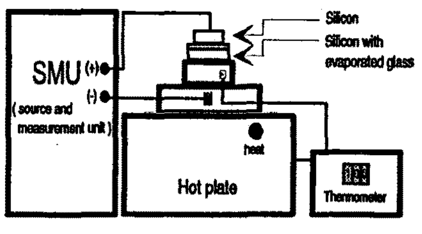


Fig. 1. Schematic experimental set-up for anodic bonding

III. Mechanism of anodic bonding

A. *Theoretical approach*

Pyrex glass has been mostly used in the anodic bonding, because it has metallic atoms such as sodium or lithium. Especially, Corning #7740 Pyrex glass which has sodium is the popular material in the anodic bonding, since then anodic bonding was invented by G.Wallis and D.I.Pomerantz in 1969[3]. Sodium plays very important role in the field assisted silicon-to-silicon bonding using glass thin film interlayer or in the silicon-to-Pyrex glass bonding. The sodium can be easily ionized at room temperature. The positive sodium ions in glass layer have high mobility at certain elevated temperature. When d.c.voltage is applied at the gap between the silicon and the glass layer, the positive sodium ions in glass layer are transported toward the cathode by the applied negative voltage. The sodium depletion layer is formed in the surface of glass layer, leaving the fixed negative ions(oxygen ions) in the glass layer adjacent to the bare silicon to be bonded. As a result, the space charge region is formed in the interface between the surface of glass layer and the surface of bare silicon to be bonded. The resulting large electrostatic force pulls them into contact. The charge, electric field and potential distribution across the silicon-glass layer-silicon are shown in Fig. 2.

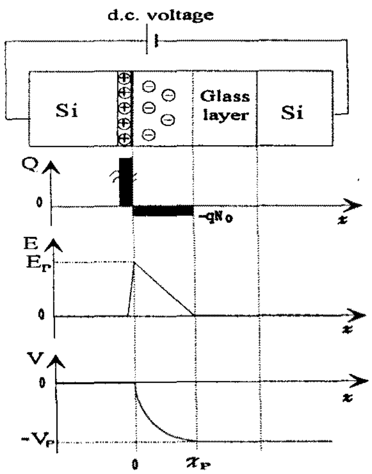


Fig. 2. Electric field and potential distribution for the silicon-to-silicon anodic bonding using evaporated glass layer.

Based on the given explanation, in order to obtain the profile of potential distribution, the Poisson's equation must be solved. The Poisson's equation in the glass layer is given by :

$$\frac{d^2V}{dx^2} = -\frac{dE}{dx} = -\frac{Q(x)}{\varepsilon_g} = \frac{qN_o}{\varepsilon_g} \quad (1)$$

where Q(x) is the charge in the depletion region due to the presence of fixed negative ions, ε_g is the dielectric constant of evaporated glass, q is the electron charge, N_o is the fixed negative ion concentration in the glass layer. An integration of Eq. (1) with the boundary condition that the electric field must go to zero at the edge(x_p) of depletion region, provides a solution for the electric field distribution :

$$E(x) = \frac{qN_o}{\varepsilon_g}(x_p - x) \quad (2)$$

An integration of the electric field through the depletion region with boundary condition that the potential is zero in the bare silicon region provides the potential distribution :

$$V(x) = \frac{qN_o}{\varepsilon_g}(x_p x - \frac{x^2}{2}) \quad (3)$$

The potential is peak at $x = x_p$ by using the boundary condition :

$$V_p = \frac{qN_o x_p^2}{2\varepsilon_g} \quad (4)$$

The thickness of the depletion region in glass layer, x_p is given from Eq. (4) :

$$x_p = \sqrt{\frac{2\varepsilon_g}{qN_o}V_p} \quad (5)$$

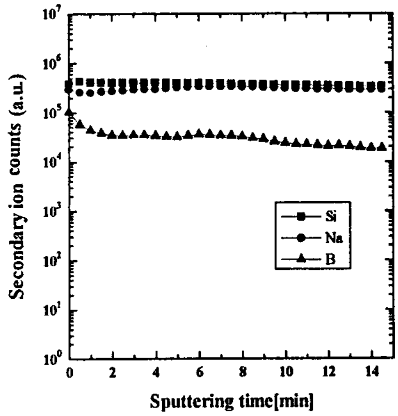
The electrostatic force P between the glass layer and the bare silicon is given by [6]:

$$P = \frac{1}{2}\varepsilon_0 E^2 = \frac{1}{2}\varepsilon_o\left(\frac{qN_o x_p}{\varepsilon_o}\right)^2 = \varepsilon_g' qN_o V_p \quad (6)$$

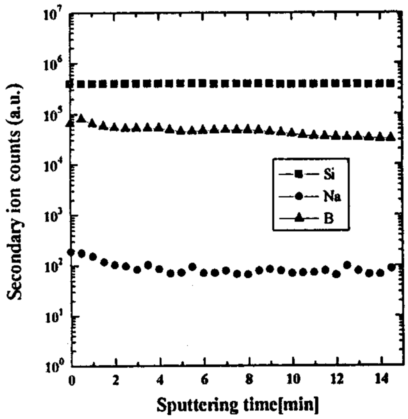
where ε_g' is the relative permittivity of glass layer ($\varepsilon_g = \varepsilon_g'\varepsilon_o$)

B. *Experimental approach*

In order to investigate the role of sodium ions for anodic bonding, we performed secondary ion mass spectroscopy(SIMS) analysis of the evaporated glass layer. Fig. 3 obtained by SIMS shows that the sodium ion counts in the surface of deposited glass layer were reduced after bonding. Sodium ions were almost depleted from the surface region of glass layer in the contact with the bare silicon to be bonded, which was agreed very well with the model suggested in the theoretical approach. The sputtering velocity of SIMS was about 100Å/min.



(a) Before bonding



(b) After bonding

Fig. 3. Depth profile of the sodium ions in the surface of evaporated glass layer before and after bonding.

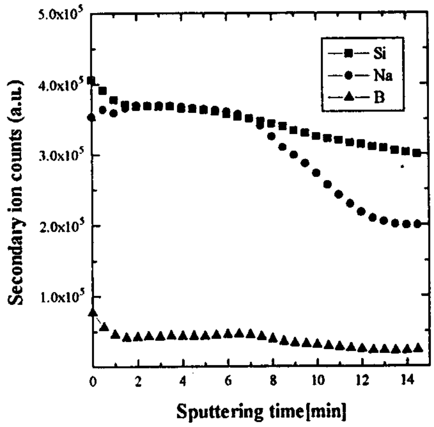


Fig. 4. Depth profile of the sodium ions in the back side of evaporated glass layer after bonding

Sodium ions which was depleted from the surface region of glass layer are accumulated at the back side region of glass layer and neutralized there. The bonded samples were broken in order to observe the accumulation of sodium ions at the back side of glass layer. The evaporated glass was almost all apart from the glass deposited silicon and bonded on the bare silicon to be bonded. Then, sodium ion concentrated at the back side of glass layer was detected by SIMS analysis. Fig. 4 shows that sodium ions are accumulated at the back side and decrease abruptly from the back side to the bulk region of glass layer.

Ⅳ. Results and Discussion

A. *Electrical characteristics*

Current-time characteristics showed the rapid decay of bonding current during the start period as shown in Fig. 5. The bonding current was measured at temperature in the range of 135-145℃ with an electrostatic voltage of $55V_{DC}$. The dependence of bonding current on the temperature is shown in Fig. 5. At an elevated temperature, the bonding current is caused by the transport of sodium ions in evaporated glass layer. The increase of bonding temperature results in higher diffusion rate of the sodium ions which in turn causes higher bonding current.

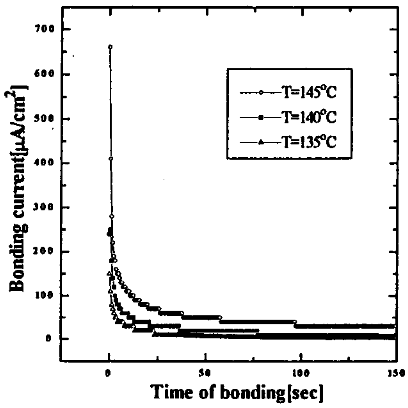


Fig. 5. Dependence of the bonding current on temperature during the initial bonding stage.

B. *Microphotograph observation of the bonded specimens*

The bonded samples were cut and polished to see the bonded interface region of silicon to silicon assembly(Fig. 6). The bonded samples were broken in order to observe the some change of evaporated glass layer after bonding. The strongly bonded samples showed that the evaporated glass was almost all apart from the glass deposited silicon and bonded on the bare silicon to be bonded. The obtained result indicates that the bonding strength is more higher than the adhesion of deposited glass. On the other hand, the evaporated glass was partially apart from the weakly bonded specimens(Fig. 7).

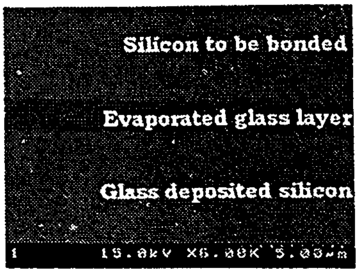
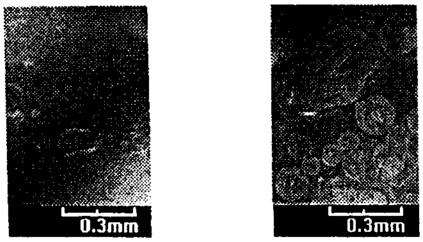


Fig. 6. SEM photograph of the bonded interface region after polishing



(a) Entirely bonded specimen

(b) Partially bonded specimen

Fig. 7. Optical microscopic photographs of the bare silicon surface with the glass apart from the glass deposited silicon.

V. Summary

The method using evaporated Pyrex glass has the advantages of high deposition rate and small surface roughness. AES analysis showed that the composition of evaporated glass layer was nearly same as the bulk #7740 glass. Silicon-to-silicon anodic bonding was possible at 135℃ with an applied voltage of $35V_{DC}$. The obtained result can be applied for the vacuum packaging of microelectronic devices and microsensors.

Acknowledgments

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