Anodic bonding technique under low temperature and low voltage using evaporated glass

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A silicon-to-silicon anodic bonding process using a glass layer deposited by electron beam evaporation will be described. Wafers are bonded at a temperature as low as 135 °C with an applied voltage as small as 35 V_{dc}, enabling this technique to be applied to vacuum packaging of microelectronic devices. Experimental results reveal that an evaporated glass layer of more than 1 μm thick is suitable for anodic bonding. Finally, the role of sodium ions in anodic bonding was also studied by investigating the theoretical bonding mechanism and examining the results of secondary ion mass spectroscopy analysis. © *1997 American Vacuum Society.* [S0734-211X(97)04502-2]

I. INTRODUCTION

Silicon-to-silicon anodic bonding has become one of the important technologies in the fabrication of micromachining devices. Many bonding techniques have been used for bonding a transducer to a substrate or for achieving the final seal in hermetic packages, and examples include silicon fusion bonding,[1–3] eutectic bonding,[4–6] and electrostatic bonding.[7–9] Anodic bonding is a particularly promising technique for it does not require either a postheat treatment at high temperature or hydrophilic cleaning.[10,11] Since 1972,[12] the sputtered Pyrex glass has been commonly used for this method, but unfortunately the sputtering of the glass layer has the disadvantage of a very low deposition rate and different composition compared with the glass target.[13] The Pyrex glass can, however, be deposited by electron beam evaporation, having a high deposition rate and resulting in minimal surface roughness and nearly same composition compared with the glass source. Anodic bonding process in the environment of high temperature and high voltage can bring the degradation of device lifetime, so anodic bonding has been investigated to accomplish the bonding process at temperature and voltage as low as possible.

II. EXPERIMENT

The glass layer was deposited on (100) *n*-type silicon wafers by electron beam evaporation. The glass layer was deposited at substrate temperature of 200 °C under 2×10^{-5} Torr. Corning No. 7740 glass was used as the source material of electron beam evaporation. Using Auger electron spectroscopy (AES) analysis, the composition of the deposited glass layer was compared with the bulk glass. Table I shows that the deposited glass film is nearly the same as the composition of bulk Pyrex No. 7740 glass, whereas a sputter coated Pyrex No. 7740 glass layer is normally silicon rich. The deposition rates of evaporation were up to 50 Å/s. The surface roughness of the deposited glass layer is one of the most important parameters in anodic bonding. If the surface roughness is substantial, it may reduce the bonding strength or even cause the failure of bonding. Figure 1 shows atomic force microscope (AFM) images of the surface roughness of the silicon and the deposited glass layer. The surface roughness of the deposited glass layer was less than 150 Å peak to valley. The deposited glass layers with thicknesses ranging from 0.4 to 2.5 μm were used for this study. We used 4 in. (001) silicon wafers. The assemblies were placed on specially designed field-assisted bonding equipment (Fig. 2). Anodic bonding was performed at temperatures in the range of 135–160 °C with an electrostatic voltage in the range of 35–55 V_{dc}. A negative voltage was applied to the silicon wafer having the deposited glass layer for 10 min, and the bonding current was recorded by SMU (Kiethly 237 high voltage source and measure unit).

III. MECHANISM OF ANODIC BONDING

A. Theoretical approach

Pyrex glass has been mainly used in the anodic bonding process, because it contains metallic atoms such as sodium or lithium. Corning No. 7740 Pyrex glass contains sodium and is the most popular material used in anodic bonding, since the process was invented by Wallis and Pomerantz in 1969.[8] Sodium plays a very important role in the field assisted silicon-to-silicon bonding using a glass thin film inter-

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TABLE I. Comparison of the composition of deposited glass thin film with bulk glass plate.

Material	Element		
	Si (%)	O (%)	B (%)
Evaporating source	23.70	68.56	7.74
Deposited glass layer	25.90	69.69	4.41

FIG. 2. Schematic of experimental setup for anodic bonding.

layer or in silicon-to-Pyrex glass plate bonding. The sodium can be easily ionized at room temperature and the positive sodium ions in the glass layer have high mobility at elevated temperature. When a dc voltage is applied across the silicon-glass-silicon sandwich (Fig. 3), the positive sodium ions in the glass layer are transported toward the cathode silicon by the applied negative voltage. A sodium depleted layer is formed at the surface region of the glass layer, leaving fixed negative ions (oxygen ions) in the glass layer adjacent to the bare silicon to be bonded. As a result, a space charge region is formed at the interface between the surface of the glass layer and the surface of bare silicon to be bonded. The resulting large electrostatic force pulls them together. The charge, electric field, and potential distribution across the silicon-glass-silicon are shown in Fig. 3.

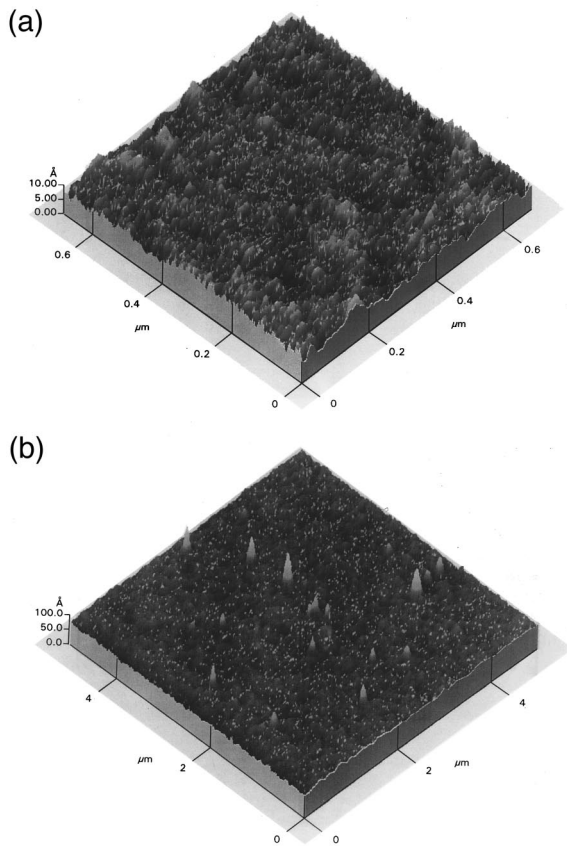In order to obtain the profile of potential distribution, Poisson's equation must be solved. The equation for the glass layer is

$$\frac{d^2V}{dx^2} = -\frac{dE}{dx} = -\frac{Q(x)}{\epsilon_g} = \frac{qN_0}{\epsilon_g}, \tag{1}$$

where $Q(x)$ is the charge in the depletion region due to the presence of the fixed negative ions, ϵ_g is the dielectric constant of the deposited glass layer, q is the electron charge, and N_0 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 the

(a)

(b)

FIG. 1. AFM images of the surface roughness. (a) Silicon and (b) the deposited glass layer.
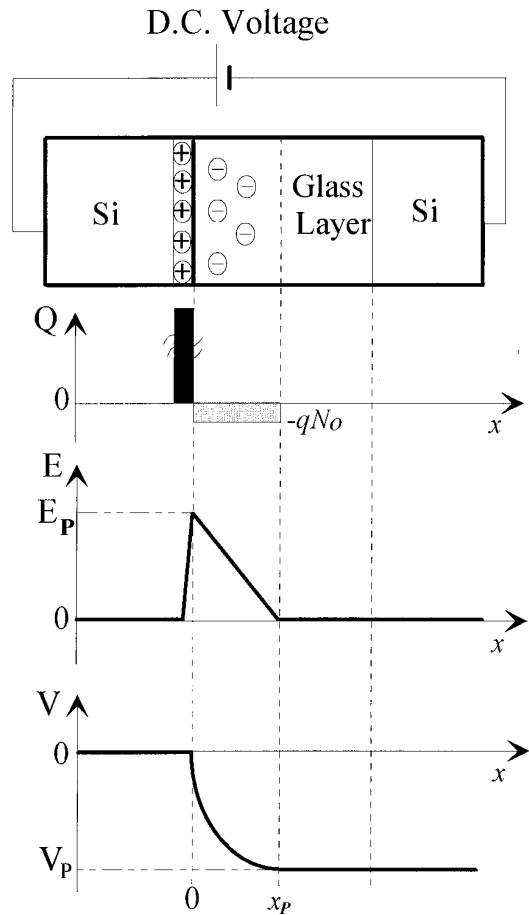

FIG. 3. Electric field and potential distribution for the silicon-to-silicon anodic bonding using evaporated glass layer.

space charge region, provides a solution for the electric field distribution:

$$E(x) = \frac{qN_0}{\epsilon_g}(x_p - x).$$

(2)

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

$$V(x) = \frac{qN_0}{\epsilon_g}\left(x_p x - \frac{x^2}{2}\right).$$

(3)

Using the boundary condition, the potential is peak at $x = x_p$ by

$$V_p = \frac{qN_0 x_p^2}{2\epsilon_g}.$$

(4)

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

$$x_p = \sqrt{\frac{2\epsilon_g}{qN_0}V_p}.$$

(5)

The electrostatic force P between the glass layer and the bare silicon is given by[14]

$$P = \frac{1}{2}\epsilon_0 E^2 = \frac{1}{2}\epsilon_0\left(\frac{qN_0 x_p}{\epsilon_0}\right)^2 = \epsilon_g' qN_0 V_p,$$

(6)

where ϵ_g' is the relative permittivity of the glass layer ($\epsilon_g = \epsilon_g'\epsilon_0$).

B. Experimental approach

In order to investigate the role of sodium ions in anodic bonding, ion mass spectroscopy (SIMS) analysis of the deposited glass layer was carried out. Figure 4, obtained by SIMS, shows that the sodium ion count at the surface region of the deposited glass layer was reduced after bonding. The sodium ions were almost depleted from the surface region of the glass layer in contact with the bare silicon to be bonded. This agrees with the suggested theoretical model. The sputtering velocity of the SIMS was about 100 Å/min. The sodium ions that are depleted from the surface region of the glass layer accumulate at the back side region of the deposited glass layer and are neutralized there. The bonded samples were pulled in order to measure the bond strength. When the pull tests were performed, it was observed that the deposited glass layers were partly or totally removed from the silicon, on which they were originally deposited, and found on the surface of the silicon to be bonded. So using the SIMS analysis on the deposited glass layer totally removed, it was possible to determine that the sodium ions accumulate at the back side region of the deposited glass layer. Figure 5 shows that the sodium ions are accumulated at the back side and decrease abruptly from the back side to the bulk region of the deposited glass layer.
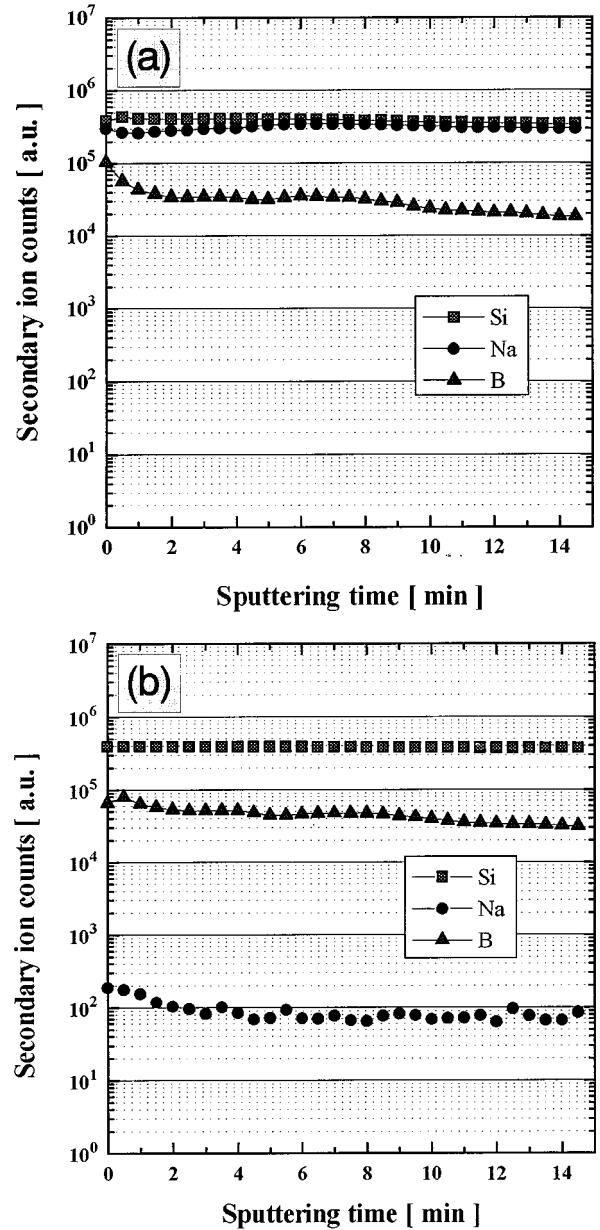

FIG. 4. Depth profile of the sodium ions in the surface of the deposited glass layer before and after bonding. (a) Before bonding and (b) after bonding.

IV. RESULTS AND DISCUSSION

A. Electrical characteristics

Current-time characteristics show the rapid decay of bonding current during the start period as seen in Fig. 6. The bonding current was measured as a temperature in the range of 135–145 °C with an applied electrostatic voltage of 55 V_{dc}. The dependence of the bonding current on temperature is shown in Fig. 6. The bonding current is due to the transport of sodium ions in the deposited glass layer; an increase in bonding temperature results in a higher diffusion rate of the sodium ions which in turn causes a higher bonding current.
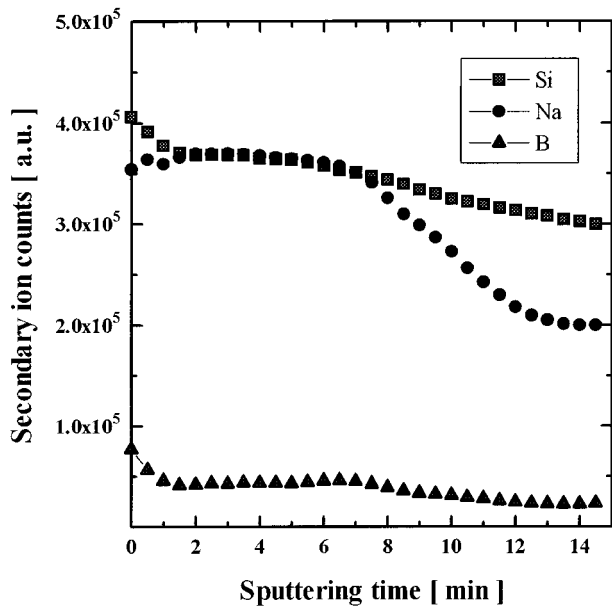
FIG. 5. Depth profile of the sodium ions in the back side of the deposited glass layer after bonding.

B. Microphotograph observation of the bonded specimens

The bonded samples were cut and polished to see the bonded interface region of the silicon-to-silicon assembly (Fig. 7). In this figure, the white powder is alumina used in the polishing. The cavity of 15 mm×15 mm×8 μm was formed on the silicon substrate by etching the silicon substrate in ethylenediamine-pyrocatechol-water (EPW). Using anodic bonding, the cavity was sealed by the silicon with the
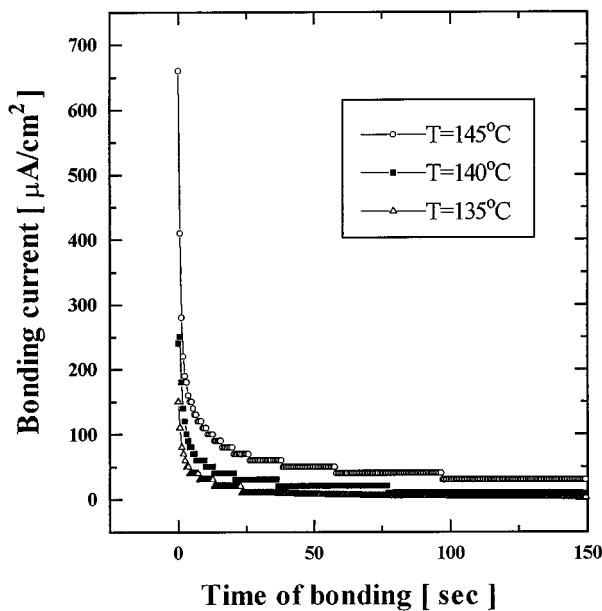

FIG. 6. Dependence of the bonding current on temperature during the initial bonding stage.
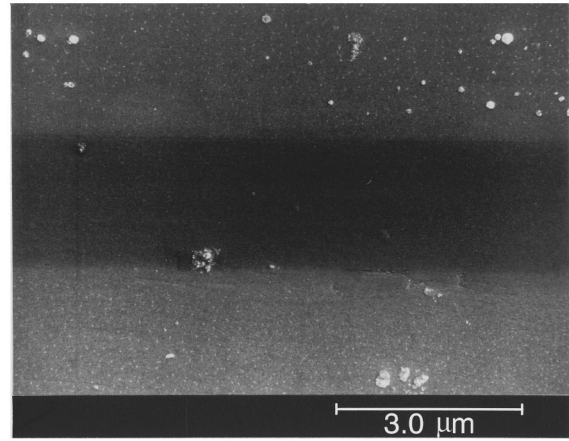

FIG. 7. SEM photograph of the bonded interface region after polishing.

deposited glass layer (Fig. 8). As previously mentioned, when the pull tests were performed, it was observed that the deposited glass layers were partly or totally removed from the silicon on which they were originally deposited, and found on the surface of the silicon to be bonded. The strongly bonded samples showed that the deposited glass layers totally were removed from the glass deposited silicon and bonded on the bare silicon to be bonded. The obtained result indicates that the bond strength is stronger than the adhesion of the deposited glass layer. On the other hand, the deposited glass layers were partly removed from the weakly bonded specimens (Fig. 9). The dark area is the glass layer removed from the silicon on which the glass layer was originally deposited and the bright area is the surface of the silicon to be bonded. The bonded wafer sets were inspected by infrared camera (Hammatsu voide inspector). Figure 10 shows the interference fringe for transmission of (IR) light through the bonded specimen. The dark areas are the uncontacted region.

V. SUMMARY

The silicon-to-silicon anodic bonding that uses a glass layer deposited by electron beam evaporation has the advan-
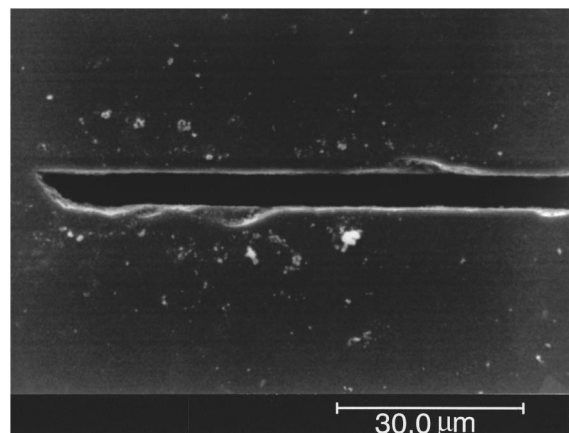

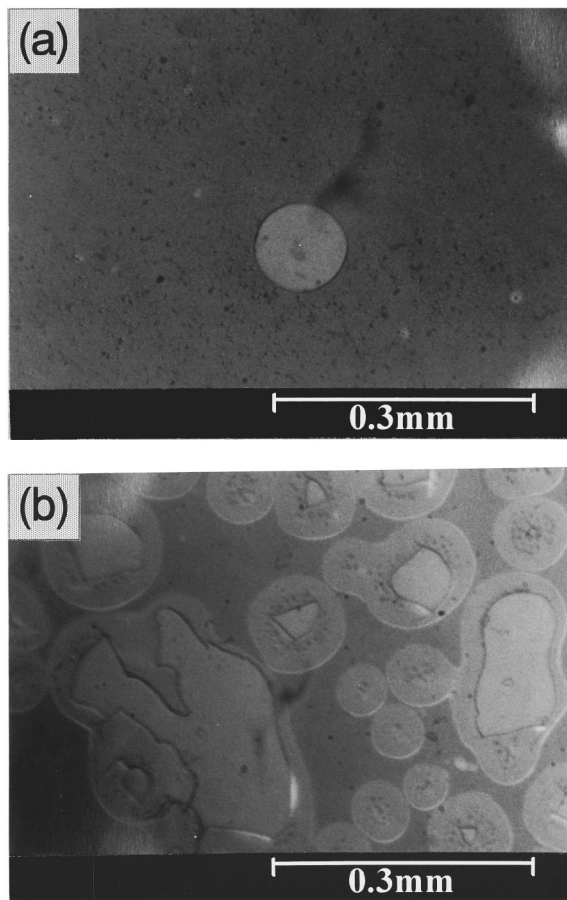FIG. 8. SEM photograph of the cavity sealed by anodic bonding.

FIG. 9. Optical microscopic photographs of the bare silicon surface with the deposited glass layer partly or totally removed from the silicon on which the glass layer was originally deposited. (a) Entirely bonded specimen and (b) partially bonded specimen.

tage of a high deposition rate. The surface roughness of the deposited glass layer determined by AFM was less than 150 Å peak to valley. AES analysis showed that the composition of the deposited glass layer was nearly same as that of the bulk No. 7740 glass. The silicon-to-silicon anodic bonding
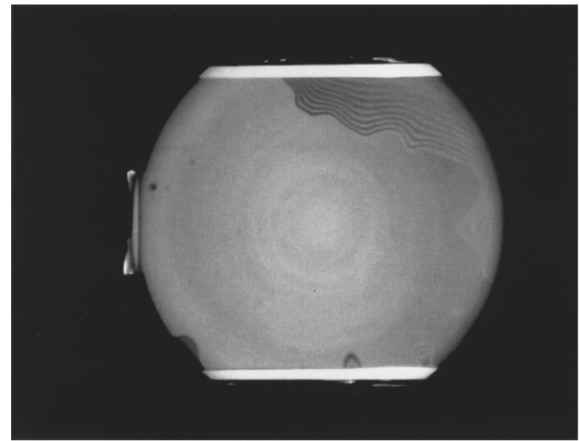

FIG. 10. Infrared photograph of the silicon-to-silicon bonded specimen.

was possible at a temperature of 135 °C with an applied voltage of 35 V_{dc}. The results obtained show that the process can be applied to vacuum packaging of microelectronic devices and microsensors.

ACKNOWLEDGMENT

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