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THE SILICON-TO-SILICON ANODIC BONDING USING SPUTTER DEPOSITED INTERMEDIATE GLASS LAYER

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Glass-to-silicon anodic bonding is an attractive process for packaging of microelectronics devices and Micro-electro-mechanical Systems (MEMS). Silicon to silicon anodic bonding can also be accomplished by incorporating an intermediate glass layer. In the present work, silicon-to-silicon anodic bonding has been studied with an intermediate borosilicate glass layer deposited by RF magnetron sputtering process. The bonding was carried out at low dc voltage of about 48 V at 400 °C. Surface roughness of the deposited intermediate glass film plays a critical role in the success of the bonding process. The surface roughness was observed to be dependent on the thickness of the deposited glass film. It was seen that the surface roughness decreases with increasing thickness of the glass film. The sputter deposited glass layer of 3 μm thickness was found to have very low roughness and this thickness was used as an intermediate layer for silicon-to-silicon bonding process. Alkali ion concentration plays an important role in successful anodic bonding. The concentration of alkali ions was measured by EDX in the sputter deposited film and also in the sputtering target used for preparing the film.

Keywords: *ANODIC BONDING, LOW TEMPERATURE BONDING, RF MAGNETRON SPUTTERING, BOROSILICATE GLASS THIN FILM, SILICON-TO-SILICON ANODIC BONDING.*

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1. INTRODUCTION

Anodic bonding of silicon to glass is one of the preferred techniques for packaging of microelectronics devices and Micro-electro-mechanical Systems (MEMS) [1, 2]. This technique has been extended to bond silicon-to-silicon wafer by incorporating an intermediate layer of sodium-rich glass [3]. The anodic bonding process requires that a voltage be applied at elevated temperature across the silicon pair to be bonded together. As a result, the positive sodium ions in the deposited intermediate glass layer move towards the cathode. A space charge region is formed at the interface between the surface of the glass layer and the bare silicon. The resulting electrostatic force pulls the silicon wafers together, allowing the formation of atomic bonds [4]. For silicon to glass bonding, the process requires a temperature between 300 °C to 600 °C and voltage between 1.0 kV to 1.5 kV [1, 4]. On the other hand, silicon-to-silicon anodic bonding with intermediate glass layer can be accomplished at much lower applied voltages. Silicon-to-silicon wafer bonding (with or without intermediate oxide layer) can also be achieved without applying dc bias in the bonding process commonly referred to as direct wafer bonding (DWB) [4, 5]. However, DWB process requires heating the silicon pair to nearly 1000 °C for improved bonding strength, although the weak initial bonding can be achieved at room temperature. It is envisaged that silicon-to-silicon anodic bonding using an intermediate glass layer will be advantageous where the process temperature has to be kept below 400 °C or so. For example, the devices having a metallization pattern can be advantageously packaged by silicon-to-silicon anodic bonding. Another advantage envisaged with silicon-to-silicon anodic bonding is the ease of making through-holes in one of the silicon wafers (compared to drilling holes in glass plate) by bulk micromachining process for certain type of MEMS devices. RF sputtering technique being a low temperature deposition technique can be used to deposit borosilicate glass film [6-8].

Borosilicate glass (Corning 7740) has been commonly used for anodic bonding because of close matching of its thermal expansion coefficient with that of silicon [3-5]. This glass contains elements such as potassium, aluminum, and sodium etc. [7, 9]. Among these, sodium plays an important role in bonding process because of its high mobility at elevated temperature [3]. It is therefore a requirement to make sodium rich glass films for use as an intermediate layer in silicon-to-silicon anodic bonding. For this purpose, the thickness of the glass film is kept in the range of 0.5 to 4 μm [8]. For these thicknesses, the applied voltage is reported to be in the range of 30 to 200 V and the temperature ranges from 25 to 450 °C [10-12].

In the present work, anodic bonding of silicon-to-silicon wafer with an intermediate layer of borosilicate glass is reported. The oxide layer was deposited by RF Magnetron sputtering. The effect of sputtering parameters such as sputtering pressure and RF power on deposition rate was investigated. Surface roughness and sodium content in borosilicate glass thin films were studied. Scanning electronic microscopy (SEM) and atomic force microscopy (AFM) characterization techniques were used to study the surface morphology and surface roughness respectively. The bonding was carried out in a home-built apparatus. The bonding current during anodic bonding process, when a dc voltage was applied at elevated temperature, was measured. It was observed that the success of the bonding process critically depends on several parameters such as: initial flatness and surface roughness of the silicon wafers, the surface roughness of the deposited film and sodium contents in the oxide layer. Successful bonding of silicon-to-silicon was achieved when these parameters are closely monitored and controlled.

2. EXPEIMENTAL

2.1 Glass thin film deposition

Borosilicate glass thin film was sputter deposited by RF magnetron sputtering process. The sputtering target was procured from a standard supplier (Vin Karola Instruments USA) and the elemental analysis of the target was carried out using energy dispersive X-ray (EDX). The results are summarized in Table 1. The composition of commonly used borosilicate glass is also included in the table for reference. It can be seen that the elemental composition of the sputtering target closely matches with the Corning 7740 material commonly used for silicon to glass anodic bonding. The sputtering parameters are summarized in Table 2. Silicon wafers of 2-inch diameter were used as the substrate. Before deposition, the flatness of silicon wafer was estimated by Fizeau Interferometer (Prisms India Pvt. Ltd.) and silicon substrate was cleaned by standard cleaning process.

Table 1 – *Elemental compositions of borosilicate (Corning 7740) sputtering target*

Elements	Chemical composition (%)	
	Standard Corning 7740 material [3]	Measured Values on the target using (EDX)
Silicon (Si)	37.7	42.05
Oxygen (O_2)	53.9	51.42
Boron (B)	4.0	3.28
Aluminum (Al)	1.16	1.17
Sodium (Na)	2.81	2.08

Table 2 – *Parameters used for intermediate glass film deposition by RF Magnetron sputtering process*

Deposition parameters	
Target material	Borosilicate glass (75 mm diameter and 6 mm thickness).
Base pressure	1×10^{-5} Torr
Sputtering Pressure	5, 10 and 20 mTorr
RF power	100, 200 and 300 W
Target to substrate spacing	50 mm (sputter-up mode)
Sputtering gas	Ar

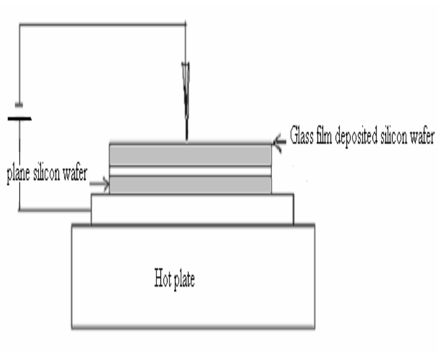
Thin film analyzer (Filmetrics F20) was used for thickness measurement of deposited films. AFM measurements of the films were performed to evaluate the surface roughness for different thickness. Also, EDX was carried out to know the sodium content in deposited films at different sputtering pressure.

2.2 Cleaning and bonding

A standard cleaning process was followed for cleaning of silicon wafer having deposited glass film and the bare silicon wafer used in the bonding experiment. The hydrophilic property of the surfaces, which are to be contacted in the bonding process, was ensured during the cleaning process. The final cleaning step was thorough rinse in DI water and the wafers were spin dried. The wafers were then brought in contact in a clean bench and the contacted pair was loaded on the hot plate of the bonding system. Fig. 1 a shows the schematic diagram of the anodic bonding system. The equipment was assembled in the Lab and the photograph is shown in Fig. 1 b. The bonding was performed at 400 °C with a dc voltage of 48 V applied using a pointed electrode. The negative voltage was applied to the silicon wafer having deposited glass layer and the bonding current was recorded.

3. RESULTS AND DISCUSSION

The deposition rate is an important parameter for preparing the films of desired thickness. Fig. 2 shows the deposition rate of borosilicate glass films as a function of sputtering power and sputtering pressure. From the Figure, it can be seen that the maximum deposition rate is obtained at 300 W and 5 mTorr. The deposition rate strongly depends on RF power and increases with increase in sputtering power, which is consistent with published results



a

b

Fig. 1 – *The schematic diagram of the anodic bonding system (a) and the photograph of the equipment assembled in Lab for anodic bonding (b)*

[6, 13]. As reported in published literature, wafers with a sputtered glass thickness of less than 0.5 μm could not be bonded [14]. Accordingly, we have selected an intermediate layer thickness in the range of 2 to 5 μm.

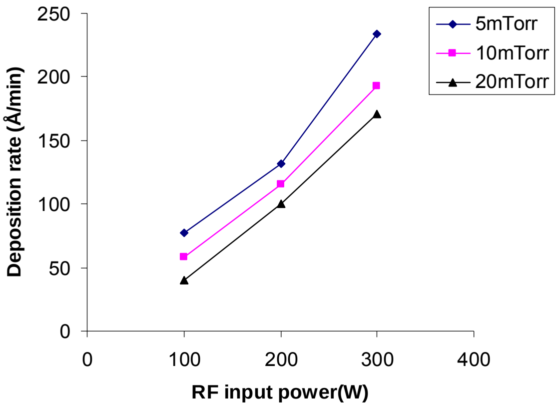
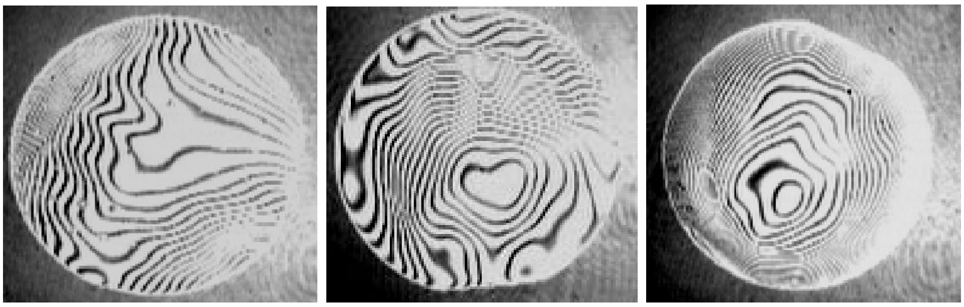


Fig. 2 – *Deposition rate of borosilicate glass film as a function of sputtering power at different sputtering pressure*

The initial flatness of silicon wafer also plays a critical role in anodic bonding of silicon-to-silicon wafers. The flatness was estimated using Fizeau Interferometer. Fig. 3 shows the optical image of a 2-inch diameter silicon wafer obtained on the Fizeau Interferometer. A wafer showing countable number of bright and dark fringes (10-15) was considered acceptable for bonding and these were used for bonding experiments.

Surface roughness (Ra) of deposited film of borosilicate glass plays an important role in anodic bonding. Rough surface may result in weak or unsuccessful bonding [7, 9]. Fig. 4 shows the three-dimensional AFM image of the deposited glass surface having different thickness. The average surface roughness (Ra) for the films deposited at 300 W RF power and 5 mTorr pressure is plotted in Fig. 5 as a function of the film thickness. It can be seen that the Ra values decreases with increasing film thickness. From the above results, it was anticipated that bonding will be successful



a b c

***Fig. 3** – Optical image representing the flatness of silicon wafer which was bonded with intermediate glass layer. (a) Plane Si wafer, (b) and (c) another Si wafer before and after deposition of borosilicate glass layer*

using 3 μm thick film as intermediate layer. This thickness was used in all the bonding experiments and its surface roughness is shown in Fig. 4c. The surface roughness (Ra) of 3 μm film deposited at 300 W and 5 mTorr was found to be 6 Å.

The EDX analysis was performed to estimate the percentage of sodium ions in intermediate glass layer deposited at different sputtering parameters and the results are summarized in Table 3. It can be inferred that borosilicate glass film deposited at maximum deposition rate (300 W and 5 mTorr) has maximum sodium content. The sodium content of the target material was measured to be 2.08 %. It is evident that there is loss of sodium in the sputtered film compared to its value in the target.

***Table 3** – Comparison between Atomic percentages of sodium ions for particular thickness of film deposited at different sputtering pressure*

Sputtering parameter		Atomic Percentage of sodium content, %
RF power, W	sputtering pressure, mTorr	
300	5	1.72
300	10	1.06
300	20	0.81

The bonding current was measured during bonding process. Fig. 6 shows the current versus time plot during the bonding process. Unlike the case of silicon-to-glass bonding, the silicon-to-silicon anodic bonding process cannot be viewed using optical techniques. The measurement of current during the bonding process provides some indication of the progress of the bonded interface. Fig. 6 shows the decay in the current at 400 °C with an applied dc voltage of 48 V for 5 min as the bonding process progresses. It can be inferred from Fig. 6 that initially the bonding current was 250 μA which decreases rapidly and reaches a low value of about 50 μA. The saturation of the current at low value was used as an indicator of completion of the bonding process. The hot plate was cooled down to room temperature with the DC voltage still applied to the bonded pair. The samples were then removed for further testing.

The bonded samples were cut and cross-section of the sample was polished

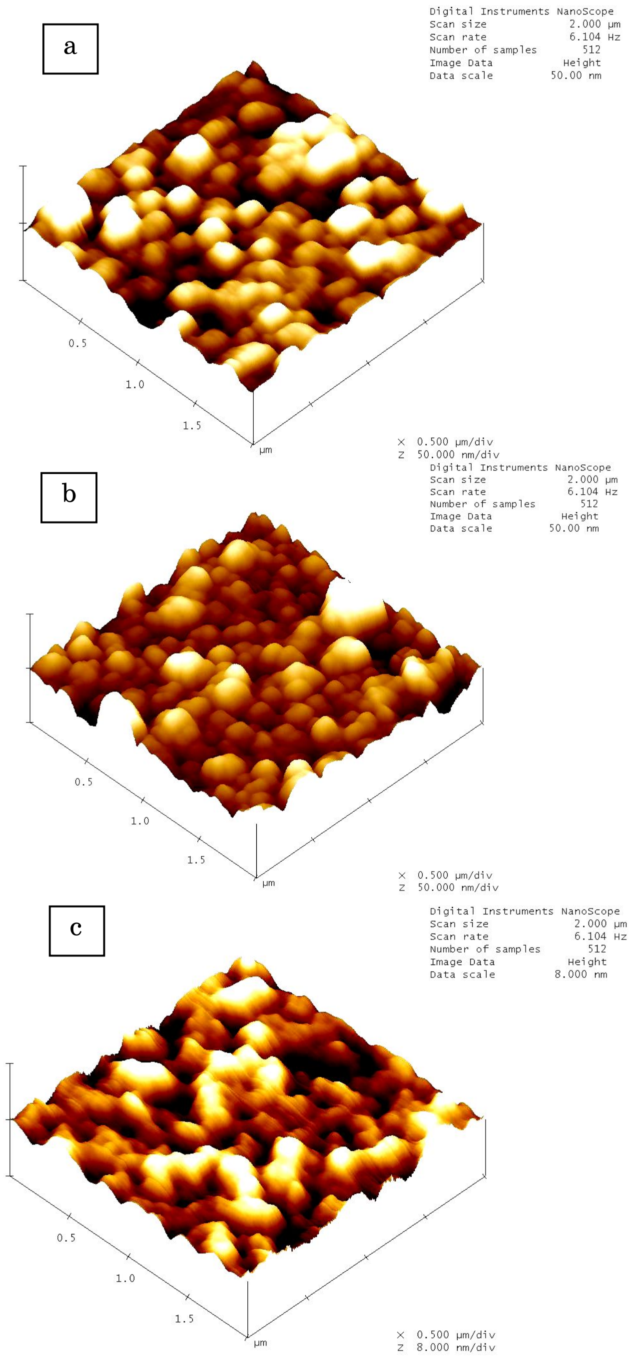


Fig. 4 *– 3D AFM image of surface of borosilicate glass film of different thickness deposited at* 5 *mTorr and* 300 *W; (a)* 0.5 *µm thick film (*46 *Å); (b)* 1.5 *µm thick film (*12 *Å); (c)* 3.0 *µm thick film (*6 *Å)*

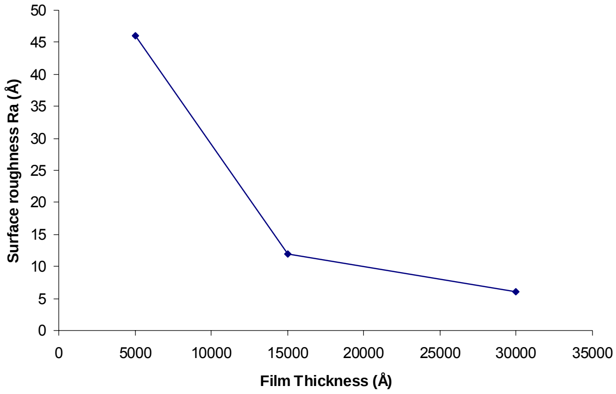


Fig. 5 *– Surface roughness (Ra) versus thickness of borosilicate glass film deposited at 300 W RF power and 5 mTorr sputtering pressure*

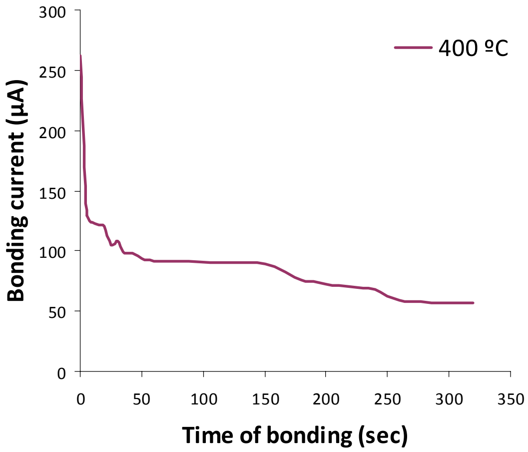


Fig. 6 *– The current versus time plot during the initial bonding process*

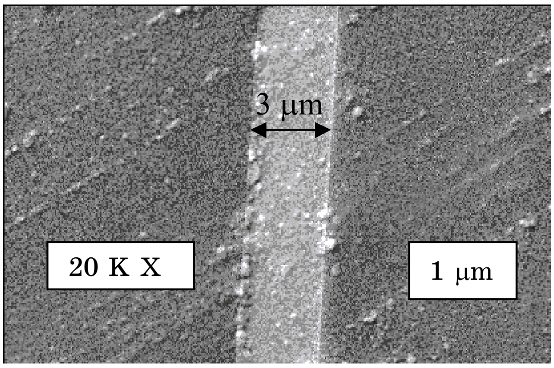


Fig. 7 *– The cross sectional SEM image of silicon-to-silicon bonded wafer*

to observe the bonded interface region. The cross sectional SEM image of silicon-to-silicon bonded wafer is shown in Fig. 7. The SEM image shows that the bonded interface was smooth with no bubble formation at the interface. This indicates that bonding was good. From SEM image, it can be seen that the intermediate layer thickness was unaffected during bonding.

4. CONCLUSION

In this work, we studied the anodic bonding of silicon-to-silicon wafers using sputter deposited borosilicate glass as intermediate layer. Surface roughness of sputter deposited borosilicate glass thin film decreases with increasing film thickness. It is envisages that the roughness can be further decreased by increasing film thickness or by performing polishing of the film. The thickness of 3 μm was chosen for bonding experiments and the films were deposited at a set of parameters which gives maximum deposition rate (300 W and 5 mTorr) and also maximum sodium content. Temperature of 400 °C was used for the bonding process as this was considered compatible with metallization patterns, if present on the wafers. Bonding was carried out at an applied dc voltage of 48 V. The bonding current initially was measured to be 250 μA which falls to about 50 μA. This was taken as an indicator for the completion of the bonding process. The sodium ion concentration in deposited film was observed to be lower than the corresponding value in the target. It is not uncommon to get different percentage of constituent elements in the sputter-deposited film compared to the composition of the target. Based on these results, it is proposed that the concentration of sodium in the target should be suitably increased to get the final composition of constituent elements in the film matching with the bulk counterpart. This may further improve the yield of the bonding process. It is concluded that RF sputtering is a viable process for preparing sodium rich borosilicate films for use as intermediate layer in silicon-to-silicon anodic bonding process.

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