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Reus, Roger De; Lindahl, M.

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Si-to-Si wafer bonding using evaporated glass

Roger de Reus and Michael Lindahl
Mikroelektronik Centret, DTU bldg. 345-East, DK–2800 Lyngby, Denmark

Summary

Anodic bonding of Si to Si four inch wafers using evaporated glass was performed in air at temperatures ranging from 300 °C to 450 °C. Although annealing of Si/glass structures around 340 °C for 15 minutes eliminates stress, the bonded wafer pairs exhibit compressive stress. Pull testing revealed maximum bond strengths greater than 50 N/mm^2 and an average bond strength of 30 N/mm^2. The bond strength is independent of both the bonding temperature and the feature size. We observed no fracture at the actual bond interface.

Keywords: anodic bonding, evaporated glass.

1 Introduction

Low-cost production of micromechanical devices requires reliable bonding at the wafer scale. Anodic bonding is a candidate because of the relatively low required temperatures (350 °C–450 °C) and high mechanical and chemical stability [1, 2]. Furthermore, anodic bonding is attractive because of its capability of sealing cavities and even filling 18 nm deep trenches [3]. Processes for anodic bonding of Si to bulk glass and Si to Si using thin glass layers have been developed. Typically Pyrex 7740 or Schott 8330 are used. The thermal expansion of these glasses is matched to the thermal expansion of Si, favoring low stress in the bonded devices. The thin glass films are usually deposited by sputtering. Recently the use of evaporated glass (Schott 8329) for anodic bonding purposes was reported [4]. The deposition rates of evaporated glass are at least three orders of magnitude greater than of sputter-deposited glass [2], which favors industrial applications. In this paper we evaluate the evaporated glass and its use for anodic bonding as a function of bonding temperature and feature size.

2 Experimental

A 5 μm thick sodium-containing boro-silicate glass (Schott 8329) was deposited by electron-beam evaporation onto clean four inch Si wafers. The wafers were either smooth or contained a test pattern. The base pressure of the vacuum chamber is better than 2×10^{-4} Pa. The deposition rate is proportional to pressure, with 5×10^{-3} Pa corresponding to a deposition rate of 20 nm/s.

Secondary ion mass spectrometry (SIMS) was used for compositional analysis of the glass. A stylus-type surface profiler was used for roughness and wafer curvature measurements. Thin-film stress was derived from the wafer curvature.

Annealing and bonding experiments were performed in air on a hot plate. A plate electrode (the hot plate itself) and a three-point load with a weight of 3.25 kg were used as electrical contacts to the wafer pair during bonding. Bonding was performed at temperatures ranging from 300 °C to 450 °C. The bonded wafer pairs were inspected using infrared microscopy. Unstructured bonded wafer pairs were submerged in a 28 wt% KOH solution at 80 °C for several hours and exposed to a qualitative wedge test by pressing a razor blade between the wafers. The structured Si wafers contained features approximately 15 μm high with a line width varying from 50 to 300 μm and a bond

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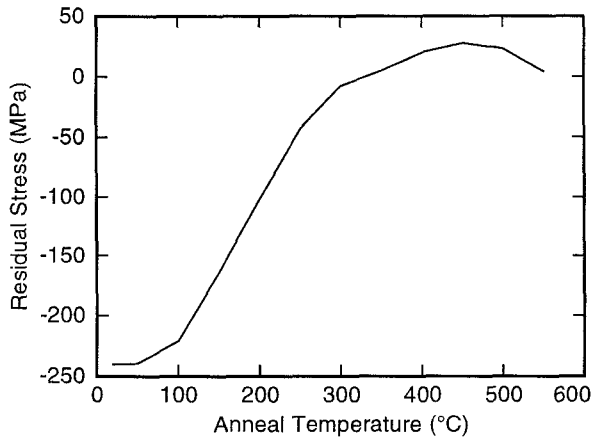

Figure 1: Residual stress of evaporated glass as a function of anneal temperature. After annealing around 340 °C for 15 minutes in air the glass is free of stress.

area of 3 mm^2 per item. Pull tests were performed after dicing the bonded wafers into chips.

3 Results and discussion

As compared to Pyrex 7740 and Schott 8330, two types of glass which are frequently used in anodic bonding [2, 5], the sodium content of bulk Schott 8329 glass is reduced with a factor of approximately two (maximum 2.1 wt%). However, our SIMS measurements show that the deposited thin films are greatly enriched in sodium, which is advantageous for the anodic bonding process. The composition of the glass films appears to be independent of deposition rate in the range 5 nm/s to 50 nm/s.

A stylus type surface profiler was used for roughness and wafer-curvature measurements. Values for the average and root-mean-square roughness below 2 nm were measured for all deposition rates. The peak roughness was less than 15 nm for a deposition rate of 20 nm/s. The roughness of the as-deposited glass films did not change during annealing in air at temperatures up to 500 °C. Residual stress in the evaporated glass films was derived from wafer curvature difference measurements. Without annealing the films exhibit a high compressive stress (typically around 225 MPa), as can be seen in Fig. 1. This initial stress is independent of deposition rate. Upon annealing in air for 15 min at temperatures above 100 °C and cooling down to room temperature the stress is relieved. Annealing around 340 °C results in stress-free films.

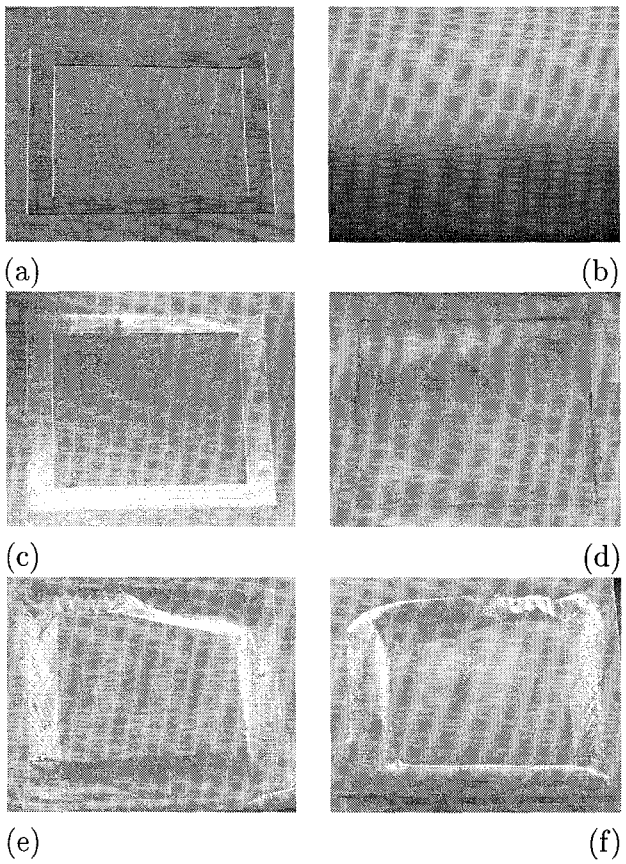

Figure 2: Pull test of bonded structures. A 15 μm high structure in Si (a). The square measures 3×3 mm^2 and the line width is 300 μm. The structures are bonded to plane Si covered with glass (b). After bonding and pulling the structure apart, the Si structures either remain intact (c) and the glass is removed from its original substrate (d), or the Si is torn apart (e) and transferred to the glass (f).

During bonding in air in the temperature range from 300 °C to 450 °C, typically a current flow was observed above a voltage of 15 V. Electrical breakthrough of the 5 μm thick glass layer usually occurred above 100 V. We observed a maximum cur-

rent up to 1 mA within 1 s after a voltage increase. Thereafter, the current drops rapidly and stabilizes at 0.005 mA after approximately 15 min.

Inspection of bonded wafer pairs with an IR-sensitive camera reveals that a bonded area of more than 95% of the total four inch wafer area can be achieved routinely. Although annealing of Si/glass structures around 340 °C eliminates stress, the glass of the bonded wafer pairs exhibits compressive stress. This is derived from the wafer curvature after bonding of wafers with different thicknesses. This residual stress is observed for all bonding temperatures. This issue requires further investigation.

Wafer pairs bonded at 450 °C were exposed to a 28 wt% KOH solution at 80 °C for 6 hours. A slight attack of the glass was observed at the outermost edge, whereas the central area retained its initial bond strength. A qualitative measure of the bond strength was obtained by pressing a razor blade between the bonded wafers, which were found impossible to separate without breaking.

Pull test experiments on chips diced from the structured wafer pairs quantified the bond strength. A typical example is shown in Fig. 2, which shows a rectangular test structure before bonding (a and b) and after pull testing. Fracturing at the bond interface was never observed. Instead, either the glass was transferred to the Si structure (c and d), or the Si structure itself was fractured (e and f).

The average bond strengths obtained from the pull test are depicted in Figs. 3 and 4. The average values are around 30 N/mm^2 with a standard deviation of 5 N/mm^2. Maximum values in excess of 50 N/mm^2 were observed. From Fig. 3 it is observed that the bond strength is independent of bonding temperature. In Fig. 4 the data are rearranged and it can be seen that, within the error limits, the bond strength is independent of the line width of the test structures as well.

The bond strengths reported in this paper compare to those reported in Ref. [4], where the same type of evaporated glass was used and bonding was

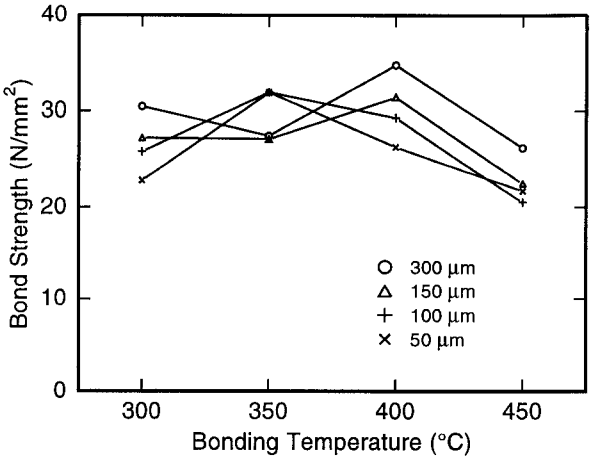

Figure 3: Bond strength versus bonding temperature for various line widths of the bonded areas. The standard deviation of the bond strength is approximately 5 N/mm^2. The bond strength is independent of bonding temperature.

performed at 400 °C and 450 °C after pre-annealing between 450 °C and 500 °C. According to our results the pre-annealing step seems not to be necessary. However, this may be related to a peak roughness less than 15 nm of the glass films deposited at a rate of 20 nm/s, which is considerably lower than the value of 100 nm for films deposited at a rate of 67 nm/s [4].

In this work we show that the temperature range for successful bonding using evaporated glass can be extended at least down to 300 °C. Although anodic bonding of Si to glass substrates is performed successfully in the range from 300 °C to 450 °C, temperatures above 400 °C are usually applied to Si-to-Si anodic bonding. We did not observe a relation between bond strength and bonding temperature as reported in [6,7] for bonding of Si to bulk Pyrex. As reported in [7], by raising the bonding temperature from 300 °C to 450 °C, the bond strength increases and reaches the strength of the Pyrex glass substrate. Failure of the bond then occurs when the bulk glass fractures [7,8]. In general, the strength of the anodic bond using evaporated glass (> 30 N/mm^2) is greater than a bond where sputtered glass [2] or bulk glass [6,8] is used

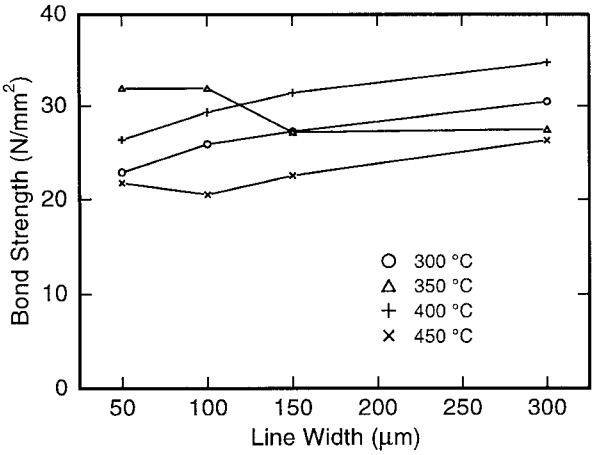

Figure 4: Bond strength versus line width for various bonding temperatures (same data as in Fig. 3). The bond strength is independent of line width.

(≤ 25 N/mm^2).

4 Conclusions

Evaporation of Schott 8329 glass for anodic bonding purposes was done at a rate of 20 nm/s. This is a fast deposition method which favors industrial applications. Low stress can be achieved by annealing at 340 °C for 15 min. Full area bonding of four inch Si(100) wafers was obtained at temperatures between 300 °C and 450 °C and between 15 V and 100 V. The glass of the bonded wafer pairs exhibit compressive stress. The bond is stable against KOH etching (28 wt%, 80 °C) for at least six hours. The average bond strength of 30 N/mm^2 is higher than for bonding of Si to bulk glass or Si to Si using sputtered glass. Furthermore, samples subjected to a pull test show that the glass-to-Si bond interface remains intact. The bond strength is independent of bonding temperature in the range 300 °C to 450 °C and independent of line width of the test structures. Since no degradation of bond strength is observed in the above-mentioned temperature range, lower bonding temperatures may be possible.

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