Considerations of anodic bonding for capacitive type silicon/glass sensor fabrication

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Abstract. This paper discusses the suitability of various glass types for different applications, and in particular for absolute capacitive pressure sensors. Some process induced effects which can affect the yield and performance of such devices are investigated and solutions suggested for improving these properties. Effects considered include electrolysis and process induced compositional changes. These can manifest themselves as bowed or warped assemblies, degraded bonds and metallized layers, and poor sensitivity and temperature stability of the resulting devices. Some solutions to these problems are discussed.

1. Introduction

The technique of anodic bonding [1–4] has found many applications in the field of silicon microengineering [5–8]. This has been primarily due to the low temperature utilized in the process as compared with conventional glass/metal sealing. With process temperatures below the glass transition point, the glass thermal expansion coefficient remains constant, enabling the possibility of stress free bonding [9]. In addition, with low temperature bonding, no appreciable flow of the glass occurs, hence enabling sealing around previously machined grooves, cavities, etc. without any loss of dimensional tolerances. This aspect is very important in the fabrication of capacitive type sensors since capacitance is essentially a geometrically defined quantity and reproducibility of capacitance gaps, which can typically be ~1 μm, is essential for low cost manufacture.

Anodic bonding has other features that make it attractive for capacitive sensors. Firstly, as an insulator, the glass enables low levels of parasitic capacitance to be achieved (compared with silicon/silicon bonding). Secondly, the bonding process can readily be performed in vacuum, allowing hermetically sealed zero-pressure reference cavities to be produced for absolute pressure sensors, or in special gas mixtures for other sensors. In addition, glass transparency to optical wavelengths enables simple alignment procedures for bonding pre-patterned silicon and glass to high alignment accuracy.

Many glasses are available with good thermal-expansion matching to silicon. We have concentrated on various Corning glasses for which the thermal-expansion matches to silicon are shown in figure 1.

![Figure 1. Thermal expansion for glasses 7740, 7070, 1729 and silicon.](image)

Other properties of these glasses dictate which is the most suitable for a given application. For instance the high temperature capability and low alkali content of 1729 glass make it suitable for devices requiring subsequent integrated electronics [10] or for high temperature optically addressable sensors. The low cost and ease of bonding of 7740 glass have made it the most widely used glass for non-critical bonding applications. However, for capacitive sensors which commonly employ a dielectric layer on the silicon, the relatively low electrical resistivity of 7740 glass can cause yield problems due to electrical breakdown during bonding. For such applications, 7070 glass is the preferred choice. However, even with this glass, other factors need to be considered in the fabrication of absolute pressure sensors employing capacitive sensing.

2. Anodic bonding problems and solutions

The two main problems that can adversely affect yield and performance of absolute, capacitive, silicon/glass pressure sensors are:
(i) bow/warp during bonding;
(ii) electrolysis products during bonding.

Causes of and solutions to these problems are discussed below.

3. Bow/warp

Thermal expansion mismatch is only one of the contributors towards the bow often found in silicon/glass bonds after cooling. Referring to figure 1, bond temperatures in excess of 400°C for 7070, should result in bonded assemblies with silicon convex. However, in practice, the assemblies exhibit concave silicon for bonding temperatures up to 460°C.

The origin of this effect is in the diffusion of the mobile ions within the glass, which under the prevailing temperature and electric field for bonding can produce significant deviations from the bulk glass composition at the silicon/glass interface and opposite glass face. Previous studies [11, 12] have shown that the positive alkali ions can migrate during bonding to produce a depleted glass layer up to 10 μm deep. A corresponding enhanced layer will occur at the opposite face. The volumetric changes which occur in order to accommodate the movement of these mobile species result in a bow being induced in the glass disc. More recent work [13] has suggested that more complete dissociation of the glass occurs during bonding after which the depletion layer could resemble silica more than the original borosilicate. This implies that the volumetric changes could be of considerable magnitude, thus accounting for the considerable bow (up to 30 μm, even for 3 mm thick glass discs) that occurs for Si/7070 bonded at 400°C.

4. Flatness control

Two methods can be utilized for overcoming this glass bowing effect. These are:

(i) reverse polarity treatment subsequent to bond formation [14];
(ii) offset of bow with opposite curvature deliberately introduced by thermal expansion mismatch.

Both of these techniques have been investigated and enable us to reduce bow to as little as 15% of the normal value. However, both processes have their drawbacks.

5. Reverse polarity

Although this process works exceptionally well for restoring flatness to a non-bonded glass component, it can adversely affect the quality of the bond, the nature of sealed cavities and the condition of deposited layers such as metallic leadthroughs. The origin of these effects is due to the electrolysis products discussed below.

6. Thermal expansion offset

The disadvantage of this technique is the considerably higher process temperature required (typically 460°C for silicon/7070). In addition, since bonding will initiate from certain points and spread out with time from such points, the degree of offset required will not be constant across the wafer. This generally produces bonded assemblies with warped profiles. Since the bonding process does not progress uniformly across the wafers, the depletion layer depth can also vary. During bonding, this high resistivity region can result in significant localized Joule heating which tends to raise the temperature at the interface above the defined process value. If the depletion depth varies, this temperature rise will vary and hence aggravate the warp effect. One method of overcoming this non-uniformity is to control the bonding front with segmented annular electrodes powered sequentially from centre to edge.

7. Electrolysis effects during anodic bonding

The anodic bonding process itself relies on the availability of electrolytically generated oxygen being available at the silicon/glass interface to permit the formation of the high strength chemical bond. However, hermetically sealed cavities within the bonded regions can become filled with oxygen during the bonding process. For instance our silicon/glass capacitive pressure sensors with an internal sealed reference cavity of \(5 \times 10^{-11} \text{ m}^3\) can possess internal pressures of \(\sim 1 \text{ Bar}\) even though bonded in a chamber at \(\sim 10^{-6} \text{ m Bar}\). For low pressure devices, this internal pressure can seriously affect the sensitivity and temperature stability. In addition, metallic layers within this volume can themselves become oxidized, and hence exhibit high resistance properties. We are currently investigating a process employing vented cavities and subsequent sealing to overcome these effects.

Reversing the polarity does not improve the situation since glass contains considerable amounts of water [15] which will result in hydrogen evolution into the sealed cavities. Within the bonded regions, this hydrogen can attack the interface bond resulting in porous, non-hermetic sealing. Within sealed regions metallic layers can be degraded.

One other aspect of electrolysis is that when active metals such as titanium are present at the interface, the supply of oxygen for bond formation is considerably reduced. Longer bonding times (for the same temperature and applied voltage) are therefore required for hermetic sealing.

8. Conclusions

Although anodic bonding has been extensively investigated by many workers over the past 25 years, many aspects of the process are still poorly characterized.
Various glasses with good thermal expansion matching to silicon can be used for different applications but some basic process limitations such as compositional gradients and electrolysis effects cannot be avoided. However, with a proper understanding of the bonding process and modifications to device design and process parameters, these adverse effects can be minimized.

References