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Glass-frit bonding of silicon strain gages on large thermal-expansion-mismatched metallic substrates

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ABSTRACT

Bonding of silicon strain gages on stainless-steel substrates is a critical issue in diaphragm-type pressure sensors because of the large mismatch in coefficients of thermal expansion between silicon and metal resulting in serious reliability problems. A new method to significantly improve the glass-frit bonding of silicon gages on metal diaphragms is reported based on an intermediate thin glass plate onto which silicon strain gages are fabricated. The glass interlayer enables very reliable bonds without post-bond misalignment, debonding, or cracking through the selection of glasses that very closely match silicon and the compressive surface strengthening of glasses. Furthermore, the proposed gage structure provides great improvement in the electrical performance, especially the thermal drifts of offset (zero) and span of Si strain-gage-based bridge transducers.

1. Introduction

Glass-frit bonding, also referred to as glass soldering, has been successfully used for capping and packaging of surface or bulk micromachined MEMS devices such as inertial sensors, resonators, and RF switches [1–3]. A glass-frit is much superior to conventional epoxy adhesives in that mechanical creep is greatly reduced and the temperature capability of the bond is significantly increased [4]. Glass-frit as a dielectric material does not need additional passivation for preventing leakage currents between the metal lines crossed by the glass-frit up to 125 °C [5]. Furthermore, glass-frit bonding is possible on top of the passivation of highly integrated CMOS wafers without significantly influencing the integrated circuits [6].

Recently, glass-frit bonding has been widely applied to the silicon strain gage attachment on different stainless-steel substrates in diaphragm-type high pressure sensors [7,8]. Generally, four strain gages configured as a Wheatstone bridge are bonded to a pressure gathering diaphragm using a glass-frit. When a diaphragm pressure sensor is designed, special consideration must be given to the material properties, especially the coefficient of thermal expansion (CTE) mismatch between the silicon gage and the metal substrate. The thermal expansion of silicon material is much lower than that of glass-frit paste and metal substrate to which the gages are usually bonded. Significant thermal stress can be generated within gages after the assembly cools down to room temperature because of the large CTE mismatch between the silicon gages and the metal diaphragm. These residual stresses cause the resistance of the bonded gage to be smaller than the unbonded resistance and cause the gage to crack or delaminate from the substrate.

Several methods to improve adhesion and reduce strain gage chip breakage have been investigated [9,10]. One of the most common techniques is wafer thinning [10]. Thin wafers (<50 μm) are expected to reduce gage breakage and decrease the effect of mismatch stress. However, the wafer thinning method is limited to approximately 30 μm by the low yield of the CMP process and has been only partially successful in the low CTE mismatch stainless steel diaphragms (for example, SUS 630) because the thermal stress is still high enough to break the sensor chip on a large CTE mismatch substrate like SUS 316L. Another approach to reduce chip cracking or debonding is to use a thicker glass-frit layer. However, thicker glass-frit causes a lower sensitivity and makes post-bond misalignment worse.

In this study, we provide a completely different approach to glass-frit bonding of silicon strain gages on large thermal-expansion-mismatched metallic diaphragms. First, the silicon strain gages are fabricated on an anodic bonded silicon-glass wafer. Then, the silicon gages on glass substrate are glass-frit

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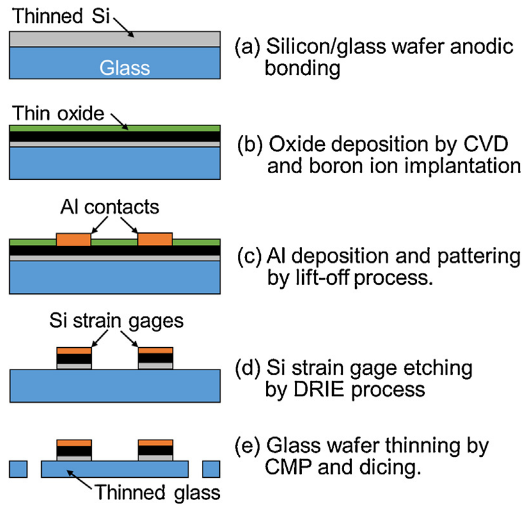

Fig. 1. Schematic depiction of fabrication sequence for silicon strain gages onto glass substrates.

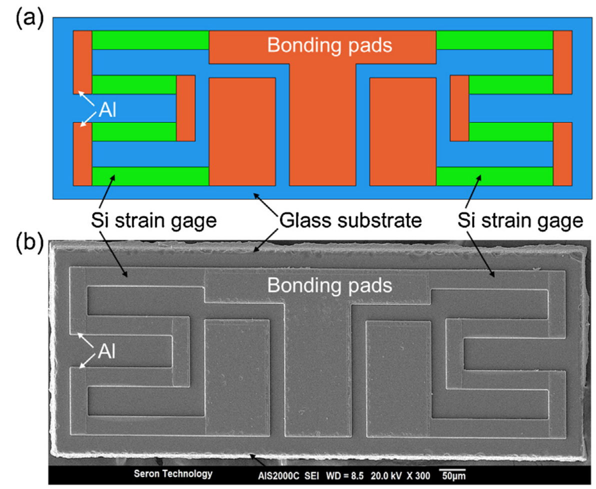

Fig. 2. Silicon strain gage on glass substrate: (a) layout and (b) SEM.

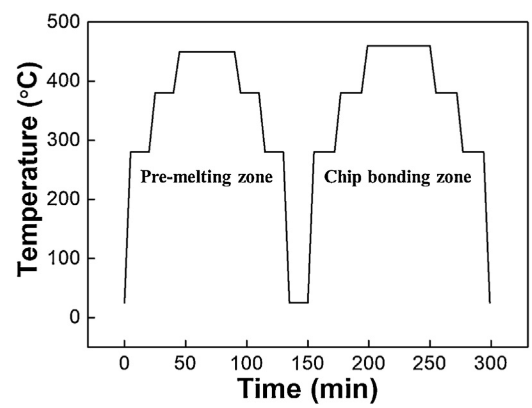

Fig. 3. Pre-melting and bonding profiles of screen-printed glass-frit on metal diaphragm.

bonded on stainless steel diaphragms. The thin glass plate, typically 20 μm thick, forms an intermediate layer between the silicon gage and the glass-frit. The glass interlayer inherently has the same advantages as the glass-frit, such as the reduced mechanical creep, low leakage current, and high temperature capabilities of the bond, compared with conventional organic epoxy adhesive. Furthermore, this interlayer is preferable because glass-frits usually fail to match the silicon gage with respect to thermal expansion (about 2.6×10^{-6} cm/cm/°C for silicon as compared to 8.5×10^{-6} cm/cm/°C for glass-frit). The marked mismatch in thermal expansion increases cracks and detachment of silicon gages. In contrast, a glass interlayer permits the selection of glasses that match silicon very closely (for example, 3.17×10^{-6} cm/cm/°C for Eagle XG glass). More importantly, very uniform and reliable bonds free of cracks and misalignments are obtainable by using a thin glass interlayer between the silicon gages and the glass-frit. In addition, the combination of reliable bonding and CTE matching offers high electrical performance silicon gages.

2. Experiment

2.1. Silicon strain gage

The fabrication process for the strain gage chip with a glass base is outlined in Fig. 1. The gage sensor was fabricated using a p-type 8-in silicon wafer. The wafer was bonded anodically to an 8-in glass wafer. Clean silicon and glass wafers were brought into contact with a potential of 1750 V with the former used as the anode and the latter as the cathode. The process was carried out at 500 °C for 40 min in a vacuum. After Si-glass wafer bonding, the top silicon was thinned down to 10 μm by chemical-mechanical polishing (Fig. 1(a)).

P-type piezoresistors were formed by boron ion implantation with doses ranging from 5×10^{14} cm^{-2} at 80 keV through a 500-Å oxide layer into silicon thinned to 10 μm or less leading to a 257.4 Ω/sq. sheet resistance (Fig. 1(b)). The thin oxide in the area where Al is to be deposited was etched by reactive ion etch (RIE) for Si and Al contact. Subsequently an 800-nm-thick Al layer was deposited for metallization and patterned by a lift-off process and annealed at 450 °C in dry N_2 for 30 min (Fig. 1(c)). Next, the thin oxide and silicon were etched using RIE and a deep reactive ion etch (DRIE) process, respectively, to define the silicon strain gages and bonding pads (Fig. 1(d)). The DRIE process was performed at 2500 W for about 10 min. Finally, the rear-side glass was thinned down to about 20–50 μm by chemical-mechanical polishing, and then the entire wafer was diced into strain gage chips using a sawing machine (Fig. 1(e)). For comparison, conventional SOI-based silicon strain gages were also fabricated following the same procedure. Fig. S1 shows the cross sectional structure of present and conventional devices.

Fig. 2 shows an SEM image of a finished silicon strain gage chip with size of 328 × 948 μm^2 on a 20-μm-thick glass substrate base. The width and total length of the silicon strain gage are 31 μm and 726 μm, respectively. The sensor chip contains two silicon strain gages (a so-called half-bridge) and three bond pads on the glass substrate, and the expected resistance value of the silicon gage is 6.03 kΩ (23.4 sqs. × 257.4 Ω/sq.). One strain gage is subjected to compressive stress, while the other is subjected to tensile stress.

2.2. Glass-frit bonding

The fabricated silicon strain gages were evaluated using circular metal diaphragms with inner diameter of 6.8 mm and thickness of 0.4 mm. The glass-frit with different thicknesses depending on the gage type was screen printed at the location where the gage chips are to be placed on the top surface of the diaphragm. After screen printing, the diaphragm was passed through a furnace with a multi-step temperature profile as shown in Fig. 3 to transform the paste into real glass. The pre-melting step is very important to prevent void formation inside the bonded glass, which would lower its strength and reliability [5] because of gas generation by organic