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Research on low-temperature anodic bonding using induction heating

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Abstract: This paper presents a new low temperature silicon-glass anodic bonding process using induction heating. Anodic bonding between silicon and glass (Pyrex 7740) has been achieved at temperature below 300°C and almost bubble-free interfaces have been obtained. A 1KW 400KHz power supply is used to induce heat in graphite susceptors (simultaneously as the high-voltage electrodes of anodic bonding), which conduct heat to the bonding pair and permanently join the pair in 5 minutes. The results of pull tests indicate a bonding strength of above 5.0MPa for induction heating, which is greater than the strength for resistive heating at the same temperature. The fracture mainly occurs across the interface or inside the glass other than in the interface when the bonding temperature is over 200°C. Finally, the interfaces are examined and analyzed by scanning electron microscopy (SEM) and the bonding mechanisms are discussed.

1. Introduction

Wafer bonding is a cost-effective method for zero-level MEMS packaging and has increasingly become a key technology for materials integration in various areas of MEMS, microelectronics and optoelectronics. Different wafer bonding approaches are currently used in the MEMS industry: fusion, adhesive, eutectic, anodic, solder bonding, et al.[1–2]. As fusion bonding processes require a high temperature annealing which is not always suitable for the devices with aluminium or copper integrated circuits; adhesive bonding is non-hermetic, more and more interests are focused on low temperature bonding (maximum process temperature below 300°), which can not only reduce process cost and time, but also minimize bonding-induced stress and warpage after cooling. Moreover, the wafers with large difference in coefficient of thermal expansion (CTE) can also be bonded.

Anodic bonding is one of the most used wafer level packaging procedures. In anodic bonding, the substrates are heated to a typical temperature above 400° and a typical voltage above 600V is applied to the wafer pair to be bonded, electrostatic force and the migration of ions lead to an irreversible chemical bond at the boundary layer between the individual wafers. Conventionally, this is done in the furnace or on the hotplate, which require long ramp times, consume large amounts of power, and have significant manufacturing footprints. Currently, many efforts are focusing on improving anodic bonding quality [3-5]. However, the bond quality is reduced with decrease in the bonding temperature, low bonding strength will result in the bubbles or cavities at the interface, only few literature reports the success in low temperature anodic bonding with high bond strength and bubble-free interface [6-7]. In this work, silicon-glass anodic bonding by induction heating is carried out at temperatures ranging from 200° to 350°. The bond quality, such as bond strength and interface integrity, is determined and the anodic bonding mechanisms are discussed.

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2. Principle of induction heating bonding

Induction heating is based on the principle of the electromagnetic induction and heat transfer. Faraday's law states that a changing magnetic field will induce an electric field, and a changing electrical current will create a magnetic field according to Bio-Savart's law. The induction heating system usually consists of a high-frequency power supply, an induction coil and the workpiece. In most induction heating applications, an alternating current is passed through the induction coil to create an alternating magnetic field, and the workpiece is placed inside this magnetic field such that an electrical current is generated on the workpiece, resulting in resistive heating. The major advantages over conventional heating lie in fast, non-contact and selective heating with respect to both material and geometry [8].

According to the characteristics of the induction heating, only electrically conductive materials can be directly heated, non-conductive materials, such as plastics and silicon, must use a conductive susceptor in induction heating, That is, heat is induced in the susceptor and transferred to the target workpiece through conduction or radiation. Graphite is frequently used as a susceptor because it offers best machinability, anti-oxidation, high resistivity (ideal for induction heating), and melting temperature up to 3000°C.

For induction heating, there is a relationship between the operating frequency of the power supply and heating speed and the geometry of workpiece, the higher the frequency, the higher the heat rate. Low frequency is effective for thick materials while high frequency is effective for small parts requiring shallow heat penetration.

Heating through induction can provide reliable, repeatable, accurate and energy-efficient heating in minimal amount of time, so it provides many advantages over other heating methods and is commonly used for bonding applications [9-11], which requires accurate heating control while still reaching temperature that cause the bonds to form.

3. Experimental details

3.1 Wafer preparation and bonding

In this study, single-side polished p-type (100) standard bare wafers with resistivity of 7.5–11.5 $\Omega\cdot\text{cm}$ were prepared for the bonding experiments. The glass was the 4 in Pyrex 7740 from Corning with the thickness of 500 μm , the surface roughness of the glass wafers, R_a , of less than 20 nm and the flatness better than 10 μm . Firstly, silicon and glass wafers were cut into about 16mm \times 16mm square-shaped dice using a diamond cutter, with the size of glass made slightly larger than that of silicon to prevent possible electrical discharge during the bonding process. After ultrasonical cleaning in stand RCA solutions at temperature of 80°C, the silicon dice were then rinsed with deionized (DI) water and dried by pure N_2 . At the same time, glass pieces were ultrasonically cleaned by acetone followed by alcohol and DI water, then purged by pure N_2 . Immediately after drying, the stacked silicon and glass dice were prebonded manually in air and sandwiched between the two graphite blocks.

3.2 Experimental setup

The induction heating bonding system consisted of a high-frequency power supply operating at 400KHz with an output power of 1KW, an induction coil made from copper tubing and cooled with water, a quartz rod, thermocouple, two graphite blocks and the bonding pair, as shown in Fig.1. The graphite blocks were hold in the center of the three turn helical coils with an inside diameter of 40mm. Pre-cleaned silicon and glass pieces were sandwiched between the graphite blocks which were connected to the high-voltage power

supply, ensuring a positive electrode potential on the silicon side with respect to the glass. The quartz rod was used to press the bonding pair through the graphite blocks and the thermocouple was used to measure the process temperature.

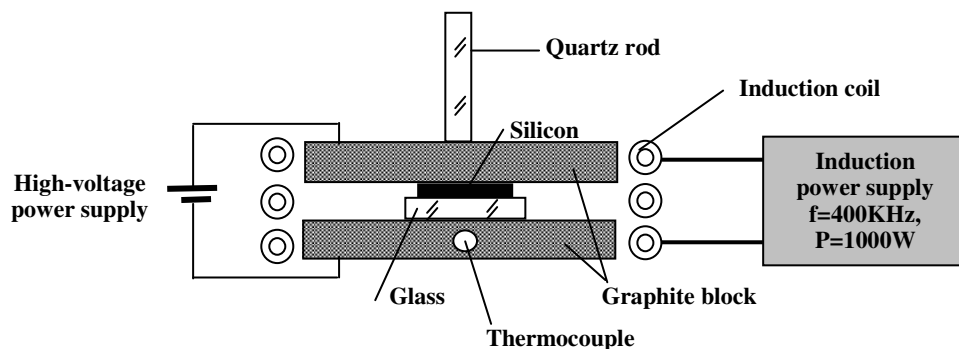


Fig. 1 Schematic of the experimental set-up

When the power supply sending an alternative current to the coil, the magnetic field created in the coil traversed perpendicular to the surface of the graphite and bonding pair, so the graphite blocks were heated by induction heating and heated the bonding pair to a predetermined temperature. Next, a DC high-voltage was applied to the graphite electrodes, just as in an ordinary silicon-glass anodic bonding.

3.3 Bonding strength and interface integrity

In this work, the temperature varying from 200° to 350°, the voltage 400V to 600V and bonding time of 5 minutes were chosen to investigate the effects of induction anodic bonding in details. All bonding experiments were carried out in a class 100 clean room.

After the anodic bonding, the bonded pairs were diced into about 8×8mm² die for tensile strength measurement with an in-house tensile testing machine [12]. Although the test is not a very accurate measure, but rather provides a quick estimate of the relative bond strengths of two different bonds. Prior to tensile test, the two surfaces of the bonded pairs were roughened with abrasive paper and ultrasonically cleaned in acetone, and then the bonded pairs were clung by epoxy glue between two aluminum alloy collets. After curing in air for over 24 hours, the pairs were tested by applying a mechanical force from the step-motor. To maintain the consistency and stability of the experiments, the four samples were tested and the average bond strength was calculated based on the four for each bonding condition, then some fracture interfaces were analyzed with SEM.

4. Results and discussions

The bonding strength is defined as the maximum force the bonded pairs could withstand divided by the bonded area, and it is a very important factor relating to bond quality and reliability. High bond strength indicates that a good bond has been achieved. Table 1 summarizes the bonding conditions and bonding evaluation. Just as the anodic bonding by resistive heating, the average tensile strength of the bonded pairs by induction heating increases with increasing bonding temperature, but the value is greater than that of the former at the same temperature with the same tensile testing machine [12]. Moreover, except that at 200°, at which we observed a low tensile strength (5.35MPa) and fractured along the silicon-glass interface, the bonded pairs at temperature ranging from 250°-350° fractured either across the interface from glass to

silicon or inside the bulk of the glass, but no significant difference in bonding strength could be observed between these two kinds of fracture. Fig. 2 shows some typical fracture surfaces by induction heating after the pull test, they all show that silicon and glass are densely bonded together.

Table 1 Summary of bonding conditions and bonding evaluation*

Sample No.	Bonding temp.(°)	Bonding Volt.(V)	Average tensile strength (MPa)	Fracture description
A	200	600	5.35	Fracture along the interface
B	250	600	7.90	Fracture across the interface
C1	300	400	9.50	Fracture across the interface
C2	300	500	9.34	Fracture across the interface
C3	300	600	9.59	Fracture across the interface
D	350	600	10.42	Fracture across the interface

* The contact force by quartz rod is 50N, and the bonding time is 5 min.

As Table 1 shows, no significant variation of bonding strength at 300° was observed as the voltage was increased from 400V to 600V, which is also different from anodic bonding by resistive heating [4, 13]. It is believed that the voltage of 400V is sufficient for the completion of the anodic bonding reaction by induction heating and further increase of the voltage will not add any apparent advantage.

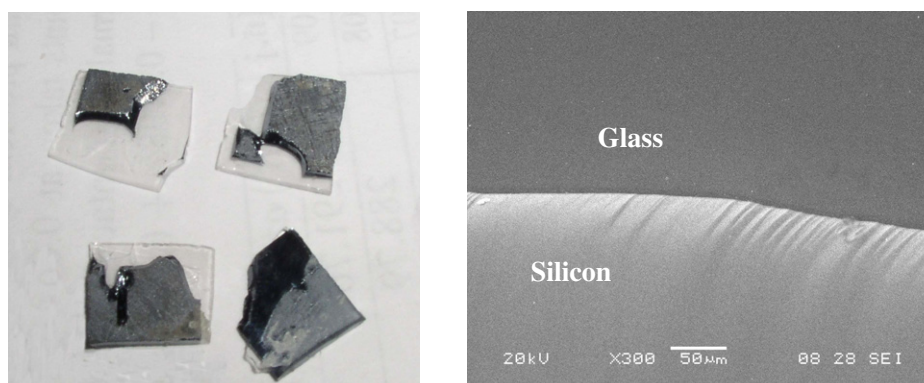


Fig. 2 Fractured samples after tensile test

Induction heating has two energy dissipation mechanisms, hysteresis loss and resistive loss. The former is present only in magnetic materials and is not considered in this work. Resistive loss is the dominant heating mechanism, and it is the result of eddy currents flowing in a conductive workpiece. We all know that silicon is a semiconductor and glass is an insulator at room temperature, and they cannot be directly heated by induction heating, so the susceptor must be used to couple the electromagnetic energy to them. As the temperature is raised, the resistivity of silicon and glass decrease exponentially. When the silicon is heated to a temperature, such as 200°, ohmic heating of silicon can be effective through induction of AC current even at low frequencies, e.g., less than 1MHz [11]. This is the same as glass, there are more mobile ions (Na^+ , K^+ , et al.) when heated. Then in the anodic bonding using induction heating, much more free carriers and ions will be excited in the bulk of silicon and glass by the high frequency electromagnetic field and drifted to the interface with the assistance of the high electric fields, resulting in high bonding quality even at lower temperature. That is, the high frequency electric fields present during induction heating provide an

additional driving force toward bonding activation[11], which boosts the ion mobility. In fact, there are higher bonding current that was observed when the electromagnetic field existed.

In resistive anodic bonding, the voltage imposes a positive effect on bond strength improvement, just as the bonding temperature. This is because the voltage applied across the silicon-glass stack sets up an electrostatic field in the gap, which in turn generates the electrostatic forces at the interface that pulls the pair into intimate contact [14], the higher voltage, the more intimate contact and resulting in higher bond quality. But for induction anodic bonding, although the voltage is also an necessary, the electromagnetic force between the pair can help to pull them into intimate contact, so the voltage does not exhibit significant influence on bond quality as that in anodic bonding using resistive heating.

5. Conclusions

A novel low temperature (below 300°) anodic bonding using induction heating is reported. Just as the anodic bonding by resistive heating, the average tensile strength of the bonded pairs by induction heating increases with increasing bonding temperature, but the value is much greater than that of the former at the same temperature. In induction anodic bonding, the electromagnetic field boosts the ion mobility and helps to pull the pair into more intimate contact, so the voltage does not exhibit significant influence on the bonding quality. From the bonding strength measurements, a temperature of 300° seems to be sufficient as long as the voltage is at least 400V. Finally, the bonding mechanisms based on the experimental observations are proposed.

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Biographies

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