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Direct bonding of micromachined silicon wafers for laser diode heat exchanger applications

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Abstract. A novel application of silicon direct-thermal-wafer bonding is demonstrated using micromachined wafers. Two (110) Si wafers are patterned and micromachined using wet chemistry. The prepared wafers are cleaned, leaving only native chemical oxides on the Si surfaces. After the cleaning steps, the wafers are thermally bonded without electrostatic pressure. The points of bonded contact are 410 μm × 25 μm. Hydraulic pressure testing on the bonded wafers has substantiated a bond strength comparable to contiguous SiO_2. The final structure is intended as a micromachined heat exchanger for cooling laser diodes.

1. Introduction

Silicon direct bonding (SDB) is process in which two separate wafers are brought into contact at room temperature (contact bonded) and then annealed in a furnace to form a single piece. When two silicon wafers with highly hydrophillic surfaces are brought into contact at room temperature, an initial weak bond is formed via Van der Waals forces at the surfaces [1, 2]. If subsequently annealed at a high temperature (e.g. $T > 700°C$) in dry oxygen or an inert ambient, the native oxides of the weak-bonded wafer pair merge to form a contiguous SiO_2 layer attaching them [2, 3].

It has been established that particles on the wafers prior to bonding produce voids (e.g. disbonded regions) between the bonded wafers [3, 4]. Particles in the micrometer range can produce voids with average diameters in the millimeter range [3]. For this reason, it is essential that the initial contact of the two wafers is made in a particle-free environment. Infrared transmission imaging of the bond can aid in the detection of voids. Another parameter of importance for wafer bonding is the flatness of the silicon wafers being used: flatter wafers tend to bond easier since their surfaces are in closer proximity when the two wafers are at first in contact. The wafers do not have to be absolutely flat, however; the hydrophillic surfaces necessary for contact bonding produce an attractive force between the two wafers, which draws the two wafers together. As a result, there is some microscopic deformation of the wafers, which can overcome minimal non-flatness.

SDB was used to bond (110) oriented wafers that had deep micromachined structures in them. The application of this bonded structure is for micro-channel heat sinks, the operational concepts of which are described elsewhere [5]. A simplified depiction of the bonded structure, along with the dimensions can be seen in figure 1. This figure is not to scale but, rather, is shown conceptually to emphasize the nature of the micromachined structure; it also shows the cross-sectional features of the two micro-machined wafers. The top structure is referred to as the 'manifold wafer' and is used to feed cooling water to the bottom structure, referred to as the 'heat channel' wafer. Once bonded, the manifold wafer is to be sealed by an anodic bond to an additional plate made of soft glass. Holes in the glass plate directly access the manifold grooves. High-pressure water can be forced through the glass plate to the manifold, in turn, cooling the heat channels. With this design it is possible to cool several hundred watts per square centimeter. The significance of this value of power dissipation capability is that it is sufficient for the cooling of continuous wave (CW) operation semiconductor laser diode arrays.

2. Experimental procedure

Both the manifold and heat-channel wafers are fabricated using anisotropic etching of (110) oriented, 3-inch diameter, silicon wafers. The (110) oriented silicon wafers are used to obtain deep vertical channels, taking advantage of the highly anisotropic etching characteristics using

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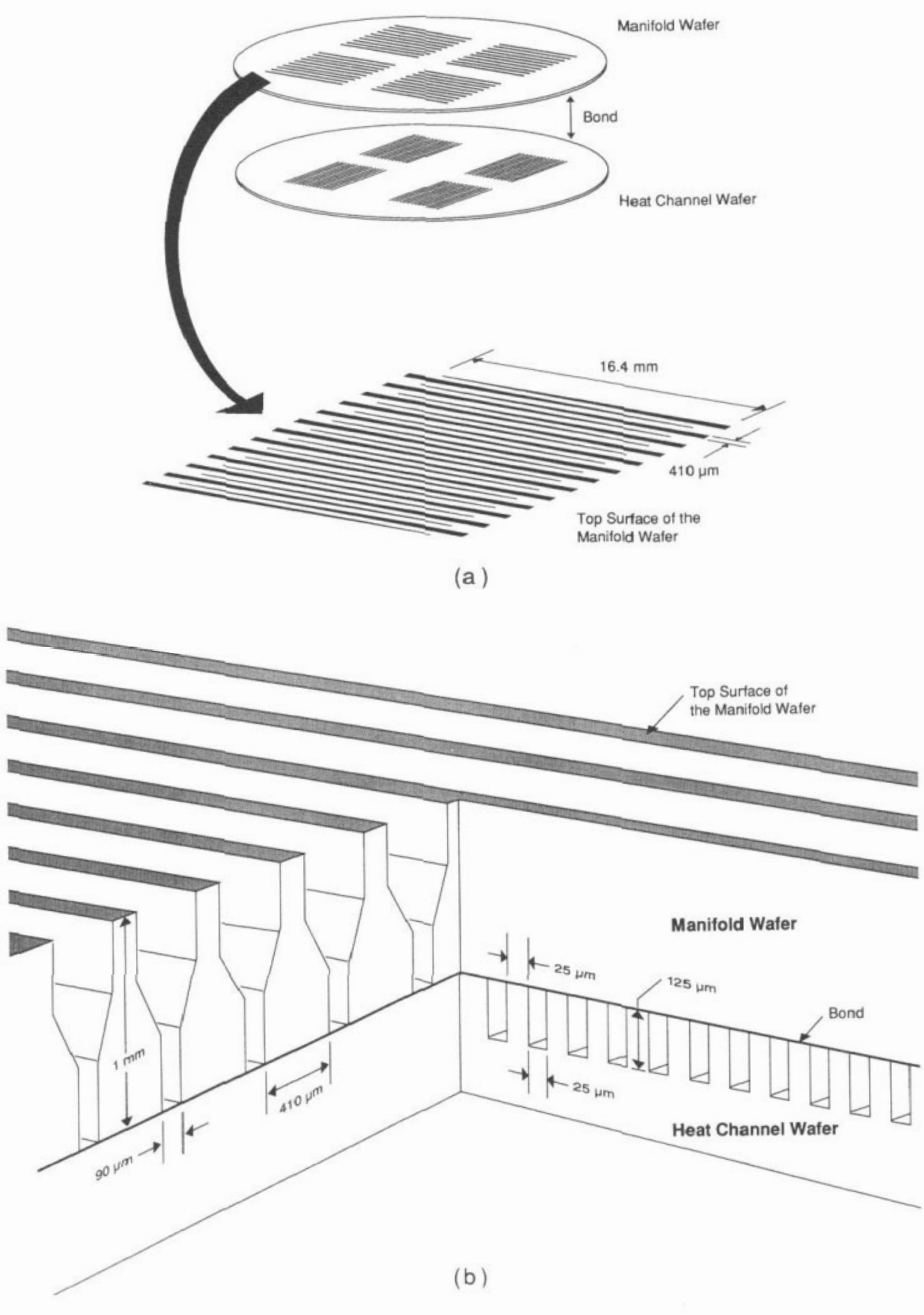

Figure 1. Schematic representation of the micromachined wafer structure (scale distorted for clarification). (a) The actual 3-inch wafers have four final cooling structures, each with 125 heat channels bonding to 40 manifold slots. (b) Detail of a single cooling structure with cross section and dimensions.

KOH solution. The best wafer flatness in this work is a 3–5 μm variation, peak to valley, over the 3-inch diameter surface as measured with a ZYGO interferometer. More typical is a 10–15 μm peak to valley variation. The manifold wafers are 40 mils thick and are double-side polished. Double-side polishing is required on the manifold wafer since it undergoes a silicon bond on one side and a glass-plate anodic bond on the other. The heatsink wafers are 17 mils thick and only single-side polished. Laser diodes are later attached to the unpolished side of the heat-sink wafers.

The slots in the manifold wafer are etched all the way through as is seen in figure 2, which shows a cross-sectional SEM photograph of the final bonded structure. The intersection of the slot with the wafer surface is 16.4 mm long, with a trapizoidal-shaped layout having an initial width of 560 μm and tapering to a minimum width of 70 μm. The manifold slots are all spaced with a (*a*) (*b*)

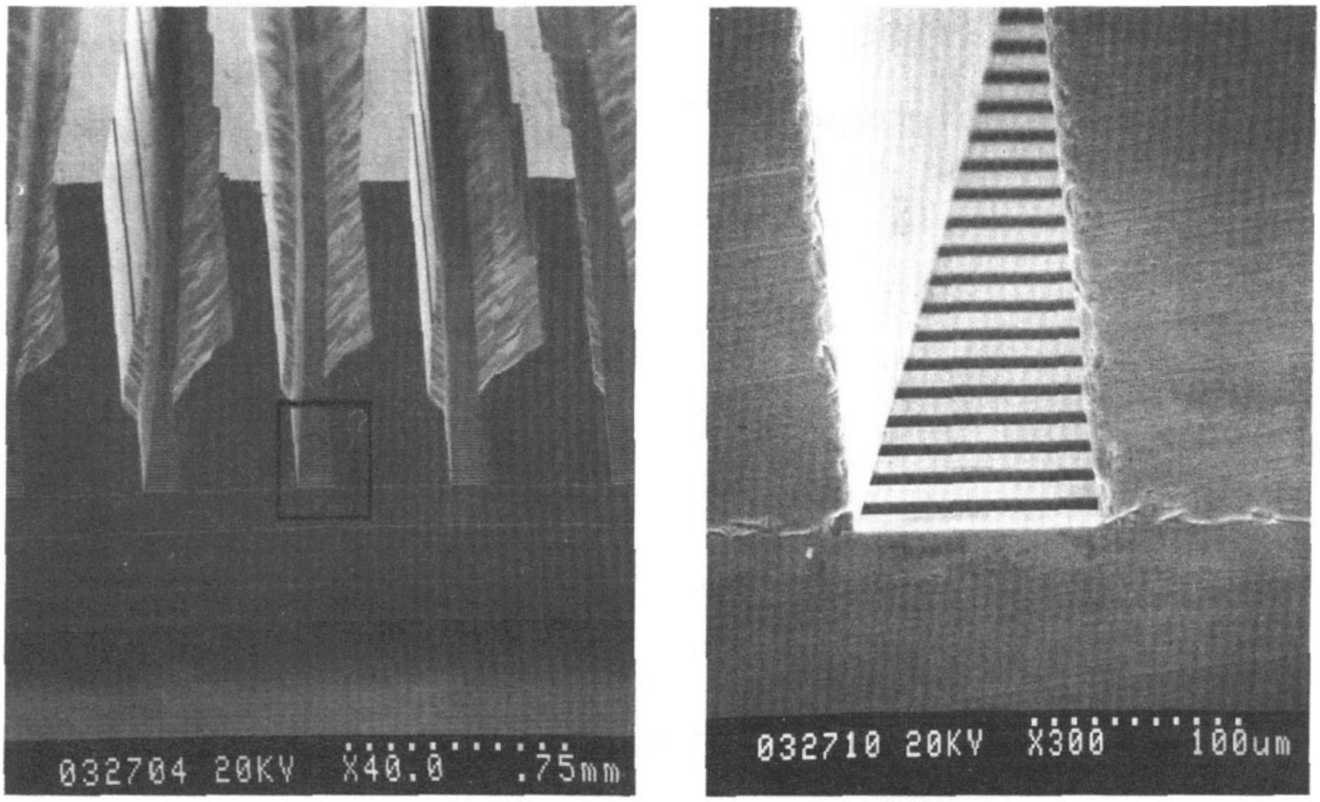

Figure 2. Cross section scanning electron micrograph of a bonded structure and detail. The rough edge seen at the location of the contact plane is a result of fracturing the structure for the cross section and not a bond interface.

500 μm pitch. The manifold slots taper down through the thickness of the wafer so that the bottom half of the slot always intersects the bonding surface of the wafer as a uniform 90 μm wide by 16.4 mm long rectangle. The result is that there are uniform 410 μm stripes of the original manifold wafer surface, ordered with a 500 μm pitch, which will bond to the heat channels. When the wafers are bonded together, the tapered manifold slots are at right angles to the heat channel slots. Adjacent manifold slots alternate between water feed and water return functions. The heat channel slots are 25 μm wide and 125 μm deep, with a 50 μm pitch. For the work described here, 3-inch wafers, each with four cooling structures, were used. Each structure consists of an array of 125 heat channels bonded to 40 manifold slots, resulting in 5000 points of (25 μm × 410 μm) repetitive contact area.

The manifolds and heat channels are wet-chemical micro-machined in Si_3N_4-coated silicon wafers. The patterned Si_3N_4, which was used as a masking material, was removed before bonding. After micromachining the heat channels and manifolds a modified RCA clean, omitting the buffered HF dip, is performed. Immediately after a fifteen minute deionized water rinse, the wafers are put in a spin rinser/dryer. The resistivity set point of the effluent water from the spin rinser/dryer is greater than 14 MΩ cm to assure maximum wafer surface reactivity.

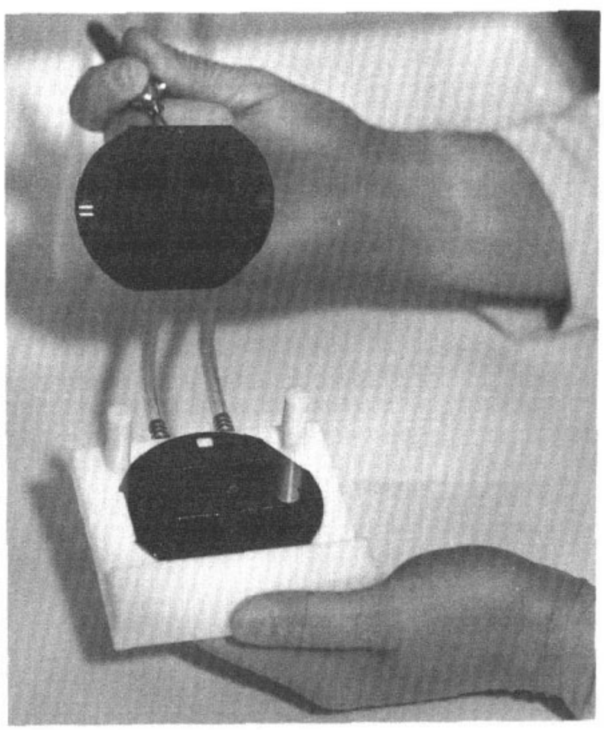

Figure 3. Teflon alignment jig with wafers about to be bonded. Vacuum lines feed to the underside of the manifold slots.

The wavers are then immediately aligned and bonded while the surfaces remain reactive.

Wafers are bonded in a class-100 clean room. Vacuum tweezers are used exclusively to handle the wafers. An alignment jig, seen in figure 3, is used to provide rough alignment of the manifold and heat channel wafers. This fixture is made from Teflon and contains four vacuum holes: one vacuum hole for each manifold in the 3-inch manifold wafer. After the cleaning treatment, the manifold wafer is placed on the vacuum fixture. The heat channel wafer is then positioned over the manifold wafer so that the direction of the heat channels is perpendicular to the direction of the manifold channels. Both wafers have alignment flats etched into their perimeters to obtain precise $x-y$ and rotational alignment. After the wafers are in position, vacuum is applied to the bonding fixture. It should be noted that the weak-bonding phenomenon will transpire without any use of vacuum assistance. However, use of the vacuum does increase the yield. The vacuum is held on the fixture for approximately 5 min. Once the wafers are brought together, the bond quality is monitored using IR transmission imaging. Figure 4 is an example of an IR image of the weak-bonded micromachined wafers. The four rectangular regions on the bonded wafers represent four separate heat sinks. Fringing can be seen around the outer regions of the wafer indicating areas where some voids exist.

Annealing is performed at a temperature of 1200°C for forty minutes in a dry N_2 ambient. The wafers are placed in a quartz holder designed to hold 3-inch wafers in a horizontal position in the furnace. Figure 5 shows a C-scan acoustic micrograph of the same wafer as in figure 4 after annealing. Again, areas of fringing can be seen where the wafers are not bonded.

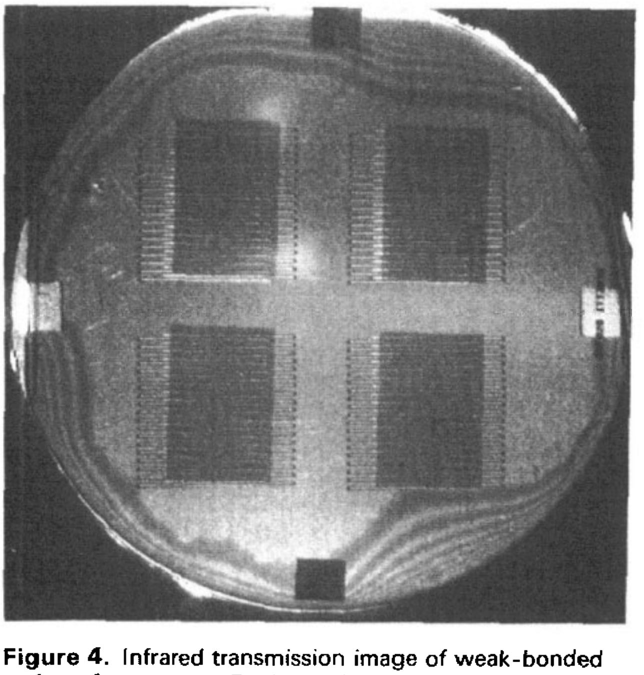

Figure 4. Infrared transmission image of weak-bonded wafers after contact. Regions of no bonding can be seen along the edges.

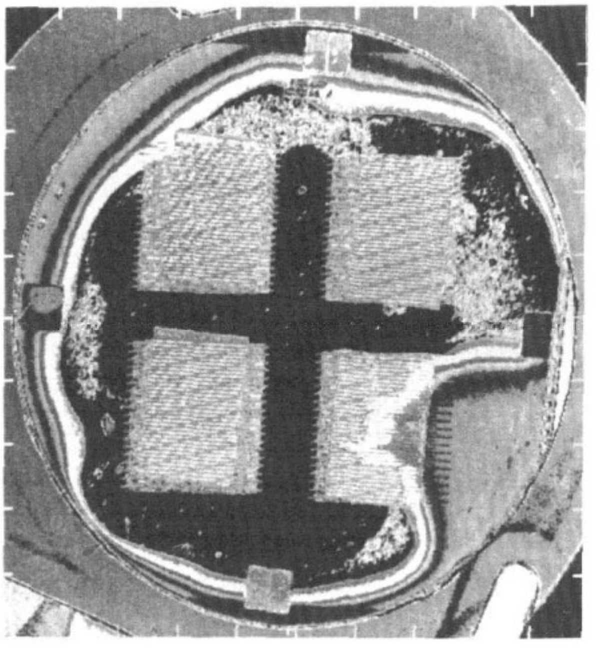

Figure 5. C-scan acoustic micrograph of wafers as shown in figure 4, after the contact bond has been annealed. The image clearly shows all regions of bonds and voids.

3. Testing

The heat sink assembly is designed to operate at a pressure of 50 psig using water as the coolant. Pressure tests were conducted to assess the ultimate strength of the bonded assembly. Water was supplied to the slots in the bonded pyrex glass plate with a water pump. The assembly failed catastrophically at a pressure of 320 psig. Inspection of the failed assembly showed that the bulk silicon fractured rather than the bonded regions. This result is in agreement with the findings of Lasky [1], where microscopic inspection of the interlayer between bonded whole wafers reveals the elimination of the bond interface after the annealing step.

The completed microchannel cooling assembly has successfully demonstrated cooling of approximately $100\,W\,cm^{-2}$, for CW laser diode array operation in accordance with the design specification. However, no independent testing has been performed to verify the maximum cooling capacity of these structures.

4. Conclusion

Two micromachined wafers were bonded together using silicon thermal direct bonding, without electrostatic assistance. It is believed that the $25\,\mu m \times 410\,\mu m$ area of the discrete points of contact between the two wafers represents the smallest bond area utilized reproducibly over a large total region of silicon to be attached. The bonded wafers withstood water pressures as high as 320 psi, indicating not only a well bonded structure, but complete bonding of the total 5000 distinct points of contact for each of the heat channel structures being fabricated.

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