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# Formation of Silicon-Gold Eutectic Bond Using Localized Heating Method

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A new bonding technique is proposed by using localized heating to supply the bonding energy. Heating is achieved by applying a dc current through micromachined heaters made of gold which serves as both the heating and bonding material. At the interface of silicon and gold, the formation of eutectic bond takes place in about 5 minutes. Assembly of two substrates in microfabrication processes can be achieved by using this method. In this paper the following important results are obtained: 1) Gold diffuses into silicon to form a strong eutectic bond by means of localized heating. 2) The bonding strength reaches the fracture toughness of the bulk silicon. 3) This bonding technique greatly simplifies device fabrication and assembly processes.

KEYWORDS: microheater, localized heating, eutectic bonding, silicon-gold system, microfabrication

Silicon-gold eutectic bonding has been a very important technique in microfabrication.[1,2] It provides high bonding strength and good stability at a relatively low processing temperature (about 363°C). However, bonding problems related to defects and nonuniformity have been reported.[3] Moreover, the conventional bonding process is useless when materials that can not survive the bonding temperature of 363°C are present in the to-be-assembled substrates. A simple and widely applicable gold-silicon bonding technique is proposed in this paper. The concept of localized heating is introduced to confine the high temperature bonding region in a small area such that damage to temperature-sensitive materials at other regions can be avoided. More importantly, stronger and faster eutectic bond is expected because higher processing temperature can now be conducted effectively. Potential preferable applications of this technique include: (a) replacement of time-consuming, global eutectic-bonding processes that use regular furnaces, (b) formation of strong eutectic bond faster than before due to the high but localized heating technique, (c) device assembly or packaging for substrates having temperature-sensitive materials, (d) investigations of interface bonding mechanism *in situ* and locally.

Figure 1 shows the experimental set-up for the newly proposed bonding system and technique. Both the microscope and micromanipulators are used for the alignment of the top silicon substrate to the gold microheater which was deposited on the bottom silicon substrate. The alignment the electrical probes to the contact pads is also performed under the microscope to provide interconnections for power transmission. In preparing the bottom substrate samples for experiments, a layer of 1 $\mu$m thick thermal silicon dioxide is grown on the top of a silicon wafer. Two layers, including 500Å of Chromium and 4500Å of gold, are sputtered on top of the oxide layer, respectively. Two types of heaters with widths of 5 and 7 $\mu$m are patterned and fabricated using the lift-off process. A second piece of silicon is then placed on top of the micro heater. About 1 MPa of pressure is applied to create intimate contact between the interface of silicon substrate and gold microheaters. The silicon dioxide film serves as the electrical as well as the thermal insulation layer. The silicon substrate acts as a heat sink because of its high thermal conductivity. Recent heat transfer studies on microheaters have shown that it is feasible to create a high temperature area in a confined, local region[4] as shown in Fig. 2.

The temperature on the resistive heater is characterized by

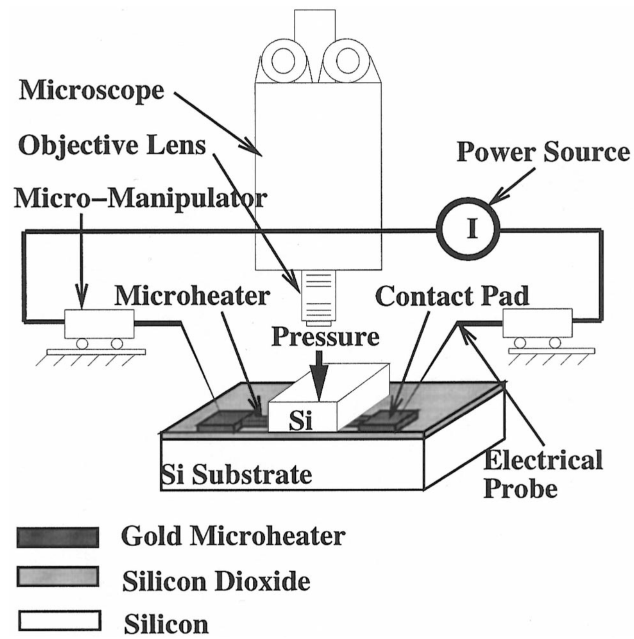


Fig. 1. Experimental setup for the localized bonding system.

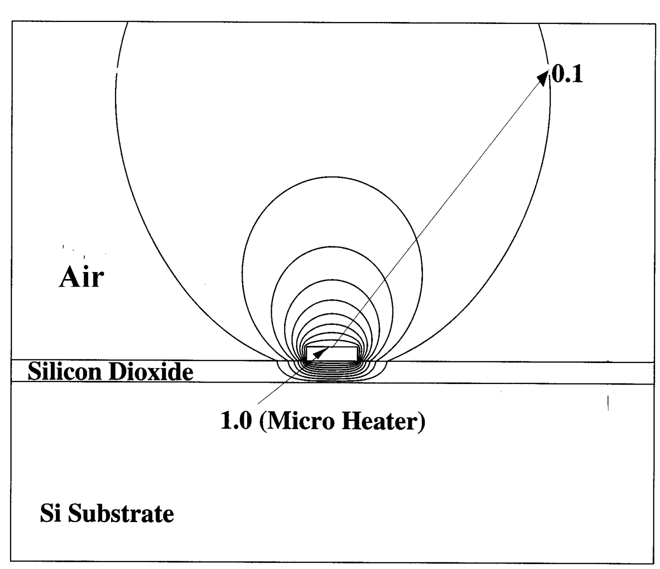


Fig. 2. Numerical simulation of isotherms around a microheater on top of silicon substrate.

assuming a linear dependence of resistivity changes with respect to temperature:

$$\rho(T) = \rho_o(1 + \alpha(T - T_o)) \tag{1}$$

Here $\rho$ is the resistivity of gold and $\alpha$ is the temperature coefficient of resistivity. Subscript "o" represents the room temperature environment. The resistivity of gold is measured to be $2.65 \times 10^{-8}$ Ω-cm at room temperature and $\alpha$ is estimated[5] to be $3.32 \times 10^{-3}$/°K.

Figure 3 shows the temperature measurements for 5 and 7 $\mu$m wide gold resistive heaters with respect to different input currents. The temperatures rise very quickly when the input currents are close to 0.28 and 0.38 Amp for the 5 and 7 $\mu$m wide gold microheaters, respectively. Experimentally, localized silicon-gold bonding starts when the input currents are slightly above these values. During the eutectic bonding process, gold diffuses into silicon and the resistivity of the heater increases. The current density has to be increased to maintain a high temperature during the bonding process. The whole bonding process was found to be accomplished in about 5 minutes. The same structures are put in a regular furnace and the conventional silicon-gold bonding process is performed for comparison. In this global heating and bonding process, the temperature is ramped to 410°C in 10 minutes and is maintained for 10 minutes before cooling down to room temperature. The whole process takes more than one hour.

The bonding characteristics are examined by forcefully breaking the silicon-gold eutectic bonds. The bond formed by the conventional process is shown first in Fig. 4. Non-uniform bonding characteristics can be clearly identified. This result is similar to that reported by A. L. Tiensuu *et al.*[6] According to the gold-silicon eutectic bonding mechanism, gold silicide will epitaxially grow on the silicon substrate. Since (100) silicon substrate was used in these experiments, square-shape silicide forms at the interface.

The result from the proposed localized bonding process is shown in Fig. 5. After the bond is forcefully broken, it is observed that the entire gold line disappeared in this case and only silicon residues are left. The fact that the silicon-gold interface remains intact and either bulk silicon or gold-oxide interface is broken indicates a strong silicon-gold eutectic bond which has comparable or higher fracture strength than the bulk silicon. Previous experiments[7–9] have shown that silicon-gold alloy is formed when the temperature of the silicon-gold system is above the eutectic temperature. According to the silicon-gold phase diagram,[10] more gold-silicon liquid phase alloy forms at higher temperatures. Therefore, it is desirable to increase the processing temperature to achieve thicker and more uniform silicon alloy.[11,12] This can be easily conducted by using the technique of localized bonding process proposed here.

In order to investigate the compound of the silicon-gold system, gold etchant is applied for about 30 minutes to analyze the debris of Fig. 5. The enlarged SEM micrograph of

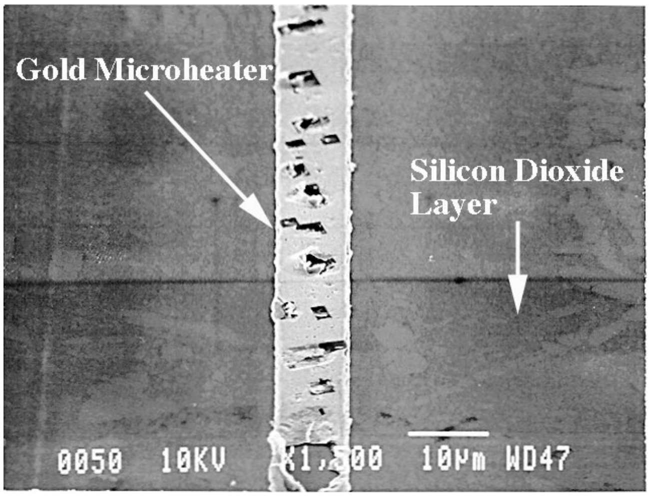


Fig. 4. Non-uniformity is observed on the surface of gold after forcefully breaking the eutectic bond which was formed by using a conventional heating process.

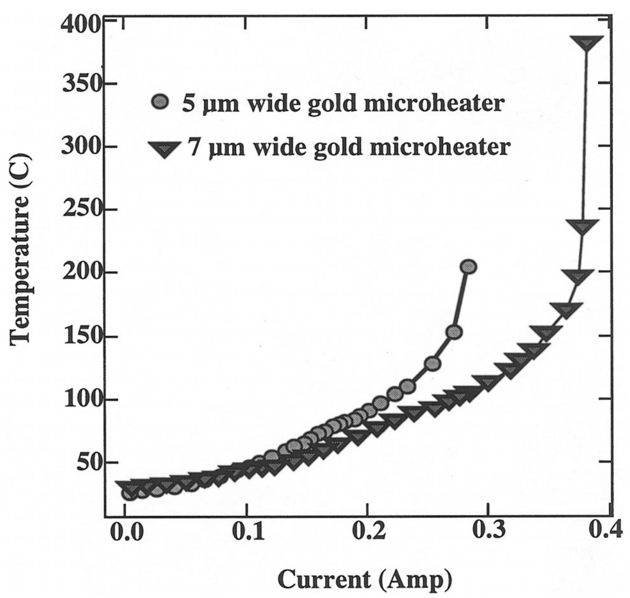


Fig. 3. Measured input current with respect to estimated temperature.

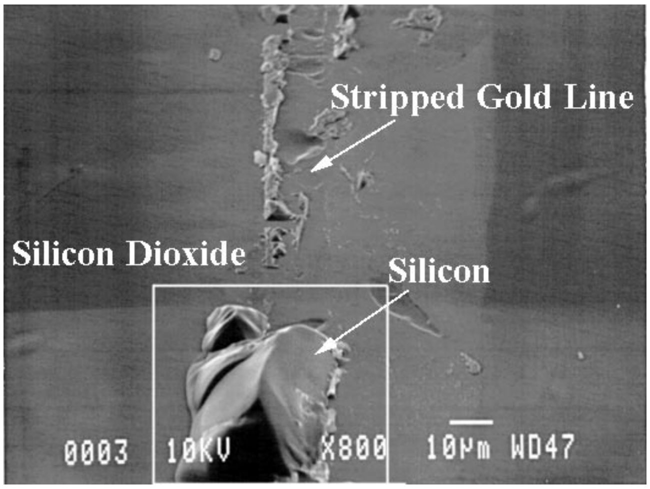


Fig. 5. A SEM micrograph showing the gold microheater after forcefully breaking the silicon-gold eutectic bond which was formed by using the localized heating method. Gold microheater is disappeared. The strength of the bond is comparable with the fracture toughness of the bulk silicon such that the fracture and separation occur either in the bulk silicon or at the gold-silicon dioxide interface.


Fig. 6. Enlarge view showing the square box portion of Fig. 5 after the sample was immersed in gold etchant for 30 minutes. Part of the residues were etched away due to the diffusion of gold into the silicon substrate.

Fig. 6 shows that some debris is etched away. Since gold etchant has little effect on silicon, pure silicon can survive the etching process. The part being etched away must have gold composition that was diffused into the bulk silicon during the bonding process.

Strong silicon-gold eutectic bond has been achieved by the newly proposed localized bonding process. It appears that high temperature heating can be confined in a small region by using microheaters as the heating sources. Stronger and more uniform bonding is achieved by increasing the processing temperature locally and keeping the temperature low globally at the wafer level. We believe this technique can greatly simplify device fabrication and packaging at both the wafer and chip levels.

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1) W. H. Ko, J. T. Suminyo and G. J. Yeh: *Micromachining and Micropackage for Transducers* (Elservier Science Publishers, 1985).
2) P. M. Zavracky, and B. Vu: SPIE **2639** (1995) 46.
3) M. B. Cohn, Y. Liang, R. T. Howe and A. P. Pisano: Tech. Dig. of Solid State Sensor & Actuator Workshop, 1996, p. 32.
4) Liwei Lin: Ph. D Thesis, Mechanical Engineering Dept., University of California at Berkeley, 1993.
5) R. A. Matula: J. Phys. Chem. **8** (1979) 147.
6) A. L. Tiensuu, M. Bexell, J. A. Schweitz, L. Smith and S. Johansson: Sensors & Actuators A**45** (1994) 227.
7) M. Moniwa, K. Kusukawa, E. Murakami, T. Warabisako and M. Miyao: Appl. Phys. Lett. **52** (1988) 1788.
8) L. H. Allen, J. W. Mayer and K. N. Tu: Phys. Rev. B **41** (1990) 8213.
9) A. Hiraki: J. Appl. Phys. **22** (1983) 549.
10) H. Okamoto and T. B. Massalski: *Binary Phase Diagrams* (1986) p. 312.
11) P. H. Chang, G. Berman and C. C. Chen: J. Appl. Phys. **63** (1988) 1473.
12) K. Sedar, G. Kuri, P. V. Satyam, B. Sundaravel, D. P. Mahapatra and B. N. Dev: Phys. Rev. B**51** (1995) 1433.