Thermal-Electrical FEA of Localized Heating for MEMS Packaging

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ABSTRACT

Localized silicon fusion and eutectic bonding for MEMS packaging have been preliminarily investigated through the U.S. Army SBIR Phase I program entitled “Multi-Power Source for MEMS Packaging”, contract #: W56HZV-05-C-0092. This methodology allows localized heating at the bonding area without overheating the temperature-sensitive MEMS device. This paper presents the newly developed three-dimensional finite element analysis (FEA) of localized heating for MEMS packaging, for analysis of the electrical problem, thermal problem, and the coupling between the two problems. It was confirmed that high temperature is confined and controllable in the heater-on-circuit localized heating technology.

1. INTRODUCTION

Micro electro-mechanical system (MEMS) represents the integration of mechanical components, sensors, actuators and electronics on a silicon wafer. MEMS devices are in demand for applications that range from automobiles and aerospace to biomedical, navigation and cell phones, including accelerometers, gyroscopes, pressure sensors, optical scanners, RF switches, etc [1-5]. While MEMS are shrinking sensors and actuators into micro and nanometer scales, MEMS packaging, the most expensive and time-consuming step in overall MEMS manufacturing, emerges as the bottleneck for successful device commercialization [6]. Usually, MEMS packaging starts after micromachining is complete or released. This post-packaging process must not damage either pre-fabricated MEMS microstructures or microelectronics. The key additional requirements on MEMS packaging beyond the

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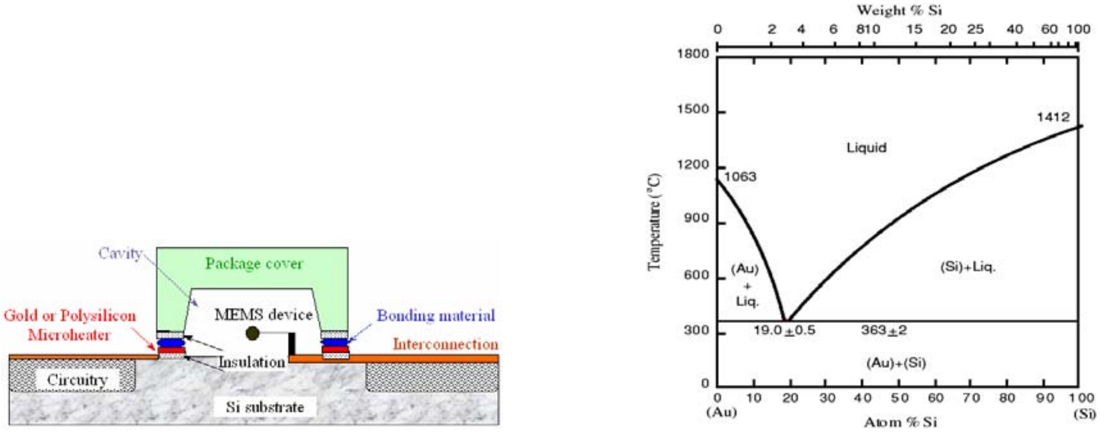
packaging requirements of standard semiconductor devices are to maintain a cavity for the motion of the MEMS and to prevent contamination due to the sensitive nature of the MEMS' moving structures and their exposed surfaces. The rigorous MEMS packaging requirements involve wafer-level packaging, hermetic sealing, and long-term stability [7-12]. The processes may need to be done at 200~1000°C, however, the temperature-sensitive electronic circuitry and MEMS devices must be kept from overheating (<400°C). A potential solution is to develop localized heating method to ensure reliable bonding without affecting other components. This work is focusing to develop a methodology of the three-dimensional finite element analysis (FEA) for MEMS packaging on die level by localized heating and silicon-gold eutectic bonding, a heater-on-circuit technology is being investigated.

2. LOCALIZED HEATING AND Au-Si EUTECTIC BONDING

Using microheaters instead of global heating furnaces, as shown in Fig.1 (a), provides localized heating. These microheaters are constructed in a way that heating is restricted in a small region surrounding by insulation materials. Based on the principle of silicon-gold eutectic bonding, gold microheaters was built and subject to be bonded to a cap substrate, A Si wafer was used as the substrate. A SiO_2 thin film was deposited on the Si wafer surface, which serves as the thermal and electric insulation. The gold resistive heater was sputtered on the top of the oxide layer. The gold microheater was used as the heating and bonding material. A silicon cap substrate was placed on the top of the microheater and in intimate contact. When an electrical current is applied, the temperature of the microheater rises to activate the bonding process. The gold in intimate contact with the silicon is heating up to at least 363°C, which causes the gold atoms to diffuse into the silicon. When the eutectic composition (19 at% of Silicon) is reached, as shown in Fig.1 (b), a liquid layer is formed at the interface and the eutectic alloy grows until the gold is exhausted. The alloy can then be cooled slowly, causing it to solidify and hence forming the bond.

Based on the principle of localized heating and Au-Si eutectic bonding, gold microheaters was built and subject to be bonded to a cap substrate, as illustrated in Fig. 2. A P-type Si wafer with (100) orientation was used as the substrate. A silicon dioxide (SiO_2) thin film was deposited on the Si wafer surface, which serves as the thermal and electric insulation. Then, the gold resistive heater was sputtered on the top of the oxide layer. The microheater was patterned in a line-shape with contact pads in two ends. The gold microheater was used as the heating and bonding material. A silicon cap substrate was placed on the top of the microheater and in intimate contact. When an electrical current is applied, the temperature of the microheater rises to activate the bonding process. The gold in intimate contact with the silicon is heating up to at least 363°C, which causes the gold atoms to diffuse into the silicon. This process is suitable to bond silicon wafer to wafer with hermetic packaging.



(a) (b)

Fig. 1 (a) MEMS packaging by localized heating and bonding, (b) Binary phase Diagram of Au-Si alloy.

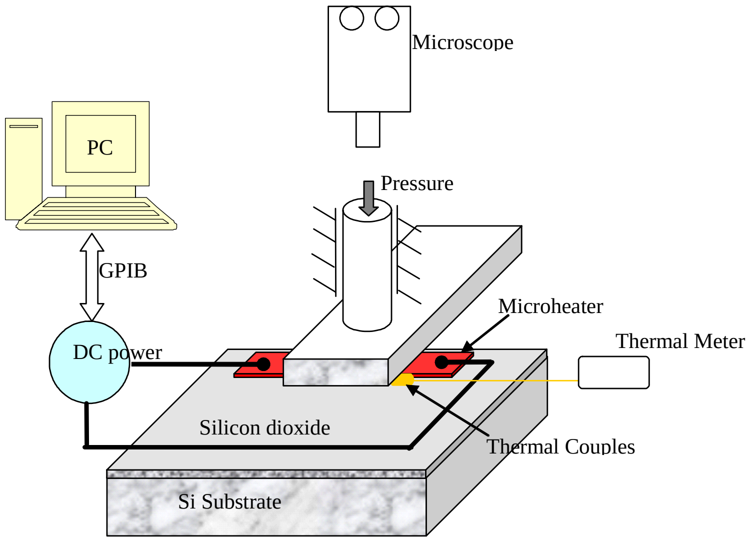


Fig.2 Schematic of the bonding stage.

3. THERMAL-ELECTRICAL FE MODELING OF LOCALIZED HEATING FOR MEMS PACKAGING

A three-dimensional finite element (FE) modeling was established for analysis of the coupled thermal-electrical problems of MEMS packaging. Joule heating arises when the energy dissipated by an electrical current flowing through the gold microheater is converted into thermal energy for bonding.

3.1 Line-shape Model

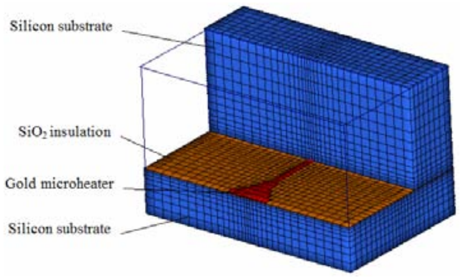
The cross-sectional view of a line-shape model is shown in Fig.3 (a). The structure configuration and dimensions of the model were designed based on our fusion bonding experimental setup described above. ABAQUS/Standard was used for analysis of the coupled thermal-electrical procedure, including analysis of the electrical problem, the thermal problem, and the coupling between the two problems [13]. The physical properties used in the simulation are listed in Table 1.

Fig.3 (b) shows temperature distribution on a gold microheater with the dimensions of 100×8×1.5 µm. It was found that under an input current of 1.3Amp, the heater could generate a temperature of about 450°C. The simulated heat transfer is shown in Fig.3 (a) and b) illustrating the isotherms of the silicon-gold bonding process. The steady-state isotherms on the cross section diagram clearly demonstrate that the high temperature region is confined in a small area surrounding the heater. When temperature on the center of the microheater reaches 450°C, the temperature is only 50°C, in a distance of less than 1µm into the insulation layer. The most area of the silicon substrate maintains at room temperature during the process. Therefore, localized heating can be achieved without affecting the microelectronics or other temperature sensitive materials at the wafer-level. It was confirmed that high temperature is confined and controllable in the heater-on-circuit localized heating technology.

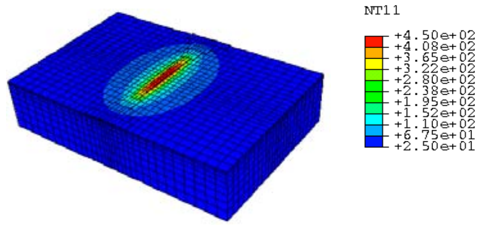
Table 1. Physical properties

	Thermal conductivity W/(m K)		Electrical conductivity (1/Ω-m)		Specific heat cal/(g K)		Density (g/cm^3)
Gold	317.0	at 313K	4.5×10^{7}	at 313K	108.0	at 313K	19.32
	304.0	at 500K	1.1×10^{7}	at 1000K	205.0	at 1100K	
	284.0	at 800K					
	255.0	at 1200K					
Silicon	136.0	at 313K	1.6×10^{-3}	at 313K	0.180	at 298K	2.2
	105.0	at 800K	3.0×10^{-4}	at 1100K	0.253	at 1800K	
Silicon dioxide	1.4	at 313K	1.0×10^{-6}	at 313K	700.0		2.2

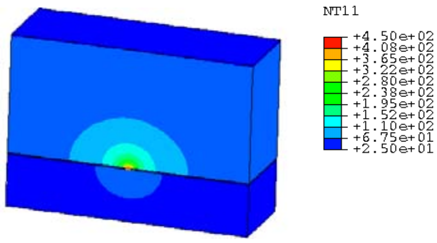
0.1	at 800K	1.0×10^{-5}	at 110K



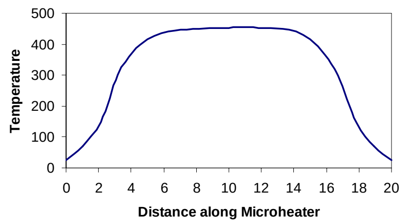
(a) FE model



(b) Isotherms of the device substrate and the gold microheater.



(c) Isotherms of the cross-section



(d) Temperature distribution along the longitudinal direction of the gold microheater

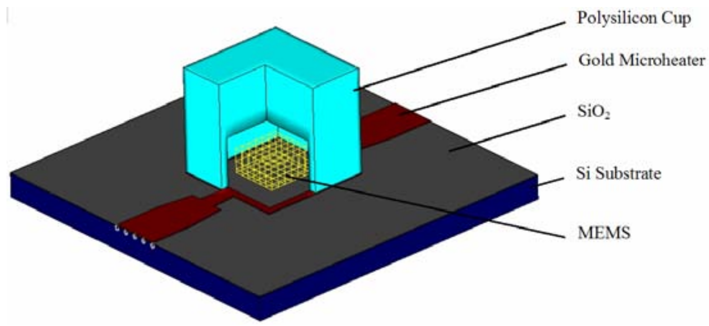
Fig.3 Line-shape FE modeling of localized heating

3.2 Cup Model

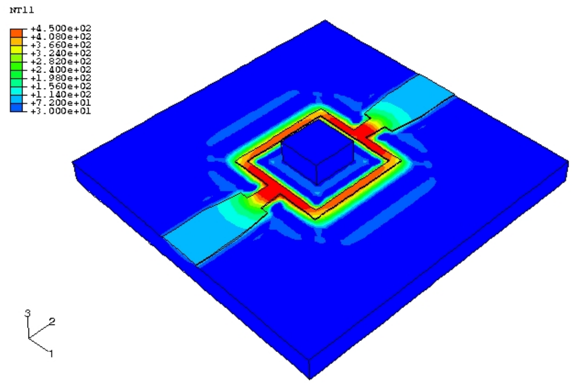
A three-dimensional FE modeling was established for MEMS packaging with localized heating/bonding. It consists of MEMS, Si substrate, SiO_2 insulation, microheater, and polysilicon cup, as shown in Fig.4 (a). The MEMS' dimensions are 60×60×30μm. The cross-section and the edge dimensions of the gold microheater in the bonding area are 10×1.5×120μm. The simulation results as shown in Fig. 4 (b-c) infer that:

1) The temperature of the MEMS inside the package remains below 30°C while the temperature of bonding area is above 450°C in steady status, which confirmed the concept of localized heating.

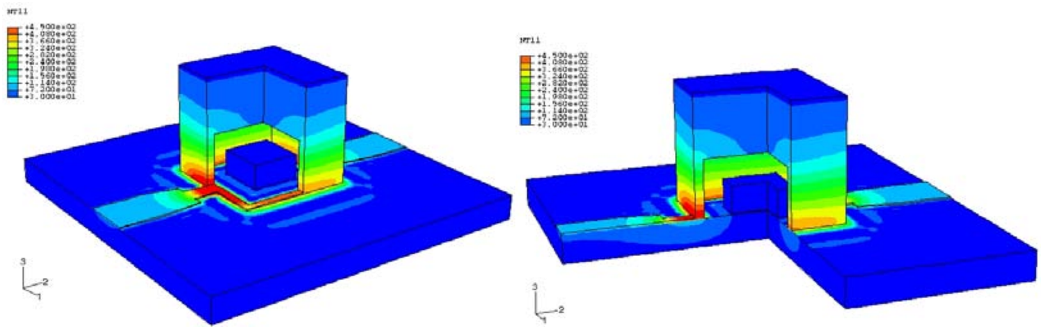
2) The distribution of temperature on the microheater is not uniform. The temperature of the corner is lower than that of the center because of the difference of cross-section area.



(a) Cup Shape Model



(b) Isotherms of the device substrate and the gold microheater



(c) Isotherms of the MEMS, substrate and gold microheater

Fig.4 Cup model of MEMS packaging with localized heating

4. DISCUSSIONS AND CONCLUSION

MEMS post-packaging by localized heating and bonding provides unique opportunities in developing packaging processes for microsystems with theoretical, experimental and engineering challenges. The phase I work addressed the fundamental issues and approaches in the packaging of MEMS devices and provides directions for future research. From the thermal-electrical modeling of localized heating, it was confirmed that high temperature is confined and temperature is controllable.

In order to achieve a successfully localized heating and bonding technology applied to a uniform, high-yield, reproducible, Au-Si eutectic bonding for wafer-level MEMS vacuum packaging, several fundamental and challenging problems should be carefully studied in both theoretical and experimental regimes. Specific areas to be explored are as follows:

1) Characterizations of localized bonding mechanisms such as the bond quality and uniformity between silicon-gold, and polysilicon-gold.
2) Investigations of the effects of temperature, environment, time, applied pressure and surface roughness on the bonding processes.
3) Investigations of long term stability of localized bonds such as tensile and shear tests, hermeticity, leakage with respect to time and harsh environment and accelerated test.
4) Schemes and processes for massively parallel MEMS post-packaging by localized heating and bonding that can be conducted as batch fabrication.

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