

# MEMS Post-Packaging by Localized Heating and Bonding

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**Abstract**—This work addresses important post-packaging issues for microsystems and recommends specific research directions by localized heating and bonding. Micropackaging has become a major subject for both scientific research and industrial applications in the emerging field of microelectromechanical systems (MEMS). Establishing a versatile post-packaging process not only advances the field but also speeds up the product commercialization cycle. A review of engineering bases describing current technologies of MEMS packaging and wafer bonding is followed by an innovative post-packaging approach by localized heating and bonding. Process demonstrations by selective encapsulation are presented, including an integrated low pressure chemical vapor deposition (LPCVD) sealing process, localized silicon-gold eutectic bonding, localized silicon-glass fusion bonding, localized solder bonding and localized CVD bonding processes.

**Index Terms**—CVD bonding, eutectic bonding, fusion bonding, MEMS, packaging, solder bond.

## I. INTRODUCTION

**M**ICROELECTROMECHANICAL systems (MEMS) are shrinking sensors and actuators into micro- and nanometer scales [1] while micropackaging emerges as the bottleneck for successful device commercialization. In the conventional integrated circuit (IC) fabrication, packaging contributes about one third of the manufacturing cost [2], [3]. MEMS packaging has stringent requirements due to the fragile microstructures and is generally considered to be the most expensive step in MEMS manufacturing. It has been suggested that MEMS packaging should be incorporated in the device fabrication stage as part of the micromachining process. Although this approach solves the packaging need for individual devices, it does not solve the packaging need for many microsystems. Especially, many MEMS devices are now fabricated by foundry services [4], [5] and there is a tremendous need for a uniform packaging process.

The MEMS post-packaging process must meet several requirements. It should not damage either pre-fabricated MEMS microstructures or microelectronics. It should be applicable to different MEMS processes for various applications. It should adopt the well-developed IC packaging technology to save research and development efforts. In addition, some MEMS devices require *hermetic vacuum sealing* [6], [7] and some others require *low temperature packaging*. In order to accomplish

these goals, several key elements are proposed: a cap to protect MEMS devices, a strong bond for hermetic sealing, wafer-level and batch processing to lower the manufacturing cost, low temperature processing to prevent damages to MEMS devices. The existing MEMS packaging technologies, including packaging and bonding research, are discussed first and followed by the innovative approach of “MEMS post-packaging by localized heating and bonding.”

### A. MEMS Packaging Research

Fung *et al.* has edited a book, *Micromachining and Micropackaging of Transducers* [8], which summarized many MEMS packaging issues before 1985. In addition to this book, Senturia and Smith [9] discussed the packaging and partitioning issues for microsystems. Smith and Collins [10] used epoxy to bond glass and silicon for chemical sensors. Laskar and Blythe [11] developed a multichip modules (MCM) type packaging process by using epoxy. Reichl [12] discussed different materials for bonding and interconnection. Grisel *et al.* [13] designed a special process to package micro-chemical sensors. Special processes have also been developed for MEMS packaging, such as packaging for microelectrode [14], packaging for biomedical systems [15] and packaging for space systems [16]. These specially designed, device oriented packaging methods are aimed for individual systems. There is no reliable method yet that would qualify as a versatile post-packaging process for MEMS with the rigorous process requirements of low temperature, hermetic sealing and long-term stability.

Previously, an integrated process by using surface-micromachined microshells has been developed [17]. This process applies the concepts of sacrificial layer and LPCVD sealing to achieve wafer-level post-packaging. Similar processes have been demonstrated. For example, Guckle *et al.* [18] developed a reactive sealing method to seal vibratory micromachined beams. Ikeda *et al.* [19] adopted epitaxial silicon to seal microstructures. Mastrangelo *et al.* [20] used silicon nitride to seal mechanical beams as light sources. Smith *et al.* [21] accomplished a new fabrication technology by embedding microstructures and CMOS circuitry. All of these methods have integrated the MEMS process together with the post-packaging process such that no extra bonding process is required. However, these schemes are highly process dependent and not suitable for pre-fabricated circuitry.

Recently, several new efforts for MEMS post-packaging processes have been reported. In 1997, Butler *et al.* [22] demonstrated an advanced MCM packaging scheme. It adopts the high density interconnect (HDI) process consisting of embedding bare die into pre-milled substrates. Because the MEMS struc-

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TABLE I  
SUMMARY OF BONDING MECHANISMS. LH = LOCALIZED HEATING

Bonding Methods	Temperature	Roughness	Hermeticity	Post-Packaging	Reliability
Fusion bonding	very high	highly sensitive	yes	yes by LH	good
Anodic bonding	medium	highly sensitive	yes	difficult	good
Epoxy bonding	low	low	no	yes	???
Integrated process	high	medium	yes	no	good
Low Temp. bonding	low	highly sensitive	???	no	???
Eutectic bonding	medium	low	yes	yes by LH	???
Brazing	very high	low	yes	yes by LH	good

tures have to be released after the packaging process such that it is undesirable for general microsystems. Van der Groen *et al.* [23] reported a transfer technique for CMOS circuits based on epoxy bonding. This process overcomes the surface roughness problem but epoxy is not a good material for hermetic sealing. In 1996, Cohn *et al.* [24] demonstrated a wafer-to-wafer vacuum packaging process by using Silicon-Gold eutectic bonding with a 2  $\mu\text{m}$ -thick polysilicon microcap. However, experimental results show substantial leakage after a period of 50 days. These recent and on-going research efforts indicate the strong need for a versatile MEMS post-packaging process.

### B. Wafer Bonding Research

It is well known that “*intimate contact*” and “*temperature*” are two major factors for the bonding process and bonding is the key in device packaging. “*Intimate contact*” puts two separated surfaces together and “*temperature*” provides the bonding energy. In 1983, Anthony did a theoretical study on the effects of surface roughness to the anodic bonding process [25]. He concluded that surface imperfection affects the bonding parameters including temperature, time and applied forces. Although “*reflow*” or “*mechanical polishing*” processes can improve the surface flatness, yet these processes are not readily applicable in most of the MEMS fabrication processes. On the temperature side, many commonly used bonding methods such as fusion and anodic bonding require high temperatures that may damage the devices and cause thermal stress problems. On the other hand, raising the processing temperature may be inevitable to achieve good bonds.

Previously, silicon-bonding technologies have been used in many types of MEMS devices. For example, devices like pressure sensors, micropumps, bio-medical sensors or chemical sensors require mechanical interconnectors to be bonded on the substrate (see for example [26]–[28]). Glass has been commonly used as the bonding material by anodic bonding at a temperature of about 300–450°C (see for example, [29], [30]). Peterson [31] and Schmit [32] have demonstrated different types of silicon fusion bonding and Si-SiO<sub>2</sub> bonding processes at very high temperatures of over 1000 °C. Ko [33], Tiensuu [34], Lee [35] and Cohn [24] have used eutectic bonding for different applica-

tions. Silicon fusion bonding is mostly used in silicon-on-insulator (SOI) technology such as Si-SiO<sub>2</sub> bonding [36] and Silicon-Silicon bonding [37]. It is a proven method and the bonding strength is enormously strong. Unfortunately, since the temper-

ature requirement is generally higher than 1000 °C, it is not suitable for MEMS post-packaging. Recently, there are reports for low temperature Silicon-Silicon bonding [38]–[40]. These new methods have to be conducted with special surface treatments that are not desirable for MEMS post-packaging.

The invention of anodic bonding dates back to 1969 [41] when Wallis and Pomerantz found that glass and metal can be bonded together at about 200–400 °C below the melting point of glass with the aid of a high electrical field. This technology has been widely used for protecting on-board electronics in biosensors [see for example [42]–[44] and sealing cavities in pressure sensors [see for example, [45]. Many reports have also discussed the possibility of lowering the bonding temperature by different mechanisms [46], [47]. Unfortunately, the possible contamination due to excessive alkali metal in the glass; possible damage to microelectronics due to the high electrical field; and the requirement of flat surface for bonding limit the application of anodic bonding to MEMS post-packaging [48].

In addition to the above solid type silicon bonding, liquid type bonding mechanisms have been demonstrated. Gold has been the most common material used in silicon eutectic bonding. Gold can form a eutectic alloy with Silicon at 363 °C which is a much lower melting temperature than either that of pure Gold or Silicon. In order to get good eutectic bond, process conditions including temperature and time have to be well controlled.

Table I summarizes all the MEMS packaging and bonding technologies and their limitations. An innovative bonding approach by localized heating and bonding is also presented. This new approach aims to provide *high temperature* in a *confined region* for achieving excellent bonding strength and to keep the temperature low at the wafer-level for preserving MEMS microstructures and microelectronics. The localized heating approach introduces several new opportunities. First, better and faster temperature control can be achieved. Second, higher temperature can be applied to improve the bonding quality. Third, new bonding mechanisms that require high temperature such as brazing [49] may now be explored in MEMS applications. As such, it has potential applications for a wide-range of MEMS devices and is expected to advance the field of MEMS packaging.

## II. MEMS POST-PACKAGING

Fig. 1 shows a microaccelerometer fabricated by Analog Devices Inc. [4]. The most fragile part on this device is the mechanical sensor at the center that is a freestanding mechanical, mass-

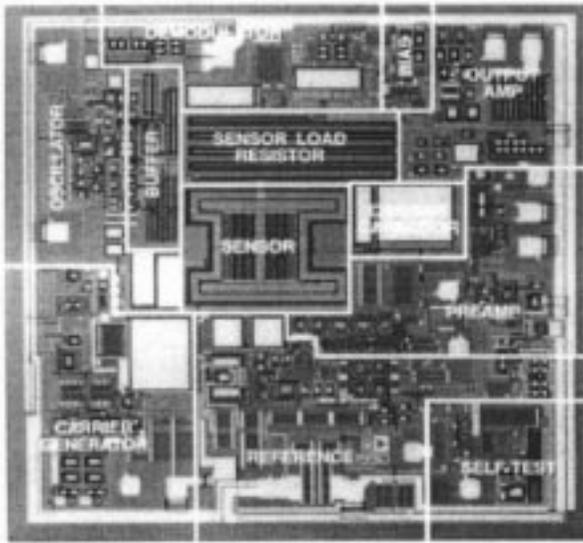


Fig. 1. MEMS sensor with integrated circuit [4].

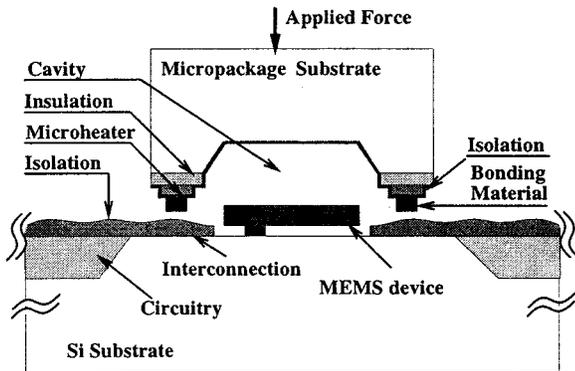


Fig. 2. Schematic diagram of MEMS post-microelectronics packaging by localized heating and bonding.

spring microstructure. It is desirable to protect this mechanical part during the packaging and handling process. Moreover, vacuum encapsulation may be required for these microstructures in applications such as resonant accelerometers or gyroscopes [6], [7]. Therefore, the proposed approach must be versatile. Fig. 2 shows the schematic diagram of “MEMS post-packaging by localized heating and bonding.” A “packaging cap” with properly designed micro cavity, insulation layer, microheater and micro glue layer is to be fabricated to encapsulate and protect the fragile MEMS structure as the first-level MEMS post-packaging process. The wafer can be diced afterwards as shown in Fig. 3 and the well-established packaging technology in IC industry can follow and finish the final packaging.

#### A. MEMS Post-Packaging by Global Heating

Several MEMS post-packaging processes have been demonstrated before based on the global heating schemes. An integrated vacuum sealing process by LPCVD is presented here as a comparison for the localized heating and bonding processes. This global heating process can encapsulate comb shape microresonators [17] in vacuum at the wafer-level.

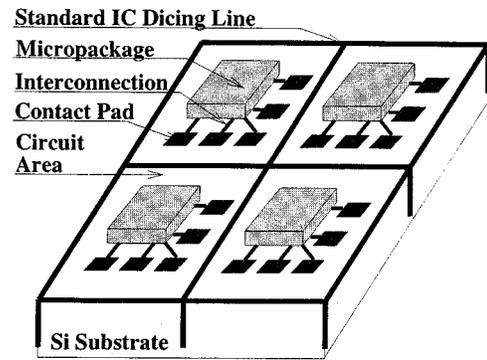


Fig. 3. Schematic diagram showing the concept of MEMS post-packaging.

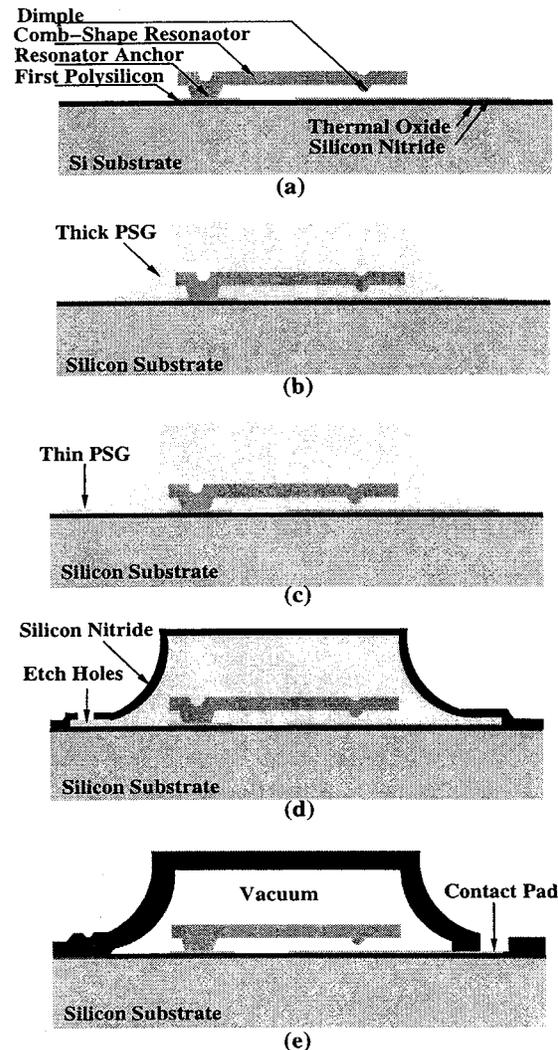


Fig. 4. Integrated MEMS post-packaging process by global heating [17].

Fig. 4 illustrates the cross sectional view of the manufacturing process. First, standard surface-micromachining process [50] is conducted by using four masks to define first polysilicon layer, anchors to the substrate, dimples and second polysilicon layer as shown in Fig. 4(a). The process so far is similar to the MCNC MUMP's process [5] and comb-shape microstructures are fabricated at the end of these steps. In the standard surface

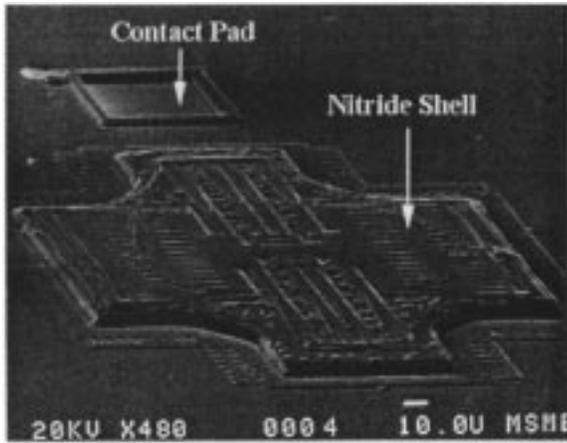


Fig. 5. SEM microphoto of a packaged microresonator by the integrated MEMS post-packaging process with global LPCVD sealing [17].

micromachining process, the sacrificial layer (oxide) is etched away to release the microstructures. In the MEMS post-packaging process, a thick PSG (phosphorus-doped glass) of  $7\ \mu\text{m}$  is deposited to cover the microstructure and patterned by using 5:1 BHF (buffered HF) to define the microshell area as shown in Fig. 4(b). A thin PSG layer of  $1\ \mu\text{m}$  is then deposited and defined to form etch channels as illustrated in Fig. 4(c). The microshell material, low-stress silicon nitride, is now deposited with a thickness of  $1\ \mu\text{m}$ . Etch holes are defined and opened on the silicon nitride layer by using a plasma etcher. Silicon dioxide inside the packaging shell is now etched away by concentrated HF and the wafer is dried by using the supercritical  $\text{CO}_2$  drying process [51]. After these steps, Fig. 4(d) applies. A  $2\text{-}\mu\text{m}$ -thick LPCVD low-stress nitride is now deposited at a deposition pressure of 300 mTorr to seal the shell in the vacuum condition. Finally, the contact pads are opened as shown in Fig. 4(e).

Fig. 5 is the SEM (Scanning Electron Microscope) microphoto of a finished device with protected microshell on top. The total packaging area (microshell) is about  $400 \times 400\ \mu\text{m}^2$ . A contact pad is shown with the covering nitride layer removed. The shape of the microresonator, with beams of  $150\ \mu\text{m}$ -long and  $2\ \mu\text{m}$ -wide is reflected on the surface of the microshell due to the integrated packaging process. The total height of the nitride shell is  $12\ \mu\text{m}$  as seen standing above the substrate. Spectrum measurement of the comb resonator inside the packaging reveals that a vacuum level of about 200 mTorr has been accomplished [52].

### B. MEMS Post-Packaging by Localized Heating

Although the above integrated global heating and sealing process successfully achieves MEMS Post-Packaging, it has several drawbacks. First, several high temperature steps were used after the standard surface-micromachining process. As such, no circuitry (such as those shown in Fig. 1) or temperature-sensitive materials will survive due to the global heating effect. Second, this post-packaging process is very specific and process dependent. MEMS companies or researchers have to adopt this post-packaging process with their own micro-manufacturing process. It can not be conducted in the

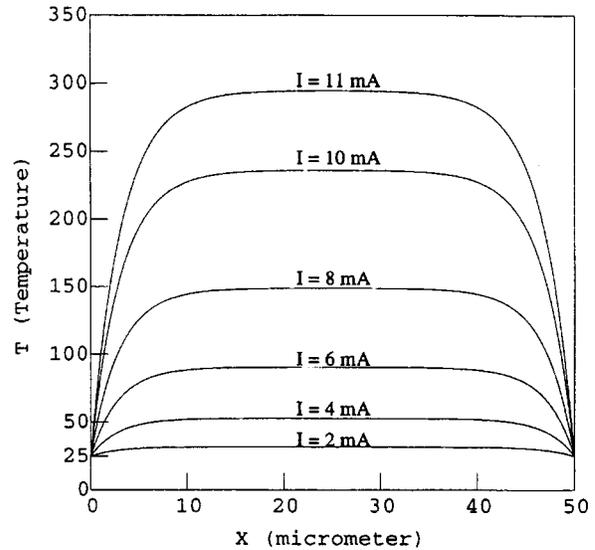


Fig. 6. Temperature distribution on a heated,  $50\text{-}\mu\text{m}$  long polysilicon microheater [53].

multi-user MEMS process such as the MCNC MUMP's [4]. Third, the thickness of the microshell is limited by the thin film deposition step that generally has the range of a few micrometers. There is a big concern if the thin microshell can survive the high-pressure plastic molding during the final packaging process.

The approach of MEMS post-packaging by localized heating and bonding is proposed to address the problems of global heating effects. In this paper, resistive microheaters are used to provide localized heating. It is important to characterize the heat transfer behavior of microheaters in order to control the bonding and packaging process. A one-dimensional electrothermal model is established based on conservation of energy for line-shape microheaters [53]. A heat conduction shape factor [54] is used to account the heat transfer to the other dimension and a heat equation is derived

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} + \varepsilon(T - T_r). \quad (1)$$

Where  $T$  is the temperature along the microheater;  $t$  stands for time;  $\alpha$  is the thermal diffusivity of the heater. Both  $\varepsilon$  and  $T_r$  are parameters that are functions of the structure dimensions, thermal properties, input current and the heat conduction shape factor [55]. The steady state solution of the temperature profile is

$$T(x) = T_r - (T_r - T_\infty) \frac{\cosh \left[ \sqrt{\varepsilon} \left( x - \frac{L}{2} \right) \right]}{\cosh \left( \sqrt{\varepsilon} \frac{L}{2} \right)}. \quad (2)$$

$L$  is the total length of the microheater. Fig. 6 shows the input current-temperature simulation of a heavily phosphorus-doped polysilicon resistor with geometry of  $50 \times 2 \times 0.5\ \mu\text{m}^3$ . It is found that under an input current of 11 mA, the heater can generate a temperature of about  $300\ ^\circ\text{C}$ . More importantly, the temperature profile is uniform at the central regions of the heater

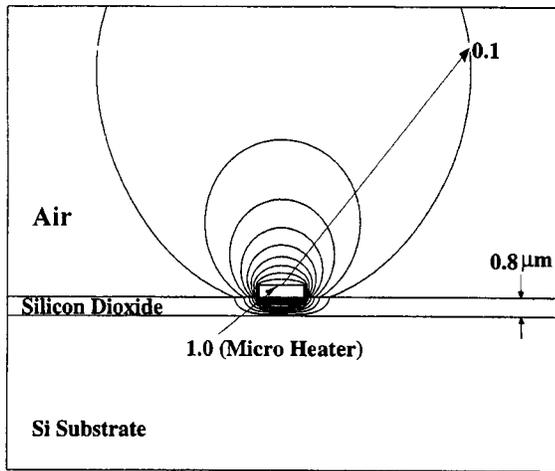


Fig. 7. Cross-sectional view of FEM simulation showing temperature isotherms [53].

and this helps the temperature control in the localized heating and bonding process.

When the bonding material is heated, the cross sectional heat transfer process is simulated by finite element analysis. A proof-of-concept simulation is conducted here. This simulation uses silicon as the substrate material and a single  $\text{SiO}_2$  layer to represent the passivation layers. The microheater at a high temperature is put on the top of the device substrate as shown in Fig. 7. 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. For example, even if the temperature on the microheater is  $1000^\circ\text{C}$ , the temperature quickly drops to 10%, or only  $100^\circ\text{C}$ , in a distance of less than  $1\ \mu\text{m}$  into the insulation layer. 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.

### III. LOCALIZED BONDING PROCESSES

Based on the concept of localized heating, several localized bonding processes for MEMS post-packaging are presented, including localized eutectic bonding, localized fusion bonding, localized solder bonding and localized CVD bonding.

#### A. Localized Silicon-Gold Eutectic Bonding

Silicon-gold eutectic bonding has been used widely in microfabrication [33], [56]. It provides high bonding strength and good stability at a relatively low bonding temperature at  $363^\circ\text{C}$ . In the demonstration of localized silicon-gold eutectic bonding [57], silicon substrate is first thermal oxidized to grow a  $1\ \mu\text{m}$ -thick oxide as the thermal and electrical insulation layer. Gold of  $0.45\ \mu\text{m}$  in thickness is deposited by using a  $0.05\ \mu\text{m}$ -thick chromium layer as the adhesion material. Line-shape microheaters with width of  $7\ \mu\text{m}$  are defined by the lift-off process. Clean silicon cap substrates are placed on top of these device substrates with applied pressure of about 1 MPa. Two eutectic bonding experiments by global heating and localized heating, respectively, are conducted and compared. It takes about one hour for the conventional eutectic bonding process to

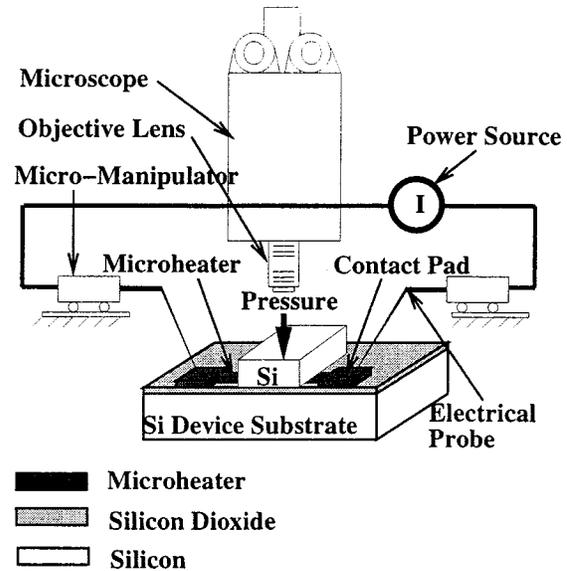


Fig. 8. Experimental setup for localized heating and bonding test [57].

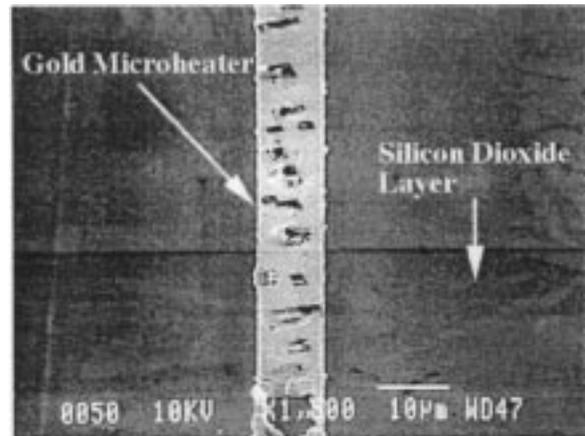


Fig. 9. Silicon-Gold eutectic bonding by global heating method in an oven [57].

ramp up the temperature to  $410^\circ\text{C}$ , stay there for 10 min and cool down to room temperature. The localized eutectic bonding process takes less than 5 min by applying input current to reach an estimated temperature of  $800^\circ\text{C}$  based on the electrothermal model of (2). The experimental setup is shown in Fig. 8.

The silicon-gold eutectic bonds are forcefully broken at the completion of the bonding processes and the device substrates are examined under SEM. Figs. 9 and 10 shows the bonding result by using the global and localized heating methods, respectively. Nonuniform bonding characteristics can be identified in Fig. 9. The whole gold line is striped away in Fig. 10. Moreover, part of the cap silicon is broken and left on the device substrate as shown. These experimental results suggest that the localized silicon-gold eutectic bond can be uniform and can have the bonding strength that is as strong as the fracture toughness of silicon.

#### B. Localized Silicon-Glass Fusion Bonding

The demonstration of localized silicon-glass fusion bonding is conducted by using the same experimental setup as shown

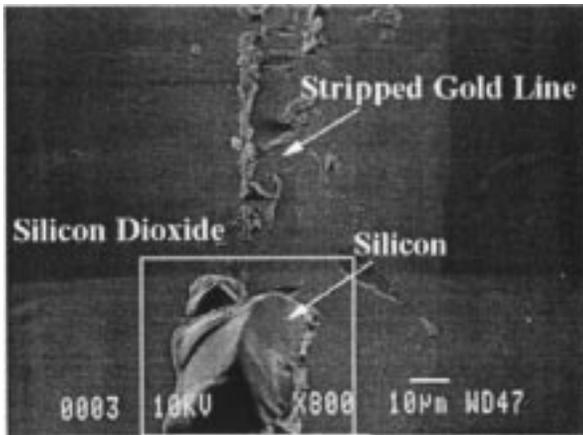


Fig. 10. Bonding result by localized silicon-gold eutectic bonding [57].

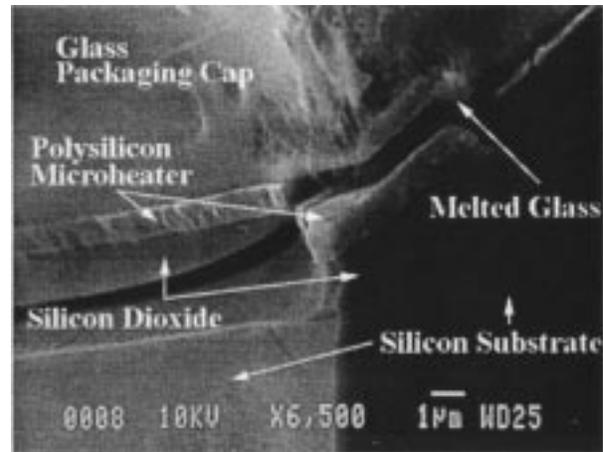


Fig. 12. After dipping into HF solution, polysilicon microheater is delineated [58].

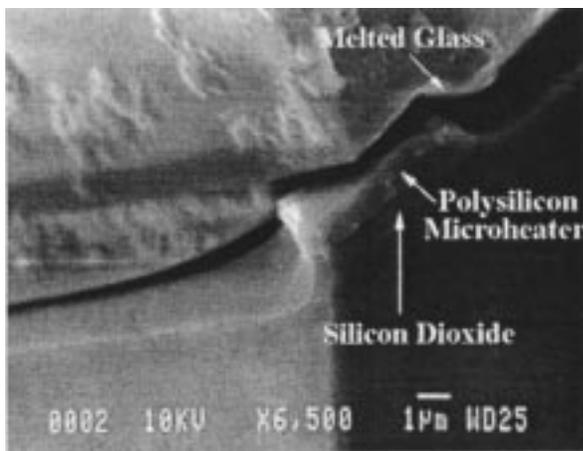


Fig. 11. Localized silicon-glass fusion bonding (after breaking the bond forcefully) [58].

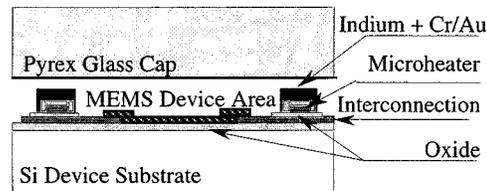


Fig. 13. Schematic diagram of the testing sample for localized solder bonding [60].

in Fig. 8. The silicon device substrate is constructed with 1  $\mu\text{m}$ -thick thermal oxide and 1.1  $\mu\text{m}$ -thick heavily phosphorus-doped polysilicon as the microheater. A Pyrex glass (7740 from Dow Corning) is placed and pressed on top of the polysilicon microheater. A 31 mA input current is heating up the microheater to achieve a temperature very close to the melting temperature polysilicon for 5 min. The glowing color of the microheater can be observed in real-time under the microscope to confirm the high temperature status. Unlike the conventional fusion bonding experiments that takes more than 2 h, localized silicon-glass fusion bonding is completed in 5 min [58].

The fusion bond is then forcefully broken and examined under SEM. Fig. 11 shows the SEM microphoto taken on the silicon device substrate. Silicon dioxide layer, polysilicon microheater and the glass cap can be clearly identified. In this photo, glass is seen melted and reshaped at those regions that are in close contact to the microheater. This microphoto demonstrates two very important features for the localized fusion bonding experiment. First, it is easy to raise the temperature in a very short time to be above the melting temperature of the glass softening point of 820  $^{\circ}\text{C}$ . Second, the applied pressure is high enough to cause intimate contact between the glass cap and device substrate for bonding.

The sample in Fig. 11 is then dipped into HF solution that will attack oxide and glass but not silicon or polysilicon. Fig. 12 shows the result taken at the same location as in Fig. 11. The polysilicon heater is now clearly delineated. The fact that no polysilicon-glass interfaces can be identified in Fig. 11 and they only show up after the HF dip implies a strong fusion bond was formed. Moreover, this polysilicon-glass fusion bond seems to be stronger than the original polysilicon-oxide adhesion bond as the broken trace seems to occur at the polysilicon-oxide interface. All of these results strongly suggest that excellent silicon-glass fusion bond has been achieved by localized heating and bonding.

*C. Localized Solder Bonding*

Solder bond technology is widely used in the connection-to-chip process in IC packaging. For example, the popular Pb-Sn solder bond is processed at a temperature of 360  $^{\circ}\text{C}$  [1], [59]. Several solder materials have been applied in MEMS packaging based on global heating [60]. The concept of “intermediate” layer is introduced in the localized solder bonding experiments. Fig. 13 shows the schematic diagram for the sample preparation. A thermal dioxide layer of 1  $\mu\text{m}$  in thickness is grown on the silicon device substrate. The process continues with the deposition and definition of 1  $\mu\text{m}$  thick, phosphorus-doped polysilicon to emulate the interconnection line. A layer of 0.15  $\mu\text{m}$ -thick LPCVD silicon oxide is deposited on top of the interconnection line as electrical insulation. Phosphorus-doped polysilicon microheater is then deposited and patterned to form microheaters and another 0.15  $\mu\text{m}$  thick LPCVD silicon oxide is deposited for electrical insulation. The soldering material consisting of 0.05  $\mu\text{m}$  chromium

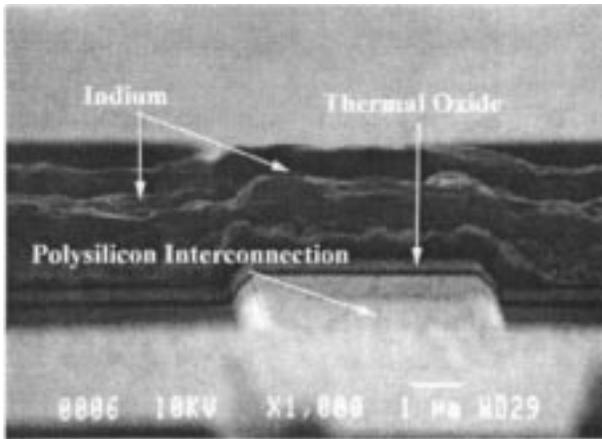


Fig. 14. Localized indium solder bonding (after indium deposition before the bonding process) [60].

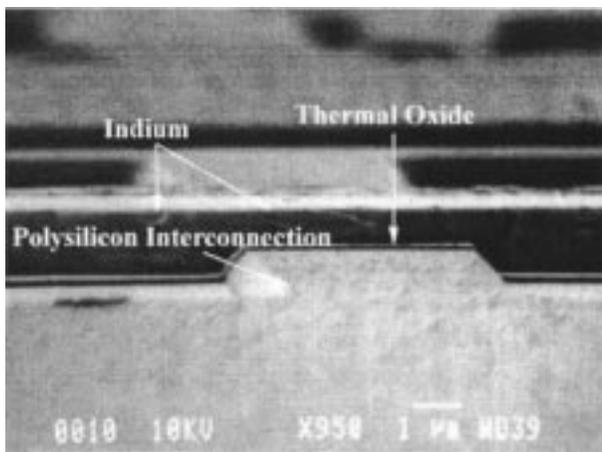


Fig. 15. After localized indium bonding, the indium solder has been reflowed [60].

and  $0.45 \mu\text{m}$  gold for adhesion and  $3 \mu\text{m}$  thick indium is now deposited and defined [61].

The bonding process is conducted at a bonding stage as in Fig. 8. The temperature of the microheater is estimated to rise to  $300^\circ\text{C}$  and with applied pressure at  $0.2 \text{ Mpa}$ . The bonding process is complete in two minutes and the bond is forcefully broken to examine the bonding interface. Fig. 14 shows the solder material right after the deposition and patterning processes. Two very important packaging issues are shown in this figure. First, the interconnection as shown creates a bump-up step and this surface roughness problem is the failure source for existing bonding process such as fusion or anodic bonding. Second, the as-deposited solder material has granular structure but after the localized solder bonding process, the solder can actually reflow to form a flat surface as shown in Fig. 15. Therefore, this localized solder bonding method can overcome the surface roughness problem and create excellent step coverage by the reflow of solder material.

#### D. Localized CVD Bonding

The global LPCVD vacuum sealing process was demonstrated in the previous section for MEMS post-packaging. Although the problems of high temperature and process

dependency have hindered its potential MEMS packaging application, localized heating provides a way to conduct CVD sealing but avoids those drawbacks.

In order to demonstrate the localized CVD bonding process, two substrates are prepared as shown in Fig. 16(a). Both substrates are made of silicon and thermally grown a layer of  $1.2 \mu\text{m}$  thick thermal oxide as the insulation layer. Phosphorus-doped polysilicon is deposited and patterned as the interconnection line on the device substrate and microheater on the packaging cap, respectively. A layer of  $1.4 \mu\text{m}$ -thick PECVD (Plasma Enhanced Chemical Vapor Deposition) is then deposited on the device substrate as the electrical and thermal insulation layer. The device and packaging substrates are pressed together and put into a chamber with silane flowing at  $500 \text{ mTorr}$  [62].

An input current of  $40 \text{ mA}$  is used to generate a high temperature to activate the decomposition of silane locally. According to the electrothermal model of (2), the estimated temperature is about  $800^\circ\text{C}$ . The CVD filling and bonding process as shown in Fig. 16(b) finishes in 2 h and the CVD bond is forcefully broken for examination. Figs. 17 and 18 show the device substrate and the packaging cap, respectively. It is found that microheater, that was originally deposited on the packaging cap is detached as shown in Fig. 18. It is now attached to the device substrate as illustrated in Fig. 17. The localized CVD polysilicon layer completely fills the gap between the device and cap substrate. Moreover, it appears that the CVD bond is comparable or stronger than the polysilicon-thermal oxide adhesion bond. Only two traces of material can be identified in Fig. 18 and they are probably the deposited CVD polysilicon on the edges of microheater.

#### IV. CONCLUSIONS

“MEMS post-packaging by localized heating and bonding” provides unique opportunities in developing packaging processes for microsystems with theoretical, experimental and engineering challenges. This work addresses the fundamental issues and approaches in the packaging of MEMS devices and provides directions for future research.

In the process demonstration by means of global heating, an integrated LPCVD encapsulation process has been successfully accomplished. This process starts at the end of the standard surface-micromachining process and utilizes various microfabrication processes to construct microshells and to selectively encapsulate micro-devices. The drawbacks of this global heating process are high temperature and strong process dependency such that it is not versatile for general MEMS post-packaging applications. Localized heating and bonding processes can address these problems and are demonstrated experimentally, including localized silicon-gold eutectic bonding, localized silicon-glass fusion bonding, localized solder bonding and localized CVD bonding. These new processes provide promising ways to accomplish MEMS post-packaging.

Before localized heating and bonding can be successfully applied to MEMS post-packaging, several fundamental and challenging problems should be carefully studied in both theoretical and experimental regimes. Specific areas to be explored are as follows.

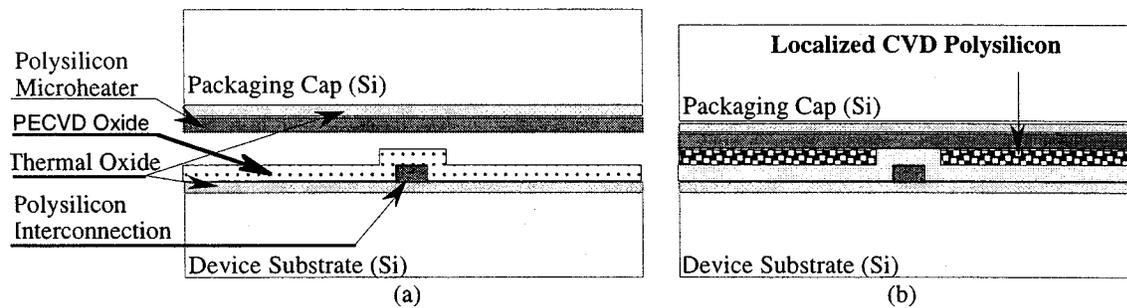


Fig. 16. Schematic diagram of the localized CVD bonding process. (a) Before bonding. (b) After bonding [62].

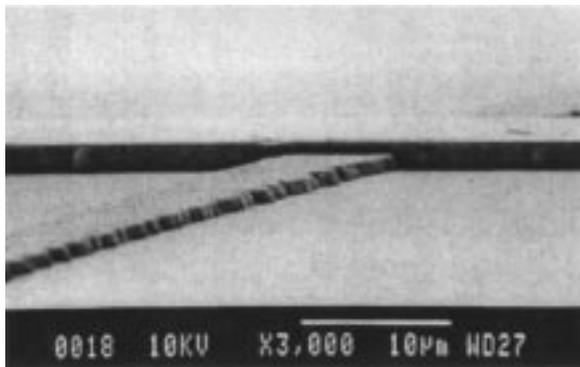


Fig. 17. Localized CVD bonding showing microheater is attached to device substrate [62].

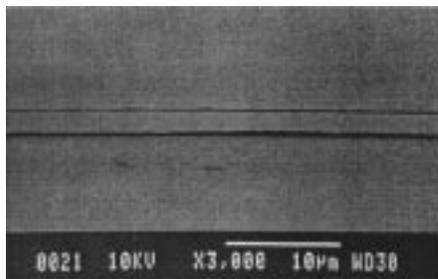


Fig. 18. Only two trace of deposited polysilicon is found on the packaging cap [62].

- 1) Models and simulations for localized heating and bonding during steady state and transient operations and the heating effects at the wafer-level.
- 2) Characterizations of localized bonding mechanisms and processes such as the effects of temperature, time, applied pressure and surface roughness.
- 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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