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Microwave bonding of polymer-based substrates for potential encapsulated micro/nanofluidic device fabrication

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Abstract

Microwave-based bonding of polymer substrates is presented in this paper to illustrate a promising technique for achieving precise, localized, low temperature bonding. Microwave power can absorbed by a very thin film metal layer deposited on a polymer (PMMA) substrate surface. The intense thin-film volumetric heating promotes localized melting of refractory metals such as gold. One of the advantages of the process is that PMMA is relatively transparent to microwave energy in the 2.4 GHz regime. This makes it an excellent substrate material for microwave bonding. Selective heating and melting of the thin layers of metal also causes localized melting of the PMMA substrates and improves adhesion at the interface. We have shown that $\sim 1\ \mu m$ of interfacial layer can be generated that is composed of the melted gold and PMMA, and which can hold two substrates together under applied tension greater than 100 lb/in.^{2} (7 kg/cm^2). We also used lithographically patterned metal lines on a PMMA substrate to demonstrate that the PMMA remains optically transparent after microwave processing. A numerical simulation was also performed and validated with experimental results to show that globally the PMMA substrates indeed remained below its melting point during the microwave bonding process. The novel bonding process will open up possibilities for precise and total encapsulation of polymer-based micro/nanofluid devices—which are impossible to built using existing polymer bonding techniques.
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Keywords: Microwave bonding; Polymer substrates bonding; Microfluidic devices; Nanofluidic devices

1. Introduction

Since the publication of results from silicon die microwave bonding experiments at the Jet Propulsion Laboratory (JPL) in 1999 [1], there has been interest in selective heating for MEMS applications using electromagnetic energies at frequencies from radio frequency (rf) up to microwaves. A group from the University of Wisconsin [2] showed that direct silicon wafer bonding, which usually requires temperatures greater than 1000 °C, was possible using a 2.45 GHz microwave source with a power output of 1500 W. Complete, void free bonding was achieved using this process in less than 5 min. Similarly, a group from the University of Minnesota [3] used RF heating to bond silicon wafers together via a dielectric insulator interface. This group applied 500 W of power from a 14 MHz source for 7 min below 280 °C to bond silicon wafers via a 2–20 μm thick polyimide dielectric layer. Other groups have attempted sealing using compression waves at ultrasonic frequencies to get hermetic sealing, similar to that achieved by the JPL group using electromagnetism. One group from UC Berkeley [4] used ultrasonic frequencies at up to 25 W for almost 2 s to bond approximately 2 mm^2 of In/Au and up to 50 W for 5 s to bond approximately 2 mm^2 of Al/Al. However, until now, there has not been much focused attention on using selective microwave heating to join thin film metal layers between polymer substrates.

In recent years, polymer-based microfluidic devices have become increasingly important in biological applications [5]. However, polymer substrates must be bonded to make functional microchannels, and adhesion between the substrates is a problem of great practical concern. Existing polymer-to-polymer substrate bonding methods includes thermal compression, ultrasonic, or gluing by application of either epoxy or methanol. Unfortunately, these techniques are not precise when compared to standard IC/MEMS bonding processes, i.e., they may induce global and localized geometric deformation of the substrates or leave an

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interfacial layer with significant thickness variation. For channels in the millimeter to a few hundred micrometers range, these drawbacks are tolerable. However, it is implausible to construct micrometer- and nanometer-sized channels using these techniques since significant global and local material deformations may distort the micro/nanochannel geometries.

In this paper, we will present our ongoing work to use localized microwave heating to bond polymer (PMMA) substrates without causing any global deformation to the substrates and resulting in a precise and well-controlled interfacial layer thickness of 1 μm. Thus far, we have shown that microwave energy can be used to selectively melt a film as thin as 50 nm of gold deposited on each side of the two PMMA substrates to be bonded. Melting of these thin layers of gold caused localized melting of the PMMA substrates and allowed them to bond. The 1 μm interconnect layer is composed of the melted gold and PMMA and has been shown to hold the substrates together under applied pressure greater than 100 lb/in.^{2} (7 kg/cm^2).

2. Microwave bonding

The central idea behind microwave bonding is to use the nature of the interaction of high frequency energies with thin film metals that are used as bonding interfacial layers in a single mode cavity (SMC). In such a cavity, the power delivered to metal contact is proportional to the conductivity and the electric field (E^2), as shown in Eq. (1) [6]. In Eq. (1), ω_0 is the fundamental frequency, ε_0 the permittivity of free space, ε' the real component of the material dielectric permittivity and $\tan\delta$ the loss tangent of the material:

$$P_{\mathrm{ave}} = \frac{1}{2\omega_0\varepsilon_0\varepsilon'(\tan\delta)E^2} \quad (1)$$

In microwave bonding, most of the power is delivered through a microwave transparent substrate and is absorbed by a very thin-film metal of less than 1 μm thick (skin depth). This power induces heating that leads to high temperature melting of refractory metals such as gold. The low electrical conductivity of a polymer or semiconductor substrate, relative to a metal, allows the substrate to essentially remain unaffected by the energy deposited in the SMC. The high intensity fields found in a SMC is unique to these types of cavities and allows the melting of high-melting-temperature thin films or contact points as found in this application. The thinness of the metal (skin depth), the high intensity, and the short application time contribute to the following critical advantages:

1. Localized power concentration allows for strong hermetically bonded areas between the substrates. High bond strength results from the utilization of high melting temperature metals at the interface. This means higher device reliability.
2. Selective heating of the thin metal means the bonding process is a globally low-temperature process. The temperature of bulk substrate is less then 100 °C, which is lower than the melting point of the bond metal; this means a polymer with a low-melting temperature could be used as a substrate. Also, since the substrate temperatures remains low, adverse thermal coefficient of expansion mismatches are minimized.
3. Unlike some laser welding and ultrasonic bonding techniques, the process is low cost because the bonding occurs simultaneously and quickly.

3. Microwave bonding to polymer

In general, we succeeded in bonding PMMA to silicon and PMMA to PMMA substrates together using selected microwave frequencies to locally melt the interface metallic thin films between the substrates. As shown in Fig. 1, the prototype equipment is capable of handling test dies up to 45 mm in diameter.

Our bonding experiments showed that PMMA is relatively transparent to microwave energy near the 2.4 GHz frequency band. This makes PMMA an excellent material for microwave bonding. Most of the microwave energy is absorbed by the thin film metals at the interface, thus minimizing heating in the bulk PMMA substrate. An oscilloscope was attached to a diode antenna that measures the amplitude of the resonance peak in the microwave processing chamber as the frequency was swept from 2.3 to 2.5 GHz. Data captured from an oscilloscope is shown in Fig. 2. The resonant peak of the empty chamber is shown in Fig. 2a. The resonant peak of the chamber loaded with two sample blocks of PMMA is shown in Fig. 2b. The y-axis is the measured output voltage in millivolts. We found a maximum reduction in the value of the resonant peak between the loaded and empty chamber configurations of less than 1%.

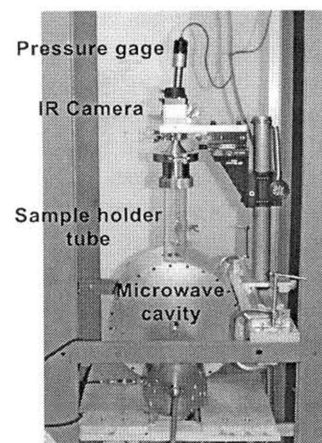

Fig. 1. The prototype of the microwave bonding equipment. The current design allows up to 45 mm in diameter sample to be fitted in to the sample holder.

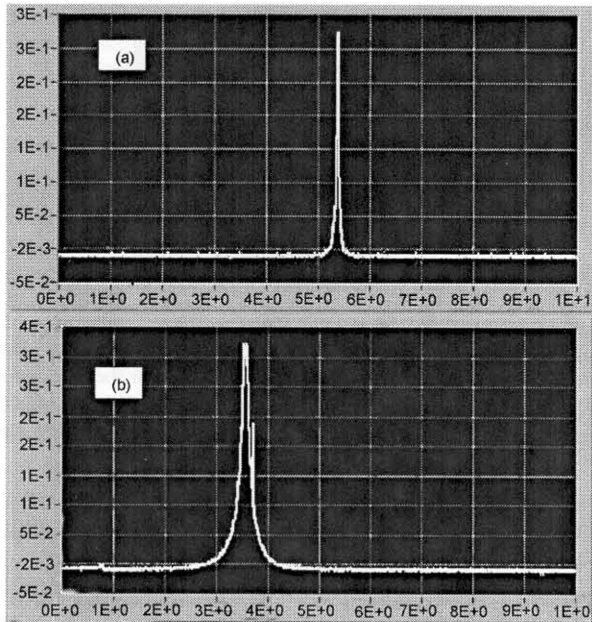

Fig. 2. Resonant peak in the microwave-processing chamber as the frequency is swept from 2.3 to 2.5 GHz: (a) empty chamber; (b) PMMA-loaded chamber. The x-axis presents time-sequenced data. The y-axis is the measured output voltage in millivolts.

This shows PMMA essentially transparent to microwave energy.

4. Experimental result

4.1. Silicon to PMMA bonding

Silicon to PMMA bonding was achieved by using thin film 63% Sn and 37% Pb solder pre-forms to address the problem of PMMA substrate flatness, as shown in Fig. 3. The thickness of silicon and PMMA are 1 and 3 mm, respectively. A 500 Å Cr adhesion layer and 500 Å Au bonding layer were e-beam evaporated onto both surfaces. The pre-form is 50 μm thick and melts at 183 °C. Microwave bonding of PMMA to a silicon die is shown in Fig. 4. This was done at approximately 30 W of applied power for 180 s. Note the critical fact that the Au surface of the PMMA was unaffected (by visual examination) after processing and the bulk PMMA was still transparent. It was possible to look through the backside of the PMMA to see the unaffected Au top layer.

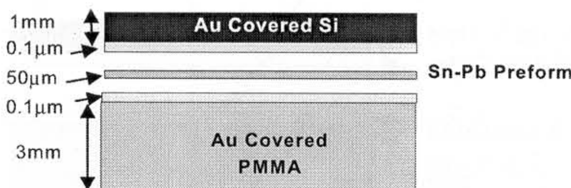

Fig. 3. Illustration of die stack for Au covered silicon and Au covered PMMA bonding experiment. Solder pre-form films of 63% Sn and 37% Pb were used to enhance PMMA–Si bonding.

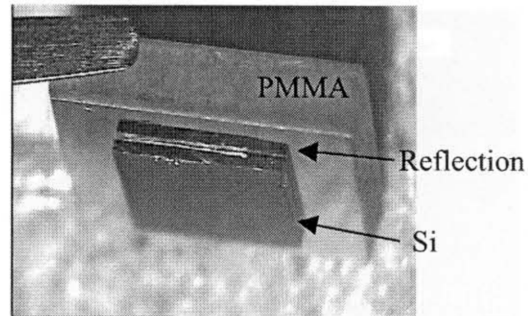

Fig. 4. PMMA to silicon bond. Note, the apparent bottom Si substrate is a reflection of the top Si substrate off the Au film on PMMA substrate.

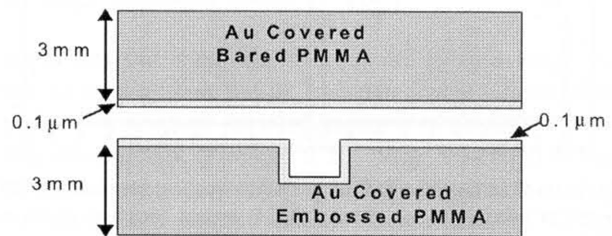

Fig. 5. Illustration showing the dimensions of the PMMA substrates and Au thin film layers used in the PMMA–PMMA bonding experiment.

4.2. PMMA to PMMA bonding

Embossed PMMA and PMMA bonding is possible via thin film Au already deposited on the surface, as shown in Fig. 5. Using hot embossing technique [5], microchannel can be created on the PMMA. A 500 Å Cr adhesion layer and a 500 Å Au bonding layer were e-beam deposited onto both embossed PMMA and bare PMMA surface. An example of two PMMA substrates successfully bonded together is shown in Fig. 6. Two substrates were bonded at 10 W for approximately 120 s. Again, the substrates were not affected based on visual examination after the microwave bonding processing.

An SEM image of the cross-section of the PMMA–PMMA substrates is shown in Fig. 7. As shown in the figure, the

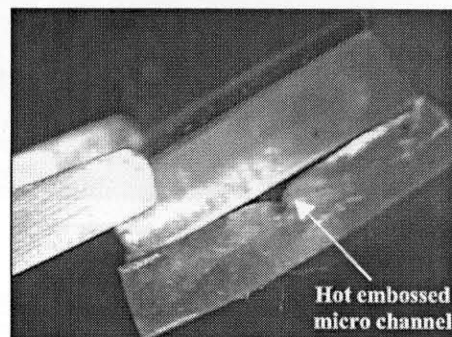

Fig. 6. Embossed PMMA to bare PMMA bond.

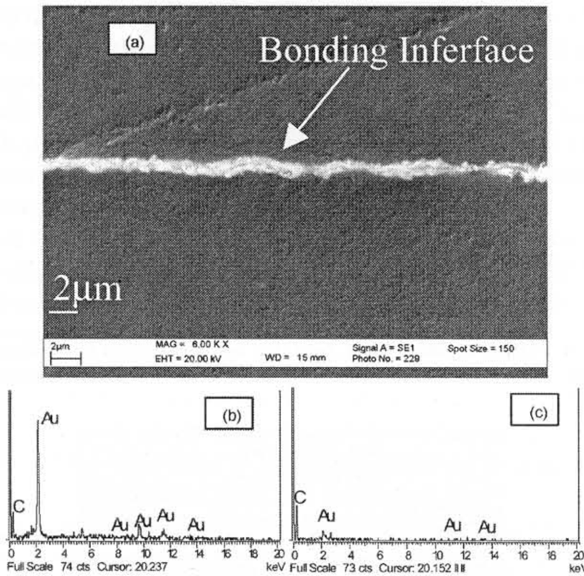

Fig. 7. (a) SEM image of PMMA to PMMA bonding interface. (b) EDX spectra of interface region showing that it mainly composes of Au. (c) EDX spectra of PMMA, showing that it is mostly carbon.

thickness of the interfacial layer is approximately 1 μm and is a precise and well-controlled layer. From the EDX spectra, as shown in Fig. 7b and c, the interfacial layer composes of the mixture of Au and carbon, which indicates that the microwave energy melted the Au layer causing localized melting of the PMMA substrates to be bonded. This bond was shown to hold the substrates together under applied tension greater than 100 lb/in.^{2} (7 kg/cm^2).

4.3. Si–In to Au–PMMA bonding

We have also successfully bonded PMMA substrates with patterned Au layers to Si substrates with patterned In layers. The Si substrates are 1 cm × 1 cm × 400 μm thick, lightly doped silicon covered with patterned thin film layers of 300 Å Cr/1000 Å Au and 2 μm In. The PMMA substrates are 2 mm thick with patterned thin film layers of 500 Å Au/500 Å Cr. Samples were bonded using less than 5 W of power processed for exactly 45 s. An example of bonded substrates is shown in Fig. 8.

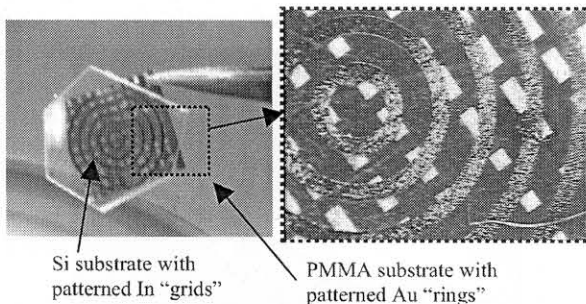

Fig. 8. An example if Si–In to Au–PMMA bond. Note that the PMMA is still transparent after the bond and the Au "rings" are still clearly defined. This proves that microwave bonding affects only the interfacial metal layer and will not globally heat the PMMA substrate.

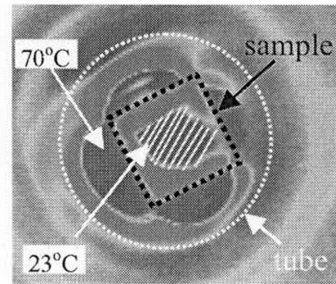

Fig. 9. IR image of PMMA stack in the microwave chamber after 20 W of power is applied for 5 s. Note that edges are heated (darker shade), possibly caused by IR emission from gold visible on the sides of the sample due to misalignment; IR reflection from the sides of the sample holder tube is also visible. Clearly, the center body of the PMMA stack is near room temperature (stripes).

IR measurements, as shown in Fig. 9, were carried out in real-time during the bonding process of 20 W power in 5 s to study the temperature distribution on the bonding substrates. In general, we found that some parts of the bonding substrates reached 70 °C, which is below the melting temperature of PMMA, but the bulk of the bonding substrates remained near room temperature. After the microwave bonding process, the transparency of bulk PMMA was not changed and there was no global deformation to the substrates.

5. Heat transfer numerical simulation

A thermal–dynamical two-dimensional time-dependent simulation was performed using a finite element method solver to provide insight into the heat transfer mechanism during the microwave bonding process. The two-dimensional heat transfer equation solved is:

$$\rho C\frac{\partial T}{\partial t} - \nabla(k\,\nabla T) = Q + h(T_a - T) + C(T_a^4 - T^4) \qquad (2)$$

where ρ is the density of the material, C the specific heat, k the thermal conductivity, T the temperature at a point inside the material, h the convective heat coefficient, T_a the ambient temperature, and Q the generated heat density.

In the simulation, the three main structural layers are silicon, PMMA and gold as illustrated in Fig. 10. The gold

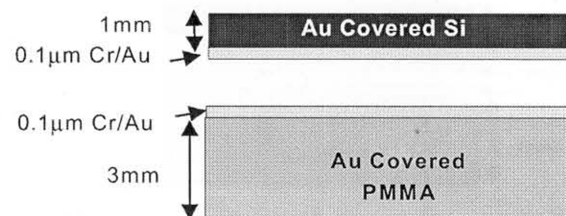

Fig. 10. Illustration showing the substrate and thin film used in the heat transfer simulation.

Table 1
Properties used to model the structural layer in the simulation

	Density (kg/m^3)	Specific heat (J/(kg K))	Thermal conductivity (W/(m K))
Silicon	2333	700	142
Gold	19300	128	320
PMMA	930	2386	0.217

metallization is locally and volumetrically heated via microwave processing techniques. Heat is generated mainly inside the gold layer. The microwave power is dissipated uniformly inside the gold layer. This heat is transferred to PMMA and silicon by thermal conduction. The heat from the surface is dissipated to the surroundings by convection and radiation.

As the sample is symmetrical in length, only half of the sample was simulated. The thickness of silicon and PMMA layers used were 1 and 3 mm, respectively, and the total gold layer thickness was 0.2 μm. The convective heat transfer coefficient at the boundary of the sample, h, is $3\,W/(m^2\,K)$, based on previous experimental and simulated results with other silicon die stack combinations. Heat transfer through radiation was also taken into consideration. In order to accurately model the existence of thermal impedance at inter-layer boundaries, two artificial junction layers are added to the simulation. They represent the omnipresence of surface irregularities between the layers leading to a lower thermal conductivity than an ideal case, allowing the model to better approximate measured data and reality. One layer (25 μm thick) is between the silicon and the gold and the other layer (75 μm thick) is between the gold and the PMMA. Both layers were given a thermal conductivity of 0.05 W/(m K). A summary of the relevant physical parameters used for the materials in the simulation is given in Table 1.

As shown in Fig. 11, the experimental heating profile (in solid line) and numerical simulation (in dotted line) match well for the given power input and heating time (35 s). The experimental data was taken by a pyrometer targeted at the top silicon surface of the stack inside of the microwave cavity during processing. This measured temperature serves as one boundary condition for the simulation, and it should be

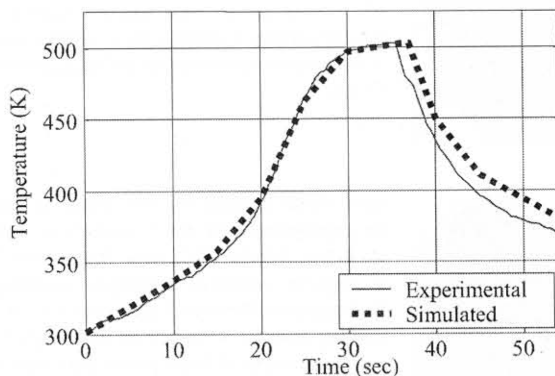

Fig. 11. Temperature (K, vertical axis) vs. time (s, horizontal axis) profile of top surface of the silicon as power is being applied.

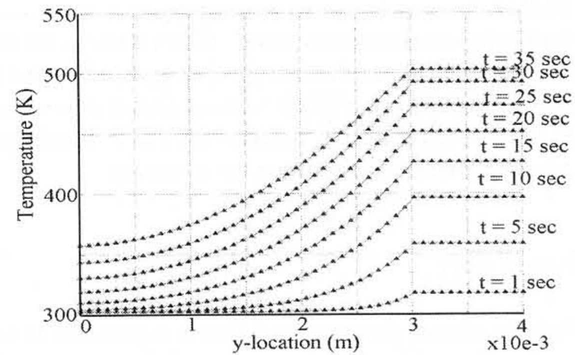

Fig. 12. PMMA and silicon die stack centerline temperature (K) profile at different times during heating.

noted that this measured temperature is an average value due to the fact that the IR transparency of silicon is temperature dependant. All temperature is in degrees Kelvin. In this simulation, a Q of $4.05 \times 10^9\,W/m^3$ was input to match the experimental power input, and the physical requirement that the melting point of indium was reached. Fig. 12 shows the centerline temperature profile at various times during the 35 s that power is applied. Along the x-axis, at $x = 0$ corresponds to the bottom of the PMMA layer. Due to the high thermal conductivity of silicon, the temperature at $x = 3$ (the approximate thin film interface location in Fig. 12) and $x = 4$ (the top of the silicon layer) is almost identical at any instant in the simulation. The centerline position is illustrated by the vertical line through the die stack in Fig. 12.

Based on the close match with the experimental data at the top silicon surface, we argued that these calculated internal centerline values accurately measure the internal temperature distribution of the stack. Thus, although the temperature at the metal layer ($x = 3$) is high enough to melt any indium or solder pre-forms that may be inserted during the physical bonding experiments, the PMMA temperature ($0 < x < 3$ in Fig. 12) remains below its melting point due to the localized heating advantages of microwave processing. The simulated spatial temperature distribution of the Si-Au-PMMA bond at this time is shown in Fig. 13. As shown, most of

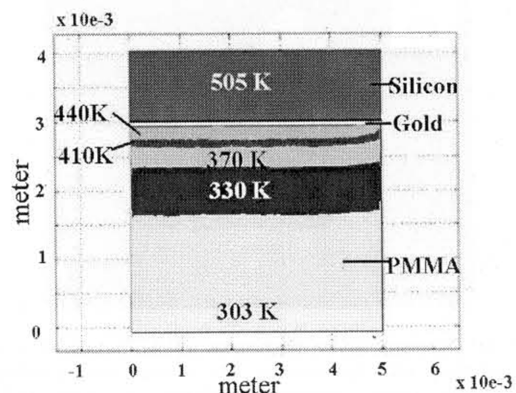

Fig. 13. Simulation result at time 35 s. Temperature distribution across the entire die stack immediately before the input power is turned off (x-axis and y-axis are distance in (m)).

the PMMA layer is below its melting point, with an average bulk temperature around 380 K. This reinforces the conclusion that microwave thermal processing can be used for bonding of metals and PMMA without global deformation of the PMMA substrate, i.e., heating only occurs locally near the bonding metal layer between the substrates.

6. Future work

We have already demonstrated that it is possible to produce micro/nanostructure using micromolding technique [7], as shown in Fig. 14. It includes mastering and replication processes. In the mastering process, a molding master is fabricated by lithography and electroforming. After obtaining the molding master, the micro/nanostructures on the molding master can be transferred to a polymer substrate by a hot embossing machine. However, none of the existing bonding techniques, such as thermal compression, ultrasonic, or gluing, would allow us to seal them. From the above initial microwave bonding results, we have proved that microwave bonding can be used to bond polymer substrates to Si or other polymer substrates. So, our ongoing work is to use microwave bonding technique to seal the microcavities by lithographically patterned metal lines around the cavities and bond them with a flat substrate. We will shortly report our experimental results on this process elsewhere.

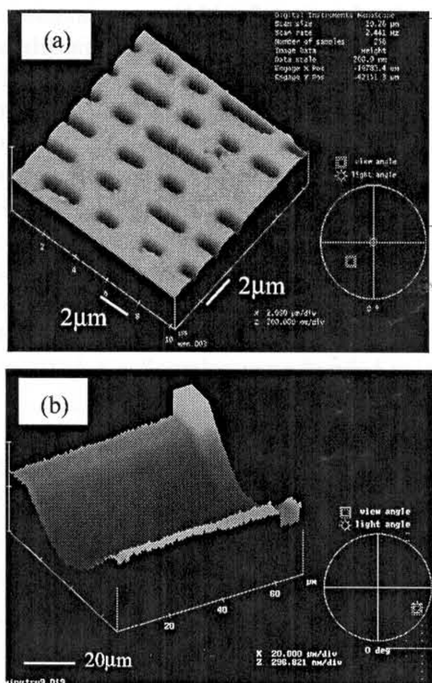

Fig. 14. (a) Scanning probe microscope (SPM) image of a molded PMMA substrate with nanocavities. The cavities have dimensions of width ∼680 nm, depth ∼200 nm, and lengths of ∼1.08, ∼2.19, and ∼3.88 μm, respectively. (b) AFM image of a microchannel made by compact disc-based injection molding process. The dimension is 51.9 μm in width, 283.2 nm in depth.

7. Conclusions

A low temperature bonding technique for polymer-based substrates to achieve a precise and well-controlled bonding interfacial layer has been described. These initial results indicate that microwave bonding has great advantages over thermal compression and other conventional polymer-to-polymer bonding techniques, especially when micro/nanostructure is to be encapsulated. For micro/nanofluidic applications, microwave bonding will give much advantage for bonding polymer substrates to make functional devices.

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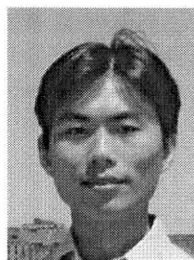
Biographies



Kin Fong Lei received his MPhil degree in mechanical and automation engineering from The Chinese University of Hong Kong (CUHK) in 2000. His research interest is in microfluidic device, micro total analysis system, and bio-engineering. Currently, he is a PhD candidate in automation and computer-aided engineering at CUHK.

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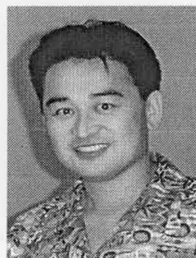
Dr. Nasser K. Budraa received the PhD degree in condensed matter physics from the University of California Riverside. Before co-founding MBI, Dr. Budraa was a post-doctorate fellow at California Institute of Technology and later became an employee of NASA JPL. He performed his research on material bonding initially at JPL. This effort was in concert with his effort on carbon nanotube synthesis and material interaction with microwaves. He is a member of the American Physical Society.



Prof. Wen J. Li received the BS and MS degrees in aerospace engineering from USC in 1987 and 1989, respectively. His industrial experience includes The Aerospace Corporation, Silicon Microstructures Inc., and the NASA/CalTech Jet Propulsion Laboratory. He received the Aerospace Corporate Fellowship, Silicon Microstructures Inc. Employee Award, and a NASA technical innovation award for his technical contributions to those organizations. He obtained his PhD degree from UCLA in 1997 specializing in MEMS. Prof. Li joined the Department of Automation and Computer-Aided Engineering in 1997. He has since then been active in MEMS and nanotechnology research. In the past 6 years, he has published more than 110 papers in professional journals and conference proceedings on MEMS and nanotechnology related work. Recently, his group work on nanosensing and micromanipulation has received the Best Student Poster Paper Award from the IEEE Nano 2003, and the Best Conference Paper Award from the IEEE ICRA 2003, respectively. Prof. Li is currently the Guest Editor for the Focused Section on Micro and Nano Manipulations of the *IEEE/ASME Transactions of Mechatronics*, and has also been commissioned to write the chapter on "Nanoscale Robotics and Manipulation" in the *Encyclopedia of Nanoscience and Nanotechnology* (American Scientific Publishers). Prof. Li is serving as the Director of the Center for Micro and Nano Systems at CUHK, is a member of the Technical Committee on Nanorobotics and Nanomanufacturing of the IEEE Nanotechnology Council, and also a Distinguished Scholar of the Chinese Academy of Sciences. His research interest is to develop micro- and nanodevices for micro/nanoscale sensing and manipulation.

Dr. John Mai received a PhD in aerospace engineering, with a major field in MEMS, from UCLA (2000). His thesis research involved investigating microconvection cooling. He also received his MS (1995) and BS (1993) degrees in aerospace engineering from UCLA. He also was a member of the In situ Exploration Technology Group at the Jet Propulsion Laboratory (1996–2000). He is currently the President of Microwave Bonding Instruments Inc.