Flip-Chip Packaging with Micromachined Conductive Polymer Bumps

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ABSTRACT

A new conductive polymer flip-chip bonding technique has been developed and characterized using micromachined conductive polymer bumps. By the use of UV-based photolithography with thick photoresists, molds for the flip-chip bumps have been patterned, filled with conductive polymers, selectively cured, and then stripped away, leaving molded conductive polymer bumps on contact metal pads. After flip-chip bonding with the micromachined conductive polymer bumps, the contact resistances measured for 25 μm-high bumps with 300 μm x 300 μm area and 400 μm x 400 μm area were 35 mΩ and 12 mΩ, respectively. The conductive polymer flip-chip bonding technique developed in this work showed a very low contact resistance, simple processing steps, a high bumping alignment resolution (< ± 5 μm), and a lower bonding temperature (~170 °C).

I. INTRODUCTION

The use of flip-chip bonding technology has inherent advantages of improved reliability, lower costs, and higher I/O density in less packaging space. Flip-chip bonding is preferred for the mounting or inverting of photonic devices on optical communication systems or recently emerging bio/chemical micro total analysis systems (μ-TAS), where precise input/output coupling is required between photonic devices and optical waveguides or optic fibers [1], [2]. In developing flip-chip bonding techniques for sensor and actuator systems, optical MEMS, or optical interconnections, the most difficult problems usually come from the precision formation of bumps and the lower temperature for flip-chip bonding. Although the conventional solder bump technology provides sufficient bumping alignment, it has several drawbacks due to high soldering temperature and multiple depositions of metal layers, thereby a high-cost technology [3]-[5].

Conductive polymers have generated considerable interest as possible solder replacements in a variety of applications from surface mount technology to die attach [6]. Nowadays, it is possible to buy conductive polymers tailored for specific electronic packaging applications from commercial suppliers. These conductive polymers are usually made using a silver flake fill in a polymer matrix. Since conductive polymer requires a low bonding temperature as well as simple processing steps, the conventional solder bonding techniques are being challenged by conductive polymer flip-chip bonding techniques. However, currently available stencil or screen printing techniques to form the conductive polymer bumps have a quite crude bumping alignment resolution because the printer offers registration accuracies of ± 10 μm [7].

This paper describes a new approach to address possible problems caused by the solder bump technique and the screen printing-based polymer bonding technique, such as high bonding temperature and poor bumping alignment. Fig. 1 illustrates a new flip-chip bonding technique using micromachined conductive polymer bumps. Using micromachining techniques with thick photoresists, an innovative conductive polymer flip-chip bonding technique that achieves both a low processing temperature and a high bumping alignment resolution has been developed and characterized in this work.

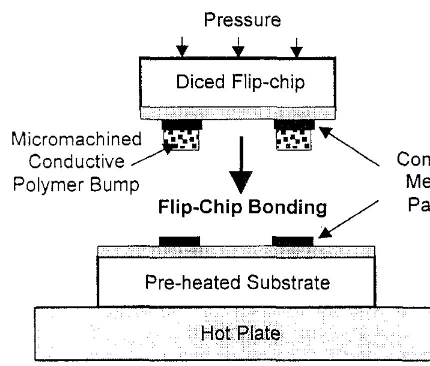

Fig. 1. Schematic illustration of a new flip-chip bonding technique using micromachined conductive polymer bumps.

II. DESIGN AND FABRICATION

A. Micromachined Conductive Polymer Bumps

Fig. 2 summarizes fabrication steps of the micromachined bumps by employing thick photoresist bump-holes as molding patterns. Initially Cr/Au contact metal pad lines and pads for the conductive polymer bumps were formed by lift-off on a silicon dioxide layer, which serves as an insulation layer. Following this, the thick photoresist (AZ 4000 series) was patterned for bump-holes. High aspect ratio and straight side-wall patterns are very important since they are crucial for the molding of conductive polymer bumps. After the lithography, thermoplastic conductive polymer materials were applied into the bump-hole patterns. Overflowing materials were immediately squeezed off by a

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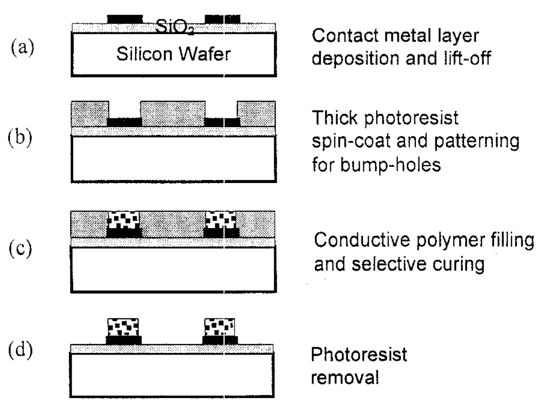


Fig. 2. Summarized fabrication steps for the formation of conductive polymer bumps on contact metal pads.

rubber pad. The wafer was cured in a convection oven at 100 °C for 15 minutes. Due to the different curing conditions between the thick photoresists and the conductive polymers, the photoresist molds can be removed, leaving the conductive polymer bumps on the contact metal pads. After this selective curing, photoresist molds were stripped away in conventional photoresist stripper, leaving the polymer bumps on the contact metal pads. The wafer was then cured in a convection oven at 150 °C for 1 hour, to achieve a better conductivity for the conductive polymers. The wafer was now ready to go for dicing and flip-chip bonding.

Fig. 3 shows a micromachined thermoplastic conductive polymer bump, which has a flat surface morphology, with a thickness of 25 μm and an area of 400 μm x 400 μm on a 500 μm x 500 μm gold contact pad. A high bumping alignment resolution of less than 5 μm was accomplished by the use of the thick photoresist molding process summarized in Fig. 2.

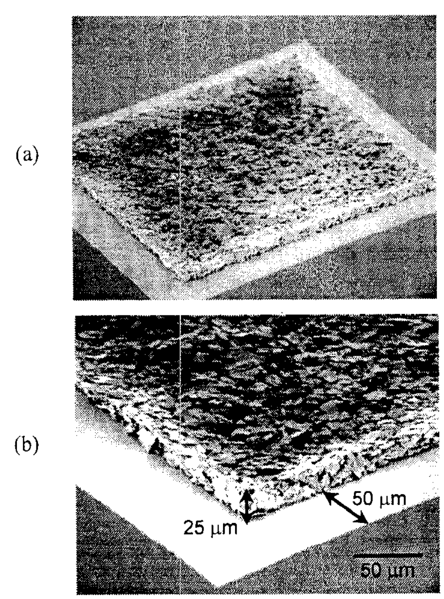


Fig. 3. SEM photographs: (a) a 25 μm high conductive polymer bump (400 μm x 400 μm) on gold contact pad (500 μm x 500 μm) and (b) close-up view of the corner of the bump.

B. Test Vehicles

Fig. 4 shows three mask set of test structures to evaluate the electrical properties of the micromachined conductive polymer bumps. The first mask was designed to define contact metal pads for polymer bumps on the flip-chip wafer. The second mask contained the rectangular patterns with various sizes for thick photoresist bump-holes on the flip-chip wafer. The third mask was used to define contact pad lines and terminal electrode pads for passing a current and reading a voltage drop through a conductive polymer bump sandwiched between a flip-chip wafer and a substrate. To align with a diced flip-chip, a set of guidelines was included in the mask.

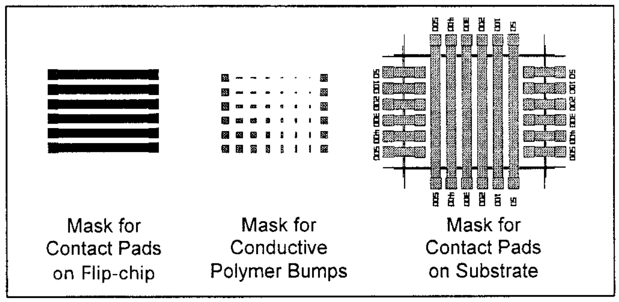


Fig. 4. Three-mask set of test structures to evaluate the electrical properties of the thermoplastic conductive polymer bumps by using a four-point terminal method.

C. Packaging

Chips with micromachined thermoplastic conductive polymer bumps were processed as shown in Fig. 1. The thermoplastic conductive polymers (Epo-Tek K/5022-115BE) used in this work possess the property of melting or re-wetting when heated to a specific temperature (150 °C). After the wafer was sawed into chips, the thermoplastic bumps were then contacted to substrate preheated to approximately 20 °C above the thermoplastic polymer melting temperature. The thermoplastic bumps then melted onto the conductor pads of the substrate. The mechanical and electrical bonds were established as the substrate cooled below the melting temperature of the thermoplastic materials. To enhance the mechanical bonding strength, a small amount of pressure was applied by placing a weight on the chip.

III. EXPERIMENTS

A conductive polymer bump sandwiched between the flip-chip and substrate has a certain amount of so-called contact resistance. This contact resistance is obviously an important parameter that impacts the behavior of devices, if flip-chip bonding is involved in their packaging. Quantitative determination of the contact resistance in ohms can be evaluated by using a four-terminal method [8].

A schematic diagram of a flip-chip bonding for the contact resistance measurement using a four-terminal method is illustrated in Fig. 5(a). An equivalent circuitry of the four-terminal method to measure the contact resistance of $Bump_2$ is shown in Fig. 5(b). Current is forced between contact pads 1 and 2, and the voltage is measured between contact pads 3 and 4. There are two voltage drops between pad 1 and pad 2. The first is between pad 1 and upper pad B and the second is between upper pad B and pad 2. A high-impedance voltmeter used to measure the voltage, V_{34}, allows a negligibly small sensing current, I_{SENSE}, to flow between pads 3 and 4. Hence, the potential at the pad 3 is essentially identical to that in the upper pad B. V_{34} is solely due to the voltage drop across $Bump_2$, known as R_2. The contact resistance of $Bump_2$ is

$$R_2 = \frac{V_{34}}{I}, \qquad (1)$$

where it is simply the ratio of the voltage measured to the current applied. The contact resistance as defined here is the total resistance through $Bump_2$, which includes the bulk resistance of the bump and the two contact resistances between the metal pad B and bump.

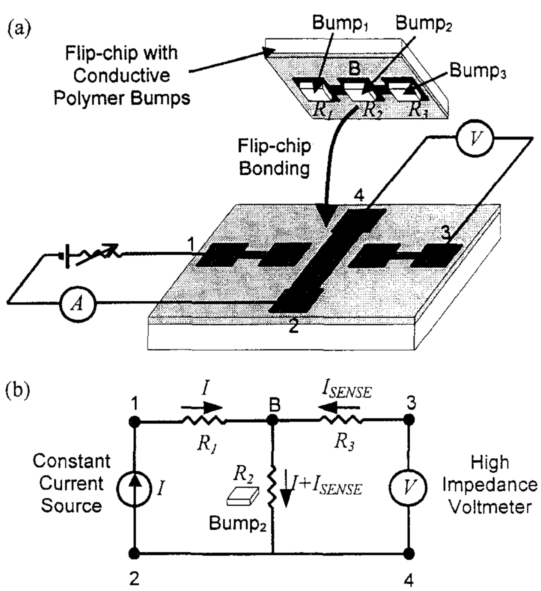


Fig. 5. Four-terminal method: (a) Schematic view of contact resistance measurement and (b) equivalent circuitry of a four-terminal method to measure the contact resistance of $Bump_2$.

Fig. 6 shows the actual flip-chip, substrate, and their assembly used for the contact resistance measurement. White rectangles shown in Fig. 6(a) are the micromachined thermoplastic conductive polymer bumps on the gold contact pad lines. The two bumps on each end of the individual contact pad lines are used as conducting bumps, like R_1 and R_3 in Fig. 5, to be connected with the probe pads on the substrate. Fig. 6(b) shows the substrate with the other set of contact pad lines, guidelines to aid the alignment, and the numbers to indicate the dimensions of bumps sandwiched between metal pad lines on the flip-chip and substrate. For example, a 500 μm x 500 μm bump is in the upper left hand corner of Fig.

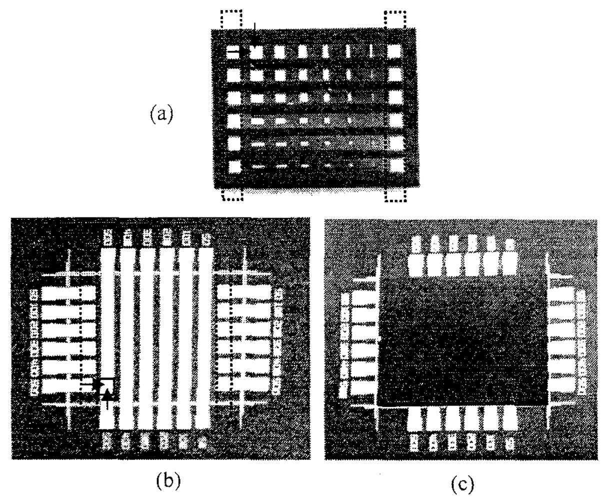


Fig. 6. Microphotographs of flip-chip assembly: (a) flip-chip; (b) substrate; and (c) their assembly used for the contact resistance measurement of the bumps.

6(a). This bump will be centered on the intersection of the arrows in Fig. 6(b). Fig. 6(c) shows their flip-chip assembly used for the contact resistance measurement.

IV. RESULTS AND DISCUSSION

A. Bonding Status

Fig. 7(a) and (b) show a flip-chip wafer before and after the formation of bumps with 100 μm x 100 μm, 200 μm x 200 μm, and 300 μm x 300 μm squares on contact metal pads. The micromachined bumps have a *flat surface* morphology as shown in Fig. 3, instead of a *mountain peak* morphology as when formed with the screen printing technique [7]. Each bump was uniformly micromachined on the contact pads with a thickness of about 25 μm. To test the thermoplastic conductive polymer flip-chip bonding arrangement, the flip-chip wafer with bumps and a substrate with a gold metal layer were used. During the bonding on a hot plate, the thermoplastic bumps melted onto the gold layer of the substrate. As the substrate cooled below the melting temperature of the thermoplastic materials, the mechanical and electrical bonds were established. To simply test the mechanical bonding strength and the bonding status, the flip-chip bonded assembly was separated into individual wafers. Separating the assembly, the bumps were left on the sides of both the substrate (Fig. 7(c)) and the flip-chip wafer (Fig. 7(d)), indicating a successful flip-chip bonding.

Fig. 8(a) and (b) are SEM photographs, which show the bonding status of conductive polymer flip-chip packaging. The top and bottom silicon wafers were oxidized with a thickness of about 2 μm for a purpose of insulation. The bump was placed between gold metal pads of the top flip-chip and the bottom substrate. Fig. 8(a) shows the cross-sectional view of the bump with a width of about 300 μm and a thickness of about 15 μm, which was originally an area of 300 μm x 300 μm and a thickness of about 25 μm. Fig. 8(b)

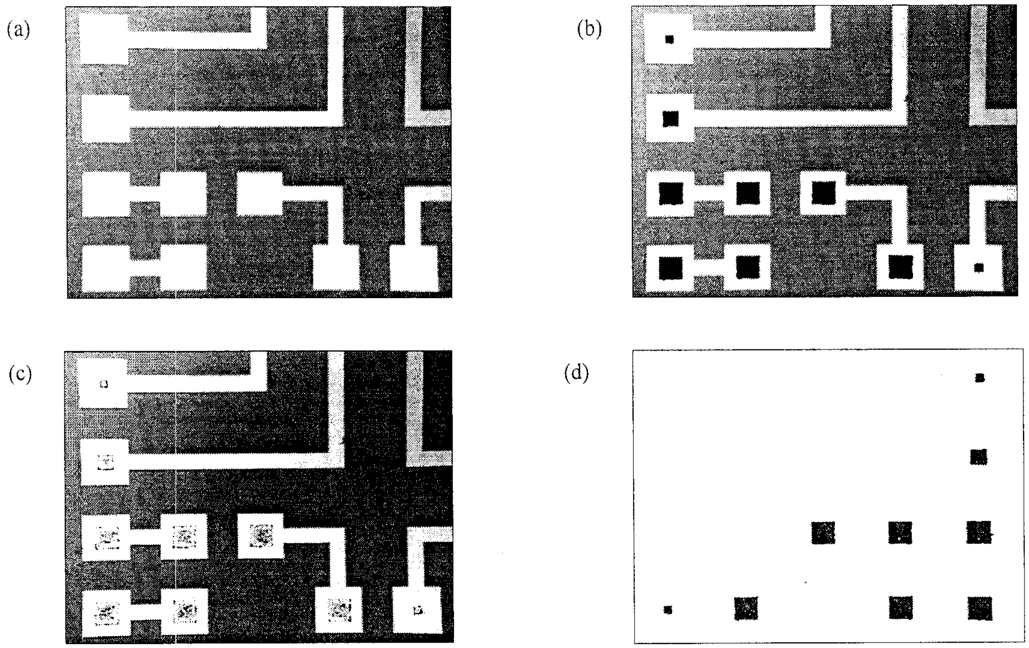
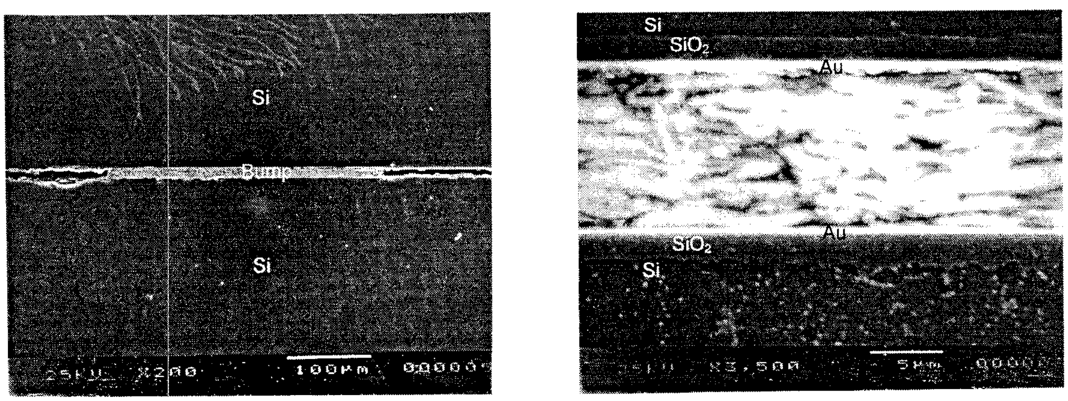


Fig. 7. Microphotographs: (a) a flip-chip wafer before formation of bumps on contact metal pads; (b) the wafer after formation of bumps with 100 μm x 100 μm, 200 μm x 200 μm, and 300 μm x 300 μm areas on contact metal pads; (c) the wafer with bumps left after separation of the testing assembly; and (d) a substrate with bumps left after separation of the testing assembly.



(a) (b)

Fig. 8. SEM photographs of flip-chip packaging: (a) cross-sectional view of a conductive polymer bump on gold contact pads and (b) close-up view of the bump.

shows the size, shapes and orientations of the silver flakes in thermoplastic conductive polymer materials. The size range of these flakes was about 5 μm.

B. Contact Resistance

The I-V characteristics measured for 25 μm high bumps with various sizes are shown in Fig. 9. The voltage drop was measured as the constant direct current was forced through the bumps up to 50 mA. The contact resistances measured for 25 μm high bumps with 400 μm x 400 μm, 300 μm x 300 μm, 200 μm x 200 μm, and 100 μm x 100 μm area were 12 mΩ, 35 mΩ, 75 mΩ, and 122 mΩ, respectively. The voltage drop obtained was proportional to the current with the contact resistance as simply the ratio of the voltage to the current. The slopes of the I-V graphs were linear with different driving currents. The linearity of I-V curves was not disturbed as the current was forced up to 50 mA.

In principle, the contact resistance decreases as a function of contact area for square contacts. Fig. 10 (closed circles) shows the trend as a function of the contact area. The specific contact resistance, defined as the contact resistance multiplied

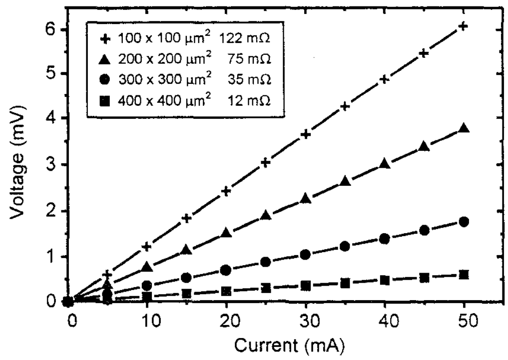


Fig. 9. I-V characteristics measured for 100 μm x 100 μm, 200 μm x 200 μm, 300 μm x 300 μm, and 400 μm x 400 μm bumps.

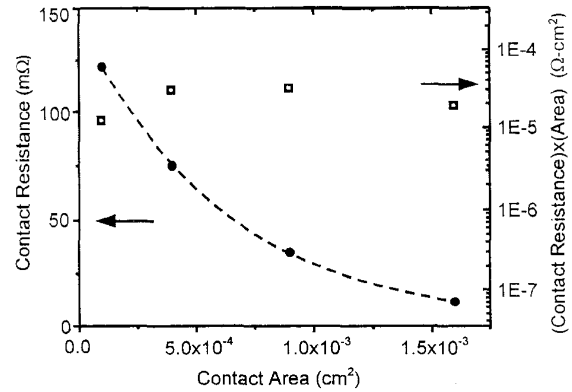


Fig. 10. Contact area dependence of contact resistance (close circles) and area times contact resistance dependence of contact resistance (open squares).

by contact area, for the micromachined conductive polymer bumps was on the order of $\sim 10^{-5}$ Ω-cm². In the case of metal-semiconductor ohmic contacts, typical ohmic contact with specific contact resistance of $\sim 10^{-5}$ Ω-cm² has contact resistance of ~11 mΩ for an area of 300 μm x 300 μm and is considered a good quality contact [9]. The typical flat surface morphology shown in Fig. 3 of the micromachined polymer bumps suggests that modeling the area as a simple rectangle may not suffice. The actual effective areas between the bumps and gold pad may not be the same as the calculated square areas due to the large grain size of the conductive polymer materials as can be seen in Fig. 8. In addition, there may be variation from bump to bump with respect to the fraction of polymer matrixes used as adhesive and silver flakes used as conductive filler. Nevertheless, the contact resistance of the micromachined conductive polymer bumps measured here is comparable to the values achieved by solder metal bumps and shows satisfactory values over a wide range of bump sizes and applied currents.

V. CONCLUSION

Using micromachining techniques with thick photoresists, an innovative conductive polymer flip-chip bonding has been developed and characterized in this work. By the use of UV-based photolithography with thick photoresists, molds for the flip-chip bumps have been patterned, filled with conductive polymers, selectively cured, and then stripped away, leaving molded conductive polymer bumps. After flip-chip bonding with the bumps, the contact resistances measured by a four-terminal method were 35 mΩ and 12 mΩ for 25 μm-high bumps with 300 μm x 300 μm area and 400 μm x 400 μm area, respectively. The conductive polymer flip-chip bonding technique developed in this work showed a very low contact resistance, simple processing steps, a high bumping alignment resolution (< ± 5 μm), and a lower bonding temperature (~170 °C). The new flip-chip bonding technique has high potential to replace conventional flip-chip bonding techniques for sensor and actuator systems, bio/chemical μ-TAS, optical MEMS, OE-MCMs, and electronic system applications.

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