DEVELOPMENT OF AN INNOVATIVE FLIP-CHIP BONDING TECHNIQUE USING MICROMACHINED CONDUCTIVE POLYMER BUMPS

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ABSTRACT

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. By the use of UV-based photolithography with thick photoresists, molds for the flip-chip bumps have been patterned, filled with conductive polymers, and then removed, leaving molded conductive polymer bumps. After flip-chip bonding with the 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 m Ω and 12 m Ω , respectively. The conductive polymer flip-chip bonding technique developed in this work shows a very low contact resistance, simple processing steps, a high bumping alignment resolution ($< \pm 5 \mu\text{m}$), and a lower bonding temperature ($\sim 170^\circ\text{C}$). This new bonding technique has high potential to replace conventional flip-chip bonding technique for sensor and actuator systems, bio/chemical μ -TAS, optical MEMS, OE-MCMs, and electronic system applications.

INTRODUCTION

In recent years, the use of flip-chip bonding technology has grown in many packaging schemes. This is due to the advantages of improved reliability, lower costs, and higher I/O density in less packaging space. In developing flip-chip bonding techniques for sensor and actuator systems, optical MEMS, or optical interconnections, the most difficult problems usually come from precision bumping alignment and bonding temperature. Flip-chip bonding is preferred for the mounting or inverting of photonic devices on optical communication systems or recently emerging bio/chemical μ -TAS, where precise input/output coupling is required between photonic devices and optical waveguides or optic fibers, as shown in Figure 1 [1, 2]. Furthermore, low bonding

process temperature is also required for compound semiconductor-based photonic devices. Although the conventional solder bump technology provides quite sufficient bumping alignment, it has several drawbacks due to high soldering temperature and multiple depositions of metal layers [3].

Nowadays, it is possible to buy conductive polymers tailored for specific electronic packaging applications from commercial suppliers. These conductive polymers are most often made using a silver flake fill in a polymer matrix. Since conductive polymer requires a low bonding temperature as well as fairly simple processing steps, the conventional solder bonding technique is being challenged by conductive polymer flip-chip bonding technique [4]. However, currently available screen printing techniques for the conductive polymer bumps have quite a crude bumping alignment resolution because the printer offers registration accuracies of $\pm 10 \mu\text{m}$. 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.

TEST ASSEMBLY DESIGN

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 is very important and can be evaluated by using a four-terminal method [5].

Figure 2 shows test structures to characterize the electrical properties of the micromachined conductive polymer bumps. The first mask is used to define contact pad lines and terminal electrode pads for passing a current and reading a voltage drop through a conductive bump sandwiched between a flip-chip wafer and a

Figure 1. Schematic diagram of an optical I/O coupler by the use of flip-chip bonding technique using micromachined conductive polymer bumps.

Figure 2. Three-mask set of test structures to evaluate the electrical properties of the thermoplastic conductive polymer bumps by using a four-point terminal method.

substrate. To align with a diced flip-chip, a set of guidelines is included in the mask. The second mask contains the rectangular patterns with various sizes for thick photoresist bump-holes on the flip-chip wafer. The third mask is designed to define contact pad lines for bumps on the flip-chip wafer and guidelines for the dicing of the wafer.

FABRICATION

Figure 3 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 the insulation layer (Figure 3(a)). Following this, the thick photoresist (AZ 4000 series) was patterned for bump-holes. High aspect ratio and straight side-wall patterns are very important as they are crucial for the molding of conductive polymer bumps (Figure 3(b)). After the lithography,

Figure 3. Summarized fabrication steps for the formation of conductive polymer bumps on contact metal pads.

Figure 4. SEM photographs: (a) a 25 μm high conductive polymer bump ($400\ \mu\text{m} \times 400\ \mu\text{m}$) on gold contact pad ($500\ \mu\text{m} \times 500\ \mu\text{m}$) and (b) close-up view of the corner of a 25 μm high bump.

thermoplastic conductive polymers were applied into the bump-hole patterns. Excess materials were immediately scraped off by a sharp blade or rubber pad (Figure 3(c)). The wafer was cured in a convection oven at 100 $^{\circ}\text{C}$ for 15 minutes. Due to the different curing conditions between the patterned thick photoresist and the conductive polymer filling in the bump-holes, the photoresist can be stripped away with a commercial photoresist stripper, leaving the conductive polymer bumps on the contact metal pads. After the removal of photoresist, the wafer was cured in a convection oven at 150 $^{\circ}\text{C}$ for 1 hour to achieve a better conductivity for conductive polymer bumps (Figure 3(d)). Figure 4 shows a micromachined thermoplastic conductive polymer bump with a thickness of 25 μm and an area of $400\ \mu\text{m} \times 400\ \mu\text{m}$ on a $500\ \mu\text{m} \times 500\ \mu\text{m}$ gold contact pad.

CONDUCTIVE POLYMER FLIP-CHIP BONDING

Figure 5 illustrates flip-chip bonding technique using thermoplastic conductive polymer bumps. 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 $^{\circ}\text{C}$). After substrate is pre-heated to approximately 20 $^{\circ}\text{C}$ above the thermoplastic polymer melting temperature, a diced flip-chip is flipped, aligned, and contacted onto it. The thermoplastic bumps then melt or re-wet onto the conductor pads of the substrate. The mechanical and electrical bonds are established as the substrate cools below the melting temperature of the thermoplastic materials. To enhance the mechanical bonding strength, a small amount of pressure is applied by placing a weight on the chip.

Figure 5. Schematic illustration of an innovative flip-chip bonding technique using micromachined conductive polymer bumps.

Figure 6(a) and (b) show a flip-chip wafer before and after the formation of bumps with $100\ \mu\text{m} \times 100\ \mu\text{m}$, $200\ \mu\text{m} \times 200\ \mu\text{m}$, and $300\ \mu\text{m} \times 300\ \mu\text{m}$ squares on contact metal pads. The micromachined bumps have a flat surface morphology as shown in Figure 4 instead of a mountain peak morphology as when formed with the screen printing technique [4]. Each bump was uniformly micromachined on the contact pads with a thickness of 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

Figure 6. Microphotographs: (a) a flip-chip wafer before formation of bumps on contact metal pads; (b) the wafer after formation of bumps with $100\ \mu\text{m} \times 100\ \mu\text{m}$, $200\ \mu\text{m} \times 200\ \mu\text{m}$, and $300\ \mu\text{m} \times 300\ \mu\text{m}$ 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.

assembly was separated into individual wafers. Separating the assembly, the bumps were left on the sides of both the substrate (Figure 6(c)) and the flip-chip wafer (Figure 6(d)), indicating a successful flip-chip bonding.

EXPERIMENTS

A schematic diagram of a flip-chip bonding for the contact resistance measurement using a four-terminal method is illustrated in Figure 7(a). In the four-terminal structure, a bump is sandwiched between two metal pad lines crossing each other. A constant direct current is made to flow through two of the contacts from each end of the metal pad lines, and the voltage across the other two contacts is measured with a high-impedance-voltmeter. An equivalent circuitry of the four-terminal method to measure the contact resistance of Bump₂ is shown in Figure 7(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 Bump₂, known as R_2 . The contact resistance of Bump₂ is

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

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 Bump₂, which includes the bulk resistance of the bump and the two contact resistances between the metal pad B and bump.

Figure 8 shows the actual flip-chip, substrate, and their assembly used for the contact resistance measurement. White rectangles shown in Figure 8(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

Figure 7. 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 Bump₂.

Figure 8. Microphotographs of flip-chip assembly: (a) flip-chip; (b) substrate; and (c) their assembly used for the contact resistance measurement of the bumps.

lines are used as conducting bumps, like R_1 and R_3 in Figure 7, to be connected with the probe pads on the substrate. Figure 8(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 $50\ \mu\text{m} \times 50\ \mu\text{m}$ bump is in the lower right hand corner of Figure 8(a). This bump will be centered on the intersection of the arrows in Figure 8(b). Figure 8(c) shows their flip-chip assembly used for the contact resistance measurement.

RESULTS AND DISCUSSION

The I-V characteristics measured for 25 μm high bumps with various sizes are shown in Figure 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 $\mu\text{m} \times 400 \mu\text{m}$, 300 $\mu\text{m} \times 300 \mu\text{m}$, 200 $\mu\text{m} \times 200 \mu\text{m}$, and 100 $\mu\text{m} \times 100 \mu\text{m}$ area were 12 m Ω , 35 m Ω , 75 m Ω , and 122 m Ω , 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.

Figure 9. I-V characteristics measured for 100 $\mu\text{m} \times 100 \mu\text{m}$, 200 $\mu\text{m} \times 200 \mu\text{m}$, 300 $\mu\text{m} \times 300 \mu\text{m}$, and 400 $\mu\text{m} \times 400 \mu\text{m}$ bumps.

In principle, the contact resistance decreases as a function of contact area for square contacts. Figure 10 (closed circles) shows the trend as a function of the contact area. The specific contact resistance, defined as the contact resistance multiplied by contact area, for the micromachined conductive polymer bumps was on the order of $\sim 10^{-5} \Omega\text{-cm}^2$. In the case of metal-semiconductor ohmic contacts, typical ohmic contact with specific contact resistance of $\sim 10^{-5} \Omega\text{-cm}^2$ has contact resistance of $\sim 11 \text{ m}\Omega$ for an area of 300 $\mu\text{m} \times 300 \mu\text{m}$ and is considered a good quality contact [6]. The typical flat surface morphology shown in Figure 4 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 polymers.

Figure 10. Contact area dependence of contact resistance (closed circles) and area times contact resistance dependence of contact resistance (open squares).

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.

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, and then removed, leaving molded conductive polymer bumps. After flip-chip bonding with the bumps, the contact resistances measured by a four-terminal method were 35 m Ω and 12 m Ω for 25 μm -high bumps with 300 $\mu\text{m} \times 300 \mu\text{m}$ area and 400 $\mu\text{m} \times 400 \mu\text{m}$ area, respectively. The conductive polymer flip-chip bonding technique developed in this work shows a very low contact resistance, simple processing steps, a high bumping alignment resolution ($< \pm 5 \mu\text{m}$), and a lower bonding temperature ($\sim 170^\circ\text{C}$). This new bonding technique has high potential to replace conventional flip-chip bonding techniques for sensor and actuator systems, bio/chemical $\mu\text{-TAS}$, optical MEMS, OE-MCMs, and electronic system applications.

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