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Shaking assisted self-assembly of rectangular-shaped parts

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ABSTRACT

A process for shaking assisted self-assembly of rectangular-shaped parts is presented. Rectangular parts are assembled to their corresponding binding sites on a glass substrate in an air environment. Rectangular binding sites are the only hydrophilic areas on the substrate. By a dip-coating process, molten solders wet only the binding sites on the substrate. The parts with misalignment angle up to 90° can be rotated and translated to align with the binding sites during orbital shaking. Before the shaking, the solder is reflowed by heating to 120 °C. The alignment completed within 3 s. The yields of the self-assembly for misalignment angles ranging from 15° to 90° are at least 80%. The integrity of the bonding between the parts and the binding sites is confirmed by a static debonding test.

1. Introduction

It is a major challenge to develop micro and meso scale assembly methods for discrete components in complex heterogeneous integrated systems. Assembly of microparts has been done by the conventional pick and place robotic assembly (Mølhave et al., 2004), microstructure transfer between aligned wafers (Holmes and Saidam, 1998; Singh et al., 1999), and dynamic self-assembly (Grzybowski et al., 2004). Mølhave et al. (2004) demonstrated that micro tweezers can pick up nanowires and an electron beam deposition of carbon residues can be used to assemble nanotubes. Success of their pick-and-place assembly requires a careful design of the shape of the tweezers and precise control of the gripping force. Pick-and-place assembly is a serial process and can be subject to adhesion forces resulting from handling and positioning micro/nano components. Another limitation of the pick-and-place assembly is its inefficiency with large number of components. Holmes and Saidam (1998) performed a wafer-scale assembly of hybrid devices. Their method is applicable to devices which can be assembled by adding components from one direction only. Singh et al. (1999) achieved wafer-level transfer and assembly of microstructures using break-away tethers and solders. Wafer-level transfer is an inherently two-dimensional fabrication method and cannot generate truly three-dimensional structures (Saeedi et al., 2006). Self-assembly where micro-fabricated components are integrated and constructed automatically as functional units is suitable for the development of complex microsystems and because it requires that the target structures be the thermodynamically most stable ones open to the system, it tends to produce structures that are relatively defect-free and self-healing (Whitesides, 1996).

Parts assembled by self-assembly need a method for the mechanical connection to hold the final structure together and electrical connection between components to make the final assembled structure functional. Different ways can be applied to make the electrical connection between components. Solders applied by electroplating, screen printing or sputtering can produce reliable electrical connection for wafer to wafer bonding (Sparks et al., 2001). However, the electrical contacts produced by electroplated solders suffer from poor mechanical properties (Xiong et al., 2003). Polymer interconnections show great promise as conducting materials in a wide range of application areas due to their tolerance of mechanical stress, ease of processing and their chemical tunability (Videlot et al., 2004). Nevertheless, their electrical resistivity is high, their contact area may be limited to asperities, and at the molecular level they may not be able to withstand high-temperature processing and operation (McCreery, 2004; Saeedi et al., 2006). Soldering processes for assembly of parts to each other or to a substrate can provide excellent electrical, thermal, and mechanical properties.

Methods of assembling parts using molten solder have been developed with different driving mechanisms (Harsh et al., 1999; Jacobs et al., 2002; Greiner et al., 2002; Lienemann et al., 2003; Stauth and Parviz, 2005; Ye et al., 2006; Fang et al., 2006; Liu et al., 2007; Morris and Parviz, 2008). Based on surface energy minimization of molten solder balls, Harsh et al. (1999) demonstrated an assembly of a hinged plate through control of solder volume. Jacobs et al. (2002) showed a patterned assembly of LEDs involving liquid solder. The components were suspended in water and agitated gently. Minimization of the free energy of the solder–water inter-

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face provided the driving force for the assembly. Their experiments were performed in water in order to reduce capillary and gravitational forces. Greiner et al. (2002) coated the microparts and the on-substrate binding sites with a self-assembled monolayer (SAM), and applied a lubricant liquid to the binding sites while the entire system was immersed in water. They showed that the microparts were attracted to the lubricant sitting on the binding sites due to capillary forces. Lienemann et al. (2003) described a technique of self-assembling microparts onto Au binding sites patterned on a substrate. A SAM layer was adsorbed on the Au binding sites, and a lubricant was applied onto the binding sites. In their assembly process, the microparts were attracted to the binding sites in a water environment with agitation. Stauth and Parviz (2005) performed a fluidic self-assembly of micro-fabricated silicon components on a flexible, plastic substrate. Their self-assembly was driven by a combination of gravity, capillary forces and dynamic fluid flow. Liu et al. (2007) demonstrated a fluid self-assembly method, which is able to integrate micro components in a multi-batch-wise manner. They patterned solders with different melting points, and activated them separately and sequentially to achieve programmable self-assembly of micro components. A magnetic field was employed by Ye et al. (2006) to integrate nanowires with a solder-padded substrate. A few drops of a suspension of the nanowires in ethanol were placed on top of the substrate in a vial. The vial was then agitated during assembly. Morris and Parviz (2008) assembled circular and square micropart to the binding sites on a silicon template in a fluid environment. In most self-assembly processes, effective part-to-substrate assembly were achieved in fluid environments. Mild fluid self-assembly conditions (temp < 100 °C, pH ≈ 3.5) are required for most electronics and photonics components (Stauth and Parviz, 2005). Without immersing micro components in fluid, Fang et al. (2006) demonstrated an orbital shaking assisted self-assembly of square PZT parts in an air environment.

In this paper, a simple process to achieve on-substrate self-assembly of rectangular parts using molten solder is reported. The assembly technique is assisted by an external shaking and provides accurate placement of parts in an air environment. Fabrication steps for the parts and binding sites are described. Experiments for parts with various misalignment angles and shift distances are carried out. Bonding strength between parts and binding sites is investigated by a debonding test.

2. Shaking assisted self-assembly

Surface tension has been the driving force for the self-assembly technique using molten solder, especially in fluid environment (Scott et al., 2004; Chung et al., 2006). Self-alignment of parts to binding sites via a layer of molten solder occurs due to surface energy minimization of the solder. In practice, most parts are rectangular. The number of minimum energy states depends on the width-to-length ratio of the rectangular parts. Based on calculations of the overlap area carried out by Fang et al. (2006), a square part has four preferred in-plane orientations with rotation angle intervals of 90°, where the surface energy has its local minimums. For micro/nano scale parts, the self-assembly process can be driven by surface tension with fluid agitation (Morris and Parviz, 2008; Chung et al., 2006) or simply through minimization of the interfacial free energy (Chung et al., 2006). With proper agitation in fluid environment, millimeter-sized parts can settle into the orientations with the local minimum surface energy (Xiong et al., 2003; Liu et al., 2007). When assembling millimeter-sized parts in air environment, a means to provide external agitation to assist the assembly process is needed.

To assist self-assembly, orbital shaking can be employed to provide a centrifugal force to the part. The centrifugal force may drag

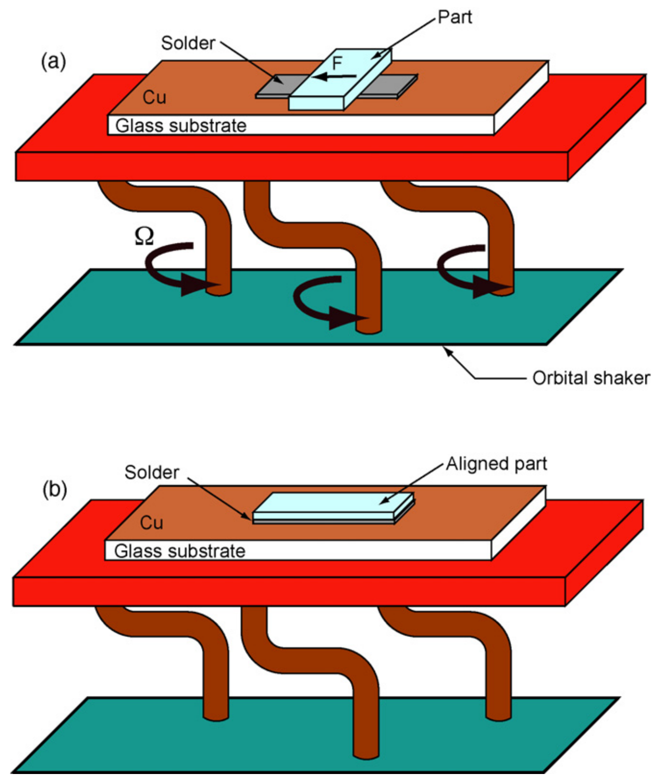

Fig. 1. Two-step operation of the self-assembly of a part. (a) The shaking of an orbital shaker. (b) The resulting alignment of the part.

and balance the part on the molten solder so that self-alignment of the part can be achieved through surface energy minimization. Random shaking can also drag and balance the parts on the molten solder, orbital shaking is chosen here for the availability of the experimental apparatus. Fig. 1 illustrates the operation steps of the self-assembly assisted by orbital shaking. Fig. 1(a) shows a misaligned part resting on a binding site. The glass substrate is shaken with the orbital shaker at an angular velocity Ω. This external agitation introduces a centrifugal force F to agitate the part. Then the part is rotated to the states of lower surface energy by surface tension and aligned with the binding site as shown in Fig. 1(b).

2.1. Model

Successful alignment of the part to the binding site requires that the magnitude of the centrifugal force F is less than the restoring force T induced by the surface energy minimization. The centrifugal force is given as

$$F = mR\Omega^2 \tag{1}$$

where m is the mass of the part and R is the rotating arm length of the orbital shaker. Using Eq. (1) and the fact that $F < T$ for successful alignment, the angular velocity of the orbital shaker has an upper limit $\Omega_{\max}$

$$\Omega_{\max} = \sqrt{\frac{T}{mR}} \tag{2}$$

2.2. Estimation of the restoring force

For systems with simple geometry, 2D analytical models have been used to determine the surface force (Lienemann et al., 2003). For systems with complex shapes, numerical simulations can model the 3D surface and nonlinear effects better than 2D analytical