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AREAL ARRAY JETTING DEVICE FOR BALL GRID ARRAYS

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INTRODUCTION

Package designs for microelectronics devices have moved from through-hole to surface mount technology in order to increase the printed wiring board real estate available by utilizing both sides of the board. The traditional geometry for surface mount devices is peripheral arrays where the leads are on the edges of the device. As the technology drives towards high input/output (I/O) count (increasing number of leads) and smaller packages with finer pitch (less distance between peripheral leads), limitations on peripheral surface mount devices arise [1-2].

A solution to the peripheral surface mount issue is to shift the leads to the area under the device. This scheme is called areal array packaging and is exemplified by the ball grid array (BGA) package. In a BGA package, the leads are on the bottom surface of the package in the form of an array of solder balls.

The current practice of joining BGA packages to printed wiring boards involves a hierarchy of solder alloy compositions. A high melting temperature ball (e.g., 90Pb-10Sn that melts at 300°C) is typically used for standoff. These balls are made by either a spray forming operation or by cutting wire to specific lengths then reflowing them in flux. Both techniques result in a range of solder ball size that requires an expensive sieving operation to produce solder balls of uniform dimensions. The process to create the balls represents a significant fraction of the overall BGA package manufacturing cost, and it is estimated that solder balls alone make up 13% of this cost. A lower melting temperature solder (e.g., 63Sn-37Pb near eutectic solder) paste is used to join the balls to the package substrate and board. One method of attaching high melting temperature balls to the substrate involves loading a graphite fixture, drilled with holes of the same diameter as the balls, in the desired areal array pattern. The package substrate is patterned with the lower melting temperature solder paste using either a dispensing, screen printing, or stenciling method. The substrate and fixture are placed together so that the balls make intimate contact with the solder paste. After the ball placement operation, the assembly goes through a reflow furnace that melts the solder paste and joins the paste to the balls and substrate. The substrate is cleaned to remove flux residue. Final assembly involves aligning the substrate/ball assembly to the board having the lower melting temperature solder paste on its lands. This assembly then undergoes reflow and cleaning.

A promising alternative to current methods is the use of jetting technology to perform monolithic solder ball attachment. This paper describes an areal array jetter that was designed and built to simultaneously jet arrays of solder balls directly onto BGA substrates [3].

JETTING TECHNOLOGY

Jetting is a process whereby a molten stream of liquid material (in this case molten solder) is broken up into discrete droplets, in a uniform and controlled manner. The liquid exits through a small orifice as a stream (or jet), and droplets are formed by externally imposing instabilities to the stream. The instabilities cause the stream to break up into droplets having a diameter of approximately the width of the original stream of solder. The droplets form spheres, due to the minimization of surface energy of the liquid.

Continuous jetting is an option for the creation of uniform balls of solder. Continuous jetting is most extensively used in printing (e.g., ink jet printers). In ink jet printing, there is a constant source of droplets, all the same size, and the pattern is controlled by moving the jetting head or electrostatically moving the droplets. However, continuous jetting is not a good means to directly deposit solder balls to form an array of interconnects because it is very difficult to control the location of the deposited balls.

"On-demand" jetting is an option for the direct deposition of solder balls where a single ball of liquid, rather than a stream of balls, is ejected with a single command. The advantage of on-demand jetting is that the location of the jetted ball can be precisely determined by motion of the head to the location desired. The current technology associated with on-demand jetting results in the formation of balls with a diameter of < 0.005" (125μm). To create a ball of the required

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diameter (~0.030" (0.75mm) for BGA interconnects would require that the jetter deposit 215 balls of 0.005" diameter on top of one another. The assembly would then be reflowed from a single, spherical 0.030" ball. This process would have to be repeated for every solder joint in the array. This would be time consuming and expensive. Therefore, a new technique using an areal array methodology was developed that could jet an entire array of solder balls with diameters as large as 0.035".

The premise of the on-demand areal array jetter is that the array of balls is jetted through an orifice plate and the array is defined by the location of holes in the plate. The creation of an instability just below the orifice plate causes the balls to form and project into an array on a substrate.

Description of the Equipment

The equipment designed to jet arrays of solder balls is shown in Figure 1 and includes:

- The solder pulse generator, which consists of:
  - Piezoelectric actuator.
  - Belleville spring washer oriented to pre-load the piezoelectric actuator.
  - Anodized aluminum pulse chamber, solder reservoir and cartridge heater housing.
- A graphite orifice plate.
- A chamber that surrounds the jetting device and provides an inert atmosphere of nitrogen gas.
- A custom analog high voltage pulse generator.
- Temperature controllers for the solder melt and printed wiring board heater.

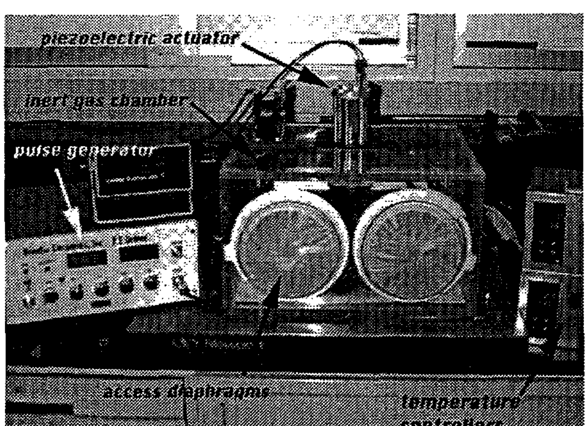


Figure 1 Photograph of the areal array jetting device.

Figure 2 is a diagram that shows a section view of the solder pulse generator. A voltage pulse (up to 800 volts) causes the piezoelectric actuator to expand, pushing the piston down into the molten solder and forcing the solder through the orifice plate. As the voltage drops, a Belleville spring washer returns the piston to its original position. The withdrawal of the piston causes an instability in the fluid displaced from the orifice. As this instability grows, necking of the fluid occurs until "pinch-off" is achieved and a free droplet is formed. The rate of piston motion, piston displacement, solder temperature and orifice size were optimized to form stable solder droplets through fluid mechanics modeling and fine tuning by experiment.

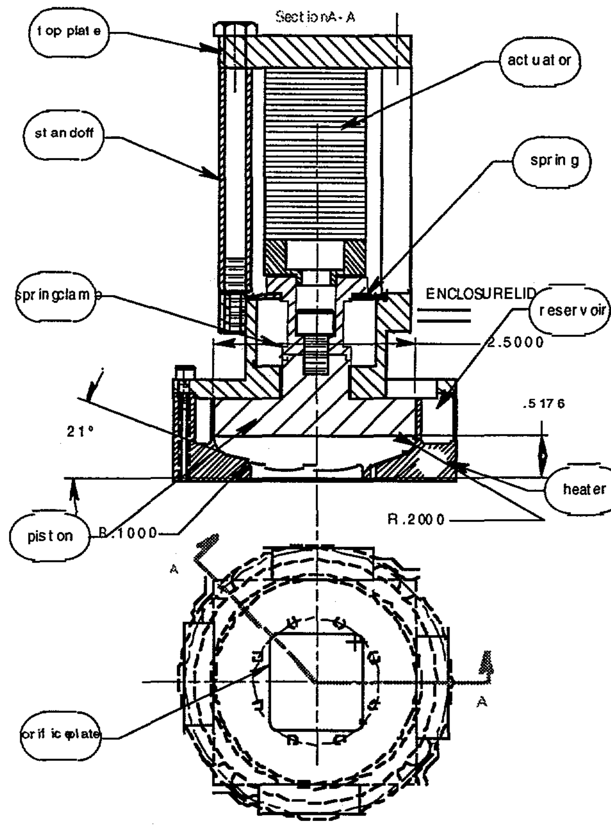


Figure 2 Section view of the jetter.

The piezoelectric actuator allows precise control of the piston, with a displacement of up to 0.002" and rates from 0. 3 to 1.7 in/sec. A hold time can be inserted into the pulse at the peak from 0 to 9 msec. The piston must only travel about 0.0014" to displace the volume necessary to form 400 spheres of 0.030" diameter.

The Belleville spring washer is compressed by the spring. The spring pre-loads the piezoelectric actuator and drives the piston up after the voltage to the actuator is reduced. The compressive pre-load of the spring is 300 to 400 lb. and is overcome by the force of the piezoelectric crystal.

The reservoir/pulse chamber is made from anodized aluminum that resists wetting/alloying with the molten solder. The piezoelectric crystal is sensitive to elevated temperatures, so heat conduction through the device requires a continuous source of cooling air to the piezoelectric actuator.

The solders used in electronic packaging are typically Sn-Pb based materials that rapidly oxidize in air when in the molten state. To minimize oxidation, the atmosphere is controlled by placing the entire jetting assembly inside a plexiglas container that is equipped with a flow-through source of pure nitrogen gas. The plexiglas enclosed system is shown in Figure 1. While in operation, nitrogen continuously flows through the chamber, lowering the oxygen level to near 100 parts per million.

The orifice plate from which the solder balls are jetted is shown in Figure 3. The grid is made of pyrolytic graphite. Graphite was chosen because it can be accurately machined to the tolerances required for the hole spacing and distribution, does not dissolve into the molten solder, and has sufficient strength to withstand the solder pulses.

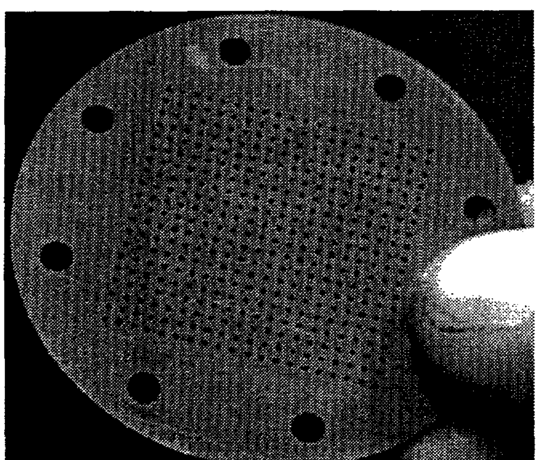


Figure 3 Graphite orifice plate with a 20x20 array of 0.020" holes.

After the solder balls are jetted, they must land on, and metallurgically bond to, the metallized substrate. If the balls were jetted to a substrate at room temperature, heat would rapidly conduct from the balls to the substrate and there would not be sufficient time for metallurgical bonding to occur, or for a stable spherical ball shape to form. Therefore, the substrate is preheated to temperatures near, or at, the melting temperature of the solder. Preheating is performed by aligning the substrate onto an aluminum block heated with a cartridge heater, Figure 4.

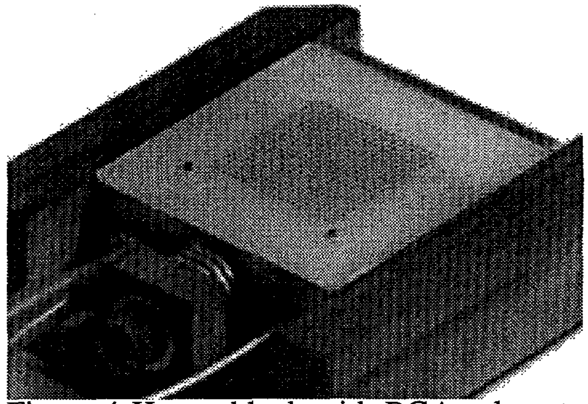


Figure 4 Heater block with BGA substrate with copper lands.

Modeling of the Jetter

Fluid dynamics modeling was used to perform computational simulations of the delivery of molten solder from a piston driven system operating above an array of orifices. The simulations were needed to optimize the jetting parameters. Fine-tuning of these parameters could then be performed experimentally on the jetter itself. Computational simulations were also performed to determine the relationship between the orifice diameter and the volume of displaced fluid that leads to stable droplet formation.

The first detailed analysis of the fluid dynamics of an infinitely long column of fluid was the work of Rayleigh [4], who showed that the free surface of a column of fluid will undergo periodic oscillations as a result of hydrodynamic instability. The amplitude of this instability is given by:

$$a = a_0 e^{\frac{t}{\tau}} \cos\left(\frac{2\pi z}{\lambda}\right) \qquad [1]$$

where a_0 is the initial disturbance in the radius of the column created at the nozzle, τ is the characteristic time, z is the propagation distance, and λ is the wavelength of the disturbance. As the column propagates through space, energy minimization will take place in the form of constriction of the column, as surface tension acts to minimize the column's surface area. This results in a necking of the fluid, which may lead to breakup and droplet formation. The characteristic time τ gives an approximate time for necking to occur. For on-demand production of droplets, the force applied to the fluid should be tailored such that necking occurs near the orifice. The application of this type of force is needed to produce single droplets without undesirable satellite droplets. The characteristic time is related to the orifice size and the fluid properties by:

$$\tau = \sqrt{\frac{\rho D_0^{\,3}}{8\sigma}} \qquad [2]$$

where ρ is the fluid density, D_0 is the orifice diameter, and σ is the surface tension. Rayleigh's analysis was used as a guide for the production of molten solder droplets. Indeed, given the fluid properties, the characteristic time can be determined for different orifice sizes. In a typical simulation, the piston is displaced so that the volume displacement is equivalent to the volume of the droplet to be produced. The velocity of the piston is chosen so that the required displacement occurs in a time approximately equal to τ.

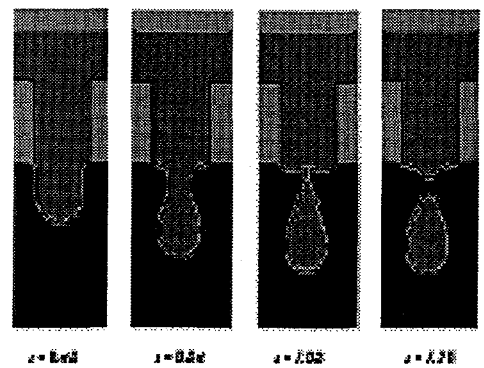
Computational simulations were performed using Flow-3D, a commercially available fluid dynamics code. Hirt has described the code and its application to modeling of fluid dynamics problems [5-7]. To simplify the computations, the fluid flow for a single orifice was simulated, keeping the ratio of the area of the piston to the total orifice area constant. The fluid properties used for 60Sn-40Pb were: density: 8.0 gm/cm^3, viscosity: 2.85 cp, and surface tension: 440 dynes/cm.

The formation of a droplet is governed by the length of the orifice channel, the width of the orifice, the fluid properties, and the piston displacement. In simulating the delivery process, an obstacle was constructed in the model to represent the walls of the device. A moving obstacle was also constructed to represent the piston, and its velocity is specified as a function of time. These velocities were chosen so that the initial downward piston displacement, Δz, occurred in a time approximately equal to τ. The magnitude of this downward displacement was determined by equating the volume displaced by the cylinder to the volume of a sphere with a radius equal to the radius of the orifice. Therefore Δz is given by

$$\Delta z = \frac{4R_0^3}{3R} \qquad [3]$$

where R_0 is the radius of the droplet and R is the radius of the piston.

Simulations [8] have shown that the most well-formed single droplet develops when a critical volume is displaced from the orifice within a time given approximately by equation 2. This critical volume V_0 has a spherical diameter which is equal to the diameter of the orifice. If the piston displacement is such that the volume V_0 is displaced in a time $t > \tau$, necking may not occur, inhibiting the formation of a free droplet.



Time —>

Figure 5 Simulation A results for optimized jetting paramters.

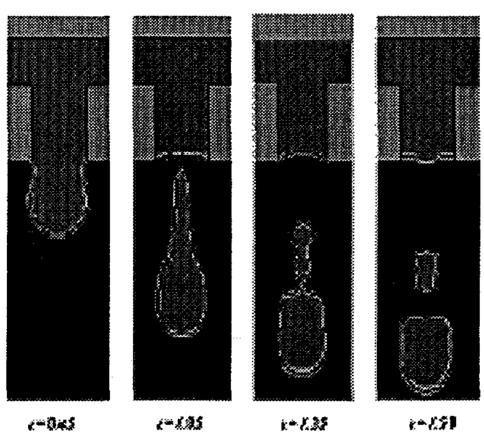


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Figure 6 Simulation B results for jetting parameters that result in the formation of satellites.

The results of two simulations are shown in Figures 5 and 6 respectively. For these simulations, D_0=458 μm (0.018") and t=0.47 ms. Simulation A is for a volume displacement of V_0, while simulation B corresponds to a volume displacement of 2.05V_0. In simulation A (Figure

5) necking begins around 0.48 ms. Near this time, the downward velocity of the piston goes to zero and fluid is no longer forced from the orifice. The negative or upward piston motion begins at 0.5 ms. This piston motion aids necking and by 1.08 ms, a pendant droplet has formed with a narrow neck region. Pinch-off occurs around 1.1 ms and a free droplet is formed. Subsequent simulations also show that, for the orifice sizes investigated and for the fluid properties of molten solder, the minimum duration of the upward motion of the piston was about 0.1 ms. Durations shorter than ~0.1 ms cause elongated tail regions to form on the free droplet, leading to the production of satellite droplets. Simulation B (Figure 6) also shows that satellite droplets may be produced when the volume displacement is too large. In this case, the droplet produced has a diameter that is 20% larger than the diameter of the orifice. In terms of the argument given above, Figure 6 shows that at $t=\tau$, a volume larger than V_0 has been extruded from the orifice. This fluid region begins to form an elongated tail at about 1.05 ms, leading to droplet breakup. At 1.50 ms two distinct fluid regions have been formed.

Prototype Results

Fluid dynamics modeling results were used as a basis to initialize the jetting parameters. Experiments were performed while varying:

- piston displacement
- orifice size (hole diameter)
- orifice thickness
- piston displacement distance
- piston displacement rate
- solder bath temperature
- jetting atmosphere (air or flowing nitrogen).

Results of the experiments were determined by characterizing the solidified, deposited balls on the substrates and through the use of high speed photography.

To demonstrate the deposition of solder on copper pads, a test board was designed to fit under the jetter. The boards were made from 0.062" thick FR-4 with a matching 20x20 array of 0.028" diameter 1/2 oz. copper interconnect lands. The board was positioned 0.100" under the orifice plate and exactly aligned with the holes in the orifice plate. The board was preheated to 180° C to aid the wetting of the copper interconnect lands. To test the prototype and bound the scope of the project, one ball size of 0.030," and one array dimension of 20 x 20 (1"x1"), was defined as the baseline.

Experiments were conducted with several orifice sizes. Experimental graphite orifice plates included 1) 0.040 in. thick with 0.008 in. diameter. and 0.010 in. diameter holes and 2) 0.025 in. thick with 0.022, 0.020, 0.018, 0.016, 0.014, 0.012, 0.010, 0.008 and 0.006 in. diameter holes. These tests were performed to determine the effects of hole size and plate thickness on the size and shape of the solder droplets created. For example, 0.030 in. diameter solder balls could be formed through 0.012, 0.014, and 0.016 in. orifices with adjustment of the piston displacement, pulse time and hold time. The most reliable 0.030 in. solder drop creation, at 205°C, was performed with the 0.014 in. orifices. The experimental results confirmed the modeling predictions of hole geometry, pulse duration, and piston displacement to within a few percent, indicating that the fluid dynamics modeling is an effective means of determining optimum operational parameters.

The optimal solder bath temperature was found to be 205°C (60Sn-40b solder melts at 183°-188°C). When the solder bath temperature was varied, the pulse characteristics had to be varied to obtain the same solder droplet size. A large range of droplet sizes(<50% or >150%) may be formed by adjusting the displacement and solder temperature. Higher temperatures resulted in larger solder balls primarily due to a decrease in the fluid viscosity.

As predicted from the fluid dynamics simulations, changes in pulse characteristics affected the size uniformity of the solder balls in the array. At a given piston displacement, a non-optimized displacement rate caused tails, or pendant droplets, to form on the orifice plate, Figure 7. This result can be compared with the simulation shown in Figure 6. With the proper combination of ramp rate and hold, a uniform front of droplets would emerge from the orifice plate with no tails or satellites. An array of solidified solder balls under optimized jetting conditions is shown in Figure 8.

Conclusions

An areal array solder jetting device for depositing solder balls on substrates for BGA applications has been successfully designed and built. The device can simultaneously jet an entire array of solder balls at one time with all the balls having uniform dimensions and spacing. The device was built, as a prototype, based upon fluid mechanics computational simulations. The results of a cost analysis indicate that the incorporation of the areal array jetting device into a ball grid array attachment system could lower costs from 3 to 5 times that of the current process, at an increased rate of manufacture. The prototype is now available for commercialization..

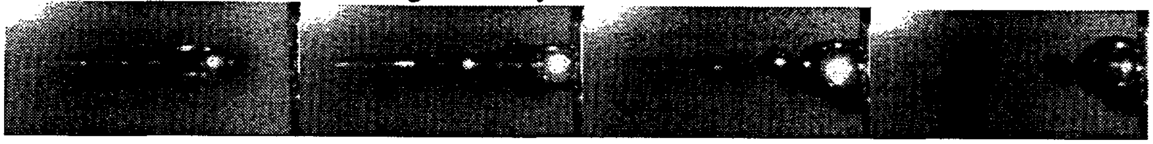

Figure 7 Select high speed digital photographs taken at 1000 frames per second, 30 microsecond exposure time from left to right at the edge of a 20x20 array of orifices. Note that in this case that the parameters were not optimized and satellite formation occurred.

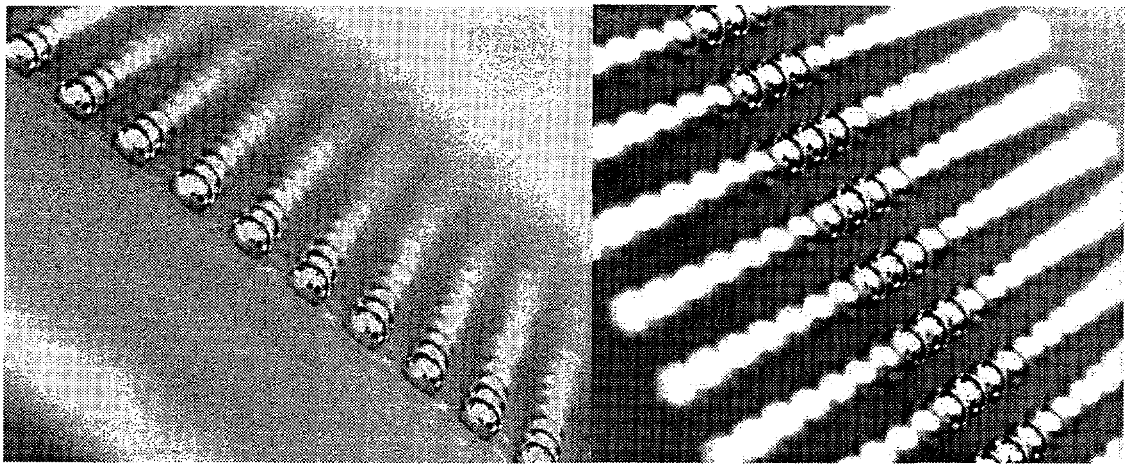

Figure 8 Photographs of a BGA substrate with a 20x20 array of .030" wetted solder balls deposited simultaneously by solder jetter.

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