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High Precision Solder Droplet Printing Technology: Principle and Applications

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ABSTRACT

Solder droplet printing technology, which is low-cost, non-contact, flexible, data-driven, and environmentally friendly, has emerged as an enabling technology for precisely placing fine solder deposits onto a variety of small substrates. It is suitable for a variety of applications including direct chip attach site preparation, 3-D substrates, fine line interconnect, substrate via fill, optoelectronics and many others. It enables manufacturing techniques that are impossible or unfeasible with current technology, such as localized replacement of solder on board, depositing solder in different thickness on the same board, or using more than one type of solder on the same board. This makes the solder droplet printing technology a must evaluate tool for the microelectronics industry. In this paper, the principle of the solder droplet printing technology is described, recent experimental results are included, and potential applications of the technology in the microelectronics industry are evaluated.

Keywords: Solder Droplet Printing, Solder Bumps, Microelectronics

1. INTRODUCTION

The microelectronics industry is one of the most fascinating, dynamic, and important industries. One of the key technologies supporting these products is electronic packaging and assembly technology. The continuing drive toward more complex Integrated Circuits devices having lower cost, higher inputs/outputs, greater operating speeds, increased functions per chip, and smaller device geometry has pushed the package requirements far beyond the capability of traditional packages, such as solder paste printing (SPP). In response to this situation, manufacturers have developed a variety of innovative packaging technologies to place solder and other materials onto PCBs, packages and wafers etc. At present, the solutions involve complex, expensive, and time-consuming processes including photolithography, vapor deposition, etching, sputtering, and plating. However, all of these methods have concerns: the vacuum processes are slow and require expensive equipment; photolithography and plating methods require acid washes and substantially larger amount of solder material [1]. Solder droplet printing technology has been discussed as an enabling technology for precisely placing fine solder deposits onto a variety of smaller substrates [2,3]. There are several different technologies available in a broad category generally referred to as solder droplet printing. This paper will introduce two types: the continuous solder droplet printing and the drop-on-demand solder droplet printing. The continuous solder droplet printing system works by applying a back pressure to a reservoir of molten solder creating a constant stream. The stream is perturbed with a low-energy, constant-amplitude mechanical vibration, breaking the stream into uniform drops at high rates. The droplets are selectively charged and deflected to the substrate at high rates of speed. The drop-on-demand solder droplet printing system used in microelectronics industry applies low-frequency, high-energy pulses to an annular PZT, which surrounds a capillary tube and squeezes out a droplet. Advantages of the drop-on-demand method lie in two ways: (1) they are CAD data driven systems which do not require hard tooling such as masks or stencils and the associated cost to purchase, cost to store, time to acquire and time to change the tools; (2) they selectively deposit solder droplet only where required, need no mask or secondary resist removal, use materials more efficiently and create less waste than other aforementioned methods. They are, therefore, low-cost (no tooling required), non-contact, flexible & data driven (no masks or screens required because the printing information is created directly from CAD information and stored digitally), and environmentally friendly (because it is an additive process with no chemical waste).

Solder droplet printing will provide the industry with a technique to address, in a cost-effective manner, the continuing pressures for miniaturization and higher performance and at the same time will enable new packaging designs and is suitable for a variety of applications including direct chip attach site preparation, 3-D substrates, fine line interconnect, substrate via fill, optoelectronics and many others. It would also allow

manufacturing techniques that are impossible or unfeasible with current technology, such as localized replacement of solder on board (for rework or custom connections), depositing solder in different thickness on the same board (components differ in the amount of solder required for the best connection), or using more than one type of solder on the same board (temperature-sensitive components could be attached with lower-temperature solder after other components are already in place).

The ability to place material fast and accurately makes the solder droplet printing technology a must evaluate tool for current and future ICs packages and PCBs. Many theoretical and experimental studies have been performed till now. In this paper, the principle of the solder droplet printing technology is described, recent experimental results are included, and potential applications of the technology in the microelectronics industry are evaluated.

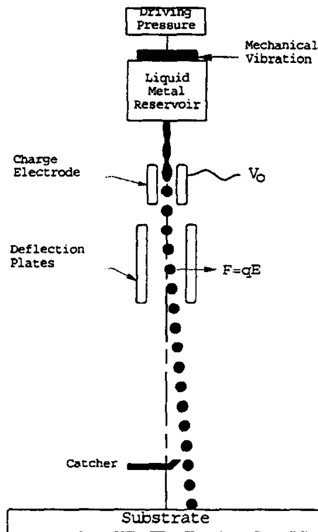


Figure 1: Schematic of Continuous Solder Droplet Printing.

2. SOLDER DROPLET PRINTING TECHNOLOGY

2.1 Continuous Solder Droplet Printing

The phenomenon of uniform drop formation from a stream of liquid issuing from an orifice was noted as early as 1833 by Savart [4] and described mathematically by Lord Rayleigh [5]. The ability to accurately deliver electrostatically charged and deflected droplets has been the subject of many experimental investigations, most of which dated from the early 1960's due to the advent of the ink-jet printing technology [6]. Those works detailed many careful experiments and described comprehensive theories of droplet charging and deflection for conditions applicable to ink-jet printing. Recently, significant interest has been directed towards the area of microelectronics industry [1-3]. The continuous solder droplet printing system (see Fig.1) is a high speed system depositing molten solder spheres, typically 50 to 300 microns in diameter. The molten solder spheres are precisely placed at rates of thousands of drops per second, offering packaging manufacturers new capabilities not otherwise feasible with other methods of metal deposition. Solder droplet formation in a liquid stream is caused by surface tension instabilities [7-9]. This break-up phenomenon, which occurs naturally in many liquids, is aided and made repeatable by adding mechanical vibrations in the vicinity of the natural drop forming frequency of the jet. The solder droplet printing system constantly excites the molten liquid solder reservoir with a piezoelectric transducer. When combined with a driving pressure on the molten solder in the reservoir, this induced sinusoidal disturbance delivers a stable stream of droplets from a jet through an orifice. A flow of inert gas should be introduced around the orifice and through the duration of the droplet flight to allow for droplet breakaway from the stream and to minimize solder oxidation.

The continuous solder droplet printing system produces a continuous stream of liquid metal which is subjected to a carefully controlled disturbance causing the liquid stream to break up into extremely uniform molten metal droplets. As the droplets break away from the stream they are charged and pass through deflection plates, directing their ballistic flight to the intended target; operating in a manner somewhat similar to an electron gun in a CRT. The combination of electrostatic droplet deflection in the (vertical) Y-axis and substrate motion in the X-axis produces a fast and extremely accurate method of depositing solder which is called "print-on-the-fly." This approach allows solder droplet printing to deliver precise material deposition at very high speeds.

The frequency range of droplet formation is very broad occurring at rates between 5,000 and 44,000 Hz. To direct the stream of solder droplets to the targets specified in the CAD data, desired droplets are selectively charged. The amount of charge applied to each droplet determines how far each droplet is deflected as it passes through the electric field between the deflection plates. In a continuous solder droplet printing system it is important to note that only those droplets programmed to target the substrate are charged and hence deflected. The solder droplets that are not deflected to the substrate follow a straight path to a capture point and the solder is reused. Droplet placement accuracy has been shown to be well within the tolerances of many advanced microelectronics applications [1].

2.2 Drop-on-Demand Solder Droplet Printing

One of the drawbacks of the continuous type system is that fluid must be jetting even when little or no printing is required. In the 1950's, the production of droplets by electro-mechanically induced pressure waves was observed by Hansell [10]. In the drop-on-demand printing system, a volumetric change in the fluid is induced either by the displacement of a piezoelectric material that is coupled to the fluid, or by the formation of a vapor bubble in the liquid, caused by heating a resistive element. This volumetric change causes pressure/velocity transients to occur in the fluid and these are directed so as to produce a drop that is issued from an orifice [11]. A droplet is created only when it is in demand. Fig.2 shows the principle of operation schematically. An annular PZT, which surrounds a capillary tube, is adopted here.

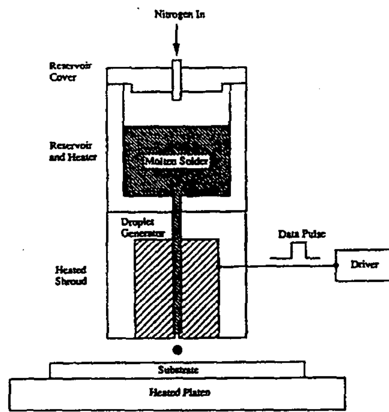


Figure 2: Schematic of Drop-on-demand Printing System

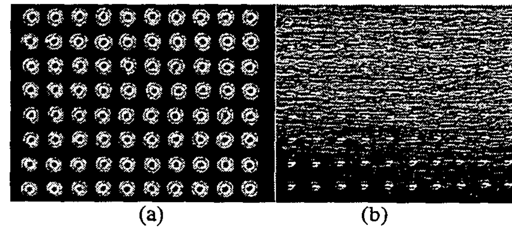
As can be seen from the Fig.2, a pre-filled cartridge of solder is heated to the solder liquid temperature. The molten solder wicks down a capillary tube and forms a meniscus at the end of the tube. To release a solder drop, a high-energy pulse is generated from an annular piezoelectric transducer (PZT) around the capillary tube to disturb the solder meniscus and release a gravity-accelerated drop. Since the tube orifice is only 1mm away from the substrate surface, a droplet's flight time is brief and its path is virtually unaffected by external forces. A flow of high purity inert gas maintains a low oxygen content around the orifice, assisting solder droplet formation and minimizing oxidation during droplet travel. To position the solder droplets on a set of desired locations, an X-Y table moves the substrate into place below the orifice. This permits relatively fast and extremely accurate deposition. This approach allows the system to deliver smaller and more precise solder drops at moderate speeds. Again, placement accuracy has been shown to be well within the tolerances of many advanced microelectronics applications. The current research platform configuration is accurate within +/- 30 microns. Future platforms will be accurate within +/-10 microns.

3. EXPERIMENTAL RESULTS AND POTENTIAL APPLICATION

There are many potential applications of solder droplet printing technology in microelectronic packaging and assembly. In the following we will introduce some applications of solder droplet printing technology.

3.1 Solder Ball Deposition

It is important to remember that a solder droplet printing system produces solder droplets, which freezes quickly upon contact with a substrate. The solder is all metal; it contains no flux, organics or solvents. Because the molten material is deposited directly onto the substrate, there is no need for physical intermediary patterns, such as stencil or screens. As I/O lead counts increase and pitch geometries shrink, solder droplet printing becomes more advantageous to materials deposition processing.



(a) (b)

Figure 3: Solder bumps of 63/37 printed onto (a) Cu-Al (b) Aluminum

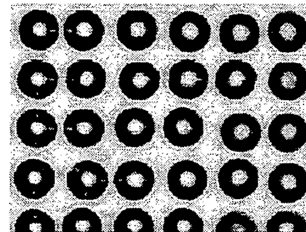


Figure 4: 25μm bumps of 63/37 deposited on 35μm pitch

When the liquid droplets hit the target, the drops solidify into well-controlled solder deposits. The shape of the droplet on the pad is affected by the solder impact dynamics as well as the heat dissipation of the solder to the wafer. For flip-chip interconnects, MicroFab [12] finds a process that allows solid bumps to bond directly to a metallization system acceptable to semiconductor front-ends. Fig.3(a) illustrates the results obtained by printing onto an upper metallization of Cu-

Au with 63/37, and Fig.3(b) illustrates the results obtained by printing doped 63/37 directly onto Al.

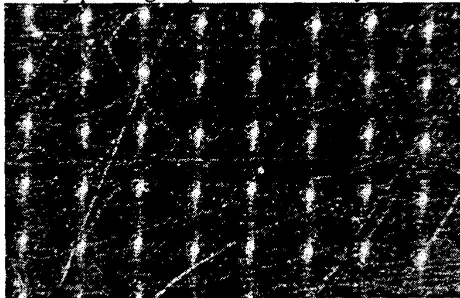


Figure 5: Sample from 39×39 array of 60μm diameter balls of 63/37 printed on-the-fly on 300μm spacings at 60mm/s (200bumps/s) onto a copper substrate.

Solder bumps currently used in flip chip processes are typically in the 100-125μm diameter range. As higher circuit densities and/or greater I/O counts are achieved in integrated circuit devices, there is likely to be a need for smaller bumps for flip chip processes. Initial experiments were conducted to evaluate the suitability for smaller bump sizes by MicroFab [13]. Fig.4 shows a small section of an array of 25μm, 63Sn/Pb37 bumps deposited at a 35μm pitch onto a silicon wafer.

3.2 High Rate Deposition

The ability to deposit bumps onto a substrate at rates of greater than 200Hz is critical to the commercial viability of solder droplet printing technology because the platforms limitation has prevented researchers from demonstrating bump rates this high. Two research platform have been completed that have the ability to deposit bumps while the substrate and/or the print head are moving. This operating mode is referred to as "print-on-the-fly." Ref. [13] has fabricated such kind of research platform that allows for print-on-the-fly operation at rates up to 600 bumps/second. Initial print-on-the-fly experiments were conducted on this platform by printing 39×39 arrays on unpatterned copper substrate. Fig.5 shows an example of the results from these experiments. Operation conditions for this experiment were as follows: substrate translation velocity = 60mm/s; 300μm spacings between bumps; 200 Hz bump rate; bump size 60μm; copper substrate; and bidirectional printing. The distance between bumps in the direction of travel reflects stage, droplet velocity, and straightness errors, while the distance between bumps normal to the direction of travel is indicative of stage and straightness errors. The standard deviation of drop-to-drop distance was 0.005mm for the vertical direction and 0.007mm for the horizontal direction. Both values are on the order of the stage accuracy.

3.3 Chip Scale Packaging

As the density of the boards and packages increases, the size of the vertical interconnects between layers must get smaller. Ultrafine pitch substrates are required to handle the many new packaging alternatives, micro-BGA, chip-scale packages, flip-chip on board, etc. A direct-write wafer-level chip-scale packaging concept satisfying these requirements is presented by the MicroFab [14-16]. Fig.6 illustrates the three major steps in one version of the proposed direct-write, wafer-level, chip-scale package assembly process. First, solder columns with an aspect ratio of 2 or greater and approximately the same width as the pads are printed onto each pad using one solder droplet printing device. Second, a dielectric polymer coating is printed onto the die surface and cured. Finally, solder spheres 0.25-0.30mm in diameter (the size of sphere used today in μBGA and state-of-the-art CSP's), are printed for interconnect to the substrate pads using a second device. The solder for the bumps would have a lower melting point than that of the columns so that the columns would not reflow when the CSP is attached to a substrate. Fig.7 illustrates how the concept of Fig.6 could be extended to a three-dimensional interconnect structures for redistributing leads. The first layer would be printed as discussed above. Horizontal and vertical solder interconnects would be printed in the next process step, followed by another polymer layer. This process could then be repeated.

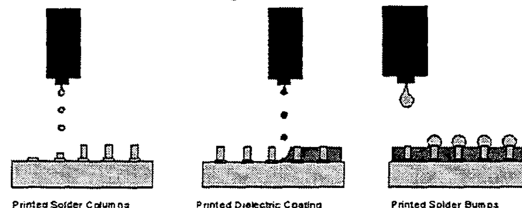


Figure 6: CSP method of manufacturing

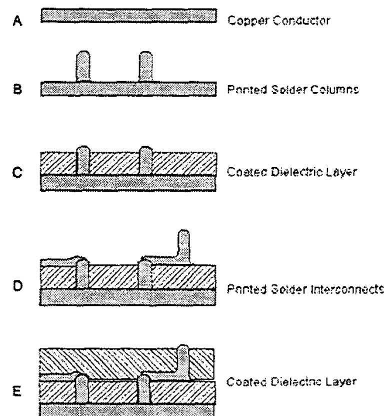


Figure 7: Printed solder interconnect concepts

3.4 Circuit Board Printing

In MicroFab, the locations of the pads of an integrated circuit test vehicle with over 1400 pads were programmed into the initial demand mode research platform [17]. Since this platform moves to each bump location and stops before printing, the net throughput is 4-5 bumps/second. For these tests, droplets of Sn63/Pb37, 70μm in diameter, were deposited onto several of these test vehicles. Actually, the solder bump was deposited onto a nickel pad metallization, covered by a flash of gold which promotes adhesion during the droplet impact and freezing process. Fig.8 shows the results from one test vehicle.

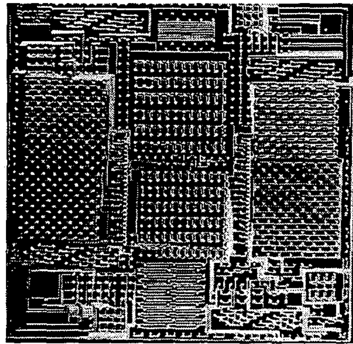


Figure 8: IC test vehicle with 1440 pads, bumped with 63/37 using demand mode printing technology. Ball size is 70μm.

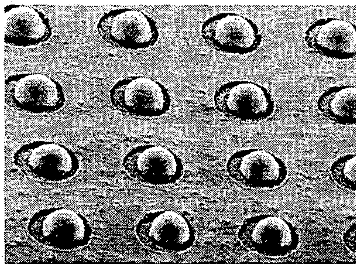


Figure 9: eutectic solder spheres placed on 250μm pads by the continuous solder droplet system.

Several new technologies appear to be well-suited for the continuous-mode solder droplet printing platform. Ref. [18] has conducted many experiments to demonstrate. But the ultimate range of droplet sizes and material types suitable for continuous solder droplet deposition is still in process of being finalized. A square laboratory test target array composed of 225 of 250μm copper pads with a 625μm pitch was selected to demonstrate the continuous printing technique. The selected target can be generally described as a fine to very fine pitch array.

Fig.9 is a SEM picture of the printed test array with no reflow. Fig.10 shows the detail of a solder bump in Fig.9. Since the solder balls are still molten when they impact the pads, surface tension keeps the solder from splashing provided that the impact induced rate of change of momentum is small compared to the surface tension forces. Splashing of the droplet during its impact with the pad produces undesired variations of the ball's volume as well as unwanted micro drops between pads. Splashing is minimized both by lowering the speed of the droplets and by optimizing the targeting accuracy. The shape of the deposited solder can be controlled by varying the temperature of the solder at the time of impact. In this example, the frequency of the full stream was 8.4kHz, the diameter of the orifice 150μm, and the driving pressure difference 6 psi. The target array was translated at a constant speed of 10cm/sec. To eliminate the influence of the interaction between the charged droplets, one out of every four spheres was charged so that effective substrate deposition rate is 2400 drops per second. The total time it took to print the 15×15 array is less than 0.3 second. Plating the pads with a Ni/Au flash prior to printing is necessary to insure that the molten solder wets the deposition sites and adheres to them after solidification. Data indicate that the adhesion strength of jetted and reflowed spheres is satisfactory.

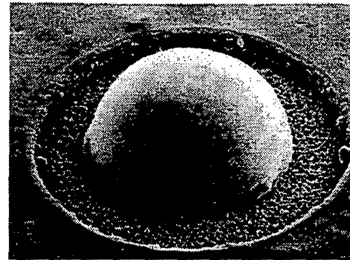


Figure 10: detail of previous solder bump.

3.5 Product Labeling

Solder droplet printing technology is very suitable for product labeling owing to its data driven nature. Fig.11 (courtesy of Motorola and Texas Instruments) illustrates the data driven nature of demand mode solder droplet printing technology. 70μm diameter 63/37 Sn/Pb solder bumps were placed onto metallized silicon for the Motorola logo. The solder droplets used to produce these bumps were 60μm in diameter[12].

The high precision solder droplet printing laboratory in University of California at Irvine printed the characters "UCI" (shown in Fig.12) using a home-made continuous mode solder droplet printing research platform[19]. The characters "UCI" were printed by electrostatically deflecting the charged droplets along the x-axis as shown while the substrate was in continuous motion along the y-axis. The maximum charge used to generate the characters is -6×10^{-13} coulombs. To eliminate the interaction between the

charged droplets and avoid the observable errors in droplet targeting, every other droplet was charged.

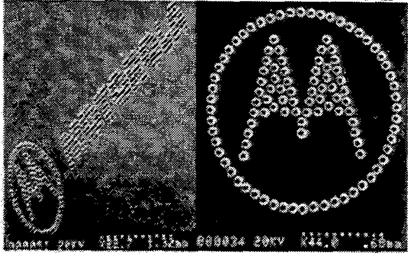


Figure 11: 70μm diameter 63/37 solder bumps placed onto metallized silicon for the Motorola logo

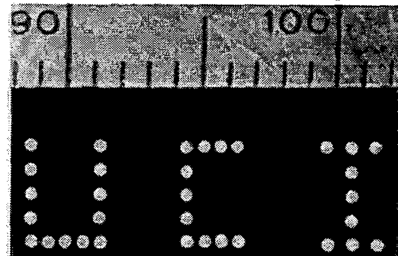


Figure 12: Molten solder splats composing the characters "UCI"

4. CONCLUSION

The principle and advantages of the solder droplet printing technology have been discussed in this paper. Recent experimental results and potential application of the technology in the microelectronics industry have been demonstrated. This technique is set to change the way that solder is applied to substrates, and enables the development of new electronics assembly packaging methods. Therefore, it can be seen that the solder droplet printing system has the potential of being widely used in the microelectronic industry.

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