Variable Droplet Size Molten Solder Ejection Tool for Microelectronics Packaging

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Abstract

A unique piezo-drive diaphragm type head, which enables molten solder droplets to be ejected over a wide range of diameters, has been developed in order to apply the solder droplet deposition method for various applications in microelectronics packaging. The features of this method are a mask-less process and lead-free soldering without soldering flux, therefore a flexible and eco-friendly operation can be realized in contrast to conventional plating or screen-printing methods. The prototype head can continuously adjust the droplet diameter from 35 μm to 200 μm.

In this paper, a simple analytical model of the droplet formation process is proposed and an empirical formula, which estimates the droplet diameter affected by the nozzle diameter and the piezo-drive period, is derived from the experimental investigation. It is also confirmed that the estimated values agree with the results by Flow-3D fluid dynamics simulation software.

Using the prototype head and formula, it becomes easier to adjust the droplet size suitable for each application. We also show application examples such as a solder sealed vacuum package fabricated with the droplet diameter of 200 μm, and a solder filled through-hole with one of 40 μm.

Introduction

Solder joining still remains the primary method used in electronics packaging owing to its high reliability. The packaging density gets higher year by year, and therefore the FC-BGA package, which directly bonds a semiconductor chip to a substrate at many interconnection pads using micro amounts of solder, is widely adopted for advanced LSIs such as CPUs or ASICs. Plating and screen-printing methods are widely used to supply solder to the interconnection pads however it is considered to be difficult to supply a very small amount of solder at the pads, less than 100 µm pitch, by using these methods. As an alternative implement, a solder droplet deposition method has been proposed by applying the ink-jet technologies. The first paper to describe the concept of this method was reported by IBM in 1972 [1], since then, a tube-type head was developed [2] and many applications have been investigated [3]. The features of this method are a mask-less process and lead-free soldering without soldering flux, therefore a flexible and eco-friendly operation can be realized. The authors also developed a unique piezo-drive diaphragm type head and confirmed that it enabled molten solder droplets to be ejected over a wide range of diameters [5].

In this paper, the outline of our head and the variable droplet size characteristics derived by the experimental investigation are shown first. Based on the experimental results, a simple analytical model of the droplet formation process and an empirical formula which estimates the droplet diameter are proposed.

Molten Solder Droplet Ejection Tool

Basic Structure

Figure 1 shows the basic structure of the prototype molten solder ejection head. The head is surrounded by a heater and the solder inside is in the molten state. The molten solder in the reservoir is led between the bottom end nozzle and the diaphragm located right above the nozzle through the flow channel. The diaphragm is driven by the piezoelectric element in pulse form and causes the molten solder to be ejected in droplets through the nozzle opening. The solder droplets reach the substrates on the stage, such as the wafer, chip, etc, in a molten state before being mounted. Since the stage is moved and controlled in programmed positions, it is possible to deposit the solder on the substrate in any pattern. The surface of a solder droplet ejected in a molten state, on the other hand, becomes rapidly oxidized due to oxygen in the air, so that, under such circumstance, excellent bonding with the substrate can not be expected. Therefore, inert gas such as N_2 is blown from the nozzle side to cover the solder droplet ejected from the nozzle opening in order to prevent oxidation. This allows excellent bonding between the solder and the substrate.

Head Driving Method and Droplet Size Control

The voltage applied to the piezoelectric element makes a cosine wave of offset voltage V_0 and drive period T_1 with one such wave repeated at the ejection period T_2 as shown in Figure 2. The diaphragm carries out intermittent repetition of push and pull according to the fall and rise of the voltage, with one droplet of solder being ejected each time. The solder droplet size can be controlled by the drive period and nozzle diameter. Figure 3 shows the experimental results of the relation between drive period T_1

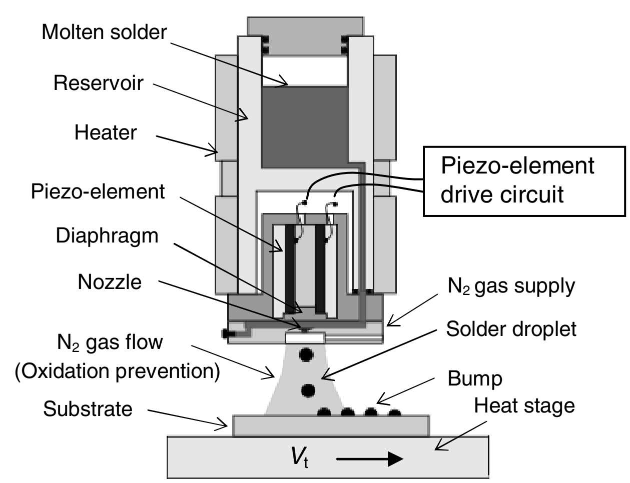

Figure 1. *Basic structure of the molten solder droplet ejection tool*

and solder droplet diameter D_s measured by varying the nozzle diameter D_n. The solder droplet diameter is found to decrease as the nozzle diameter and the drive period become smaller even if the nozzle diameter is the same. The prototype head used in the experiment had nozzle diameters ranging from 50 µm to 200 µm, and the solder droplet diameter was adjustable from 35 µm to 200 µm. The ejection conditions marked I and II in Figure 3 are shown in Table 1. When solder droplets of diameters 68 µm and 35 µm are ejected under Conditions I and II, they make bumps with diameters 100 µm and 50 µm, respectively. Figure 4a shows examples of solder droplets mounted in the form of bumps. Since the ejection period T_2 is constant, the droplet mounting interval can be set by means of the stage velocity V_t. When the stage velocity is low and the mounting interval is smaller than the bump diameter, the bumps join together, enabling line-shaped mounting as shown in Figure 4b. Although the Sn-3Ag-0.5Cu solder was used in the above example, the newly developed head can be used for solders of various compositions.

Estimation of Droplet Size

Simple Model for Droplet Formation

As shown in Figure 3, the ejected solder droplet has a diameter smaller than the nozzle diameter. In this case, the solder droplet is considered to be formed due to the interference of the surface wave occurring at the nozzle opening. A simplified process of solder droplet formation is shown in Figure 5, where the fluid surface at the nozzle opening protrudes during the pressurized process (a), while the surface traveling wave starting from the nozzle edge occurs during the depression process (b), after which the surface traveling wave moves towards the nozzle center (c), then collides (d) before the separation of solder droplet (e). Further, the volume of the solder droplet thus formed is thought to be proportional to the volume of the surface wave protrusion excited by the nozzle edge.

Empirical Formula

Figure 6 shows an expanded view of the surface traveling wave excited at the nozzle edge. The drive voltage waveform of the piezoelectric element shown in Figure 2 causes a pressure pulsation of period T_1 in the molten solder. The velocity V_c and the wavelength λ_c of the surface traveling wave starting from the nozzle edge can be obtained from Equations (1) and (2), respectively [4].

$$V_c = \sqrt{2\pi\sigma/(\rho\lambda_c)} \tag{1}$$

$$\lambda_c = \sqrt[3]{2\pi\sigma T_1^{\,2}/\rho} \tag{2}$$

Here, ρ: density and σ: surface tension of the molten solder.

The volume of the surface traveling wave protrusion can be obtained by the product of the wave sectional area A and the edge length L_n, i.e. the nozzle perimeter πD_n. Here, supposing that amplitude α of the surface traveling wave which allows stable ejection of solder is proportional to the wavelength λ_c, the sectional area A can be obtained from Equation (3) and the solder droplet volume V_s from Equation (4) by substituting Equation (2).

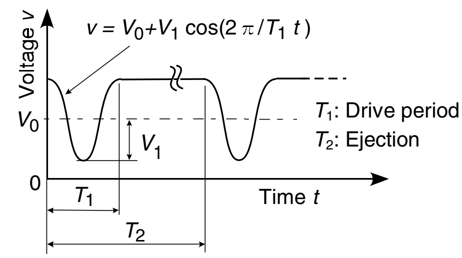

Figure 2. *Waveform of the piezo-element drive voltage*

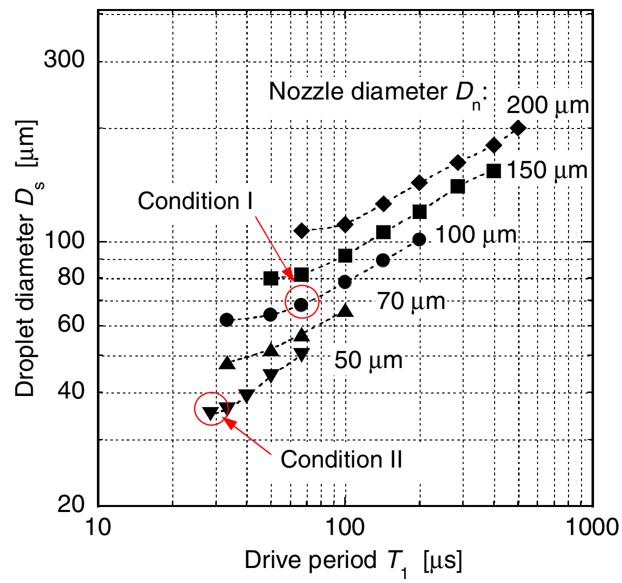

Figure 3. *Experimental results of droplet diameter vs. drive period*

Table1. Examples of the ejection conditions

Condition	I	II
Drive period T_1	67 µs	29 µs
Ejection period T_2 (Ejection rate $1/T_2$)	5 ms (200 drop/s)	5 ms (200 drop/s)
Drive voltage ℃1	26 V	20 V
Nozzle diameter D_n	100 µm	50 µm

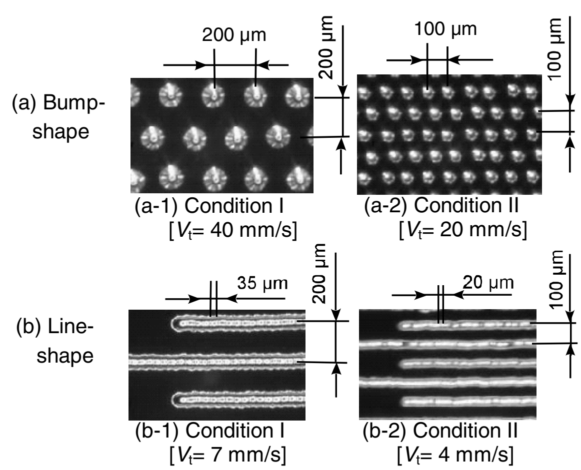

Figure 4. *Mounted solder samples in bump and line shape*

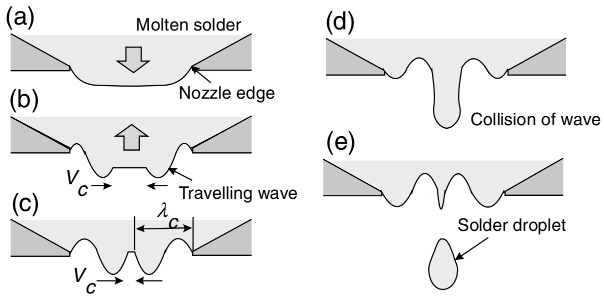

***Figure 5.** Simple model for droplet formation process*

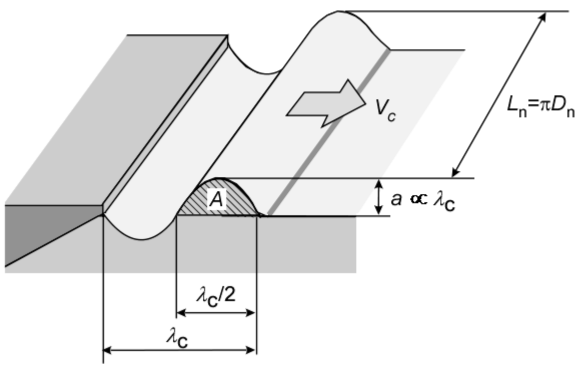

***Figure 6.** Expanded view of the surface traveling wave at the nozzle opening*

$$A \propto \lambda_c^{\,2} \tag{3}$$

$$V_s \propto \pi D_n \lambda_c^{\,2} = \pi D_n (2\pi\sigma/\rho)^{2/3} T_1^{\,4/3} \tag{4}$$

On the other hand, a solder droplet can be considered as a sphere with volume V_s, whose diameter D_s can be obtained from Equation (5) by substituting Equation (4).

$$D_s = (6V_s/\pi)^{1/3} = \beta(\sigma/\rho)^{2/9} D_n^{\,1/3} T_1^{\,4/9} \tag{5}$$

Here, β is proportional constant and is set, through experimental data, to the optimum value to provide the empirical formula.

In Figure 7, the relation between solder droplet diameter and drive period at each nozzle diameter, estimated through the empirical formula provided by Equation (5) is shown by the solid lines. Here, β is set to 0.83. The plots in the figure are the experimental values shown in Figure 3 and are confirmed to show excellent agreement. In particular, the solder droplet diameters from 0.7 to 1.0 times as large as the nozzle diameter almost agree with the empirical formula. Here, the properties of the molten solder are taken as; surface tension σ= 0.54 kg/s^2 and density ρ=7.4×10^3 kg/m^3.

Results by the Fluid Dynamics Simulation

Figure 8 shows the solder droplet formation process simulated by using Flow-3D fluid dynamics simulation software, indicating the fluid surface starting to protrude from the nozzle opening, being drawn from the nozzle edge before a solder droplet smaller in size than the nozzle diameter is separated from the nozzle center. The simulated data are plotted in Figure 9 to indicate the

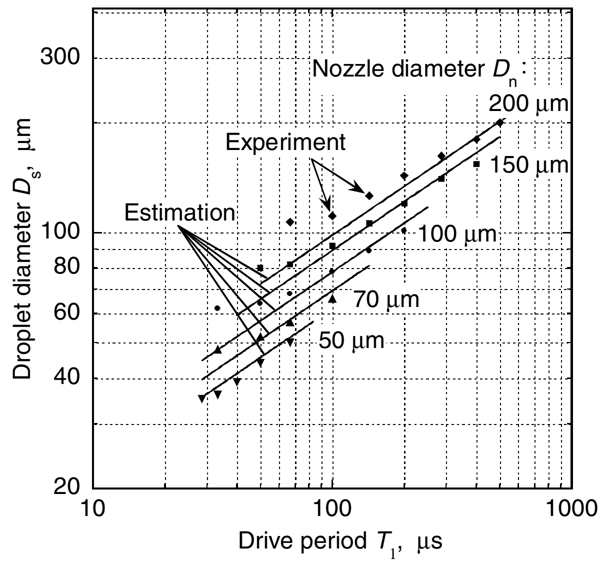

***Figure 7.** Estimated droplet diameter vs. drive period by the empirical formula*

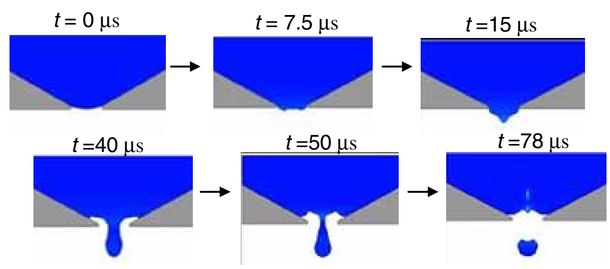

***Figure 8.** Droplet formation process simulated by the fluid dynamics simulation software under the condition D_n = 100 μm, T_1 = 50 μs*

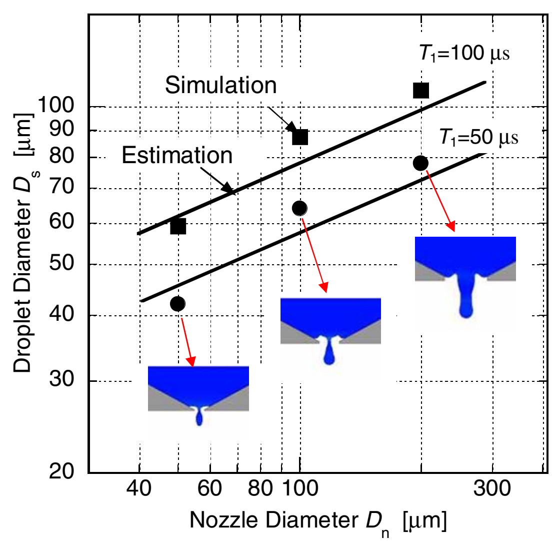

***Figure 9.** Simulated droplet diameter vs. nozzle diameter*

relation between the solder diameter and nozzle diameter. The simulated results show a slight error, attributed to the model being limited to the nozzle periphery and to inadequate optimization. However, the tendency of the data shows agreement with the values obtained through the empirical formula indicated by the solid lines.

Applications

Solder Sealed Wafer Level Vacuum Package

The present tool has been applied to a wafer level vacuum package which seals the sensor elements on the wafer directly by using a cap wafer in order to improve the productivity of MEMS sensor packaging [5]. Figure 10 is a schematic of the process. First, the solder is deposited in a line shape on the under-layer metals patterned for the sealing sections of the element wafer and the cap wafer using the molten solder ejection head (a). Next, wafers are stacked with a spacer in-between (b), before allowing heat to reflow the solder in the vacuum chamber (c), after which the wafers are cooled down to end the process. Here, the sealing section has a comparatively large range, 0.5 mm, and since the solder is deposited effectively, the solder droplet diameter was set to be a maximum of 200 µm. As is obvious from the sectional view, it is confirmed that the joint section has no voids, ensuring excellent bonding.

Solder Filled Through-Hole Interconnection

The present tool has also been applied to the formation of substrate through-hole interconnection for highly integrated packaging such as stacked structures of MEMS devices and semiconductor devices [6]. Figure 11 is a schematic of the process for filling solder into the through-hole of a substrate, where 70 solder droplets with a diameter of 40 µm injected into a through-hole with a diameter of 100 µm and a depth of 300 µm. As is obvious from the sectional view, it is confirmed that void-free, excellent solder filling can be achieved.

Conclusion

A diaphragm type molten solder ejection head has been developed for various microelectronics packaging applications. The head is capable of ejecting solder droplets from 35 µm to 200 µm in diameter by varying the drive period and nozzle diameter. This paper has described a simple model of the solder droplet formation process, and proposed an empirical formula which indicates that the formed solder droplet has a diameter 1/3 the power proportional to the nozzle diameter, and 4/9 the power to the drive period. The estimated solder droplet diameter obtained from the empirical equation has been confirmed to agree well with the experimental data and the simulated data obtained by using fluid dynamics simulation software. The empirical formula thus ensures easy setting of the nozzle diameter and drive period so that the solder droplet diameter is suitable for various applications. When used together with the newly developed head, it is expected to be a useful tool for microelectronics packaging.

Finally, it has been proved that excellent results can obtained by applying the tool to device packaging, giving the wafer level vacuum package and solder filled through-hole interconnection as examples.

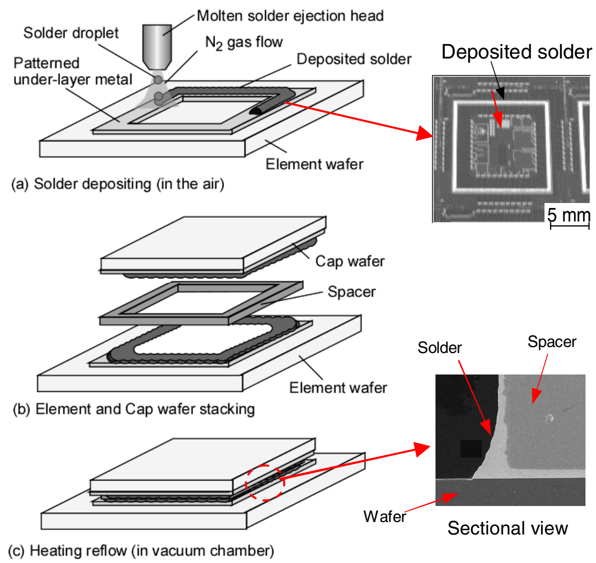

Figure 10. *Schematic of solder sealed wafer level vacuum package*

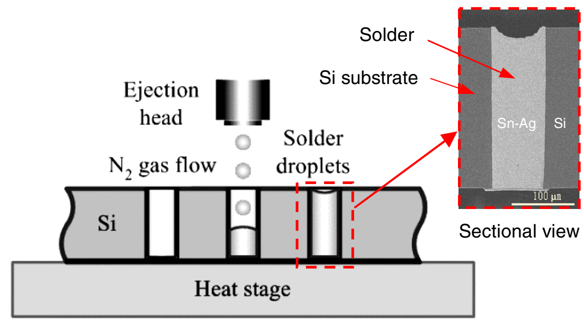

Figure 11. *Schematic of solder filled through-hole interconnection*

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Author Biography

Hiroshi Fukumoto is currently Manager of the Sensing Technology Department in the Advanced Technology R&D Center, Mitsubishi Electric Corporation. He has been working on the research and development of microelectronics packaging since 2001, after 15 years of working with ink-jet devices and sheet handling mechanisms. He received his B.E. and M.E. degrees in Mechanical Engineering from Tokyo Institute of Technology in 1983 and 1985, respectively.