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Laser direct printing of solder paste

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ABSTRACT
We experimentally demonstrated a laser-based approach for the maskless printing of solder paste with a predefined size and position. In this work, a 532 nm laser marking system is used to induce the formation of a solder paste bridge between the donor and acceptor substrate. After the donor is removed vertically, the bridge will rupture and a high aspect ratio voxel can be obtained on the acceptor substrate. The width and height of transferred voxels can be controlled by modifying the laser fluence. In order to find out the specific conditions for the solder paste bridge formation, we carried out transfer experiments at different gap distances and found out a bridge formation threshold. Solder paste bridges can be produced only when the gap distance is smaller than the threshold. Furthermore, the threshold can be affected by the film thickness and spot size. In this condition, a solder paste array with an average size of 100 μm and a pitch of 200 μm has been successfully transferred. Compared to conventional printing methods, the method proposed in this paper can effectively improve the transfer accuracy and reduce the production cost.

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I. INTRODUCTION

As the size of electronic devices shrinks rapidly, soldering these small devices onto electronic circuits has become a considerable manufacturing challenge. Stencil printing, as a traditional solder paste printing (SPP) process, is quite mature and widely used in electronic manufacturing. However, according to the investigation of previous work,1–3 the stencil printing process has a limiting factor when 03 015 metric (0.30 × 0.15 mm²) and 0201 metric (0.20 × 0.10 mm²) components are used, as well as when the pitch of the component goes down to 0.3 mm. In addition, as the aperture of the stencil becomes smaller, the stencil should be cleaned more frequently to prevent clogging of the stencil during the production process, which causes the wastage of solder paste and reduces the production efficiency. As for other solder paste transfer methods, such as solder jets and drop-on-demand, although they can solve the above problems to some extent, they are more expensive and take more time to transfer, which cannot meet the actual production requirements.

Laser induced forward transfer (LIFT) is a versatile direct-write printing technique suitable for numerous materials.7 As a high-resolution printing technique, LIFT does not have the problem of clogging and it can print different patterns without a mask, which can effectively reduce the printing costs. Therefore, applying LIFT to SPP is very promising. LIFT was first reported by Bohandy et al.7 in 1986. Since then, many different kinds of materials including solid,7 liquid,9,10 and paste11–13 have been successfully transferred by LIFT. Time-resolved systems were used to find out the specific principles of LIFT. According to the observation in previous work, low viscosity inks can be transferred by using laser-induced jets.14–17 In this case, regular and well-defined droplets with high-resolution can be obtained from a large gap distance (more than 300 μm). As for high viscosity paste, regular and high aspect ratio voxels can be transferred by using a laser-induced bridge between the donor and acceptor substrate.11 Solder paste is also a high viscosity paste; the properties observed in LIFT of silver paste11,13 can be used as the reference for LIFT of solder paste. Although the laser-induced high viscosity paste bridge was first observed in Ref. 11, there is still a lack of research on the bridge formation conditions. In this paper, through the transfer experiments at different gap distances, we found out a bridge formation threshold in LIFT of solder paste, and the threshold can be affected by the film thickness and spot size. Matthews et al.14 have successfully transferred solder paste by LIFT using silver paste as the absorbed layer.
Although this work proves the feasibility of SPP by LIFT for the first time, there are still several serious problems. First, all the transfer experiments were carried out at very close gap distances (25 μm or even no gap). In this case, the transfer mechanism presented in his paper is not plausible. According to this mechanism, after the laser pulse shoot on the donor, a droplet of solder paste will separate from the donor and deposit on the acceptor substrate. However, considering that the gap distance is very close, the acceptor substrate will block the propulsion of solder paste before it separates from the donor, which means that the situation described in this mechanism can hardly appear. In addition, the experimental results lack the measurements of the solder paste voxel height, which is an essential parameter for SPP. In order to solve the above problems, we propose a bridge-based transfer regime to explain the transfer mechanism at close gap distances and use a 3D laser scanning microscope to measure the height of solder paste voxels. According to the measurement results, the relationship between the voxel height and relevant parameters was concluded.

In this paper, regular and high aspect ratio solder paste voxels were successfully transferred by using the laser-induced solder paste bridge. In order to find out the specific conditions for the solder paste bridge formation, we first experimented at different gap distances and found out a bridge formation threshold. Solder paste bridges can be produced only when the gap distance is less than the threshold. On this basis, we further researched the effect of the film thickness and spot size on the bridge formation threshold. According to the experimental results, we can obtain the voxels we want by adjusting the film thickness, spot size, and laser fluence. Finally, a solder paste array with an average size of 100 μm and an average pitch of 200 μm has been successfully transferred.

II. EXPERIMENTAL METHOD

In our experiments, an industrial laser marking system with a Diode Pumped Solid State (DPSS) laser (Bright Solutions, λ = 532 nm; 6 ns FWHM; 10 kHz repetition rate) was used. The laser pulse energy with a Gaussian intensity distribution ranges from 0.07 mJ to 0.7 mJ. With a galvanometric mirror head, the system can scan at speeds up to 5 m/s on a predetermined path. An f-theta lens with a focal length of 120 mm is used to focus the laser beam reflected from the galvanometer onto the donor. By adjusting the distance from the donor to the f-theta lens, the size of the laser spot can be varied as desired.

The material used in our experiments is a Pb-free solder paste with a composition of Sn 96.5/Ag 3.0/Cu 0.5 (BNL-CF305-T7, with a particle size of 2–8 μm and a viscosity of 10 k–25 k cps). The solder paste was coated onto the silica glass (75 mm × 25 mm × 1 mm) with a coater (RK 101) to form the donor (film roughness is around 0.8 μm, measured by using a 3D laser scanning microscope), and the same silica glass was utilized as the acceptor substrate. Polyimide tape was adopted as the spacer to adjust the gap between the donor and acceptor.

Figure 1 illustrates the basic principle of solder paste printing using this system. The laser beam is focused by the f-theta lens onto the interface between the transparent substrate and the solder paste film. During the pulse duration, the laser energy is absorbed by the solder paste and evaporates a small amount of the flux. The expansion of this vapor will push and accelerate the nonvaporized part of the solder paste film toward the acceptor substrate. If the gap is close enough, a stable solder paste bridge can be established between the donor and acceptor substrate. After the donor is removed vertically, the bridge will rupture and a high aspect ratio voxel can be obtained on the acceptor substrate. After transfer, the morphology of transferred voxels was measured by using a 3D laser scanning microscope (Keyence VK-X160).

III. RESULTS AND DISCUSSION

According to the transfer regimes proposed in Ref. 11, when the gap is close enough, regular shape and high aspect ratio voxels can be obtained from laser-induced silver paste bridges. However, it has not been confirmed whether a similar phenomenon exists in the LIFT of solder paste. In order to confirm that a laser-induced solder paste bridge can be formed between the donor and acceptor substrate, we first researched the transfer process at different gap distances. Figure 2 shows the confocal microscope images of transfer voxels and corresponding donors. In the case of 10 μm and 30 μm gap distance, the voxels showed a regular shape and high...
FIG. 2. Confocal microscope images of [(a)–(d)] transferred voxels and [(e)–(h)] corresponding donors; the voxels were transferred under the conditions of 150 μm spot size and 50 μm film thickness.

aspect ratio without any fragments [Figs. 2(c) and 2(d)]. At the corresponding donor [Figs. 2(g) and 2(h)], protrusions appeared at the position of laser irradiation, which has not been observed in previous papers. The result not only proved that a solder paste bridge can be formed between the donor and acceptor substrate but also indicated that when the donor is removed vertically, the rupture occurs in the middle of the solder paste bridge. This is different from the transfer regimes proposed in Refs. 11 and 13. During the transfer process, the rupture does not occur from the root of the bridge but somewhere in the middle. In the case of 50 μm gap distance [Fig. 2(b)], at a low laser fluence (1.18 J/cm² and 1.40 J/cm²), the transfer results were similar to the situation of 10 μm and 30 μm. However, with the increase in the laser fluence, the shape of voxels became irregular, and some voxels were even broken into several pieces. At the corresponding donor [Fig. 2(f)], the depressions appeared at the position of laser irradiation instead of protrusions. The results indicated that there is a bridge formation threshold near 50 μm gap distance. If the gap distance continues to increase, the solder paste bridge will not be produced even at a low laser fluence. In the case of 70 μm gap distance [Fig. 2(a)], at a low laser fluence (1.18 J/cm²), nearly no transfer occurred. At a high laser fluence (1.40 J/cm², 1.61 J/cm² and 1.81 J/cm²), the transfer voxels were broken into numerous fragments and only depressions appeared at the corresponding donor [Fig. 2(e)]. The results indicated that there is a transfer threshold where transfer can occur near 1.18 J/cm² laser fluence. Based on the observed results, three transfer regimes for different gap distances were proposed:

1. Splashing transfer [Fig. 3(a)]: Laser irradiation on the donor will vaporize small amounts of material and generate a bubble. If the gap distance is large enough, the bubble will continue to expand until the solder paste film cannot withstand the pressure of expansion, causing the film to rupture, and the transferred voxels will break into numerous fragments. During the whole process, the acceptor substrate is not in contact with the solder paste film.

2. Irregular shape voxel transfer [Fig. 3(b)]: When the distance of the gap is reduced below the maximum size of the bubble expansion, the solder paste film will reach the acceptor substrate before the film rupture and the acceptor substrate will block the expansion of the bubble in the downward direction, while the expansion in the other direction will continue until the film breaks. In this case, although the acceptor substrate is in contact with the solder paste film, a stable solder paste bridge is not produced. Therefore, the transferred voxels are irregular in shape and have a low aspect ratio.

3. Bridge-based transfer [Fig. 3(c)]: If the gap is close enough, the solder paste film will gradually stop expanding upon reaching the acceptor substrate and eventually establish a stable solder paste bridge between the donor and acceptor.
substrate. After the donor is removed vertically, the rupture will occur in the middle of the solder paste bridge. A portion of the solder paste bridge remaining on the donor forms a small protrusion, while another portion remaining on the acceptor substrate forms a regular shape and high aspect ratio transferred voxel.

It is obvious that for the first two transfer regimes, the transferred voxels cannot form an effective electrical connection after reflow. For bridge-based transfer, the morphology of transferred voxels is regular in shape and has a high aspect ratio without any fragments. In this case, the transferred voxels can provide sufficient solder paste to form effective electrical connection after reflow. Therefore, we also call it a “successful transfer.”

To further research the impact of the laser fluence and gap distance, we carry out the experiments at the gap distances below 110 μm. A summary of all transfer results is presented in Fig. 4(a). It can be seen that there are two thresholds in this figure: one

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**FIG. 3.** Schematic diagram of three transfer regimes at different gap distances: (a) splashing transfer; (b) irregular shape voxel transfer; and (c) bridge-based transfer.

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**FIG. 4.** The dimensions of voxels vs laser fluence; the voxels were transferred at 10 μm, 30 μm, 50 μm, 70 μm, 90 μm, and 110 μm gap distances, with a film thickness of 50 μm and a spot size of 150 μm. (a) Summary of all transfer results, where no transfer appears in the blue area, successful transfer appears in the white area, and fractured voxels appear in the red area. The blue triangles indicate that, both successful transfer and no transfer may appear; the red triangles indicate that, both successful transfer and fractured voxels may appear. (b) Width, (c) height, and (d) aspect ratio vs laser fluence. Each data point represents the average of 8 measurements, with error bars denoting one standard deviation.
is the transfer threshold and the other is the bridge formation threshold. When the gap distance is larger than the bridge formation threshold (70 μm, 90 μm, and 110 μm), only splashing transfer occurs in this area. In this case, the transfer threshold will not be affected by the change in the gap distance. When the gap distance is smaller than the bridge formation threshold (10 μm, 30 μm, and 50 μm), successful transfer occurs in this area. In this case, as the gap distance decreases, the transfer threshold will become smaller and the laser fluence window for successful transfer will become larger. This is mainly because as the gap distances become smaller, the solder paste film can touch the acceptor substrate at a lower laser fluence and produce a stable bridge. On the other hand, as the gap distances become smaller, the acceptor substrate can block the expansion of the bubble earlier and further prevent the film from being broken, resulting in an increase in the area of the laser fluence window for successful transfer. Figures 4(b)–4(d) show the morphology of voxels (width, height, and aspect ratio) as a function of the laser fluence at different gap distances. With the laser fluence increasing, the width is also gradually increased. In fact, an increase in the voxel width means that the root area of the solder paste bridge at the acceptor substrate side also increases. Furthermore, as the root area increases, the position of the bridge rupture will also move upward, finally leading to an increase in the voxel height. However, since the growth rate of the height is smaller than that of the width, the aspect ratio of the voxel becomes smaller as the laser fluence increases. On the other hand, with the gap distance increasing, both the width and height decrease, and a minimum size voxel can be obtained when the gap distance (50 μm) approaches the bridge formation threshold.

According to the experimental results in Fig. 4(a), when the gap distance is greater than the bridge formation threshold and the laser fluence is greater than the transfer threshold, only splashing transfer occurs. However, the splashing transfer only occurs when the film cannot withstand the pressure caused by bubble expansion, so there must be some connection between the maximum pressure the film can withstand and the two thresholds. The film thickness is one of the parameters which can directly affect the maximum pressure that the film can withstand and further affect the values of the two thresholds. In order to verify whether the film thickness is one of the main factors determining the transfer threshold and the bridge formation threshold, we conducted transfer experiments with a 25 μm thick film and an 80 μm thick film. When the film thickness is 25 μm, the solder paste bridge is produced only when the gap distance is below 5 μm. However, in this situation, undesired contact can easily occur between the film and the acceptor substrate. In the case of other gap distances, only splashing transfer occurs, and the transfer threshold also decreases. Therefore, as the film thickness decreases, the maximum pressure that the film can withstand also decreases, resulting in a significant decrease in the transfer threshold and bridge formation threshold. Figure 5(a) shows a summary of transfer results in the case of the 80 μm thick film. The bridge formation threshold and the transfer threshold are greatly improved compared to the case of the 50 μm thick film. Therefore, as the film thickness increases, the two thresholds also increase significantly. Figures 5(b)–5(d) show the morphology of voxels (width, height, and aspect ratio) as a function of the laser fluence at different gap distances. It can be seen that the tendency of the change in the width and height is substantially unaffected by the increase in the film thickness, but the aspect ratio is more stable than in the...
case of the 50 μm thick film. In addition, at the same laser fluence and gap distance, the width and height of voxels transferred at the 80 μm thick film are greater than those transferred at the 50 μm thick film.

In addition to the film thickness, the spot size also has an impact on the bridge formation threshold. As shown in Figs. 6(a) and 6(b), when the spot size is reduced, it is apparent that the film is subjected to a greater pressure. When the gap distance is much smaller than the bridge formation threshold, the reduction in the spot size has no significant effect on the formation of the solder paste bridge [Fig. 6(a)]. When the gap distance approaches the bridge formation threshold, the reduction in the spot size may cause the solder paste film to rupture before it touches the acceptor substrate [Fig. 6(b)]. In order to verify the above conclusions, we performed different spot size transfer experiments at gap distances of 20 μm and 40 μm. When the gap distance is 20 μm [Fig. 6(c)], no fracture voxel appeared. As the spot size decreases, the transfer threshold becomes larger. The results indicate that a smaller spot size requires a higher laser fluence to expand the solder paste film by the same distance. When the gap distance is 40 μm [Fig. 6(d)], as the spot size decreases, the area of the successful transfer window decreases sharply. When the spot size is below 100 μm, almost no successful transfer occurs. In other
words, as the spot size decreases, the bridge formation threshold also decreases.

Based on the above experimental conclusions, we chose a film thickness of 50 μm, a gap distance of 30 μm, a spot size of 150 μm, and a laser fluence of 1.18 J/cm² to ensure the formation of the solder paste bridge. Finally, a solder paste array was successfully transferred at a scanning speed of 2200 mm/s. Figure 7 shows the transfer result; the average width of the voxels in the array is around 100 μm ± 15 μm. The average height of the voxels is around 25 μm ± 5 μm. It can be seen that even in the case of high-speed printing at 2200 mm/s, the transfer voxel position offset is extremely small. In fact, our laser system can also transfer smaller sizes of solder paste arrays by using a smaller spot size or a larger gap distance, but the range of fluctuations in the voxel size will be larger and no transfer may occur. Therefore, this technology still has a lot of room for improvement. By using a higher precision laser system and adding a flat top beam shaper, the laser spot will be more uniform and the system can be further improved.

IV. CONCLUSION

In this paper, regular and high aspect ratio solder paste voxels were successfully transferred by a laser-induced solder paste bridge between the donor and the acceptor substrate. According to the experiments transferred at different distances, the bridge formation threshold was found. When the gap distance is larger than the bridge formation threshold, only splashing transfer occurs. In this case, the transfer threshold cannot be affected by the change in the gap distance. When the gap distance is smaller than the bridge formation threshold, the solder paste bridge can be produced between the donor and acceptor substrate. In this case, the transfer threshold will become smaller as the gap distance decreases. Furthermore, the experiments carried out with different film thicknesses indicated that as the film thickness increases, both the transfer threshold and bridge formation threshold increase significantly. The experiments performed with different spot sizes show that as the spot size decreases, the transfer threshold becomes larger and the bridge formation threshold becomes smaller. Based on the above experimental conclusions, we can ensure the formation of solder paste bridges by adjusting relevant parameters and further obtain regular shape and high aspect ratio voxels. Finally, a solder paste array with an average size of 100 μm and an average pitch of 200 μm has been successfully transferred.

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