

EVALUATION OF INNOVATIVE NANO-COATED STENCILS IN ULTRA-FINE-PITCH FLIP CHIP BUMPING PROCESSES

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ABSTRACT

Stencil printing remains the technology route of choice for flip chip bumping because of its economical advantages over traditionally costly evaporation and electroplating processes. This paper brings up all the technological challenges and up to date advancements in all processing steps of 6" wafer bumping of peripheral array structures at Ultra-fine-pitches (UFP) of 80µm and 60µm pitch. Innovative laser-cut stencils with nano-treatment of the sidewalls and the bottom surface have been manufactured with a thickness down to 20µm and apertures of 40µmx100µm and 35µmx80µm, respectively. Both type 6 (5-15µm) and type 8 (2-8µm) pastes of lead-free Sn4Ag0.5Cu compositions have been successfully employed for wafer bumping at 80µm and 60µm pitch. Bumping using a 20 µm laser-cut nano-treated stencil has yielded a bump height of 23µm. Nano-treatment of stencils improves significantly the paste release from apertures even for very fine apertures. In addition, nano-stencils may extend the use of commercial type 6 pastes for pitches even smaller than 100µm due to improved paste release. Printing results with nano-stencils are very promising even at aspect and area ratios smaller than 1.5 and 0.66 which have been considered as the "rules of thumbs" for stencil printing. The combination of type 8 paste printing and nano-treatment can open new horizons for stencil printing at pitches even smaller than 80µm. Bumping at 80µm pitch with laser-cut stencils yields bumps of 23µm. Printing at 60µm pitch has also yielded very promising results and has proved the capability of electroformed technology to manufacture accurate and robust thin stencils. The bump height at 60µm pitch was measured to be 28 ± 3 µm.

Keywords: wafer bumping, flip chip, Ultra fine pitch, stencil printing, type 8 paste, type 6 paste, nano-stencils, electroformed.

1. Introduction

The attractiveness of flip chip technologies lays on the superior electrical performance, higher thermal conductivity, smaller size and higher I/O counts which are mandatory requirements for advanced semiconductor applications. However, a substantive shift towards flip chip interconnection technologies will be witnessed only with

accomplishment of cost reduction, reliability improvement and cost-efficient high density substrate technologies [1]. Low-cost flip chip bumping technology has become a reality with implementation of electroless nickel plating process for under bump metallization (UBM) in conjunction with stencil printing of solder pastes for the formation of solder bumps [2]. Stencil printing of solder paste for flip chip wafer bumping offers

among others the advantages of cost-effectiveness and compatibility with pre-existing printing equipment in a surface mount assembly line [3-7]. The state-of-the-art in wafer bumping at production level using the conventional stencil printing technology (laser-cut steel and Nickel-electroformed stencils) is at about 120 μm pitch for peripheral arrays and 150 μm for area arrays [3]. Significant technological improvements have been reported in literature regarding the capability of Ultra Fine Pitch (<120 μm) (UFP) wafer bumping [9-11]. This progress is extremely significant especially in view of Moore's law prediction that the bits/chip grow by a factor of 4x every three years [8]. However, the advancements to UFP bumping can not be realised without parallel progression to very fine paste and stencil manufacturing. The emergence of ultra fine type 7 pastes (2-11 μm) and lately of type 8 (2-8 μm) pastes as well as recent developments in fabrication of very thin electroformed and laser-cut stencils with very small aperture dimensions have sparked significant work in the area of UFP wafer bumping.

Fraunhofer IZM printing group has developed stencil printing processes to meet the current trends in wafer bumping roadmaps. Mainstream wafer bumping has been performed by using innovative Type 5 (15-25 μm) and Type 6 (5-15 μm) pastes with both Sn-Pb and Pb-free compositions from 300 μm up to 100 μm pitches for peripheral pad configurations and up to 120 μm for area array configurations. At R&D level, IZM has advanced stencil printing very close to its technological limits at pitches even down to 50 μm . Innovative electroformed and laser-cut with nano-treatment stencils have been manufactured with an extreme thinness of 20 μm for bumping wafers at Ultra fine pitches (UFP) of 100 μm , 80 μm and 60 μm . Paste-in-Resist technology has been developed as an alternative to stencils in order to overcome the manufacturing difficulties of making extremely small apertures. Paste is printed in resist apertures which have been opened by photolithographic processes. In this way, bumping has been demonstrated up to 50 μm pitches.

Complimentary to stencil printing processes, IZM has developed balling technologies up to 400 μm pitch up to 8" wafers with a thickness of 150 μm . Solder balling can be achieved either by "perform ball print" using conventional stencil printers with specially designed stencils or by "ball drop" techniques. Balling technologies have demonstrated the application of 300 μm and 250 μm Sn-Pb and Pb-free balls at respective area array pitches of 500 μm and 400 μm , the main I/O pitches for WL-CSP bumping.

This paper discusses in depth the latest advancements in laser-cut stencil technologies with the introduction of nano-treatments for the apertures in comparison with established electroformed technologies. It presents the results of our recent studies on UFP stencil printing of type 6 and type 8 solder pastes for bumping of 6" wafers with pitches at 80 μm and 60 μm .

2. Technology Implementation

2.1 Wafer Designs & Chemical Metallisation

The wafers used in this study had a diameter of 6". The wafer at 80 μm pitch had a thickness of 680 μm whereas the wafer at 60 μm pitch had a thickness of 320 μm . The electroless Ni/Au plating technology of (TUB) was used to deposit 2 μm Ni /80 nm flash Au (over the chip passivation layer) high UBM pads on the Al metallization pads. The lateral overlappment of the Ni/Au UBM pads on the chip passivation layer is also 2 μm on both sides. Detailed description of TUB's Electroless Ni/Au technology approach (ENIG) can be found in literature [2].

The wafers at 80 μm pitch have 606 chips 2.5mmx2.5mm in size and a number of 80 pads per chip. A total number of 48840 I/Os correspond to the wafer. Wafers at 80 μm pitch have 60 μm pad dimensions after 2 μm Ni/Au processing. Correspondingly, the wafer with peripheral arrays at 60 μm pitch has 577 chips with a size of 5mmx5mm with 296 pads per chip. A total number of 170792 pads exist. The passivation opening on the Al pad was 20 μm and the same ENIG process was applied to deposit 4 μm Ni/80nm Au over the chip passivation layer. The UBM size of the wafer after application of Ni/Au is 28 μm . Figure 1 shows the Ni/Au UBMs at 60 μm pitch which proves that the ENIG process is feasible to very small wafer pitches.

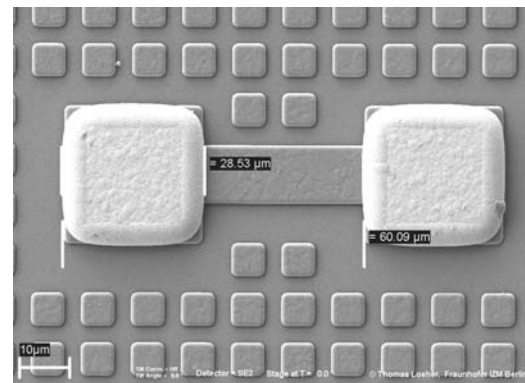


Figure 1: Electroless Ni/Au UBMs at 60 μm Pitch. UBM size is 28 μm .

2.2 State-of-the-art stencils & solder paste Materials

2.2.1 State-of-the-art stencils

The criteria for the selection of stencil manufacturing technology are always aperture wall quality, dimensional consistency, positional accuracy and stencil production cost. The two main stencil manufacturing methods for UFP bumping are laser-cutting stencils and electroformed stencils. Especially for the laser-cut stencils the quality is dependent on the technical expertise of laser stencil manufacturers, and the availability of fine-tuned laser guns in the market [9].

Recent refinements in the laser cutting process like smaller laser spot sizes and water guided laser cutting techniques have brought about large improvements in wall quality and ability to cut very small apertures. One advantage of laser-cut stencils compared to electroformed is that the material is pre-tensioned on the frame prior to cutting, which in turn reduces the stencil deformation. Laser cutting is a sequential process; therefore as the number of I/O increase on the design so does the time to manufacture the stencil. The cost factor becomes profoundly significant considering an approximate cost of 3 \$/100 laser-cut apertures and the large number of apertures needed for UFP structures. The latest development in laser-cut stencils has been a nano-coating applied on the inner walls of the apertures and the bottom surface of the stencil to enhance paste release and thereby reduce stencil cleaning intervals [12]. Nano-coated laser cut stencils have started to be used extensively in SMD industry and they are still under examination for usage in UFP bumping. A nano-coated stencil has been used in the present work for bumping the 80 μ m pitch wafer. The nano-treatment improves the smoothness of the aperture wall and also makes the bottom surface highly hydrophobic which can be very beneficial for less flux/paste bleeding.

On the other hand, electroformed stencils present excellent aperture wall quality and have a reasonable manufacturing cost per wafer design and not per aperture as is the case for laser-cut stencils. In the area of UFP bumping with more than 50000 I/O's the cost of an electroformed stencil is acceptable as compared to the high cost of a laser-cut stencil. Nevertheless, it should be mentioned that electroformed stencils are framed after aperture manufacturing and the associated stretching can lead to even slight nickel expansion and therefore misalignment problems during printing set-ups. In the present study, an electroformed stencil was selected for the bumping at 60 μ m pitch with extreme care from our partner to avoid stencil deformation

during foil framing/stretching. At 80 μ m pitch, a laser-cut stencil was manufactured with 20 μ m foil thickness and apertures of 48 μ m $\times$ 108 μ m. For sake of comparison another stencil with the same design at 80 μ m was nano-coated in order to test the effect of nano-treatment to the bumping performance. The nano-coated stencil had slightly larger oblong apertures of 53 μ m $\times$ 110 μ m than the one without treatment. Figure 2 shows a SEM picture of the nano-coated apertures at 80 μ m pitch. As it can be seen the nano-treatment smoothens significantly the inherent wall roughness of laser-cut stencils. Figure 3 shows representative pictures of QFP apertures without and with nano-treatment. In all pictures aperture tapering is witnessed.

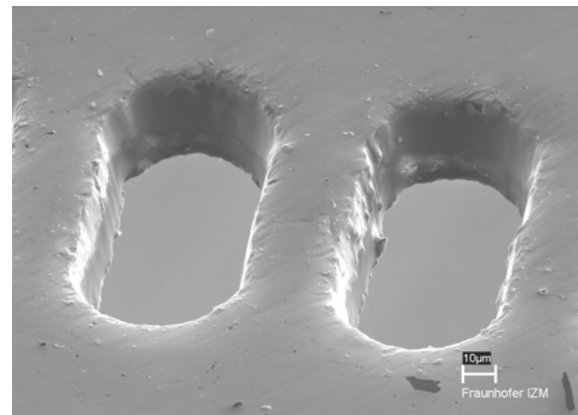


Figure 2: Nano-coated apertures at 80 μ m pitch.
Aperture size: 53 μ m $\times$ 110 μ m.
Stencil thickness: 20 μ m.

For bumping at 60 μ m pitch, an electroformed stencil of 20 μ m thickness with 35 μ m $\times$ 80 μ m apertures was prepared in a R&D level. Figure 4 shows nickel apertures of 35 μ m $\times$ 80 μ m at 80 μ m pitch. Figure 4 evidences the excellent smoothness of electroformed apertures and shows clearly the vertical aperture walls (almost no tapering) by using special masks in the electroforming process [13] which underlines the difference with the tapered walls of laser-cut stencils. Further developments in electroformed stencil manufacturing concentrate on different nickel hardness up to 480HV. This harder nickel material will be less likely to wear from the printing forces and will also deform less from both the framing and the printing process. Other changes in the plating setup target to modify the surface roughness of the stencils. The aperture design for wafer bumping always takes into consideration the existing rules for fulfilment of aspect (>1.5) and area (>0.66) ratios for efficient paste transfer on the pads but also considers

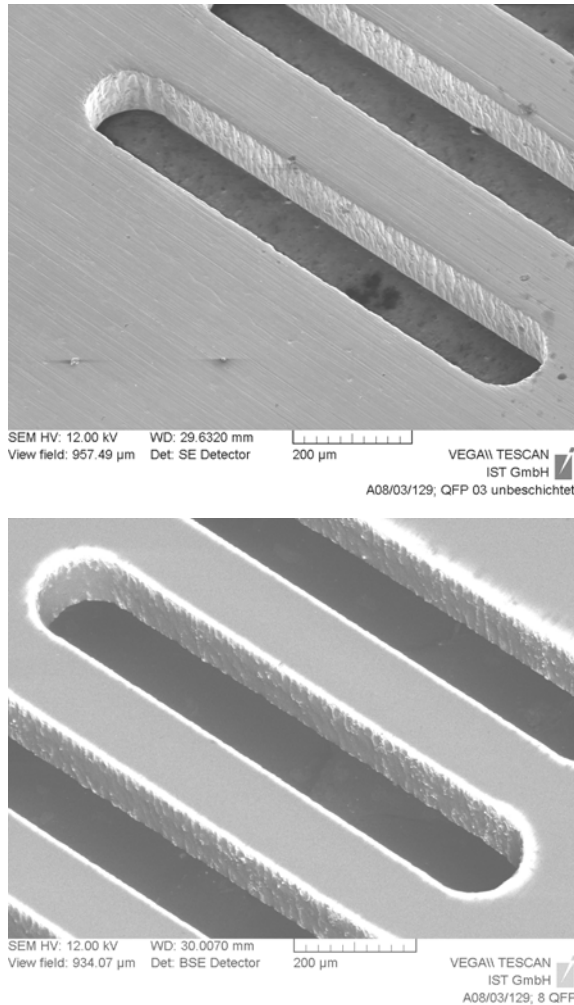


Figure 3: QFP apertures without nano-coating (top picture) and with nano-treatment (bottom picture).

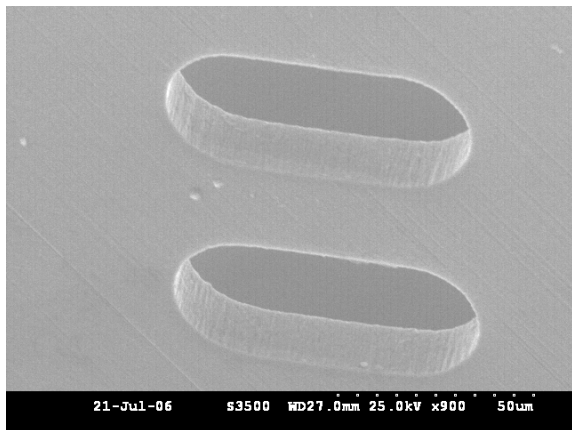


Figure 4: Electroformed nickel apertures 35µm x 80µm at 60µm pitch. Stencil thickness: 20µm.

to hold the minimum separation distance to avoid paste bridging.

The largest challenge in bumping at UFP is to find the gold solution to satisfy the above mentioned design principles for good paste release and sufficient paste volume and on the other hand to avoid paste and bump bridging [4,9,11]. For 80µm pitch the aspect and area ratios were 2.45 and 0.84 for the stencil without nano-coating and 2.65 and 0.89 for the nano-stencil, respectively. The slightly larger aspect and area ratio for the nano-stencil will facilitate further the paste release from the apertures. Correspondingly, for 60µm pitch wafer the respective ratios were 1.75 and 0.61 by using also a 20µm thick nickel stencil. One of the main goals of the present UFP studies is to examine if state-of-the-art stencils and materials can facilitate qualitative printing even at designs with lower aspect and area ratios than 1.5 and 0.66 as well as help improve production times by avoiding frequent stencil cleaning [9-12]. In this respect, a test coupon was also manufactured at 80µm pitch with the same apertures 49µm x 108µm but with a thickness of 35µm so as to create printing designs with aspect ratio of 1.4 and area ratio 0.48, smaller than those dictated by the conventional design rules (1.5 and 0.66) [4].

Apart from stencil developments, stencil printing is very dependent on printing machine capabilities. Most of IZM's R&D bumping work has been performed by using a DEK Horizon machine which has the capability of +/- 25µm alignment. It should be noted that alignment at UFP especially smaller than 120µm is very challenging and very close to limits of the today's printing machines. Figure 5 shows a "real-time, in-situ" very critical alignment at 80µm pitch, with a wafer of 60µm Ni/Au pads in contact with the nano-treated stencil with apertures of 53µm x 110µm.

2.2.2 State-of-the-art solder paste materials

Previous studies have shown that type 6 (5-15µm) and even finer pastes are appropriate for UFP bumping (pitches < 120µm). It has been shown that type 6 may marginally be used up to 100µm pitch wafer bumping based on the aperture design [3,11]. Experimental studies have compared bumping results at 100µm pitch of type 7 (2-11µm) paste with the standard type 6 (5-15µm) paste [11]. The difference in printing and bump height distribution was not significant and therefore the differentiation of type 7 from type 6 is not necessary. Type 6 paste which has been already established in the market for wafer bumping can be used for wafer bumping applications ranging from 300µm to 100µm pitch.

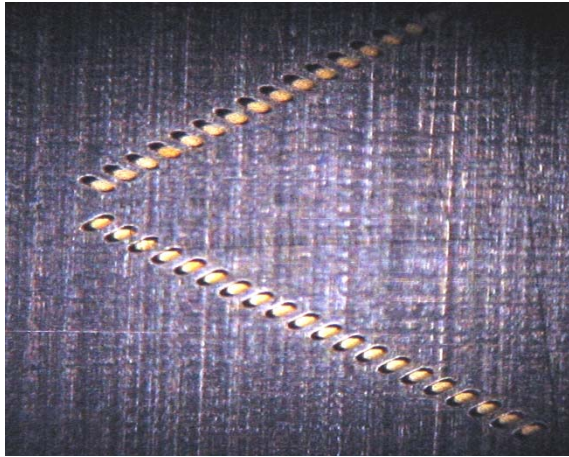


Figure 5: View of a “real-time” (at the stencil printer platform) alignment of Ni/Au pads (gold color) with stencil apertures of 53µm x 108µm at 80µm pitch. (Stencil thickness: 20µm)

For UFP applications (<120µm) and always based on the aperture design decided for each specific application, a new type 8 powder was fabricated and was provided as paste. Type 8 has a powder size from 2-8µm. Type 8 was used in the present study for bumping at 80µm and 60µm pitch (35µm x 80µm apertures). The standard type 6 paste is commercially available whereas the type 8 paste is a developmental product. The powder size of type 8 paste has been confirmed to be 2-8µm at a percentage larger than 90%. Our studies have shown that type 6 paste may be used up to 25µm stencil thickness and 80µm pitch provided that the stencil design is appropriate (at least 5 particles) and the stencil has a nano-treatment which improves paste release. The rheological properties of both pastes are similar since it was decided by the manufacturer to use the same chemistry for the newly type 8 as for the standard type 6 paste. The viscosity of both pastes at a shear rate of 10/sec is 240 ± 50 Pa sec. Figure 6 shows print deposits of type 8 paste at 60µm pitch on monitor wafer after short heating for flux evaporation.

3. Bumping applications-Results & Discussion

3.1 Printing at UFP using stencils

Printing speeds in the range of 5-15 mm/sec were applied along with a printing pressure of 2-3 Kg for a 300mm long stainless steel squeegee with 60 degrees printing angle. These parameters could ensure a clean print sweep with the minimum pressure used and proper filling of the apertures. The printing speed range is in agreement with other reported values in the literature [4]. Contact printing

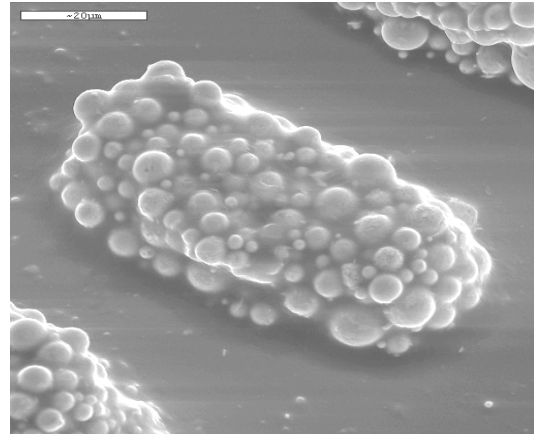


Figure 6: Developmental type 8 paste. Print deposits at 60µm pitch. Powder size range: 2-8µm.

is used and in general is the most appropriate choice compared to snap-off printing for wafer printing at pitches smaller than 120µm. In fact, the 20µm thin foil at 80µm and 60µm pitches can severely be flexed upon snap-off printing resulting in significant stencil deformation. In contrast, contact printing might protect the thin foil from repeated elastic deformations.

Printing at 80µm pitch with the stencil which did not have any nano-coating was very successful. The paste was released from all apertures and a good packing of particles in the deposits was achieved due to the usage of very fine type 8 paste. The aspect and area ratios of 2.4 and 0.83 are well above the aspect and area ratio rules for acceptable printing. Type 8 is also necessary for such a thin stencil in order to have a good coverage of the UBM pad with solder paste; at least 4 particles in the z-axis direction. Such a requirement would not be possible with type 6 paste which can yield by average only 2 particles in the vertical direction. The nano-coated stencil with the same design at 80µm pitch had slightly larger apertures than the one without nano-coating and has also shown very good printing behaviour. The results show that the paste has been released better using a nano-coating stencil especially from the long sides of the aperture walls compared to the release by using a normal stencil. The nano-treatment makes also the bottom side of the stencil hydrophobic which prohibits extensive flux bleeding. Flux bleeding is in general a very common phenomenon by printing very fine pastes because very fine particles flow under print pressure in the flux and can bridge the deposits or can yield extensive bridging during reflow. Figure 7 shows a representative print of type 8 paste at 80µm pitch

using a non-nano coating stencil with deposits of $48\mu\text{m} \times 116\mu\text{m}$. Both laser-cut stencils at $80\mu\text{m}$ pitch had a slight irregular cut in one side of the oblong aperture which is quite normal taking into account the manufacturing difficulty of making such fine apertures. However, it should be underlined that the better paste release by using the nano-stencil can be due to a “combination” effect of the nano-treatment and also the slight larger aspect and area ratios of the nano-stencil rather than the nano-effect solely. It becomes obvious that it is extremely difficult to see clearly the nano effect in UFP as in the case of $80\mu\text{m}$, but it would be more clear at larger bumping pitches or for QFP, BGA and other SMD applications [12].

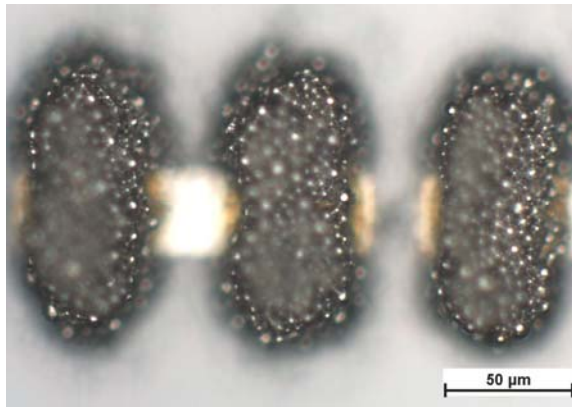


Figure 7: Print deposits of type 8 paste at $80\mu\text{m}$ pitch. Deposits $48\mu\text{m} \times 116\mu\text{m}$. Distance between deposits $\sim 30\mu\text{m}$.

Prints of type 6 paste were also tried with the above stencils to examine if commercial paste can be also used up to $80\mu\text{m}$. The paste release was good from both stencils because the aspect and area ratios were satisfactory but the deposit thickness was too little (~ 2 -3 particles) and therefore type 6 is not recommended for the application discussed in this paper. It should be mentioned that the nano-treatment of the sidewalls helps the paste release even in the case of type 6 paste where the packing of the particles is less than 4 in the aperture. Therefore, the usage of type 6 at $80\mu\text{m}$, dependent on each individual application, may be considered if the laser-cut stencil has been nano-treated.

As mentioned in section 2.2.1, a nano-treated test coupon with a stencil thickness of $35\mu\text{m}$ and aspect and area ratios of 1.4 and 0.48 was created to check if printing at lower aspect and area ratios was possible. The test coupon had the same dimensions as the framed nano-stencil. The printing results were also good with outstanding paste release

at smaller aspect ratios. These results can open a new era in stencil printing technology because smaller and taller deposits can be printed minimising also the risk of bridging even at very small pitches. The paste release at smaller ratios is attributed solely to nano-treatment since printing with test coupon without nano-treatment at the same 1.4 and 0.48 ratios could not yield any paste release. The encouraging results with the test coupons will be verified in a future publication where a framed nano-stencil will be used with an experimental matrix with ratios under the established “rules of thumb” for printing. Figure 8 provides evidence of the capability of nano-stencils to print even at aspect and area ratios smaller than 1.5 and 0.66 with the use of fine pastes. Most of the paste has been released out from the apertures. Figure 9 shows a view of the good filling of the apertures at $80\mu\text{m}$ pitch. About 8 particles can be packed in the $40 \times 100\mu\text{m}$ apertures.

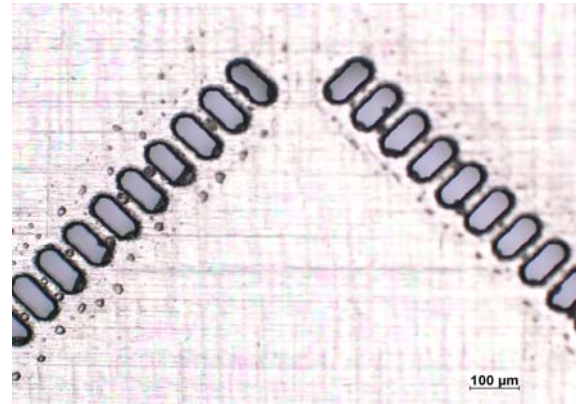


Figure 8: Complete paste release from apertures with 1.4 and 0.48 aspect and area ratios ($< 1.5, 0.66$) with the use of nano-stencils.

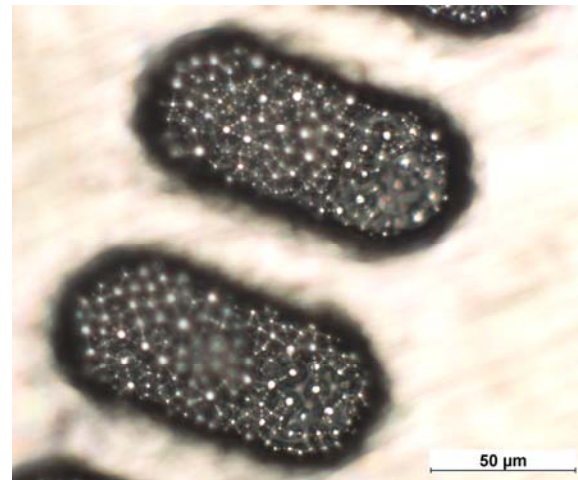


Figure 9: Packing of type 8 paste in $40\mu\text{m} \times 100\mu\text{m}$ apertures at $80\mu\text{m}$ pitch. Powder size: $2\mu\text{m}$ - $8\mu\text{m}$.

Printing at 60 μm pitch with a 20 μm electroformed stencil is in fact very challenging for the alignment between wafer pads and the stencil apertures. Although 3 fiducials have been used for alignment always an offset should be always used to improve the registration. In addition to deformation due to the framing process, repeated printing may also contribute to stencil stretching. In the present study, measurements were taken to monitor deformation to ensure that the alignment of the framed stencil to the wafer was acceptable. After 20 prints and manual cleaning of the stencil-which may also deform it- good alignment was always achieved. Figure 10 shows print deposits of type 8 paste at 60 μm pitch. The deposit thickness is 20 μm in agreement with the foil thickness. The deposits have dimensions about 35 μm x 77 μm on the top surface and about 41 μm x 84 μm at the bottom surface.

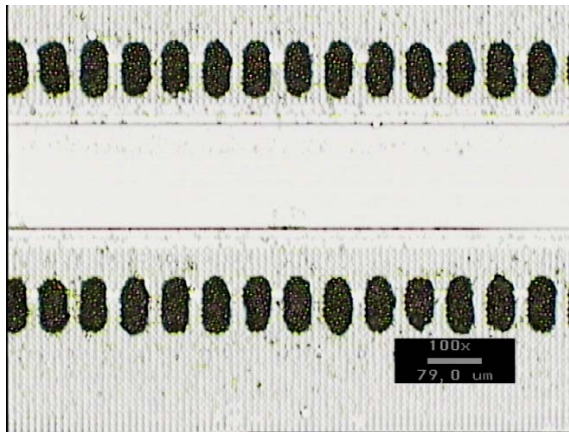


Figure 10: Wafer printing at 60 μm pitch with type 8 (2-8 μm) paste.

3.2 Bumping results and discussion

For bumping at 80 μm pitch, the nano-coated stencil has yielded better paste release even at very marginal aspect and area ratios. For 80 μm pitch, both type 6 and type 8 were used and compared. All reflow results of type 8 paste have shown extremely small satellite balls around the main bumps which are floated in a flux medium. Cleaning and appropriate satellite removal yield a very clean bumped wafer with bumps of 23 μm height which look more like caps due to the relatively large UBM pads (60 μm). Wafer bumping at 80 μm pitch has shown about 98% chip yield. Figure 11 shows a view of a bumped chip at 80 μm pitch. The reflow of type 8 paste creates many tiny solder balls. Furthermore, flux bleeding can carry particles between the deposits which can not fully coalesce to the main bump during reflow and appear as tiny balls on the bump foot. Solder balling is much more intense for bumping at 60 μm

and 80 μm pitch than for bumping at 100 μm pitch with type 6. Bumping at 60 μm pitch yields bumps with a height of 28 μm $\pm$ 3 μm . The larger bump height at 60 μm pitch compared to 80 μm pitch can be explained by the smaller UBM size of the wafer at 60 μm . Figure 12 shows a wafer bumped at 60 μm pitch.

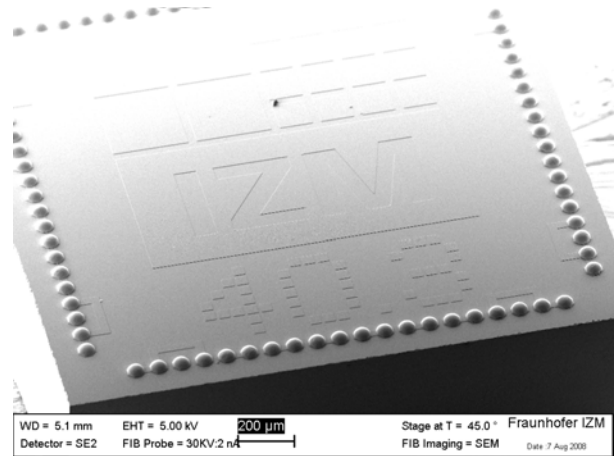


Figure 11: Bumped chip at 80 μm pitch. Bump height is 23 μm .

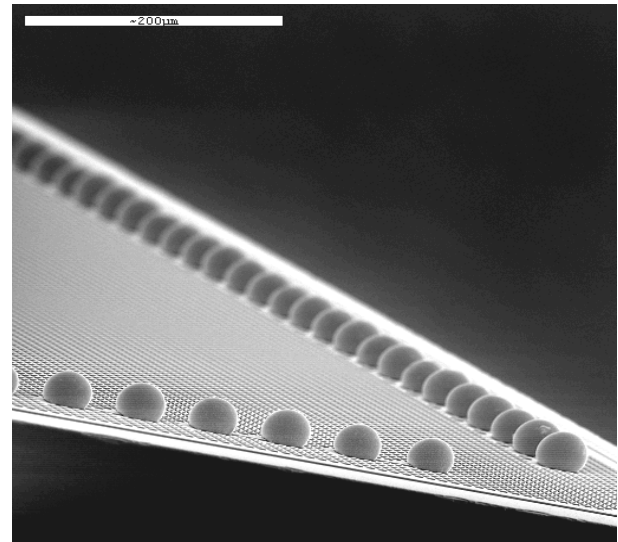


Figure 12: Bumped wafer at 60 μm pitch. Bump height: 28 μm $\pm$ 3 μm .

4. Conclusions

IZM has developed stencil design rules for any demanding wafer bumping application and offers a complete service portfolio for wafer bumping including: stencil design & selection, paste printing & reflow, fluxing/balling, wafer cleaning, bump height measurements & yield statistics, microstructural characterisation of UBM/solder

bump interfaces, and reliability assessment of assembled flip chips. Many investigations have devoted to UFP bumping by stencil printing of solder paste. Bumping at pitches smaller than 120µm has been demonstrated up to 60µm using developmental type 8 pastes. Specially fabricated laser-cut stencils with nano-coatings and very thin electroformed stencils have been employed through collaborative R&D work with international companies to bring printing capabilities very close to the limits of stencil manufacturing. Nano-treatment of the sidewalls and the bottom surface of the stencils improves the paste release and can set new rules in stencil printing by lowering the aspect and area ratios necessary for efficient paste printing. This means that good printing can be achieved also with smaller and taller deposits maximising solder paste volume, avoiding bump bridging and therefore improving wafer yield. Significant care should be taken with innovative cleaning solutions and processes for cleaning the wafers from the small satellite balls created by reflow. Electroformed stencils also are a strong candidate especially for UFP printing but extreme care should be taken upon framing to avoid stencil deformation. Wafer bumping at 80µm and 60µm pitches resulted in heights of 23µm and 28µm, respectively.

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