Deposition of Fine-Pitch Indium Bumps on Single Die

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***Abstract*— Photolithographic lift-off at wafer level is a well-established method for depositing indium bumps onto pixels of electronic components such as sensors and application-specific integrated circuits (ASIC). These indium bumps form interconnects between pixels of the components during flip-chip bonding to make devices such as radiation detectors. Such components are not always available on wafer-scale, and single dies need to be processed in small-scale production, R&D, or for Cd(Zn)Te detector material. Photolithography on single dies is ineffective due to the edge-bead of photoresist that compromises perfect indium deposition onto pixels near the periphery of the die. To utilize the maximum surface area of a die, a rigid mask with apertures (shadow mask) is an adequate substitute for the photoresist. Different mask designs and production techniques for fine-pitch indium bump arrays are investigated by testing electroformed stencils or micromachined silicon (Si) membranes as shadow masks. For the indium deposition, the sensor and ASIC dies are clamped into custom-made jigs that include shadow masks. Alternatively, dies can be adhered to shadow masks with soluble adhesive. The apertures of a mask are aligned to the pixel array of the detector component. Bump arrays with 250µm- and 100µm-pitch were demonstrated with electroformed stencils. For smaller pitch (55µm) and bump diameter of ~20µm, specialized masks from Si membranes are tested. Components with successfully deposited indium bump arrays were subsequently flip-chip bonded at room temperature without reflowing the indium. A bond yield of at least 99.9% pixels for such flip-chip bonded radiation detector was shown using the read-out signal from exposure with a flat field X-ray radiation of an Am-241 sealed source.**

Keywords—shadow mask, indium bumps, flip-chip bonding, fine-pitch, radiation detectors

I. Introduction

X-ray and gamma-ray detectors for imaging and spectroscopy in scientific experiments at synchrotron light sources and X-ray Free Electron Lasers (XFEL) are often pixel detectors that are hybridized sensors with application-specific integrated circuits (ASIC). For advanced experiments at modern and next-generation synchrotrons and XFELs, these detectors need to be suitable for high radiation energy and extreme photon flux [1,2]. For quite some years, high-quality radiation grade $CdZn_xTe_{(1-x)}$ ($0 \leq x \leq 0.1$) has been the choice of material [1,3,4,5] for those sensors due to its electrical and radiation absorption properties. For desirable high spatial resolution, small pixels on a 55µm pitch are required. Such detectors are largely utilized with Si sensors hybridized to Medipix ASICs [6]. First detectors with CdTe and Cd(Zn)Te hybridized to 55µm-pitch ASICs were presented as early as 2004 [7]. Those were fabricated on wafer-scale and using PbSn for interconnects. In addition, processes are carried out on single die but no details of the hybridization/flip-chip bonding were given [7]. Currently commercially available small pixel detectors are fabricated by Advacam with CdTe sensors and Timepix3 ASIC [8] for specialized medical applications (positron emission tomography). High-quality detector-grade Cd(Zn)Te is provided by Redlen in the form of single dies that are fabricated by selecting monocrystalline defect-free areas from ingots [9]. Processing such single die with photolithography using negative photoresist (PR) in lift-off processes of subsequently deposited indium for interconnects is not trivial [10]. The edge-bead of PR compromises perfect indium deposition onto pixels near the periphery of the die. Processes using a rigid mask with apertures (shadow mask) – as shown by other research groups for deposition of thin layers [11] – are a suitable alternative. The shadow-mask technique presented here enables the deposition of µm-high indium bumps on single die without photolithography and with fewer, simpler process steps. The paper presents different shadow masks that will be capable for small-pitch size of 55µm. This technique is important when single dies are processed in small scale production or for R&D projects that require high yield.

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II. Process Preparation

The hybridization of sensors and ASICs for radiation detectors is conventionally carried out with single sensor and ASIC dies in a flip-chip bonding process. This requires the deposition of some form of bond material for each pixel between sensor and ASIC. For large pixel pitch (~250µm) this can be achieved by printing electrically conductive adhesive onto the sensor pixel array and subsequently the sensor is flip-

chip bonded to the matching array of gold ball studded pixels of an ASIC [12]. However, those processes have limitations due to the size of bumps that can be formed. For smaller pitch, indium bump bonding is preferred. Also solder bumps such as eutectic Sn-Pb [13] may be suitable for this process. Conventionally this is carried out on wafer scale and involves a large number of process steps [14]. Wafer processing allows the spinning coating of negative PR and subsequent high-precision and fine-structure (pitch) patterning using photolithography. On such wafers indium is deposited and after stripping the PR indium bumps remain on the desired pixel position (lift-off). RAL conventionally achieves 20µm-∅ indium bumps with 55µm-pitch on 8-inch wafer using this lift-off method. However, in a following fabrication step individual sensor/ASIC dies have to be singulated from these wafers using mechanical dicing or similar processes which is delicate because the existing indium bumps can be easily damaged. For the flip-chip bonding, the indium deposition/bumping is carried out on both sensors and ASICs -- the malleable indium bumps can form the interconnects between sensor and ASIC pixels in the bonding process. Often an additional indium reflow process is executed to improve alignment between sensor and ASIC pixel arrays as well as better bond formation [14]. However, STFC-RAL demonstrate that such reflow process is often not necessary, and a cold indium welding process [15] can be used instead.

A process that enables the indium bump deposition onto single die without photolithography will reduce several process steps that conventionally used as described in [14]. In addition, indium bumping of CZT dies that are frequently used for high-quality radiation-grad sensor material will be much simpler without the disadvantages of photolithography on single dies as explained in the introduction of this paper. Instead using PR, these single sensor/ASIC dies need to be masked using a solid stencil with apertures (shadow mask) which will be aligned with the pixels of the component. Consequently, indium bumps will match and reveal the same aperture array pattern on the component after the evaporation and the removal of the shadow mask..

A. Masking of Sensors and ASIC Dies

For masking dies with shadow masks, two different types of mask material were studied. Initially for aperture pitches ≥100µm, electroformed nickel stencils fabricated by ASMPT to RAL's pixel design were chosen. ASMPT's "DEK Electroform process" [16] stencils which are usually utilized for printing solder paste (surface mount technology for miniLED dies) is specified for minimum aperture size of 50µm and a minimum gap of 50µm between apertures that is equivalent to a 100µm-pitch. The smallest thickness of such stencil is 23µm. These dimensions are compatible with most radiation detector pixel arrays and hence suitable for shadow masks of large indium bump pattern (≥100µm-pitch). Electroformed masks used for this study here were 40µm to 50µm thick. According to ASMPT [16], laser cut stencils are not able to meet the same requirements as those electroformed stencils. RAL designed customized jigs for holding single dies with a clamping mechanism that mounts the shadow mask to the die. The alignment of the aperture array of the shadow mask to the pixel array on sensor/ASIC dies is carried out optically before the mask is fixed to the jig. Further details are given in [17,18].

For detector applications with pitch <100µm currently micro-machine Si membranes are tested for indium bumping with shadow masks. Si membranes with thickness 50µm and 100µm, respectively, were fabricated on ~380µm-thick 4-inch Si wafers by Kelvin Nanotechnology. Ltd. Rrecesses for 9 membranes with arrays of 256 × 257 apertures (55µm-pitch) were etched on each wafer. For initial test purposes, the diameter of the apertures ranges from 25µm to 45µm. Due to the fragility of the membranes, those membranes were not used with the custom-made jigs yet, instead single individual dies are temporarily attached across the membranes of the Si wafer with soluble adhesive. The adhesive will be applied in dedicated areas of the wafer in close vicinity of the membranes. Three different adhesives were examined (IPA-diluted adhesive, acetone-diluted adhesive, and double-sided tape comprising similar solid adhesive). The IPA-diluted adhesive generates a viscous fluid that was dispensed with an ASYMTEK X1010 dispenser using an Auger screw. The acetone-diluted adhesive is less viscous than the IPA-diluted adhesive mix and, therefore, was not used with the ASYMTEK dispenser. Instead, droplets of the mixture were dispensed manually from a needle syringe. Alternatively, a thin film was spread with a doctor blade and it was investigated to transfer material from this film to surrounding areas of membrane of the shadow masks using a stamp or similar applicator. The adhesive on tape is based on the same material as the diluted adhesives and is a solid adhesive that is commercially available as a single-sided tape. In order to tape die and mask together, two of those adhesive tapes were joint together with a 3M double-sided tape creating an approx. 500µm thick double-sided tape. The adhesive of such tape is soluble in acetone.

B. Indium Bump Deposition

For the indium deposition, a MPS800 thermal evaporator with integrated in-situ Argon (Ar) plasma system was used. The plasma system allows stripping oxide layers and other residues from the substrates prior to the metal deposition (plasma cleaning). After plasma cleaning, a ~10nm thin chromium barrier/adhesion layer is deposit followed by the indium deposition of a thick (~6µm) layer. The thickness of the indium layer is monitored by a quartz crystal microbalance. Up to 8-inch wafers as well as the custom-made jigs for single die can be mounted on a rotating table of the evaporator. With a special adaptor (and depending on the size of the dies) about 16 jigs with shadow masks can be mounted on this table. The distance between crucibles with indium to the table is approx. 1m for achieving a good uniformity of an indium layer. Hence the MPS800 evaporator can be utilized for indium deposition with standard wafer-scale photolithographic lift-off processes as well as for deposition on single die using shadow masks.

C. Flip-Chip Bonding

The flip-chip bonding of sensor to ASIC dies is carried out on either a SET FC150 or FC300 bonder at RAL. Even though the FC300 has the capability of an in-situ reflow process with formic acid that reduces any surface of indium oxide before bonding, an indium cold welding bonding process at room temperature without reflow and formic acid was carried out in the FC150 for any hybrid detector. The bond force is typically 0.5gf/pixel so that the insignificant and negligible oxide layer of the indium bump surface is ruptured and a sufficient bond between pixels is formed. Usually after hybridization of sensor and ASIC, the ASIC is wire bonded to a PCB and connected to a data-acquisition system.

III. Results

Utilizing the shadow mask technique with electroformed stencils, a prototype indium bumped hybrid radiation detector with 250µm pixel pitch was successfully demonstrated [18]. Applying an exposure of the detector with a flat field X-ray radiation of an Am-241 sealed source, a significant signal was detected in 99.9% of pixels of the detector that was fabricated

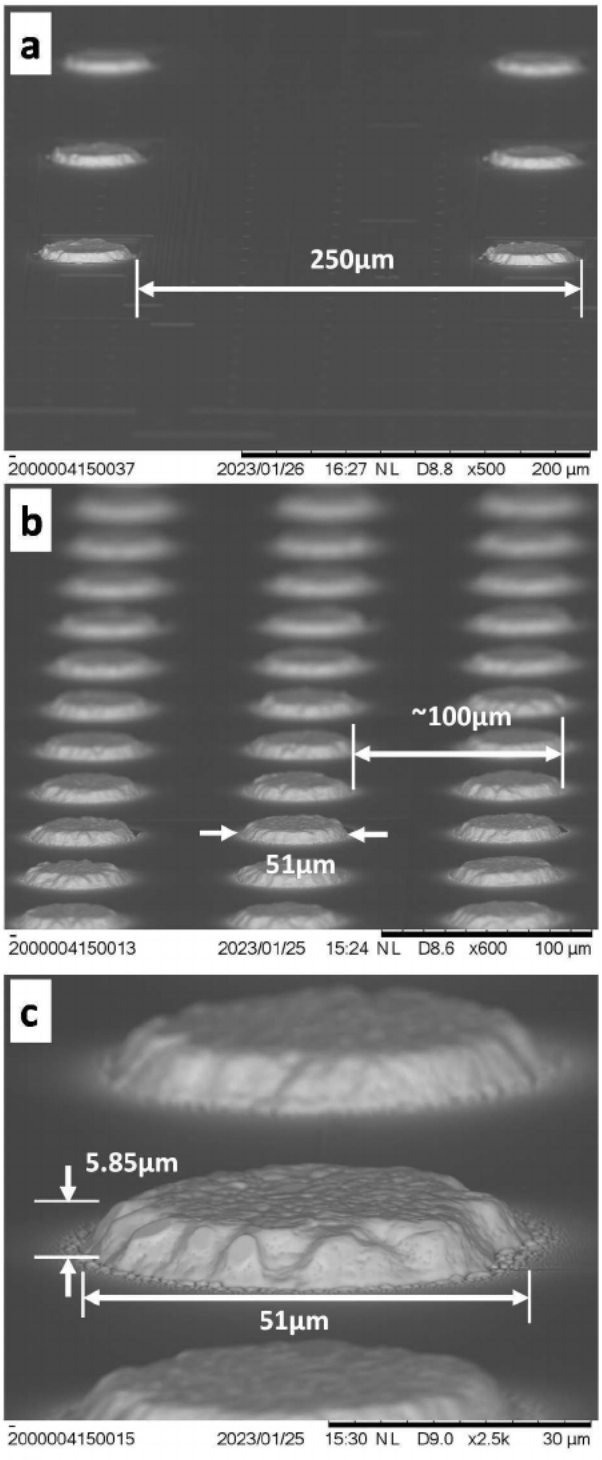

Fig. 1. a) 250µm-pitch ASIC with indium bumps; b) indium bumps on 100µm-pitch; c) detail of a bump.

with the shadow mask method [18]. The indium interconnect bond yield is potentially higher than 99.9% because diminishing signal in detector pixels can also be contributed by defects in sensor and ASIC that cannot be distinguished from missing bonds with the test used here. A detailed SEM image of such bumps with 250µm-pitch on an 80×80 pixel ASIC is shown in Fig.1a. Electroformed shadow masks are limited to an aperture pitch of 100µm. Initial trials on test substrates achieved indium bump arrays with ~100µm-pitch (Fig.1b+c) with those electroformed stencils and mechanical clamping of shadow masks to dies in dedicated jigs. Each indium bump (~50µm diameter, ~6µm high) has a small, insignificant amount of thin indium (width of ~3µm) around the bumps. This additional halo of thin indium material is potentially caused by indium penetrating under the edges of the mask apertures because the shadow mask is not in full contact to the die surface. In contrast, such halos were not observed for indium bumps on wafers that were prepared with a standard photolithography lift-off process. A spin-coated PR covers a wafer surface perfectly with only a minute intended undercuts of the openings in the PR that facilitate the lift-off of PR and indium. It is important to take these additional indium halos into account for the pixel array design on sensors and ASIC (pixel size > 56µm) when using electroformed shadow masks. Nevertheless, this is still sufficient for any 100µm-pitch device.

For trials with 55µm-pitch shadow masks, two 4-inch Si wafers with membranes were fabricated. Recesses were initially etched to create the membranes. On the opposite unetched side of the wafer apertures for membranes and additional pattern (dimples and trenches) adjacent to the membrane areas were photolithographically formed and etched until aperture openings in the membrane occurred. The dimples around the membranes are intended to confine adhesive in these areas for die attachment and trenches are intended to protect adhesive from flowing onto the membranes. Nine different membrane configuration per wafer were constructed (Tab. 1). In addition to the membrane wafers, a further dummy wafer with the same pattern for apertures, dimples, and trenches but without the membrane recesses was produced for testing the different adhesives for die attachment. All three wafers are shown in Fig. 2 with an example of apertures on a 50µm-thick membrane in the inset of Fig.2.

TABLE I. Membrane Apertures and Dimples/Trenches

#	Membrane apertures	Adhesion area		
	Diameter ⌀	*Trench width*	*Dimple ⌀*	*Dimple pitch*
1	25µm	20µm	20µm	80µm
2	35µm	5µm	20µm	40µm
3	45µm	10µm	20µm	60µm
4	35µm	20µm	5µm	80µm
5	35µm	5µm	5µm	20µm
6	35µm	10µm	5µm	40µm
7	40µm	20µm	10µm	80µm
8	35µm	5µm	10µm	20µm
9	30µm	10µm	10µm	40µm

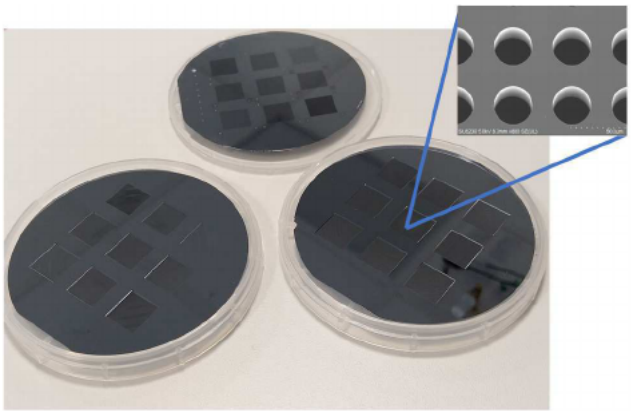

Fig. 2. Three 4-inch wafers for tests with 55µm-pitch shadow masks - inset shows an SEM image of apertures (35µm-diameter, 55µm-pitch on ~50µm-thick membrane).

Using these Si wafers with membranes, a die attachment with dissolvable adhesives to the wafers seems to be a better solution rather than handling and mounting the fragile membranes dies into the customized jig described above. Three different adhesives (IPA-diluted, acetone-diluted, double-sided tape) which were tested compares as follows:

IPA-diluted adhesive (2/3 mix in weight): Small droplets of viscous solution that were dispensed through an Auger screw of the ASYMTEK dispenser was not easy to control and was inconsistent in shape, height, and amount that resulted on the Si wafers. There is some tendency to achieve smaller droplets with increased gap (0.6mm) between dispensing needle and Si surface as well as shorter dispensing time (0.5sec). These adhesive dots vary in height from 100µm to 300µm and in diameter from 0.8mm to 1.6mm. Further optimization achieved smaller dots with a height between 25µm and 55µm, but these dots did not always form uniform circular dots. When just dispensed and left drying, the dimple diameter and pitch on the patterned surface area where adhesive was applied did not have any significant effect on the dot height. Remelting of these dried dots (initial height approx. 38µm) changes size and shape to approx. 3µm to 5.3µm in height on a flat surface after heating on a hot plate at 150°C for ~15min. Due to surface tension, these remelted dots are often taller at the edges than in the middle of the dot, sometimes resulting in a diminishing/vanishing amount of adhesive in the center of the dot. Dots on surfaces patterned with dimples are usually thinner compared to the flat surface because the dimples take up some of the adhesive. Therefore, the remaining dot height has a slight tendency to be smaller with increasing dimple diameter but is insignificantly influenced by the dimple-pitch.

Acetone-diluted adhesive (1/1 mix in weight): This type of mixture was too fluid to be used in the ASEMTEK dispenser. Dispensing such mixture manually from a syringe in small quantities allows to form small droplets up to a height of 400µm; especially with mixtures that contain less acetone. Keeping droplets of this mixture at room temperature for several hours or heating at 90°C for at least 10min on a hot plate does not evaporate all acetone, and droplets remained soft. This may create difficulties to correctly attach a die to the mask due to outgassing. A longer drying process at higher temperature (150°C for ~15min) forms more solid adhesive dots with a height between 5µm to 15µm which are more likely to perform a good adhesion of dies to shadow masks. To further improve control over the dot height and size of this adhesive (1/1 mix), a thin film was created with a doctor blade on a rotating plate and then small portions of the thin adhesive film were transferred with a stamp to the shadow mask. This creates features of adhesive which are confined to the area of the stamp impression. The typical height is between 5µm to 16µm but can also occasionally be as high as 45µm or no adhesive at all in parts of the stamped area. The height is independent of the area where the adhesive was deposit with the stamp (flat Si or patterned with dimples). After reheating at ~150°C for several minutes, these adhesive spots decrease slightly in height by a few µm when those were stamped on flat Si or area with dimples of 5µm diameter. Only in areas with dimples of diameter ≥10µm the adhesive almost completely retracts into the dimples leaving only a minute amount of adhesive on the surface in this area. The dimple pitch has no significant influence on height or shape. This mixture stamped on areas with dimples of diameter ≥10µm seems to be well suited to attach dies to shadow masks with a minimal gap.

Double-sided adhesive tape: The constructed tape had a far better thickness consistency compared with the droplets but is approx. 500µm thick. This increases the distance between shadow mask and die considerably, potentially increasing halos of indium around the bumps as seen for indium bumps created with electroformed masks (Fig. 1c). The tape is easy to use and experiments with glass slides attached to each other with this tape, were separated again by simply leaving the assembly in acetone for approx. 13 hours.

Due to current unavailability of the indium evaporator and expected upgrade of the equipment, no indium deposition could be carried out with the 55µm-pitch Si wafer masks so far. We expect further results by the time of the EMPC'23 conference.

IV. Conclusion

Applying electroformed stencils as shadow masks demonstrated that indium bumps of 250µm- and 100µm-pitch arrays can be produced on individual dies. The shadow mask aperture array is aligned to the pixel array of the die and clamped together in a custom-made jig that can be mounted into an indium evaporator. To date this method was employed for flip-chip bonding a prototype radiation detector with 250µm pixel pitch indicating an interconnect bond yield better than 99.9%. To further decrease the pixel pitch suitable for 55µm-pitch radiation detectors, shadow masks of Si membranes with apertures were produced on 4-inch wafers. Three different soluble adhesives (IPA-diluted, acetone-diluted, double-sided tape) are currently tested for adhering single dies temporarily to such Si shadow masks instead of mounting Si membrane and die in a custom-made jig. A process with double-sided tape or stamping acetone-diluted adhesive from a thin film onto the shadow mask seems to be promising for the alternative attachment. This is a considerable step towards the fabrication of radiation detectors with 55µm-pitch made from single sensor and ASIC dies which will be further tested in future.

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