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Calibration and Operation of the Research Devices, Inc., Flip-Chip Hybridization Bonder Model M8-A with Discussion of Solder Materials

by Kimberley Olver

NOTICES

Disclaimers

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14. ABSTRACT

Precise flip-chip hybrid bonding is achievable using the Research Devices, Inc., Model M8-A Hybridization Bonder after a complete calibration of the equipment is performed. All calibration steps must be completed in sequence prior to any bonding of real parts. Several types of solder material are discussed, and consideration needs to be given to the specific solder material used for a given die and submount pair that will be bonded together.

15. SUBJECT TERMS

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1. Introduction

Flip-chip hybridization is a microelectronics packaging and assembly process that directly connects an individual chip (die) to a substrate (submount) facedown, eliminating the need for wirebonding directly to the array. Conductive connections are made between the two parts using interconnect bumps consisting of a solder material. Both parts are placed into a Flip-Chip Hybrid Bonder and, using thermo-compression as the bonding technique, are "flipped" together. Flip-chip assembly is also known as direct chip attach (DCA) because the chip is directly attached to the substrate via conductive bumps (Fig. 1). DCA is a well-proven packaging technique used for the direct connection of processed device chips to readout devices and submounts. A grid of solder bumps on the surface of the active area on the device chip is joined directly to a corresponding set of solder bumps on the substrate. The main advantage of flip-chip hybridization over other packaging techniques is that the very short electrical connections allow for lower lead resistances. It is a robust, reliable technique due to the solder joint connections and capable of high-density connections with a very low profile. Furthermore, because wire bonding directly to a device is not needed, tighter spacing of devices in an array can be achieved, therefore allowing larger-format arrays and/or smaller components.

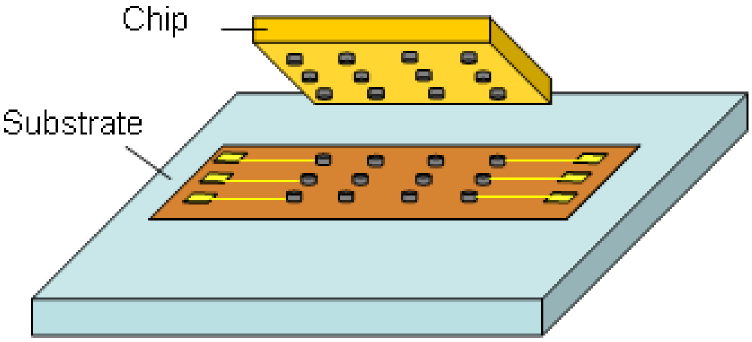


Fig. 1 Chip and substrate with solder bumps

The primary function of the Research Devices, Inc., Flip-Chip Aligner Bonder, Model M8-A, is to provide a stable platform for repeatable alignment of a die and substrate for the purpose of hybridization of those parts. The benefit of this particular equipment platform is the computer-controlled optics system using a borescope.[1] A borescope enables the user to see the die and the substrate fiduciaries (alignment marks) simultaneously on a monitor screen by inserting an optical probe assembly (borescope) between the two parts, allowing the user to move the lower chuck assembly until it is both parallel and properly aligned with the upper chuck assembly, thus allowing for precise bonding. This optical alignment is especially beneficial, as most parts being hybridized are not transparent. Figure 2 shows the inner workings of the optical probe system.

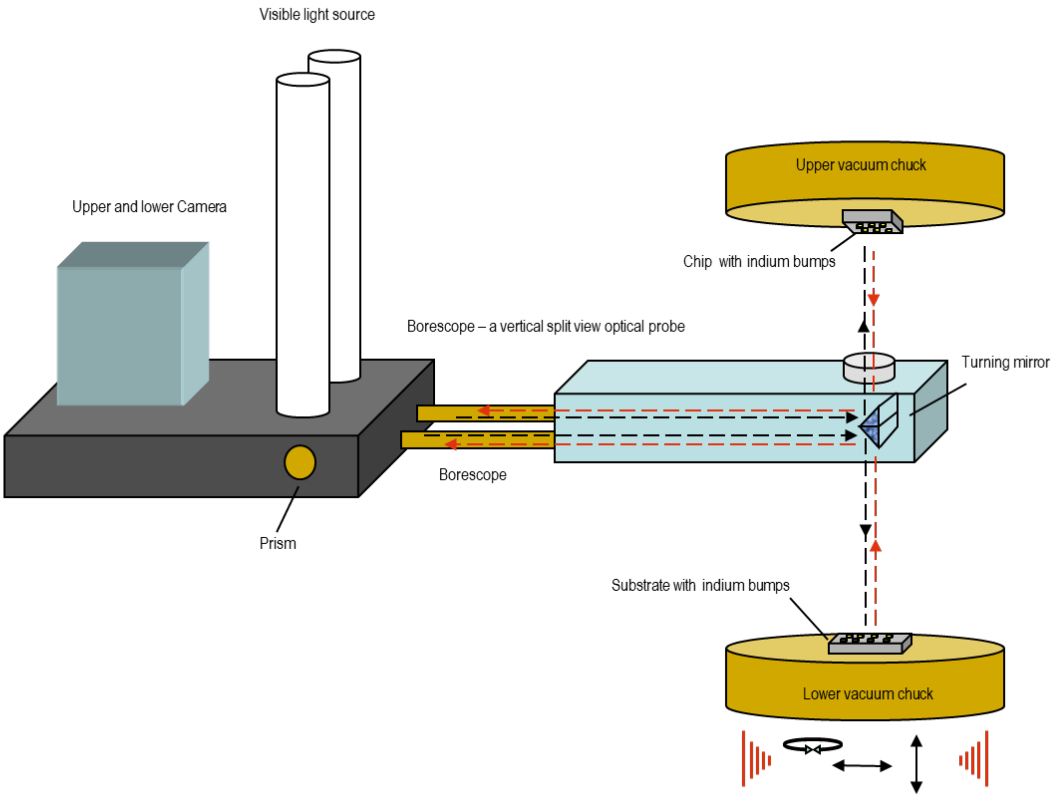


Fig. 2 Optical assembly

2. Procedure

Calibration of the M8-A must be performed before any parts are to be flip-chip bonded (hybridized). One absolute requirement for this equipment to properly work is that the upper and lower chucks and the optical system be in a static association with each other. So a complete calibration involving alignment of x and y and rotation, as well as parallelism, must be done, and cameras must be brought into a known fixed relationship with the optical system *before* precision bonding can be accomplished.[1,2] As a good rule of thumb, perform the calibration, complete the bonding for the day, and if hybridization is to be continued the following day, perform the calibration prior to starting again. Parallelism is an important component of the bonding process. If the parts to be bonded are not planar with respect to each other, a wedge will form. This can cause solder bumps to either not connect (opens) or to spread out and contact adjacent bumps (shorts) (Fig. 3). Therefore, the parts must be free of debris and contaminants on the back surface. They must lie flat on the chuck face. On the front surface, all of the solder bumps must be planar. There is a slight amount of parallelism correction that the M8-A is able to provide using its pitch and roll capabilities. The lower chuck is capable of ±3° of leveling range for pitch and roll.

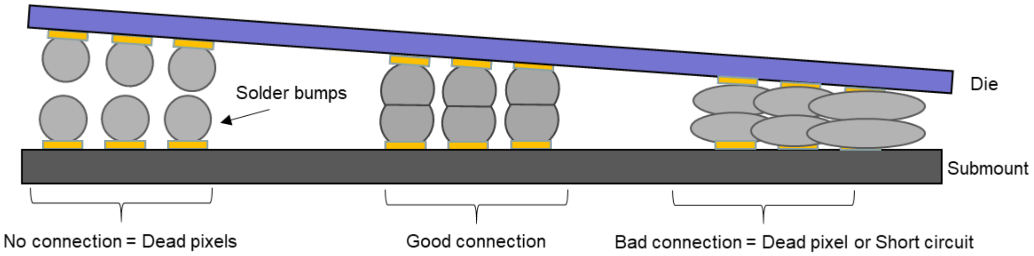


Fig. 3 Unconnected bumps, good connections, and shorts with regard to parallelism of die and submount

The M8-A system is semi-automated, and many of the system's components are computer controlled using the keypad/joystick unit located to the left of the bonder (Fig. 5). Bonding cycles with ramp, hold, temperature, and vacuum can be programmed into the unit prior to bonding. The main moving part on the M8-A is the lower chuck assembly. The upper chuck assembly is stationary. *All* parts of the calibration must be performed before moving to real parts. Use the following procedure for the calibration process.

2.1 Calibration Process Prior to Bonding

The following are the steps, in sequence, for calibrating the M8-A. Figures illustrate the location or position of the equipment with regard to each step.

The M8-A is started by pressing the red switch (circled in Fig. 4) on the back of the chassis to the On position.

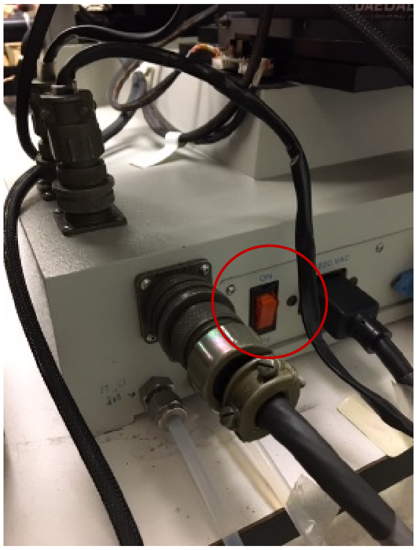


Fig. 4 M8-A power switch

The computer unit will emit several beeps. Do not press any keys on the keypad until the unit finishes the On procedure, then press any key on the keypad to open a status window on the monitor screen (Fig. 5).

```
RESEARCH DEVICES

MODEL M8-A
Flip Chip Aligner Bonder
With AUTOMATIC BONDING

                Main  control: RLC144-V03-6
                Motor control: RLC142-V02-3
RLC Software:   Temp  control: RLC141-V02-3
                Video control: RLC143-V02-3
                Joystick.....: RL610-V01-4

Press any key to begin operation
```

Fig. 5 M8-A keypad and initialization screen on the monitor

1) Press the Initialize (1) key on the keypad for the unit to find its x, y, and theta positions.
2) Press the Begin (2) key to bring up the main control screen (Fig. 6).

```
RESEARCH DEVICES
PURGE: OFF
CALIB: SAFTY ON
JOYST: CAM SCAN
SPEED: HI
CAMRA: UP /LO
ILLUM: 97 /98
VAC  :    /
CLAMP: OFF
RISER: DOWN
UTEMP: +25°C
LTEMP: +26°C
WARN : XY LIMIT
```

Fig. 6 M8-A main control screen

3) Take the M8-A out of calibrated mode by pressing the CALIB key, then the ENT key. The status window will indicate that calibration safety is off: the NO SAFETY icon will flash red on the monitor screen. It is critical that once the safety mode is in the Off position, the unit will be vulnerable to incorrect commands, which may lead to running the borescope/camera assembly into the lower chuck, causing damage.

4) The upper chuck is on a pivot (Fig. 7). Flip the upper chuck toward the operator, out of the way of the lower chuck.

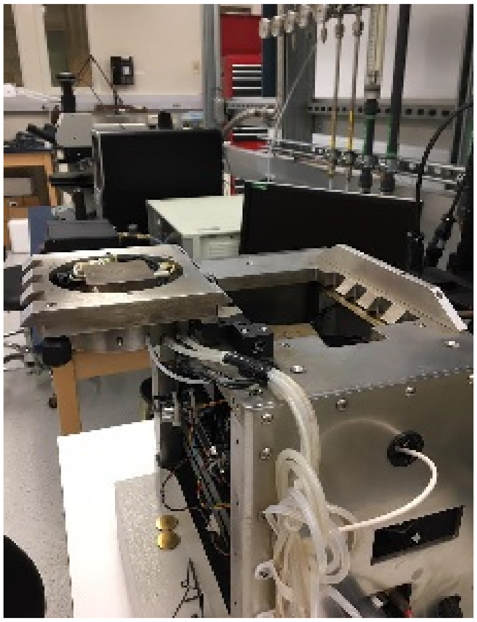
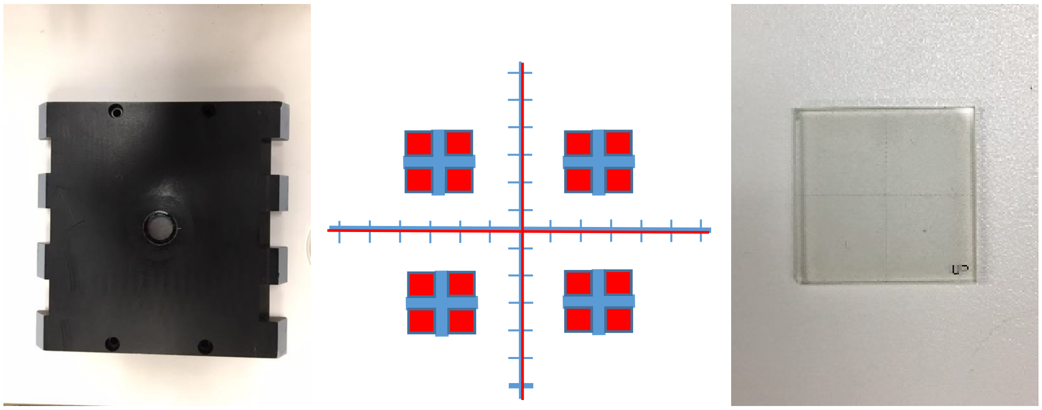


Fig. 7 Upper chuck pivoted toward the front in calibration mode

5) Reticles are used in the calibration and alignment operation. The patterns on the upper and lower target reticles are illustrated in Fig. 8. Prior to using the reticles (Fig. 8a and c), both the reticles and the chuck face plates must be cleaned with isopropyl alcohol using a lint-free cloth and blown dry. Use dry nitrogen to ensure the plates are free of debris so that there are no particulates between either the reticle faces or between the reticle backside and the chuck face.



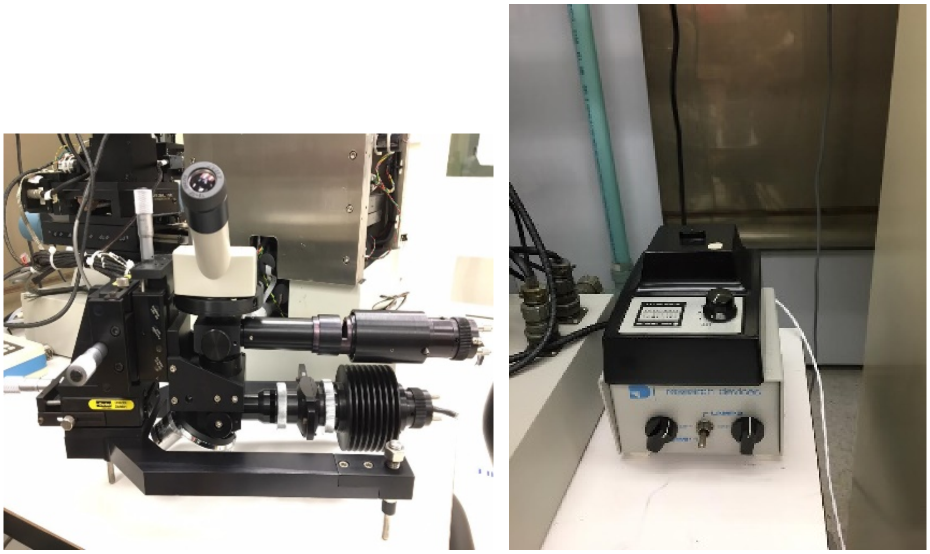
(a) (b) (c)

Fig. 8 a) Upper reticle plate, b) diagram of reticle pattern (upper reticle in blue and lower reticle in red), and c) lower quartz reticle

6) Place the lower quartz reticle onto the lower chuck, centering it on the vacuum hold-down ring, and press LoVac on the keypad. This toggles the lower chuck vacuum to On. The word Up etched into the reticle should be in the lower right corner. This reticle will have a box pattern for the crosshairs (four boxes), which will form an empty space in the shape of a cross.

7) Place the upper reticle mount (plate) into the right side of the upper slide frame grooves where the upper chuck usually sits, and slide the mount to the left as far as it will go (all the way to the left). Press Clamp on the keypad. This will close the clamp and lock the upper reticle mount into place. You should be able to see the lower reticle through the upper reticle if it is in the correct orientation.

8) Place the calibration bridge legs (three) into the appropriate holes on the top of the unit so that the optics eyepiece is directly over the upper and lower reticle fiduciaries. The lamp housing should be facing to the right (Fig. 9).



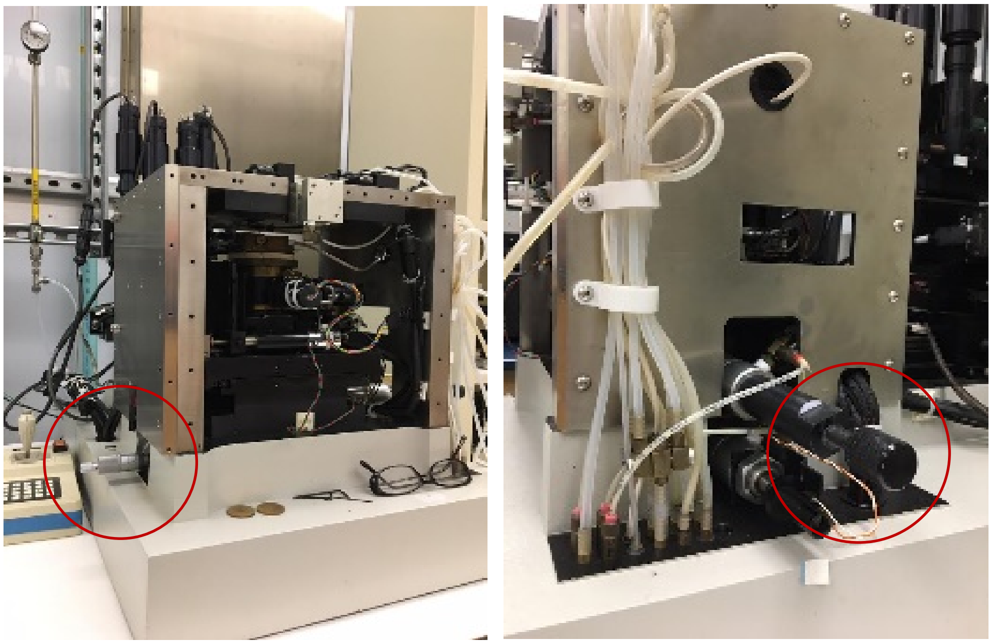
(a) (b)

Fig. 9 a) Calibration bridge showing the mounting direction, and b) light-control source located to the right of the M8-A bonder

9) Check to make sure the riser stop micrometer on the lower left side of the M8-A is at the black mark. This micrometer is the fine vertical for the lower chuck. Then rotate the side knob located on the right side counterclockwise until the lower chuck assembly is at its minimum height position. This is the course vertical knob (Fig. 10).

10) Press Riser key on the keypad. This will bring the lower chuck up. Looking into the M8-A, there should be a gap between the upper and lower reticles between 5 mm and 1 cm.

11) Raise the lower chuck using the left micrometer (turn counterclockwise) until the upper and lower reticles are about 1 mm from each other. Look through the upper chuck to the lower chuck and move the lower chuck crosshair to meet the upper chuck crosshair by using LO VAC on the joystick.



(a) (b)

Fig. 10 a) Fine vertical micrometer location, and b) course vertical knob location

12) Place the calibration bridge into the top of the M8-A, matching the bridge legs with the appropriate openings: one leg into the hole on the left of the upper chuck area and two legs into the holes on the right of the upper chuck area.

13) The lamp control for the calibration bridge is to the right of the M8-A. Lamp 1 is for the 40× objective, and Lamp 2 is for the autocollimator objective. Using the 40× objective and the x and y micrometers on the calibration bridge, look through the eye piece and center the upper chuck reticle crosses to the center of the viewing area. Focus the reticle image using the z micrometer. Moving the focused crosses across the viewing area, try to locate the lower chuck reticle boxes. The outline of the boxes and/or the crosshair will be barely visible. If they are not found, raise the lower chuck assembly using the left micrometer (counterclockwise) slightly and look again for the crosshair. Once the lower chuck reticle has been located, with the M8-A in LoScan mode, move the lower chuck reticle to match the upper chuck reticle at the centers.

14) Switch the 40× objective to the autocollimator objective. Switch from Lamp 1 to Lamp 2. Press the P/Roll key on the keypad. The screen will indicate that you are in Pitch and Roll mode.

15) Looking through the eyepiece, move the joystick and align the two crosses on top of each other. Press the joystick button twice when finished. This will toggle back to LoScan.

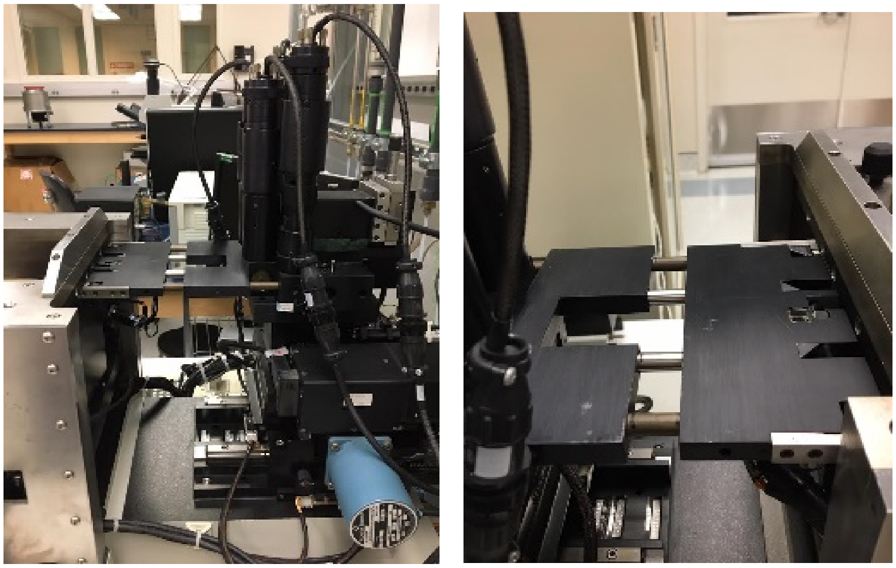
16) Rotate the 40× objective into place and switch to Lamp 1. Looking through the eyepiece, bring the lower chuck assembly up slowly until the reticle is in focus. Make sure there is no pressure registering on the monitor indicator. The reticles should be very close but not touching.

17) Correct theta by pressing Rotate (the screen will indicate that you are in Rotate mode) and, using the joystick, first rotate the lower chuck into parallel alignment with the upper chuck reticle, then press the joystick button, toggle to LoScan, and move the reticles into perpendicular and horizontal alignment. Toggle back to Rotate and repeat this sequence, moving the microscope out and away slightly from the center to get a better view of rotation needed on the lower chuck.

18) Once the rotation has been corrected, move the autocollimator objective into place and check on the parallelism between the two reticles. If the reticles are still parallel, move on to the next step. If not, correct the parallelism and check rotation and alignment again.

19) Lower the lower chuck by pressing Riser and turn off the lamp control.

20) Press Load/Align three times to move the borescope optics assembly into position between the upper and lower chucks (Fig. 11). At this point, the screen will indicate F Vert.



(a) (b)

Fig. 11 a) Optical assembly showing lamps and borescope with prisms, and b) close-up of borescope

21) Turn the Bausch & Lomb light-source control knob to position 2.

22) Press the joystick button until CAM SCAN (camera control) is indicated on the screen. The top reticle fiducials should be barely visible on the screen.

23) Press the Camera key on the joystick box until UP/ is indicated on the screen next to CAMRA:

24) Press the FOCUS key to control the camera optics, moving the borescope in the y direction (up and down) to bring the top chuck fiducials into focus. Be careful not to move the borescope up too far, as this will make the borescope plate run into the top reticle plate and will damage both the reticle and the borescope.

25) Press the joystick button and toggle to LoScan.

26) Press the Camera key again and this time toggle CAMRA: to /Low. This is to focus the lower chuck fiducials. The image on the screen will now show just the lower camera image, and the image is focused with the knob on the right side of the machine. This knob moves the lower chuck up and down. Focus the lower fiducials.

27) Press the Camera key again and toggle the CAMRA: to UP/LO to view both the top and lower chuck reticles—one on top of another. The top crosses should be centered between the lower boxes in each of the four corners.

28) If the crosses and boxes do not line up properly, the camera must be corrected. On the back of the machine, on the top and side of the camera, are small micrometers that correct for any anomaly in the camera image. The lower vertical micrometer located on the camera optics moves the camera image in the x direction, and the upper vertical (top) micrometer moves the camera image in the y direction. Align the crosses and boxes for the camera image (Fig. 12).

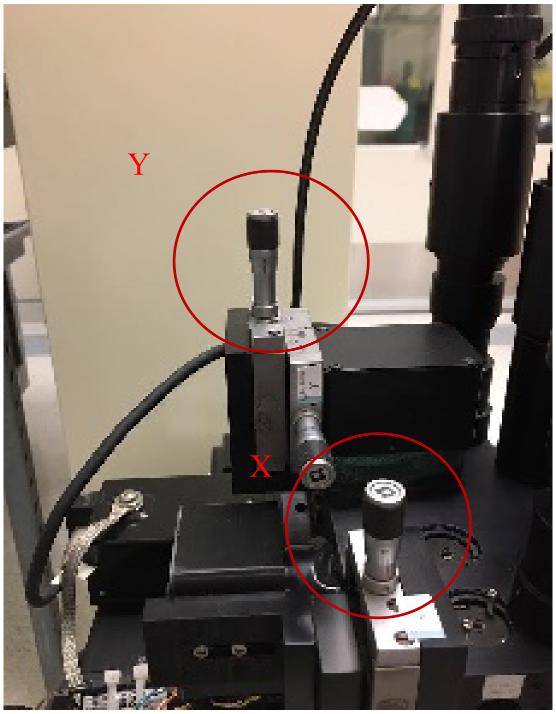


Fig. 12 X and Y micrometers on top of camera

29) Press the IL/COL key to locate the collimation crosshairs. The borescope will move slightly to a second set of prisms, and they should show up on the screen as overlapping crosshairs. If they are not aligned, press the P/Roll key, but DO NOT move the joystick. At this point, a prism adjustment will take place. Correction of the prism is very slight. Remember this is a camera image adjustment and not a lower chuck adjustment. On the right side of the camera housing is the collimator mounting. The collimators are the light sources for the crosshairs. Below the collimator on the right side is a small hole that leads to a 0.05-inch allen screw. There is another small hole in the back below the collimator light source. Turning these allen screws moves the lower chuck collimator prism, thus moving the lower chuck crosshair, which needs to align with the top collimator crosshair (Fig. 13.)

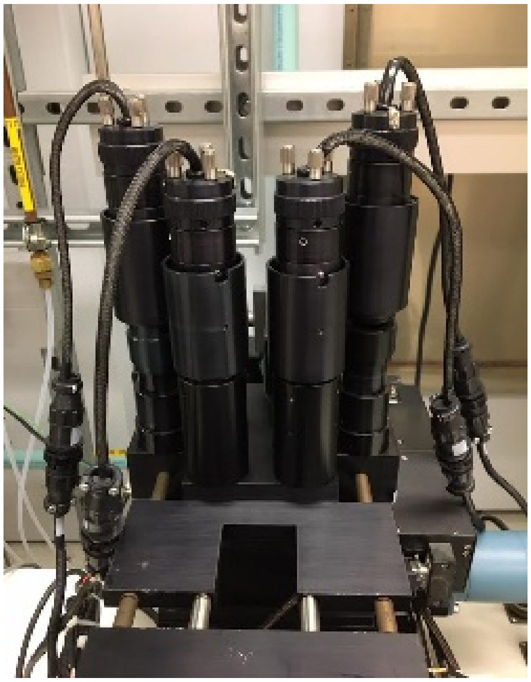


Fig. 13 Lamps for the borescope and camera systems

30) After correcting the camera image collimator settings, press the IL/COL key to toggle back to the Load/Align position with the borescope and recheck the camera image for reticle alignments and theta. If nothing has changed, move to the next step.

31) Move the borescope (camera optics) back to home position by pressing the Load/Align key.

32) Press the Riser key and bring the lower chuck back into position with the upper chuck assembly. Turn on the lamp control and toggle to Lamp 1. Check the x and y alignment of the upper and lower reticles. Check the rotation. Toggle to Lamp 2 and move the collimator objective into place and check the planarity of the reticles. If any of these positions has changed, redo the calibration. Remember that the camera must be in agreement with the alignment of the upper and lower reticles or correct hybridization cannot take place.

33) Turn off the lamp control to the calibration bridge.

34) Bring the lower chuck to its lower resting position by pressing Riser.

35) Remove the Calibration Bridge and place it in the cabinet to the side of the machine.

36) Rotate the left-side micrometer close to zero, and the right-side lower chuck knob counterclockwise to allow the lower chuck to come to its lowest position.

37) Press Clamp to release the clamp holding the upper chuck reticle in place. Slide the upper chuck reticle to the right and remove.

38) Press LO VAC to release the lower reticle from its vacuum hold on the lower chuck, and place in its box.

After completing the calibration procedure, press the CALIB key to apply the safety mode to the system. The monitor screen will indicate Safety On.

The M8-A is now ready to be used for hybridization of real parts.

2.2 Bonding Process for Hybridization of Real Parts

The M8-A is now calibrated and ready to accept a die and submount for hybridization. The following steps will vary slightly depending on the unique requirements for the parts to be bonded together.

Correct hybridization parameters for two parts include calculating an approximate force to be applied and, if used, heating for either one or both chucks. These parameters can be found through trial and error, but in general depend on the material the solder bumps are made of, the area of the solder bump surface, the heat applied (if used), and the total number of solder bumps being bonded. The Research Devices, Inc., M8-A Hybrid Bonder has a minimum force allowable of 100 g and a maximum force capability of 22,680 g (22 kg). It has a temperature range for both upper and lower chucks of 25–400 °C. One approach in determining the correct force for a specific bonding process is to measure the resistance between outside bond pads as an indicator of opens, good connections, or shorts. Another helpful tool in developing a correct bonding process is to engage a stud-pull apparatus that will give the force needed to pull the hybridized solder bumps apart.

For hybridization of smaller parts, brass fixtures are used to reduce the vacuum hold-down diameter. The height of these fixtures must be taken into account when bringing the lower chuck up to meet the upper chuck (Fig. 14).

1) At this point the upper chuck assembly is flipped backward toward the operator. Place a part over the vacuum hole on the brass chuck plate. Press the UpVac key to activate the upper chuck vacuum and secure the part.

2) Place the second part over the vacuum hole on the bottom chuck assembly and secure the part by pressing the LoVac key on the keypad.

3) Carefully flip the upper chuck assembly over and fit into the slots on top of the M8-A, then slide it all the way to the left against the mechanical stop. Press the Clamp key to lock the clamp into position.

4) **This next step is very important.** Looking through the front of the M8-A, visually ensure the optical (borescope) assembly will fit in between the two parts without incident. If needed, press CAMRA, FOCUS, and toggle to UP FOCUS. Using the joystick, move the borescope assembly vertically (either up or down) until you are sure the borescope can move in between the parts freely.

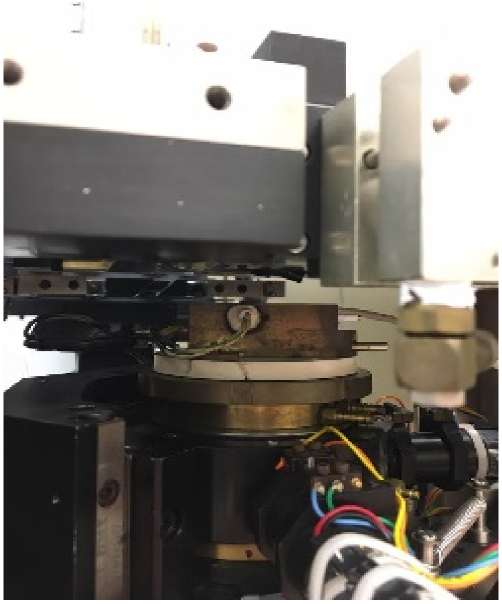


Fig. 14 Tight spacing between the lower chuck, the borescope, and the upper chuck

5) Press Lo/Al on the keypad to move the optical assembly from its resting (home) position to in-between the top and bottom chuck. This key will have to be pressed a total of three times. The optical assembly will move in between the parts mounted on the upper and lower chucks, and the parts will be visible on the monitor screen.

6) Press CAMRA on the keypad until UP appears on the monitor screen. This will turn on only the upper camera, and only the part on the upper chuck will be seen.

7) Focus the image on the screen by pressing FOCUS until UP can be seen on the screen. Using the joystick, focus the image. Remember that the optical assembly is actually moving up or down depending on the joystick motion, so care needs to be taken to not move the assembly too much or there is a danger that the optical assembly will run into the upper chuck.

8) Press the button on the top of the joystick until CAM SCAN appears. This will allow the camera to move around using the joystick, allowing the upper part alignment marks to be found. The upper part is stationary, so the part on the

lower chuck is moved to match up to the part on the upper chuck. When the first alignment mark is located, center the alignment mark on the monitor, then press GO TO followed by MEM A to lock in the alignment mark position. Search for the second alignment mark using CAM SCAN and, when located, press GO TO and then MEM B to lock in the second alignment mark.

9) Press CAMRA again until LO appears on the monitor screen. Focusing the lower part requires turning the knob on the lower right side of the M8-A (lower chuck "up and down"). Focus the part on the lower chuck.

10) Now press CAMRA until both the upper and lower parts are visible on the monitor.

11) Press the button on top of the joystick and toggle until LO SCAN shows up on the monitor screen. LO SCAN will move the lower chuck in the x and y directions. The part on the upper chuck will be stationary, so the corresponding alignment marks on the part held to the lower chuck will be moved into position with the alignment marks on the upper part.

12) Press GO TO and then MEM A to move the camera to the first saved alignment-mark position.

13) Align the marks at MEM A as well as possible, then press GO TO and MEM B and move to the second set of saved alignment marks. There will now be a theta (rotation correction).

14) Press the ROTATE key on the keypad; the monitor will say ROTATE. Moving the joystick in the y direction will correct the rotation of the lower chuck.

15) Press the joystick button to toggle back to LO SCAN and realign the two parts in the x and y directions.

16) Continue to repeat the correction of rotation and realignment until the alignment marks on the two parts are aligned.

17) Press the joystick button until LO SCAN appears.

18) After aligning the upper and lower alignment marks as best as possible, press IL/COL on the keypad to move the optical assembly from ILLUM to COLLUM. This is collimation mode for the camera. This will allow for pitch and roll to be corrected. Press the P/ROLL key on the keypad. Two crosshairs should appear on the monitor. Move the joystick to place the lower chuck crosshair on top of the upper chuck crosshair.

19) Press IL/COL to move the optical assembly back to illumination mode once this operation is complete.

20) Press the joystick button to toggle back to LO SCAN mode.

21) Realign the upper and lower parts after the pitch and roll correction.

22) Once the parts are aligned in the x, y, and theta directions and the pitch and roll is corrected, the optical assembly can be moved to its "home" position by pressing the LO/AL key.

23) The two parts are now ready to be hybridized.

24) Press CALIB to bring the M8-A back to SAFETY ON mode. This status will be indicated on the monitor screen.

25) Before raising the lower chuck, rotate the Riser Stop micrometer clockwise to the mark on the micrometer stem. This will limit the travel of the lower chuck and will prevent the lower part from running up and into the part on the upper chuck.

26) Press the RISER key on the keypad.

27) At this point, if heat is to be used, the programming needs to be changed. The following steps allow the operator to enter heating temperatures, if desired.

28) Press PRO on the keypad followed by AUTO. The parameters menu will appear.

29) To enter a temperature (other than zero), press 1 and the temperature will blink. Type the desired temperature and press enter. The new temperature will show up next to the upper chuck. Do the same for lower chuck. Press 2, the new temperature, and enter, and the new temperature will be displayed next to lower chuck.

30) To exit from the parameters menu, press the * key on the keypad. The chuck(s) will now heat up. There is a temperature indicator at the bottom right of the monitor screen.

31) Turning the Riser Stop micrometer counterclockwise will close the gap between the parts to be hybridized.

32) When the parts are coming into contact, the pressure (in grams) reading on the monitor will start to increase.

33) Slowly increase the pressure by either turning the micrometer counterclockwise slowly or by using the joystick while the system is in F VERT mode. This will move the parts into contact.

34) After contact has been made at the desired pressure, press LO VAC on the keypad to turn off the vacuum hold on the lower chuck.

35) Press RISER to bring the lower chuck down.

36) If there are no more parts to be bonded, the temperature in the program must be changed back to room temperature.

37) Press PRO on the keypad followed by AUTO. The parameters menu will appear.

38) Press 1 and the temperature will blink. Type the desired temperature, at this point 25 C°, and press enter. The new temperature will show up next to the upper chuck. Do the same for lower chuck. Press 2, the new temperature, and enter, and the new temperature will be displayed next to lower chuck.

39) To exit from the parameters menu, press the * key on the keypad. The chuck(s) will now start to cool down. At some point, a solenoid will open and nitrogen should start to flow through the system.

40) Press the CLAMP key on the keypad to release the clamp mechanism and slide the upper chuck all of the way to the right. Using the knob on top of the upper chuck, pull the chuck up and tilt it toward you. At this point the upper vacuum should still be on. Be careful, as the chucks and hybridized parts may still be hot.

41) Once the upper chuck is facing up, the upper vacuum may now be released. Press UP VAC key on the keypad to release the upper vacuum.

42) The hybridized part may now be carefully removed using tweezers.

43) To turn the M8-A off, lower the lower chuck to the lowest position using the course knob, turn off the light source control located to the right, remove the brass fixtures if they were used, and toggle the red switch in the back of the M8-A to the Off position.

3. Discussion and Results of Solder Bump Materials

Several images of hybridized die/submount components performed on the M8-A follow, as well as descriptive examples of a few of the different types of solder bumps commonly used in the hybridization of die to submount. For most of the industry there has been a movement away from lead-containing solders. The type of solder most appropriately used for specific flip-chip processes depends greatly on the chip/submount material being hybridized, the size of the bumps needed, and the pitch required. The most commonly used solder in industry for flip-chip is gold tin (AuSn), with an 80% Au and 20% tin composition by mass (eutectic alloy) and a melting point of 278 °C.[3] Another commonly used solder bump material is indium, which has the advantage over AuSn of being cryogenically stable, and its ductile property and low melting point (157 °C) means that it does not require the higher bonding force or high heat for good bonding.

Most metal solder bumps are typically heated (reflowed) in a hydrogen/nitrogen atmosphere, better known as forming gas. Reflowing in a forming-gas environment gives all of the bumps a uniform shape and removes the oxide crust on the bump, allowing bumps on the upper part to "meld" to bumps on the lower part. Flip-chip machines must be outfitted to do this. Unfortunately, the M8-A is not equipped to allow for reflow.

3.1 Evaporated Indium

Several different materials for solder bumps have been tested and used with our M8-A. The most commonly used material in our processes at the US Army Combat Capabilities Development Command (CCDC) Army Research Laboratory (ARL) has been indium. Bump technology includes a process used mainly for flip-chip hybridization of semiconductor components and has been part of the electronic interconnect process for over 50 years as part of a low-cost assembly process. The process involves vacuum deposition of indium bumps onto the active sites of the device die and corresponding submount. Because of its cryogenic stability, thermal and electrical conductivity, self-adhesive (ductile) nature, and relative ease of application, indium is a good material for this application: it is a soft, malleable metal with a melting point temperature of 157 °C. It is relatively inexpensive, can be easily added to a fabrication process, and has a relatively easy lift-off process.

In the evaporated indium bump process, the metal is deposited as the last step in the photolithography/metallization processing of a device wafer. A vacuum-thermal deposition of 300-Å chromium (for metal adhesion) followed by several microns of indium is completed; a metal lift-off is done; and indium bumps are the result (Fig. 15). The height and shape of the bumps are determined by the photoresist used and the mask design. Indium bump masks are designed for both top and lower parts. Both top and lower components are processed with indium bumps (Fig. 1), and, using a flip-chip bonder, the parts are either compression or thermo-compression bonded together. Bump area and the total number of bumps determine the amount of pressure needed for successful bonding. If a substantial amount of indium is being used (e.g., for thermal conductivity) thermo-compression bonding will be necessary. One formula used to calculate the force necessary for bonding is the following:

$$\frac{\text{Total number of bumps [\#]} \times \text{Area of each bump [µm2]}}{1{,}000{,}000} = \text{Force [Kg]}$$

This formula is courtesy of Dr Jonathan Schuster of CCDC Army Research Laboratory. The equation was developed for indium solder bumps bonded at room temperature (cold welding). It is suggested that using 110% to 130% of the force calculated gives a better estimate of the force needed to bond the parts.[4]

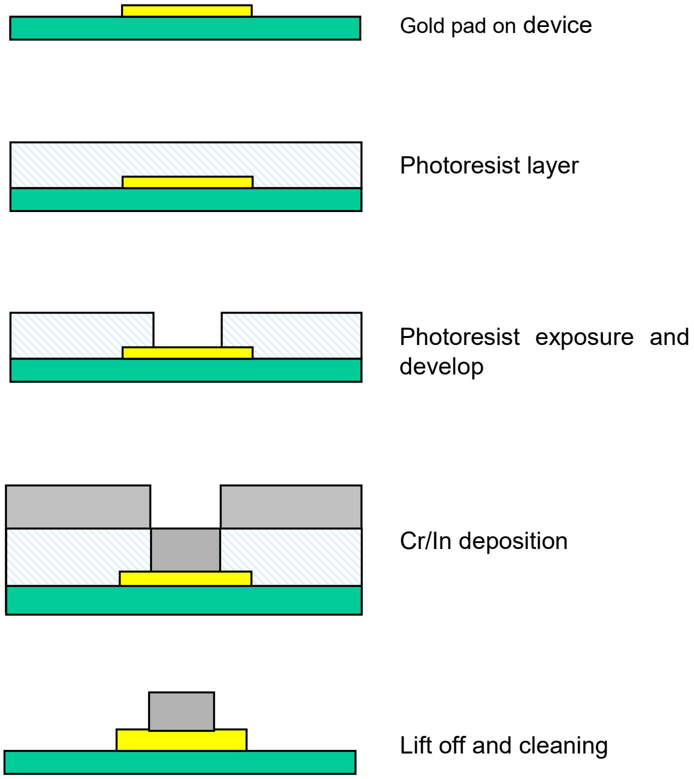


Fig. 15 Fabrication steps for deposition of indium bumps onto Au pads

In designing indium bump masks for the device and submount system, the indium bump masks for top and lower parts must be mirror images of each other for flip-chip bonding purposes. The mask design of the actual indium bump is variable. Because it is evaporated onto the wafer, the shape of the bump can be chosen to best suit the application. Round pillars, square pads, and ovals are some of the shapes of bumps used. The height of the indium is also variable simply by using a thinner or thicker photoresist and evaporating less or more material (Figs. 16 and 17). The following fabrication steps illustrate the process for forming indium bumps.

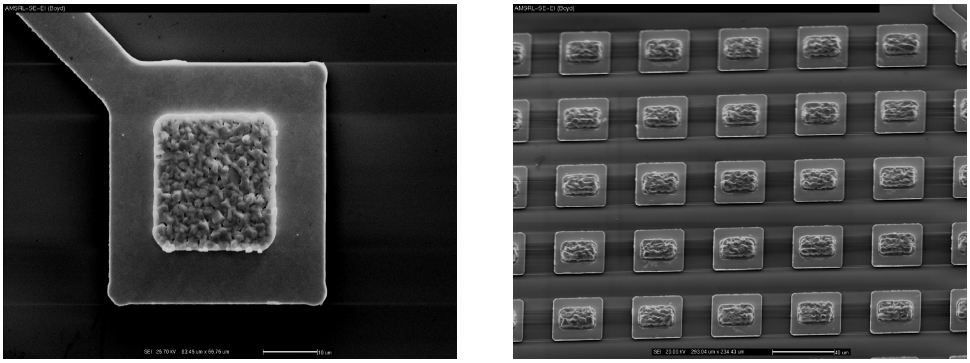

(a) (b)

Fig. 16 a) Scanning electron microscope image of a 20-µm^2 indium bump on a 40-µm^2 square Au pad, and b) 15 × 22-µm indium bumps on 30-µm^2 Au pads

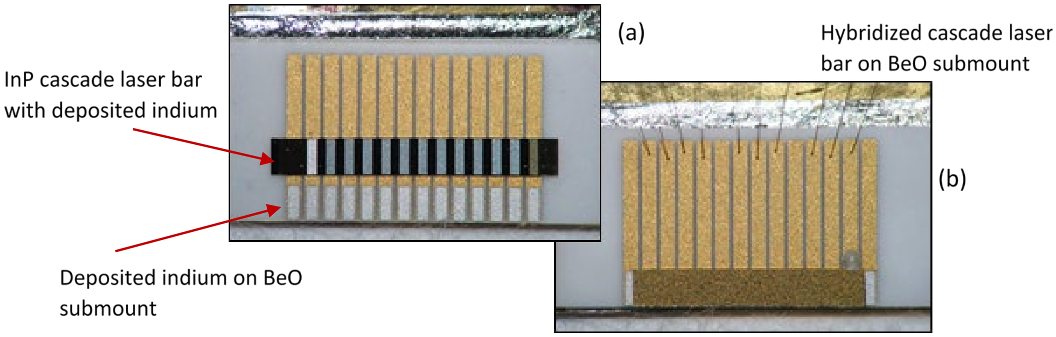


Fig. 17 Indium phosphide Cascade Laser bar and beryllium oxide submount with indium bumps on both parts: a) before flip-chip hybridization and b) after

3.2 Gold Tin

There are several reasons for choosing AuSn as a flip-chip solder material, one being it is lead-free. With a higher melting temperature (278 °C) and high thermal conductivity, it is a good choice for higher-operating-temperature devices. It has a low thermal coefficient of expansion and can be purchased as a preform in a variety of custom dimensions and thicknesses for ease of use. AuSn does not require flux and can be reflowed without the need for surface oxide removal.[5] AuSn flows best when the bonding pad underneath is Au-plated.[3]

One other advantage of AuSn solder is that it is reworkable, meaning that the attached die and submount can be reheated, separated, and rehybridized if needed.

Note that when reworking AuSn, the melting point of the solder will increase after the initial reflow, due to the change in the alloy's original composition as Au is consumed from the bonding pads. AuSn is also one of the more expensive solders due to the Au content.

AuSn solder bumps can be formed by vacuum deposition, can be purchased as preforms (Fig. 18), and can be deposited by electroplating Au and Sn in subsequent steps. When depositing by vacuum deposition, the alloy is purchased with the desired compositional stoichiometry, and the evaporation is performed at a slow evaporation rate. In electroplating, the Au is deposited first followed by the Sn, and after the plating process the bumps consist of a thick Au layer under a thinner Sn layer on top. To achieve the correct eutectic composition, specific thicknesses of both Au and Sn must be deposited. When the bumps are heated up to 278 °C (reflow) a solder cap forms that consists of the eutectic microstructure with the composition of 80%/20% Au/Sn by weight (Fig. 19). During flip-chip assembly the eutectic cap melts while the rest of the bump remains solid.[6] The Au layer and the eutectic solder cap are separated by a layer of intermetallic AuSn. This intermetallic can be a source of failure posthybridization.[8]

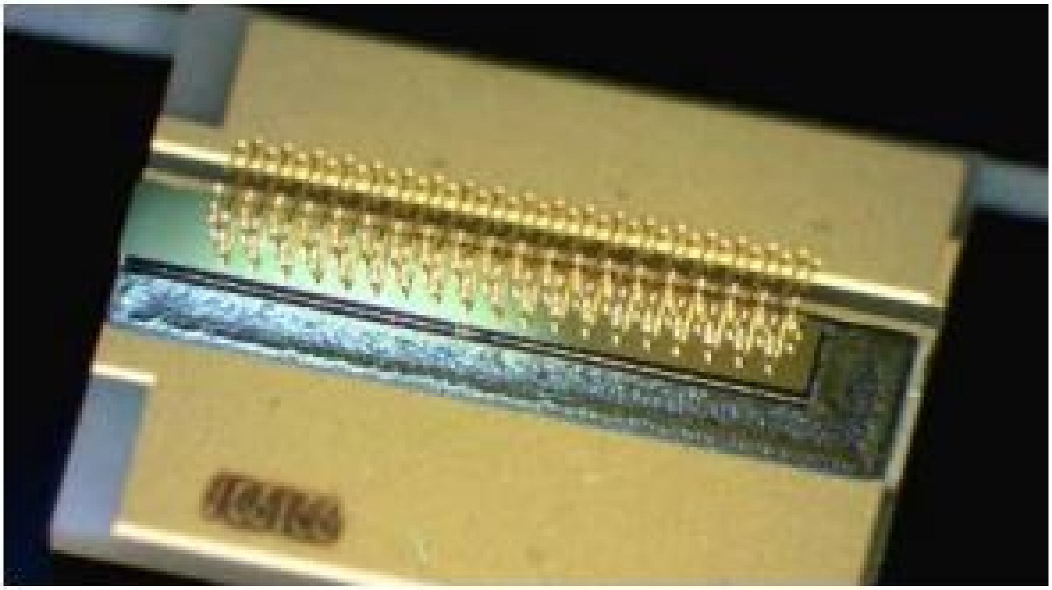
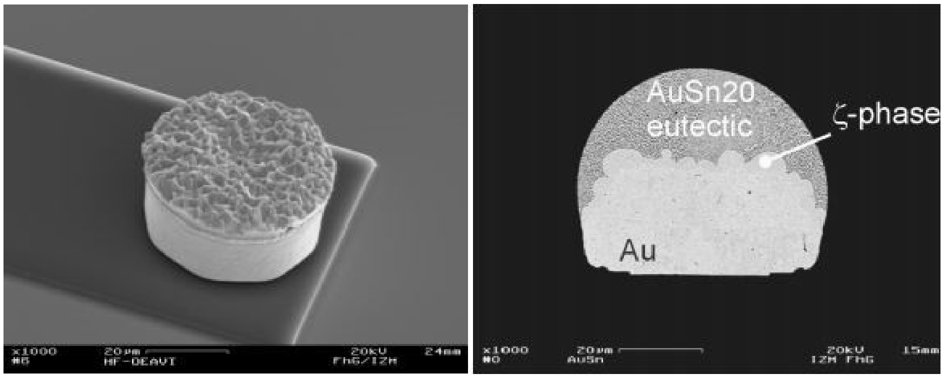


Fig. 18 Single diode laser solder-mounted with AuSn preform (Reprinted with permission of Prima Electro)



(a) (b)

Fig. 19 a) Electroplated AuSn solder bump prior to reflow, and b) AuSn bump post-reflow with separation of Au and eutectic AuSn components (Reprinted with permission of hermann.oppermann@izm.fraunhofer.de)

3.3 Electroplated Indium

Electroplating indium solder bumps is another method of depositing indium metal onto the parts to be hybridized. Both indium evaporation and electroplating require a photolithography step. Like vacuum-evaporated indium, openings in the photoresist pattern will fill with indium during the electroplating process. But in the case of electroplating, the indium is deposited via an electroplating bath with the indium metal source being the anode and an underlying copper (Cu) layer on the die and/or submount to be plated being the cathode. Indium ions are dissolved in the chemical plating solution (electrolyte) and are drawn to the exposed area in the photoresist. When the desired amount of indium has been electroplated onto the part, the photoresist is removed and the indium bumps are exposed. After the electroplated indium is cleaned, the indium is reflowed in an oxygen-free (forming gas) atmosphere and brought to 157 °C, where the indium oxide is reduced and the deposited indium forms hemispherical bumps. Electroplating indium is a less expensive alternative to vacuum deposition. One concern with this method is the grain size of the deposited indium metal. The electrolytic process must be finely adjusted to give the correct balance between grain size and rate of plating.

3.4 Indium Tin (InSn)

Indium tin (InSn) solder bumps have a lower melting point than indium alone and can be electroplated or electron beam deposited using a standard photolithography process and corresponding deposition method. Because Sn dissolves Au, nickel is used as the pad metal. Sn is deposited first followed by a deposition of indium. After the photoresist is removed, the metal stack is heated in a reflow oven using forming gas, argon, and an organic acid atmosphere, where the indium and Sn combine to create an InSn alloy with little oxide formation. This solder material is a good choice for array materials that need to be bonded at low temperatures since the melting point of InSn is 120 °C. The solder bumps are typically processed on the submount side so as not to heat the die.

3.5 Gold Stud Bumps

Another technique being used in research and industry for hybridization includes Au bumps, which require much higher pressure and/or heat to bond together—on the order of about 50 g per bump. The advantages of Au stud-bump bonding are its low inductance values, excellent electrical connectivity, and lower power requirements. The disadvantage is the higher bonding pressure and temperature needed to hybridize parts together.

Gold stud-bumping forms Au bumps using a process very similar to Au ball wire bonding. Like wire bonding, the process forms an Au ball (stud) on a metal bonding pad. However, once the Au ball adheres to the bonding pad, the wire is terminated after the first bond is made, so there is only an Au bump left on the pad (Fig. 20). Next, a coining tool levels the Au bumps to a uniform height. The die and submount are now ready to be hybridized.

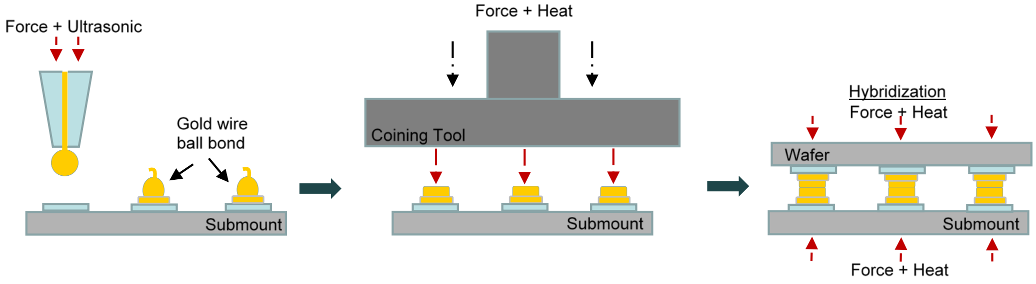


Fig. 20 Gold-to-gold "stud"-bump hybridization process

Gold stud bumps can be used on individual die or wafers and typically have much lower setup costs than a solder bump approach. The ability to bump individual die makes Au stud bumping an extremely valuable tool in the prototyping phase, as well as a viable option for volume manufacturing. For many sensitive devices such as lasers, microelectromechanical devices, and sensors, the use of flux or adhesives is detrimental, and so a thermosonic or thermocompression Au-to-Au attach process offers a reliable flux-free process while improving the device reliability.

Stud bumps with diameters of 40–100 μm can be produced with bump heights of 20–80 μm. Multistacked bumps can be used to increase the standoff distance between the die and substrate to help accommodate substrate thickness variations and minimize coefficient of thermal expansion differentials.

3.6 Tin Lead (Eutectic)

Electroplated eutectic tin lead (SnPb) solder bumps (Fig. 21) are used for mechanical strength of hybridized assemblies. The eutectic nature of the alloy means that the alloy solidifies at a single temperature, and this temperature is lower than any of the individual metals in the alloy. After a thick photoresist step has been performed, SnPb is electroplated onto nickel pad metal. After the deposition the photoresist is removed and the bumps are then reflowed using forming gas. Heat (183 °C melting point) is applied during hybridization.[7]

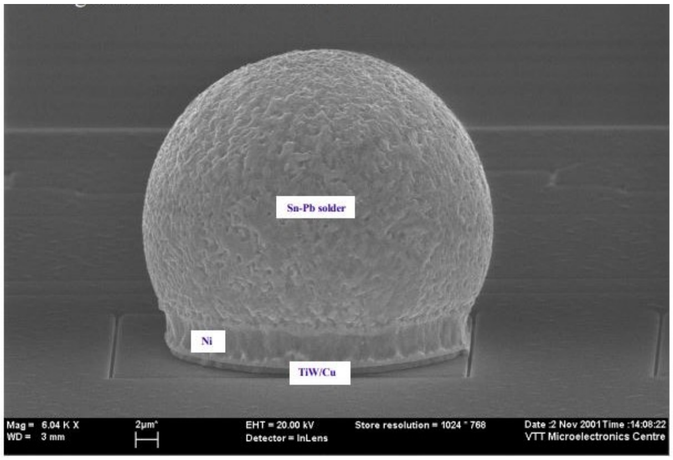


Fig. 21 Post-reflow SnPb solder bump (Reprinted with permission of J Salonen, VTT Microelectronics Center[7])

3.7 Copper Pillars

Copper pillars and solder micro-bumps are emerging as a standard flip-chip solder bump replacement in many parts of the semiconductor assembly industry, from standard chip-attach to power devices using flip-chip on a lead frame as assembly technologies.[9] Copper adds the benefit to a process by being a less-expensive alternative to Au-containing solder materials. Copper pillars are formed by first using a photolithography process, creating openings in the photoresist for the pillars to plate into. After openings are formed in the photoresist, a layer of under-bump metal consisting of a barrier metal (between pad metal and Cu bump) and an electroplating seed layer is deposited onto the surface. Next the Cu is electroplated and forms pillars where the seed layer is. Then, if desired, a solder cap—usually indium—is deposited. The photoresist is removed along with the excess metal, and the Cu pillars are left on the surface (Fig. 22).

There are several different electroplating methods used for the deposition process.

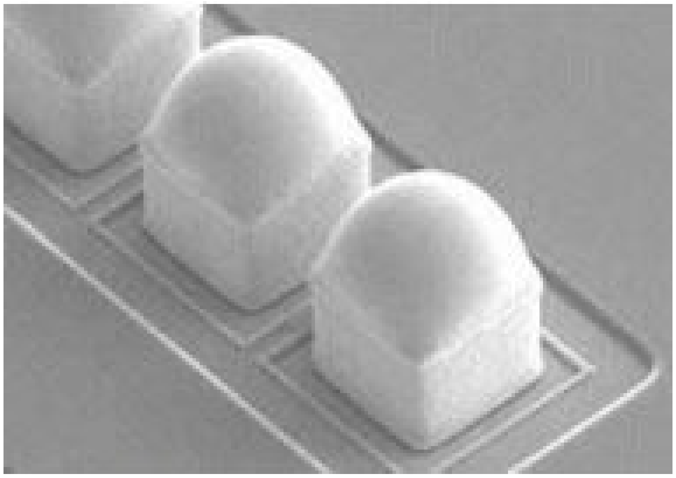


Fig. 22 Electroplated Cu pillars with solder cap (Reprinted with permission of Scott Jewler,[9] Powertech USA)

4. Conclusion

Flip-chip hybridization is a well-proven packaging technique used for the direct connection of processed device die to readout devices and submounts. A grid of solder bumps on the surface of the active area on the device die is joined directly to a corresponding set of solder bumps on the submount. One of the main advantages of flip-chip hybridization is that the very short electrical connections allow for lower lead resistances. Another advantage is that it is a robust, reliable technique due to the solder joint connections. The Research Devices, Inc., Model M8-A Flip-Chip Aligner Bonder located at ARL is able to provide a stable platform for repeatable alignment of a die and submount for the purpose of hybridization of those parts.

5. References

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List of Symbols, Abbreviations, and Acronyms

ARL	Army Research Laboratory
Au	gold
AuSn	gold tin
CCDC	US Army Combat Capabilities Development Command
Cu	copper
DCA	direct chip attach
InSn	indium tin
Sn	tin
SnPb	tin lead

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