High precision die bonding for photonics packaging

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ABSTRACT

Photonics packaging applications require significantly higher precision die bonding processes than traditional electronics and RF/microwave devices. Die placement accuracy of ±5 microns and better has been demonstrated. Key factors affecting the capability of placing die at accuracies of 5 microns in photonics packaging are discussed. Factors that enable high accuracy die bonding range from machine platform design to a combination of process parameters. Another key factor in die bonding placement accuracy is the quality of visual reference points or fiducials on the die, substrate, or surrounding package. Examples of good and poor visual references are shown and a discussion of die and package design is presented. A method of placement accuracy validation and a discussion of high accuracy die bonding applications are presented.

Keywords: Die bonding, eutectic, fiducial, photonics, packaging

1. INTRODUCTION

Historical die placement accuracy

Performance improvements and the advance of miniaturization in microelectronics has driven the need for higher placement accuracies for die bonding from 50 microns down to below 25 microns. RF and microwave packages often require even higher accuracy of 12.5 microns. Photonics applications present a unique set of challenges to die bonding machinery, as laser die applications require significantly higher accuracy than 12.5 microns to meet optical performance requirements. In order to meet the cost targets that are required to enable the deployment of next generation of optical networks, photonics packaging requires die bonding accuracies of ±5 microns and better with high throughput and yield. In order to attain this level of performance, many single mode laser applications require multiple active alignments for optical elements in addition to the laser chips, such as lenses, isolators, and fibers. Active alignments using optical signal feedback are time consuming, typically require additional equipment and signal feedback, and can adversely affect yield and assembly cost. If robust die bonding processes with accuracies of 5 microns and better are available at a reasonable cost, then cost effective packaging processes can be developed for the next generation of photonic components.

Challenges of photonics packaging

The challenges presented by photonics packaging are unique. Devices need to be placed with an even higher degree of precision. The optical path must be aligned to minimize the scattering of light and maximize the coupling of optical power into the fiber. While active alignments are frequently done at the final stages of assembly, precise alignment of the laser die and optical train ensures optimum beam quality and higher coupling efficiencies. Especially critical is the alignment of an edge-emitting laser to its submount. If the front edge of the chip overhangs the submount, the device will not properly dissipate heat into the submount, resulting in overheating and shortened device life. Due to high divergence angles, if the die facet is set back from the edge of the submount, the light signal will reflect off the submount.

Photonics devices are also smaller and harder to handle than traditional die. Thin solder performs must be oriented and delicately handled, which is tedious and costs cycle time. Diode arrays have very high aspect ratios and are made out of very fragile materials such as Gallium Arsenide and Indium Phosphide. Laser die create high heat loads, requiring high quality eutectic bonds instead of adhesive bonds. Also, all photonic packages must pass stringent performance and reliability qualification tests, which are intolerant of shifts in die position or degradation in device performance.

These precision requirements are the principal contributors to the high cost of photonics packaging. Wide deployment of next generation optical networks depends on order-of-magnitude cost reductions for photonic components. Die bonding processes capable of accuracies of 5 microns and below can reduce or eliminate costly active alignments and enable new, cost effective package designs with lower costs both in terms of bill of materials, assembly time, and yield. Achieving better than 5 micron accuracies can also enable many passive optical alignments with sufficient coupling efficiency to meet performance requirements. In fiber alignments for single mode devices, a placement accuracy of one micron equates to 3dB(50%) coupling. The alignment tolerances of various elements in multiple element optical trains require less precision, anywhere from 2-3 microns to 5-10 microns for acceptable optical coupling. Die bonding equipment capable of sub-micron accuracy is available, but at significantly higher capital cost. Also, sub-micron processes generally demand higher cycle times, often on the order of minutes, resulting in higher overall packaging costs. This paper describes the key factors which enable high precision die bonding with cycle times less than one minute, and accuracy in the range of 1 to 5 microns and shows a validation test process and data showing the capabilities of a die bonder with better than 5 micron accuracy.

2. Process and equipment for high accuracy placement

Process parameters

High precision die bonding generally requires tighter control of device and process parameters as well as more highly optimized processes. Process parameters that affect placement accuracy include tooling and collet design, inert gas environment, tool forces, and device heating. The proper inert gas environment is important to control oxides, which affect both bond quality bond shift. Gas flow over the parts can affect machine vision resolution, so care must be taken to ensure the gas flow does not disturb the die image. Gas flow rates need to be carefully developed to avoid thermal shock of the die or substrate.

Vacuum tools and pyramid collets must be designed for reliable and repeatable fixturing of parts in order to reduce placement error. Custom clamping tools may be necessary for small or irregularly shaped laser submounts. The tool must be able to exert a repeatable vacuum force strong enough to pick the parts from different sources, such as stretched wafers or new vacuum-actuated Gel-Paks. Magnetic parts, such as optical isolators, must be held firmly to overcome their affinity for the walls of a narrow Kovar package.

Control of heat at the workpiece is also important. The process for each high precision bond must be carefully developed in order to minimize time at high temperature, and to ensure that the correct values are set for dwell temperature and reflow temperature. Minimizing the time at reflow temperature reduces the likelihood that oxides will form. To reduce cycle time, it is desirable to have the capability of “fast ramping” from dwell to reflow temperature. Laser submounts and parts with high mass require carefully developed processes to ensure fully developed and reliable bonds.

Where many different components must be placed in the package, extra care must be taken to develop step soldering processes that do not cause reflow and shift previously placed parts. Often the laser die is placed first with a higher temperature solder to handle the high temperature and heat loads, so subsequent soldering processes must avoid spending excessive time at reflow temperature.

Equipment design considerations

Platform design is critical to high accuracy bonding because instability, unwanted movement or vibration will result in placement errors. Equipment parameters affecting die placement accuracy include the location of the linear encoders, the use of thermally stable materials with matched thermal coefficients of expansion, radially stiff handling of the gripper, theta encoder resolution, dynamic and static force control, and proper calibration.

Proper platform design must begin with the selection of materials that are dimensionally stable regardless of temperature and humidity variations. The use of granite or special polymers is effective to achieve this. The machine frame must be designed to match thermal coefficients of expansion between components to avoid relative movement. The robot or gantry should not be cantilevered in order to minimize force and wear on the robot that will lead to a degradation in performance.

Machine vision is especially critical to high accuracy placement. Illumination control, pixel size and choice of optics are fundamental to high resolution vision processing. Illumination must be controllable and adjustable so that the proper contrast can be achieved for fast and reliable vision processing. There are a number of approaches to achieving high accuracy using machine vision. Up-down viewing is one choice for aligning p-side down laser die. An optical probe can view features or fiducials on the down side of the die while also picking up features on the substrate.

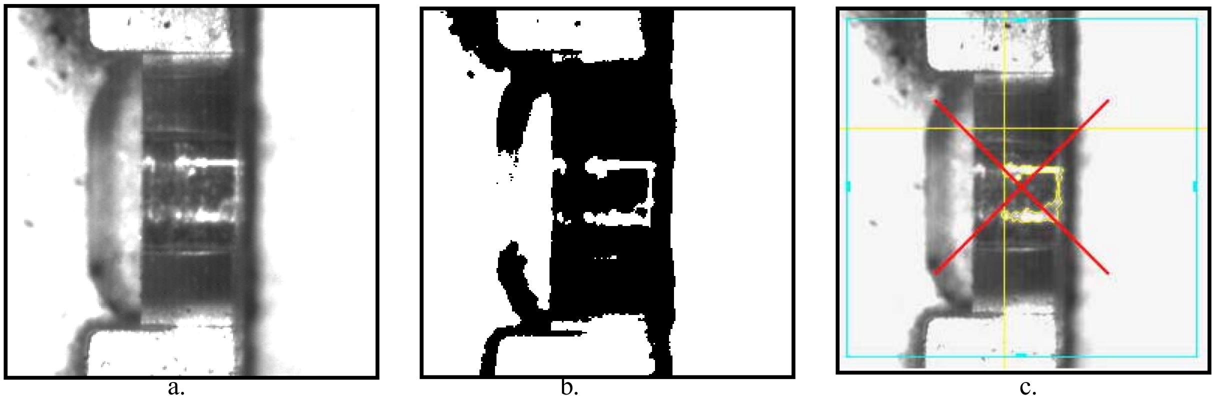
In photonics applications there is a need for distinct die features to act as fiducials and enable orientation and repeatable placement. These features must be precisely located relative to active areas of the die in order to enable precise placement. The vision system must be able to quickly find and align parts that are presented at random orientations. However, even a sophisticated vision system requires well defined visual references for successful high accuracy placements.

Die design, quality, and uniformity

One of the largest factors in die placement accuracy is the quality of the die or the component being placed. High quality eutectic bonds are required for laser die due to high heat loads that require excellent thermal contact with the substrate. This often requires a scrubbing process during the reflow cycle. Likewise, silicon optical benches have relatively large bonding areas, and require scrubbing as well. Pyramid collets are often used for eutectic bonding to allow for the scrub in X-Y or theta. The fit of the die into the collet is determined by the accuracy of the cut of the die. Though the bonding equipment can achieve high accuracy for the location of the collet, it cannot compensate for shift of die in the collet or lack of consistency in the location of the laser facet with respect to the die edges. Often, applications that require the highest placement accuracy are pushing the state of the art and thus do not have mature wafer fabrication processes which can offer better die for collet handling. Inconsistent die size also results from die separation processes such as the cleaving of wafers.

The finish of the part where the pyramid collet contacts is also important. Poor metallization can result in a shift of the part in the collet when it is picked up. The fundamental steps of the process are to image the die in the waffle pack, pick it up with the collet, image the substrate, and place the die. If there is a shift of the part in the collet due to surface finish, or if key features on the die are not located consistently relative to the die edge, there will be a placement errors. There are workarounds for this, such as moving the part to an upward looking camera and imaging the bottom surface, but this requires operator intervention and costs cycle time.

Other factors that contribute to placement accuracy include feature size and vision noise. Die features may be too small to practically process across a large selection of die. Package design also plays a role. Features on substrates need to be designed to give proper contrast under illumination to provide a proper reference for die or optical element placement. An example is shown below in Figure 1, where the edge of a GRIN lens used to provide a reference for placement of a laser die did not yield enough contrast because there was not a well defined edge. Changing the processing of the image by increasing contrast did not resolve the problem, as shown in Figure 1b. Operator intervention is then required to pick up the proper point on the edge. For this particular package, this problem was discovered during the process development and prototyping stage of package development, and changes are being made to the package design to create a crisper edge for better resolution of the corner feature as a fiducial.



a. b. c.

Figure 1. Example of poor alignment references on a GRIN lens in a package wall
a. Left image shows poor definition of GRIN lens edge; b. the middle image shows high contrast image modification fails to improve edge definition; c. right image shows machine vision failure.

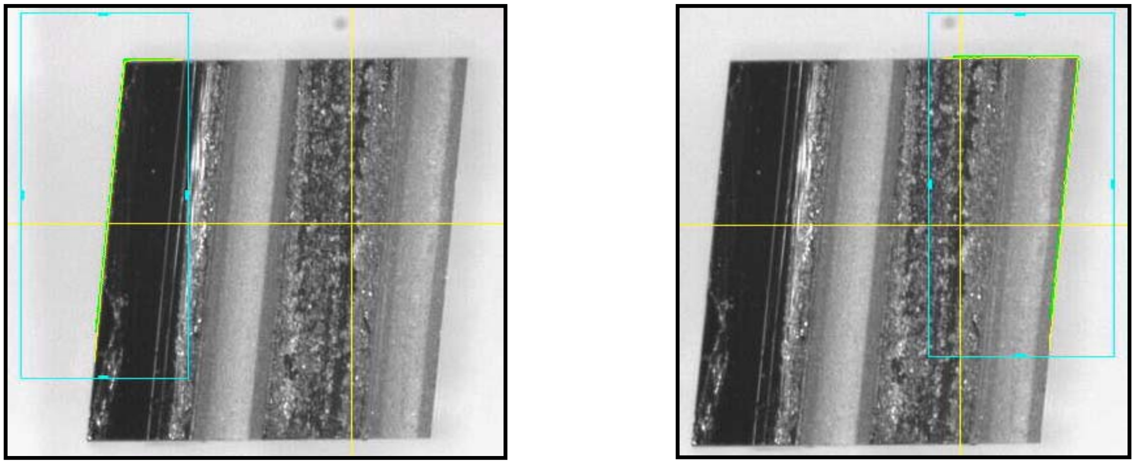


Figure 2. Examples of good alignment reference points on an isolator crystal

Perfect 90 degree corners are not necessary to create good visual references, as long as an intersection of two lines can be reliably resolved by the cameras and processed quickly without operator interventions, then the part can be accurately placed relative to other parts.

In summary, care must be taken up front during both device and package design cycles to ensure that visual references are easily resolved by the die bonder's vision system. Also, fabrication processes for die and optical components must be repeatable in order to enable high throughput, high yield assembly processes without operator intervention.

3. Experimental Results

Placement Test

The placement accuracy capability of a machine can be validated through the use of a glass die with well defined fiducials. Using a glass die eliminates the problems of the die/device/feature quality and inconsistencies described above, giving the engineers developing the machine a method for benchmarking and for calibration. This section describes the test set-up and results from such an experiment on the MRSI 5005 OPTO high precision bonder. The set-up is shown in Figure 3 below. The test process sequence starts with vision processing a glass die, then vision processing a substrate, then picking and placing the glass die on the substrate. Placement measurements are taken, and the glass die was returned to the substrate. The placement process steps were repeated with the glass die placed at 90º, 180º, and 270º. This cycle was repeated 15 time for a total of 60 data points.

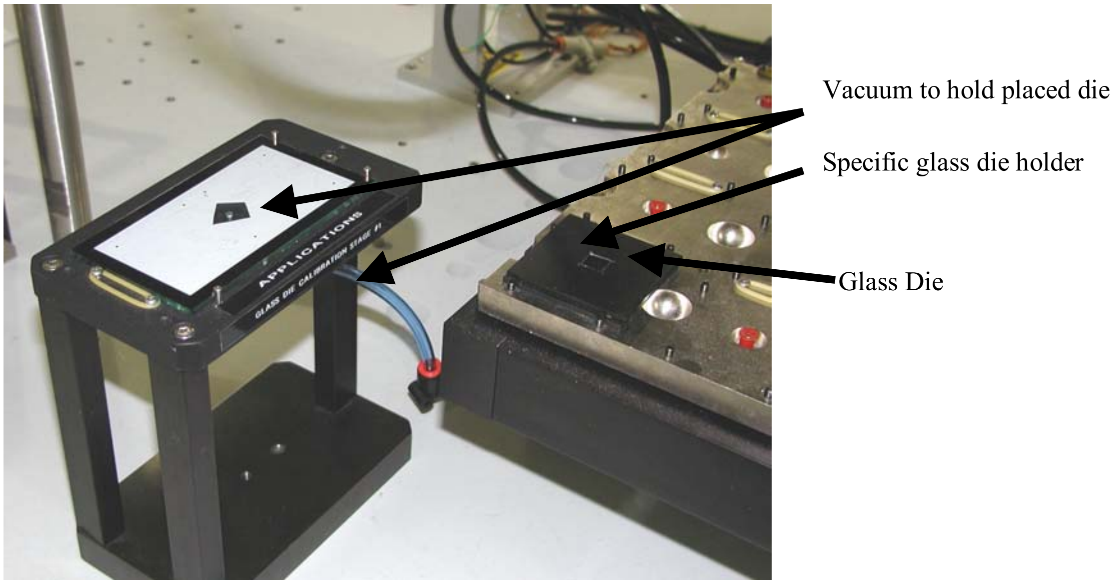


Figure 3. Set-up for placement accuracy test with stage for a glass die

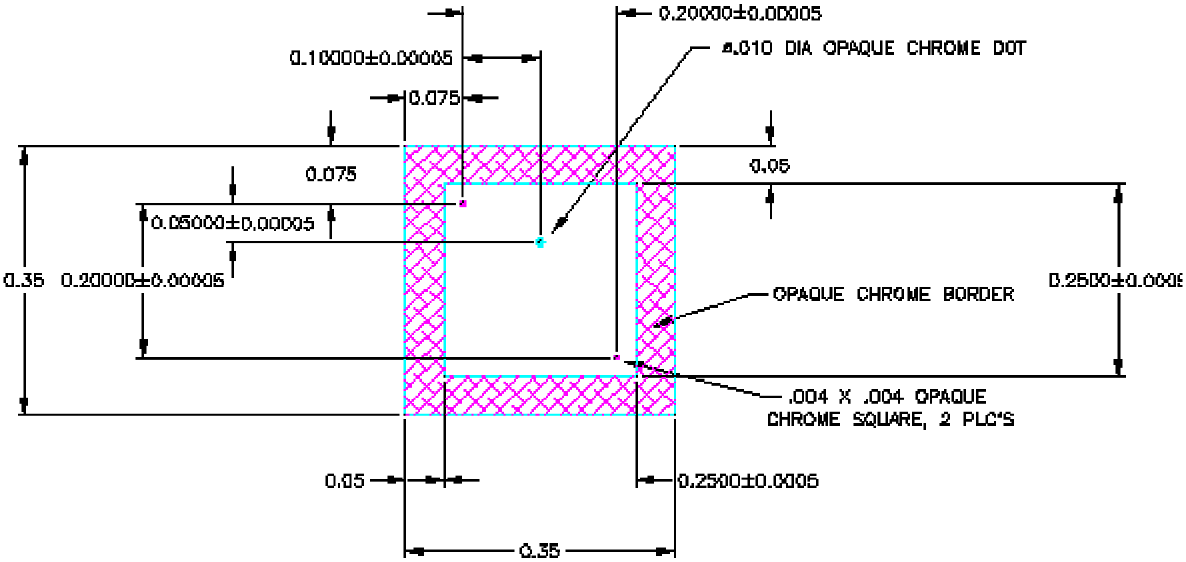


Figure 4. Glass die with two dots or fiducials to measure placement accuracy

A data summary is shown below in Table 1. The maximum, minimum, and average shift measurements were calculated for X and Y. The scatter plot of the data is shown in Figure 5. From analysis of the data, one sigma for both X and Y shift is between 1.6 –1.7, and three sigma for X and Y shift are both under 5 microns, showing that during this run the platform was capable of placing the glass die within 5 microns at 3**σ.** The cycle time for these placements ranged from 30 to 45 seconds.

Placement Data Summary		
	X shift	**Y shift**
max	2.8194	2.1844
min	-2.8956	-2.5400
ave	-0.4839	-0.0847
Range	**5.7150**	**4.7244**
stdev	1.6291	1.6632
3*stdev	**4.8873**	**4.9897**

Table 1. Summary data table

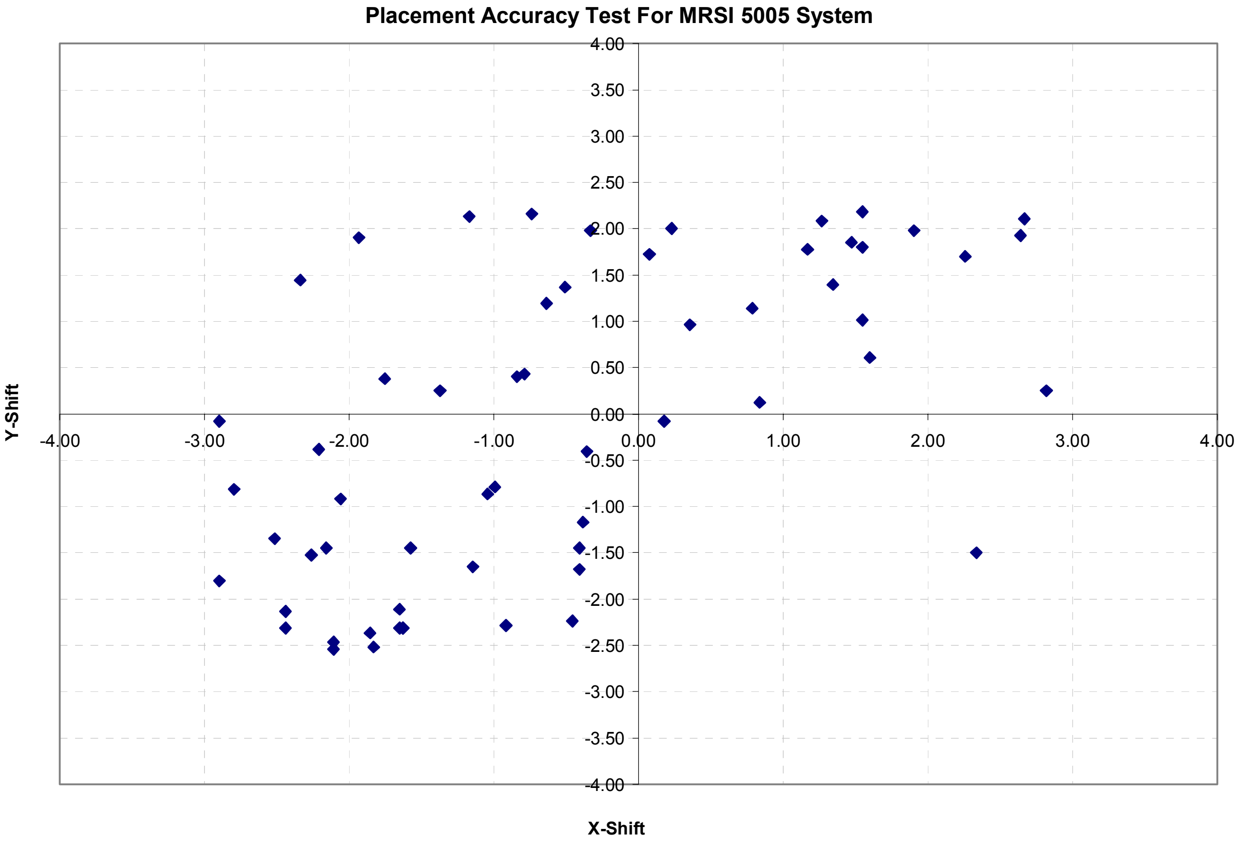


Figure 5. Placement accuracy scatter plot

4. Applications utilizing high precision bonding

The capability of sub-5 micron die bonding opens up some unique possibilities in cost effective packaging. New 2.5G and 10G directly modulated lasers and Raman pumps all require multiple optical elements for proper signal integrity and stability. High performance requirements have driven the need for active alignment of these multiple lens trains, resulting in high packaging costs. High accuracy die bonding processes can reduce both the bill of materials cost and the assembly time for these devices.

It is important to review the fully understand the alignment tolerance requirement for such devices before deciding which alignment can be performed passively. Table 2 below shows placement tolerances for the optical elements for a typical DFB optical train. This optical train comprises an aspheric collimation lens, a Faraday rotator isolator, and an aspheric focusing lens. This data was obtained by taking tolerance measurements of the positions of the lenses to determine what the effect of their misalignment on the ability to couple light into a fiber using one final active alignment.

Optical Tolerances for FW @ 95% peak power, in microns			
Component	X tolerance	Y Tolerance	Z Tolerance
Collimation Lens	15	15	2
Isolator	100-200	100-200	100-200
Focusing Lens	1	1	15

Table 2. Optical alignment tolerances for a sample DFB optical train to achieve 95% peak power

From the table, it can be concluded that with this optical train, performance in the 80-90% range can be achieved with alignment accuracies ranging from 1 to 5 microns. Optical trains using ball and GRIN lenses have looser alignment tolerances, but do not achieve the same coupling efficiencies. With sound package design utilizing substrate materials and lenses with clearly defined visual references, cost effective assembly using passive placement with die bonding equipment capable of 5 micron and better accuracy is feasible.

5. Conclusions and further work

Placement accuracy at 5 microns and below is achievable with the proper attention paid to equipment design, process development, package design and high quality parts from mature processes. Sub-5 micron processes can enable cost savings through automated pick and place as a replacement for traditional active alignment of some optical components. Further refinements to existing high accuracy platforms promise a roadmap to further expansion of this capability. The refinement of component fabrication processes and the design of easily resolved optical reference points, or fiducials, will enable the expansion of high accuracy die bonding and result in more cost effective packaging techniques.