Metrology and Defect Inspection Critical for Bonded Wafer Yield

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Three dimensional stacked integrated circuits (3DS-ICs) will provide many technological advantages in faster performance, lower power consumption, and smaller form factors. As continued shrinks in two dimensional chips become more difficult and expensive, vertically stacking the 2D chips allows more capability in the same or smaller form factor.

3DS-IC manufacturing processes utilize through silicon via (TSV) technology for 3D interconnect in wafer-to-wafer (W2W) bonding. Making a high-yield W2W bond has many prerequisites: exactly matched die patterns on both wafers (die-step and pattern offset from the center of the wafer), flat bonding surfaces, contamination-free bonding surfaces, and highly accurate W2W alignment prior to bonding. Contamination can cause voids, delamination, and other issues. Pattern offsets or overlay misalignment during bonding can cause failed or compromised electrical connections.

The 3DS-IC processes require monitoring, measuring, and controlling as many of these factors as possible before, during, and after the bonding process. Prior to bonding there are a number of metrology solutions available for single wafers, but post-bonding metrology presents a problem because device interfaces are buried inside the bonded wafer pair, and silicon is non-transparent to most metrology methods. A non-destructive, through-silicon metrology technique is required for monitoring a variety of post-bond parameters including:

- post-bond overlay alignment measurement
- bonding interface thickness variation
- bonding interface quality including pre- and post- bond defect inspection

There are several possible technologies available for through-silicon metrology including scanning electron microscopy (SEM), scanning acoustic microscopy (SAM), X-ray inspection, and infrared (IR) microscopy. However there are some limitations. SEM cannot image below the wafer surface and therefore is limited to samples that can be cleaved for cross sectioning or delayered to expose the structures of interest. This is a very time consuming process. SAM, though non-destructive, uses sound waves and requires immersion in water for transmission of the high-frequency acoustic energy to and from the wafer. Immersion in water introduces the possibility of contamination, even with post-immersion cleaning. Additional processing to seal the wafer at the edge to prevent water incursion between the wafers adds steps and cost to the process. X-ray radiation will offer high transmissivity through silicon, but has additional costs and security measures associated with the additional shielding required for safety.

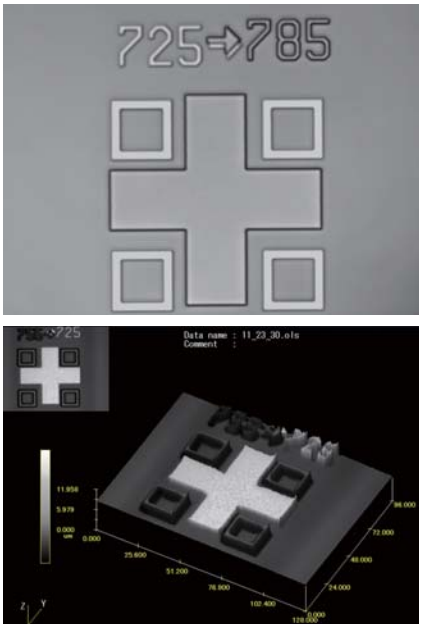
IR Microscopy for Metrology

Microscopy has long been used for inspection and metrology, but conventional visible light methods fail as silicon is non-transparent to visible light. Near infrared wavelengths do transmit through silicon and IR microscopy also offers a non-destructive solution for through-silicon metrology of the bonded interface. Confocal IR laser scanning microscopy offers the additional benefit of constructing 3D images, allowing measurement of feature heights and layer thicknesses of the bonded interface between wafers (**Figure 1**).

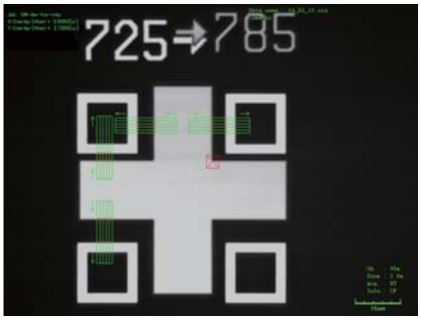
Overlay Metrology using IR Microscopy

During the bonding process, wafers are aligned to each other using fiducial marks on the top and bottom wafers. In Figure 1, the 2D image shows top and bottom wafer fiducial marks on a SEMATECH bonded wafer pair.* The bottom wafer (725 and boxes) and the top wafer (785 and cross) are aligned relative to each other prior to bonding. A perfect alignment would center the cross in between all four boxes.

Accurate alignment is required for good electrical yield of bonded wafers,



Figures 1a and b. 2D (top) and 3D (bottom) IR Images of Bonded Wafer Alignment Fiducials



Figures 2. Post-bond overlay measurement using IR microscopy shows an alignment offset of 0.5053¦Ìm in X and 2.7300um in Y

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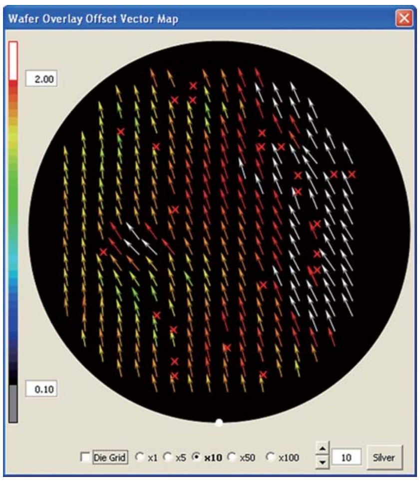
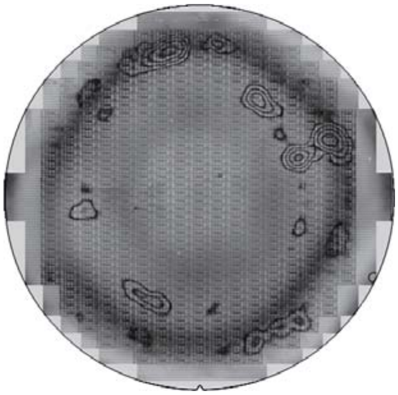
but a number of factors during the bonding process can influence the results of the wafer bond alignment (wafer slippage, heat, and pressure effects). Monitoring the immediate post-bond overlay alignment result is critical to manufacturing; if the wafers are not aligning well the yield will be impacted. Alignment issues must be detected early and resolved quickly or it will be very costly. The post-bond overlay alignment results can be measured using IR microscopy. **Figure 2** shows a post-bond overlay alignment measurement using IR microscopy.

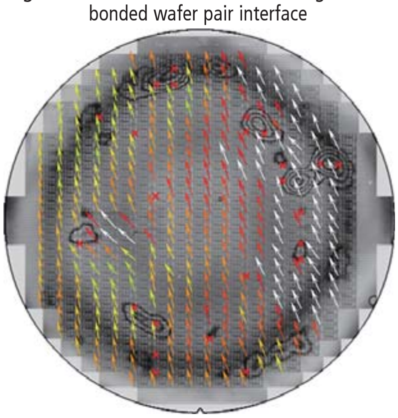
Post-bond overlay results will vary across each wafer. Automated overlay measurement of a broad sampling or all alignment points on a wafer can quickly characterize the overlay results as well as provide indications of bond quality problems. A recipe was set up to measure alignment points at each die of the SEMATECH bonded wafer pair. The data was tabulated in a spreadsheet for further review and analysis, and the overlay offset for each measurement point was plotted as a vector on a wafer map as shown in **Figure 3**, giving a quick indication of the wafer bonding result. Each vector gives the overlay offset direction and magnitude for each overlay measurement. A color scale is applied (left side) as an additional indicator of offset size: dark blue indicates an offset in the 0.2μm range, red indicates a 2μm offset and white indicates an offset > 2μm. Results for this bonded wafer pair shows that

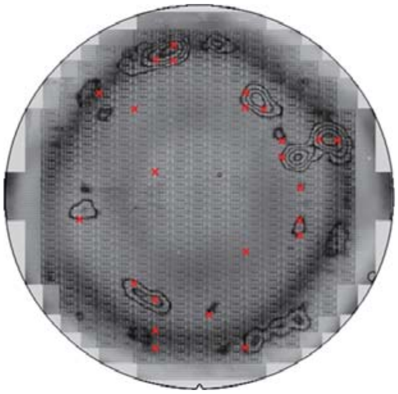


Figures 3. Post-bond overlay offset result as vector map



Figures 4. IR scanned and stitched image of the bonded wafer pair interface





Figures 5a and b. Overlay offset vector map superimposed on IR wafer scan

virtually all of the overlay offsets are >1μm, with many >2μm. If these wafers were using 1μm via structures, this bonded pair would likely have low yield due to electrical opens. By correlating electrical yield with overlay offset, IR microscopy can be used as an early indicator of electrical yield in bonded wafers.[1]

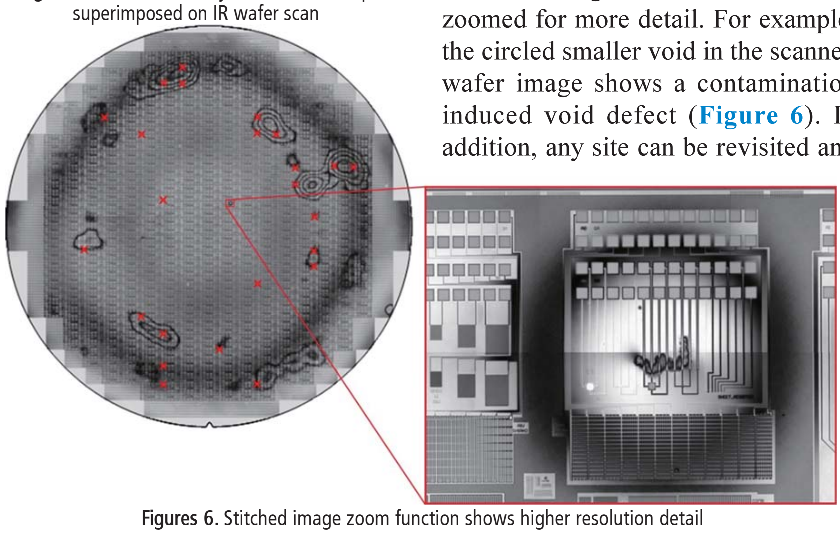
Note that the vector map contains some missing alignment points; these are failed measurements and are indicated in **Figure 3** with a red 'x'. These failed measurements show some grouping and may be indicative of some sort of anomaly in the bonded interface.

Bonded Interface Analysis

Using the IR microscope imaging capability, a recipe can be set up to automatically scan the wafer at low magnification. Software will analyze and stitch the images together into a single wafer image as shown in **Figure 4**. The IR wafer image shows some voids centered on defects and many of the characteristic topographical features that can be associated with bonding interface defects.

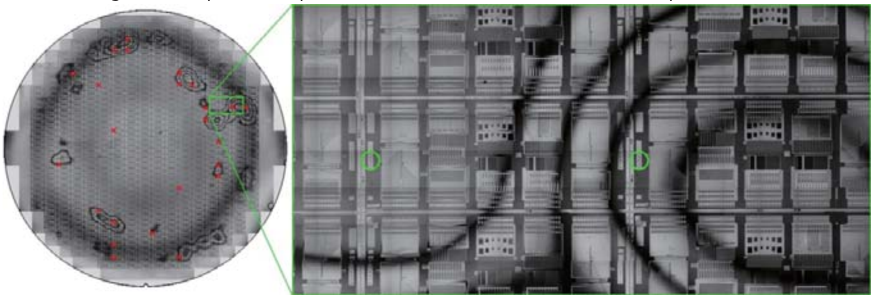
Superimposing the overlay vector map on the scanned wafer image (**Figure 5**), reveals the correlation of many failed overlay measurement points to bonded interface anomalies.

The stitched image is stored and available for further review and analysis. Because the wafer scan was done using an IR microscope, the stitched image can be viewed and zoomed for more detail. For example, the circled smaller void in the scanned wafer image shows a contamination induced void defect (**Figure 6**). In addition, any site can be revisited and



Figures 6. Stitched image zoom function shows higher resolution detail

Figures 7. XZ profile of top wafer and overlaid fiducial marks at bonded pair interface



Figures 8. Successful (left) and unsuccessful (right) overlay measurement points

the image reviewed or rescanned and imaged using the IR microscope with objective magnifications up to 90X and 0.14µm pixel resolution.

Thickness Metrology

Thickness metrology is more challenging and usually requires a technique such as SEM or focused ion beam (FIB) cross sectioning to obtain data. These methods come with high precision, but they are destructive and time consuming as the sample is usually sent to a lab for processing.

A microscope with confocal capability allows thin optical sectioning in the Z-direction, and is therefore very useful in constructing 3D images. An IR microscope with confocal capability can provide 3D images of the bonded wafer interface and structures as was shown in **Figure 1**. The 3D reconstructions can be used to create sections in the XZ plane to provide a measurable profile of an imaged structure or feature. **Figure 7** shows an XZ section of the fiducial marks at the bonded interface of the SEMATECH wafer pair at 50x magnification. The range of measurement in the Z plane was set to a large enough distance to cover the entire top wafer and bonded interface, and the step size between measurements was set appropriately to realize the desired resolution.

The IR microscope confocal functionality can be utilized to further investigate some of the anomalies indicated by the failed measurement sites on the wafer overlay vector map. These failed measurements could indicate voids or thickness variations at the bonded interface. Two adjacent measurement sites were chosen for an XZ profile. **Figure 8** (stitched image IR wafer scan) shows the two alignment sites: the left site is the successful measurement site; the right site is the failed measurement site. **Figure 9** shows the results of the XZ profile image of each fiducial mark and there is a clear difference between the two; the failed measurement site shows that the top wafer fiducial mark is raised above the bottom wafer. In other words, the bond interface is thicker at this point by 2.7µm; the fiducials have some additional separation. This difference in height between the fiducial marks is indicated not only by the failed measurement, but by the dark rings on the IR scanned image, created by the interference of diffracted light at the wafer interface.

Variations in height between sections of the bonded wafers, as can be seen between the top and bottom wafer fiducial marks, cause an improper autofocus and subsequently a measurement failure. There are software solutions to allow for overlay alignment measurement of fiducials on two different Z planes. In these cases, the overlay measurement will be successful and the difference in focal plane height can be recorded as indicators of different bond interface thicknesses.

Using the confocal capability of the microscope to take XZ measurements at various points on the wafer will provide information on the bond interface thickness uniformity.

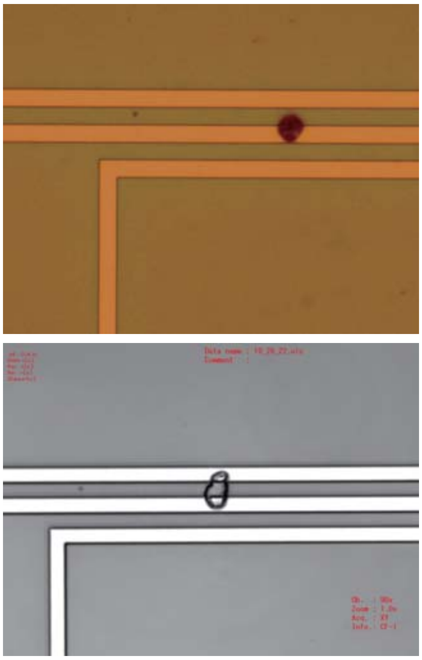
Defect Metrology

Contamination and other pre-bond defects can cause issues with the bonding process. IR microscopy allows review of pre-bond surface defects at the bonded interface after bonding. However, there are limitations as IR cannot transmit through some pattern materials. If the defect falls below a non-transparent pattern feature after bonding, it will not be visible to IR defect review.

Two examples of pre-bond defects causing a potential problem after bonding are shown in the contamination induced void (**Figure 6**) and the post-bonding short of two lines in **Figure 10**. **Figure 10** shows a pre-bond particle defect before bonding in visible light, sitting on one line but not causing a short. The post-bond IR image on the right shows the same defect after

Figures 9a. XZ profile of fiducials at a successful overlay measurement site

Figures 9b. XZ profile of an unsuccessful overlay measurement site, showing separation of top and bottom wafer fiducials



Figures 10. XZ profile of an unsuccessful overlay measurement site, showing separation of top and bottom wafer fiducials

bonding — the bonding process has compressed and enlarged the defect to short two lines.

In order to review known pre-bond defects after bonding, it's necessary to be able to read pre-bonded wafer defect files of both the top and bottom wafers. The top wafer defect file coordinate system must be flipped and combined with the bottom wafer defect file (**Figure 11**); then it's possible to navigate to pre-bond defect sites from either wafer and analyze the effects of the bonding process on the defects. Any new defects found can be imaged using IR microscopy at various magnifications and the new defect location and image information can be added to the combined defect file. Larger defects, such as voids, could optionally be rescanned at various magnifications using the stitching algorithms.

Conclusion

Technology has come a long way to accommodate Moore's law and the continued demand for miniaturization. 3DS-ICs using TSV technology are destined to help continue this trend not by shrinking, but by stacking vertically. Through-silicon metrology and defect inspection / review methodologies are required to help move 3DS-IC processes toward high volume manufacturing.

Presently, there are three areas of metrology methods that can aid in ensuring that the wafers are bonded correctly with vias properly aligned and connected. These methods are

- post-bond overlay alignment measurement
- pre- and post-bond defect inspection (voids, delamination, contamination, etc.)
- bonding interface feature heights, interface and substrate thickness variations

Traditionally these types of metrologies have been done on separate tools: IR metrology tools, SAM, SEM, X-ray. The costs associated with moving wafers through multiple pieces of equipment in terms of extra processing, time consumption, and added handling risks may outweigh the cost of the purchase and maintenance of the equipment itself. The metrology tasks discussed herein can all be achieved in a single SECS/GEM-compliant tool using confocal IR laser scanning microscopy.

References

1. Andrew C. Rudack, Pratibha Singh, J. Christopher Taylor, Vadim Mashevsky, "IR Microscopy as an Early Yield Indicator in Bonded Wafer Pairs used for 3D Integration", Proc. SPIE Advanced Lithography Conference, Jan 2010, San Jose, CA, paper #7638-39

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