Substrate Yield Enhancement Enabled by Advanced Packaging Metrology System

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Abstract

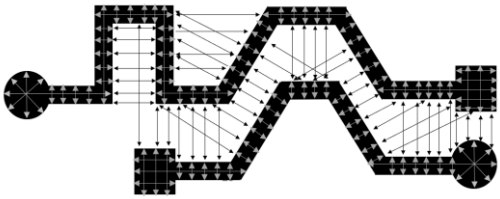
Detecting dimensional errors in substrate fabrication induced by the manufacturing process is a challenge for high-density substrates. Such detection is especially important in advanced substrates that incorporate high-speed impedance-controlled circuits where a small change in linewidth and spacing can impact circuit performance. A 100% metrology inspection system has been developed that can detect these dimensional errors and provide the data needed to correct these errors. The Beltronics system can perform up to 10-billion line width, line space and pad diameter measurements on a 510mm x 515mm substrate in 5 minutes, to an accuracy of 0.15 microns. This new system provides real-time feedback to enable continuous inline process control to monitor the sizes of all features on the substrate during the fabrication process. The system compares the dimensions of features on the substrate to dimensions from the original CAD data to detect and classify defects. This paper presents an overview of this new technology and explains how it can be used to detect machine dependent distortions, such as non-linearities in the lithography lens or direct write exposure system, and design dependent distortions resulting from etch rates varying as a function of feature size, shape, and metal density in the neighborhood of each feature.

Key words

metrology, process control, yield improvement

1. Introduction

To ensure functionality of multilayer substrate panels, manufacturers typically inspect each layer for defects prior to layer build-up. While this inspection helps to prevent the shipment of defective substrates, it does not prevent the creation of defective parts and scrapped products. If yields are low, additional parts need to be made and manufacturers must either absorb the cost of the additional units or increase prices to their customers. The Beltronics Mscan system is the first 100% metrology based inline production tool specifically designed to increase yields by enabling real-time process control. The system can perform up to 10 billion measurements on a 510mm x 515mm substrate in 5 minutes, to an accuracy of 0.15 microns. As compared to other systems which can only measure a limited number of features, the Mscan system measures every line, space, pad, and via on the entire panel to sub-micron accuracy and calculates the difference between each measurement relative to CAD data, as illustrated in Fig. 1. Measurement data is used to enable real-time process control and to detect defects.



- Minimum line/space, via: 2 µm
- Measurement spacing: 1 pixel
- Smallest detectable defect: 0.25 µm
- Measurement accuracy: 0.15 µm
- Performs up to 10 billion measurements in 5 minutes, to an accuracy of 0.15 µ.

Fig. 1- Example of measurements performed for 100% of the features on the panel

As an example, substrate measurement data can be used to:

- Provide real-time feedback to compensate for dimensional errors introduced by the manufacturing process. This expedites getting new substrates into production.
- Provide continuous inline process control to monitor the size of all features on the substrates to detect process drift, once the design is in volume production.
- Compare finished substrates to CAD data to detect and classify defects.

Fig. 2 is a flow diagram showing the measurement recipe creation and subsequent panel measurement extraction process.

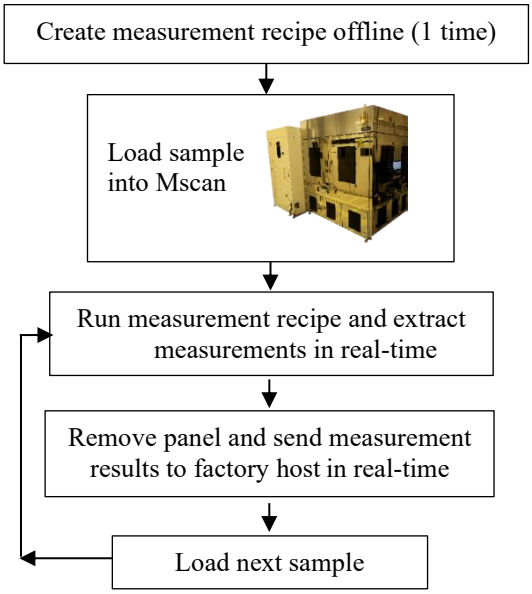


Fig. 2 - Mscan Measurement Flow Diagram

2. Theory of Operation

System Setup

1. CAD data is provided to an offline stand-alone computer station.
2. CAD data is automatically analyzed, and every trace, space, and feature in the CAD file is measured at 1-pixel increments (Fig. 3). A variety of pixel sizes are available ranging from 0.3 µm to over 1 µm to be used when scanning the panel.
3. A measurement recipe with up to 10 billion measurements is created and transferred to the Mscan system in advance of the panel being scanned.
4. A search region is defined and used to locate each feature when the panel is scanned (Fig. 4).
5. Time to generate the list offline is typically less than 15 minutes.
6. The time to transfer the measurement recipe to the Mscan system is less than 1 minute.

Performing the measurements

1. The panel is loaded from an EFEM into the Mscan and is optically scanned.
2. Fiducials on the panel are used for global alignment.
3. The Mscan automatically searches for and locates each feature in the scanned image.
4. Each feature is measured along its perimeter at 1 pixel spacing (Fig. 4).
5. Each individual measurement is compared to its corresponding measurement extracted from CAD data.
6. Measurements outside of a programmed tolerance are classified as defects.
7. Measurements within tolerance are used to provide linewidth and space statistics for process control.

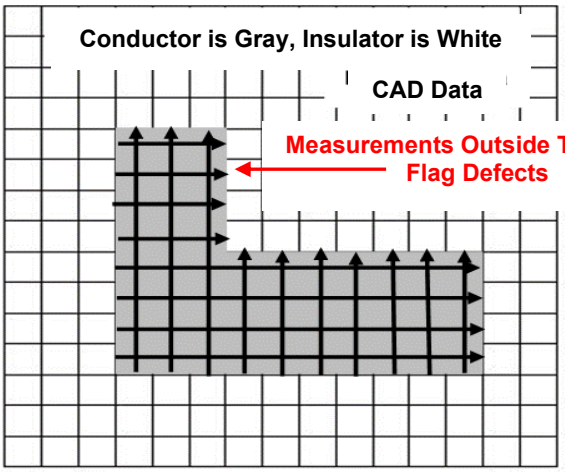


Fig. 3 - CAD Data

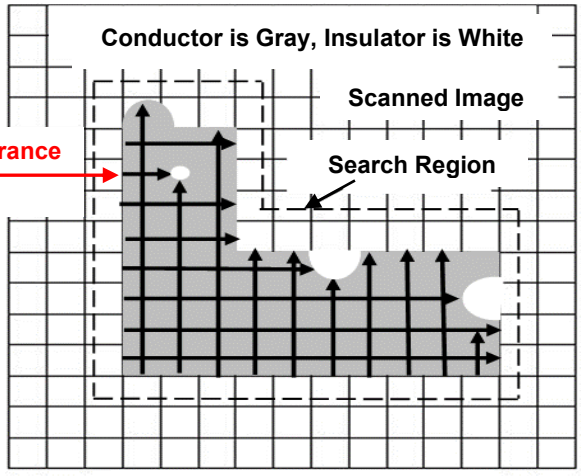


Fig. 4 - Scanned Image

If the sample being measured has high contrast conductors such as chrome on glass, white light illumination is used to scan the part and accurately measure trace width. However, when a conductor's surface consists of grainy metal, variation in brightness intensity and color can make it difficult to determine the location of the conductor's edges, as shown in Fig. 5, thereby limiting the ability to obtain accurate measurements.

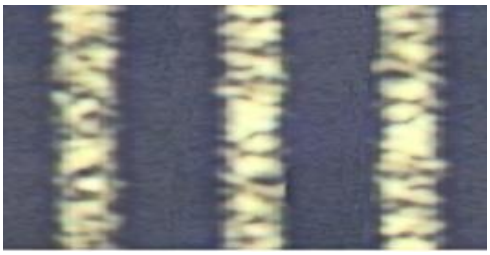


Fig. 5 - White light optical image of conductors with grain, texture and poorly defined edge boundaries

When the substrate is an organic material, fluorescent illumination is used to distinguish the non-fluorescing metallic conductors from the fluorescing organic substrate, enabling accurate measurements of trace width. In the fluorescent image of Fig. 6, metal which does not fluoresce appears black and the organic substrate which does fluoresce appears bright.

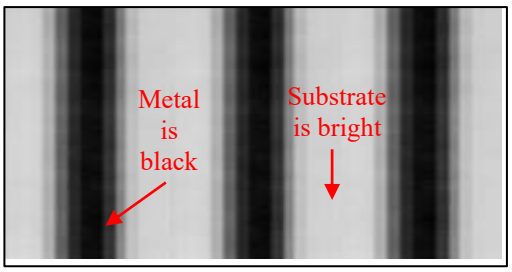


Fig. 6 - Fluorescent image with well-defined edge boundaries

3. Measuring Substrates With Shrinkage, Expansion and Warpage

Substrates are designed to tolerate a certain amount of pattern misalignment between layers due to shrinkage, expansion, and warpage during the manufacturing process. This is especially true for large thin organic substrates, frequently 515mm x 510mm or larger and 0.5mm or less in thickness.
Tolerance to layer misalignment is accomplished when the panel is designed by adding sufficiently large capture pads to ensure via connectivity between layers, should such misalignment occur, as illustrated in Fig. 7

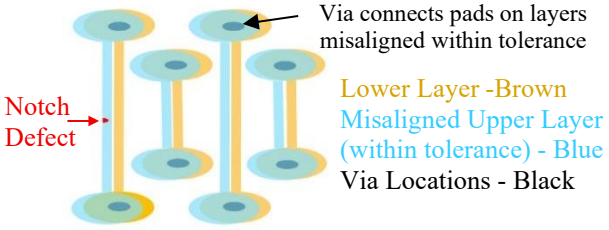


Fig. 7 - Example of pattern shifted within tolerance but with notch defect

Misalignment within the feature's tolerance is not a defect, but the notch shown in Fig. 7 is a defect. To measure such substrates, the Mscan system begins by searching for each feature within a programmable search range, relative to CAD data as illustrated in Fig. 8. Once the feature is found, the system accurately measures all linewidths, spaces, vias and identifies any defects.

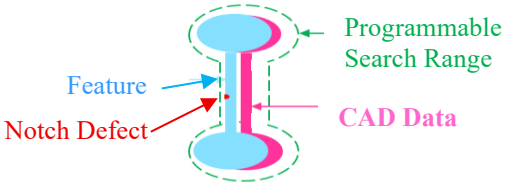


Fig. 8 - Example of pattern shifted within tolerance with notch defect

Figs. 9A and 9B are examples of a warped panel showing that misalignment within tolerance does not cause false calls or limit detection of the small notch defect.

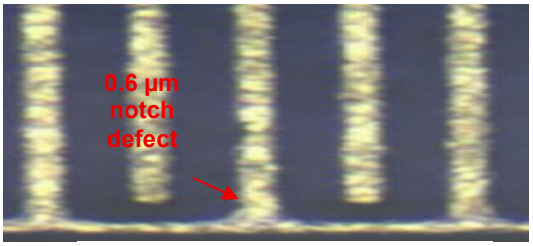


Fig. 9A - White light image

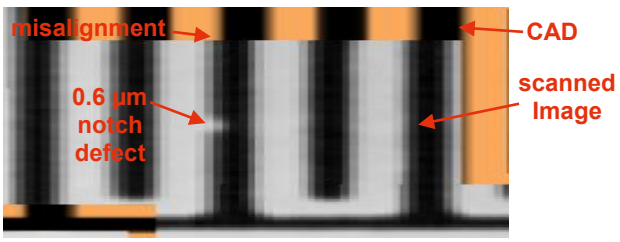


Fig. 9B - Fluorescent image superimposed over CAD

4. Calibration And Accuracy of Mscan Measurements

A chrome on glass test mask with line and space sizes ranging from 2 µm to 20 µm was used to calibrate the system. For each different line size, the center-to-center line spacing remained constant, but the width of the line was incrementally reduced in 0.25µm increments. For example a 4 µm line would reduce to 3.75 µm, 3.5 µm, 3 µm, etc. Each feature on the mask was measured with a scanning electron microscope (SEM) to determine its actual size with high precision. This high precision SEM data was used to calibrate the Mscan system. To evaluate performance in a production environment, a customer using one of their own panels performed the following verification of measurement accuracy:

1. A customer used a PRF-interferometer to manually measure linewidth at 740 locations on a 510mm x 515mm substrate panel. This took 2 days.
2. Mscan system scanned entire substrate panel (up to 10 billion measurements acquired in 5 minutes).
3. Measurements at identical 740 locations were extracted from the Mscan data.
4. The correlation coefficient between the Mscan data and the interferometer measurements is 0.98, as shown in Figure 10.
5. It was noted that the Mscan system measured width at the bottom of the trace, while the PRF-interferometer measured width at the midpoint. As a result, there was a fixed 0.5 micron offset between these two measurements. See Fig. 11.

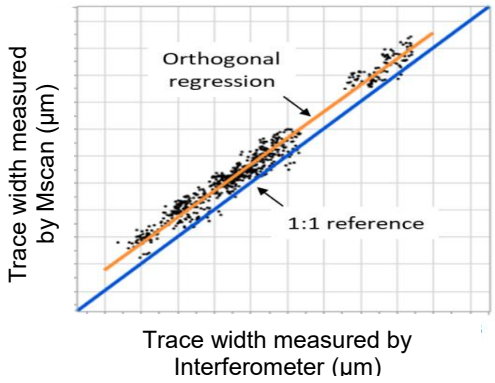


Fig. 10 Accuracy of Mscan Measurements compared to an interferometer

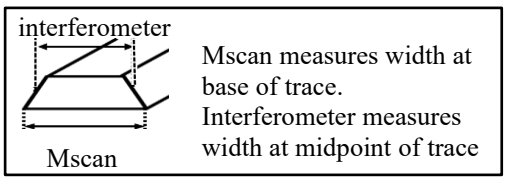


Fig. 11 - Explanation of the 0.5 micron difference

5. Statistical Data Computed From Mscan Measurements

To reduce the large number of measurements acquired (up to 10 billion), to a format that can be more readily utilized by the manufacturer to increase yield, each individual package site on the panel is subdivided into small subsection (typically 3 mm x 4 mm in size) (see Figs. 14, 15) and the following statistics are provided for each subsection:

1. Linewidth error for each different line size relative to CAD
2. Spacing error for each different space size relative to CAD
3. Maximum linewidth measured for each different line size
4. Minimum linewidth measured for each different line size
5. Standard deviation of linewidth measurements
6. Linewidth corresponding to: 10%, 25%, 50%, 75%, 90% percentile (i.e. 50% = median)
7. On drilled via substrates – the diameter, x axis offset, y axis offset, and center coordinate deviation from CAD computed for all the vias or pads in the subsection

Acceptable manufacturing tolerances can be set so that any measurement out of tolerance is reported as a defect.

For example, the conductor in Fig. 12A with well-defined edges will have a low linewidth variance. Whereas the conductor in Fig. 12B with rough edges will have a high measurement variance, indicating improper etching even though both traces are within the acceptable linewidth tolerance indicated by the red parallel lines to the right and left sides of each conductor. Providing such statical data in real-time enables immediate corrective action to be taken to maintain high yields.

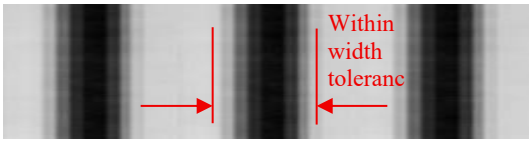


Fig. 12A - Conductors with good etch quality have low measurement variance

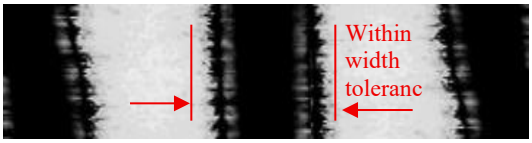


Fig. 12B - Conductors with bad etch quality have high measurement variance

6. Dimensional Errors Introduced by the Manufacturing Process

When manufacturing a substate for the first time, pattern dimensions typically do not match CAD data due to machine dependent, and pattern dependent dimensional errors introduced by the manufacturing process. To compensate for these errors, manufacturers often modify the original Customer CAD to achieve the specified pattern shape and size.

Machine dependent dimensional errors are caused by non-linearities in the lithography system. This results in feature sizes varying as a function of spatial position on the substrate [1].

Design dependent dimensional errors result from etch and plating rates varying as a function of feature size, shape, and metal density in the neighborhood of each feature [2]. Such errors can vary with the design of each layer.

Feature dimensions are especially critical in high-speed impedance-controlled circuits where small changes in linewidth and spacing can greatly affect circuit performance.

Figs. 13 and 14 are examples of machine dependent and design dependent errors in substrate dimensions measured on a 510 mm x 515 mm substrate by the Mscan system. Figure 13 clearly shows pad diameter decreasing by approximately 3.7 µm (from 51.5 µm to 47.8 µm) toward the perimeter of the imaging lens. Since this pad is the only size and shape feature on the entire panel, with uniform copper density in all 4 positions of the imaging lens, this change in diameter must be due to non-linearities in the lithography lens.

Fig. 14 is an example of a different substrate in which linewidths and line-spaces were measured for every trace on the entire substrate and compared to CAD data. Fig. 14 shows linewidths varying from -2.752 µm to +3.767 µm relative to CAD data due to design dependent distortions.

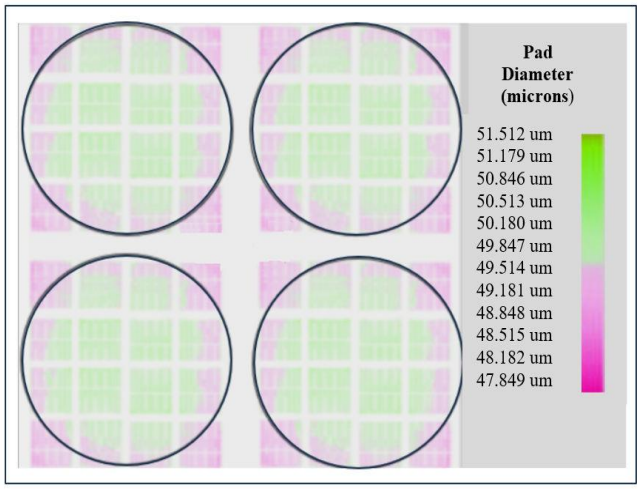


Fig. 13. - Machine Dependent Distortions. This simple example, with only one circular pad size in the CAD data, shows non-linearities in the lithography system with pad diameter size decreasing by approximately 3.7 microns toward the perimeter of the imaging lens.

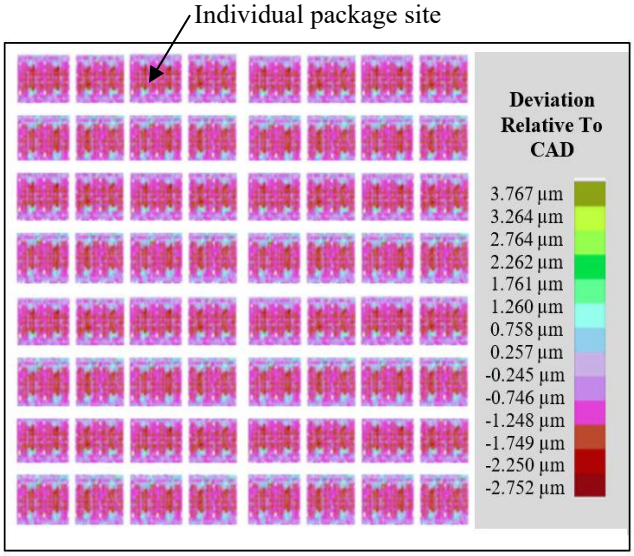


Fig. 14 - Design Dependent Distortions. In this example linewidths and line-spaces were measured along every trace on the entire substrate and compared to CAD data. Linewidths varied from -2.752 µm to +3.767 µm relative to CAD data due to design dependent distortions.

7. Compensating for Machine and Design Dependent Distortions

To compensate for machine and design dependent dimensional errors the following sequence of operations is performed:

1. The entire substrate panel is scanned.
2. Measurements are automatically extracted from the scanned image and compared to measurements extracted from the Customer CAD.
3. Differences between the measurements and Customer CAD are reported (Fig. 15).
4. A Production CAD is made to compensate for these differences so that the actual dimensions in the final manufactured substrate, produced using the Production CAD, agrees with dimensions in the Customer CAD.

As an example, Figure 16 shows the scanned fluorescent image of a trace superimposed over its corresponding image from the Customer's CAD. The horizontal section measures 10.08 µm, which is 1.92 µm smaller than the 12 µm width specified in the Customer's CAD. To make the Production CAD, shown in blue in Figure 17, Etch Bias is added to or subtracted from the Customer CAD to compensate for any differences. The result being that trace dimensions in the final manufactured substrate, shown in black in Figure 17, agree with those specified in the original Customer CAD, shown in magenta in Figure 16.

To demonstrate etch bias dependency on linewidth, etch bias was calculated to only correct for linewidth errors in the 2.5µm lines shown in Fig. 15. Prior to etch bias being applied, the 2.5 µm lines differed from CAD by approximately 0.45 µm, an 18% error. The same amount of etch bias was then applied to all the lines on the panel.

After etch bias was applied, the 2.5 µm lines varied relative to Customer CAD by only (+0.005µm to +0.093µm). However, with the same amount of etch bias applied to the 11.999µm lines, they still had errors ranging from (-1.132µm to -1.250µm), with an average error value of -1.191µm. If an etch bias of +1.191µm were now to be applied to all lines on the panel to compensate for errors in the 11.999 µm lines, the 2.5µm lines would incorrectly be increased to 3.691µm. Therefore, the amount of etch bias applied to each different line size needs to be independently calculated.

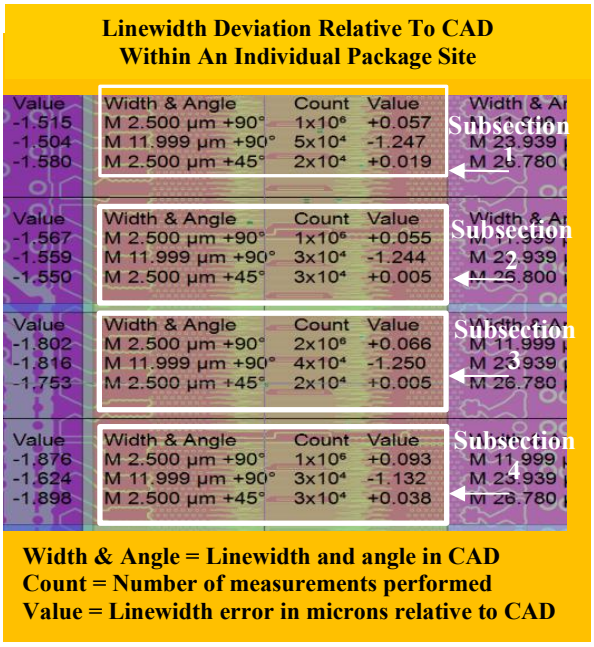


Fig. 15 - Each package site on the panel is divided into subsections and measurements are computed and reported

Being able to rapidly create a Production CAD greatly expedites getting new substrate designs into production.

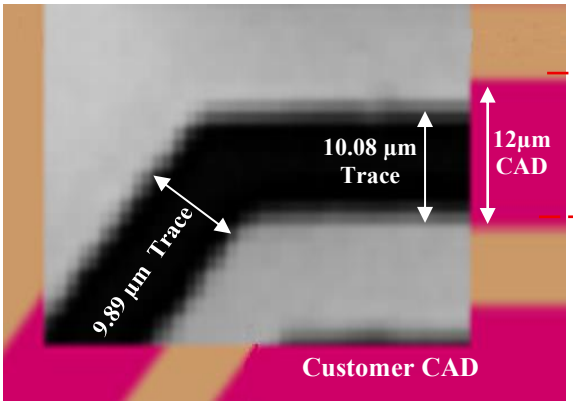


Fig. 16 - Trace Width Too Small When Manufactured Using Customer CAD

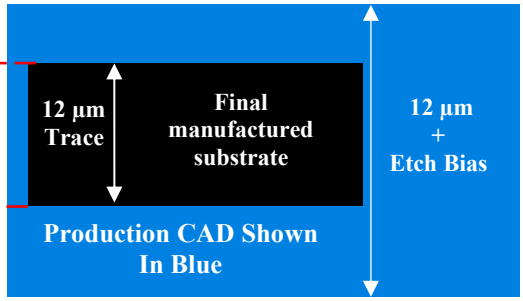


Fig. 17 - Etch Bias Is Added In Production CAD To Create Correct Linewidth In Manufactured Substrate

For substrate panels with impedance controlled traces that must be held to tighter tolerances than other conductors on the substrate, the Mscan accepts a separate CAD file or layer in the Customer CAD to indicate the location of such traces.

8. Summary and Conclusions

The Mscan is a 100% metrology based measurement system. Figure 18 summarizes all the functions performed and process control information provided by the Mscan in 5 minutes 14 seconds for a substrate 515mm x 510mm:

1. Substrate panel (18-2) compared to Customer CAD (18-3).
2. Linewidth and space measurements computed for every feature on the panel (18-4), up to 10 billion measurements performed.
3. Feature measurements beginning to drift out of tolerance (not yet a defect but deviating more than a specified amount from its specified CAD value) reported in real time (18-5) to enable immediate corrective action to be taken.
4. Measurements out of tolerance reported as defects (18-6) with pictures and coordinates (18-7).
5. Impedance controlled traces (18-8) held to tighter tolerances (18-9). Out of tolerance traces reported (18-10).
6. For substates or layers with drilled vias: center coordinate of vias provided to enable alignment of the next layer (18-11).

The measurement data provided from the Mscan can be used to:

1. Produce a Production CAD to compensate for dimensional errors introduced by the manufacturing process. This expedites getting new substate panels into production.
2. Provide continuous inline process control, to monitor the size of all features on the substrates, once in production. This provides essential information to maintain high yields.
3. Compare finished substrates to CAD data to detect and classify defects.

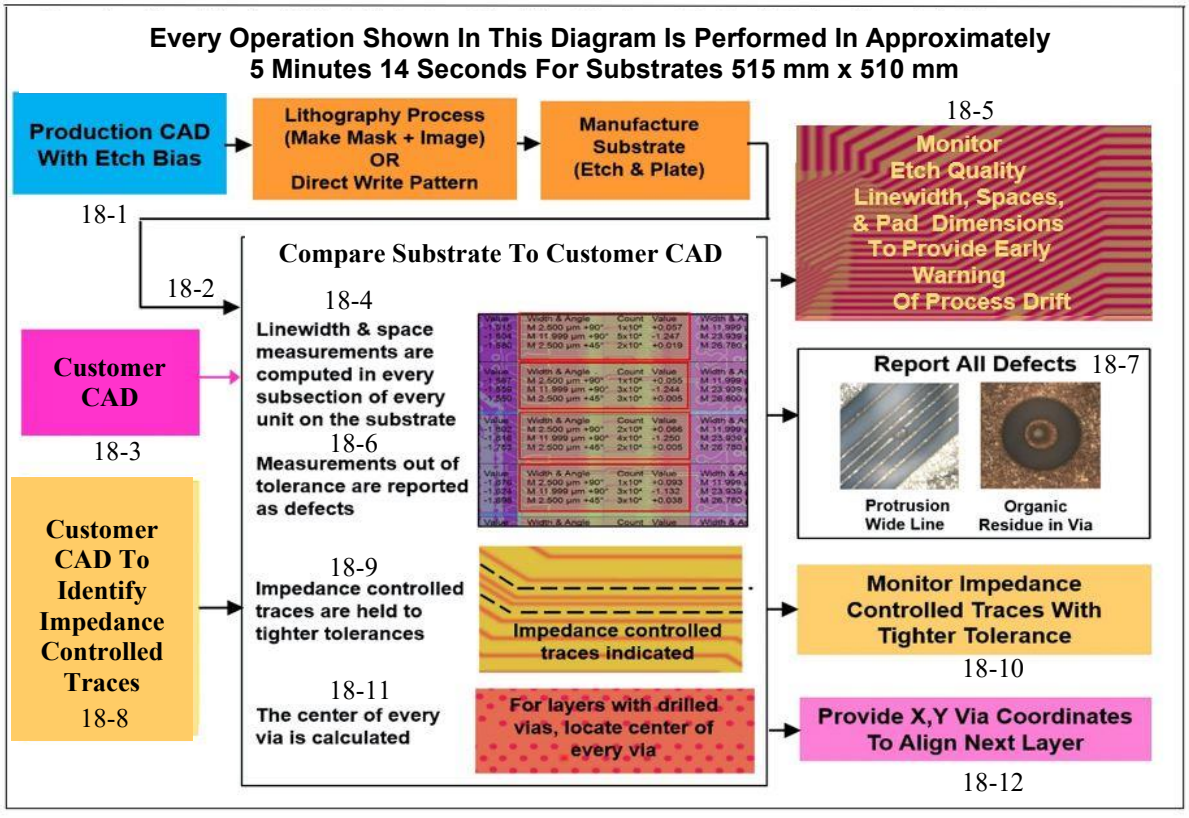


Fig. 18 - Mscan Block Diagram

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