FASTER TIME TO ROOT CAUSE WITH DIAGNOSIS-DRIVEN YIELD ANALYSIS

GEIR EIDE, PRODUCT MARKETING MANAGER, MENTOR GRAPHICS

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ABSTRACT

ICs developed at advanced technology nodes of 65 nm and below exhibit an increased sensitivity to small manufacturing variations. New design-specific and feature-sensitive failure mechanisms are on the rise. Complex variability issues that involve interactions between process and layout features can mask systematic yield issues. Without improved yield analysis methods, time-to-volume is delayed, mature yield is suboptimal, and product quality may suffer, thereby threatening a manufacturer’s profitability. Diagnosis-driven yield analysis is a methodology that leverages production test results, volume scan diagnosis, and statistical analysis to identify the cause of yield loss prior to failure analysis. This methodology can reduce the root cause cycle time with 75-90%. The methodology can be expanded with DFM-aware yield analysis to help separate design and process related yield limiters. This whitepaper describes the benefits of implementing a diagnosis-driven yield analysis flow using the Tessent® Diagnosis and Tessent YieldInsight® software products.

INTRODUCTION

While allowing for higher transistor counts, nanometer scaling inhibits the path toward high sustainable yields. At process nodes of 65 nm and below, systematic defects can contribute to more than 75% of the overall yield loss [1]. While design for manufacturing (DFM) promises to improve yield, manufacturing test and failure analysis (FA) remain at the forefront of determining why and how chips fail. Defective devices offer a goldmine of information and can provide valuable insight into defect mechanisms impacting or limiting yield.

Figure 1 shows the key components of a traditional yield analysis process. Data from the fabrication process and coarse test results are used to separate devices failing from systematic issues from those with random defects. Devices with similar fail modes are grouped together, and representatives from each group are selected for physical failure analysis (PFA), where the root cause is determined. Corrective action such as a manufacturing process change, design change, or containment can then be taken.

Figure 1 - Traditional yield analysis flow
One challenge facing IC manufacturers as feature sizes shrink, is that a larger portion of systematic defects appear spatially random. Separating random and systematic issues therefore becomes more complicated. As a result, PFA may be wasted on devices not exhibiting the systematic issues. To compensate, PFA has to be performed on an increasing number of devices. In parallel, the cycle time and cost in analyzing each individual device are skyrocketing with larger design sizes and smaller transistor sizes. On top of that, access to process data becomes challenging as companies transition from being IDMs to fabless and fablite.

Scan diagnosis is an established methodology for defect localization. In a traditional yield analysis flow, diagnosis is used together with physical localization techniques, as shown in Figure 1. Leveraging structural test and test results, it is commonly used as part of the FA process. Traditional diagnosis tools, however, do not extract sufficient information for effective yield analysis. Yield management systems (YMS) continue to prove useful in visualizing data from a variety of sources, but are not designed to process and analyze diagnosis results. To take the most advantage of test result for diagnosis-driven yield analysis, specific requirements must be met for the diagnosis process and the results analysis.

INTRODUCING DIAGNOSIS-DRIVEN YIELD ANALYSIS

In a diagnosis-driven yield analysis flow, production test diagnosis is combined with statistical results analysis. Compared to the traditional yield analysis flow introduced in Figure 1, diagnosis is moved upstream in the flow shown in Figure 2. This facilitates identification of probable cause of yield loss prior to FA and improves the selection of device for FA. This increases the FA success and relevance rates and also eliminates the need for costly physical failure localization.

The diagnosis-driven yield analysis solution from Mentor Graphics combines the automated diagnosis capabilities in Tessent® Diagnosis with advanced statistical analysis and data mining provided by Tessent YieldInsight®. This solution significantly reduces the time it takes to identify the root cause of yield loss and identifies yield limiters that may otherwise go unnoticed. While not relying on design-for-manufacturing (DFM), it can also be used to correlate actual failures with DFM violations to help prioritize verification rules.
OPTIMIZING DIAGNOSIS FOR YIELD ANALYSIS PURPOSES

When diagnosis is used for failure analysis in a traditional flow, the main goal is to localize the defect causing failures on a specific die. Diagnosis results are typically measured in accuracy and resolution: both parameters describe the localization of the defect. To fully leverage diagnosis for yield analysis, the solution has to provide more than just localization.

A key step in the yield analysis process is to identify and group devices failing for the same defect mechanism. This would be trivial if all such devices failed for the same pins for the same cycles in the test patterns, or if diagnosis determined the defect to be in the same net in all these devices. In reality, one underlying cause is likely to manifest itself in different locations and to a different degree in each failing device.

For instance, assume that a specific standard cell has a flaw such that it is more likely to fail than other cells in the library. In one die, one particular instantiation of this cell may cause a failure; while for another die, a different instantiation of that same cell may cause failures. The part of the diagnosis result that is especially valuable for yield analysis is what the failing die have in common; in this case, the type of cell, not necessarily the logic or even physical location of the defect.

In a similar case, assume the underlying cause is related to a specific type of via and 10 die have defects in 10 different nets. What is of particular interest is not the name of the net, but which layers (metal and vias) are part of the net.

Tessent Diagnosis addresses these challenges through layout-aware diagnosis [2-3]. Compared to diagnosis based simply on a logic-only design description (netlist), layout-aware diagnosis improves the diagnosis resolution and provides additional defect classifications. The following are some examples of how layout-aware diagnosis provides more detailed results:

- If a logic bridge between two nets explains a failure, it is only considered a valid suspect if these two nets are within line of sight.
- Dominant bridges, where a logic failure is only observed on one of the two nets involved, and opens are clearly separated. This is done by analyzing the nets neighboring the suspected open / bridge victim.
- The location of an open is narrowed down to a segment of a net. This is done by analyzing all the receivers in a multi-fan-out net.

Figure 3 shows a net diagnosed to have an open defect. By observing which receivers in the multi-fan-out net pass fail, the tool can narrow down the suspect location to a small segment of the overall net.
For yield analysis purposes, what is of particular interest is how the layout information is leveraged in the reporting. As shown in Figure 4, for a failing die, layout-aware diagnosis reports the physical location down to $x, y$, and layer along with logic location and classification. In this particular example, the suspected defect is an open in a net segment containing metal4, metal5, and three different types of vias. When similar information is generated for other failing dies, this information can be analyzed and processed to determine which characteristics are of particular interest.

In addition to layout-aware diagnosis, other recent advances in diagnosis technologies are beneficial to yield analysis; for example:
As much as 50% of defects can be internal to the cells. Cell-internal diagnosis ensures clear separation between defects in the interconnect ("back-end defects") and defects internal to the cells ("front-end defects") [4].

10-30% of logic failures are caused by scan chain defects [5]. Advanced chain diagnosis enables identification of scan chain defects and chain-functional compound defects [6].

Delay defects typically represent 1-5% of the total defect population. At-speed diagnosis provides clear identification of delay defects and timing errors [7].

Tessent Diagnosis provides a comprehensive set of diagnosis capabilities that provides more than 50 different attributes for each failure. These attributes, which range from failing scan chain and patterns to defect classification and affected standard cells, provide the foundation for the statistical analysis performed by Tessent YieldInsight.

In addition to accurate and meaningful diagnosis results, an important requirement for diagnosis in this context is that it must run with minimized impact on test cost. For applications such as FA or test bring-up, diagnosis is typically done on a small number of devices. To be able to effectively leverage diagnosis for yield analysis, diagnosis is typically run on a more regular basis and for a larger number of devices. This implies that diagnosis must be run on production test patterns, in presence of scan test compression, and with minimum impact on test time. Tessent Diagnosis directly diagnoses test results based on compression-mode Tessent TestKompress patterns, as well as Tessent FastScan patterns [8].

ANALYZING AND UNDERSTANDING DIAGNOSIS RESULTS

What ultimately determines the value of volume diagnosis for yield analysis is how the diagnosis results are used [9-16]. One of the main challenges is to separate valuable information from noise. For instance, there may be more defects associated with one particular type of AND gate than any other logic gate. That does not automatically mean that there is a systematic issue related to this particular AND gate because this may be the most common type of gate in the design.

On the other hand, assume an apparent random distribution of defects across the wafer. A high concentration of defects associated with that particular type of AND gate in the center of the wafer would be an indication of a systematic problem. This is because the distribution of this specific defect is significantly different than the overall defect distribution.

Tessent YieldInsight performs this type of signature analysis, comparing actual results to the expected distribution of all the signatures provided by Tessent Diagnosis. The analysis of more than 50 signatures across 8 zonal types is done automatically and presented in an analysis dashboard. This dashboard clearly indicates which signatures are worth investigating, and how significant the difference between the expected and actual distribution is. In this way, Tessent YieldInsight helps spot patterns in the failure diagnosis data that point to systematic issues.

Once a specific feature, such as a specific standard cell type, is suspected of impacting yield, additional feature analysis is performed to understand the impact of each systematic problem and to select devices for physical failure analysis. Devices associated with a particular signature are separated so that the impact of this issue is clearly observable. By
setting aside this part of the population, additional analysis can be done on the remaining material, to help identify other issues.

For example, assume a population of 1,000 failing die. Of those die, 150 are found to have open defects related to a single via. In the remaining material, 70 die are found to have a defect in different instantiations of a standard cell. By identifying multiple systematic issues, it is possible to prioritize which issue to pursue before any PFA is done.

Once a specific issue has been identified, devices are selected for PFA based on the diagnosis results. By selecting devices with a single suspect, high diagnosis score, and small physical search area, the PFA success rate can be maximized.

DFM-AWARE YIELD ANALYSIS

Resolving design-process induced systematic defects is one of the few ways that fabless semiconductor companies can directly improve yield. It is therefore desirable to have a methodology in place that clearly separates design and process related yield limiters. In a DFM-aware yield analysis flow, the goal is to identify the design-for-manufacturing (DFM) rules that best describe the actual design-process induced systematic defects. There are some challenges in this approach. First, a correlation between a defect location and a DFM violation does not necessarily mean that the DFM violation is the actual cause of the defect. Also, while the true failure mechanism may be design related, it may not necessarily be modeled by the existing DFM rules.

The approach to DFM-aware yield analysis used in Tessent YieldInsight is shown in Figure 5. Layout-aware diagnosis represents the foundation for this methodology. Each layout-aware diagnosis results is correlated with Critical Feature Analysis (CFA) results from Calibre® YieldAnalyzer®. If a suspect defect is partially or fully in the same layer and location as a DFM rule violation, this suspect is said to correlate with that DFM rule.

The DFM rules are treated as signatures in Tessent YieldInsight and the same signature and zonal analysis techniques introduced earlier in this whitepaper are used to determine whether systematic yield loss are caused by DFM violations, and to identify the most
sensitive DFM rule. At a high level, three categories of systematic defects can be identified by this process:

- Systematic defects that correlate with existing CFA rules. This process will identify the DFM rules most sensitive to systematic defects
- Systematic defects that are suspected to be CFA sensitive, but does not correlate to existing rules. Based on the initial analysis results, the user may suspect that the root cause is design related, although it does not match any of the existing DFM rules. Based on this hypothesis, additional rules may be created and the violations to these rules identified. These new violations can then be fed back into Tessent YieldInsight and analyzed. This way, a hypothesis can be tested without performing any PFA.
- Design independent (process related) systematic defects.

DEPLOYING A DIAGNOSIS-DRIVEN YIELD ANALYSIS FLOW

A fundamental requirement for diagnosis-driven yield analysis is the availability of design, test pattern, and tester failure data. An effective flow with minimum impact on test time can be realized by following some basic guidelines.

For example, most semiconductor companies use a combination of stuck-at and at-speed test patterns. The majority of defects may fail both of these pattern sets, but there is a significant difference in the effort needed to diagnose at-speed patterns that are typically more complex and longer than stuck-at patterns.

To diagnose failing scan chains, a relatively large amount of fail data is required, since data for both the chain test and some scan patterns are required for diagnosis. This may not be practical for volume diagnosis. Worth noting is that one particular defect mechanism may cause failures in the functional circuitry for some devices and the scan chains themselves for other devices. Focusing the data collection and analysis on the scan functional failures may therefore be a practical solution that often also helps resolve the root cause of chain failures.

Conventional wisdom dictates that the quality of diagnosis results depends on the amount of fail data available. Experiments have shown that effective scan functional diagnosis can be done with 256 failing cycles per die [8-9].

The minimum number of die needed depends on the type of issue to be analyzed [17]. For instance, analysis of an excursion has different requirements compared to identification of a hidden yield limiter. As a sample calculation, assume a known systematic signature has been responsible for 5% of yield loss. To have a statistically significant sample, you may need at least 25 die that have this signature. Thus, data will be needed to be collected on 500 die (25/0.05).

DIAGNOSIS-DRIVEN YIELD ANALYSIS IN PRACTICE

The following is an example of how Tessent YieldInsight can be used to identify a systematic yield problem and select devices for failure analysis. This example is based on Tessent Diagnosis layout-aware diagnosis results from 1,115 failing die from 200 wafers in 8 lots. Figure 6 shows a stacked wafer map of all failing die, illustrating that the distribution of the defects across the wafer appears to be random. The bar chart in Figure 6 indicates
that the number of failing die per wafer is also relatively random. The challenge is to determine if any systematic issues hide in the data.

Figure 6 – Stacked wafer map and failing die per wafer from Tessent YieldInsight for all failing die

Tessent YieldInsight enables exploration and visualization of the data in different ways. In a situation like this, where nothing is obvious from the initial results, a good place to start is the analysis dashboard shown in Figure 7. Tessent YieldInsight automatically analyzes over 50 failure and diagnosis signatures across 8 different zonal types. Zones are different portions of the data material, such as different parts of the die or across different wafers.

The analysis will, for instance, automatically indicate if there is a high concentration of bridge defects in the center of the wafer. The colors in the analysis dashboard indicate the probability of a systematic signature from white (very low) to yellow (medium) and red (very high).

Figure 7 – The analysis dashboard in Tessent YieldInsight

In situations where multiple signatures are flagged, a good place to start is the signature called “Suspect type: fail probability”. This signature describes the probability of whether a particular defect type caused the failure. The Pareto chart in Figure 8 shows that the most
common defect mechanism for these is that the most prominent defect mechanism in this material is opens. When normalized, about 427 of the 1,115 failing die failed due to open defects. This could just be due to critical area.

![Diagram showing defect mechanisms]

**Figure 8 – Pareto chart of probability of suspect types**

What is more interesting is that the bar for two-way bridges is show in red. In this case, the zonal type is the radial zone (R). The red color implies that there is an unexpected distribution of bridge defects across the radial zones of wafer. The wafer map for the die diagnosed to be caused by two-way bridges in Figure 9 shows a concentration of failing die in the middle of the wafer. The wafer map is in this case divided into 8 radial zones, with the same number of die in each zone.

![Wafer map and cumulative relative frequency chart]

**Figure 9 – Wafer map and cumulative relative frequency chart showing die diagnosed to have two-way bridge defects. The center zone is zone 1. The thick bar shows actual distribution. The thin bar shows delta between actual and expected distribution**

The bars in the chart to the right of the wafer map in Figure 9 show the fail probability for each of the five radial zones. Similarly to what is illustrated in the map itself, the bar representing the innermost zone (zone 1) is the highest. The thin green bar shows the delta between the actual and the expected distribution. The expected distribution is based on the
overall defect distribution and the total number of two-way bridges. The expected number is different in each zone because there is a certain variation of number of overall failing die in each zone.

The next step in our analysis process is to take a closer look at the location of the bridge defects. After filtering in on this sub-population of the failing die, the Pareto chart in Figure 10 shows the number of die diagnosed to have bridge defects in the five different metal layers.

![Figure 10 – Pareto chart showing the distribution of bridge defects in different layers](image)

The bridge defects in “route_3” follow a similar pattern as when we just looked at two-way bridges. As a result, the investigation should be focused on devices with two-way bridges in “route_3.”

To further identify devices most suitable for PFA, the population can be narrowed down based on the diagnosis results. Figure 11 shows the selection process, where devices with a single suspect and highest diagnosis score are selected.

![Figure 11 – Filtering in on devices with one diagnosis symptom and highest diagnosis score](image)

The population of die to be investigated is now narrowed down to 68 die. These all exhibit what appears to be a systematic issue and have clear diagnosis results. If physical failure analysis is performed on one of these devices, chances of successful PFA are high. It is also very likely that the results will be relevant and not point to an unrelated, random defect. From within Tessent YieldInsight, a detailed diagnosis report can be viewed that contains logic and physical location of the defect area.
The next step in a typical analysis flow would be to filter out the devices exhibiting this issue and repeat the analysis on the remaining population of die. This way, multiple systematic issues can be identified, and devices failing for each of these issues can be separated.

**DFM-AWARE YIELD ANALYSIS IN PRACTICE**

In this example, Tessent YieldInsight is used to identify DFM related yield loss. This example is based on Tessent Diagnosis layout-aware diagnosis results from 1,200 failing die. DFM analysis results are imported from a Results Database (RDB), which is Calibre’s exchange format. As shown in Figure 13, the Tessent YieldInsight dashboard in this case strongly indicates a zonally sensitive defect related to one of the DFM rules.

As shown in Figure 14, the rule “metal_cross_edge_route1” shows the strongest zonal sensitivity.
Faster time to root cause with diagnosis-driven yield analysis

Figure 14 – Pareto showing number of failing die with defect location diagnosed to correlated with DFM violations.

Figure 15 shows the wafer map for the devices diagnosed to have defects correlating with the “metal_cross_edge_route1” DFM violation. The zonal sensitivity of this category of failing devices indicates a systematic defect related to this particular DFM rule.

Figure 15 – Stacked wafermap of devices with defects diagnosed to correlate with the “metal_cross_edge_route1” DFM violation.

SUMMARY

An effective yield analysis flow can be realized by combining highly accurate volume scan diagnosis in Tessent Diagnosis with visualization and statistical analysis in Tessent YieldInsight. Applying yield analysis based on volume scan diagnosis results that incorporate design layout and failure data, rather than relying on manufacturing process data alone, can reduce the cycle time to root cause of yield loss by 75-90%. This approach can be supplemented with DFM-aware yield analysis to separate design and process related yield limiters.

REFERENCES


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