A Signature Analysis Method for IC Failure Analysis

SAND-96-2102C
CONF-961180-2

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Abstract

A new method of signature analysis is presented and explained. This method of signature analysis can be based on either experiential knowledge of failure analysis, observed data, or a combination of both. The method can also be used on low numbers of failures or even single failures. It uses the Dempster-Shafer theory to calculate failure mechanism confidence. The model is developed in the paper and an example is given for its use.

SIGNATURE ANALYSIS uses statistical inference techniques to deduce possible failure mechanisms with limited failure analysis. The goal of signature analysis (SA) is to significantly reduce the amount of failure analysis (FA) that a laboratory must perform. The knowledge obtained from prior comprehensive ("traditional") FA is used to assign a confidence level to the failure mechanism of an IC with a similar failure mode. In addition, SA can be used to determine the number of ICs that must be comprehensively analyzed to obtain a certain degree of confidence for a specific failure mechanism.

One method being applied to SA uses Bayesian statistics for a group of ICs either from an on-going ("infinite") population or from a finite population [1-4]. The following example illustrates how this might be applied to a group of failing ICs from a finite population [1]. A group of 20 ICs with a similar failure mode (signature) is to be analyzed. It is desired to select a sample from this group for comprehensive analysis so that there is 90% confidence that the remaining ICs in the group have the same failure mechanism. With this method, the comprehensive sample size is 5. If comprehensive analysis of these 5 ICs determines that they all have the same failure mechanism, then there is 90% confidence that the remaining 15 ICs also have this failure mechanism. The crucial assumptions with this method are that all 20 ICs have the same failure mode and that all 5 ICs analyzed comprehensively have the same

failure mechanism. There are several practical difficulties with this SA method. First, there must be enough failures with the same failure mode available for FA to enable selection of a statistically valid set of ICs for traditional analysis. This may be difficult for many laboratories. Second, for the SA method to be viable, there must be prior data for statistically different signatures so that it is possible to decide when a group of ICs has the same signature. A sufficient collection of signatures may be difficult or expensive to acquire. Third, signatures must be created for each new type of IC, process variation, and other controlling variable that might affect the signature and its associated failure mechanism. The effort required to build this data base may override the benefits achieved from the SA method.

A more flexible method for SA has been developed at Sandia National Laboratories that reasons from FA fundamental principles. This method can be used on low numbers of failures or even single failures. It does not require that there be a group of ICs with an identical failure signature. This approach enables calculation of increasing confidence in the failure mechanism during the analysis, giving the analyst the ability to decide when the confidence is high enough to stop. This method may be more widely useful for IC FA than other methods mainly because it follows the reasoning approach typically used by failure analysts.

Mathematical Model

There are many different schemes for modeling uncertainty. One of the most popular models uses Bayesian statistics [1,2]. Bayesian theory may be applicable when the information can be well classified and is well understood. (In this paper, "information" means FA data and knowledge.) For example, Bayesian theory will work well when we know for certain that a light emission image showing an emission site means there is an 80% chance of a gate oxide defect. There is an aspect of FA where the

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quality of information is also important. Some information may be clearly understood, while other information may be vague. Since much of the information obtained during FA can be vague to some degree, Bayesian theory is best applied to FA activities where completed analyses can be used for data.

The Dempster-Shafer (DS) theory [3,4] is a method by which information can be given a clarity or lack of clarity value. This is expressed as a belief function. The DS theory, also known as the theory of belief functions, is a generalization of the Bayesian theory of subjective probability. For example, let's say that there are N potential failure mechanisms $H_1, H_2, \dots, H_N$. After performing a certain failure analysis activity, we assign probabilities to each of these mechanisms $p(H_1|E), p(H_2|E), \dots, p(H_N|E)$. $p(H_1|E)$ is the probability of H_1 given a certain observed or deduced condition. We can also assign a probability to our uncertainty $p(\Theta)$; in other words, our judgment that the test doesn't tell us anything. These two items constitute a DS belief function $p(X)$. Therefore $p(H_1) + p(H_2) + \dots + p(H_N) + p(\Theta) = 1.00$. Two belief functions, $p_1(x)$ and $p_2(y)$, can be combined using the following rule:

$$p_3(Z) = \frac{\sum_{X \cap Y = Z} p_1(X) \cdot p_2(Y)}{1 - \left(\sum_{X \cap Y = \Phi} p_1(X) \cdot p_2(Y) \right)}$$

The SA method developed at Sandia for signature analysis uses a specific case of the DS theorem. Each particular action or technique that the analyst performs generates a signature. A signature $p(X)$ is a set of confidence values in the range of failure mechanisms given just the single piece of information. This signature is worked out ahead of time using information such as I-V curve, and wafer lot (e.g. parametric & yield) data. As the analysis is performed, the cumulative signature is modified by the new evidence (or signature) to produce a new cumulative signature.

Consider the following hypothetical example. Let's assume that we have three potential failure mechanisms: H_1, H_2 , and H_3 . Let's assume that, from the information available, our degrees of belief are given by $H_1 = 0.5, H_2 = 0.0, H_3 = 0.3$ and $\Theta = 0.2$. Let's now introduce new information (a new signature) that indicates $H_1 = 0.0, H_2 = 0.4, H_3 = 0.6$ and $\Theta = 0.0$. The old information (old signature) and the new information (new signature) can be combined using the DS combination rule above. The results are calculated using the matrix in Table 1. Using the equation below, the new running confidence vector, or signature, can be calculated.

$$\text{New } H_N = (H_N \Theta + H_N H_N + \Theta H_N) / (1 - Y)$$

The new H_1 is calculated by adding the values found in

locations $H_1 \Theta, H_1 H_1$, and ΘH_1 . The new H_2 is calculated from $H_2 \Theta, H_2 H_2, \Theta H_2$, and so on. The new Y value is calculated by summing all of the non-intersecting values Φ ($H_1 H_2, H_2 H_1, H_3 H_1, H_1 H_3, H_2 H_3, H_3 H_2$ in the case above).

$$\text{New } H_1 = (0.00 + 0.00 + 0.00) / (1 - 0.62) = 0.00$$

$$\text{New } H_2 = (0.00 + 0.08 + 0.00) / (1 - 0.62) = 0.21$$

$$\text{New } H_3 = (0.00 + 0.18 + 0.12) / (1 - 0.62) = 0.79$$

$$\text{New } \Theta = (0.00 + 0.00 + 0.00) / (1 - 0.62) = 0.00$$

Table 1: Example matrix generated from two belief vectors using Dempster-Shafer.

			previous running signature			
			H_1	H_2	H_3	Θ
			0.50	0.00	0.30	0.20
new data (signature)	H_1	0.00	0.00 (H_1)	0.00 (Φ)	0.00 (Φ)	0.00 (H_1)
	H_2	0.40	0.20 (Φ)	0.00 (H_2)	0.12 (Φ)	0.08 (H_2)
	H_3	0.60	0.30 (Φ)	0.00 (Φ)	0.18 (H_3)	0.12 (H_3)
	Θ	0.00	0.00 (H_1)	0.00 (H_2)	0.00 (H_3)	0.00 (Θ)

Assuming the signatures are constructed correctly, the cumulative signature should converge toward a value of 1.00. A correctly constructed signature should take into account not only the confidence in each failure mechanism, but the overall confidence in the validity of the signature. For example, historical data from a particular failure might provide very accurate clues as to the potential failure mechanism or a vague sense as to what the failure mechanism might be. A table showing a list of most common failure mechanisms from field return failures published by a government study might be a useful signature, but it probably doesn't reflect specific information about the types of failures seen in one particular company. The information from this type of signature that would enable discernment between the failure mechanisms is quite low ($p(\Theta)$ is high). A table published by your company on failure mechanisms associated with field returns is more specific, and the overall confidence is higher. A table published by your company on one particular part type is even more specific, and the overall confidence is higher. The more specific the information can be, the higher overall confidence for the signature. A correctly constructed set of signatures must take these factors into account.

The presentation of this method may have an

unintended, and perhaps overly limiting, implication that the degrees of belief mass functions, $(p(X))$, are constructed only at the level of individual failure mechanisms. The general presentation of belief functions often starts with the idea that mass functions exist on the set of all subsets of the population (or frame) of interest. This leads to degree of belief functions for any subset, A , that are obtained by summing the masses for the sets contained within A . The significance of considering this more general approach is that, for example, there could be a particular signature associated with failure mechanism H_1 about half the time and with mechanisms H_2 and H_3 the other half time. Allowing such a structure for the belief function poses no hardships for the rules of combination and everything presented for this method still holds. However, the expanded treatment may enable one to better model reality or make use of statistics from prior failure mechanism analysis [5].

In this presentation, there was no specific discussion on the normalizing factor in the combination rule. The mass assigned to the empty set when two degree of belief mass functions are convolved is a measure of the conflict of the two measures. This measure of conflict could be important in that it gives information about how the final degree of belief arose. Low conflict may indicate all the evidence is saying the same thing so there may be excessive redundancy in the testing, whereas high conflict may indicate that some unmodelled aspect of the various signatures is causing evidence to be contradictory [5].

The most powerful aspect of this type of signature analysis is its flexibility. We can create a signature for anything we believe is pertinent to the analysis. We can work with very general information (see following example) or we can develop very detailed signatures if we so choose.

Most importantly, we can assign a degree of belief to the information itself using the Θ variable. While signature analysis does not eliminate the need for failure analysis, it does offer the potential for reducing the amount of failure analysis work that needs to be performed. When FA requirements such as the degree of confidence required, desired information, and the time and funds available for the analysis are negotiated first, signature analysis is a powerful tool for performing FA quickly and accurately.

Example

To demonstrate the power and flexibility of the scheme, consider the following example (the list of failure mechanisms shown in Table 2 constitutes the set of potential failure mechanisms for this example). A 64k EEPROM was submitted to the failure analysis laboratory for analysis. This IC failed during electrical testing at next assembly. The assembly company observed failures on words 16-23 on each page of memory. We know from previous analyses that the manufacturer of this particular IC has had metallization problems. These problems include intralevel metal-metal shorts, interlevel metal2-metal1 shorts, and metal voiding. Given this background information and some knowledge about FA, we can begin to generate some signatures. From experience, we know that many ICs returned for FA from next level assembly suffer from electrical overstress or electrostatic discharge (EOS/ESD) problems as well as mechanical overstress. Another common problem is incorrect functional usage of an IC. Although the information from our customer indicates a functional problem that would most likely eliminate EOS/ESD or mechanical overstress as a possible failure

Table 2: Example List of Failure Mechanisms.

Electrical	Packaging	Metallization	Oxides	Bulk Silicon	Diffusions/ Implants
EOS (E1)	Mechanical Overstress (P1)	Interlevel Shorting (M1)	Pinholes (O1)	Incorrect Starting Mate- rial (S1)	Masking (D1)
ESD (E2)	Poor Lid Seal (P2)	Same Layer Shorting (M2)	Gate Oxide Shorts (O2)	Stacking Fault (S2)	Improper Implant (D2)
Incorrect Functional Use (E3)		Voiding (M3)	Charge trap- ping (O3)	Dislocations (S3)	Incorrect Dif- fusion (D3)
		Masking Prob- lem (M4)	Masking Prob- lem (O4)	Precipitates (S4)	
			Etching Diffi- culties (O5)		

mechanism, experience tells us that board level symptoms can be misleading and constraints on the technicians' troubleshooting time often result in less than adequate reporting. Obviously, we making decisions based on our experience and judgment, so there is a good deal of uncertainty. This information might lead us to the following signature shown in Table 3. As we start the analysis, we will normally try to reproduce the electrical failure mode using some type of test setup. In this case, the IC was tested on commercial automatic test equipment (ATE). ATE results showed that the IC passed continuity and failed functional testing. Further examination confirmed that words 16-23 on each page of memory fail and that the IC has excessive I_{DDQ} . These data and our experience now indicate that EOS or ESD are not likely and that incorrect functional usage is also unlikely since we were able to reproduce the same conditions observed at our customer's facility. The problem is now likely to be a die defect, possibly a manufacturing or reliability problem. Next, we performed leak testing and then delidded the IC.

Because the IC exhibited high I_{DDQ} , photon emission testing was performed next. Photon emission was done with the IC in both static (halting on a particular vector) and dynamic (running the IC in a loop of vectors) conditions. Photon emission was observed on the IC (Fig. 1). A

Fig. 1. Light emission photograph from 64k EEPROM.

comparison IC was tested and no photon emission was observed. Given these findings, we might speculate that the IC failed due to gate oxide shorts, or possibly an open interconnect. This might lead to the following signature (Table 4). The new running confidence vector or signature is shown in Table 5. As a result of the new signature, the running confidence vector has changed. The electrical failure modes have gone down, interlevel metal shorting (M1) has also gone down. There is now is the possibility of

gate oxide problems.

Table 3: Background information signature.

E1	E2	E3	M1	M2	M3	Θ
.10	.05	.20	.10	.10	.10	.35

Table 4: Light emission signature.

M3	O2	Θ
0.2	0.5	0.3

Table 5: New signature after light emission data.

E1	E2	E3	M1	M2	M3	O2	Θ
0.05	0.03	0.11	0.05	0.05	0.21	0.31	0.19

However, further examination of the photon emitting locations indicates they do not correlate with physical locations of the bad data on the die. Next, Charge Induced Voltage Alteration (CIVA) was performed. No signals were detected. After CIVA analysis, the IC was examined using dynamic voltage contrast with an electron beam prober. After determining which signals to examine, based on the failure mode, we examined the signal lines in question. A significant degradation in signal was identified on a particular address control line. The signal was strong before a metal2-metal1 contact, and weak after the contact (Fig. 2). These new data change our confidence away from a possible gate oxide short and toward some type of highly resistive contact, possibly due to metal voiding, masking, or etching problems. The following signature might be now generated (see Table 6.). Signal degradation at a metal2 - metal 1

Table 6: Electron beam analysis signature.

M3	M4	O5	Θ
0.1	0.15	0.25	0.5

contact can be the result of voiding, masking problems, or etching difficulties, according to our example failure mechanism table. Applying the DS certainty factor algebra yields the following confidence vector (Table 7). The confidence in electrical overstress failure modes continues to decrease, while masking problems (M4) and etching difficulties (O5) now appear. Although the failure has been localized to a particular contact, the failure mechanism is still not known with high confidence.

Fig. 2. Waveforms for address control lines A3 and A5. A5 exhibits degradation after contact.

Fig. 3. I-V characteristic of metal2-metal1 contact in question. Effective resistance $\approx$ 6-8 M Ω .

Table 7: New signature after electron beam data.

E1	E2	E3	M1	M2	M3	M4	O2	O5	Θ
0.04	0.02	0.10	0.04	0.04	0.23	0.05	0.25	0.08	0.15

As a check to determine if we had indeed located the failing contact, we used a focused ion beam system to lay down probe pads to facilitate probing across the contact. We observed the following I-V characteristics (Fig. 3). This plot indicated a highly resistive, somewhat non-linear contact. The contact electrical characteristics are indicative of a tunneling phenomena. This is reasonable since the materials in the via do not lend themselves to rectifying or Schottky barrier behavior. Although the electrical characterization supports the electrical failure mode that occurred on the IC, there is no further indication as to the failure mechanism involved. These data indicate that not all FA information may be useful as a signature to determine a failure mechanism. Further studies and characterization may be necessary to determine if more information can be obtained from this type of I-V curve.

After characterizing the electrical behavior of the contact, we used the focused ion beam system to cross section and image the contact (Fig. 4). We also used a field

Fig. 4. Secondary ion mode image of suspect contact after FIB cross-sectioning.

emission SEM to image the contact (Fig. 5). The FIB and

SEM images clearly show metal voiding in the contact. Observing the defect with both the FIB and SEM images gives us high confidence that the failure mechanism is voiding in the metal 2 - metal 1 contact. At this point, one might be tempted to say that the confidence value for M3 should be 1.00. While this can be done, one might also

Fig. 5. Field emission SEM photograph of suspect contact (note voiding in the contact).

argue that nothing is ever completely certain just from a viewing a set of images. The later view is reflected in the signature in Tables 8 and 9. This yields the final running

Table 8: Cross sectional analysis signature.

M3	Θ
0.95	0.05

signature for the analysis shown in Table 9. Notice that voiding (M3) is the only failure mechanism with significant confidence at this point.

Table 9: Final signature (after cross sectional data).

E1	E2	E3	M1	M2	M3	M4	O2	O5	Θ
<0.01	<0.01	0.01	<0.01	<0.01	0.91	0.01	0.03	0.01	0.02

At this point we are more than 90% confident that the failure mechanism is voiding. Depending on the level of confidence required for the analysis, one could stop or go further to increase the confidence. In this particular incident, some suggestions for further analysis to increase confidence might include: analysis of additional ICs (if available), cross sections of additional contacts, burn-in of additional samples to determine if other failures can be produced, etc.

Conclusions

A new method for signature analysis based on the Dempster-Shafer belief function theory has been described. This method provides a robust and flexible way to implement signature analysis. The most powerful aspect of this method is the ability to implement it for single failures, making it useful for field returns, qualification failures, and other "one of a kind" failures. Another important benefit of this method is the ability to use a low degree of belief with any number of signatures that are not well known or rely entirely on expert opinion. This method obviously requires a standard set of failure mechanisms as well as a standard set of terms and definitions for failure analysis. The JEDEC 14.6 Failure Analysis Committee is now addressing both standard terminology and definitions as well as failure mechanism coding. Although the DS method does not require that extensive signatures be developed for a variety of background conditions and observations, signatures should be developed to capture key information (e.g., use conditions, various I-V curves, voltage contrast data, and ATE results) as well as signatures for various image data (e.g., liquid crystal, photon emission, CIVA, FIB, optical, and SEM images). The more specific the set of signatures that can be generated, the more accurate the results will be. A set of signatures was developed for the FAST project [6].

This SA method has the ability to be incorporated into an automated IC diagnosis process that uses defect models and classes for site localization in addition to failure mechanism determination. Improved models and diagnosis procedures will help reduce the amount of testing and physical failure analysis necessary to determine a signature for the failure mechanism and its location [7-9].

Signature analysis is potentially a powerful method for reducing the level of work and improving the efficiency of an FA laboratory. While this method may reduce the level of work in a different manner than other signature analysis methodologies, it is more flexible and provides structure to the FA process.

Acknowledgments

The authors would like to thank Richard Anderson, Daniel Barton, Robert Easterling, and Floyd Spencer for their review and comments. This work was supported by the U.S. Department of Energy under contract number DE-AC04-94AL85000.

References

1. M. Pore, G. Gilfeather, and L. Levy, "Risk Assessment in Signature Analysis," to be presented at *Int. Symp. Test. and Fail. Anal.*, Nov 18-22 1996.
2. G. F. Luger and W. A. Stubblefield, *Artificial Intelligence and the Design of Expert Systems*, Benjamin Cummings Publishing Co. Inc., 1989, p. 314
3. Rich and Knight, *Artificial Intelligence*, McGraw-Hill Inc., 1991, pp. 242-246.
4. *Encyclopedia of A.I.*, ed. Shapiro, Wiley and Sons Inc., 1992, pp. 330-331.
5. F. W. Spencer, personal communication, July 25, 1996.
6. C. L. Henderson and R. D. Barnard, "The Advent of Failure Analysis Software Technology," *Proc. Int. Reliab. Phys. Symp.*, 1994, pp. 325-333.
7. R. Aitken, "A Comparison of Defect Models for Fault Location with IDDQ Measurements," *Proc. Int. Test. Conf.*, 1992, pp. 778-787.
8. C. F. Hawkins, J. M. Soden, A. W. Righter, and J. Ferguson, "Defect Classes - An Overdue Paradigm for CMOS IC Testing," *Proc. Int. Test Conf.*, 1994, pp. 413-495.
9. R. Aitken, "Finding Defects with Fault Models," *Proc. Int. Test Conf.*, 1995, pp. 498-505.

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