Improved Fault Diagnosis in Scan-Based BIST via Superposition *

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Abstract

An improved approach for diagnosis of scan-based BIST designs is proposed. The enhancement in diagnosis is achieved by utilizing the superposition principle. Scan cells are partitioned pseudo-randomly for observation and the ones provably fault free are removed from the potentially faulty list. Diagnostic resolution is improved by a novel application of the superposition principle, resulting in significant reductions in diagnosis time.

1 Introduction

Built-in self-test (BIST) has gradually achieved a leading position in the testing of today's sophisticated designs, as a test solution for the whole design or for at least various externally hard-to-test blocks of the design, such as memories, programmable logic arrays (PLA), and datapaths. While improvements in BIST technology have enabled low cost and at-speed test solutions through on-chip test generation and compaction, such compaction schemes reduce diagnosis capabilities by cutting down the test information to a single pass/fail indicator.

As time-to-market requirements continue to shrink with increased competition in industry, fast and efficient diagnosis of design flaws for correction and of manufacturing defects for process debugging and yield improvement becomes essential. While a pass/fail information is enough for testing purposes, the diagnosis procedure requires more information in order to pinpoint a fault location. The signature attained at the end of a test session, even though highly compacted, can be utilized to locate a fault or to determine failing test vectors under well-defined fault models. However, most realistic faults in VLSI circuits cannot be exactly modeled with simple fault primitives, such as stuck-at faults. Utilization of complex, exact fault primitives, on the other hand, is overwhelmed by the computational power requirements of simulating the inordinate number of plausible realistic faults.

Therefore, in practice most current approaches aim at reducing the size of the possible fault site to a very small neighborhood and then identifying the exact location of the fault through surface scan techniques. Scan-based test techniques, for example, are highly capable of narrowing down the fault site. When ATPG-based test patterns are applied through an ATE, it is a simple matter to pinpoint which scan cells contain faulty responses. However, in the case of a BIST scheme, the only available information after test application is a compacted signature. Without utilization of exact fault modeling and extensive fault simulations, it is not possible to locate a fault with the single signature acquired from a test session.

Until recently, research on diagnosis through BIST concentrated on utilization of the information hidden in the signatures. In [3], McAnney and Savir have shown that through analysis of the signature contents, it is possible to locate single errors in a test response sequence. As the number of failing patterns increases, the complexity of this scheme increases and its identification capability diminishes. In [5], they have also proposed a method that is capable of identifying multiple errors in a test sequence through utilization of cyclic registers. The drawback of this scheme is that fault masking effects for larger number of errors results in misidentification of error-free outputs as erroneous and erroneous outputs as error-free. In [6], the authors propose a technique where the characteristic polynomial is a factored polynomial and show that utilization of non-primitive polynomials may reduce the aliasing probability for multiple errors. In [1], a method is proposed in order to utilize the quotient, instead of the signature, through a fault-free sequence generator. Even though the scheme is capable of providing improved diagnostic capability by utilizing increased information, its hardware requirements are substantially higher than regular BIST. All the techniques reviewed so far aim at identifying a set of failing patterns. However, the identification capability of such schemes diminishes as the number of failing vectors increases. Excluding pseudo-random resistant faults, most of the faults are detectable through a fairly large number of vectors. Therefore, such schemes are not suitable in realistic test environments.

Recently, Rajski and Tyszer in [4] have proposed an identification scheme for failing scan cells in a scan-based BIST environment. They identify a set of failing scan cells, instead of a set of failing vectors, through the process of elimination by successive application of the same test set and observation of a random subset of scan cells. Each time only a subset of scan cell outputs is observed through a signature register and if the signature matches the fault-free one, the scan cells in the current group are pronounced fault-free. As the process continues by selecting pseudo-randomly subsets of the scan cell to be observed, the fault free scan cells are removed from the potentially faulty list. Eventually, the potentially faulty list contains only the failing scan cells. The number of test application times depends on the number of failing scan cells. Rajski and Tyszer provide analytical results for the diagnostic resolution of their scheme and indicate that the size of the partition has to be chosen depending on the number of errors in order to minimize diagnosis time. With no advance knowledge of the number of errors to occur, diagnosis time degradation is suffered. Erring on the side of over estimation may be preferable as the performance degradation in the case of underestimation is exponential.

In this work, we provide an alternative analysis scheme for the pass/fail information attained in [4] that is capable of reducing di-

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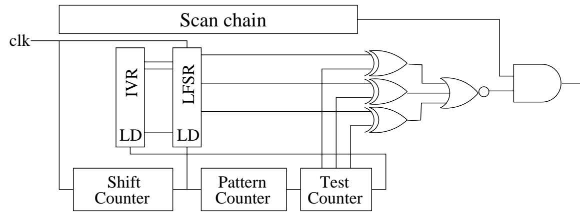

Figure 1: Scan cell selector [4]

agnosis time by 55%. Furthermore, a simple augmentation of the scheme that we subsequently show eliminates the necessity of estimating the number of faulty scan cells and provides test times within 20% of the optimum time, independent of the number failing cells, thus improving on the results of [4] by more than 45%.

2 Scan Selection and Diagnosis

Identification of failing scan cells is performed in [4] by successively partitioning the scan chain and observing the scan cell outputs for each partition separately through signature comparison. Each time a fault-free signature is attained during the test process, scan cells participating in the corresponding signature are eliminated from the list of potentially faulty cells. The diagnostic procedure is partitioned into test groups. In each test group, the scan chain is partitioned into b nonoverlapping partitions. Partitions in different test groups are required to have as little overlap as possible in order to improve diagnostic efficiency.

Figure 1 depicts the scan-cell selector proposed in [4] implemented using an LFSR and an Initial Value Register (IVR). For each partition in a test group, the LFSR is loaded from the IVR. The test counter's value is compared to an arbitrarily selected set of r outputs of the LFSR; compaction of the output of the corresponding scan cell occurs upon a match. Since the test counter has a unique value for each partition, the partitions in each test group are unique. At the end of a test group, the IVR is updated with the current state of the LFSR. Since LFSRs are known to generate uncorrelated output sequences, partitions in distinct test groups have very limited overlap. Details of this implementation can be found in [4].

Figure 2 depicts for visualization purposes a scan chain of 16 cells as a square-shaped structure. The scan chain is partitioned into four groups in two different ways. Both of these partitionings correspond to a test group. At the end of the first test session, scan cells 9 through 12 are removed from the potential list. At the end of the second test session, scan cells 2, 6, and 14 are also removed from the potential list. As can be seen, 6 fault-free cells are still in the list. Increasing the number of test groups eventually removes these cells from the potential list.

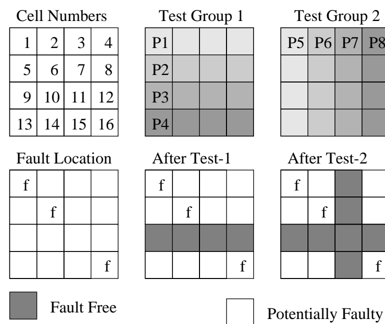

Figure 2: Scan partitioning and diagnosis

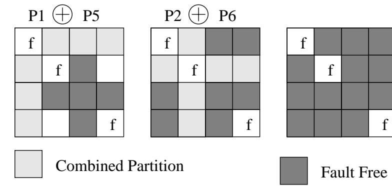

Figure 3: Diagnosis by superposition

During the diagnostic procedure above, the pass/fail indication of the applied tests is solely utilized. The signatures corresponding to various partitions can be easily computed using superposition [2], if the signatures corresponding to each individual cell are known. Superposition can also be utilized to determine the signatures of additional partitions without actually applying the test for them. The superposition principle states that the signature for a set of scan cells is equal to a simple composition of signatures of all scan cells in that set using the XOR operation. Composition is possible due to the linearity of signature generators [2].

From the above discussion, it follows that the signature for the union of two sets of scan cells can simply be determined if the intersection of the sets involved in the composition is empty. However, a more interesting case in this application occurs when the intersection of the two sets is not empty. Assume that we want to combine the signatures for two sets of scan cells, A and B, and the signatures corresponding to these sets are S_A and S_B, respectively. Simple set operations dictate that

$$A = (A - B) \cup (A \cap B) \quad (1)$$

$$B = (B - A) \cup (A \cap B) \quad (2)$$

and the superposition principle dictates that

$$S_A = S_{A-B} \oplus S_{A \cap B} \quad (3)$$

$$S_B = S_{B-A} \oplus S_{A \cap B} \quad (4)$$

Combining the equations above results in

$$S_A \oplus S_B = S_{A-B} \oplus S_{B-A} \quad (5)$$

Therefore, superposition of signatures S_A and S_B for sets A and B provides a signature for the set of scan cells that exist only in one of the participating sets, but not in both. During the derivation of equation 5, we assume that the impact of a fault on the resultant signature is the same for successive applications of the same test set. The assumption holds as long as a fault effect does not result in oscillatory or sequential behavior. Yet even such a behavior, though it will invalidate the equations derived, will not lead the diagnostic procedure to invalid conclusions. In the case of a varying fault, a composite signature will not be fault free and no scan cells will be removed from the potential list. The overall effects of such a fault, at the worst case, will be the elimination of the extra information

```
Initialize S with all scan cells
for each test group C
  for each partition P in C
    if signature is error free
      remove all cells in P from S
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for each test group C' up to C
for each partition P' in C'
if composite signature is error free
remove cells in only P or P' from S

Figure 4: Pseudo-Code for Diagnosis

n - SCAN size, b - number of partitions, c - number of test groups, k - error multiplicity

	n = 1000						
	b = 4						
k	c = 10	c = 11	c = 12	c = 13	c = 14	c = 15	c = 16
2	0.241	0.104	0.044	0.019	0.008	0.003	0.002
3	4.096	2.363	1.363	0.784	0.450	0.256	0.149
	b = 8						
5	0.736	0.358	0.174	0.084	0.040	0.019	0.009
6	2.550	1.403	0.773	0.424	0.233	0.128	0.071
7	6.731	4.084	2.480	1.502	0.910	0.552	0.335
	n = 5000						
	b = 8						
5	1.835	0.893	0.433	0.210	0.102	0.049	0.023
6	7.130	3.927	2.159	1.187	0.653	0.359	0.198
7	20.677	12.548	7.608	4.614	2.798	1.699	1.031
	b = 16						
13	9.808	5.556	3.148	1.784	1.010	0.573	0.324
14	16.369	9.720	5.772	3.429	2.035	1.207	0.716
15	25.916	16.047	9.937	6.156	3.808	2.358	1.460

Table 1: Number of undiagnosed scan cells in method of [4]

	n = 1000						
	b = 4						
k	c = 4	c = 5	c = 6	c = 7	c = 8	c = 9	c = 10
2	7.779	1.848	0.422	0.141	0.019	0.000	0.000
3	12.914	3.076	0.685	0.226	0.031	0.000	0.000
	b = 8						
5	2.078	0.278	0.057	0.015	0.001	0.000	0.000
6	4.333	0.625	0.110	0.025	0.001	0.000	0.000
7	9.169	1.541	0.282	0.057	0.006	0.001	0.000
	n = 5000						
	b = 8						
5	10.566	1.271	0.148	0.009	0.001	0.000	0.000
6	22.215	3.059	0.387	0.034	0.003	0.000	0.000
7	46.579	7.879	1.189	0.153	0.020	0.002	0.000
	b = 16						
13	26.164	3.808	0.510	0.062	0.007	0.001	0.000
14	40.062	6.581	0.983	0.142	0.021	0.003	0.001
15	60.081	11.215	1.970	0.319	0.054	0.009	0.002

Table 2: Number of undiagnosed scan cells by composition

attained by composition. Even in the case of a fault effect resulting in sequential or oscillatory behavior, the result will be in no case worse than that of a scheme without superposition, such as the scheme in [4].

Application of the superposition principle to the resultant signatures improves diagnostic resolution. Figure 3 shows the application of superposition to the partitions $P1$, $P5$ and $P2$, $P6$. Therefore, by checking the two composite partitions in figure 3, the size of the ambiguity list is reduced to the size of the faults. Depending on the fault distribution, some cells may remain in the potential list after the application of the two test groups. While it is not always possible to perfectly diagnose the faults after the application of two test groups, utilization of extra information, on the average, reduces diagnosis time appreciably.

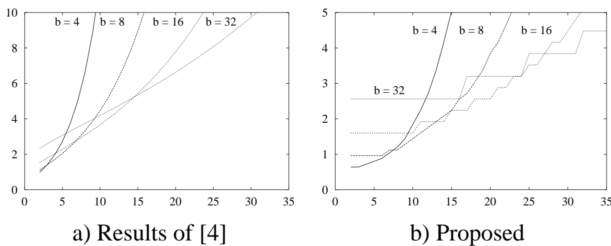
In this work, the superposition principle is utilized in order to reduce test application time. Since the partitions in a test group are independent of each other, their superposition does not provide extra information. However, partitions in different test groups do overlap and their superposition provides extra information. Figure 4 shows pseudo-code for a diagnostic procedure based on the principles formulated. The code in bold in figure 4 generates signatures for composite partitions and removes the cells in the composite partition from the potential list if the composite signature is error free. The following section provides experimental results of the method we propose and its experimental comparison to the scheme proposed in [4].

3 Experimental Results

We perform experiments by our schemes for various numbers of error multiplicity and various partition sizes. The number of errors and partitions are chosen to be the same as the ones utilized in [4] for comparison purposes. Tables 1 and 2 provide the average number of undiagnosed scan cells for various parameters. The number of tests in table 1 ranges from 10 to 16, whereas the range for the number of tests in table 2 is between 4 and 10. It can be clearly seen that the proposed scheme provides significantly improved results. Since the number of composite partitions increases quadratically with the number of tests applied, the rate of the increase in diagnostic resolution gets larger as the number of test groups increases. The rate of increase in diagnostic resolution without composite partitions, on the other hand, remains constant.

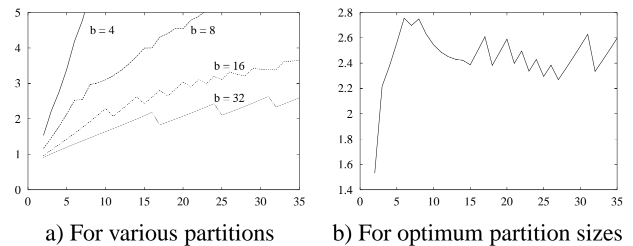
While the results in tables 1 and 2 indicate that diagnostic resolution is higher with composite partitions, the results in the tables by themselves are not sufficient to provide a quantitative improvement measure. In order to compare diagnosis times of both techniques, we perform simulations with various error counts and record how many test groups are needed in order to reach a diagnostic level wherein the average number of undiagnosed scan cells is less than ($0.1\times$ error multiplicity). The results without composite partitions are generated by utilizing the equations provided in [4] as those equations closely match the corresponding experimental results of [4].

Figure 5 provides simulation results for error multiplicity versus the number of required tests as a percentile of scan size for various partition sizes. The reported results assume a diagnostic resolution of ($0.1\times$ error multiplicity). Figure 6a, on the other hand, shows the ratio of the diagnosis time requirements of both schemes. The figure indicates that the improvement in diagnostic resolution highly varies depending on partition sizes and number of errors. However, an improved comparison of the results can be obtained, if the diagnosis times are compared for the optimum partition sizes. Figure 6b, therefore, provides the diagnosis time ratio of the two



a) Results of [4]   b) Proposed

Figure 5: Errors vs. the number of tests as scan size percentage



a) For various partitions   b) For optimum partition sizes

Figure 6: Ratio of diagnosis times of [4] to that of proposed scheme

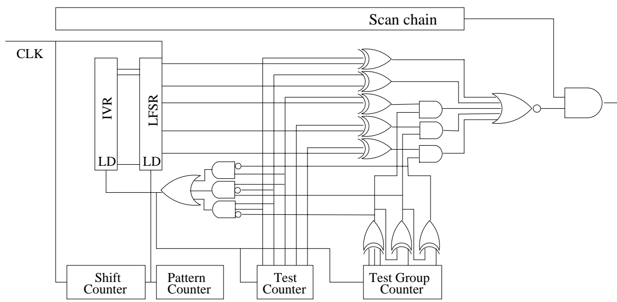


Figure 7: Error independent scan cell selector

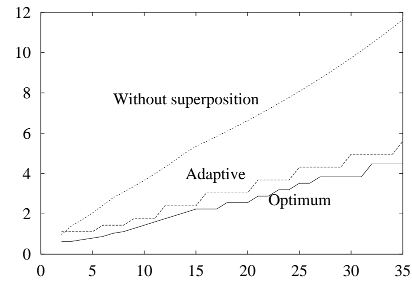


Figure 8: Errors vs. the number of tests as scan size percentage

schemes for optimum partition sizes. Comparison at the optimum point indicates that the proposed composite partition scheme improves diagnosis time by more than 55% whenever error multiplicity exceeds five.

4 Error Independent Structure

The results for the composite partitions in figure 5 clearly indicate that the number of partitions for which diagnosis time is minimized depends on the number of failing scan cells in the system. It is impossible to determine how many scan cells receive faulty responses prior to the diagnostic procedure. The number of such scan cells depends on the number of faults in the system and the logic cones effected by these faults. A single fault may effect tens of scan cells if the cells are driven, for example, by a 32-bit adder. In order to eliminate exponential growth in test application time for circuits with a large number of faults, it may be safer to utilize an increased number of partitions. However, such a scheme will unnecessarily increase diagnosis time for circuits with fewer numbers of infected scan cells.

An adaptive scheme, in which the number of partitions are adjusted dynamically, may produce results that approximate the optimum results. However, since the adaptation algorithm is to be implemented by hardware, the scheme needs to be straightforward. We propose therefore a scheme in which the number of partitions is doubled after each predetermined number of test group applications. Figure 7 shows an example implementation of such a scheme. An additional counter is utilized in order to count the number of test groups applied. Depending on the current test group count, the number of bits that are utilized while comparing the output of the LFSR to the current value of the counter is adjusted. Additionally, the time at which the test counter is reset and the IVR is loaded with the state of the LFSR is adjusted depending on the value of the test group counter.

In such a scheme, the question of the termination condition for the debugging procedure arises. Table 3 provides the expected number of scan cells in the ambiguity set for various error and test group counts. For example, if 72 scan cells remain in the ambiguity list after 7 test groups applications, we would expect to see 15 scan cells in the ambiguity list at the end of the diagnostic procedure. By utilizing an extended version of table 3, it is possible to estimate the number of failing scan cells at any time during the diagnosis procedure. As the number of test groups increases, the uncertainty of estimation is reduced. The diagnosis procedure could be safely terminated whenever the number of scan cells in the ambiguity list ceases to change.

	Number of Tests								
Errors	5	6	7	8	9	10	11	12	13
5	8	5	5	5	5	5	5	5	5
10	179	28	11	10	10	10	10	10	10
15	1124	299	72	25	15	15	15	15	15
20	2455	1105	414	149	33	21	20	20	20
25	3347	2057	1130	554	119	38	26	25	25
30	3945	2921	1984	1262	376	105	44	32	30
35	4319	3539	2751	2050	793	263	96	50	38

Table 3: Number of tests vs. number of cells in potential list

Figure 8 provides the results of the adaptive diagnosis procedure and a comparison to the optimum values. While the adaptive results display only a slight degradation in relation to the optimum ones, they do not require advance knowledge of the number of scan cells in error, a necessary piece of information if any optimum schemes are ever to be constructed.

5 Conclusion

An improved approach for diagnosis of scan-based BIST designs is proposed. The improvements in diagnostic procedure are attained by a novel application of the superposition principle to signature analysis. The diagnostic power of the scheme based on scan chain partitioning is enhanced by virtually increasing the number of partitions through composition of overlapping partitions. Experimental results indicate that the proposed approach improves diagnosis time by more than 55%. An adaptive partitioning scheme proposed in this work is capable of keeping diagnosis times very close to the optimum, which could have been attained only if advance knowledge of the number of fault manifestations in scan cells is available.

References

[1] R. C. Aitken and V. K. Agarwal. A diagnosis method using pseudo-random vectors without intermediate signatures. In *International Conference on Computer-Aided Design*, pages 574–580, 1989.

[2] J. C. Chan and J. A. Abraham. A study of faulty signatures using a matrix formulation. In *International Test Conference*, pages 553–561, 1990.

[3] W. H. McAnney and J. Savir. There is information in faulty signatures. In *International Test Conference*, pages 630–636, 1987.

[4] J. Rajski and J. Tyszer. Diagnosis of scan cells in BIST environment. *IEEE Transactions on Computers*, 48(7):724–731, July 1999.

[5] J. Savir and W. H. McAnney. Identification of failing tests with cycling registers. In *International Test Conference*, pages 322–328, 1988.

[6] C. E. Stroud and T. R. Damarla. Improving the efficiency of error identification via signature analysis. In *VLSI Test Symposium*, pages 244–249, 1995.