Improved Methods for Fault Diagnosis in Scan-Based BIST *

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Abstract

A deterministic-partitioning technique and an improved analysis scheme for fault diagnosis in Scan-Based BIST is proposed. The incorporation of the superposition principle to the analysis phase of the diagnosis algorithm improves diagnosis times significantly; furthermore, the deterministic partitioning approach results in even further reductions in diagnosis times together with higher predictability.

1. Introduction

Built-in self-test (BIST) is currently utilized in state-of-the-art designs both for improving test quality and for reducing test development and application cost. While BIST provides sizable benefits, a limitation in its further adoption as the main test methodology is inherent fault diagnosis challenges. While BIST reduces test application cost appreciably, fault diagnosis in a BIST environment is problematic since only limited information is available in a compact signature.

Until recently, research on diagnosis through BIST has concentrated on identifying methods for extracting information possibly embedded in the signatures. McAnney and Savir have shown that through analysis of the signature contents, it is possible to identify failing test vectors [3]. As the number of failing test vectors increases, the complexity of this scheme increases and its identification capability diminishes due to the aliasing effects of multiple failing vectors. They have further proposed a method that is capable of identifying an increased number of failing test vectors through utilization of cyclic registers [5]. Stroud and Damarla have proposed a technique where the characteristic polynomial is a factored polynomial and show that utilization of non-primitive polynomials may reduce aliasing probability for multiple errors [6]. Aitken and Agarwal have proposed a method in which the quotient instead of the signature is utilized through a fault-free sequence generator [1]. 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 schemes outlined above aim at identifying a set of failing test vectors. However, the identification capability of such schemes diminishes as the number of failing vectors increases. Yet fault effect manifestation cannot be typically limited to a few vectors. Excluding pseudo-random resistant faults, most faults are detectable through a fairly large number of vectors. Such schemes suffer consequently in realistic test environment applications.

Recently, Rajski and Tyszer have proposed a scan pseudo-random partitioning based approach to the fault diagnosis problem in scan-based BIST [4]. Therein the results of the application of the same test are repeatedly partitioned, observed, and compared to the corresponding fault-free signature for each partition. A fault-free signature implies that all scan cells in the corresponding partition are fault free. Successive partitioning of the scan cells into distinct partitions helps eventually sieve all fault-free cells.

In this work, we initially propose an alternative analysis scheme, based on the superposition principle, for the pass/fail information attained in [4] that is capable of reducing diagnosis time by 55%. We further propose a deterministic partitioning scheme which results in even lower diagnosis times. Not only does the proposed deterministic approach consistently exhibit superior results, but furthermore it achieves such results with high levels of predictability. An invaluable characteristic of the proposed deterministic partitioning approaches lies in their ability to incorporate design and fault information; such incorporation may further help reduce diagnosis time and model complex emerging fault models.

The next section of the paper reviews the fundamentals of partitioning-based diagnosis. Section 3 outlines how the superposition principle is incorporated into the analysis phase of the diagnosis algorithm. Section 4 illustrates mathematical and implementation challenges inherent in constituting a deterministic scheme and outlines both analytic and low cost hardware implementation solutions to the problem of deterministic partitioning. Experimental results in section 5 are followed by the conclusions in section 6.

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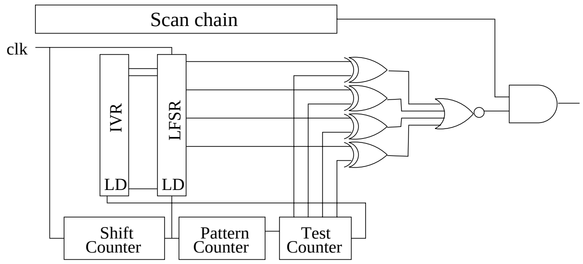


Figure 1. LFSR-based scan cell selector [4]

2. Preliminaries

In a partitioning-based diagnosis scheme, scan cells are successively grouped into a set of non-overlapping partitions, each set constituting a partition group. The observation of the signatures corresponding to each partition can provide valuable information in diagnosis, since each fault-free signature indicates that all the cells in the corresponding partition are fault free. Nonetheless, a single partition group is inadequate in identifying with certainty the failing scan cells, as all cells in a partition that exhibits a failing signature constitute a candidate set of culprits. Consequently, additional applications of the same test set, yet with differing partition elements, need to be used to provide additional snapshots of failing scan cells with consequent refinement of the candidate failures. Each of these applications of the same test set, with its repartitioning of the scan cells, constitutes a partition group.

Figure 1 depicts a possible scan cell partitioning hardware implemented using an LFSR and an Initial Value Register (IVR) [4]. While the LFSR is loaded from the IVR for generation of each partition in a particular partition group, at the end of the generation of a partition group, the IVR is updated with the current state of the LFSR. The test counter 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 partition group are distinct. Updating the IVR with the current state of the LFSR at the end of each partition group guarantees distinctness of the partition groups as LFSR generated sequences do not repeat.

3 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 provides a signature for the set of scan cells that reside in exactly one of the participating sets, but not in both. In this work, the superposition principle is utilized in order to increase the amount of information extracted from the signatures of the partitions, which in turn reduces 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.

4. Construction of Deterministic Partitions

A partitioning that has uniformly minimal overlap with all partitions, though it imposes a strict constraint on the structure of the partitions, results in lower and predictable diagnosis times as verified by the experimental results in section 6. In the case of the number of partitions equaling partition size, the uniform overlap requirement reduces to a single overlap among partitions. This constraint limits sharply the number of attainable partition groups, and makes their identification and construction nontrivial.

A deterministic partitioning that satisfies the aforementioned constraints for a scan chain size of 25 is provided in table 1. The scan chain is partitioned into 5 partition groups; each row in the table corresponds to a partition group with 5 partitions. It can easily be verified that the number of overlapping cells for the partitions in table 1 is consistently equal to 1 for partitions in distinct partition groups and to 0 for partitions in the same group.

0 5 10 15 20	1 6 11 16 21	2 7 12 17 22	3 8 13 18 23	4 9 14 19 24
0 6 12 18 24	1 7 13 19 20	2 8 14 15 21	3 9 10 16 22	4 5 11 17 23
0 7 14 16 23	1 8 10 17 24	2 9 11 18 20	3 5 12 19 21	4 6 13 15 22
0 8 11 19 22	1 9 12 15 23	2 5 13 16 24	3 6 14 17 20	4 7 10 18 21
0 9 13 17 21	1 5 14 18 22	2 6 10 19 23	3 7 11 15 24	4 8 12 16 20

Table 1. Deterministic partitioning of 25 cells

Even though such partitions have the minimum possible overlap, their hardware generation is highly challenging. Examination of the relationships across groups yields the recurrence relation in equation 6, while equation 7 can be used to denote a simple definition of the initial partition group. In the equations in this paper, c, b, i, and S correspond to the partition group number, the partition number, the location inside a partition, and the partition size, respectively. $P(c,b,i)$ indicates the numeric identifier of a scan cell in location i of partition b in partition group c.

$$P(c+1,b,i) = P(c,(b+i)\ mod\ S,i) \qquad (6)$$

$$P(0,b,i) = iS+b \qquad (7)$$

With these inductive relationships established for P, a nonrecursive solution can be determined by embedding the induction effects, resulting in equation 8.

$$P(c,b,i) = iS + (ci+b)\ mod\ S \qquad (8)$$

The existence of partitions with minimal overlap, as shown in table 1, is not coincidental. The following theorem shows that partitions generated by equation 8 always exhibit the minimal overlap of 1 for any prime number S.

Theorem: For S prime and c, b, and $i < S$, partitions generated by equation 8 have an overlap of 1 whenever they lie in distinct partition groups and have no overlap whenever they are in the same partition group.

Proof: In order for the elements of two partitions, $P(c_1,b_1,i_1)$ and $P(c_2,b_2,i_2)$, to overlap, the following equality has to be satisfied:

$$P(c_1,b_1,i_1) = P(c_2,b_2,i_2) \qquad (9)$$

Since $S > |i_1 - i_2|$, equation 9 holds iff $i_1 = i_2 = i$. Therefore, the overlap condition reduces to:

$$(c_1 - c_2)i \overset{mod\ S}{=} b_2 - b_1 \qquad (10)$$

For partitions in different partition groups, i.e. $c_1 \neq c_2$, only two cases need to be analyzed:

- $b_1 = b_2$: has a unique solution, $i = 0$.
- $b_1 \neq b_2$: a unique solution exists for S prime.

For partitions inside the same partition group, i.e. $c_1 = c_2$, overlap necessitates equality of b_1 and b_2; a partition can only overlap with itself inside a partition group.

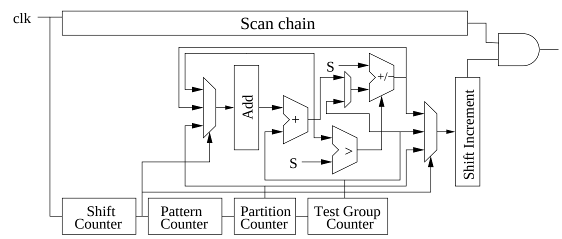


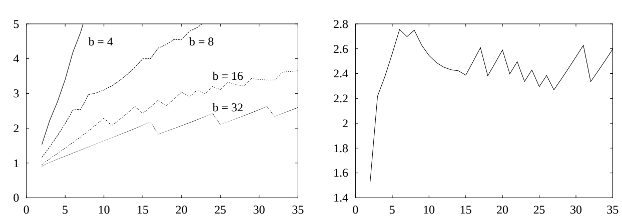
Figure 2. Successor difference based partitioning hardware

A possible hardware implementation for generation of the deterministic partitions is shown in figure 2, utilizing the difference of $D = P(c,b,i+1) - P(c,b,i)$, where $P(c,b,i)$ is defined by equation 8. The difference, D, reduces to $c+S$ unless $(c(i+1)+b)\ mod\ S < (ci+b)\ mod\ S$, in which case it reduces to c.

In this implementation, both the register *Add* and the counter *ShiftIncrement* are set to the first element of the current partition, which is always equal to the partition number. Register *Add* continuously holds the current remainder group of the current element in the partition subsequently; the current remainder group is updated whenever that element is reached in the scan chain. The *ShiftIncrement* counter is reloaded with the difference between $P(c,b,i+1)$ and $P(c,b,i)$ upon reaching zero. After the whole scan chain is shifted, the process restarts from the beginning.

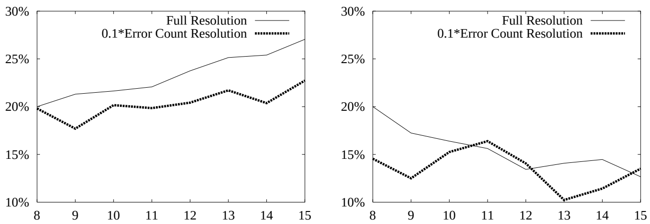
5 Experimental Results

We initially perform experiments in order to verify diagnosis time reductions, compared to the scheme proposed in [4], attainable through utilization of the superposition principle in the analysis phase of the diagnosis algorithm. Figure 3a, 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.



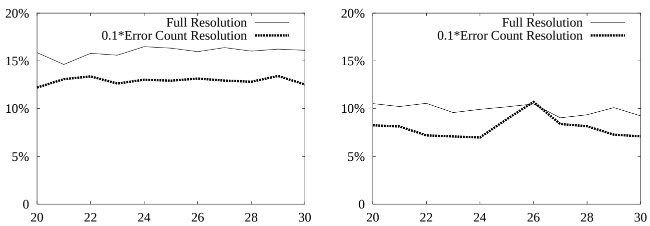
a) For various partitions b) For optimum partition sizes

Figure 3. Ratio of diagnosis times of [4] to that of proposed scheme



Without superposition With superposition

Figure 4. Improvements for $S = P = 17$



Without superposition With superposition

Figure 5. Improvements for $S = P = 31$

Figure 3b, therefore, provides the diagnosis time ratio of the two 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.

Additional experiments are performed to determine the effect of the deterministic partitioning schemes on the expected fault diagnosis time. We compare our results to ones obtained by the LFSR-based fault diagnosis procedure suggested in [4]. We also compare our results to the ones obtained by utilization of the superposition principle in order to observe additional improvements.

Simulations are performed on two prime number of partitions, 17 and 31, due to their proximity to 16 and 32; LFSR-based partitioning forces the number of partitions to be powers of two. For a fair comparison the number of partitions needs to be identical, yet the two schemes display conflicting requirements in this matter. The primes 17 and 31 are selected not only because they are adjacent to the corresponding powers of 2, but also because they end up bestowing a slight advantage on alternating schemes.

While Figure 5 shows the improvement in diagnosis time for a deterministic partitioning of 31 partitions compared to a pseudo-random partitioning of 32 partitions, figure 4 shows the improvement for a deterministic partitioning of 17 partitions compared to a pseudo-random partitioning of 16 partitions. The figures show improvement for both full diagnostic resolution in which all failing cells are exactly identified and diagnostic resolution of $0.1 \times Error\ Count$[1].

[1]The diagnosis resolution metric of $0.1 \times Error\ Count$ originally suggested in [4] is defined as the time at which that many fault-free scan cells remain unsieved and still reside in the candidate failing scan cell set.

The results of [4] have been utilized whenever available, as in the case of some of the diagnosis results for the resolution metric of $0.1 \times Error\ Count$; results have been generated otherwise by implementing the procedure outlined.

The results indicate that deterministic partitioning improves diagnosis time consistently. A few parameters effect the level of improvement; the improvement is higher for full diagnostic resolution and without superposition. While pseudo-random partitioning exhibits good diagnostic resolution up to a point easily, full resolution benefits significantly from deterministic techniques. Utilization of the superposition principle effectively removes the overlap between the partitions that are superposed and therefore reduces the improvement due to the minimal overlap property of deterministic partitions.

6. Conclusion

Utilization of the superposition principle for the analysis phase and a deterministic partitioning technique for the partitionining phase of the diagnosis procedure of designs with scan-based BIST is proposed in this work. Both proposed improvements are compared to that of LFSR-based techniques and the superiority of the proposed techniques is proven through fault diagnosis simulations.

Though hardware generation of deterministic partitioning is highly challenging especially within low area overhead, the regular partition structures identified in this work enable such low cost hardware implementations. The implementation regularity, the associated reduction in hardware overhead, and the average diagnostic time superiority introduce deterministic partitioning as a powerful new BIST-based diagnosis tool.

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