Syndrome Signature in Output Compaction for VLSI Built-in Self-Test

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In this paper, we focus on the use of signature-based output compaction technique for built-in self-testing of VLSI circuits. We give algorithm for single-output and multiple-output signature generation using exhaustive test patterns extending the syndrome concept. The signature we develop is a functional signature and is very effective for both input and internal line fault detection, as seen from simulation on various benchmark circuits. The signature generators can be easily implemented using the current VLSI technology.

Keywords: Syndrome signature, output compaction, built-in self-testing, VLSI circuits

1. INTRODUCTION

As the digital circuit technology is moving to high densities of integration, built-in self-testing (BIST) has become a primary issue in the realm of VLSI circuit design. Techniques for design for testability and built-in self-test consider the testing problem during the design stage of digital devices and have been found to be extremely effective. The central idea behind built-in self-testing or BIST is to have the chip test itself. This technique generates test patterns and evaluates output responses inside the chip [4, 9, 12]. It is already well recognized that

BIST can significantly improve the testability of VLSI chips and save testing time as well.

The test patterns used in BIST can be either random or exhaustive. Exhaustive test patterns have the following advantages over random test patterns:

- test patterns can be generated with relative ease,
- no specific fault models are required, and
- a high fault coverage can be achieved.

However, the main drawback of using exhaustive test patterns is the exponential growth of test length with increase in the number of inputs [8].

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The test output responses in BIST are compressed by output response analyzer into signature. The signature is compared with a known correct value, and faults are detected if a match does not occur. The various available output compaction techniques include parity-bit checking [1–3], transition count [6], ones count [11], Walsh coefficients [7, 13], and linear feedback shift register or LFSR [5]. Based on these approaches, the compressed response data can be used to evaluate the correctness of the circuit under test (CUT).

In this paper, we have proposed an output data compression technique called syndrome signature, particularly suited for exhaustive testing of VLSI circuits. The syndrome signature is based on and an extension of the novel idea of syndrome of a circuit originally conceived by Savir [10] and is related to the number of minterms realized by the corresponding switching function. The signature derived is an $(n+1)$ -element vector consisting of the primary syndrome of the function and n other subsyndromes corresponding to the subfunctions obtained by setting each of the n input variables to 0 or 1. The proposed technique is implemented on various ISCAS 85 benchmark combinational circuits (both single- and multiple-output), and the results look very encouraging.

2. SYNDROME SIGNATURES

A single-output syndrome signature is defined as follows. For an n -input single-output combinational switching function F with input variables $x_1, x_2, \dots, x_n$, the syndrome signature $s(F)$ of F is given by an $(n+1)$ -element vector $s(F) = \langle s_0, s_1, \dots, s_n \rangle$ where $s_0 = s_0(F)$ and $s_i(F) = s_i(F_0^i)$, $i = 1, 2, \dots, n$, s_0 denoting the primary syndrome, while s_i denoting the subsyndrome of the subfunction (F_0^i) obtained by setting the i th variable in F equal to b (0 or 1).

Example 1 Assume a 4-input combinational function $F(x_1, x_2, x_3, x_4)$ defined by the truth table of Table I. The syndrome signature $s(F)$ of F is given by the five-element vector: $s(F) = \langle 3/8, 5/8, 1/2, 1/2, 1/8 \rangle$ where $s_0 = s_0(F) = 3/8$, and $s_i = s_i(F_0^i)$, $i = 1, 2, \dots, 4$, s_0 denoting the primary syndrome of the function F , with s_i representing the syndrome of the subfunction (F_0^i) obtained by setting the i th variable in F equal to b (0 or 1) as shown in Table I.

Figure 1 shows a straightforward implementation of this $(n+1)$ -element signature in which the $(n+1)$ bit streams of interest are directed towards syndrome registers with equality checkers as an extension of the scheme as used for primary syndrome by Savir [10].

TABLE I Syndrome signature for a four-variable function

x_1	x_2	x_3	x_4	f	$f_0^{x_1}$	$f_0^{x_2}$	$f_0^{x_3}$	$f_0^{x_4}$
0	0	0	0	1	1	1	1	1
1	0	0	0	0		0	0	0
0	1	0	0	0	0		0	0
1	1	0	0	0			0	0
0	0	1	0	0	0	0		0
1	0	1	0	0		0		0
0	1	1	0	0	0			0
1	1	1	0	0				0
0	0	0	1	1	1	1	1	
1	0	0	1	1		1	1	
0	1	0	1	1	1		1	
1	1	0	1	0			0	
0	0	1	1	1	1	1		
1	0	1	1	0		0		
0	1	1	1	1	1			
$s(F) = \langle 3/8,$					$5/8,$	$1/2,$	$1/2,$	$1/8 \rangle$

FIGURE 1 An implementation of single-output syndrome signature.

The concept of single-output syndrome signature can be readily extended to the multiple-output case. Evidently, the simplest strategy to extend the single-output syndrome signature to the multiple-output case is to generate a separate signature for each output. Given an n -input m -output combinational circuit, a multiple-output syndrome signature is generated by EXORing all the outputs to produce a single new output which is then fed to a single-output syndrome signature generator.

Figure 2 shows the proposed implementation of a multiple-output syndrome signature. Consider as illustration of multiple-output syndrome signature the following example.

Example 2 A 4-input 2-output function together with its multiple-output syndrome signature is given in Table II.

3. SYNDROME SIGNATURE PROPERTIES

Some desirable properties of syndrome signature $s(F) = \langle s_0, s_1, \dots, s_n \rangle$ for an n -variable switching function F are summarized below:

FIGURE 2 Proposed implementation of multiple-output syndrome signature.

THEOREM 1 A syndrome signature $s(F) = \langle s_0, s_1, \dots, s_n \rangle$ for an n -variable switching function F is a functional signature.

Proof The proof of the theorem follows obviously since a syndrome signature does not depend on the particular implementation involved in its realization. $\square$

THEOREM 2 A syndrome signature $s(F) = \langle s_0, s_1, \dots, s_n \rangle$ for an n -variable switching function F is test-order independent.

Proof It is evident that the order in which the exhaustive test patterns are generated has no effect on the number of minterms realized by the function F as well as by the n subfunctions $s_i(F_0^i)$, $i = 1, 2, \dots, n$, and hence in the signature. $\square$

THEOREM 3 A syndrome signature $s(F) = \langle s_0, s_1, \dots, s_n \rangle$ for an n -variable switching function F is nonuniform.

Proof For an n -input arbitrary combinational function F , the parity-bit signature $s(F)$ of F is uniform since all of the $2^{(n+1)}$ possible $(n+1)$ -bit signatures are equally likely to result. With most counting procedures, this is, however, not the case. Some signatures are more likely to occur than others, thus making the signature nonuniform.

To prove the nonuniformity of the syndrome signature, consider the first element s_0 of the syndrome signature $s(F)$. Now s_0 is the syndrome of F and can have any value (nonnormalized) between 0 and 2^n .

Now there can be 2^{2^n} possible ways of assigning 2^n input combinations to F , and of these exactly $2^n C_K$ result in an F with the same number of minterms or syndrome K . Hence, the probability that the function F has the syndrome K ($0 \leq K \leq 2^n$) is $2^n C_K / 2^{2^n}$, which obviously is a function of K , unlike the probability of its parity $p(F)$ being 0 or 1, which is $1/2$.

We can similarly prove this for the other elements of the signature $s(F)$. Consider, for instance, the $(i+1)$ th signature element s_i , $0 \leq i \leq n$,

same number of minterms m , some of which are different.

Case 1 $m-1$ minterms are identical, and only one minterm is different.

Obviously, since the functions consist of the same number of minterms, their primary syndromes are identical, i.e., $s_0(F_1) = s_0(F_2)$. Assume that the minterm m_1 of F_1 is different from the minterm m_2 of F_2 . If we now examine the n -tuples corresponding to minterms m_1 and m_2 , obviously m_1 and m_2 must differ in at least one variable position, say x_i . Here, x_i is primed in one and unprimed in the other. Hence $N(\bar{x}_i F_1) \neq N(\bar{x}_i F_2)$, N denoting the number of minterms in the respective reduced functions, according to Corollary 1. Thus, $s_i(F_{10}^i) \neq s_i(F_{20}^i)$, and the syndrome signatures are different.

Case 2 $m-2$ terms are identical, and two minterms are different.

Assume m_1, m_2 of F_1 are different from m'_1, m'_2 of F_2 . Then, m_1, m_2 and m'_1, m'_2 must differ in at least two variable positions, say x_i and x_j . In this case, $N(\bar{x}_i F_1) = N(\bar{x}_i F_2)$ as well as $N(\bar{x}_j F_1) = N(\bar{x}_j F_2)$, and hence $s_i(F_{10}^i) = s_i(F_{20}^i)$ and $s_j(F_{10}^j) = s_j(F_{20}^j)$.

Thus, there may be two switching functions comprised of the same number of minterms and having the same primary syndrome but might have some identical subsyndrome as well. This implies that their syndrome signatures are also identical.

Case 3 Similarly, we may consider the case where F_1 and F_2 are identical in $m-r$ minterms and differ in r minterms, and can conclude that their syndrome signatures for the case could possibly be identical.

Thus, the theorem follows in general. $\square$

The following results are related and important in the context of syndrome signature testability.

THEOREM 6 Consider two n -variable switching functions F_1 and F_2 and let F_1 and F_2 differ in M minterms. Then the minimum number of variables in

whose assignments in the truth table these must differ equals

$$\lceil \log_2 M \rceil$$

where $M = N_1 + N_2$, N_1 and N_2 being the terms in F_1 and F_2 respectively which are different ($N_1 = N_2 = M/2$).

COROLLARY 2 Let F_1 and F_2 be two n -variable switching functions and let F_1 and F_2 have M of their minterms different. Let F_1 and F_2 need $\lceil \log_2 M \rceil$ variables with all their possible combinations in such a realization. If any variable x_i has equal number of 0's and 1's in $M/2$ minterms in F_1 , any input line fault in x_i cannot change F_1 to F_2 having the same distribution of 0's and 1's. That is, the distribution of 0's and 1's must be different and as such

$$N(\bar{x}_i F_1) \neq N(\bar{x}_i F_2)$$

and

$$s_i(F_{10}^i) \neq s_i(F_{20}^i)$$

and hence the subsyndromes must be different for at least one such x_i .

4. VLSI IMPLEMENTATION ISSUES

The primary hardware in the implementation of the proposed signature generator is the syndrome register which can be readily implemented by using a counter. However, since the proposed signature generator, besides recording the primary syndrome, needs to record, for an n -variable function, n other subsyndromes, $s_i(F_0^i)$, each corresponding to one of the variables, x_i , in a parallel implementation of the signature generator we need to use a total of $n+1$ counters, the first one counting from 0 to 2^n-1 , while the rest n counters counting from 0 to $2^{n-1}-1$ each. This apparently leads to an excessive overhead in incorporating the signature

generator in a self-test environment. This is obviously a drawback if the implementation has to be strictly a parallel implementation.

One simple way to overcome this obvious shortcoming of the proposed generator is to use a serial implementation. In the serial implementation a single counter can be used to record both the primary syndrome and the other subsyndromes. The amount of storage is the same although RAM is smaller than flip-flop. The test strategy can be appropriately modified to take into account the nature of implementation.

Finally, the recent advances in VLSI technology may not prove to be a deterrent even in the parallel implementation of the signature generator. The inclusion of only binary counters consistent with the number of primary inputs may not be big hardware overhead afterall, while compared with the complexity of the original circuit that needs to be tested using BIST.

5. SYNDROME SIGNATURE ALGORITHM

A procedure describing an algorithm for testing a circuit for syndrome signature testability is presented here. The algorithm first calculates the fault-free syndrome of the circuit and then calculates the faulty syndrome for any given fault in the circuit. If the two syndromes are different, the circuit is syndrome testable and the procedure stops; otherwise, it proceeds with the signature calculation and tests for syndrome signature testability.

Procedure

1. Given the number of inputs n , calculate the number of rows and the number of columns.
2. Given the faulty input and the fault in it, start the process of initialization:

$X(n)=0$ Fault-free input array
 $XX(n)=0$ Faulty input array
 $A_{\text{sum}}=0$ Sum of fault-free outputs, whenever the output is 1. Final value of this

will give the fault-free (actual) syndrome.

$F_{\text{sum}}=0$ Sum of faulty outputs, whenever the output is 1. Final value of this will give the faulty syndrome.

and also, for $m=1, n$

$A_{\text{subs}}(m)=0$ Sum of the fault-free outputs for each of the reduced functions, whenever the output is 1. Final value of this will give the actual subsyndromes.

$F_{\text{subs}}(m)=0$ Sum of the faulty outputs for each of the reduced faulty functions, whenever the output is 1. Final value of this will give the faulty subsyndromes.

3. Main calculation loop

Generate next fault-free and faulty input pattern (to start with, an all 0's combination will be the first fault-free input pattern and an all 0's combination with a given fault inserted will be the corresponding faulty input pattern).

Calculate actual and faulty functions, a_F and f_F respectively and perform the following assignments:

If $a_F = 1$, increment A_{sum} by 1

If $f_F = 1$, increment F_{sum} by 1

Now calculate fault-free and faulty subsyndromes as:

For $m=1, n$

– If $X(m)=0$ and $a_F=1$ increase then, $A_{\text{subs}}(m)$ by 1

– If $X(m)=0$ and $f_F=1$ increase then, $F_{\text{subs}}(m)$ by 1

Repeat Step 3 until all the combinations ($2n$) are done.

4. The decision to be made here is:

Is A_{sum} equal to F_{sum} ?

If false, then the circuit is syndrome testable and goto Step 2;

If true, try syndrome signature testing and goto Step 2 until all faults of interest are analyzed.

Note Division by 2^n on final A_{sum} and F_{sum} and by 2^{n-1} on final $A_{\text{subs}}(m)$ and $F_{\text{subs}}(m)$ are not performed here (according to the definitions of syndrome and subsyndromes), as we are doing only the comparison. Also, this avoids the round-off errors while computing these values as the circuit size increases.

6. EXPERIMENTAL RESULTS

To verify the proposed syndrome signature method, simulations were performed on combinational circuits. The simulator (implemented on a 486 PC) consists of an input pattern generator, logic simulator, output compressor, and fault generator. All possible single stuck-at faults were introduced on primary input lines and on internal lines of the ISCAS 85 benchmark circuits, and the outputs were compressed by syndrome signature technique. Fault-free signatures were compared with the faulty signatures using syndrome counters.

In general, the dominating factors in the simulation were the number of input patterns and the number of faults that were injected. Some of the benchmark circuits are not very large and can be handled quite easily whereas some others are really large with respect to the number of primary inputs, internal lines and primary outputs. Since our method of testing using syndrome signature (in case the primary syndrome fails) is exhaustive, as far as input test patterns are concerned, storage and time become a problem if the circuit has more than 20 inputs. One obvious way out of such a situation is to partition the circuit into certain subcircuits depending on the dependence of a particular output on a proper subset of the inputs to make the problem tractable. We used this technique in the case of large benchmark circuits.

The results obtained can be considered to be sufficient to show the implementation of the proposed technique on large combinational logic

circuits. We have considered both, the primary input as well as the internal line faults. Since our major objective was only to see how the benchmark circuits relate to our concept of syndrome signature for detection of single faults, no attempt has been made to keep track of the CPU time.

It can be seen from the results that benchmark circuits "C17", "CKT" and a subcircuit (considering only that output which depends on less than 20 inputs) of "C432" are syndrome testable for both input and internal line faults. The fourth circuit, "C880", was partitioned into several subcircuits. Only two subcircuits of "C880" were considered for experimentation, one with 13 inputs and 9 outputs and the other with 10 inputs and 1 output. For some input and internal line faults, these subcircuits are syndrome testable, while for some they are syndrome signature testable. There are some faults which are neither syndrome nor syndrome signature testable.

Tables III and IV show the number of faults missed by syndrome (and their percentage) as well as the number of faults missed by syndrome signature (and their percentage) with respect to the total number of faults injected in each case of single-output and multiple-output circuits. In our simulation results, in case of single-output circuits, syndrome signature has provided the same fault coverage as that of syndrome, but for multiple-output circuits syndrome signature has given better fault coverage than syndrome.

Since in most of the multiple-output benchmark circuits we used circuit partitioning, we never had to consider number of inputs exceeding 18 which generates 2^{18} test patterns and could be handled without appreciable difficulty. With today's computing power, normally 2^{20} test patterns could be generated in less than 1 ms and as such testing a particular fault of interest should not be much of a problem, even if the syndrome signature (which uses exhaustive test patterns) needs to be used. Obviously, the signature would be working in most of the cases where the syndrome fails, though there may be cases where this signature might also fail.

TABLE III Single-output circuits

CUT	N_{Tot}	M_s	$\%M_s$	M_{ss}	$\%M_{ss}$
CKT	24	none	0	none	0
C432	72	none	0	none	0
C880 (10 inputs)	84	54	64	54	64

N_{Tot} : Total number of faults injected.

M_s : Number of faults missed by syndrome.

M_{ss} : Number of faults missed by syndrome signature.

TABLE IV Multiple-output circuits

CUT	N_{Tot}	M_s	$\%M_s$	M_{ss}	$\%M_{ss}$
C17	18	none	0	none	0
C880 (13 inputs)	38	6	16	none	0

N_{Tot} : Total number of faults injected.

M_s : Number of faults missed by syndrome.

M_{ss} : Number of faults missed by syndrome signature.

7. CONCLUSIONS

In this paper, we have proposed an output data compression technique called syndrome signature, particularly suited for exhaustive testing of VLSI circuits. The syndrome signature is based on and an extension of the novel idea of syndrome of a circuit originally suggested by Savir [10] and is related to the number of minterms realized by the corresponding switching function. The results of implementation on some ISCAS 85 benchmark circuits (involving both single-output and multiple-output circuits) look very promising. Some circuits which according to Savir need extra inputs in order to make them syndrome testable, are shown to be syndrome signature testable. Also, the signature generation discussed for multiple-output circuits seems to work and preserves all the desirable properties of the single-output response analyzer. Masking effect of the proposed signature generator does not seem to be very high as only one case was reported from 11 sample circuits, use although an extensive simulation is needed for this statement to hold true, which is an important measure of a good compression technique.

Though this paper is not primarily about the VLSI implementation of the proposed signature

generator, some thought has been given in this direction. The size of the compactor seems high as compared to the commonly used methods. The counters will require $O(n^2)$ flip-flops and $O(n^2)$ XORs and ANDs. In an n -input combinational circuit, this seems an excessive overhead in incorporating the signature generator in BIST environment. If the implementation is strictly a parallel implementation, this can be considered as a drawback of the proposed signature generator. On the other hand, the serial implementation has the advantage of requiring only n flip-flops, but, a disadvantage of requiring $n \cdot 2^n$ tests (thus increasing the test time). The number of memory cells required is the same as that of in parallel implementation.

As the main drawback of exhaustive test patterns is their exponential growth with the number of inputs, such exhaustive testing is acceptable in cases (most of the benchmark circuits) where combinational circuits can be partitioned into circuits of under 20 inputs to keep the testing time under control.

Further research in this area needs to focus on relative effectiveness of the syndrome signature technique as a useful test compaction tool for fault detection through implementation of many more

real world circuits where conventional syndromes fail. Also, implementation of such a signature in VLSI could be a real worthwhile sequel to the whole exercise.

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