Test Time Reduction in Scan Designed Circuits

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Abstract

The reduction of test application time for the general scan designed circuits had been studied. The reduction problem had been investigated from three aspects: the test generation, selective scan, and rearrangement of scan path. The two phase testing strategy had been proposed to employ scan only for the hard-to-detect faults. Four cases of selective scan had also been identified. Furthermore, an ordering heuristic without layout constraint had been proposed to maximize the reduction of unnecessary scans and hence the test application time. Applying these reduction methods, the total test clock-cycles can be reduced to only 20% on average for ISCAS sequential benchmark circuits with partial scan.

1 Introduction

The progress of very large scale integration (VLSI) technology has brought tremendous improvement in chip performance as well as gate density. The increasing complexity, however, renders the testing of a VLSI chip much more difficult. For large sequential circuits, the automatic test pattern generation (ATPG) is quite time consuming and the resultant fault coverage is often unacceptably low. The remedy is naturally to take into account the testability while designing a chip, i.e., the design for testability. The most popular approach in design for testability is the scan design such as full scan[1] and partial scan[2]. In the scan design, all or part of flip-flops (FFs) in a chip are interconnected into a scan chain during test mode so that all these scan flip-flops (SFFs) can be controlled/observed by scan-in/scan-out operations. As a result, the test generation problem can be significantly reduced[4]. However, the test application time of a scan-designed circuit is in general lengthened because of the extensive scan operations to shift in the patterns and shift out the responses. The reduction of test application time for scan designed circuits is the main concern of this paper.

To reduce the scan operations in a scan designed circuit, a straightforward way is to increase the number of parallel scan chains, with additional overhead in pins. Recently, novel approaches[5, 6, 7] have been

proposed to reduce test application time by rearranging and modifying the scan path. These approaches are constrained by the given test sequence and do not exploit the benefit from test generation. Moreover, some[6, 7] even have relied on the pattern independence of the full-scan circuits, which in general does not hold in the partial-scan designed circuits.

In this paper, the reduction of test application time of general scan designed circuits is studied. The problem is investigated from three aspects: the test generation, selective scan, and rearrangement of scan path. It will be shown in our experimental result that by allowing arbitrarily ordering of scanned flip-flops in the partial scan chain, the test application time can be reduced to only 20% on average.

In the next section, the reduction methods for the test application time of scan designed circuits will be described. Then the evaluation results on the sequential benchmark circuits will be provided. And finally the conclusion will be given.

2 Test Time Reduction for Scan Designed Circuits

In this section, our reduction method for the test application time of scan designed circuits will be described.

First we will introduce a measure of test application time. In a scan designed circuit, the content of the scanned flip-flops (SFFs) can be controlled and observed by serial shift operations of the scan chains. Let S be the number of scanned FFs, T the number of test patterns, and P the number of scan chains. Then for each applied test pattern, S/P shift operations plus one actual testing operation are required. The response to be shifted out can be overlapped with the scan-in of the next pattern. Assuming that both shift operation and testing operation take the same amount of time, say one clock cycle, then for each pattern, $(S/P + 1)$ clock cycles are required and for T patterns, $T * (S/P + 1) + S/P$ where the last term S/P is due to the response scan-out of the last pattern. Define the above required clock-cycles as the total test clock-cycles (TTCs), i.e.,

$$TTCs = T * (S/P + 1) + S/P.$$

Without loss of generality, we assume that there is only one scan chain in the given circuit, $P = 1$.

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Given a scan path, the test application time can be reduced by exploiting and eliminating unnecessary scan operations. The reduction can be achieved in the test generation, selective scan, and the arrangement of scan path. They will be briefly described in the sequel.

2.1 Two Phase Test Generation

The two phase test generation strategy is based on the observation that in most scan designed circuits, a majority of faults can be easily detected even without scan. To take advantage of the above observation for reducing scan, the testing of a circuit can be separated into two phases: in the first phase, the circuit is tested as a scanless circuit, and only in the second phase is the scan path utilized. To accommodate this testing strategy, the test generation is also split into two phases: the scanless phase for easy-to-detect faults and the scan phase for hard-to-detect faults.

One might suspect that by splitting into two phases, the test application time would be adversely lengthened. It will be demonstrated later that, with careful consideration, the converse is true. Significant reduction in scan and test application time can be obtained with this simple two phase testing strategy.

The balance between these two phases can be determined as follows. In a sequential ATPG, the limit of iterative time frames (F) can be set by users. A fault which can be test generated within F is in phase 1, otherwise it belongs to phase 2. Clearly, too large an F would include many hard-to-detect faults in the first phase and inevitably lengthen the test sequence. On the other hand, a small F could drive most faults to the second phase and thus need more scan operations. Since the test cycles to place a given fault in phase 1 is no more than F and in phase 2 is proportional to $(S + 1)$, which is the test cycle number for each test pattern, we could restrict iterative time frames in phase 1 such that $F < K * (S + 1)$, where K is a given number. The implication of K is the average number of test patterns for each fault to be detected in phase 2. The number K unfortunately can not be known a priori. However, in our experiment, it is found that $K = 2$ consistently quite good result in all evaluated cases. A slightly better result is obtained by simply letting our ATPG determine when to abort a fault to phase 2.

It is also worth noting that the two phase testing strategy does not require any additional hardware, i.e., no overhead except that of an ordinary partial scan.

2.2 Selective Scan

The objective of shift operations in the scan design is to control the scan elements and to observe the effect of the previous pattern. However, it is not always necessary to control and observe every scanned element in every test pattern. Certain bits in a given pattern may be don't-care and response bits provide detection information only occasionally[5]. This sparseness of information in SFFs can be further explored during the test generation.

During the second phase of the test generation, we modify the ATPG such that it deliberately leaves the pseudo PIs (SFFs) in don't-care whenever possible.

Figure 1: Scan Facility

The results show that averagely less than 28% of the scanned FFs in a circuit are used for actual test applying purpose, and less than 8% for actual response observing purpose.

Based on the above observation, we are to identify the unnecessary scan operations from a given test sequence with sparse information and to reduce the scan operations by selectively scanning. In the discussion, we assume that the scanned circuit has separate clock lines for the scanned flip-flops and the nonscanned flip-flops as shown in Figure 1. These two clock lines can be independently controlled to hold-data(disabled) or normal-operation(enabled) in each type of flip-flops. There is an additional control line in the scanned circuits, the Scan-Enable line, which enables the shift operation of the scanned flip-flops. The extra feature requires little overhead besides that required for scan design.

With these three control lines in a partial scanned circuit, the scanned flip-flops can be operated as shift-register(S), hold-data(H), or normal-operation(N) and the unscanned flip-flops can be in normal-operation(N) or hold-data(H). For example, the phase-one testing is performed in the NN mode and the shifting operation of the scan chain is in the SH mode.

Four cases of unnecessary scans are identified and methods of selective scan are devised to eliminate them.

1. **Actual Scan Requirement:** *The scan is only performed to shift in all the effective test bits to the right position and to shift out all the fault-effect response bits.*

For a test pattern, the straightforward ($TTCs$) is $S + 1$, where S is the number of scan elements in the scan path. However, from test generation, it is possible to obtain the response bits of T_i to be shifted out and the effective test bits of T_{i+1} to be shifted in. The positions of these bits on the scan path allow us to determine the number of actual scan requirement for T_{i+1} , which is less than or

Figure 2: Actual Scan Requirement

equal to S . For example, in Figure 2, the number of shift of the pattern is $MAX(SO, SI)$, where $SO(SI)$ is the the maximum distance of the effective response(test) bits from the scan-out(scan-in) pin.

This reduction method is supported by any partial scan designs. However, the reduction is heavily dependent on the ordering of scan elements.

2. **Delayed Scan-Out:** *The scan-out operations are not performed unless a fault-effect bit is in danger of being overwritten by a new response.*

As described earlier, the observation of fault effect on SFFs only happens occasionally. Hence additional scan reduction can be obtained if the rare fault effects can be held in the scan path so that their scan-out can be overlapped with the scan-in operations of the succeeding test patterns. For example, in Figure 2, if $SO > SI$ and there is no SFF to be observed for the succeeding patterns such as T_{i+1} and T_{i+2} , then only SI bits are shifted and the remaining fault effect bits of T_i can be held in the scan path to overlap its shift-out with the scan-in operations of the succeeding patterns.

This reduction method requires the scanned flip-flops to hold the scanning data without being over-written by the new but useless responses. This ability is supported in our scan facility.

3. **Reusable Scan-In:** *The scan-in operations are performed only to the point that all effective test bits are obtained.*

In our scan facility, a bit in the scan path can be held without being over-written by the responses. This bit can be a fault effect as in the delayed scan-out. It can also be a scan-in test bit which can then be used in the succeeding patterns at the farther positions of the scan path. For example, if there is a '1' at the third SFF of the scan path for T_i and a single '1' is also needed at the fifth SFF for T_{i+1} , then only two shift operations between T_i and T_{i+1} are required instead of the original five shift-operations. Therefore the scan number

can be reduced. This reduction is possible only when T_i does not need to observe any SFF and the original pattern is kept in the scan path by the hold operation.

4. **Concurrent Shift:** *If there is no immediate fault effect to be observed after applying a test pattern, one shift operation of the scan path can operate concurrently with the test application of the circuit.*

This concurrent shift utilizes the independent clocks of our scanned circuit, in which the scanned flip-flops perform the scan-in operation of the next pattern while the unscanned flip-flops are loading the response. The concurrent shift is able to reduce at most one shift per pattern. The reduction is in general not significant but there is one advantage in the concurrent shift. Unlike previous cases, it is independent of the ordering of scan path.

2.3 Rearrangement of Scan Path

The effectiveness of most selective scan methods described above depend on the ordering of SFFs in the scan path. Here we consider the ordering problem with the assumption that all permutations of SFFs are feasible. In other words, no physical constraint on the ordering is considered in this paper. However, we would like to point out that, in our reordering procedure, it is possible to take the constraints into account.

The shift requirement of controlling/observing an SFF directly depends on the position of this SFF in the scan path. An SFF placed close to the scan-out pin will require approximately S shift operations to set its value but only a few shifts can scan out its value for observation. On the other hand, an SFF positioned near the scan-in pin is significantly easier for scan-in. The ordering consequently must be a tradeoff of these two conflictive demands. Our heuristic is to take as a weight the difference of a SFF's controlling frequency and observing frequency obtained from test generation. And the ordering of the SFFs from the scan-in pin to the scan-out pin is determined by the descending order of this weight.

By our experiments, this ordering of SFFs gives fairly good results for our reduction methods.

3 Results and Discussion

ISCAS sequential benchmark circuits[3] are used to evaluate our reduction strategy. Each circuit is first partially scanned to attain an acceptable fault coverage, then two-phase test generated, and finally selectively scanned with scan path rearrangement. The scanned flip-flops are selected based on a structural criteria[9] to achieve reasonable fault coverage. For the evaluated circuits, the performance of the selection criteria is comparable to that of [11, 12, 13]. The test pattern generator is a conventional propagate-then-justify generator and has performance comparable to STG3[10].

The evaluation result is shown in Table 1. In this table, "Nonscan" is the result of the original scanless

circuits, "Scan" the partial scan circuits with "SFF" FFs scanned, "2-Ph" the two-phase test generation, and "Redu" the final reduced result. For each case, the upper datum is the fault coverage and the lower datum is the *TTCs* (Total Test Clock-cycles).

We can see from Table 1 that the two-phase test generation alone reduces the *TTCs* to 65.6% of the conventional partial scan. This reduction is achieved with ordinary scan path and without any selective scan. Applying the selective scan techniques and the ordering of SFFs, the *TTCs* can be reduced to 20% averagely, which indicates a very significant reduction in the testing cost.

In Table 2, we show the cumulative effect of our test reduction methods. The column "2-Ph" is the same as Table 1, and "+X" is the result when deliberately leaving don't-care on SFFs in the phase-two of test generation. Note that *TCCs* of "+X" are more than "2-Ph" because the ATPG's heuristic of setting the unassigned PIs in phase-two is sacrificed for the benefit of the later selective scan. The column "+Actual" is the actual shift requirement. And the column "+IO" is the result when further applying the delayed-scan-out and reusable-scan-in methods, while column "+Concur" the concurrent-shift method. The average efficiency of every reduction methods can be found in the last row of Table 2. Note that the increase of *TCCs* in "+X" is more than justified when subsequent selective scan is applied and *TTCs* are drastically reduced. Most of our proposed methods, except concurrent shift, provide significant reduction in *TTCs*. Since the concurrent-shift at best can save one clock-cycle for every pattern, its effectiveness is not so good as the other methods. On average, 80% total test clock-cycles reduction is achieved without restriction on the SFF ordering.

One might notice that the final fault coverage is slightly different from the original "Scan". This is because the modified ATPG sacrifice the heuristics for setting the unsigned SPIs and some faults are not detected without these heuristics. But for the circuit S5378, the fault coverage after test reduction become higher. This may due to that in the scan reduction, values are assigned to the unassigned SFFs during test generation and hence unintentionally detect some previously undetected faults

4 Conclusion

The reduction of test application time in scan-designed circuits had been considered in this paper. The reduction problem had been investigated from three aspects: the test generation, selective scan, and rearrangement of scan path. The two phase testing strategy had been proposed to employ scan only for the hard-to-detect faults. Four cases of selective scan had also been identified. Furthermore, an ordering heuristic without layout constraint had been proposed to maximize the reduction of unnecessary scans and hence the test application time. Applying these reduction methods, the total test clock-cycles can be reduced to only 20% on average for ISCAS sequential benchmark circuits with partial scan.

Although the evaluation had been performed for

the partial scan case with single path, we like to point out that all our discussions are also applicable to other scan designed circuits.

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Table 1: Results of Test Reduction

bench	FFs	SFFs	Nonscan	Scan	2-ph	Redu
s208	8	3	63.72 124	90.23 671	90.23 631	90.23 336
s298	14	1	86.04 137	94.81 693	94.81 514	94.81 362
s344	15	5	96.20 77	99.12 551	98.83 256	98.54 129
s382	21	6	76.19 140	97.49 1931	97.49 1504	97.24 697
s386	6	2	81.77 250	94.79 626	94.79 480	94.79 369
s400	21	7	76.65 226	97.88 1247	97.88 953	97.88 667
s420	16	7	41.63 142	93.49 3999	93.49 3869	93.49 1057
s444	21	6	76.16 167	94.30 2967	94.30 2063	94.30 1197
s510	6	4	0.0 0	100.0 749	100.0 749	100.0 977
s526	21	7	67.03 539	98.74 7071	98.74 5202	98.74 1886
s641	19	2	86.30 146	94.00 668	94.00 256	94.00 211
s713	19	7	81.93 139	88.12 919	88.12 346	88.12 212
s820	5	2	95.76 909	100.0 1334	100.0 1073	100.0 1019
s838	32	16	29.64 109	95.10 12137	95.10 11821	95.10 3455
s953	29	3	8.25 10	99.91 2003	99.91 1925	99.91 1268
s1423	74	17	67.39 344	87.20 40643	87.86 13501	86.54 1338
s5378	179	32	70.43 261	93.31 37091	93.33 30521	93.35 7207
average	Fcov. TTCs	31%	65.005 219	95.205 6782	95.23 4451	95.12 1317
ratio				100	65.6	19.4

Table 2: Accumulative Effect of Reduction Techniques

bench	Scan	2-ph	+X	+Actual	+IO	+Concur
s208	90.23 671	90.23 631	90.23 931	90.23 399	90.23 369	90.23 336
s298	94.81 693	94.81 514	94.81 582	94.81 570	94.81 438	94.81 362
s344	99.12 551	98.83 256	98.54 322	98.54 200	98.54 142	98.54 129
s382	97.49 1931	97.49 1504	97.24 3044	97.24 1390	93.24 846	97.24 697
s386	94.79 626	94.79 480	94.79 519	94.79 506	94.79 416	94.79 369
s400	97.88 1247	97.88 953	97.88 1729	97.88 1187	97.88 744	97.88 667
s420	93.49 3999	93.49 3869	93.49 5533	93.49 1978	93.49 1326	93.49 1057
s444	94.30 2967	94.30 2063	94.30 6193	94.30 2482	94.30 1360	94.30 1197
s510	100.0 749	100.0 749	100.0 1474	100.0 1424	100.0 1160	100.0 977
s526	98.74 7071	98.74 5202	98.74 7898	98.74 3572	98.74 2244	98.74 1886
s641	94.00 668	94.00 256	94.00 325	94.00 272	94.00 223	94.00 211
s713	88.12 919	88.12 346	88.12 402	88.12 281	88.12 225	88.12 212
s820	100.0 1334	100.0 1073	100.0 1139	100.0 1127	100.0 1075	100.0 1019
s838	95.10 12137	95.10 11821	94.75 24809	94.75 12616	95.10 3944	95.10 3455
s953	99.91 2003	99.91 1925	99.91 2665	99.91 2557	99.91 1676	99.91 1268
s1423	87.20 40643	87.86 13501	78.09 12727	78.09 2165	85.08 1387	86.54 1338
s5378	93.31 37091	93.33 30521	93.31 44942	93.31 17863	93.35 7786	93.35 7207
average	95.205 6782	95.23 4451	94.60 6778	94.60 2976	94.80 1492	95.12 1317
ratio	100	65.6	99.9	43.9	22	19.4