Design for Testability Method to Avoid Error Masking of Software-Based Self-Test for Processors

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SUMMARY In this paper, we propose a design for testability method for test programs of software-based self-test using test program templates. Software-based self-test using templates has a problem of error masking where some faults detected in a test generation for a module are not detected by the test program synthesized from the test. The proposed method achieves 100% template level fault efficiency, that is, it completely avoids the error masking. Moreover, the proposed method has no performance degradation (adds only observation points) and enables at-speed testing.

key words: software-based self-test, processor, test program template, design for testability, error masking, at-speed testing

1. Introduction

In recent years, it has been essential that processors with high performance and rich functionality have accurate and at-speed testing. Though the full-scan approach is commonly used due to its simplicity, it induces performance penalty, area overhead and excessive power consumption. The hardware built-in self-test (BIST), which is one of the other widely used techniques, applies pseudo-random test patterns to modules on the circuit at the normal operational speed. However, design modifications are required to make a circuit to be BIST-ready, and involve large amount of manual effort. The BIST also induces area overhead. Furthermore, an application of random patterns results in excessive power consumption.

A number of approaches [1]–[7] have been proposed for software-based self-test (SBST) as a promising approach to resolve the above problems. In SBST, we test a processor by executing a sequence of instructions called a test program. A processor can be tested by communicating with a memory, and thus it enables at-speed testing. We use communication between the memory and an outside ATE as pre- and post-processes of the execution of the test program.

Some methods among the SBST methods generate a test program based on test program templates targeting structural faults to achieve the high fault coverage [1], [2], [5]–[7]. In this approach, gate-level test generation is applied to generate test patterns for each module under test (MUT) of a processor (MUT test generation), and a test program is synthesized from the test patterns (test program synthesis), where a test program justifies the test pattern from the memory to the MUT and propagates the test response from the MUT to the memory. To guarantee the test program synthesis, test program templates are used. A test program template is an instruction sequence with unspecified operands that delivers a test pattern to an MUT and observes the test response. The approach extracts constraints on the input and output of the MUT from each template, and applies test generation for the MUT under the constraints. In this approach, we can easily synthesize a test program from a test pattern for the MUT. However, the justification and observation parts consider only behavior of a fault-free processor, and such parts might not work as expected. In this case, some faults detected by a test pattern for an MUT may not be detected by the synthesized test program. We call such a phenomenon “error masking.”

In this paper, we propose a design for testability (DFT) method that completely resolves the problem of error masking for any test program generated by the template-based SBST approach for the stuck-at fault. We show a sufficient condition to avoid error masking and propose the DFT method to make processors which satisfy the sufficient condition. The proposed method has advantages in that (1) it has no performance degradation in a sense that it does not add any gate in a critical path but only observation point, and (2) it enables at-speed testing. In the experimental results, we show the effectiveness of the proposed method on hardware overhead and test application time.

This paper is organized as follows. In Sects. 2 and 3, we show a processor model and test program generation using templates, respectively. In Sect. 4, we analyze error masking and define template level fault efficiency. In Sect. 5, we propose a sufficient condition to avoid error masking. In Sect. 6, we propose a DFT method of SBST for processors and the experimental results are shown in Sect. 7. Finally, the paper is concluded in Sect. 8.

2. Processor Model

A processor is specified by register transfer level (RTL) description. Figure 1 illustrates an example of a processor. A processor consists of combinational modules such as arithmetic logic unit (ALU) or multiplexer (MUX), sequential modules such as a controller, signals, and buses. A signal in an RTL description has a bit width, and is referred to as an RTL signal. A bus considered to be a tri-state bus [8]. For
a fault-free processor, we also assume the following about tri-state buses.

(1) Two or more inputs of a tri-state bus are not activated simultaneously.

(2) Each output of the tri-state bus has a masking circuit that generates a logic value (‘0’ or ‘1’), and an output of a tri-state bus is masked into some specific logic value if any input of the tri-state bus is not activated.

A processor is assumed to be synthesized while preserving the hierarchy of the modules, and therefore each module can be identified in a gate-level description.

3. Template-Based Test Program Generation

We first explain test program generation using test program templates. In the rest of this paper, we call a test program template a template. Figure 2 illustrates an example of a template, which consists of three sequences: a justification instruction sequence, a test instruction sequence and an observation instruction sequence. A justification instruction sequence is utilized for delivering test patterns to registers which are adjacent to inputs of a MUT. A test instruction sequence applies test patterns to the MUT and propagates the test response to registers that are adjacent to outputs of the MUT or the memory. An observation instruction sequence propagates the test response stored in registers to the memory. For each template, we extract constraints on the input space and the output space of the MUT and perform the MUT test generation under constraints.

Figure 3 illustrates a model of an MUT test generation under constraints extracted from a template. The input and output constraint are extracted from a template, where these constraints represent the relation between operands of a template and inputs of the MUT, and outputs of the MUT and outputs to the memory, respectively, in a fault-free processor. If a processor is fault-free, a test program synthesized from test patterns can justify test patterns of the MUT and observe the test responses at some primary output. However, in the case of a faulty processor, the test program might not justify test patterns of the inputs of the MUT or observe the test responses. We call a test program obtained by the test program generation using templates template-based test program and, in the rest of the paper, we restrict fault model to a stuck-at fault.

4. Error Masking

4.1 Template Level Fault Efficiency

In the test program generation method using templates, justification instruction sequences, and observation instruction sequences are generated only in consideration of the behavior of the fault-free processor. When applying a test program to the faulty processor, errors may appear during the execution of these sequences. Therefore, we cannot guarantee that the test program justifies test patterns of the MUT, or observe the test response. This means that some faults detected in the MUT test generation may not be detected by the test program synthesized from the generated test patterns. We call this phenomenon “error masking.” In this paper, we define template level fault efficiency ($F_E T$) as a measure to evaluate error masking as follows:

$$F_E T = \frac{FTP}{FMT},$$

where $F_{MT}$ is the number of faults detected in the MUT test generation and $FTP$ is the number of faults detected by the test program among the $F_{MT}$ faults. A template level fault efficiency of 100% means that there is no error masking.

4.2 Analyzing Error Masking

Figure 4 illustrates examples of error masking using a time frame expansion model of the execution of a test program, where each time frame corresponds to one clock. In the time frame expansion model, time frames that apply test patterns...
to the MUT are called “test frame”, while time frames before the test frame are called “justification frames” and time frames after the test frame are called “observation frames.” Modules \( M_j \), \( M_f \) and \( M_o \) denote the same MUT which appears repeatedly in different time frames. In this figure, we describe the value of an RTL signal as “the value in fault-free circuit/value in faulty circuit.” We consider four values ‘0’, ‘1’, ‘X’ (uninitialized value) and ‘Z’ (high-impedance) for each bit of an RTL signal line. We consider ‘X’ and ‘Z’ to be unknown value, and an error of an RTL signal line means that at least one bit has different known values.

Figure 4 (a) illustrates an example of error masking induced by an unknown value. In Fig. 4 (a), unknown values reach an input of \( M_f \) and logic values reach another input. If \( M_f \) operates correctly, unknown values do not appear the output of \( M_f \). However, if \( M_f \) operates incorrectly under the effect of the fault, an unknown value is propagated to its output. This causes that value ‘01/0X’ is propagated to an input of \( M_f \) at the test frame and fails to excite the fault at the test frame.

Figure 4 (b) illustrates an example of error masking induced by a cycle of an RTL circuit. In this case, there is a cycle including the MUT. In Fig. 4 (b), the fault is excited at \( M_f \) in a justification frame and errors appear the output of \( M_f \). The errors reach inputs of \( M_o \) in the test frame. A fault of \( M_f \) is not excited because incorrect test patterns reach to inputs of \( M_o \).

Figure 4 (c) illustrates an example of error masking induced by a convergence of errors. In Fig. 4 (c), the same fault in \( M_f \) and \( M_o \) is excited, and the errors are propagated through two paths \( p_1 \) and \( p_2 \) meet at some module \( M_R \). The multiple errors mask each other in \( M_R \) in the observation frame and no error is propagated to the output of \( M_R \). In this case, there are reconvergent paths between the MUT and some module.

5. **Sufficient Condition to Avoid Error Masking**

In this section, we show a sufficient condition to avoid error masking. In the sufficient condition, we utilize a reconvergent path.

**Definition 1 (Reconvergent Path):** Let \( M \) and \( M' \) be modules. Paths \( p_i \) and \( p_j \) are reconvergent paths from \( M \) to \( M' \) if both \( p_i \) and \( p_j \) are paths from \( M \) to \( M' \), and \( p_i \) and \( p_j \) share no module except \( M \) and \( M' \).

We give the following two assumptions for a test program.

- The value stored in the memory cell referred to during the execution of the test program is known. That is, in the fault-free processor, unknown values are not propagated from the memory to the processor.
- The memory cell written during the execution of the test program is initialized to a different value from the expected value, which will be stored in the memory cell during the execution of the test program.

In this paper, we consider a fault is detected in the following cases.

(A1) No value or an unexpected value is stored in some memory cell where the test program should write some expected value.

(A2) The test program fails to read a value from a memory cell designated to be read in the test program.

The second condition (A2) holds if the memory address lines are observable. However, even if they are not observable, we consider such incorrect behavior would cause some observable errors.

To guarantee that the proposed method can achieve 100% template level fault efficiency, we show a sufficient condition for a processor such that error masking does not occur during the execution of the template-based test program.

**Theorem 1:** For any template-based test program, error masking does not occur during the execution of the test program if a processor satisfies the following four conditions.

1. Each register is initialized at the beginning of the execution of the test program.
2. All the control signals of each tri-state bus and its masking circuits are observable.
3. For each cycle, at least one RTL signal on the cycle is observable.
4. For each pair of reconvergent paths, at least one RTL signal on the two paths is observable.

**Proof:**

Let \( f \) be a stuck-at fault detected by an MUT test generation in template-based test program generation. We consider the execution of a test program for \( f \). Let \( M \) be a module with \( f \).
First we show that $f$ is detected or a value of any RTL signal of the processor is known. Since all the registers are initialized to known values at the beginning from condition (1), if some signal has an unknown value, it comes from the outside or is generated at the inside of the processor. If $f$ is not detected, (A2) implies that values are read from the same memory addresses in both correct and faulty processors. Since the memory cells where the test program refers to have known values, unknown values are not propagated from the outside of the processor. Moreover, if $f$ is not detected, condition (2) implies that there is no error on control signals or masking circuits of tri-state buses. Therefore, any output of any bus has a value of some activated input of the bus or a known value generated by its masking circuit. Since the value of any RTL signal can be determined by values of primary inputs, registers, and bus outputs, any RTL signal has a known value.

Then we show that $f$ is detected or the test pattern reaches $M$. We assume that the test pattern of $f$ does not reach the inputs of $M$. We consider the registers used in order to justify this test pattern in the correct operation of the processor. In this case, there is a bit $b$ of a register among them such that $b$ has a different value from the correct value. If $f$ is not detected, any RTL signals have known values and the value of $b$ is an error. Since an error is only caused by $f$ of $M$, a path $P$ through $b$ from an output of $M$ to an input of $M$ exists and the error is propagated on $P$. Since at least one RTL signal on each cycle is observable from condition (3), at least one RTL signal on $P$ is observable and the fault is detected. Therefore, $f$ is detected or the test pattern for $f$ reaches the inputs of $M$.

Finally, we show that the test response of $M$ is propagated to an intended primary output or $f$ is detected. The output of $M$ can be observed at a primary output in the fault-free processor. Therefore, there exists a path $P$ such that an error is propagated from $M$ to an primary output. Suppose the fault is not detected. In this case, an error is not propagated to any primary output, and there exists a module $M'$ such that the error is prevented from propagating on $P$. If $M'$ is not faulty and errors are propagated to $M'$ only through $P$, the errors are propagated to the outputs of $M'$. Therefore, (a) $M'$ is faulty that is $M = M'$, or (b) errors are propagated to some inputs of $M'$ which are not on $P$.

(a) If $M'$ is $M$, errors are propagated on a cycle, and are observed from condition (3) and therefore $f$ is detected.

(b) If errors are propagated to some inputs of $M'$ which is not on $P$, errors are propagated on two reconvergent paths from $M$ to $M'$. By condition (4), errors are observed and $f$ is detected.

Therefore, a fault $f$ detected by MUT test generation can be detected during the execution of a test program synthesized from the test pattern for $f$.

6. Design for Testability Avoiding Error Masking of Software-Based Self-Test

6.1 Formulation

We propose a DFT method to avoid error masking. First, we consider the following DFT elements since we add only initialization functions of registers and observable points to the original design in order to satisfy the sufficient condition in Theorem 1.

- Add an initialization function to a register
- Add an observation point to an RTL signal

Since an advantage of SBST is the possibility of at-speed testing, it is important that the processor after DFT also preserves the possibility of at-speed testing. Therefore, we capture the values of RTL signals at the normal operational speed. We use a multiple input signature register (MISR) for this purpose.

In order to satisfy the sufficient condition, it is necessary to add initialization functions to registers which do not have it. Therefore, it is no room to consider an optimization problem for initialization functions. We formulate the problem to minimize the number of observation points as follows.

**Error Masking Resolution Problem:**

**Input:** An RTL description of a processor

**Output:** An RTL description of an augmented processor that can achieve 100% template level fault efficiency for any template-based test program

**Objective:** To minimize the sum of the bitwidths of RTL signals that are made observable

6.2 Algorithm

We propose a heuristic algorithm in order to solve the error masking resolution problem. In the proposed algorithm, we utilize a circuit graph, a reconvergent structure and a path dependency graph.

**Definition 2 (Circuit Graph):** The circuit graph is a directed graph of an RTL circuit $GC = (VGC, EGC)$, where $v \in V$ is a vertex corresponding to a combinational module, a sequential module, a register, a primary input and a primary output and $e \in EGC$ is an edge corresponding to an RTL signal and has the weight corresponding to the bitwidth of the RTL signal.

**Definition 3 (Reconvergent Structure):** Let $M$ and $M'$ be modules. A set of all the paths from $M$ to $M'$ is called a reconvergent structure $S$.

**Definition 4 (Path Dependency Graph):** Let $V_{ReconvP}$ be a set of paths in all the reconvergent structures. Let $E(p)$ be a set of edges in a path $p$. A reconvergent path dependency graph is a bipartite graph $G_{PD} = (V_{ReconvP} \cup V_r, E_{PD})$, where
Step 3.1: For each cycle in the circuit graph, we can identify which paths share an edge. We find a set of RTL signals such that every path has at least one RTL signal on the cycle is made observable. For each register in the processor, an initialization function is added if the register does not have the function, and all the control signals of each tri-state bus and all the control signals of its masking circuits are made observable.

Step 3.2: Let $E_{cut}$ be a set of edges corresponding to the RTL signals to be observed. We initialize $E_{cut}$ to be empty. From the set of edges in $C_{min}$, the edge $e_i$ with the minimum weight among the edges that appear in the maximum number of cycles in $C_{min}$ is selected. The edge $e_i$ is removed from $G_C$ and added to $E_{cut}$, and the cycles that include $e_i$ are removed from $C_{min}$. This process is repeated until $C_{min}$ becomes empty.

Step 3.3: Step 3.1 and 3.2 are repeated until $G_C$ becomes acyclic. The circuit graph obtained in this step is referred to as $G_C^1$.

Step 3.4: If some of the edges in $E_{cut}$ obtained by processing from Step 3.1 to Step 3.3 is restored to $G_C^1$, the circuit graph may not become cyclic. For each $e_i \in E_{cut}$, if the circuit graph becomes acyclic when $e_i$ is added to it, $e_i$ is removed from $E_{cut}$ and $e_i$ is restored to $G_C^1$. The circuit graph obtained in this step is referred to as $G_C^0$.

Step 4: Let $P$ be a set of paths in all the reconvergent structures in $G_C^0$. We find a set of RTL signals such that every path has at least one RTL signal in the set. We perform the following four steps.

Step 4.1: We generate the path dependency graph $G_{PD} = (V_{ReconvP} \cup V_e, E_{PD})$ from all the reconvergent structures in $G_C^0$.

Step 4.2: For each vertex $v_i \in V_e$ in $G_{PD}$, we calculate a bit rate $R_{v_i}$. The bit rate $R_{v_i}$ is obtained by $R_{v_i} = \frac{W_{v_i}}{N_{v_i}}$, where $W_{v_i}$ is the bitwidth of the RTL signal corresponding to $v_i$ and $N_{v_i}$ is the outdegree of $v_i$ in $G_{PD}$. The bit rate means how many bits needed to make one path observable, and is used to observe more paths by less bitwidths.

Step 4.3: The vertex $e_i \in V_e$ with the minimum bit rate in $G_{PD}$ is selected, and $e_i$ and its neighbors are removed from $G_{PD}$. The edge of $G_C^0$ which corresponds to $e_i$ is removed from $G_C^0$, and is added to $E_{cut}$.

Step 4.4: Steps 4.2 and 4.3 are repeated until the number of paths in each reconvergent structure is less than or equal to one.

As the result of processing these steps, we observe RTL signals corresponding to edges in $E_{cut}$. These RTL signals are connected to an MISR.

We show an example of the execution of Step 3 and Step 4 by using the circuit graph $G_C$ in Fig. 7. In Step 3.1, we find the set of cycles $C_{min} = \{C_1, C_2, C_3\}$ by removing edges $e_5$, $e_3$ and $e_5$, respectively, where $C_1$ includes edges $(e_2, e_3, e_7, e_1)$ and $C_3$ includes...
edges \((e_2, e_4, e_5, e_7, e_1)\). In Step 3.2, in the set of edges in \(C_{\text{min}}\), the edge with the minimum weight among the edges that appear in the maximum number of cycles is \(e_2\), and \(e_2\) is added to \(E_{\text{cut}}\) and is removed from \(G_C\). In this case, all the cycles are cut by \(e_2\). Therefore, we complete Step 3. In Step 4.1, we generate the path dependency graph \(G_{\text{PP}}\) of \(G_C\). In Step 4.2, the vertex with the minimum bit rate is \(e_5\). In Step 4.3, the vertex \(e_5\) is selected, and \(e_5\) and its neighbors are removed from \(G_{\text{PP}}\). The edge of \(G_C\) which corresponds to \(e_5\) is removed from \(G_C\), and is added to \(E_{\text{cut}}\). However, the number of paths in each reconvergent structure is more than one. Therefore, we return to Step 4.2 and repeat similar processes. In this case, the edges \(e_6\) and \(e_{10}\) are removed in each process and are added to \(E_{\text{cut}}\). Finally, we obtain observation points \(e_2, e_5, e_6\) and \(e_{10}\) and the total bitwidth of the observation points is 38.

7. Experimental Results

We evaluate the proposed method using a non-pipelined processor SAYEH [10] and a five-stage pipelined processor DLX_N that is based on DLX processor [11]. All the registers of SAYEH processor are resetable. All the registers except for registers of the register-file of DLX_N processor are resetable.

Table 1 shows hardware overhead of the proposed method and the full-scan design for SAYEH and DLX_N. In the column “DFT,” “FS” and “PM” denote the full-scan design method and the proposed method, respectively. The columns “Area” and “HO” denote the area of the processor and the hardware overhead, respectively. In the columns “Area,” “Original” and “Additional” denote the original area of the processor without DFT and the additional area that increases by applying the proposed DFT method to the processor, respectively. A unit of the area is an area for one NOT gate. In the columns “Additional” and “HO”, the sub-columns “Init.” and “OB” denote the additional area and the hardware overhead of the initialization function and MISR that increases by applying the proposed DFT method to the processor, respectively. In these sub-columns, “.” denotes no additional area or no hardware overhead. The column “#OB” denotes the number of observable bits. In the full-scan design method and the proposed method, an observable bit means the number of scan flip-flops and the number of inputs of MISR.

There are not any additional area or hardware overhead of the initialization function of SAYEH processor since all the registers are resetable. In the case of the full-scan design method, both processors do not induce the additional area and the hardware overhead of the initialization function. The number of observable bits of the proposed method becomes less than that of the full-scan design method for both processors. For DLX_N processor, the hardware overhead of the proposed method is smaller than that of the full-scan design method. The DLX_N processor has many registers including the architecture registers that appear in instruction set architecture and the pipeline registers to enhance the performance. Therefore, the full-scan design induces a large area overhead. For details of the area for DLX_N processor, the area of the initialization function is almost the same as MISR for observable points. However, if DLX_N processor has already had the initialization function for all the registers, the area of the initialization function is not required. The area of the initialization function depends on the design specification of the processor. On the other hand, for the SAYEH processor, the hardware overhead of the proposed method is larger than that of the full-scan design method. This is because that the SAYEH processor has a very area-optimized design with a lot of loops and a few registers; therefore, the proposed method needs many observation points whereas full-scan design requires little area overhead. Moreover, the hardware overhead per one observed bit of the proposed method is larger than for the full-scan design. However, this hardware overhead can be reduced if we compress the observed space before applying it to MISR.

In order to show the effectiveness of the proposed method, we apply the proposed DFT method to the arithmetic logic unit (ALU) in DLX_N processor. Table 2 and Table 3 show the results of the MUT test generation for the ALU in DLX_N processor and the execution of the template-based test program before/after the proposed DFT method is applied, respectively. We used the SBST method in [7] as an MUT test generation and a test program synthesis.

In Table 2, the columns “Total,” “RF,” “DF,” “FC,” “FE” and “TGT” denote the number of total faults of ALU, the number of the identified redundant faults, the number of the detected faults, the fault coverage, the fault efficiency, and the total test generation time for the MUT test generation, respectively. A unit of “TGT” is second. In order to identify redundant faults, we use the method in [7]. The total fault coverage and fault efficiency are 99.83% and 100.00%,
respectively. The total test generation time is 358.70 second. This test generation time is reasonable because the method in [7] generates combinational circuits as constraint circuits, and a combinational test generation is applied.

In Table 3, the columns “DF”, “EM”, “FC”, “FE”, “FE_T” and “TAT” denote the number of the detected faults, the number of faults undetected by error masking, the fault coverage, the fault efficiency, the template level fault efficiency and the test application time during the execution of the test program, respectively. A unit of “TAT” is clock. In Table 3, there exist 54 faults undetected by error masking before the proposed DFT method. However, after the DFT method is applied, the number of faults undetected by error masking is 0. The proposed DFT method can achieve 100% template level fault efficiency. The fault coverage after the proposed DFT is larger than that of before the DFT. Moreover, the proposed DFT method can also reduce about 5% of the total test application time.

8. Conclusions and Future Work

In this paper, we showed a sufficient condition to avoid error masking for template-based test programs, and proposed a design for testability method to satisfy the sufficient condition. The experimental results reveal that the proposed method achieves less hardware overhead than full-scan design if the processor features many registers and less loops or reconvergent paths. In general, modern processors oriented to high performance have many registers to accelerate their speed, while the structure tends to be simpler than the design oriented to area optimization. From this observation, we consider that the proposed method is suitable for such modern processors. The proposed method was no performance degradation in a sense that it adds only observation points to the original design and moreover, it enables at-speed testing. The reduction of the hardware overhead caused by the DFT method is the issue to be investigated in our future work.

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