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An accurate diagnosis of transition fault clusters based on single fault simulation

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Abstract: The demand for fault diagnosis has increased with the increasing complexity of VLSI devices. Defects that result from process variations may cluster in certain areas. When a large number of defects cluster in an area, diagnosing these defects is a challenging problem because defects frequently exist that are partially or completely dominated by other adjacent defects. The most common approach for modeling delay defects is the transition fault model. We propose a diagnostic method that can handle clusters of transition faults. The experimental results for the full-scan version of the ISCAS'89 benchmark circuits demonstrate the accuracy of the proposed method.

Keywords: transition faults, fault diagnosis, cluster defects
Classification: Integrated circuits

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1 Introduction

The demand for fault diagnosis has increased with the increasing complexity of VLSI devices. Fault diagnosis is a process that deduces the location of the defect that caused the failures. An accurate fault diagnosis can identify both design and process errors, thereby improving the yield. Therefore, it is very important to develop an efficient fault diagnosis methodology in order to improve device quality and to reduce production costs.

Multiple-fault diagnosis is a challenging problem because, in theory, the search space grows exponentially with an increasing number of faulty lines. In recent years, papers regarding multiple-fault diagnosis have been published [1, 2]. Defects that result from process variations may cluster in certain areas [3]. When a large number of defects cluster in an area, diagnosing these defects is a challenging problem because defects frequently exist that are partially or completely dominated by other adjacent defects. The most common approach for modeling delay defects is the transition fault model. The diagnostic method in [3] is the state-of-the-art method for clusters of transition faults. This method selects single or double fault candidates that have maximum matches. However, it requires a great deal of diagnostic time, since it requires additional simulations of double transition faults.

In this paper, we propose an accurate diagnostic method for clusters of transition faults. The proposed diagnostic method consists of a path-tracing procedure and a final candidate selection procedure. The path-tracing procedure and the final candidate selection procedure are devised in order to diagnose faults dominated by other adjacent faults. Moreover, the proposed method only exploits simulations of a single transition fault.

2 Transition fault clusters

A delay defect causes an extra delay in the circuit, so it is a serious concern in the industry. The most commonly used delay fault model is the transition fault model since the number of transition fault sites increases linearly with the gate count of the circuit and because transition fault test generation does not need to consider circuit timing.

The clusters of transition faults defined in [3] are used in this paper, and g/vv' denotes the $v \rightarrow v'$ transition fault on line g. Two transition faults $f_{j1} = g_{j1}/v_{j1}v'_{j1}$ and $f_{j2} = g_{j2}/v_{j2}v'_{j2}$ are adjacent if one of the following conditions is satisfied: (1) For a gate G, g_{j1} is an input of G and g_{j2} is the output of G, or vice versa. (2) g_{j1} is a fanout stem and g_{j2} is one of its fanout branches, or vice versa. A cluster C is a subset of faults where, for every fault $f_{j1} \in C$, there is at least one fault $f_{j2} \in C$ such that f_{j1} and f_{j2} are adjacent.

Transition values are not considered to determine whether faults are adjacent. Examples of clusters of transition faults are illustrated in Fig. 1. The cluster $C_1 = \{c/01, g/10, j/01, l/01, n/01\}$ consists of five transition faults on the same subpath. The cluster $C_2 = \{b/10, h/10, i/01, k/10, m/01\}$ consists of five transition faults on several different subpaths.

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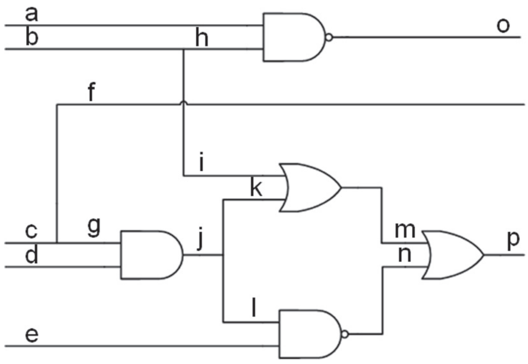

Fig. 1. Example of the transition fault clusters.

3 Path-tracing based on the transition fault model

Most diagnostic methods use path-tracing based on the stuck-at fault model to reduce the defect search space because it is a linear-time routine. Path-tracing based on the stuck-at fault model is insufficient to diagnose transition faults. The number of fault candidates is reduced more by exploiting the excitation and observation conditions of transition faults.

A test pattern for a transition fault consists of a pair of vectors $\{V1, V2\}$, where $V1$ (called the initial vector) is required to set the target node to an initial value, and $V2$ (called the test vector) is required to launch the corresponding transition at the target node and also to propagate the fault effect to a primary output. The excitation and observation conditions of a transition fault imply that a transition occurs on the fault location, and the delayed transition is propagated to a primary output [4].

Several papers regarding path-tracing based on the transition fault model using a symbolic simulation have been published [4, 5]. These methods could not be applied to a scan-chain since these methods do not consider scan-chain operations (the shift operation and capture operations). Therefore, the launch-on-shift and launch-on-capture tests could not be applied to these methods, which is impractical. Moreover, these methods [4, 5] exploit the single fault assumption, and they endeavor to find one fault that is the most likely to be an actual fault. These methods [4, 5] select the intersection of the fault candidates for every failing pattern, and actual faults can be eliminated from the fault candidates. Therefore, it is not appropriate to diagnose clusters of transition faults, since clusters consist of multiple transition faults.

To alleviate these problems, we have created a path-tracing procedure based on the transition fault model using a logic simulation. The logic simulation of the proposed method considers the operations of the scan-chain so that the LOS and LOC tests can be applied.

The proposed path tracing procedure conservatively selects fault candidates to consider the clusters of transition faults. Since a cluster of faults is the group of adjacent faults, it is likely that a particular fault may be detected more frequently than other faults. For example, in Fig. 1, we assume that two actual faults ($n/01$ and $p/01$) exist. To detect fault $n/01$, a test pattern should make the $0 \rightarrow 1$ transition on line n and a stable 0 value on line m, and

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this test pattern is able to also detect fault $p/01$. To detect fault $p/01$, a test pattern should make the $0 \rightarrow 1$ transition on line m or line n. Fault $p/01$ is detected more frequently than fault $n/01$, since fault $p/01$ is detected by the test patterns for both fault $n/01$ and fault $m/01$. In previous methods [4, 5], only fault $p/01$ is selected as a fault candidate since these methods select the intersection of the fault candidates for every failing pattern. To alleviate this problem, the proposed path-tracing procedure selects the union of fault candidates for every failing pattern.

The proposed path tracing procedure reduces the number of fault candidates by measuring the excitation and observation conditions of a transition fault. The proposed path-tracing procedure consists of the following steps:

Step 1: Perform a good simulation for one failing pattern (the $V1$ and $V2$ vectors) and store the logic values of each line.

Step 2: Measure the observation condition. From every failing observable point, perform a path tracing by marking every sensitized line.

Step 3: Measure the excitation condition and the transition on the sensitized line between $V1$ and $V2$.

Step 4: The lines that satisfy the observation and excitation conditions are included as fault candidates.

Steps 1, 2, 3, and 4 are repeated for every failing pattern.

During the path-tracing, a $\#Path - Tracing$ metric is also calculated and used at the final candidate selection procedure. $\#Path - Tracing$ is the number of implications identified through the path-tracing and indicates how often a candidate is implicated by the failing patterns. Then an accurate diagnostic result is obtained by the final candidate selection procedure.

4 Final candidate selection

The final candidate selection procedure selects the final candidates from the fault candidates and reports the diagnosis output. Candidate s_i/v_i' is said to output-explain an observable point out_j for a failing pattern t_k if the fault-free value on site s_i is v_i, and an error from s_i propagates to out_j in t_k when all of the side inputs of the on-path gates have fault-free values. Most multiple-fault diagnostic methods select the minimal group of candidates such that the combined candidates jointly output-explain all of the observed fail points and report a diagnosis output [1, 2].

However, previous methods [1, 2] cannot accurately diagnose clusters of transition faults. A test pattern for transition faults is required to propagate the fault effect to a primary output. Since the fault effect of a transition fault propagates according to a sensitized path, faults that are near a primary output are frequently detected. Such faults tend to dominate other faults. Previous methods [1, 2] cannot diagnose a fault that is dominated by other faults. For example, fault $n/01$ is not selected as a final candidate, even if it is the actual defect, because all of the fault effects of fault $n/01$ are explained by those of fault $p/01$.

To alleviate this problem, we propose a final candidate selection pro-

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cedure for clusters of transition faults. If the fail-log and the fault response are identical for a certain failing pattern, it is defined as the exact match. $\#Exact\_Match$ indicates the number of exact matches and is the most commonly used metric for diagnosis. A candidate that has a higher $\#Exact\_Match$ is more likely to be an actual defect. EM_{MAX} is the maximum $\#Exact\_Match$ with respect to all fault candidates. The fault that has EM_{MAX} tends to be the closest to a primary output in a cluster of transition faults and is easily diagnosed using previous methods [1, 2]. We devised a Diagnosis Score metric to diagnose faults that are dominated by other adjacent faults. Faults that do not have EM_{MAX} in a cluster of transition faults can be selected as final candidates according to the Diagnosis Score. The Diagnosis Score is based on the number of exact matches ($\#Exact\_Match$) and the maximum $\#Exact\_Match$ (EM_{MAX}):

$$Diagnosis\ Score = \frac{\#Exact\_Match}{\alpha \times EM_{MAX}} \tag{1}$$

where α, $0 < \alpha < 1$, is a parameter.

The diagnostic results are affected by α. As α is decreased, the diagnosability is decreased while the resolution is increased. When α is 0.5, the optimal trade-off between the diagnosability and the resolution occurs in numerous experimental results. Therefore, α is set to 0.5.

We have observed that $\#Exact\_Match$ of an actual fault is identical to or very similar to $\#Path-Tracing$ of the actual fault. Some faults are easily implicated by the path-tracing because of the circuit topology. This observation is exploited in order to remove such faults from the final candidates. To consider the mask and reinforcement effects, we assume that the buffer, which is obtained though the analysis of numerous experimental results, is $EM_{MAX}/10$. A final candidate is selected if the difference between $\#Path-Tracing$ and $\#Exact\_Match$ is smaller than the buffer:

$$|\ \#Path-Tracing\ \ -\ \#Exact\_Match\ | \leq \frac{EM_{MAX}}{10} \tag{2}$$

The proposed final candidate selection procedure consists of the following steps:

Step 1: Fault simulate the fault candidates.

Step 2: Calculate Diagnosis Score according to equation (1).

Step 3: Select final candidates whose Diagnosis Score is higher than 1 and satisfy equation (2).

Step 4: Report the final candidates as the diagnosis output.

5 Experimental results

The experiments were conducted using the full-scan combinational versions of the larger ISCAS'89 benchmarks. The LOC (broadside) test patterns were generated by a commercial ATPG (automatic test pattern generation) tool and had near 100% transition fault test coverage. We considered 60 clusters for each circuit, and the diagnostic results were averaged. Clusters

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Table I. The comparison of diagnosability and resolution with those of the prior work.

Circuits	Diaganosability		Resolution	
	[3]	Proposed	[3]	Proposed
s13207	0.32	**0.54**	0.31	**0.64**
s15850	0.33	**0.62**	0.34	**0.61**
s35932	0.45	**0.47**	0.42	**0.42**
s38417	0.27	**0.66**	0.39	**0.56**
s38584	0.54	**0.54**	0.38	**0.53**
Average	0.38	**0.57**	0.37	**0.55**

composed of 20 transition faults were injected. Since undetected faults cannot be diagnosed, only detectable faults were injected. Only one fault from a specific equivalent class was injected.

Diagnosability and resolution are two metrics that are commonly used to evaluate diagnostic quality. Diagnosability is defined as S_D/S_I, where S_D is the number of actual defect sites identified by the diagnosis, and S_I is the number of injected defect sites. The resolution is defined as S_D/S_T, where S_T is the total number of sites reported by the diagnosis. For any diagnostic approach in the ideal case, the diagnosability is 1, and the resolution is also 1; that is, $S_D/S_I = S_D/S_T = 1.0$ [2].

Table I shows a comparison of the diagnosability and resolution of the proposed method with those of the state-of-the-art method [3]. The cases in which the results of the proposed diagnostic method are better than the results reported in [3] are in bold type. In all of the cases, the diagnosability of the proposed method was better than that of the method developed in [3]. Therefore, the proposed diagnostic method is more accurate than the method in [3]. Moreover, the proposed method exploits only single-fault simulation, while the method in [3] requires a great deal of diagnostic time since it performs additional simulations of double transition faults.

6 Conclusion

In this paper, we proposed an accurate diagnosis of transition fault clusters based on single fault simulation. The proposed diagnostic method consists of a path-tracing procedure and a final candidate selection procedure, which are devised in order to diagnose faults that are dominated by other adjacent faults. The experimental results demonstrate the accuracy of the proposed diagnostic method in diagnosing clusters of transition faults.

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