A New Scan Slice Encoding Scheme with Flexible Code for Test Data Compression

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Abstract— As the design for testability (DFT) is essential in the semiconductor manufacturing, the scan-based architecture is widely used to decrease the test complexity of a chip. However, the scan-based architecture requires high test cost such as the test data volume and the test time. In order to alleviate the test cost problem of the scan-based architecture, a lot of test data compression schemes using the scan slice encoding have been presented. In this paper, we propose a new scan slice encoding scheme with flexible code for test data compression. The proposed scheme fully utilizes the flexible code as the control code or the data code. The flexible code provides supplementary encoding mode without additional control code. As a result, the test cost is significantly reduced by the various encoding mode with low test equipment pin overhead. The experiment results based on ISCAS’89 benchmark circuits show that the test data volume and the test time is reduced up to 82% compared with the original data.

Keywords- test data compression, scan chain, slice encoding

I. INTRODUCTION

As the number of transistors in a single chip has increased exponentially, the test complexity of very large scale integration (VLSI) circuits has been greatly increased. The scan-based architecture is widely used in order to reduce the test complexity of the circuit by providing the observability and the controllability. However, because the scan-based circuit test fills the scan cells with test patterns, it requires a large amount of test cost such as the test data and the test application time (TAT). In order to reduce the test cost, many test data compression schemes are suggested [1]. Scan slice encoding schemes presented recently [2]-[8], are devised using the fact that test patterns have many unspecified bits. They encode scan slices based on only specified bits to compress the original test data. Then the encoded slice codes are decompressed by the decoder on the chip to restore the original test patterns.

Among the scan slice encoding based schemes, selective scan slice encoding schemes (SSE) [6]-[7] can reduce the test data volume and the TAT using three encoding modes. However, they use the 2-bit control code to encode three modes so that the length of the slice codes is long. In order to improve the encoding scheme, a selective scan slice grouping scheme (SSG) is presented in [8]. It provides two kinds of group mapping modes which can apply the distribution information of zeros and ones. As a result, the required slice codes are reduced during the scan slice encoding process. However, this scheme also uses the 2-bit control code in the slice code. On the other hand, a grouped scan slice repetition scheme (GSR) is suggested in [5]. Since the 1-bit control code is used in the slice code, the length of the slice code is reduced. However, it uses only two encoding modes. As a result, it provides poor test data compression when there are a lot of specified bits in the test patterns.

In this paper, we propose a new scan slice encoding scheme with flexible code, which uses only the 1-bit control code and fully utilizes the 1-bit flexible code. By the use of the flexible code, it provides various encoding modes without additional control code. As a result, it significantly reduces the test data volume due to various encoding mode and hence, the TAT is decreased.

II. PROPOSED TEST DATA COMPRESSION SCHEME

Key terminology is defined as follows. The scan slice represents input values which are inserted to the scan chains at the same time. The slice code represents the encoded code which is used to decode the scan slice in a chip and it consists of the control code and the data code. The conflict bit denotes the position of the specified bit which is not matched with the mapping value. The flexible code represents the most significant bit (MSB) of the data code, and it is used as the control code or the data code according to the encoding mode. The select code is defined as the remaining data code except for the MSB.

In the scan slice encoding based test data compression schemes, the slice codes are necessary to decode the scan slices and the slice code consists of a control code and a data code. The control code indicates the required encoding mode and the data code has some information used in the encoding. For example, if the control code indicates a single conflict handling mode, the data code should have the information of the conflict bit position. Likewise, in each encoding mode, the control code and the data code make a pair and they are used to compose a scan slice. When a complete scan slice is created using some slice codes, the complete scan slice is inserted to the scan chains.
is already used as the control code in the group mode and the 1-bit control code and the B. used as the data code. In this case, the flexible code is used as the control code. The flexible code consists of the flexible code and the select code. If the control code is 0, then the encoding mode is single mode. In this case, the single mode consists of the control code and the data code according to the encoding modes. The flexible use of the data code not only increases the efficiency of the slice code, but also provides additional encoding mode, namely alternative mode. The MSB of the data code is defined as the flexible code and its practical use is shown in the Table I.

Table I shows compositions of the slice code according to the encoding modes. The second, third, and fourth column show the control code, the flexible code, and the select code, respectively, and a slice code is composed of these. The 1-bit control code is used to recognize the encoding mode in the slice code. If the control code is 0, then the encoding mode is set up to a group mode or an alternative mode; and if the control code is 1, then it is set up to a single mode. The data code consists of the flexible code and the select code. The MSB of the data code is the flexible code and the remains are the select code. If the control code is 0, then additional control code is needed to specify the exact encoding mode, and in this case, the flexible code is used as the control code. The flexible code 0 denotes a group mode and 1 denotes an alternative mode. Otherwise, if the control code is 1, additional control code is not required. Therefore, in this case, the flexible code is used as the data code.

A. Flexible use of the data code

In the conventional scan slice encoding schemes, the function of the control code and the data code is completely separated. Their independent function enhances the readability of a slice code. However, the slice codes are wasted because all the data code is not required in some encoding modes. In order to fully utilize the data code, the proposed scheme uses MSBs of the data codes as the control code or the data code according to the encoding modes. The flexible use of the data code not only increases the efficiency of the slice code, but also provides additional encoding mode, namely alternative mode. The MSB of the data code is defined as the control code and its practical use is shown in the Table I.

Table II. Several examples of entire encoding process (N = 16)

<table>
<thead>
<tr>
<th>Encoding mode</th>
<th>Slice code</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Group</td>
<td>Control code</td>
<td>Data code</td>
</tr>
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<td></td>
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<td>0</td>
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<tr>
<td>Alternative</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Single</td>
<td>1</td>
<td>X</td>
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</table>

<table>
<thead>
<tr>
<th>Scan slice</th>
<th>Slice code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group1</td>
<td>X0X0X0</td>
<td>00101</td>
</tr>
<tr>
<td>Group2</td>
<td>1X1X</td>
<td>01110</td>
</tr>
<tr>
<td>Group3</td>
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<td>00001</td>
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<tr>
<td></td>
<td>1X0X01</td>
<td>01001</td>
</tr>
<tr>
<td></td>
<td>0X0XX</td>
<td>10000</td>
</tr>
</tbody>
</table>

TABLE I. SLICE CODE COMPOSITIONS ACCORDING TO THE ENCODING MODES

A. Flexible use of the data code

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B. Various encoding modes and the applications

In the proposed scheme, the scan slice is encoded with the 1-bit control code and the n-bit data code, where n is $\log_2 N$ in order to specify every scan chain, and N is the number of the scan chains. For the 1-bit flexible code, the length of the select code, g is determined as $\lceil \log_2 \text{N} \rceil - 1$. Because the flexible code is already used as the control code in the group mode and the alternative mode, mapping the scan slice values is done by the g-bit select code. Thus, in two mapping modes, the number of the group is g which is same as the length of the select code. Each bit of the g-bit represents mapping value of a group. The scan slice encoding always starts with the group mode or the alternative mode. In the group mode, all scan slices in a group is mapped to same value using the mapping value 0 or 1. However, mapping each group with one value is sometimes inefficient because zeros and ones can be mixed even in a group.

In order to solve this problem, the alternative mode is proposed as the SSG [8]. In the alternative mode, mapping is done by mixture of zeros and ones. For example, the select code 0 represent a 0101… mapping and the select code 1 represent a 1010… mapping in the alternative mode. As a result, in zeros and ones mixed case, many conflict bits are removed by the alternative mode with one slice code.

When the decoded slice code cannot represent original scan slice, some additional slice codes are required after the group mode or the alternative mode. In this case, the single mode handles remaining conflict bits. The single mode consists of the control code 1, and the data code which denotes the position of the conflict bit. In the single mode, a conflict bit is flipped to desired value by one slice code.

The proposed encoding process is described in Table II. For example, let the number of scan chains, N be 16. In this case, n=4 and g=3 according to $\lceil \log_2 N \rceil$ and $\lfloor \log_2 N \rceil$. Thus, every scan slice is divided into three groups due to g and the size of a group is $\text{6 from } \lceil 16/3 \rceil$. In the first example, an encoding is completed using the group mode with only one slice code which contains the 3-bit select code indicating mapping value, 101. In the second example, however, the group mode is inefficient because zeros and ones are mixed in group1 and group2. Therefore, an alternative mode is preferred in this case. The group1 and group2 of the scan slice have X01X10 and 10X0XX, respectively. In this case, the scan slice can be mapped using 101010 in both groups and 0101 in group3. As a result, the select code is 110 and this scan slice is encoded
The decompression is achieved using the control code and the flexible code. In the group mode, both scan slices contain nine specified bits. In the alternative mode, the odd SIC and even SIC can provide different mapping values. As a result, the alternative mode is feasible due to different input components of the SIC. When the control code is 1, the encoding mode is the single mode. In the single mode, the conflict bit is flipped because the position of the conflict bit is specified by the decoder output. Meanwhile, other bits are not changed. In order to realize this function, an XOR gate is also used.

A. SIC input selector

Fig. 2 depicts the SIC input selector. The SIC input selector is connected to the N-bit SIC and it selects the input of the SIC. The control code decides the input value $SI$ and it selects input $0$ in the group mode and the alternative mode or input $1$ in the single mode, respectively. In the group mode and the alternative mode, the g-bit select code is selected as the input value and each $m$-bit SI is same in the same group, where $m=[N/g]$. On the other hand, in the single mode, the $N$-bit $n$: $N$ decoder output is selected as the input value.

B. SIC

Fig. 3 shows the architecture of the SIC. As shown in Fig. 3, there are two kinds of SIC, these are the odd SIC and the even SIC. When the control code is 0, the encoding mode is the group mode or the alternative mode therefore mapping values are inserted to the SIC. The $i$-th SIC in a group has an additional XOR gate on the multiplexer (MUX) input 0 to implement the alternative mode, where $i$ is even number in a group ($0 \leq i \leq g-1$). In the alternative mode, the odd SIC and the even SIC can provide different mapping values. As a result, the alternative mode is feasible due to different input components of the SIC. When the control code is 1, the encoding mode is the single mode. In the single mode, the conflict bit is flipped because the position of the conflict bit is specified by the decoder output. Meanwhile, other bits are not changed. In order to realize this function, an XOR gate is also used.

IV. EXPERIMENTAL RESULTS

We evaluate the performance of the proposed scheme based on the ISCAS’89 benchmark circuits. The proposed scheme is compared with other compression schemes in terms of the reduction ratio of the test data volume and the TAT. Design Compiler [9] and TetraMax [10] are utilized to synthesize benchmark circuits and generate the test patterns, respectively. Table III shows the information of the benchmark circuits. The $T_D$ represents the original test data volume.
automatic test equipment (ATE) and the TAT. The CH represents the number of channels of the SSG [8], and GSR [5] is calculated by 2+⌈log2(N+1)⌉, 2+⌈log2(N)⌉, and 1+⌈log2(N)⌉, respectively. The CH of SSE [7], SSG [8], and GSR [5] under the same CH limit. The result is easily expectable because the proposed scheme fully utilizes the flexible code and reduces a lot of conflict bits using two mapping modes. In all benchmark circuits, the best compression ratio is achieved under the same CH limit. Since the CH represents the pin overhead, fewer CH is preferred. Especially, the proposed scheme shows much better performance than other schemes under the low CH limit. Since the CH represents the pin overhead, fewer CH is preferred. Especially, the proposed scheme shows much better performance than other schemes under the low CH limit.

Table IV shows experimental results of the test data volume and the TAT. The CH represents the number of channels of automatic test equipment (ATE) and the \( R_{vol} \) represents the reduction ratio of the test data volume and the \( R_{TAT} \) represents the reduction ratio of the TAT. The \( R_{vol} \) and the \( R_{TAT} \) are calculated by \((TD_{\text{TAT}})/TD\times100\) and \((TATD-TAT_{\text{vol}})/TATD\times100\), respectively. \( TD \) and \( TAT_{\text{vol}} \) are the default test data volume and the default TAT. \( TD \) and \( TAT_{\text{vol}} \) are the default test data volume and the TAT at encoding schemes. The proposed scheme is compared with SSE [7], SSG [8], and GSR [5] because they are recently published scan slice encoding schemes. The CH of SSE [7], SSG [8], and GSR [5] under the same CH limit. The result is easily expectable because the proposed scheme fully utilizes the flexible code and reduces a lot of conflict bits using two mapping modes. In all benchmark circuits, the best compression ratio is achieved under the same CH limit. Since the CH represents the pin overhead, fewer CH is preferred. Especially, the proposed scheme shows much better performance than other schemes under the low CH limit due to the use of the 1-bit control code. GSR [5] also uses the 1-bit control code but it provides only one mapping mode. As a result, its encoding performance is less efficient than the proposed scheme, and this results in lower reduction ratio. The gap of the reduction ratio between GSR [5] and the proposed scheme is reduced in s38584 circuit because the test patterns are grouped in s38584 have a few specified bits. The reduction ratio of the TAT shows almost the same result with the test data volume because the TAT is proportional to the test data volume. Therefore, both the test data volume and the TAT can be reduced effectively using the proposed scheme with low ATE pin overhead.

V. CONCLUSION

In this paper, we propose a new scan slice encoding scheme with flexible code. Since the proposed scheme fully utilizes the flexible code as the control code or the data code, an additional encoding mode is provided with the 1-bit control code. In addition, many conflict bits are dramatically reduced by the various encoding modes. For this reason, the proposed scheme shows better test data compression in terms of the reduction ratio of the test data volume and the TAT with low ATE pin overhead.

ACKNOWLEDGMENT

The authors would like to appreciate CAD tool support from IC Design Education Center (IDEC).

REFERENCES