Strongly Secure Scan Design Using Generalized Feed Forward Shift Registers

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SUMMARY In our previous work [12], [13], we introduced generalized feed-forward shift registers (GF2SR, for short) to apply them to secure and testable scan design, where we considered the security problem from the viewpoint of the complexity of identifying the structure of GF2SRs. Although the proposed scan design is secure in the sense that the structure of a GF2SR cannot be identified only from the primary input/output relation, it may not be secure if part of the contents of the circuit leak out. In this paper, we introduce a more secure concept called strong security such that no internal state of strongly secure circuits leaks out, and present how to design such strongly secure GF2SRs.

key words: design-for-testability, scan design, generalized feed-forward shift registers, security, scan-based side-channel attack

1. Introduction

It is important to find an efficient design-for-testability (DFT) methodology that satisfies both security and testability, although there exists an inherent contradiction between security and testability for digital circuits. Scan design is a powerful DFT technique that provides high controllability and observability over a chip and yields high fault coverage [1]. However, this also accommodates reverse engineering, which damages security. For secure chip designers, there is a demand to protect secret data from side-channel attacks and other hacking schemes [2]. Different approaches [3]–[9] have been proposed to solve this problem. All the approaches except [7] add extra hardware outside of the scan chain. Disadvantages of this are high area overhead, timing overhead or performance degradation, increased complexity of testing, and limited security for the registers part, among others.

In a previous paper [10], we reported a secure and testable scan design approach by using extended shift registers called SR-equivalents that are functionally equivalent but not structurally equivalent to shift registers. We then extended the class of SR-equivalents to a wider class of SR-quasi-equivalents [11]. We further introduced generalized feed-forward shift registers (GF2SR, for short) to apply them to secure and testable scan design [12], [13]. Our proposed approach is only to replace part of the original scan chains with modified scan chains, which satisfy both testability and security of circuits. This method requires very little area overhead and no performance overhead. Moreover, no additional keys and controller circuits outside of the scan chain are needed, thus making the scheme low-cost and efficient.

We considered the security problem from the viewpoint of the complexity of identifying the structure of GF2SRs [12], [13]. There is another viewpoint for the security, i.e., the possibility of leakage of the contents of GF2SRs. In this paper, by looking at the security problem from this viewpoint, we introduce a more secure concept called strong security such that no internal state of strongly secure circuits leaks out, and present a method for designing such strongly secure GF2SRs.

2. Testability of Generalized Feed-Forward Shift Registers

In our previous papers [12], [13], we introduced a class of extended shift registers called generalized feed-forward shift registers (GF2SR). Figure 1 illustrates a general structure of GF2SRs. In this figure, \( f_0, f_1, \ldots, f_k \) are arbitrary logic functions. Figure 2 (a) shows an example of a 3-stage GF2SR, \( R_1 \). Generally, for any GF2SR with \( k \) flip-flops, the input value applied to the input \( x \) at any time \( t \) appears at the output \( z \) after \( k \) clock cycles with exclusive-OR of some logic function \( f \) of \( x(t+1), x(t+2), \ldots, x(t+k) \), i.e., the output \( z \) at time \( t+k \) behaves in accordance with the following equation.

\[
z(t+k) = x(t) \oplus f(x(t+1), x(t+2), \ldots, x(t+k)).
\]

As an example, consider a 3-stage GF2SR, \( R_1 \), given in Fig. 2 (a). By using symbolic simulation, we can obtain an output sequence \( z(t), z(t+1), z(t+2), z(t+3) \) and the output \( z(t+3) = x(t) \oplus f(x(t+1))x(t+1) \) as shown in Fig. 2 (b). From the result of symbolic simulation, we can derive equations to obtain an input sequence \( x(t), x(t+1), x(t+2) \) that transfers \( R_1 \) from any state to the desired final state \( y_1(t+3), y_2(t+3), y_3(t+3) \) as illustrated in Fig. 2 (b). Similarly, we can derive equations to determine uniquely the initial state \( y_1(t), y_2(t), y_3(t) \) from the input/output sequence as illustrated in Fig. 2 (b).

Generally, as for any circuit \( C \) of GF2SR with \( k \) flip-flops, the output value \( z(t+k) \) at time \( t+k \) is a function of the input value at time \( t \) and some logic function \( f \) of the input values at times \( t+1, t+2, \ldots, t+k \). For secure chip design, there is a demand to protect secret data from side-channel attacks and other hacking schemes [2]. Additionally, there is a demand to protect secret data from side-channel attacks and other hacking schemes [2].

Fig. 1 Generalized feed-forward shift register (GF2SR)
flops, (1) for any internal state of C a transfer sequence (of length k) to the state (final state) can be generated only from the connection information of C, independently of the initial state; (2) any present state (initial state) of C can be identified from the input-output sequence (of length k) to the state (final state) can be generated only from flip-flops, (1) for any internal state of C a transfer sequence (of length k) to the state (final state) can be generated only from flip-flops, (1) for any internal state of C a transfer sequence (of length k) to the state (final state) can be generated only from flip-flops, (1) for any internal state of C a transfer sequence (of length k) to the state (final state) can be generated only from flip-flops.

Therefore, for the class of GF$^2$SRs, we can easily generate scan-in and scan-out sequences such that both scan-in and scan-out operations can be overlapped and hence testing can be done in the same way as the conventional scan testing. The test sequence is of the same length as the conventional scan design. There is no need to change traditional ATPG algorithm though a logic implication process is needed only for the GF$^2$SR after ATPG. To reduce the area overhead as much as possible, not all scan chains are replaced with modified scan chains. Only parts of scan chains necessary to be secure are replaced with modified GF$^2$SR scan chains. The delay overhead due to additional logic and XOR gates influences only scan operation, and hence there is no delay overhead for normal operation.

### 3. Security of Generalized Feed-Forward Shift Registers

When we consider a secure scan design, we need to assume what the attacker knows and how he can potentially make the attack. Here, we assume that the attacker does not know the detailed information in the gate-level design, and that the attacker knows the presence of test pins (scan in/out, scan, and reset) and modified scan chains. However, he/she does not know the structure of extended scan chains. Based on this assumption, we consider the security to prevent scan-based attacks.

In previous papers [11]–[13], we introduced a concept called scan-secure as follows. A circuit $C$ with a single input $x$, a single output $z$, and $k$ flip-flops is called scan-secure if the attacker cannot determine the structure of $C$. The security level of the secure scan architecture based on those GF$^2$SRs is determined by the probability that an attacker can identify the structure of the GF$^2$SR used in the circuit, and hence the attack probability approximates to the reciprocal of the cardinality of the class of GF$^2$SRs. In [12], [13] we showed the cardinality of the class of $k$-stage GF$^2$SRs is $2^{2^{k+1} - 1}$. Hence, it is very hard and intractable to identify the structure of a given GF$^2$SR from the information on input/output relation only.

Although the structure of a GF$^2$SR is hard to be identified, it may not be secure if part of the contents of the GF$^2$SR leak out. For example, consider again the GF$^2$SR, $R_1$, and the result of symbolic simulation, shown in Fig. 2. When $y_1(t + 3) = 0$, it holds that $(x(t), x(t + 1), x(t + 2)) = (y_2(t + 3), y_2(t + 3), y_1(t + 3))$, i.e., any input sequence $(x(t), x(t + 1), x(t + 2))$ that transfers $R_1$ from any state to the desired final state $(y_1(t + 3), y_2(t + 3), y_3(t + 3))$ becomes $(y_2(t + 3), y_2(t + 3), y_1(t + 3))$ when $y_1(t + 3) = 0$. This means $R_1$ behaves in the same way as a shift register during scan-in operation when $y_1(t + 3) = 0$, and hence it is not secure when the attacker regards $R_1$ as a shift register and tries to initialize it to a final state with $y_1(t + 3) = 0$. Similarly, when $x(t) = 0$, it holds that $(y_1(t), y_2(t), y_3(t)) = (z(t + 2), z(t + 1), z(t))$, i.e., the output sequence $(z(t), z(t + 1), z(t + 2))$ equals to $(y_2(t), y_2(t), y_1(t))$ when $x(t) = 0$. This means $R_1$ behaves in the same way as a shift register during scan-out operation when $x(t) = 0$, and hence it is not secure when the attacker regards $R_1$ as a shift register and tries to observe a present state of $R_1$ by applying an input sequence such that the first
input $x(t)$ happens to be 0. In this way, it may happen that
the attacker succeeds in initializing the contents of $R_1$ and/or
observing the contents of $R_1$, though he/she does not notice
them.

To avoid such leakage, we consider more secure scan
registers whose contents never leak out. We define new con-
cepts in the following. Consider a circuit $C$ with a single in-
put, a single output, and $k$ flip-flops. $C$ is called to be scan-
in secure if for any internal state of $C$ a transfer sequence
(of length $k$) to the state (final state) can be generated only
from the connection information of $C$, independently of the
initial state, such that the transfer sequence is always di-
fferent from that of a $k$-stage shift register. $C$ is called to be
scan-out secure if any present state (initial state) of $C$
can be identified only from the input-output sequence
(of length $k$) and the connection information of $C$, such that the output
sequence is always different from that of a $k$-stage shift reg-
ister. $C$ is called to be strongly secure if $C$ is scan-in secure
and scan-out secure.

Consider a 3-stage GF2SR, $R_1$, given in Fig. 2 (a). As
we mentioned above, $R_1$ behaves in the same way as a 3-
stage shift register during scan-in operation when $y_1(t+3) =
0$, and hence it is not scan-in secure. Also, $R_1$ behaves
in the same way as a 3-stage shift register during scan-out
operation when $x(t) = 0$, and hence it is not scan-out se-
cure. Next, consider another 3-stage GF2SR, $R_2$, given in
Fig. 3 (a). From the result of symbolic simulation shown in
Fig. 3 (b), we can see $y_2(t+3)$ never equals $x(t+1)$, and
hence $R_2$ is scan-in secure. Similarly, we can see $z(t)$ never
equals $y_3(t)$, which implies $R_2$ is scan-out secure. Therefore,
$R_2$ is strongly secure. In the following section, we consider
how to design strongly secure GF2SRs.

4. How to Design Strongly Secure GF2SRs

Consider a GF2SR $C$ with input $x$, output $z$, and $k$ flip-flops
$y_1, y_2, \ldots, y_k$, such that the most left XOR gate is located
between $y_p$ and $y_{p+1}$ as shown in Fig. 4 (a) and the most
right XOR gate is located between $y_{q-1}$ and $y_q$ as shown in
Fig. 4 (b). As illustrated in Fig. 4 (a), if there is at least one
NOT gate between a primary input $x$ and flip-flop $y_p$, the
final state of $(y_1, y_2, \ldots, y_p)$ of $C$ is always different from that
of a shift register. Hence, we can see $C$ is scan-in secure.
Similarly, as illustrated in Fig. 4 (b), if there is at least one
NOT gate between flip-flop $y_q$ and a primary output $z$, the
output sequence of $C$ is always different from that of a shift
register, and hence $C$ is scan-out secure. If there is no flip-
flop between the most right XOR gate and a primary output
$z$, we need to add a dummy flip-flop between them so that
we can insert a NOT gate on the flip-flop and make $C$ scan-
out secure.

From the above observation, we can see that any
GF2SR can be modified to be scan-in secure by inserting
at least one NOT gate as illustrated in Fig. 4 (a). Also, we
can see that any GF2SR can be modified to be scan-out se-
cure by inserting a dummy flip-flop if necessary and at least
one NOT gate as illustrated in Fig. 4 (b). We present these
methods in the following.

**Method for making scan-in secure:**

1. If there is no NOT gate between a primary input $x$ and
flip-flop $y_p$ (see Fig. 4 (a)), insert at least one NOT gate
between them.

**Method for making scan-out secure:**

1. If there is no flip-flop between the most right XOR gate
and a primary output $z$, add a dummy flip-flop between
them.
2. If there is no NOT gate between flip-flop $y_q$ and a pri-
mary output $z$ (see Fig. 4 (b)), insert at least one NOT
gate between them.

As an example, consider GF2SR, $R_1$, shown in Fig. 2.
As mentioned in the previous section, \(R_1\) is neither scan-in secure nor scan-out secure. We apply step (1) of the method for making scan-in secure. Here, flip-flop \(y_p\) is \(y_2\) in \(R_1\). Since there is no NOT gate between the primary input \(x\) and flip-flop \(y_2\), we insert a NOT gate between them. Figure 5 (a) shows a result by inserting one NOT gate. It is obvious that the modified circuit is scan-in secure since the content of flip-flop \(y_1\) is always different from that of the shift register.

Next, we apply the method for making scan-out secure to \(R_1\). Here, flip-flop \(y_q\) is \(y_3\) in \(R_1\), and hence we apply step (2) by inserting a NOT gate between \(y_3\) and the primary output \(z\). Figure 5 (b) shows a result. It is obvious that the modified circuit is scan-out secure since the first observed content of flip-flop \(y_3\) is always different from that of the shift register.

Figure 5 (c) shows a result that both methods for making scan-in secure and scan-out secure are applied to \(R_1\) so that it is scan-in secure and scan-out secure, and hence strongly secure.

As another example, consider a GF\(^2\)SR, shown in Fig. 6 (a), which is neither scan-in secure nor scan-out secure. Since there is no flip-flop between the most right XOR gate and a primary output, we add a dummy flip-flop, and then insert two NOT gates to make it scan-in secure and scan-out secure as shown in Fig. 6 (b).

5. Conclusion

In our previous work, we reported a secure and testable scan design approach by using generalized feed-forward shift registers [12], [13], where we considered the security problem from the viewpoint of the difficulty or complexity of identifying the structure of GF\(^2\)SRs. There is another viewpoint for the security, i.e., the possibility of leakage of the contents of GF\(^2\)SRs. In this paper, by looking at the security problem from this viewpoint, we have introduced a new concept of strong security such that no internal state of strongly secure circuits leaks out, and presented how to design such strongly secure GF\(^2\)SRs. We have shown a straightforward method for making a given GF\(^2\)SR strongly secure by adding inverters and at most one dummy flip-flop.

References