SeqL: Secure Scan-Locking for IP Protection

Seetal Potluri  
Department of ECE  
North Carolina State University  
Raleigh, U.S.  
spotlur2@ncsu.edu

Aydin Aysu  
Department of ECE  
North Carolina State University  
Raleigh, U.S.  
aaysu@ncsu.edu

Akash Kumar  
Department of Computer Science  
Technical University of Dresden  
Dresden, Germany  
akash.kumar@tu-dresden.de

Abstract—Existing logic-locking attacks are known to success-fully decrypt functionally correct key of a locked combinational circuit. It is possible to extend these attacks to real-world Silicon-based Intellectual Properties (IPs, which are sequential circuits) through scan-chains by selectively initializing the combinational logic and analyzing the responses. In this paper, we propose SeqL, which achieves functional isolation and locks selective flip-flop functional-input/scan-output pairs, thus rendering the decrypted key functionally incorrect. We conduct a formal study of the scan-locking problem and demonstrate automating our proposed defense on any given IP. We show that SeqL hides functionally correct keys from the attacker, thereby increasing the likelihood of the decrypted key being functionally incorrect. When tested on pipelined combinational benchmarks (TSCAN, MCNC), sequential benchmarks (ITC) and a fully-fledged RISC-V CPU, SeqL gave 100% resilience to a broad range of state-of-the-art attacks including SAT [1], Double-DIP [2], HackTest [3], SMT [4], FALL [5], Shift-and-Leak [6] and Multi-cycle attacks [7].

Index Terms—IP Piracy, Logic Locking, Scan-chains

I. INTRODUCTION

Logic-locking is a solution that was touted to address IP piracy threats in the semiconductor supply chain. This technique adds key-gates with one input driven by secret key, to obfuscate IP’s inner details. The transformation is reversed only upon application of the programmed secret key, thus preserving the IP’s original function. Unfortunately, logic-locking has been a cat-and-mouse game where existing locking proposals [8]–[14] fail to ever-advancing attacks [1]–[5]. Although these attacks primarily target combinational circuits, they can be extended to real-world sequential circuits through scan-chains. But the fundamental attack assumption is that inputs are controllable and outputs are observable. Thus, if the scan-chains are secured, it would be possible to provide a secure logic locking solution.

This paper proposes SeqL, a new logic locking technique that secures scan-chains. SeqL advances the prior work on design-for-security (DFS) [7], [15], [16], by conducting a formal study and empirically validating the security against a broad class of state-of-the-art attacks. Although attacks on large-scale sequential designs through functional execution is an open problem, attacks through the scan-chains currently exist. Thus, SeqL serves as the proper first line of defense. We demonstrate how to automate SeqL and quantify its low overheads on large-scale circuits. Therefore, SeqL addresses both the security and practicality challenges of logic locking.

Figure 1 outlines the system we consider. We highlight a simple setting for ease of explanation and elaborate later in our threat model. We assume that the primary inputs and primary outputs of the IP under consideration are not accessible, while only the scan-chains are accessible to the attacker, in embedded deterministic test (EDT)-bypass mode. The input register $R_i$ applies primary inputs to the IP, and the output register $R_o$ stores the primary outputs. The scan-chain connects all flip-flops in $R_i$, subsequently to the flip-flops internal to the IP and finally the flip-flops in $R_o$. The scan-input (SI) and scan-output (SO) ports are controllable and observable respectively by the attacker. Hence, the attacker can apply selective inputs to the IP and observe corresponding IP responses through these ports.

The main contributions of this paper are as follows:

1) We identify there is 100% correlation between flip-flop input (FI) locking and functional output corruption;
2) Exploiting this property, we propose SeqL, that: (a) isolates functional path from the locked scan path; (b) locks FIs and causes functional output corruption;
3) SeqL hides majority of the scan-correct keys which are functionally correct, thus maximizing the probability of the decrypted key being functionally incorrect;
4) The security of SeqL is also empirically evaluated and verified against a broad set of best known attacks;
5) The small overheads of SeqL and its ease of implementation makes it attractive for industry practice.

II. PRIOR WORK

The first wave of logic locking techniques [8]–[10] have been shown to be vulnerable to Boolean Satisfiability (SAT) attack [1]. In SAT-attack, distinguishable input patterns (DIPs) are obtained from the locked circuit and incorrect keys are pruned-off based on oracle’s responses to the DIPs. Several defenses were then proposed to mitigate SAT-attack, such as Anti-SAT [13], SARLock [12] and Cyclic Obfuscation [17], but they have failed to address the vulnerability to AppSAT [18], Double-DIP [2], CycSAT [19], HackTest [3], BeSAT [20] and machine-learning [21] attacks. While [22] proposes a new cyclic logic locking technique to defend CycSAT [19], TTLock [11] and Secure Function Logic Locking (SFL) [14] were the only locking schemes that were broadly resilient to these attacks, yet they recently failed against functional analysis of logic locking (FALL) [5] and SMT [4] attacks.
Fig. 2: (a) EFF-style: Sample sequential circuit with logic locking and FO locking; (b) Scan-unrolled equivalent of Fig. 2(a); (c) SeqL-style: Functional isolation and locked FIs/SQs; and (d) Scan-unrolled equivalent of Figure 2(c). SeqL considers flip-flops without feedback.

Additionally, to address the issue of defending against SAT-attack on sequential circuits, several DFS techniques have been proposed: (1) FORTIS [15], (2) Robust DFS (RDFS) [7] and (3) Encrypt Flip-Flop (EFF) [16]. FORTIS [15] is vulnerable to multi-cycle-test attacks [7]; RDFS [7] addresses these issues but necessitates routing of a global Test signal to all the key-based scan flip-flops, adds significant overheads, vulnerable to shift-and-leak [6] attack and increases test generation effort. EFF [16] addresses these issues by locking scan flip-flop outputs (FOs). But EFF is insecure against ScanSAT [23], thus there is a need for a better defense that is both secure and practical.

III. PRELIMINARIES

This section discusses the vulnerability of prior work on scan-locking and highlights the threat model.

A. Scan-Locking [16] & State-of-the-Art Attacks [4], [5], [23]

In EFF technique [16], flip-flops (FFs) on the non-critical timing paths of a sequential circuit are selected, and XOR/XNOR-type key gates are added to lock the Q-outputs, which drive combinational logic as well as the scan-chain. Figure 2(a) shows a sample sequential circuit with 2 out of 4 FFs encrypted using EFF-style scan-locking. In Figure 2(a):

- G0 and G1 are the primary inputs. SI and SO are the circuit’s scan-input port and scan-output port respectively;
- FFs 1 and 2 have feedback, while FFs 3 and 4 do not have feedback. G2, G4, G6 and G8 are corresponding FF inputs (FIs) respectively. G3, G5, G7 and G9 are corresponding FF outputs (FOs) respectively; and
- c1 and c0 are the combinational key bits, while f0 and f1 are key bits used to lock the FO G3 (XOR-type key gate) and FO G5 (XNOR-type key gate) respectively.

ScanSAT [23] shows that it is possible to convert this scan-locked instance to the scan-unrolled locked instance of Figure 2(b), launch the SAT-attack on the unrolled instance and decrypt the functionally correct sequential key. Here, in scan-mode of operation: SI(G3) and SI(G5) are the scan-input-bits corresponding to FFs 1 and 2 respectively; and ESO(G2) and ESO(G4) are the locked-scan-output bits corresponding to FFs 1 and 2 respectively. Hence, EFF technique is not secure. Similar to ScanSAT [23], it is possible to extend some of the state-of-the-art attacks like HackTest-attack [3], functional-analysis-attacks on logic-locking (FALL) [5], and SMT-attack [4]. We thus evaluate SeqL on all these attacks.

B. Threat model

We consider a malicious foundry that offers fabrication, assembly and testing services [24]. Thus, the attacker has access to layout and mask information, and is thus able to reverse-engineer the gate-level netlist. There are two possible scenarios: (1) The attacker uses an activated IC (oracle), and applies scan patterns to the IP, and observes corresponding scan responses in EDT-bypass mode. Since the IP is located somewhere deep inside the SoC, we assume that the IP is controllable/observable, only through scan-chains. Typically, scan ports are not deactivated to facilitate debug of customer returns, which the attacker exploits to launch the SAT-attack; or (2) The attacker is at the outsourced tester, where the attacker can place the dies in EDT-bypass mode, applies desired scan patterns to the IP, and observes corresponding scan responses.

IV. SOLUTION INSIGHT

As discussed in the previous section, when SAT-attack is launched on the scan-unrolled EFF-style scan-locked circuit, the SAT solver returns the functionally correct key. In the discussion that follows, we exploit the following principles:

1) In EFF-style scan-locking, the FO key-gate corresponding to the FF appears both in the scan-input and scan-output paths of the FF in the scan-unrolled instance;
2) Functional path can be isolated from the locked scan path used by the attacker, thus achieving resilience;
3) To prevent vulnerability to multi-cycle-attack [7], it is important to selectively lock FFs without feedback;
4) Since the FO key gates cascade with FI key gates to form XOR/XNOR-chains, it is possible to obfuscate the solver.

Figure 2(c) shows the proposed SeqL-style scan-locking by transforming the circuit in Figure 2(a), using above principles. Figure 2(c) is different from Figure 2(a) in the following ways:

- There is a separate Q and SQ, and the key gate is added at SQ (SQ key-gate), thus leaving the functional output Q unencrypted. This is referred to as functional isolation;
- FFs without feedback e.g., 3 and 4 are selected for locking;
- sqk0 and sqk1 are the key bits used to lock the SQ output of FFs 3 (with XOR-type key gate) and 4 (with XNOR-type key gate) respectively; and
- Extra key gates (both of XOR type and without additional obfuscation logic in this case, for ease of explanation) are added to lock FFs of both these FFs, using fik0 and fik3 key bits respectively. These key gates are referred to as FI key gates in the rest of this paper.
Figure 2(d) shows the corresponding scan-unrolled equivalent combinational circuit. The purple dashed line is the functional boundary. This means that the key gates to the right of this boundary (SQ key-gates) only affect scan-operation, and do not affect normal functional operation of the circuit. This is because the attacker uses the scan mode of operation, and hence observes ESO(G2) and ESO(G4). However, the circuit’s normal functional operation is purely influenced by E(G2) and E(G4), and hence the XOR/XNOR-chains (in red) cease to exist. This renders the scan-correct decrypted key, being functionally incorrect. After running SAT-attack on circuit in Figure 2(d), when the combinational portions of the sequential circuit, the original unencrypted sequential circuit and the solver key are inputted to the formal equivalence checker, the result was not equivalent. Hence, by functional isolation and FI locking, resilience was achieved, thus making the proposed SeqL-style scan-locking mechanism secure. Next subsection explains this behavior using an abstract model.

A. Abstract model

Figure 3 shows an abstracted model of the sequential circuit, with the combinational logic abstracted into a source-sink circular vertex C, each FI key-gate abstracted into a blue circular vertex, and each FF key-gate abstracted into a red rectangular vertex. Figures 3(a) and 3(b) show models corresponding to circuits in Figures 2(a) and 2(c) respectively.

In the abstract model corresponding to the proposed scan-locking shown in Figure 3(b), the following are functional paths:

- \( FP_0 : fik_0 \rightarrow G_7 \)
- \( FP_1 : fik_3 \rightarrow G_9 \)

and the following are scan-out paths:

- \( SP_0 : fik_0 \rightarrow sqk_0 \rightarrow sqk_1' \rightarrow SO \)
- \( SP_1 : fik_1 \rightarrow sqk_1' \rightarrow SO \)

Figure 3(b) shows that the number of inversions for the scan-output-paths \( SP_0 \) and \( SP_1 \), are 2 and 0, respectively. Since all scan-output-paths have even inversion parity, the proposed locked circuit is correct for scan operation. However, for functional paths, the number of inversions for \( FP_0 \) and \( FP_1 \), are 1 and 0. Since functional path \( FP_0 \) has odd-inversion-parity, the circuit is incorrect for functional operation.

To understand the behavior systematically, Table I enumerates all possibilities for the scan-lock \( \{ fik_1, sqk_1', fik_0, sqk_0 \} \) for the circuit in Figure 2(c). The rows in this table, that show up as true for the scan-correct column, are the possible keys returned by the SAT-solver. Among the four functionally-correct rows only one is scan-correct, thus SeqL hides \( \frac{4}{7} \) functional-correct keys from the attacker. Similarly, among the four scan-correct rows, only one is functionally correct, thus SeqL maximizes the odds against the functionally-correct-key among the scan-correct-keys. Figure 4 shows the corresponding key assignment graph (KAG). The sequential key returned by the solver is the second leaf from the left. Since this leaf is a functionally incorrect key, the technique is able to achieve resilience. In this example, odds against the functionally correct key is \( p = \frac{3}{4} = 0.75 \).

B. Analysis

This section formally analyzes the security of logic locking and proves that if SeqL is used to lock \( n \) flip-flops in the sequential circuit, then the odds against the functionally-correct-key among the scan-correct-keys equals \( 1 - \frac{1}{2^n} \), assuming the attack is launched in EDT-bypass mode.

Given an FI-SQ key-pair \( \{ fik_i, sqk_i \} \), there are 4 possible assignments \( \{00, 01, 10, 11\} \). Let \( n \) be the number of locked FI-SQ pairs. Let \( KAG = (V, E) \) be a vertex-labelled edge-weighted directed graph, where the vertices correspond to FI-SQ pairs and the edges correspond to inversion parity. The direction of edges is opposite to the scan-out-path direction. In \( KAG \), the children of every vertex at depth \( i \) from the root correspond to \( i^{th} \) flip-flop from the end of the scan-out-path. All node and edge assignments are performed to ensure scan-correctness. \( KAG \) is a tree, whose root vertex is a dummy node, with exactly two children 00 and 11.

The labels on the vertices in \( KAG \) are 00, 01, 10 or 11, corresponding to \( \{ fik_i, sqk_i \}, \{ fik_i, sqk_i', \}, \{ fik_i', sqk_i \} \) or \( \{ fik_i', sqk_i' \} \) depending on whether FI key-gate, SQ key-gate combination is \{XOR, XOR\}, \{XOR, XNOR\}, \{XNOR, XOR\} or \{XNOR, XNOR\} respectively. 00 and 11 are even-
The odds against the functionally-correct-key (FQ) and 10, are odd-parity vertices. The children of 00 and 01 are even-parity vertices. The children of 10 and 11 are odd-parity vertices. Hence, every non-root vertex has exactly 2 children. The possible weights on the edges in vertex. invk equals 0 or 1, depending on whether kth flip-flop along the scan-chain from the scan-output is locked with an XOR or XNOR key-gate respectively.

**Theorem 1:** Parities of both edges of a vertex are identical.

**Proof:** Assume vertex vi in KAG at depth i. In order to ensure scan-correctness, (fik, ⊕ sqki, ⊕ invi) ⊕ ∑k=1i−1(sqkb, ⊕ invk) should equal 0. If ∑k=1i−1(sqkb, ⊕ invk) equals 0, (fik, ⊕ sqki, ⊕ invi) becomes 0 (possible children of vi are 00 and 11, in both cases parity of edge is 0).

On the other hand, if ∑k=1i−1(sqkb, ⊕ invk) equals 1, (fik, ⊕ sqki, ⊕ invi) becomes 1 (possible children of vi are 01 and 10, in both cases parity of edge is 1). Thus, parity of left and right edges of a vertex are identical, hence the proof.

**Theorem 2:** KAG is a binary tree.

**Proof:** Root vertex has exactly two children. Additionally, every non-root vertex has exactly two children. Since every vertex has exactly two children, KAG is a binary tree, hence the proof.

**Theorem 3:** The odds against the functionally-correct-key among the scan-correct-keys is p = 1 − 1/n.

**Proof:** The path from root to a functionally-correct leaf should have all 00 nodes, there is exactly one such leaf in KAG. Since, the total number of leaves in KAG = 2n, odds p = 2n − 1/2n, hence the proof.

V. AUTOMATING SEQL DEFENSE

So far, we have seen the effectiveness of SeqL in defending attacks on scan locking. This section shows how to automate SeqL, so that it can be practically deployed on large circuits.

**Objective:** Lock selective scan flip-flops (FI-SQ pairs) without feedback such that functional output corruption is achieved, while area-overhead is minimized.

**Solution:** The likelihood of functional output corruption is maximized with increase in p = 1 − 1/n, whereas area-overhead increases linearly with n. Hence, the chances of functional output corruption increases rapidly with n, with minimal increase in area overhead. Figure 5 shows SeqL flow, which exploits this principle to iteratively lock scan flip-flops (FI-SQ pairs) from the end of the scan-chain(s) until functional output is corrupted. Thus, the proposed scan-locking solution has two parts:

1) An functionally-isolated scan-locked flip-flop design.
2) An iterative FI-SQ locking algorithm.

A. Functionally-isolated scan-locked flip-flop design

We define the sequential key to be K = {Kc, Kfi, Ksq}, where Kc, Kfi and Ksq are portions of the key that lock the combinational logic (excluding the FIs), the FIs and the SQs respectively. In EFF technique, all these components influence the sequential circuit’s normal functional operation. Figure 6(a) shows the EFF-style scan-locking scheme, where the FO key gate output, is broadcasted to Scan-Q (referred to as SQ in the figure), as well as Functional-Q (referred to as FQ in the figure). The proposed isolation-based scan-locking is shown in Figure 6(b), which isolates the functional path from the locked scan path. Hence, the SQ key gate locks only SQ and has no influence on FQ. Thus, in the proposed SeqL technique, only Kc and Kfi influence (while Ksq has no effect on) the sequential circuit’s normal functional operation. This assists in returning the functionally incorrect key, thus aiding in functional output corruption when applied with the key returned by the SAT-solver. There is an additional transmission gate added to this structure in the scan path to avoid toggling of the locking key gate along the scan path. Although this adds 2 extra transistors per flip-flop, the overhead is marginal compared to the benefit of savings obtained in Energy-Per-Toggle (EPT) of the flip-flop during normal functional operation, similar to CSP-scan [25]. The comparison of area, timing and EPT of the EFF as well as SeqL flip-flops are provided later in Section VI.

B. Iterative key pushing algorithm (IKPA) for pipelined combinational circuits

Algorithm 1 shows the iterative key gate pushing algorithm, that takes a logic-locked combinational circuit with pipeline stages both at its inputs and outputs. Since the circuit already has key gate overhead, to avoid any further overhead, the algorithm iteratively pushes some of the key gates inside combinational logic to the output boundary. We measure the success of the IKPA algorithm using formal equivalence checking. If the
Algorithm 1: Iterative key pushing algorithm for pipelined logic-locked combinational circuits

Input: C

while C' = C do
  Identify a combinational key gate pair k_i, an unvisited FI-SQ pair for a flip-flop without feedback k_o, and mark corresponding k_o as visited;
  Push k_i to k_o;
  Run SAT-solver and update K_{f_i}, C';
end
Result: C', K_{f_i}

Algorithm 2: Iterative boundary locking algorithm for sequential circuits

Input: S, K

while S' = S and |K_{f_i}| + |K_{s_j}| <= γ do
  Identify an unvisited FI-SQ pair for a FF without feedback and mark corresponding pair as visited;
  Obfuscate corresponding FI-SQ pair;
  Run SAT-solver and update K_{f_i}, S';
end
Result: S', K_{f_i}

returned solver key makes the two circuits different or in other words not equivalent, then we are successful i.e., functional output corruption is achieved. Additionally, even with SeqL, we have found that in all the cases, the decrypted K_c is correct. Hence, it is only K_{f_i}, that causes functional output corruption. Section VI demonstrates the detailed results.

C. Iterative boundary locking algorithm (IBLA) for sequential circuits

Unlike pipelined logic-locked combinational circuits, there are no existing key gates for sequential circuits. Hence, FI-SQ locking or in other words, boundary locking has to be done afresh. Moreover, since K_{c} is always successfully decrypted, combinational logic except FIs is not locked to ensure cost-effectiveness. Since the higher the number of inserted key gates at the FI-SQ boundary, the higher the area overhead, we make this parameter, γ, user-configurable. Algorithm 2 takes a sequential benchmark as input, and iteratively obfuscates unvisited FI-SQ pairs with XOR/XNOR-type key-gates, until functional output corruption is achieved or |K_{f_i}| + |K_{s_j}| > γ. Since the implementation is simple and security is achieved with low overheads, this is attractive for industry practice.

VI. EXPERIMENTAL EVALUATION

We validate the security of SeqL against a multitude of state-of-the-art attacks and quantify its reduced overheads compared to prior work. This analysis confirms our claims on genericness, robustness, and scalability of SeqL. Algorithms 2 (IBLA) and 1 (IKPA) were used for scan-locking the sequential benchmarks and pipelined combinational benchmarks, respectively. Both the locking algorithms were implemented in Perl. Since the locking algorithm execution times across all the benchmarks were very small (matter of seconds), the execution times were not reported.

### Table II. Resilience of SeqL for Pipelined Combinational Benchmarks for 5% logic locking.

| Bench | RND | DAC'12 | ToC'13/13xor | ToC'13/max |
|-------|-----|--------|--------------|------------|
| apex1 | EFF | SeqL   | EFF | SeqL | EFF | SeqL | EFF | SeqL |
| apex4 | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| 14    | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| 17    | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| 18    | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| 19    | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| seq   | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| k2    | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| ex1010| ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| du1u  | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| c432  | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| c499  | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| c880  | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| c1355 | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| c1908 | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| c3540 | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| c5315 | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |
| c7552 | ☑️  | ☑️     | ☑️  | ☑️   | ☑️  | ☑️   | ☑️  | ☑️   |

### Table III. Resilience of SeqL against state-of-the-art attacks on pipelined combinational benchmarks.

| Bench   | Oracle-guided | Oracle-less |
|---------|--------------|-------------|
| apex2   | ☑️           | ☑️          |
| apex4   | ☑️           | ☑️          |
| 14      | ☑️           | ☑️          |
| 17      | ☑️           | ☑️          |
| 18      | ☑️           | ☑️          |
| 19      | ☑️           | ☑️          |
| seq     | ☑️           | ☑️          |
| k2      | ☑️           | ☑️          |
| ex1010  | ☑️           | ☑️          |
| du1u    | ☑️           | ☑️          |
| c432    | ☑️           | ☑️          |
| c499    | ☑️           | ☑️          |
| c880    | ☑️           | ☑️          |
| c1355   | ☑️           | ☑️          |
| c1908   | ☑️           | ☑️          |
| c3540   | ☑️           | ☑️          |
| c5315   | ☑️           | ☑️          |
| c7552   | ☑️           | ☑️          |

All experiments are run on IBM BladeCenter® Cluster with abort-limit of 1 week. ‘☒’ is secure and ‘☒’ is insecure. ‘☒’ indicates decryption time exceeds abort-limit, while ‘NK’ indicates No-Key.

A. Resilience of SeqL vs. EFF [16] against SAT-Attacks on pipelined combinational benchmarks

Table II shows the results of applying the procedure shown earlier in Figure 5 on 4 different encryption schemes validated in [1], and compared against EFF [16]. This table shows that SeqL secured all sequential circuits against SAT-attack in 100% of the cases. As explained in Section IV, (1) K_{c} was successfully decrypted in all cases, while (2) K_{f_i} was incorrect, hence causing functional output corruption, thus achieving resilience. Results on IOLTS’14 encryption scheme [1], [10] gave 0% resilience in EFF case and 100% resilience in SeqL case, across all benchmarks, hence not reported in Table II for brevity.

B. Resilience of scan-unrolled versions of SeqL-locked design to state-of-the-art attacks on logic locking

Table III confirms the resilience of SeqL-locked design to state-of-the-art attacks on logic locking like Double-DIP (DDIP) [2], ScanSAT (SS) [23], HackTest (HT)-attack [3], functional-analysis-attacks on logic-locking (FALL) [5], and SMT-attack [4]. All experiments were run on IBM BladeCenter® Cluster, with an abort-limit of 1 week. Those entries in the table which are empty, correspond to all those
cases which have crossed this abort-limit while performing key decryption. Similarly, for some cases the solver returns No-key (indicated as NK in the table). The resilience verification flow for oracle-guided attacks is similar to the flow in Figure 5. For the oracle-less attacks, the resilience verification flow is slightly different because of absence of the oracle, however lcmp verifier is still used for formal-equivalence-checking.

C. Resilience of SeqL vs. EFF against SAT-Attacks on sequential benchmarks

Table IV shows the results of applying the procedure shown in Figure 5 on ITC’99 open-source sequential gate-level benchmarks and flattened RISC-V CPU netlist. The RISC-V CPU RTL is obtained from [26], and gate-level synthesis is performed using NanGate 45nm library using Synopsys Design Compiler®. Scan chains and ETD-compresion are inserted into the gate-level netlist using Mentor Graphics TestKompress® (decompressor and compactor will not be used because the attack is launched in EDT-bypass mode).

The scan-inserted gate-level-verilog is converted to the bench format used in the attack tools, using an in-house Python script. The attack tools only support basic gates like AND/OR/NAND/NOR/XOR/XNOR/NOT/BUF/MUX. However the RISC-V gate-level-verilog contains more complex gates like AOI (and-or-invert), OAI (or-and-invert), HA (half-adder) and FA (full-adder). Our Python script internally converts each of these complex gates into a composition of basic gates, before final conversion to bench, which is acceptable because IBLA algorithm inserts scan-locks and does not affect combinational logic. The compression hardware is not converted because the attacks are meant to be launched in EDT-bypass mode. The columns #SFFs, #SCs, Res. and Ov. indicate number of scan-flip-flops, number of scan-chains, resilience and overhead respectively. The resilience rate of EFF was 0%, while that of SeqL was 100%, thus indicating the superiority of SeqL over EFF. An abort limit of 1 week was used for key decryption.

D. Resilience to Multi-cycle attacks [7]

So far, we discussed attacks using a single capture cycle. The attacker can also run the circuit for N > 1 capture cycles (multi-cycle test), without affecting the shift cycles. This attack can be modeled by time-unrolling the reverse-engineered netlist as well as the oracle N times. Since scan-in and scan-out phases span hundreds of clock cycles and N is in general relatively very small, running at slow-speed or at-speed will not significantly affect test-time/attack-time. Table IV shows results for this attack. Similar to single-cycle attack (N = 1), SeqL was resilient to multi-cycle attack (N = 2, 5) across all benchmarks.

| Bench. | #gates | #SFFs | #SCs | T\textsubscript{\text{setup}} | EFF [16] | SeqL | Res. | Ov. | n | p | t\textsubscript{\text{setup}} | t\text{\textsubscript{\text{FS}}} | % Inc. | EPT | % Inc. |
|--------|---------|-------|------|----------------|----------|------|------|-----|----|---|---------------|---------------|-------|-----|-------|
| b14    | 10,012  | 245   | 3    | 54            | ✔        | ✔    | 3.3% | 8   | 0.99 | 0.24% | ✔        | ✔    | ✔    | 19 min | 2 min | 2 min |
| b15    | 12,993  | 440   | 5    | 70            | ✔        | ✔    | 4.3% | 9   | 0.99 | 0.2%  | ✔        | ✔    | ✔    | 47 min | 11 min | 164 min |
| b16    | 52,192  | 1,415 | 15   | 97            | ✔        | ✔    | 5.2% | 8   | 0.99 | 0.06% | ✔        | ✔    | ✔    | 10 min | 17 hrs | 41 hrs |
| b18    | 114,561 | 3,330 | 34   | 23            | ✔        | ✔    | 3.8% | 10  | 0.99 | 0.03% | ✔        | ✔    | ✔    | 53 hrs | abort-limit | abort-limit |
| b19    | 231,266 | 6,642 | 67   | 30            | ✔        | ✔    | 3.7% | 10  | 0.99 | 0.01% | ✔        | ✔    | ✔    | 91 hrs | abort-limit | abort-limit |
| b20    | 20,172  | 490   | 5    | 22            | ✔        | ✔    | 3.3% | 10  | 0.99 | 0.15% | ✔        | ✔    | ✔    | 10 min | 15 min | 37 min |
| b21    | 20,517  | 490   | 5    | 22            | ✔        | ✔    | 3.2% | 10  | 0.99 | 0.15% | ✔        | ✔    | ✔    | 9 min  | 34 min  | 36 min  |
| b22    | 29,897  | 735   | 8    | 32            | ✔        | ✔    | 3.3% | 10  | 0.99 | 0.1%  | ✔        | ✔    | ✔    | 11 min | 31 min  | 91 min  |
| RISC-V Flat. | 25,596 | 2,031 | 20   | 226           | ✔        | ✔    | 4.9% | 10  | 0.99 | 0.00% | ✔        | ✔    | ✔    | 2 min  | 15 min  | 6 hrs  |

N denotes the number of capture cycles in the multi-cycle scan-based test. The scan-flip-flops without feedback, R\textsubscript{\text{setup}}, are stitched by designer as a separate scan-chain for security considerations. IBM BladeCenter® Cluster with abort limit of 1 week is used. ✔ is secure and ✗ is insecure.

E. Resilience to Shift-and-Leak attack (SaLa) [6]

RDFS [7] inserts special secure cells (SCs) into scan-chains to drive the key-gates. Unlike RDFS, SeqL key-gates are directly driven by the tamper-proof memory, without SCs in between. The first goal of SaLa is to find leaky cells, and shift the content of SCs into leaky cells. Due to absence of SCs in SeqL, this first goal is never achieved. The second goal of SaLa is to find the leak condition and satisfy it. Since SeqL locks the scan-chain itself, it is mandatory to know the scan-key upfront to invoke test generator and find the leak condition. Since the goal is itself key-decryption, it is not possible to find the leak condition, let alone satisfy it. Thus, SeqL is inherently resilient to SaLa.

F. Overheads

Table V shows the comparison of area, timing and energy for original, EFF-style and proposed SeqL-style locked scan flip-flops, obtained using SPICE transistor-level simulation.

- **Table V. Area, Timing and Energy Overhead Comparison**

| FF | # t\textsubscript{\text{setup}} | t\text{\textsubscript{\text{FS}}} | % Inc. | EPT | % Inc. |
|----|----------------|-----------|-------|-----|-------|
| Orig. | 48 | 143 ps | 143 ps | 13.1% | EPT | 31% |
| EFF | 48 | 145 ps | 163 ps | 44% | 17 hrs | 31% |
| SeqL | 50 | 127 ps | 12% | 13 hrs | 6% |

For EFF, since key is successfully recovered for N = 1 itself, resilience results for N > 1 were not shown.

VII. CONCLUSIONS

We have proposed SeqL, that performs functional isolation and FI-SQ locking. SeqL hides a major fraction of the functionally correct keys, thus maximizing functional output corruption. We have shown both the theoretical and empirical improvements in the security of scan-locking. The results have shown 100% resilience to state-of-the-art oracle-guided as well as oracle-less attacks. Furthermore, since combinational key (excluding FIs) is completely recovered, it is sufficient to lock FI-SQ pairs, making SeqL cost-efficient. Moreover, we have demonstrated SeqL on large designs such as RISC-V CPU, demonstrating its applicability in mainstream industry practice.

VIII. ACKNOWLEDGEMENTS

This work is supported in part by the German Research Foundation (DFG), Cluster of Excellence Center for Advancing Electronics Dresden, Technische Universität Dresden.


REFERENCES

[1] P. Subramanyan et al, “Evaluating the security of logic encryption algorithms,” in IEEE HOST, 2015, pp. 137–143.

[2] Y. Shen and H. Zhou, “Double DIP: Re-evaluating security of logic encryption algorithms,” in IEEE GLSVLSI, 2017, pp. 179–184.

[3] M. Yasin et al, “Testing the trustworthiness of IC testing: An oracle-less attack on IC camouflaging,” IEEE TIFS, vol. 12, no. 11, pp. 2668–2682, 2017.

[4] K. Z. Atar et al, “SMT attack: Next generation attack on obfuscated circuits with capabilities and performance beyond the SAT attacks,” in CHES, 2019.

[5] D. Strone et al, “Functional analysis attacks on logic locking,” in IEEE/ACM DATE, 2019, pp. 936–939.

[6] N. Limaye et al, “Is robust design-for-security robust enough? attack on locked circuits with restricted scan chain access,” in IEEE ICCAD, 2019.

[7] U. Guin et al, “Robust design-for-security architecture for enabling trust in IC manufacturing and test,” IEEE TVLSI, vol. 26, no. 5, pp. 818–830, 2018.

[8] J. Roy et al, “EPIC: Ending Piracy of Integrated Circuits,” in IEEE/ACM DATE, 2008, pp. 1069–1074.

[9] J. Rajendran et al, “Fault analysis-based logic encryption,” IEEE Transactions on Computers, vol. 21, no. 5, pp. 410–424, 2015.

[10] S. Dupuis et al, “A novel hardware logic encryption technique for thwarting illegal overproduction and hardware trojans,” in IEEE IOLTS, 2014, pp. 49–54.

[11] M. Yasin et al, “TTLock: Tenacious and traceless logic locking,” in IEEE HOST, May 2017, pp. 166–166.

[12] M. Yasin et al, “SARLock: SAT attack resistant logic locking,” in IEEE HOST, May 2016, pp. 236–241.

[13] Y. Xue et al, “Mitigating SAT attack on logic locking,” in CHES. 2016, pp. 127–146.

[14] M. Yasin et al, “Provably-secure logic locking: From theory to practice,” in ACM CCS, 2017, pp. 1601–1618.

[15] U. Guin et al, “FORTIS: A comprehensive solution for establishing forward trust for protecting IPs and ICs,” ACM TOLSAE, vol. 21, no. 4, pp. 63:1–63:20, 2016.

[16] R. Karmakar et al, “A scan obfuscation guided design-for-security approach for sequential circuits,” IEEE TCAS II: Express Briefs, pp. 1–1, 2019.

[17] K. Shahs et al, “Cyclic obfuscation for creating SAT-unresolvable circuits,” in IEEE GLSVLSI, 2017, pp. 173–178.

[18] K. Shahs et al, “AppSAT: Approximately deobfuscating integrated circuits,” in IEEE HOST, 2017, pp. 95–100.

[19] H. Zhou et al, “CycSAT: SAT-based attack on cyclic logic encryptions,” in IEEE/ACM ICCCAD, 2017, pp. 49–56.

[20] Y. Shen et al, “ReSAT: Behavioral SAT-based attack on cyclic logic encryption,” in IEEE ASP-DAC, 2019, pp. 657–662.

[21] P. Chakraborty et al, “SAIL: Machine learning guided structural analysis attack on hardware obfuscation,” in IEEE AsiaHOST, 2018, pp. 56–61.

[22] A. Rezaei et al, “CycSAT-unresolvable cyclic logic encryption using unreachable states,” in IEEE ASP-DAC, 2019, pp. 358–363.

[23] L. Alrahis et al, “ScanSAT: Unlocking obfuscated scan chains,” in IEEE ASP-DAC, 2019, pp. 352–357.

[24] “TSMC integrated backend services.” [Online]. Available: www.tsmc.com/english/dedicatedFoundry/services/integratedbackend.htm

[25] S. Potluri, A. S. Trinadh, S. B. Ch., V. Kamakoti, and N. Chandrachoodan, “Dft assisted techniques for peak launch-to-capture power reduction during launch-on-shift at-speed testing,” ACM Transactions on Design Automation of Electronic Systems, vol. 21, no. 1, pp. 14:1–14:25, 2015.

[26] A. Magyar, V-scale, an implementation of an RV32IM core in Verilog. [Online]. Available: https://riscv.org/2015/09/risc-v-in-verilog/