Test and Hardware Security
Marion Doulcier, Giorgio Di Natale, Marie-Lise Flottes, Bruno Rouzeyre

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Test & Security

G. DiNatale, M. Doulcier, M–L. Flottes, B. Rouzeyre

Pastis 2008
Circuit testing is mandatory to guarantee a good security level

A hardware defect may induce some security vulnerability

But

<table>
<thead>
<tr>
<th></th>
<th>Test</th>
<th>Security</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observability</td>
<td>![Green Arrow]</td>
<td>![Red Arrow]</td>
</tr>
<tr>
<td>Controlability</td>
<td>![Green Arrow]</td>
<td>![Red Arrow]</td>
</tr>
</tbody>
</table>
- **External Test + Scan path**

  - High fault coverage
  - Automatic generation of scan chains
  - Easy test sequence generation

**Vulnerability**

- Control and observation of internal states of CUT
- => secret data retrieval
- Built-in Self Test (BIST)

- No control/observation from the outside
- Area overhead
- Fault coverage (pseudo-random testing)?
Securing the scan chain

- **Goal**
  - No observation or control of the functional data processed by the secure system

- **Principle**
  - Prevent illegal scan shift operations

- **Solutions**
  - Test mode protection
    - Scan protocol
    - Test Patterns watermarking
  - System mode protection
    - Scan chain scrambling
    - Scan enable tree protection
    - Spy FFs

<table>
<thead>
<tr>
<th>Protection against</th>
<th>Illegally used test mode</th>
<th>Protection against</th>
<th>Scan chain probing attacks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Scan protocol

- The circuit is initialized before and after test mode
- Initialization is checked before switching to another mode
- Switch between the 2 modes, bypassing the initialization, is detected
- Test pattern watermarking
  - Test patterns embed authentication keys
  - Keys are dynamically changed (e.g. LFSR-based)
System mode protection

- Scrambling method
  - Scan path with a prefixed segment organization during test mode
    - Segment 1 → Segment 2 → Segment 3 → Segment 4
  - Scan path with random segment organization if shift during system mode
    - Time T1
      - Segment 1 → Segment 2 → Segment 3 → Segment 4
    - Time T2
      - Segment 1 → Segment 2 → Segment 3 → Segment 4
- **Scan–Enable Tree Protection**
  
  ✓ Compare the scan enable signals at different locations

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**Diagram: System mode protection**

- **Test Controller**
- **Scan Enable**
  - Connects to **Scan FFs**
- **Check the state of the test controller to any switch to 1**
- **Clk**

If 1, then error
- Spy Flip-Flops
  - Include Spy cells in the scan chain
  - Control the spy cells to a constant value
  - Observe the spy cells states
## Experimental results

<table>
<thead>
<tr>
<th></th>
<th>Scrambling</th>
<th>Scan enable</th>
<th>Spy cell</th>
<th>Pattern watermarking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Insertion flow</strong></td>
<td>RTL</td>
<td>RTL + place&amp;route</td>
<td>RTL</td>
<td>RTL</td>
</tr>
<tr>
<td><strong>Test</strong></td>
<td>Test time</td>
<td>0%</td>
<td>1%</td>
<td>5%</td>
</tr>
<tr>
<td><strong>Design</strong></td>
<td>Area</td>
<td>0.2%</td>
<td>0.3%</td>
<td>1.8%</td>
</tr>
<tr>
<td></td>
<td>power c.</td>
<td>7%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td><strong>Security</strong></td>
<td>+++</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
</tbody>
</table>
To resume

- Countermeasures address two kinds of attack
  - ![_tick] Legal activation of the test circuitry
    - corruption of the authentication scheme
    - malfunction of the security
    - insider attack
  - ![_tick] Physical access to the chip
    - high knowledge of the circuit
    - very expensive equipment
BIST

- Reduced ATE cost
- In-situ testing
- Reduced external access

But
- Circuitry overhead
- Self-test of crypto-core
- Use the crypto-core as a test resource (TPG/SA)
- AES/DES
"Randomness" of cipher

- 1 vector per encryption

$\approx$ 1 vector every 10 clock cycles
"Randomness" of cipher

- 1 vector per encryption

≈ 1 vector every 10 clock cycles
"Randomness" of cipher

- 1 vector per round cycle

"Randomness"? (Diffusion, Confusion, Bijection)

Checked by NIST statistical package suite (15 randomness tests)
Randomness comparison

AES round / DES round : as good random pattern generators as LFSRs
- Looped Crypto-core ↔ random number generator

- First step
  ✓ 1\textsuperscript{st} cycle
- **Second step**

  ✓ Cycles 2, 3, ……, n
Theoretical result

- AES: Fault-coverage = 100% after $n \in \{2520,\ldots,2590\}$ clock cycles
- DES: Fault-coverage = 100% after $n \in \{620,\ldots,710\}$ clock cycles

In practice

- AES
  - Fault-coverage = 100% after 2200 clock cycles ($\forall$ key, $\forall$ clear text)
- DES
  - Fault-coverage = 100% after 560 clock cycles ($\forall$ key (not wk), $\forall$ clear text)
Crypto-core as TPG/SA

- **STUMPS Architecture**

- **Proposed solution**

TPG for other cores
Test response compactor for other cores
TPG : ISCAS'89 benchmarks

- s9234
- s13207
- s38548
- **Response compaction mode**:
  - $SA = Selection = 1$

- **Functional mode**
  - $SA = 0$

---

![Diagram](image-url)
Fault-masking probability

- **AES/DES**

\[ P(M_n) = \frac{1}{2^m} - \left( \frac{1}{2^m} \right)^n \]

- **MISR**

\[ P(M_n) = \frac{2^{n-1} - 1}{2^{m+n-1} - 1} \]

\[ P(M_{128}) \xrightarrow{n \to \infty} \frac{1}{2^{128}} \approx 10^{-40} \]

n = \#test responses and m = 128 or 64
Cryto-core (AES/DES) as a test resource:

- Test Fault Coverage: \( \cong \) LFSR
- Error Masking Probability: \( \cong \) MISR
- Reduced area overhead
- No impact on ciphering frequency/latency

Potential attacks (2 successive round results observable))

\[ \Rightarrow \text{use a specific key for test} \]
Simultaneous TPG and Compaction

Core 1
Core 2
Core 3
Core 4
Crypto processor AES
Core 5

Controller
Round key generator
Add Round Key
Mix Columns
Shift Rows
Sub Bytes
CUT responses
SA
Start
Selection
0, 1
Key
Round Key
End ciphering
Register R1
Register R2
Test vectors
## Area overhead

<table>
<thead>
<tr>
<th>Round</th>
<th>AES generator</th>
<th>AES compactor</th>
<th>AES Self-test</th>
<th>AES 4 modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>-SubBytes</td>
<td>803 734</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>-ShiftRows</td>
<td>0</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>-MixColumns</td>
<td>59 847</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>-AddRoundKey</td>
<td>49 945</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Controller</td>
<td>6 345</td>
<td>+ 5.72%</td>
<td>+ 8.72%</td>
<td>+ 6.58%</td>
</tr>
<tr>
<td>Key generator</td>
<td>301 162</td>
<td>+ 0.015%</td>
<td>+ 0.015%</td>
<td>+ 0.015%</td>
</tr>
<tr>
<td>Glue logic</td>
<td>153 620</td>
<td>+ 0.04%</td>
<td>+ 17.95%</td>
<td>+ 0.04%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1 374 655</strong></td>
<td><strong>+0.03%</strong></td>
<td><strong>+2.05%</strong></td>
<td><strong>+0.04%</strong></td>
</tr>
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**Overhead 2.1%**

Synthesis: VHDL + Synopsys Design Compiler
Technology: 0.35 um CMOS libraries (AMS)
## Area overhead

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<td>-ShiftRows</td>
<td>0</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>MisCode</td>
<td>59 617</td>
<td></td>
<td></td>
<td></td>
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For comparison:

- Implementing a LFSR ⇒ 3.67%
- Implementing a BILBO ⇒ 7.64%

Overhead 2.1%

Synthesis: VHDL + Synopsys Design Compiler
Technology: 0.35 um CMOS libraries (AMS)
Special attention must be paid when testing secure circuits

- Scan-based designs
  - Counter-measures

- Bist (random test)
  - Self-test
  - Test resource
  - ECC?
Publications

SCAN

- [IOLTS'06] "Secure Scan Techniques: a Comparison" 12th International On–Line Testing
- [DATE'06] "Secure Scan Design" Design, Automation and Test in Europe, 2006
- [ETS'05] "Test Control for Secure Scan Designs" European Test Symposium, 2005
- [IOLTS'04] "Scan Design and Secure Chip" On–Line Testing Symposium, 2004

BIST

References

- [Yan04]: B. Yang, K. Wu, R. Karri, Polytechnic University, "Scan–based Side–Channel Attack on Dedicated Hardware Implementations on Data Encryption Standard", International Test Conference (ITC 2004), Charlotte, USA, October 26–28, pp 339–344


- [NIST 800–22]: A statistical test suite for random and pseudorandom number generators for cryptographic applications NIST Special Publication 800–22 (with revisions dated May 15, 2001)