Test Data Compression and Hardware Decompression for Systems on a Chip

Francis G. Wolff, Case Western Reserve University, fxw12@po.cwru.edu
Outline

- Motivation
- System-on-a-Chip testing
- Lempel-Ziv compression
- Test data compression
- Hardware decompression
- Conclusion & future works
Motivation: Moore’s Law

Every 18 months:
- Gate count doubles
- Vector set grows 10x
- Frequency increases 50%

Benchmark Design
- 0.18µ
- >600 MHz
- 10 million gates

SoCs by the year 2005, predicts that the state of the art ICs will exceed 100 million gates.

SoC chip testing technology based on ATE (automatic test equipment) taking longer.
Processor-on-a-Chip: PowerPc 603

Year: 1994 / 66 to 80 MHz
Process: 0.5-micron CMOS / 1.6 million transistors
Cache: 8 Kb Inst. / 8 kb Data

Year: 1997 / 225 Mhz to 300 Mhz
Process: 0.5 to 0.35-micron CMOS
Cache: 16 Kb Inst / 16 Kb Data
System-on-a-Chip: SoC

- *Systems* are traditionally composed of many separate chips: microprocessor, RAM, audio chips, …

- SoCs goal is to integrate all these components on a single chip: Better, Faster and Cheaper.

- Alternative Note: NASA says it’s Faster, Better and Cheaper.
SoC: System on a Chip

- SoC is an enabling technology for embedded systems.
- Embedded systems handle and manipulate large volumes of data in real-time.
- Some Examples: Internet Appliances, PDAs, cell phones, MP3 players, ...
SoC: Design Methodology

Ref: www.eedesign.com and www.synopsys.com
ATE: Automatic Test Equipment

- Several major difficulties arise with SoC chip testing technology based on ATE (automatic test equipment).
- One is the ATE cost that keeps on growing and growing.
- Another serious problem is that ATE speed is behind the chip native speed, and this speed gap keeps increasing.
- A third related problem is that the volume of test data is now very large, especially for large SoCs with many embedded cores.
# ATE: Agilent 93000 SoC series

<table>
<thead>
<tr>
<th>ATE Type</th>
<th>C200e</th>
<th>C400</th>
<th>P600</th>
<th>P1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Digital Channel Count</td>
<td>512 - 1024</td>
<td>512 - 1024</td>
<td>512 - 1024</td>
<td>512 - 1024</td>
</tr>
<tr>
<td>Max Vector Memory</td>
<td>28M</td>
<td>28M</td>
<td>112M</td>
<td>112M</td>
</tr>
<tr>
<td>Maximum Scan Memory/pin</td>
<td>336M</td>
<td>336M</td>
<td>336M</td>
<td>326M</td>
</tr>
<tr>
<td>Maximum I/O Data Rate (Mbits/Sec)</td>
<td>200</td>
<td>400</td>
<td>660</td>
<td>1Gb/s</td>
</tr>
<tr>
<td>Target Applications</td>
<td>Wafer sort, low end DSPs, baseband wireless devices, ASICs, etc.</td>
<td>PC-Graphics, PC-Chipset, PC133/PC166 &amp; DDR266/DDR333 memory interfaces, high end DSPs, Characterization of high-speed ASICs and high-speed communication devices.</td>
<td>Headroom for &quot;at speed&quot; test applications</td>
<td></td>
</tr>
</tbody>
</table>

At $1.5k/pin the Agilent 93000 SoC Series Model C200e is the first tester to break the $2k/pin price barrier for SoC test.

Test Data: Vectors

- Boundary scan (JTAG) test vectors are used to test the wires on circuit board between the chip pins.
- Scan chain test vectors are used to test the internal logic of each embedded system with the chip itself for manufacturing defects.
- Not every bit is required when a test vector is applied to the chip. These bits are labeled as don’t cares (X).

<table>
<thead>
<tr>
<th>Test#</th>
<th>Input/Scan-In Values</th>
<th>Output/Scan-Out Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 0 X 1 X X X X X X</td>
<td>X X X X 1 X X X X 0 X</td>
</tr>
<tr>
<td>2</td>
<td>X 0 1 1 0 1 X X X X</td>
<td>X X X 1 X X X X X X</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
**Test Data: Don’t Cares**

- It is not intuitively obvious how many of these Don’t Cares actually exist.
- *Well, it turns out lots, if you know how to get them!*

<table>
<thead>
<tr>
<th>ISCAS 89 Benchmark</th>
<th>s420.1</th>
<th>s838.1</th>
<th>s9234.1</th>
<th>s35932</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudo Primary Inputs (PPI)</td>
<td>34</td>
<td>66</td>
<td>247</td>
<td>1763</td>
</tr>
<tr>
<td>Total number of test vectors</td>
<td>71</td>
<td>154</td>
<td>171</td>
<td>22</td>
</tr>
<tr>
<td>Total test set size in bits</td>
<td>2414</td>
<td>10164</td>
<td>42237</td>
<td>38786</td>
</tr>
<tr>
<td>Total Don’t Cares in percent</td>
<td>60%</td>
<td>68%</td>
<td>78%</td>
<td>71%</td>
</tr>
<tr>
<td>Average Length of DC string</td>
<td>200</td>
<td>400</td>
<td>660</td>
<td>1Gb/s</td>
</tr>
<tr>
<td>Maximum Length of DC string</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>
Test Data: Compression

- One approach to alleviate these problems is to reduce the volume of test data by using data compression techniques.

- Lempel-Ziv compression (LZ77, LZ78, LZW) schemes are well known in the software world.

- Belong to a family of dictionary-based compression techniques using a sliding text window.

- Software tools that use these techniques successfully are PKZip, GNU gzip, and GIF & PNG image formats.

- Lossless by nature as opposed to other lossy compression techniques used in image compression such as JPEG or MPEG formats.
Test Data: Lempel-Ziv Compression

- Not only reduces the size of the data but also reduces the communication time to transfer this reduced data.

- Are finding their way into hardware, specifically embedded systems

- A novel adaptation of the much utilized Lempel-Ziv compression in software as it applies directly to hardware.

- The large presence of don't cares is exploited in uncompressed test sets that we generated using commercial ATPG tools.
Lempel-Ziv Compression: Example

Compressed Pattern

- A
- A B
- A B (5,2)
- A B (5,2) (3,4)
- A B (5,2) (3,4) (2,4)

Sliding Window

1 2 3 4 5 6

Uncompressed Pattern

- Lookahead Buffer

- A B A B A B A B A B
- B A B A B A B A B A B
- A B A B A B A B A B
- A B A B B A B A B
- A B A B B A B A B

Lookahead Buffer

- A  B (5,2)
- A  B (5,2) (3,4)
- A  B (5,2) (3,4) (2,4)
Compression: Don’t Care Pattern Matching

There are several possible matches: AA (1,2,5,6,7), AAB (2), …

The longest string match is always used

Assign

Default X=A
## Compression: Size Results

<table>
<thead>
<tr>
<th>Window Size</th>
<th>s420.1</th>
<th>s838.1</th>
<th>s9234.1</th>
<th>s35932</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 bits</td>
<td>15%</td>
<td>26%</td>
<td>27%</td>
<td>24%</td>
</tr>
<tr>
<td>32</td>
<td>26%</td>
<td>45%</td>
<td>44%</td>
<td>36%</td>
</tr>
<tr>
<td>64</td>
<td>28%</td>
<td>52%</td>
<td>52%</td>
<td>42%</td>
</tr>
<tr>
<td>128</td>
<td>29%</td>
<td>57%</td>
<td>54%</td>
<td>42%</td>
</tr>
<tr>
<td>256</td>
<td>31%</td>
<td>59%</td>
<td>55%</td>
<td>53%</td>
</tr>
</tbody>
</table>

| Don’t Cares | 60%    | 68%    | 78%     | 71%    |
| Avg. DC     | 6.8    | 13.4   | 9.6     | 4.3    |
| Test set size | 2414  | 10164  | 42237   | 38786  |
Hardware Test Data Compression: related work

- Run Length Encoding (RLE) schemes have been developed using Golomb codes. (see: Chanda, Date 2001 conference). RLE encoding requires a simple state machine to implement and does give good to fair results.

- Microprocessor implementations of Lempel-Ziv are well known but have poor hardware performance and hence impractical for real time manufacturing testing.

- Other exotic schemes have been proposed (i.e. cycle scan chains) but this methods place a constraint on place & route tools. This constraint hinders the original design performance.
Hardware Decompression: Decompressor

- Decompressor Controller
- Offset-Length Register
- TAP Controller

Input:
- TDI
- TMS
- TCK

Output:
- TDO
Hardware Decompression: Example a.

Test Data Packets

<table>
<thead>
<tr>
<th>Offset</th>
<th>Length</th>
<th>Bit string...</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compressed Pattern

A B (5,2) (3,4) (2,4)

Head Sliding Window

Tail Shadow Window

Tail

Tail

Tail

Tail

Compressed Pattern

(5,2) (3,4) (2,4)

Tail Shadow Window

Tail

Tail
Hardware Decompression: Example b.

Compressed Pattern

(5,2) (3,4) (2,4)

Copy Window to Shadow

Shift Right based on offset (i.e. 5)
Hardware Decompression: Example c.

**Compressed Pattern**

(5,2) (3,4) (2,4)

**Copy Tails**

**Shift Left**
Hardware Decompression: JTAG

**Boundary scan** (JTAG) is used to test the wires on circuit board between the chip pins.

**Scan Chains** are used to test the internal logic of each embedded system with the chip itself.

In order to further reduce the hardware decompressor chip area overhead, we enhance the existing JTAG boundary scan cell already connected to SoC pins feeding the internal test scan chain.
Hardware Decompression: JTAG
JTAG cell: input

Shift In

0
1 S

D Q

D Q

0
1 S

ShiftDR CaptureDR UpdateDR From TAP Controller Mode

Shift Out

From TAP Controller

In

Out

Boundary Scan Cell
JTAG cell: normal input mode
JTAG cell: Shift mode
JTAG cell: modified

Shift Forward Out

Shift In Reverse

Shift In Forward

Shift Out Reverse

In

Out

ShiftDR

CaptureDR

Copy

UpdateDR

Mode

From TAP Controller
## Compression: Timing Results

Tradeoff between decompress time and compression ratio.

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</thead>
<tbody>
<tr>
<td>16 bits</td>
<td>2984</td>
<td>11764</td>
<td>49132</td>
<td>46107</td>
</tr>
<tr>
<td>32</td>
<td>3412</td>
<td>12415</td>
<td>51771</td>
<td>49896</td>
</tr>
<tr>
<td>64</td>
<td>4540</td>
<td>14663</td>
<td>60738</td>
<td>41793</td>
</tr>
<tr>
<td>128</td>
<td>6517</td>
<td>19494</td>
<td>83222</td>
<td>55386</td>
</tr>
<tr>
<td>256</td>
<td>10517</td>
<td>28533</td>
<td>118634</td>
<td>81772</td>
</tr>
</tbody>
</table>

- **Minimum time**
- **Best Size Compression**

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</tbody>
</table>
Conclusions & future work.

- A new test data compression method was presented based on Lempel-Ziv compression for bit strings rather than character sets.

- High compression ratio are due to the heavy exploitation of Don’t Cares in the test data sets.

- An efficient hardware decompressor with minimal area overhead was presented using a modified boundary scan cell.

- Future work will extend this scheme to multi--scan chains.