INTRODUCTION

- Basics of using embedded instruments (EI) for life-time prediction
- Behaviour and implementation of *environmental* embedded instruments
- The dependence of delay from $V_{dd}$ and $T$ for decision-making counteractions
- Behaviour and implementation of *performance* embedded instruments
- Data fusion of measurements of EIs and correlations
- Life-time predictions using machine-learning
- Conclusions

EMBEDDED INSTRUMENTS AND LT PREDICTION (LTP)

- Embedded instruments around processor core for life-time prediction [$F_{max}(VDD, T)$] under aging
- Adapting lifetime via embedded instrument measurement results

IMPLEMENTATION OF BASIC EMBEDDED INSTRUMENTS

- Four *temperature* ($T$) monitors
- A power-*voltage* ($V$) monitor
- Slack-*delay* (SD) monitors
- A $I_{ddx}$ current embedded monitor

Chip design implementation (ASIC 40nm, TSMC CMOS)

All EIs are Hitag compatible, and Hitag infrastructure is included
ON-CHIP MEASURING TEMPERATURE AND VOLTAGE

Actual T and VDD measurements over time

Also used in DVFS systems!

ENVIROMENTAL CONDITIONS OF T AND VDD ON DELAY

(T and VDD relation)

Fault-free situation!

I_{DDT} MONITOR PRINCIPLE AND SPECIFICATIONS

Monitoring principle
- Current signal from unbalanced current mirror (CM)
- \( R_{\text{PAD}} \) → Metal sheet resistance
- Proposed monitor → Use unbalanced CM technique for \( I_{\text{DDT}} \) measurement

Derived Specifications:
- Sampling rate: close to the processor frequency (200MHz)
- Measurement range: 0.5mA - 10mA
- Resolution: < 17uA (in case 10b ADC)
- Area: < 0.017 mm² (40nm CMOS)
- Robust to process variation and aging

DESIGN AND BEHAVIOUR OF THE ANALOGUE \( I_{DDT} \) MONITOR
**SLACK-DELAY EMBEDDED INSTRUMENTS (1ST GEN)**

Example circuit design
(Time to Digital Converter (TDC) not shown)

**Derived Specifications:**
- Measurement range: 15ps - 480ps
- Resolution: 15ps
- Area: < 0.0054 mm² (40nm, CMOS)
- Robust to process variation and aging

Measured slack-delay (sim)

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**SIMULATIONS ON I_{DDX} AND SLACK-DELAY VERSUS AGING**

- Slack-delay EI post-layout simulation versus aging during lifetime

Previously measured correlation

- I_{DDX} current EI post-layout simulation versus aging during lifetime

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**MEASUREMENTS EXAMPLE OF SLACK DELAY AND I_{DDX} (2)**

Example of logic unit and several critical paths monitored via slack delay

- Down if slack delay = 0

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**MEASUREMENTS EXAMPLE OF SLACK DELAY AND I_{DDX} (1)**

- Example of logic unit and several critical paths monitored for correlated delay

All are related to Fmax…. (cause of failure!).

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**Lifetime Prediction Basics (from Experiments)**

\[ f(t) = a + b \times t^c \]

- From many delay measurements!
- Delay model building (directly related to Fmax)

**New Procedure for Life-Time Prediction (LTP)**

\[ f(t) = a + b \times t^c \]

- T and VDD included
- EI data fusion
- Delay model
- ML genetic algorithm
- Remaining Lifetime Probability (RLP)

**Embedded Instrument Data Fusion at Time \( T_X \)**

<table>
<thead>
<tr>
<th>Embedded Instrument (EI):</th>
<th>Mean: (ns)</th>
<th>Standard deviation:</th>
<th>Variance:</th>
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<tbody>
<tr>
<td>EL-SD1</td>
<td>6.00</td>
<td>0.024063</td>
<td>0.00058</td>
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<tr>
<td>EL-DDX</td>
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<td>EL-SD2</td>
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<td>EL-SD3</td>
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<td>0.01615</td>
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<tr>
<td>Fusion</td>
<td>5.65</td>
<td>0.031259</td>
<td>0.00101</td>
</tr>
</tbody>
</table>

Conditions:
- Measurements synchronized in time
- Correlation of slack-delay & \( I_{DDX} \) (NR)
- Aging is time parameter
- Adaptive measurements over time

**Fusion of Slack Delay and \( I_{DDX} \) Instruments**

- Simple implementation via Central Limit Theorem (MIPS)
  \[ X3 = \frac{1}{(\sigma_1)^2 + (\sigma_2)^2} \cdot ((\sigma_1)^2 \cdot X_1 + (\sigma_2)^2 \cdot X_2) \]
- Improvement via Kalman filtering, more complex calculations (ARM)

**Reliability control center**

- Genetic Algorithm
  - Degradation trend feature: \( a_0, b_0, c_0 \)
  - Degradation trend feature update: \( a_i, b_i, c_i \)

- RL-P results

**Sample Processors**

- Historic data
  - Slack-delay & \( I_{DDX} \)

- Genetic Algorithm
  - EI Fusion & Build mapping

- Remaining Lifetime Probability (RLP)

- Field usage Processes
CONCLUSIONS

- Several embedded instruments have now been used for LTP:
  - Environmental (T, VDD)
  - Performance (SD, I_{DDX}) (technological EIs not used yet)
- Data fusion of slack-delay and I_{DDX} embedded instruments implemented using different algorithms
- Developed enriched RLP flow diagram for more accurate predictions
- Usage of single-variable machine-learning genetic algorithm
- Use of more than one EI can provide better accuracy & diagnosis
- In future much more EIs will be fused and ML for improved prediction