Centip3De: A 64-Core, 3D Stacked, Near-Threshold System

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The Problem of Power

Dynamic dominates

\[ U \approx \frac{C V_{dd}^2}{A} + \frac{I_{\text{leak}} V_{dd}}{Af} \]

A = gate area \(\to\) scaling \(1/s^2\)

C = capacitance \(\to\) scaling < \(1/s\)

The emerging dilemma:
More and more gates can fit on a die, but cooling constraints are restricting their use
Today: Super-$V_{th}$, High Performance, Power Constrained

Large gate overdrive favors performance with unsustainable power density

**Must design within fixed TDP**

Goal: maintain performance, improved Energy/Operation
Subthreshold Design

Operating in sub-threshold yields large power gains at the expense of performance.

Applications: sensors, medical
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Phoenix 2 Processor, ISSCC’10
Near-Threshold Computing (NTC):

- >60X power reduction
- 6-8X energy reduction
- Enables 3D integration
Measured NTC Results

Phoenix 2 Processor
Silicon Measurements

- Sub Vt
- Near Vt
- Super Vt

Energy / Inst (J)

Normalized Energy/Inst

Frequency

180 nm

32nm Ring Oscillator
Simulation

- Sub Vt
- Near Vt
- Super Vt

Normalized Frequency

32 nm

10x
7x

9x
5.3x
Architectural Impact of NTC

- Caches have higher $V_{opt}$ and operating frequency
- Smaller activity rate when compared to core logic
- Leakage larger proportion of total power in caches
- New Architectures Possible
Proposed NTC Architecture

- SRAM is run at a higher $V_{DD}$
  - Caches operate faster than core
- Can introduce clustered architecture
  - Multiple cores share L1
  - Cores see private L1
  - L1 still provides single-cycle latency

- Advantages:
  - Less coherence/snoop traffic
  - Larger cache for processes that need it

- Drawbacks:
  - Core conflicts evicting L1 data
    - Not dominant in simulation
  - Longer interconnect
    - 3D addressable
Proposed Boosting Approach

Measured results for 130nm LP design
10MHz becomes ~110MHz in 32nm simulation
140 FO4 delay core

Baseline
- Cache runs 4x core frequency
- Pipelined cache

Better Single Thread Performance
- Turn some cores off, speed up the rest
- Cache de-pipelined
- Faster response time, *same* throughput
- Core sees larger cache
  - Faster cores needs larger caches
**Cache Timing**

**NTC Mode (3/4 Cores)**
- Low power
- Tag arrays read first
- 0-1 data arrays accessed

**Boost Mode (1/2)**
- Low latency
- Data and tags read in parallel
- 4 data arrays accessed
Cache Timing

NTC Mode (3/4 Cores)
Low power
Tag arrays read first
0-1 data arrays accessed
Cache Timing

Boost Mode (1/2)
Low latency
Data and tags read in parallel
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Centip3De System Overview
Centip3De System Overview

- 7-Layer NTC system
- 2-Layer system completed fabrication with measured results
- Full 7-layer system expected End of 2012
Centip3De System Overview

- **Cluster architecture**
  - 4 Cores/cluster
  - 1kB I$, 8kB D$
  - Local clock controller operates cores 90° Out-of-phase
  - 1591 F2F connections per cluster

- **Organized into layer pairs (cache <-> core)**
  - Minimizes routing
  - Up to two pairs
  - 16 clusters per pair
  - Cores have only vertical interconnections
Centip3De System Overview

- Bus interconnect architecture
  - Up to 500 MHz
  - 9-11 cycle latency
  - 1-3 core cycles
- 8 lanes, each 128b
  - One per DRAM interface
  - Each cluster connects to all eight
  - 1024b total
- Vertically connected through all four layers
  - Flipping interface enables 128-core system
Centip3De System Overview

- 3D-Stacked DRAM
  - Tezzaron Octopus

- 1 control layer
  - 130nm CMOS

- 1 Gb bitcell layers
  - Up to two layers
  - DRAM process

- 8x 128b DDR2 interfaces
  - Operated at bus frequency (up to 500 MHz)
Centip3De System Overview

28485 F2F

3024 B2B

28485 F2F

3624 B2B
Centip3De System Overview

130nm process
12.66x5mm per layer
28.4M device core layer
18.0M device cache layer
Layer Partitioning & Floorplanning

- Michigan Designed
- Tezzaron Octopus DRAM

Diagram showing layered architecture withCore Layer, Cache Layer, Communication Column, DRAM Control Layer, DRAM Bitcell Layer, and detailed cluster design.
2-Layer Stacking Process Evaluated

For the measured 2-layer system, aluminum wirebond pads were used instead

Core Layer

Cache Layer

Wirebonds

Aluminum wirebonding pads connected to perimeter TSVs like for 7-layer

F2F
Cache 3D Connections
Core 3D Connections

Core 0

Core 1

Core 2

Core 3

Sea of Gates
Cluster 3D Connections

1591 F2F Connections
Each saved ~600-1000um in routing
Prevented wiring congestion around SRAMs
Silicon Results
Die Shot

Looking through back of core-layer

DRAM Interface/Bus Hub

4-Core Cluster

Aluminum wirebond pads

130nm process
12.66x5mm per layer
28.4M device core layer
18.0M device cache layer
System Configurations

4 Core Mode

- Cache Bus Hub: 160 MHz, 1.15 Volts
- $I$/D$:
  - Div 4x 40 MHz, 0.80 Volts
- 0 Core Boosted, 0 Cores Gated

2 Core Mode

- Cache Bus Hub: 160 MHz, 1.15 Volts
- $I$/D$:
  - Div 2x 80 MHz, 1.15 Volts
- 2 Core Boosted, 2 Cores Gated

3 Core Mode

- Cache Bus Hub: 160 MHz, 1.15 Volts
- $I$/D$:
  - Div 2x 80 MHz, 1.15 Volts
- 3 Cores Boosted, 1 Core Gated

1 Core Mode

- Cache Bus Hub: 320 MHz, 1.6 Volts
- $I$/D$:
  - Div 2x 160 MHz, 1.65 Volts
- 1 Core Boosted, 3 Cores Gated

- 1 Core Boosted, 3 Cores Gated
- Div 2x 80 MHz, 1.15 Volts
Measured Results

Boosting a single cluster to 1-core mode requires disabling, or down-boosting other clusters.

1-core cluster:
- 15x 4-core clusters
- 6x 3-core clusters
- 4.5x 2-core clusters

Baseline configuration depends on TDP and processing needs.

![Power consumption chart]

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Measured Results

- Graph showing single-threaded performance (DMIPS) for different system configurations:
  - 4-Core: 12.5
  - 3-Core: 25
  - 2-Core: 50
  - 1-Core: 100

- Graph showing power consumption (mW) for different system configurations:
  - 4-Core: 203 (113 Core Power, 90 Cache Power, 0 Memory System Power)
  - 3-Core: 339 (175 Core Power, 164 Cache Power, 0 Memory System Power)
  - 2-Core: 463 (266 Core Power, 197 Cache Power, 0 Memory System Power)
  - 1-Core: 1851 (155 Core Power, 1696 Cache Power, 0 Memory System Power)
Measured Results

Centip3De – 3,930 (130nm)

Industry Comparison:
ARM A9 – 8,000 (40nm) [1]

Estimated Results:
Centip3De – 18,500 (45nm)

Conclusion

- Near threshold computing (NTC)
  - Need low power solutions to maintain TDP
  - Achieves 10x energy efficiency => 10x more computation to give TDP
  - Offers optimum balance between performance and energy
  - Allows boosting for single threaded performance (Amdahl's law)

- Large scale 3D CMP demonstrated
  - 64 cores currently
  - 128 cores + DRAM in the future
  - 3D design shown to be feasible

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