LightSim : A Leakage Aware Ultrafast Temperature Simulator

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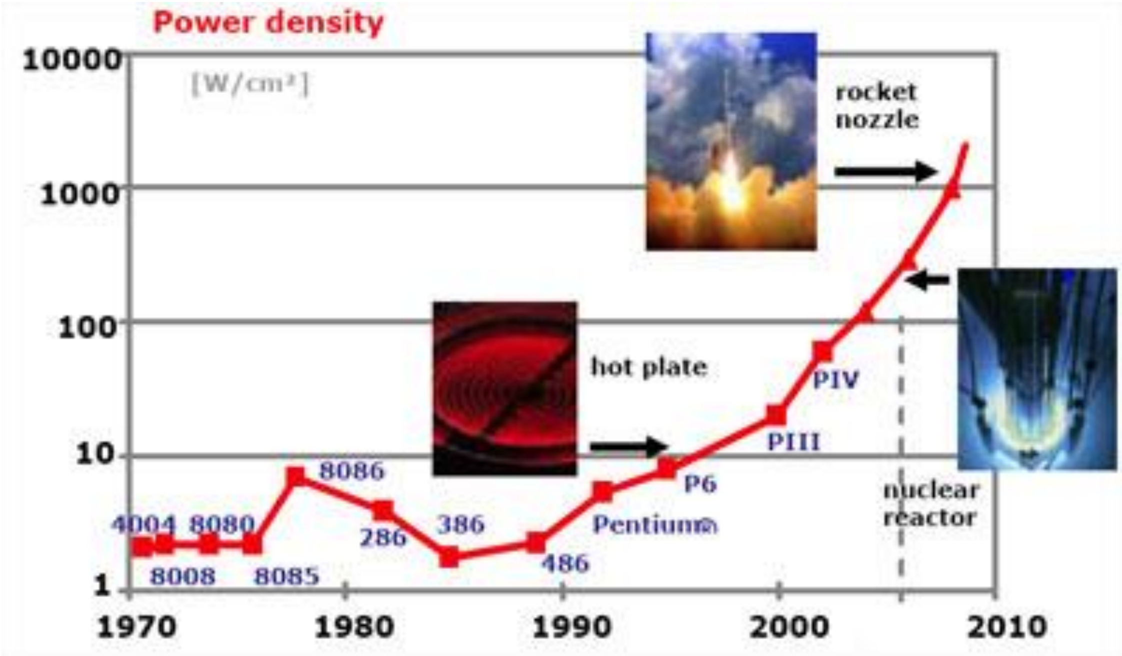
Outline

- Motivation
- Problem Description
- Related Work
- Proposed Model
- Results
- Summary

Temperature – First Order Design Constraint



Heat Flux Trends over the Years

Source: [1]

Temperature – First Order Design Constraint

Performance	Increase in Wire delay
Reliability	Decrease in MTTF Timing Errors
Thermal Rundown	Temperature – Leakage Feedback Loop

Temperature Estimation – Need and Importance

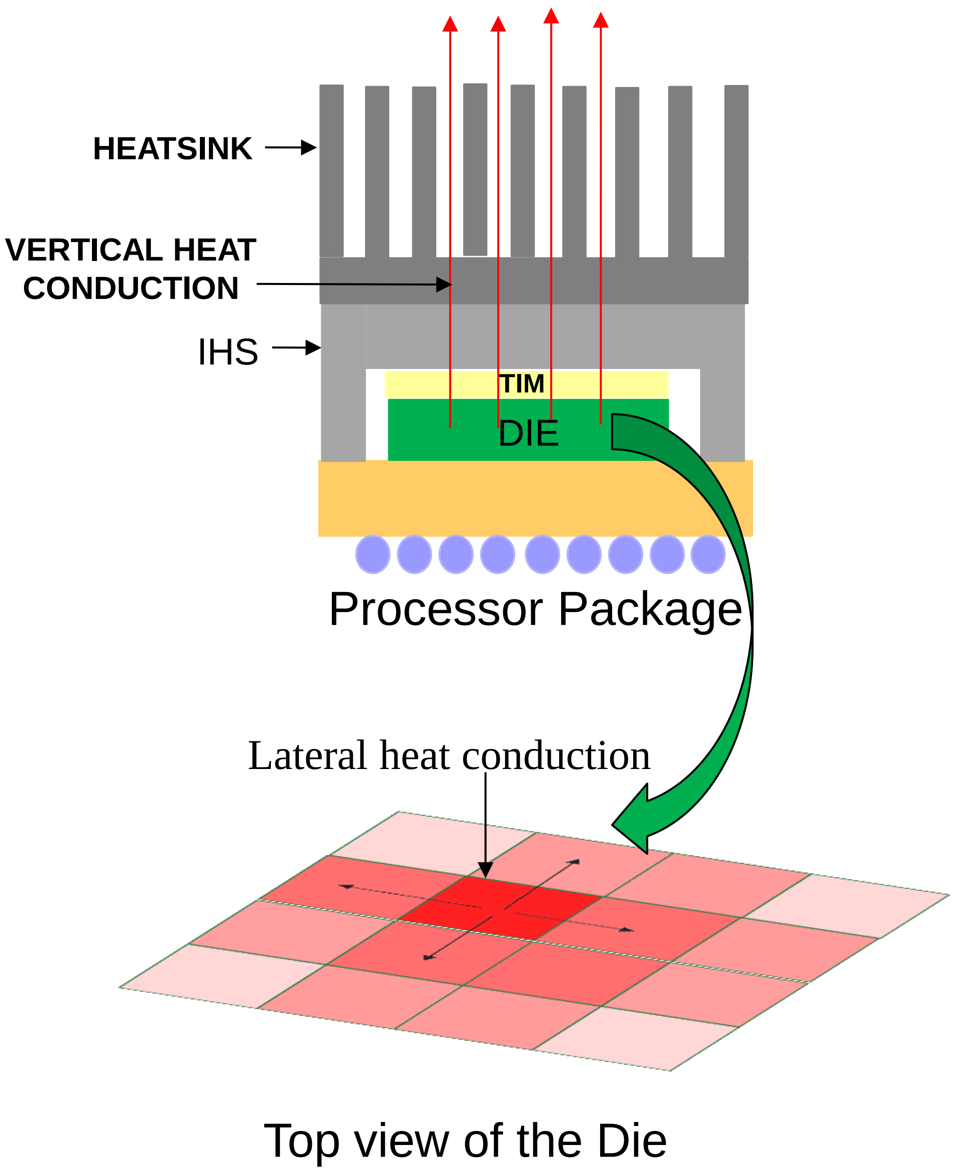
- Floorplanning and Placement
- Leakage convergence – Slow Process

Need of the hour

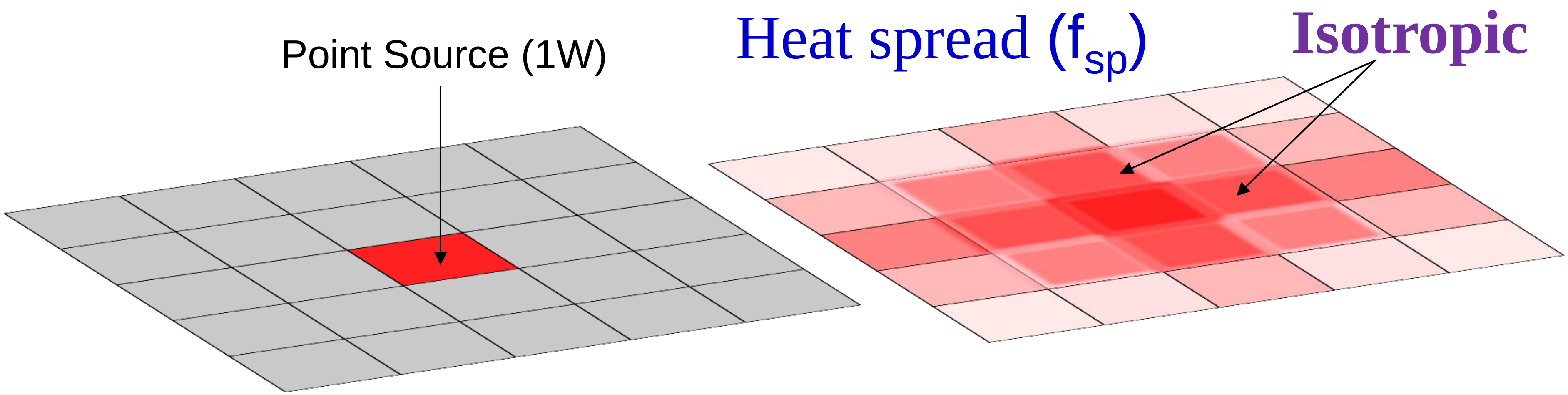
Source: [2]

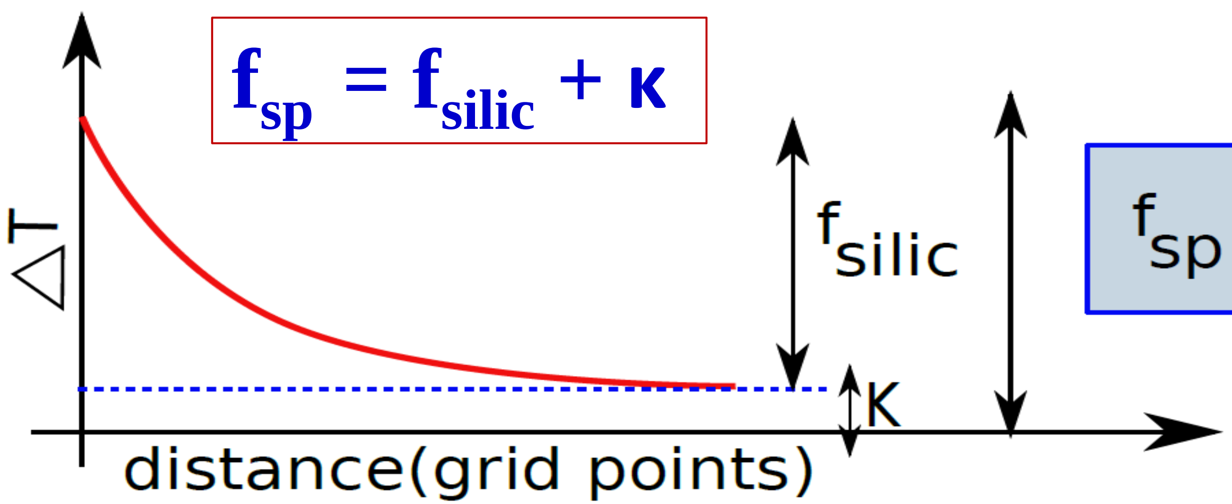
Source: [3]

Heat Conduction in Microprocessors



Temperature Distribution in a Chip





Relation between ΔT and radial distance (r)

Temperature Distribution in a Chip

- Fourier's heat equation – $\frac{\partial \mathcal{U}}{\partial t} = \alpha_1 \nabla^2 \mathcal{U} + \alpha_2 Q$

U = Temperature Field , Q = Power Flux

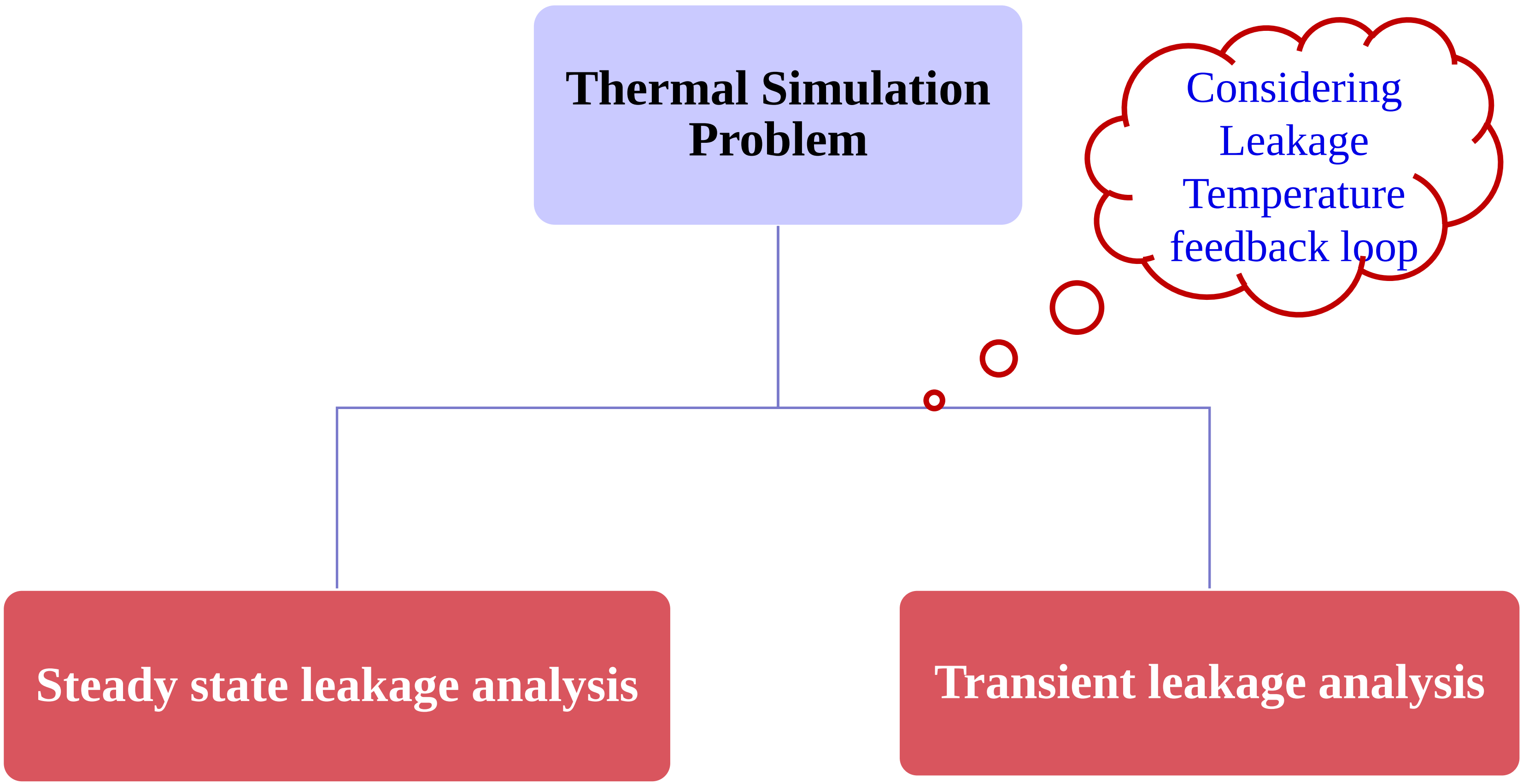
- Green's function (G) - Impulse response of an inhomogeneous differential equation defined on a domain

$$U(x'y'z') = \int G(x, y, z | x', y', z') Q(x'y'z') dx'dy'dz'$$

$$\mathrm{U} = \mathrm{G} \otimes \mathrm{Q}$$

- Heat Spread function - Green's function of the system

Problem description



Problem description

To develop a faster and accurate temperature estimation tool

- Derive a transient and steady state Green's function of the chip

(Considering leakage-temperature feedback loop)

Related Work

Existing thermal simulators essentially use one of the following methods

- Finite element method
- Finite difference method
- Boundary element method
- Spectral based method

Krylov Subspace
Alternate Direction Implicit
Adaptive Meshing
Multigrid methods

Related Work

- Hotspot (Skadron et al. ISCA'03)
  - Thermal electrical duality and FDM
- CONTILTS (Han et al. J.LPE'07)
  - Piecewise Constant Approximation of power trace
- Power Blurring (Park et al. SemiTherm'10)
  - Thermal mask convoluted with power density distribution

Proposed Model

Obtain the Impulse response of the system without leakage

Approximate the leakage with a linear model and include the leakage feedback component

Compute the Green's function using Hankel and Fourier Transform Equivalence Relation

Benefits

- Traditionally Impulse response is converted to Fourier transform and inverse Fourier transform is used to obtain the Green's function
- Fourier Transform (2D space) – Complexity : $O(N^2)$
- Our Model uses Hankel Transform (1D space) – Complexity: $O(N)$

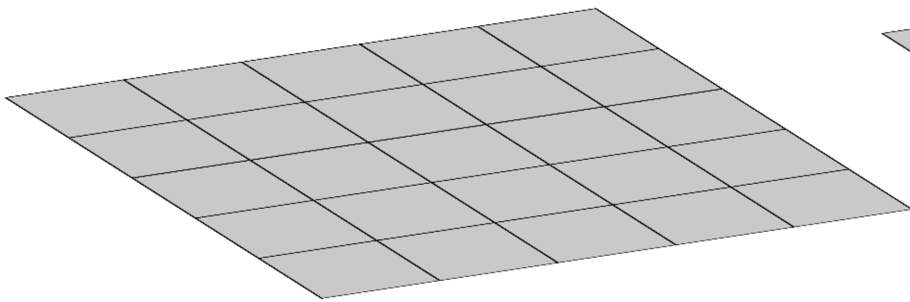
Assumptions

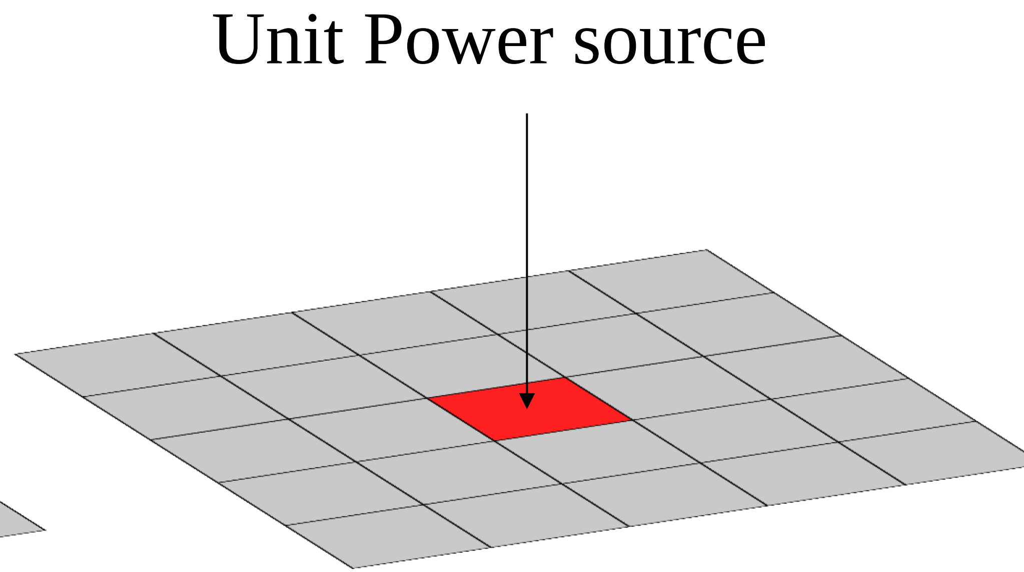
- **Die is very large (theoretically infinite)**
- **f_{silic} is radially symmetric**
- **Heat sources are on the die surface and we restrict our computations to the top surface of the die**
- **Leakage power increases instantaneously**

Crux of our Technique

$U_0 = T_{ambient}$

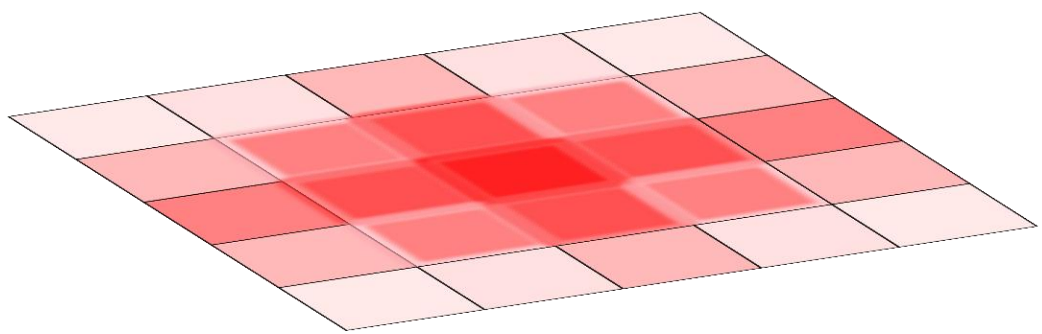
$P_{leak} = P_{leak0}$ & $P_{dyn} = 0$





$U_p = T$

$P_{leak} = P_{leak}$ & $P_{dyn} = 1$



Steady state Leakage Problem

$Q = P_{dyn} + P_{leak}$ = Total Power dissipation

$\Delta T = U = U_p - U_0$ = Change in Temperature Field

$U = G \otimes Q = (\mathbf{f_{sp}}) \otimes (\mathbf{P_{dyn}} + \boldsymbol{\beta}\mathbf{U})$

Linear Leakage Approximation

$\boldsymbol{\beta}\mathbf{f_{sp}} \otimes U =$ Leakage Feedback component

$U = f_{silic} + \kappa + \beta f_{silic} \otimes U + \kappa_1$

Fourier Hankel Equivalence

- 2D Fourier Transform F(s,t)

$$\frac{1}{2\pi}\iint_{-\infty}^{\infty} e^{-j(xs+yt)}\,dx\,dy$$

- Zero Order Hankel Transform H(k)

$$\int_{0}^{\infty} f(r) J_0(\mathrm{sr})\mathrm{rdr}$$

f_{silic} is radially symmetric

Zero Order Hankel Transform is equivalent to 2D Fourier Transform of radially symmetric functions in polar co-ordinates

Hankel Transformation

- $\mathrm{H}(U) = \frac{H(f_{silic}) + (\kappa + \kappa_1) H(1)}{1 - 2\pi\beta H(f silic)}$

- Inverse Hankel = $\mathrm{H}^{-1}\mathrm{H}(U) = f_{leaksp}$

Modified Green's function

$$f_{leaksp} = f_{silic} + 2\pi\beta \mathrm{H}^{-1}(\mathrm{H}(f_{silic})^2) + \phi$$

Transient Leakage Problem

Here we start with

$$\mathbf{U} = \mathbf{f}_{\mathbf{sp}} + \boldsymbol{\beta}\mathbf{f}_{\mathbf{sp}} \otimes \mathbf{U} - \mathbf{C}\mathbf{f}_{\mathbf{sp}} \otimes \frac{\partial U}{\partial t}$$

- We follow similar steps and use Leibnitz rule
- Boundary conditions :
  - At $t = 0$, $H(U) = 0$
  - At $t = \infty$, $H(U) = H(f_{leaksp})$

Transient Leakage Problem

- Solving for t and applying boundary conditions

$$\mathcal{H}(\mathcal{U}) = \mathcal{H}(f_{leaksp}) \times (1 - e^{-\frac{t}{f_{\alpha}(s)(\kappa\delta(s)/s+\mathcal{H}(f_{silic}))}})$$

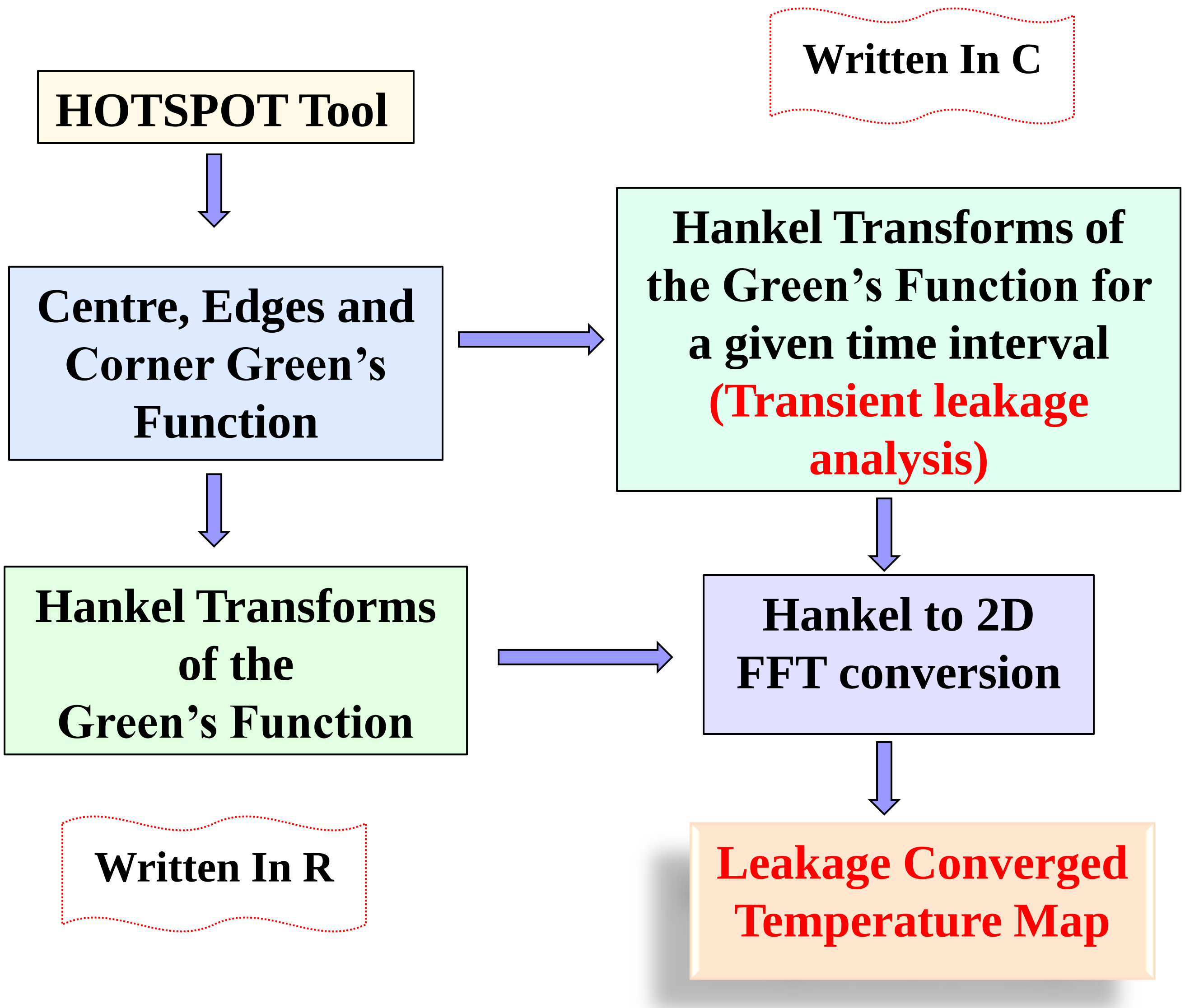
- Inverse Hankel transformation ⇨ $f_{trans}(r,t)$

Effect of heating up the entire package

Transient temperature rise in the neighborhood

$$f_{trans}(r,t) = fleaksp\,(r) - f_{inv\,0}^{\varepsilon}(r,t) - f_{inv\,\epsilon}^{\infty}(r,t)$$

Experimental Setup



Experimental Configuration

PARAMETER	VALUE
Die Size	400 mm^2
Silicon Conductivity	130 W/m-K
Spreader Conductivity	370 W/m-K
Heat sink Conductivity	237 W/m-K
Convection Resistance	0.1 K/W
Spreader Thickness	3.5 mm
Heatsink Thickness	24.9 mm

Hotspot tool Configuration

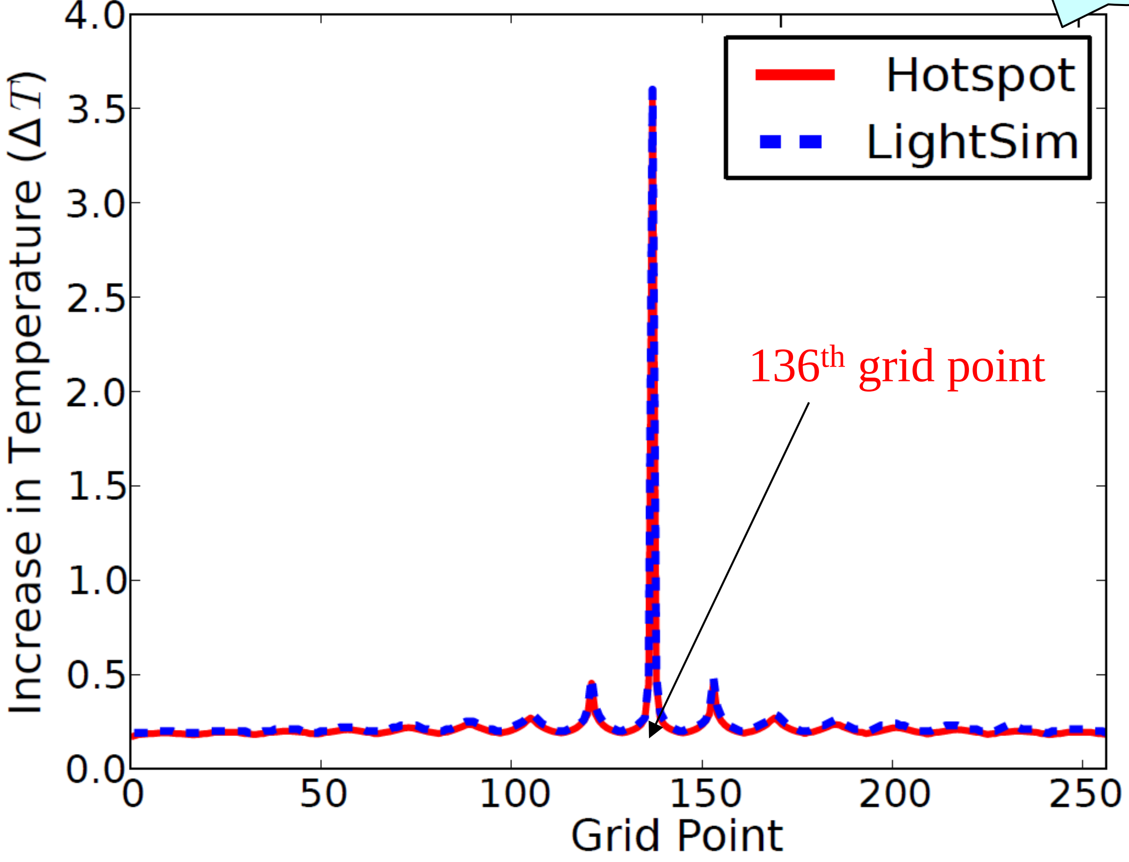
ARCH	Quad Core 3.1 Ghz Intel i7 processor
OS	Ubuntu Linux 12.10
RAM	4GB

Experimental Environment

Results - Accuracy

Steady state Leakage Green's function

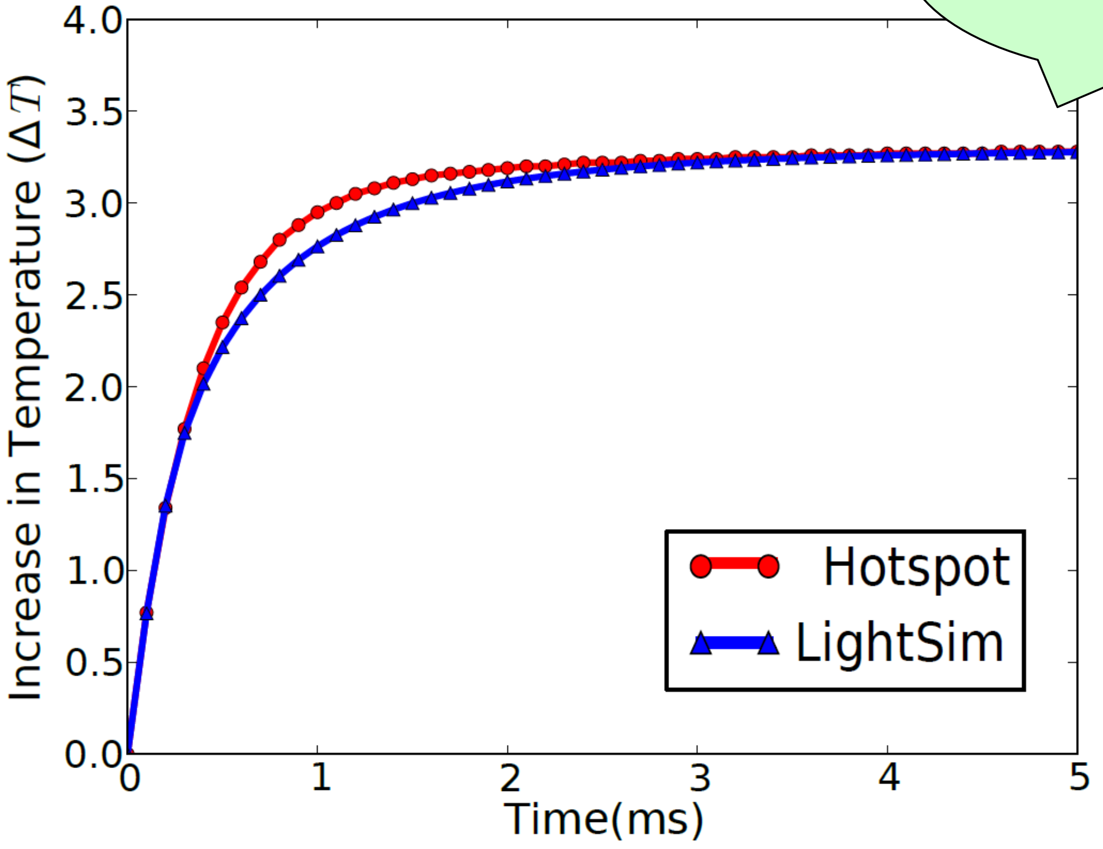
Error is < 2 %



Results – Accuracy

Transient Leakage Green's function

Max Error is
4.5% (0.18℃)



Results - Speed

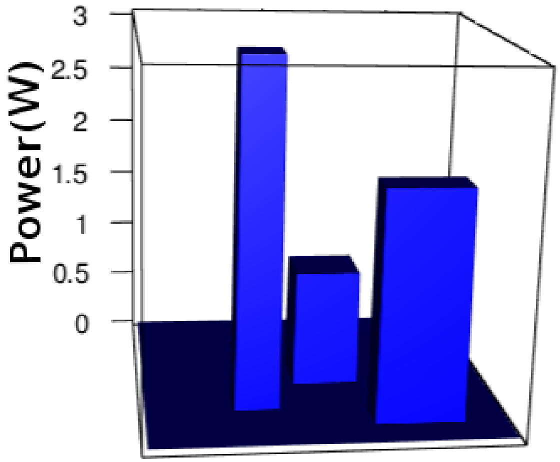
SIMULATOR	STEADY STATE LEAKAGE	TRANSIENT LEAKAGE
HOTSPOT 5.02	30.3 ms	45s
CONTILTS	25.2 ms	206.4 ms
Liu et. al.	39.3 ms	264.8 ms
PowerBlur	20.1 ms	58.2 ms
LightSim	8.7 ms	12.8 ms

3500 X

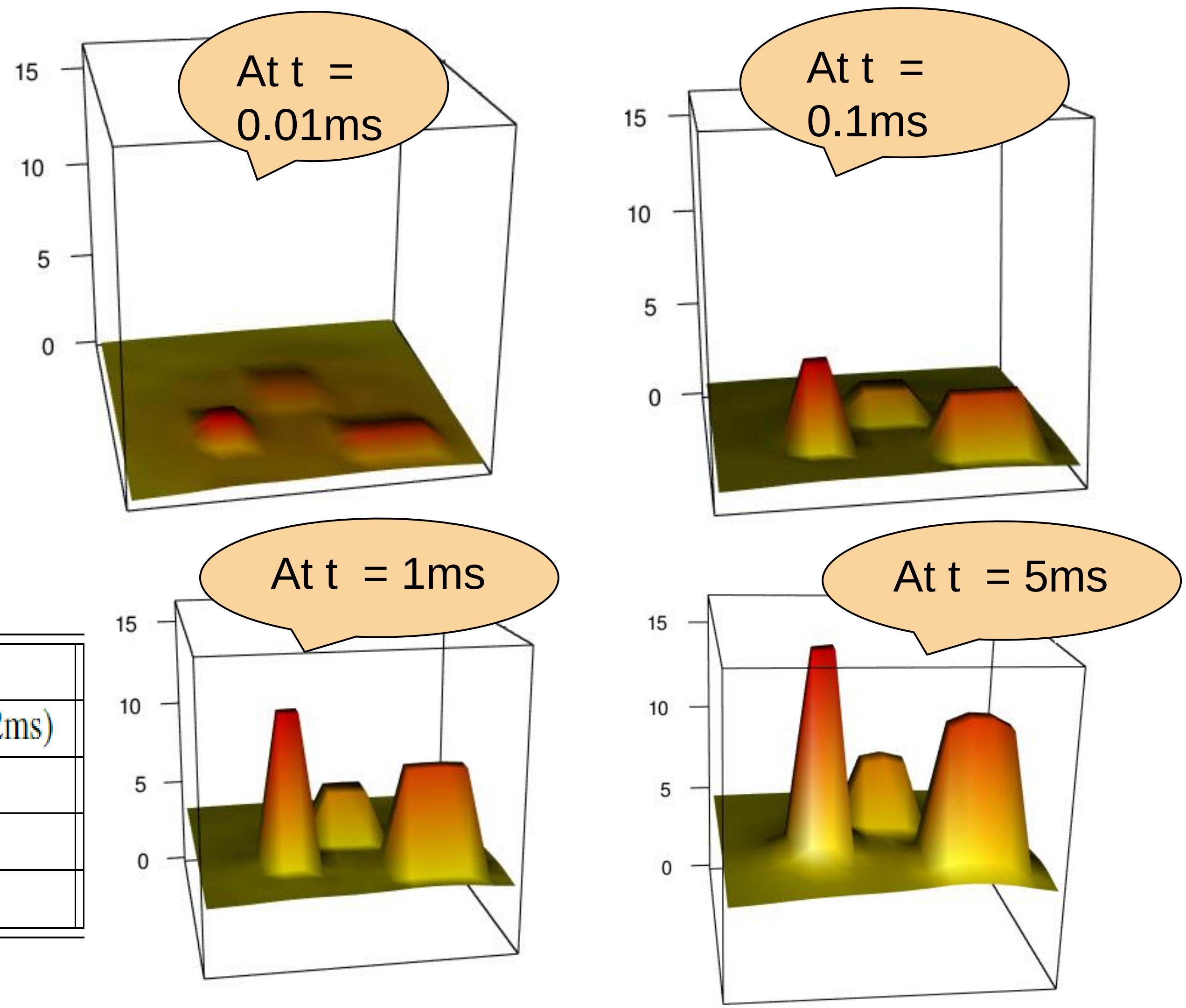
4.5X

Results – Sample Simulation

Sample Power Map



ΔT variation with TIME



Errors of different regions

Location	Error (%)	
	steady state	transient(at 2ms)
Center	0.6%	1%
Edge	1%	1.8%
Corner	1.8%	2.4%

Summary

- An efficient Hankel transform based thermal simulator has been developed
- Has a complexity of O(nlog(n)) time
- Experimental results show that our model is fast and accurate.

Future Work:

- To develop more accurate models for edges and corners
- Comparison with ANSYS/COMSOL simulation

Figure Sources

1. http://www.nanowerk.com and Intel
2. http://www.ausmotive.com
3. www.facegfx.com

THANK YOU !!