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Thermal Sensor Distribution Method for 3D Integrated Circuits Using Efficient Thermal Map Modeling

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Introduction

- In a three-dimensional integrated circuit (3DIC) two or more layers of active components are integrated vertically into a single chip.
- Stacking active layers of silicon increases power density which results in higher junction temperatures.
- Thermal sensors are crucial for run-time thermal management of 3DICs.
- A thermal sensor distribution method customized for 3DICs is proposed in this work.
- Any thermal sensor distribution algorithm should consider possible thermal maps of the 3DIC to find an optimum number of sensors and their proper locations.
- A fast 3D thermal map modeling is proposed to be used in thermal sensor distribution algorithm.

Motivation

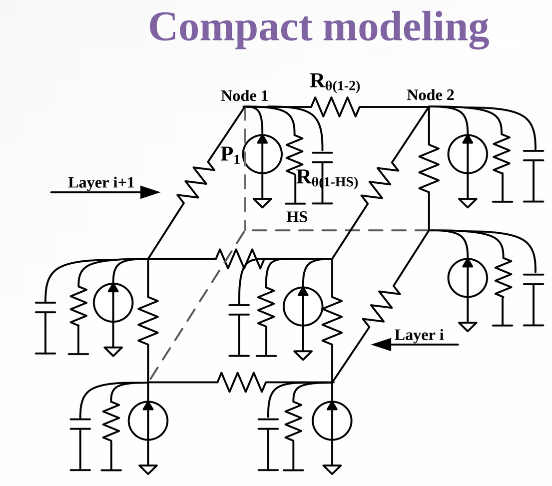
- Previous 3DIC thermal modeling approaches are detailed and very time-consuming.

The Finite Element Analysis (FEA)

$$\rho c_p \frac{\partial T(r,t)}{\partial t} = \nabla.[k(r,T)\nabla T(r,t)] + g(r,t)$$

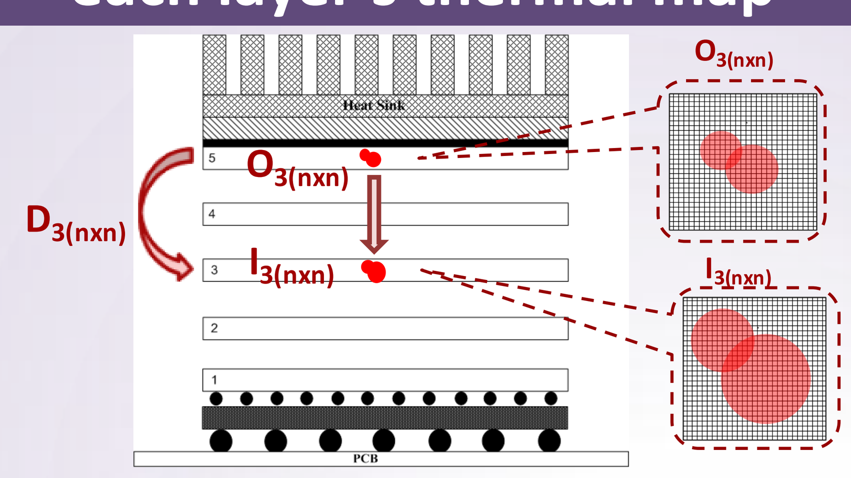
$$k(r,T)\frac{\partial T(r,t)}{\partial n_i} + h_i T(r,t) = f_i(r_{s_i}, t)$$

Compact modeling



- Our 3DIC thermal model is:
- Fast
- Developed with conventional 2D CAD tools
- Developed in three steps:
  1. Capturing effect of distance from heatsink on each layer's thermal map
  2. Finding each layer's thermal effects on others
  3. Each layer's final thermal map: superposition of its own scaled thermal map and other layers' effects

Effect of distance from heatsink on each layer's thermal map

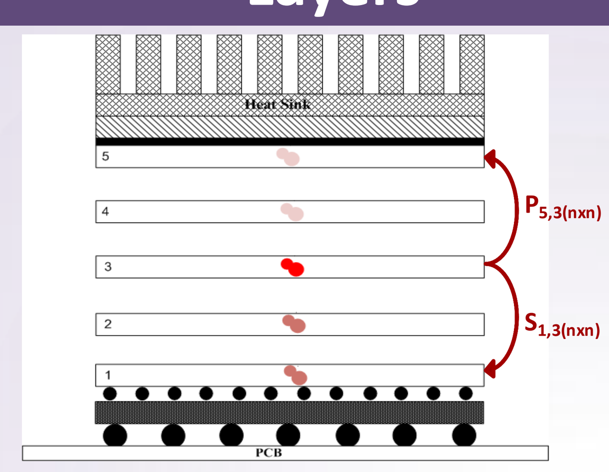


$$I_{k(n\times n)} = \left(a_k O_{k(n\times n)} + b_k \Delta O_{k(n\times n)} + c_k\right).D_{k(n\times n)}$$

$$D_{k(n\times n)} = \mathop{}_{i=k}^{i=m-1} D_{i,i+1(n\times n)}$$

$O_{k(nxn)}$: Original-thermal-map matrix of layer k
$I_{k(nxn)}$: Intermediate-thermal-map matrix of layer k
$\Delta O_{k(nxn)}$: Horizontal-thermal-gradient matrix of layer k
a_k, b_k, c_k: fitting coefficients
D_k: Vertical scaling matrix to layer k
$D_{i,i+1}$: Vertical scaling matrix between layer i and i+1
n: number of grid cells
m: number of stacked layers

A Layer's Thermal Effects on Other Layers



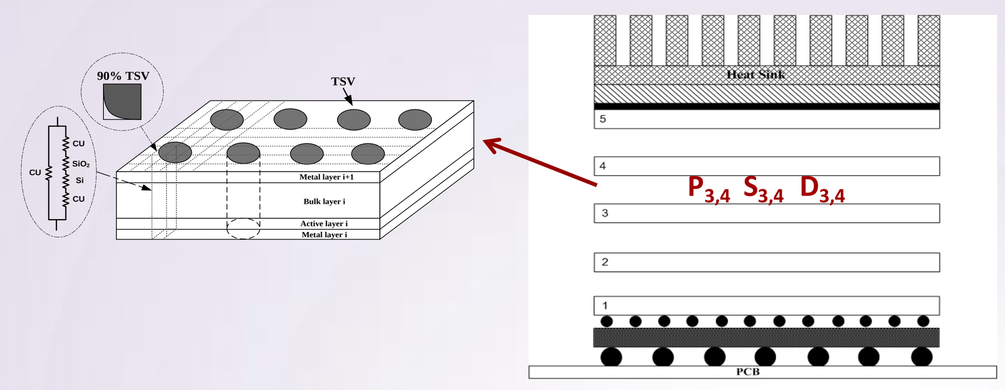
$$I'_{l(n\times n)} = \begin{cases} \left(a'_l I_{k(n\times n)} + b'_l \Delta I_{k(n\times n)} + c'_l\right).P_{lk(n\times n)} & l > k \\ \left(a'_l I_{k(n\times n)} + b'_l \Delta I_{k(n\times n)} + c'_l\right).S_{lk(n\times n)} & l < k \end{cases}$$

$$P_{lk(n\times n)} = \mathop{}_{i=k}^{i=l-1} P_{i,i+1(n\times n)}$$

$$S_{lk(n\times n)} = \mathop{}_{i=l}^{i=k-1} S_{i,i+1(n\times n)}$$

$I'_{l(nxn)}$: A thermal-map matrix in layer l generated solely based on the thermal effect of layer k.
$I_{k(nxn)}$: Intermediate-thermal-map matrix of layer k (heat source).
$\Delta I_{k(nxn)}$: Horizontal-thermal-gradient matrix of matrix I_k
$P_{lk(nxn)}$: primary path scaling matrix from k to l.
$S_{lk(nxn)}$: secondary path scaling matrix from k to l.
$P_{i,i+1(nxn)}$: primary path scaling matrix between layer i and i+1.
$S_{i,i+1(nxn)}$: secondary path scaling matrix between layer i and i+1.
a'_l, b'_l, c'_l: fitting coefficients
n: number of grid cells
m: number of stacked layers

Scaling Matrices



$$K = (fK_1 + (1-f)K_2)$$

$$K_1 = \frac{1}{R_{cu}}$$

$$K_2 = \frac{1}{R_{cu} + R_{SiO2} + R_{Si} + R_{cu}}$$

$$p = \beta_{(i,i+1),l} K \qquad i \geq l$$

$$s = \gamma_{(i,i+1),l} K \qquad i < l$$

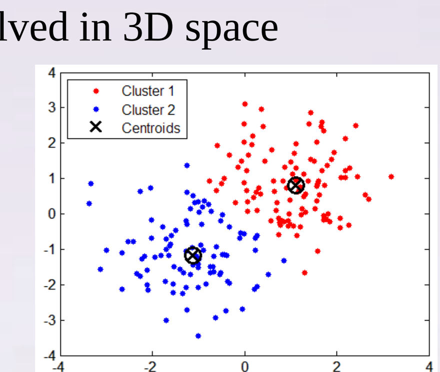
$$d = \delta_{i,i+1} \; K$$

K: Equivalent thermal conductivity
f: fraction occupied by TSV
K_1: thermal conductivity of TSV
K_2: thermal conductivity of fraction not occupied by TSV
p, s, d=elements of matrices $P_{i,i+1}$, $S_{i,i+1}$, $D_{i,i+1}$
$\beta_{(i,i+1),l}$=fitting factor models distance from heat source l on its primary path
$\gamma_{(i,i+1),l}$=fitting factor models distance from heat source l on its secondary path
$\delta_{i,i+1}$=fitting factor models distance from heatsink

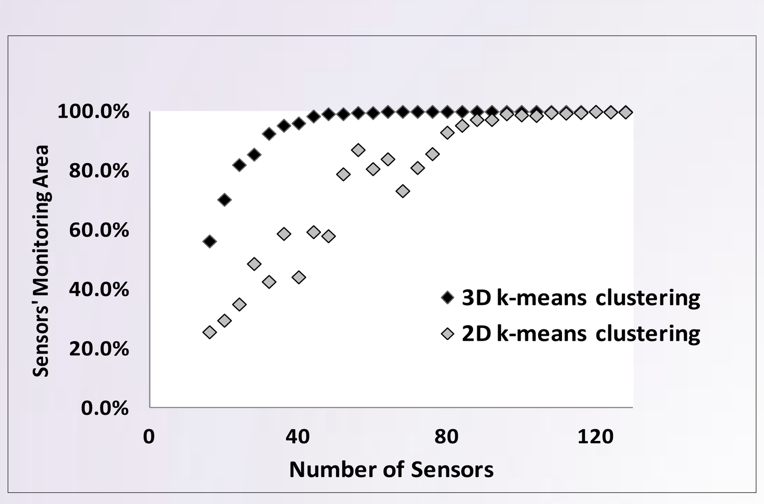
Thermal Sensor Distribution for 3DICs

- Employs our fast 3D thermal map modeling
- Employs k-means clustering problem solved in 3D space

Given an integer *k* and a set of *n* data points in an *m*-dimensional space, determine *k* centers such that the mean-square distance from each data point to its nearest center is minimized.

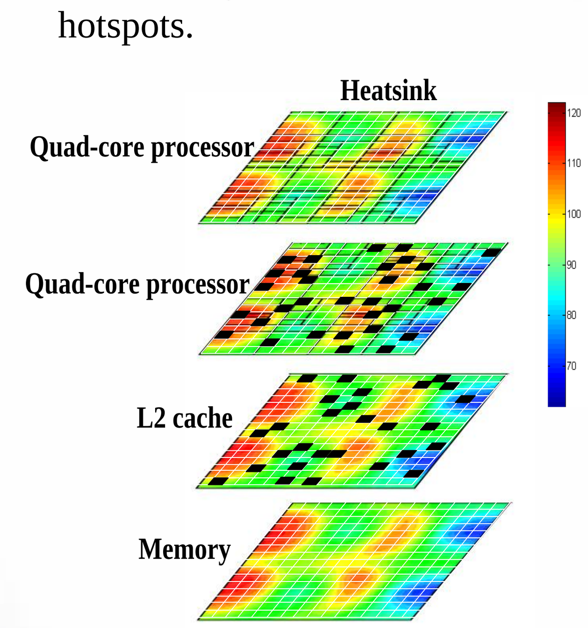


- k: number of sensors n: number of hotspots



- Figure shows the efficiency of using the k-means clustering algorithm in the 3D space instead of solving the problem for each individual layer.
- With the same number of sensors and error tolerance, using 3D k-means clustering covers a much higher percentage of the critical macro cells than 2D k-means clustering.
- Using 3D k-means clustering we avoid assigning an excessive number of unnecessary sensors to the same spatial hotspots.

- The optimum thermal sensor positions using a 3D k-means clustering algorithm for sensor allocation are shown in the figure.
- We can see that with a minimum number of sensors, for 100% coverage of the critical area and an acceptable reading error of less than 5%, thermal sensors are only located in middle layers and they also monitor their adjacent layers' temperatures.



Experimental Results and Conclusion

Applications	Benchmarks running on core 1 through core 8	Max Modeling Error (%)
1	apsi/equake/gcc/bzip/bzip/gcc/equake/apsi	2.72
2	apsi/equake/gcc/bzip/apsi/equake/gcc/bzip	2.35
3	apsi on all cores	2.13
4	equake on all cores	5.46
5	gcc on all cores	3.53
6	bzip on all cores	2.96

- Layers are divided into 128×128 grid cells, and the error represents the difference between the temperatures of the grid cells calculated with HotSpot 5.0 and the results provided by our proposed 3D thermal map modeling.

- Employing proposed 3D thermal map modeling in the thermal sensor allocation algorithm results in a 53x speedup compared to HotSpot 5.0 thermal modeling.

Applications	Benchmarks running on core 1 through core 8	Max Sensor Reading Error (%)
1	apsi/equake/gcc/bzip/bzip/gcc/equake/apsi	2.95
2	apsi/equake/gcc/bzip/apsi/equake/gcc/bzip	3.27
3	apsi on all cores	3.28
4	equake on all cores	4.40
5	gcc on all cores	4.08
6	bzip on all cores	3.63

- The proposed modeling yields maximum error of less than 5.5%, which is quite acceptable for the purpose of a sensor distribution algorithm.
- With the proposed method less than 4.4% error in maximum sensor reading of the temperature is accomplished.
- The algorithm uses the proposed 3D thermal map modeling, which improves evaluation time by 53x compared with using of HotSpot 5.0 embodied in the algorithm.
- Thermal sensor distribution for 3DICs must be solved as a 3D problem, which results in 44% fewer sensors.

[1] F. Kashfi, and J. Draper, "Thermal sensor distribution method for 3D integrated circuits using efficient thermal map modeling," in Proc. THERMINIC, Sep. 2012.
[2] F. Kashfi, and J. Draper, "Thermal sensor design for 3D ICs," in Proc. MWSCAS, pp. 482-485, Aug. 2012.

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