Fast thermal and multi-physics simulation using model reduction and Sub-models for Electronics

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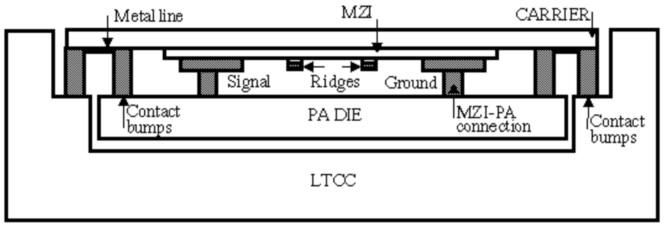
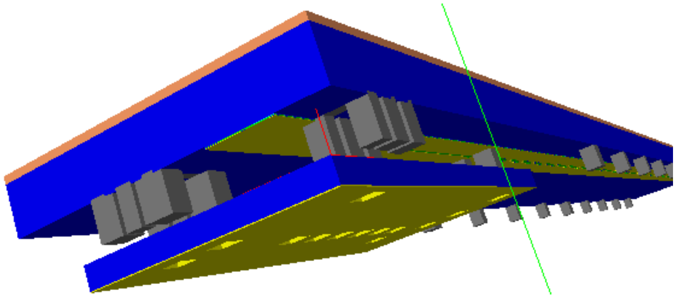
Outline

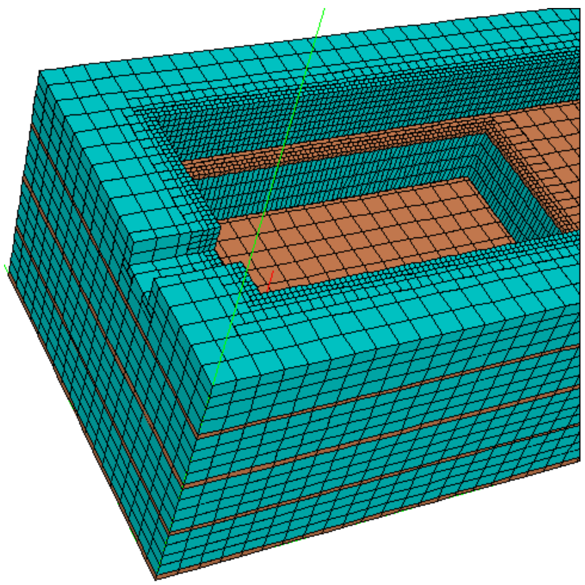
- **Motivation and background**
- **State of the Project.**
- **Introduction to thermal simulations using multi-dimensional model reduction**
- **Applications of sub-models and model reduction**
- **Future Work**

Complicated thermal/multi-physics design problems

- **High power and non-uniformities ($P\uparrow$, $f\uparrow$, chip size$\downarrow$, functionality $\uparrow$)**
- **Development of new packaging/module technologies**
- **Multi-scale — dev $\rightarrow$ chip $\rightarrow$ board $\rightarrow$ ...**
- **Reduction of production cycle-time and reliability.**
- **Reliability issues — appropriate thermal management**
- **Multi-physics — thermal/EM/optical/mechanical coupling.**





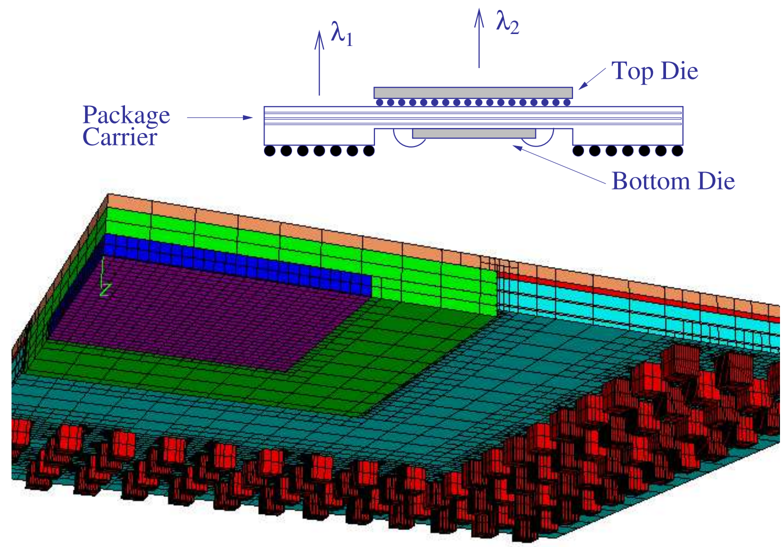


Current state of the project

- **Fast Thermal Modeling**
  - **Developed sub-modeling techniques to allow for use of thermal library parts and enable fast simulation.**
  - **Incorporated parameterized model reduction to create small BCI models for fast SS, transient simulation and compact models.**
  - **Confirmed speed-ups of 100+ and accuracy of better then 1%.**
- **EM/optical simulation**
  - **Fullwave integrated EM – based on TLM**
  - **Simplified models base on thermal/electrical/optical interactions.**
- **Mechanical modeling**
  - **Integrated FEM based stress/strain solver**
  - **Developing the use of model reduction for stress/strain analysis.**

Simulation tools required for system and module design.

- **Analytical — Simple geometries and boundary conditions.**
- **Fully detailed numerical simulations:**
  - **Become very large (200,000+ blocks) and computationally intensive.**
  - **Limited by model complexity.**
  - **Coupled physics simulation possible but time consuming. Bottleneck is often the need for a multi-scale thermal simulation.**

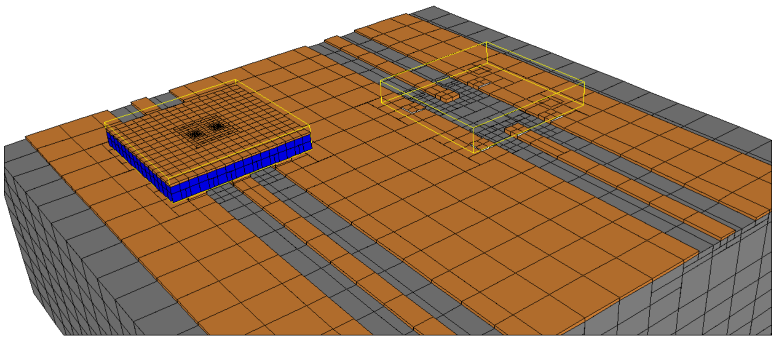


Simulation tools Simplified or Compact models

- **Types**
  - **Spreading resistances and multi-layer models.**
  - **Optimized resistor networks – delphi.**
  - **Matrix methods – model reduction**
- **Boundary condition Independence?**
- **Limited to a small set of junction temperatures?**
- **Limited accuracy, flexibility and predictive capability.**
- **Questions arise for multiple power sources, transient and multiple points of interest.**

Quick thermal numerical solutions of full models

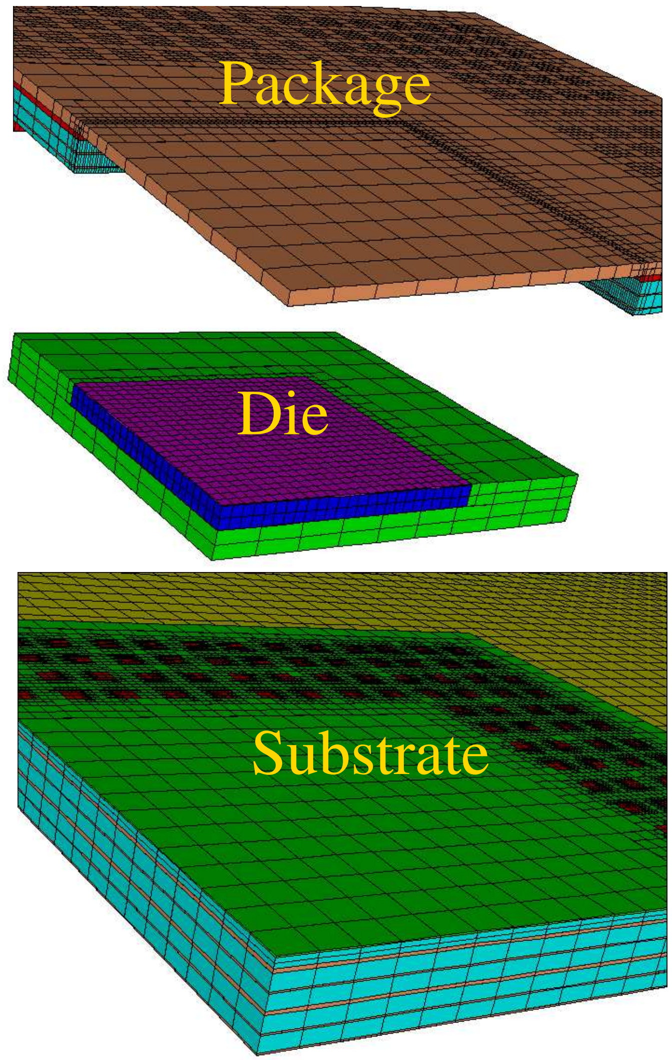
- **Use a Finite Difference numerical tool we have developed — Atar.**
  - **Unstructured meshing**
  - **Multi-scale – device to board**
  - **Builds from geometry and a technology description**
  - **Extendable: Electro/optic/thermal coupling and Mechanical/thermal modeling.**



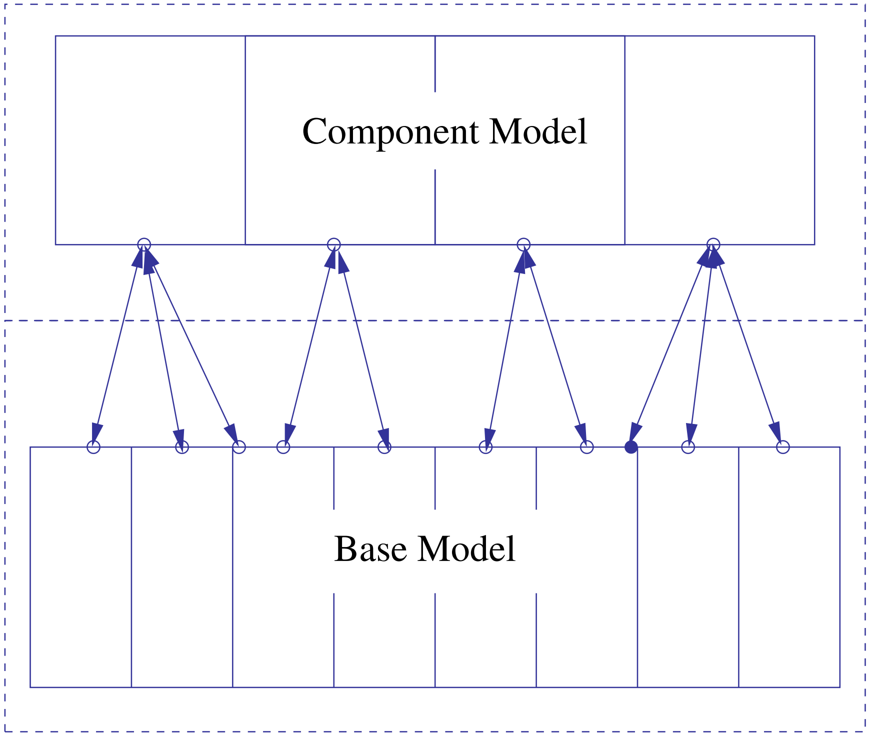
- **How to solve the problem of building and solving very large models?**
  - **Break the model in to pieces (which we call sub-models).**
    - ▷ ***Each piece is attached using a simple equation***
    - ▷ ***All temperatures are determined***
  - **Mathematically reduce the problem size using model reduction.**

Sub-models: breaking the model up.

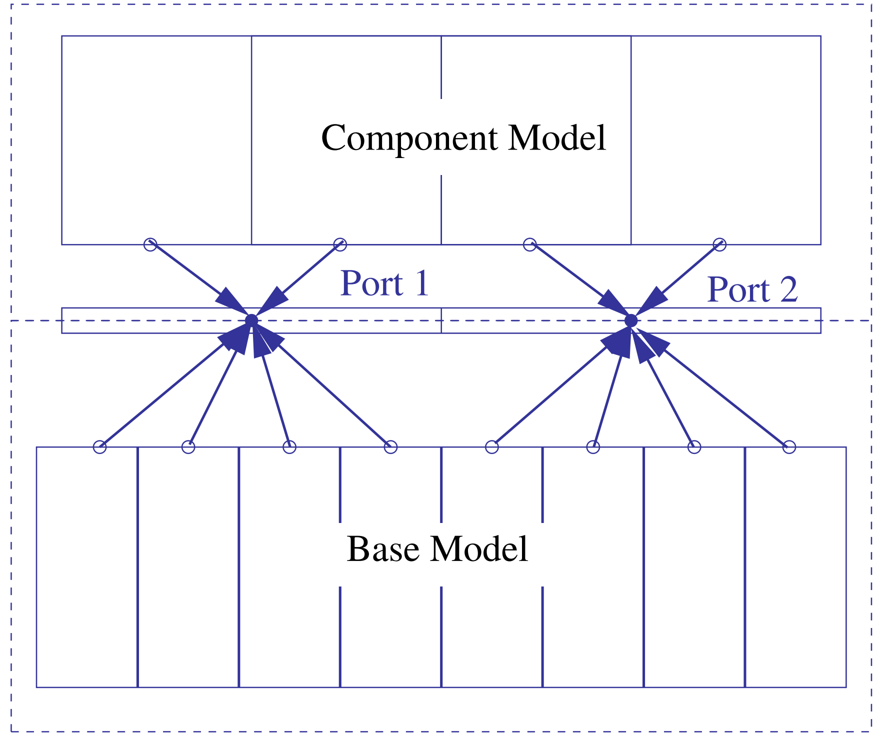
- **Break large detailed model into sub-models (well defined pieces)**
  - **Connected by thermal ports which exchange heat.**
  - **Represented by a simple mathematical equation.**
  - **Complete response of component is captured**
  - **Can have "external" boundary conditions applied – usually as heat flow represented by external resistance.**
- **Solve a "mixed model" of detailed base and connected sub-models.**
- **All internal temperatures of sub-model are available.**



Creation and application of sub-models



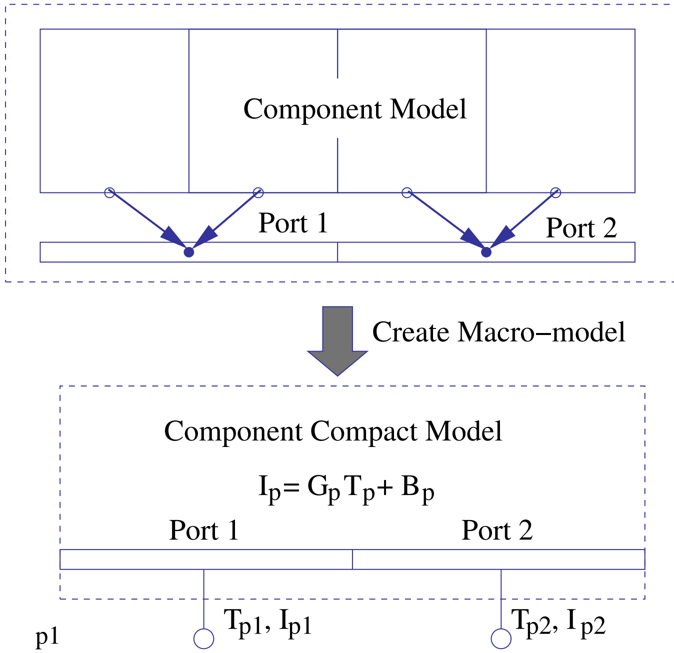
Fully detailed Model

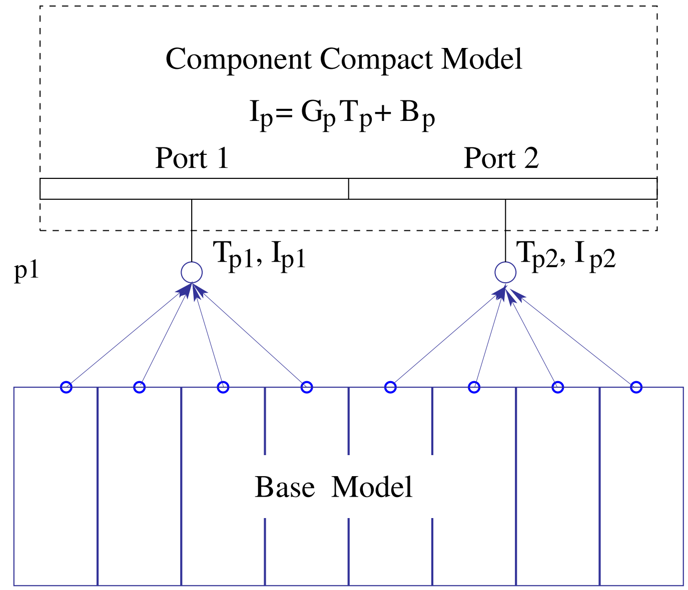


Definition of Ports

- **Separate model into pieces (base and sub-model).**
- **Define linking surface nodes to exchange heat.**
- **Define port surfaces between the two models.**
- **If port/block then an exact solution.**

Creation and application of sub-models





Create Sub-model

Link sub-model to base

- **Create mathematical form of sub-model in terms of port temperatures (T_p) and currents (I_P).**
- **Connect sub-model to base using “attachment equation” .**
- **Solve “Mixed Model” for base model temperatures and port temperatures.**
- **Use port temperatures to obtain internal temperatures of sub-model.**

Direct Generation of Sub-Model

- **The discretized form of the the thermal equation for the sub-model:**

$$G_S\boldsymbol{T} = B_S + M_p\boldsymbol{T}_p \quad (1)$$

$$\boldsymbol{I}_p = M_p^T\boldsymbol{T} \quad (2)$$

$$G_S(\lambda) = G + \sum_i^n \lambda_i G_{\lambda_i}$$

$$B_S(\lambda, T_m, T_f, P) = B + \sum_1^n \lambda_i T_{m_i} B_{\lambda_i} + \sum_1^m T_{f_k} B_{f_k} + \sum_1^p P_j B_{p_j}$$

- **Conductance matrix G – from discretization of detailed model.**
- **External boundary conditions are explicit — λ, T_m, T_f**
- **Internal powers are parameters — P**
- **Ports are defined using matrix M_p**
- **BCs are mapped using matrices B_f, B_λ and B_p.**

Direct Generation of Sub-Model

- **Port currents can be defined as:**

$$\boldsymbol{I}_p = M_p^T G_T^{-1} B_T + M_p^T G_T^{-1} M_p \boldsymbol{T}_p \quad (3)$$

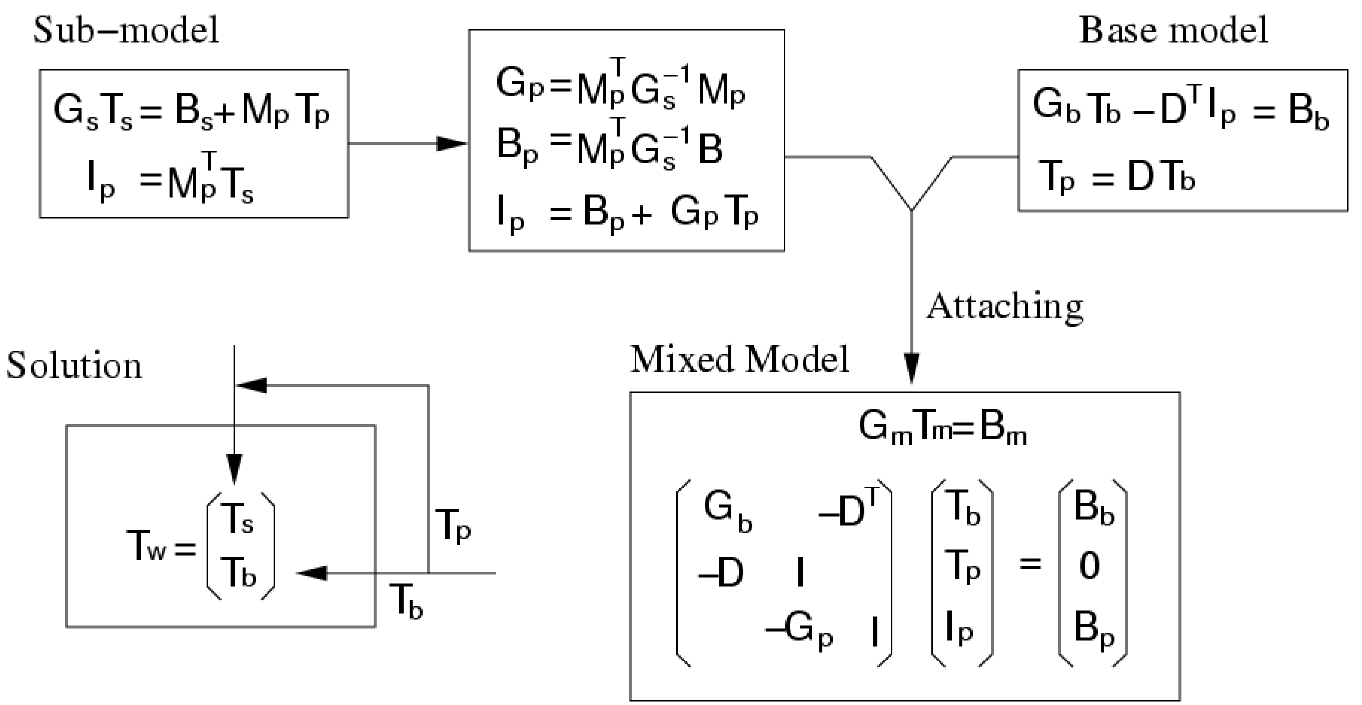
$$G_p = M_p^T G_T^{-1} M_p; \quad (4)$$

$$B_p = M_p^T G_T^{-1} B_T \quad (5)$$

$$\boldsymbol{I}_p = B_p + G_p \boldsymbol{T}_p \quad (6)$$

- **This is the "attachment equation"- it is small ($n_p \times n_p$).**
- **We call this a "direct sub-model" as it is generated directly from the detailed model equations for the sub-model.**

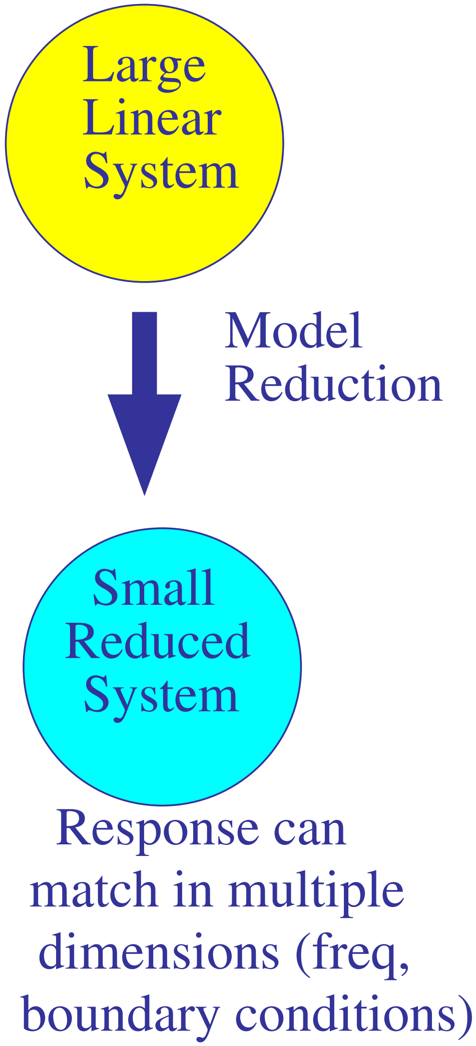
Solution of a mixed model with direct sub-models



- **Can simulate a large complex model by breaking to pieces.**
- **Speed-up simulation and reduce memory requirements**
- **Create hierarchical sub-models**
- **However, each specification for a BC set of G_p and B_p requires a new LU decomposition of G_s. *Not Boundary condition independent!***

Model Reduction: making the problem smaller

- **Replace a large system of linear equations with a much smaller but equivalent one.**
- **Solution or creation of a sub-model can be performed in the reduced solution space.**
- **Very fast and accurate.**
- **The use of Multi-Dimensional Model Reduction allows us to include the boundary conditions applied to the model.**
- **Essentially making the reduced models boundary condition independent.**



Using Model Reduction

- **A large (sparse) system replaced by a small (dense) system.**
- **Congruent transformation ($\boldsymbol{T}$ is mapped to $\hat{\boldsymbol{T}}$)**
- **Uses QR decomposition to form a multi-dimensional sub-space where:**

$$\boldsymbol{T} = Q\hat{\boldsymbol{T}} \tag{7}$$

- **Reduced network equation (much smaller size):**

$$(\hat{G}_S + \sum_{i=1}^{n} \lambda_i \hat{G}_{h_i})\hat{\boldsymbol{T}} = \hat{\boldsymbol{B}}_S + \sum_{i=1}^{n} \lambda_i T_m \hat{\boldsymbol{B}}_{h_i} + \sum_{k=1}^{m} T_{f_k} \hat{\boldsymbol{B}}_{f_k} + \sum_{j=1}^{p} P_j \hat{\boldsymbol{B}}_{p_j} + \hat{M}_p \boldsymbol{T} \tag{8}$$

- **Boundary conditions are still explicit.**

Reduced Sub-model creation

The attachment equation:

$$\boldsymbol{I}_p = B_p + G_p\boldsymbol{T}_p$$

$$G_p = \hat{M}_p^T \hat{G}_S^{-1} \hat{M}_p$$

$$B_p = \hat{M}_p^T \hat{G}_S^{-1} \hat{B}_T$$

Internal temperatures:

$$\hat{\boldsymbol{T}} = \hat{G}_S^{-1}(\hat{\boldsymbol{B}}_S + \hat{M}_p\boldsymbol{T}_p)$$

$$T_S = Q\hat{\boldsymbol{T}}$$

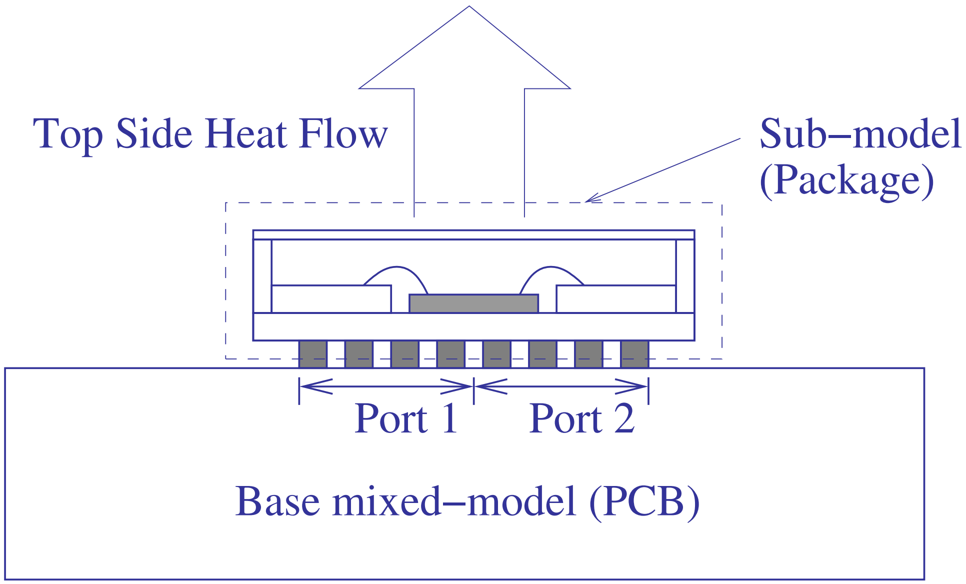
Junction temperatures

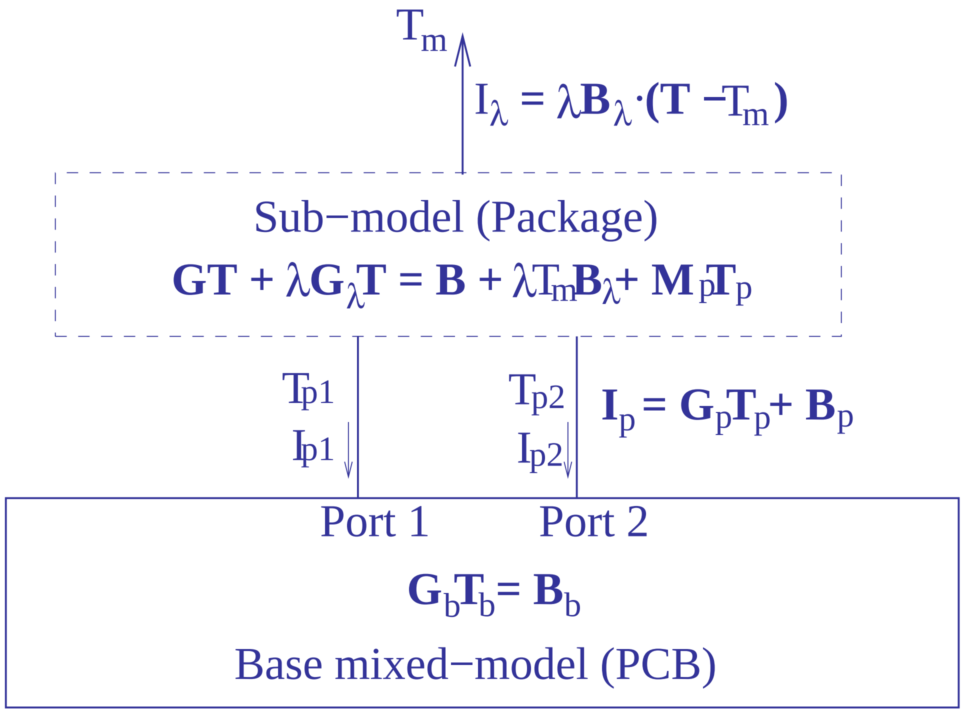
$$\boldsymbol{T}_{jct} = SQ\hat{\boldsymbol{T}}$$

$$I_{\lambda_i} = \lambda_i B_{\lambda_i} \cdot (Q\hat{\boldsymbol{T}} - T_{m_i})$$

- **As $\hat{G}_S$ is much smaller then G_S we can form G_p and B_p in less than a second prior to simulation of the mixed model.**
- **Model reduction does introduce some error**

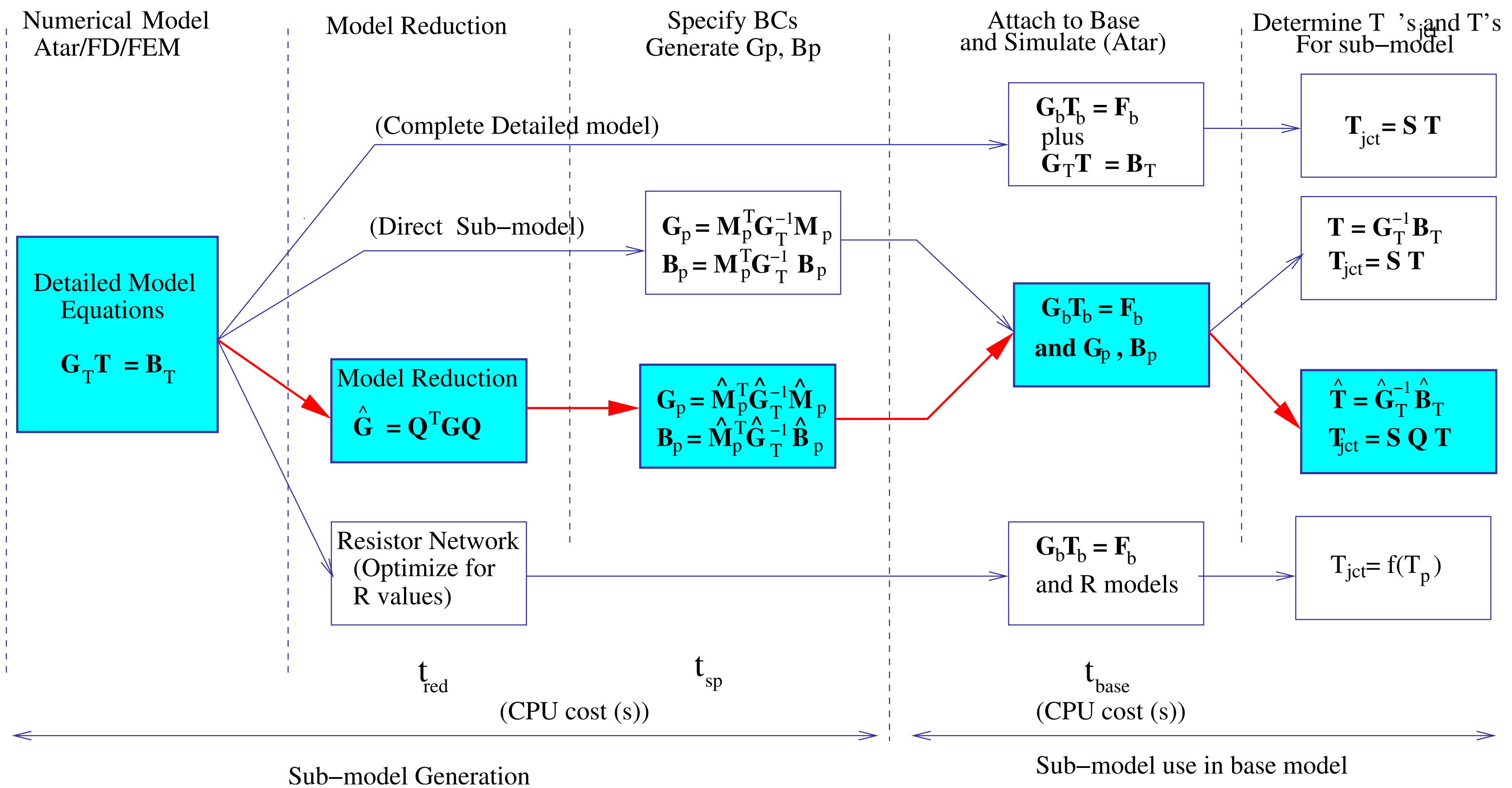
Reduced Sub-model Summary





- **Characterize submodel using — T_p and I_p.**
- **External boundary conditions parameterized.**
- **Use Model reduction so we can generate G_p and B_p very quickly (less then a second)**

Overview of Simulation algorithms

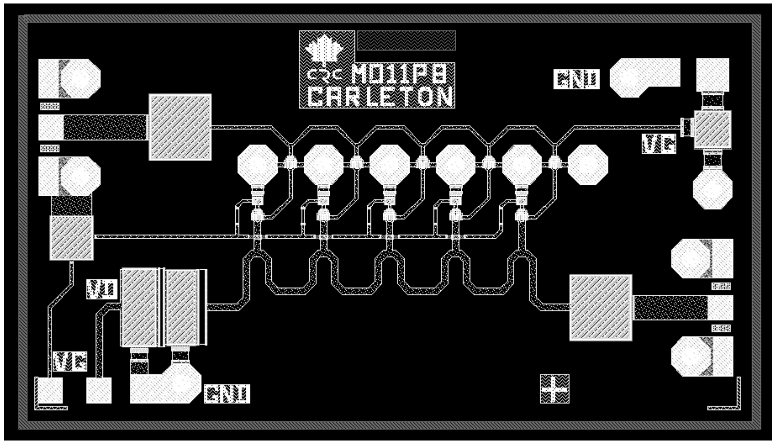


- **Comparison of four simulation schemes.**
- **Use of MDMR and submodels is quick and supplies all temperatures.**

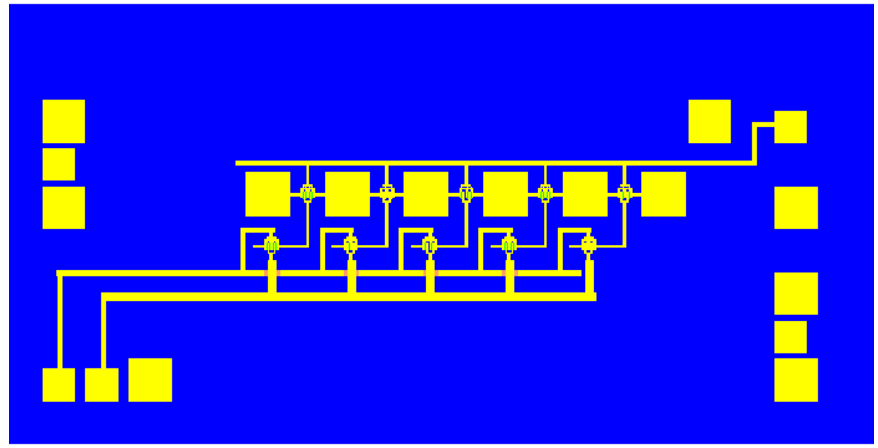
Summary of Atar, MR and Sub-modeling

- **Sub-modeling allows us to solve big models on "normal" computers**
- **Model Reduction allows us to build BC parametrized models.**
  - **One LU (SS solution) to do MR for BCI model.**
  - **Size reduction from 100,000s to 10's of nodes.**
  - **FAST!**
  - **All internal temperatures!**
- **New attachment procedure – constant heat flow ports.**
- **Verification**
  - **Compared both transient and SS models with analytical solutions for simple problems (<1% error).**
  - **Compared both transient and SS models with "fully detailed" numerical models (Atar and commercial solvers) (<1**
  - **Math works!**
  - **Input is correct (Geo, power, material properties) output is correct (T(t)).**

Example: Power Amplifier for optical modulator



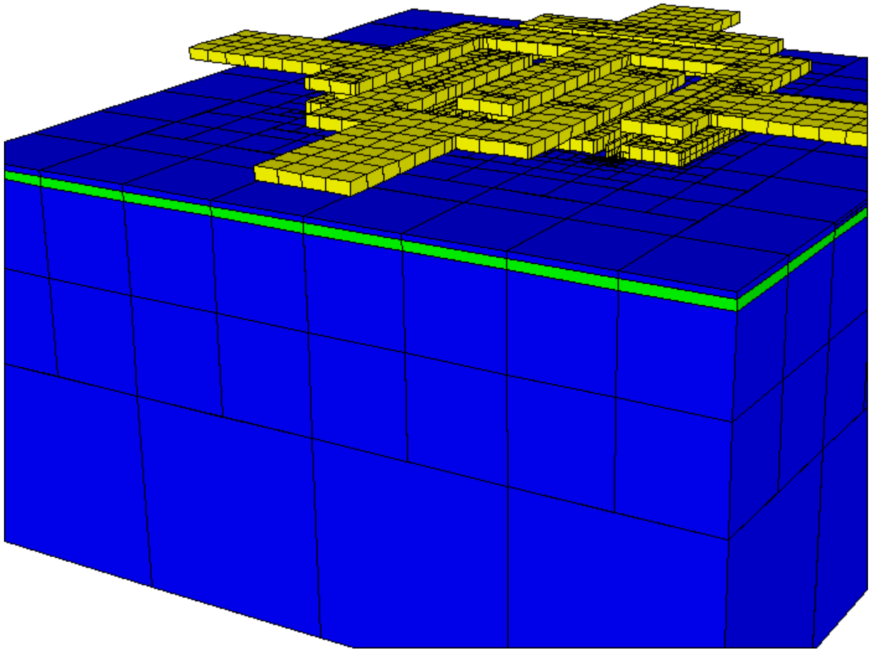
Photograph of Die



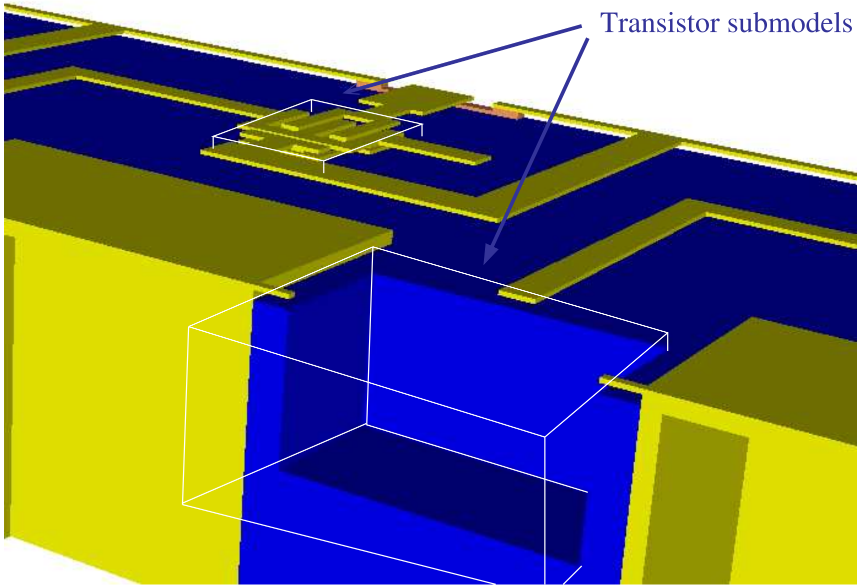
Atar model of complete PA

- **5-section cascode gain PA**
- **10 multi-finger GaAs FET transistor power cells**
- **Fine meshing of pinch-off region.**
- **Detailed description of backend metalization**
- **Fully detailed model is very large! (300,000 blocks)**

Sub-model transistor



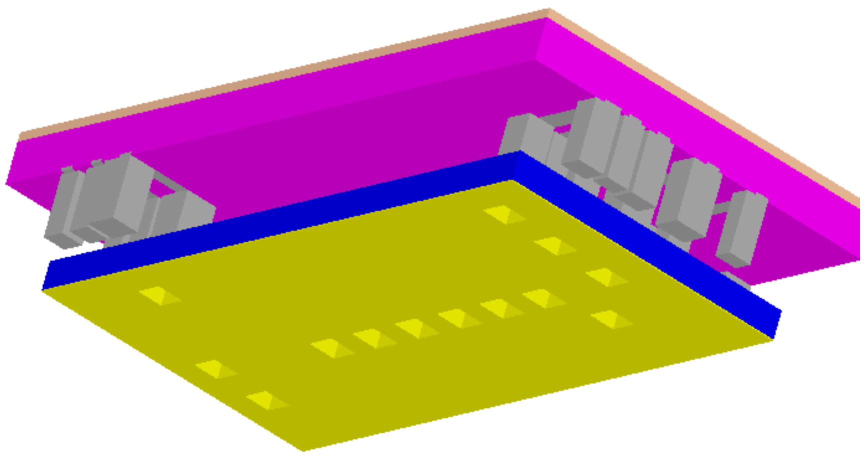
Transistor sub-model

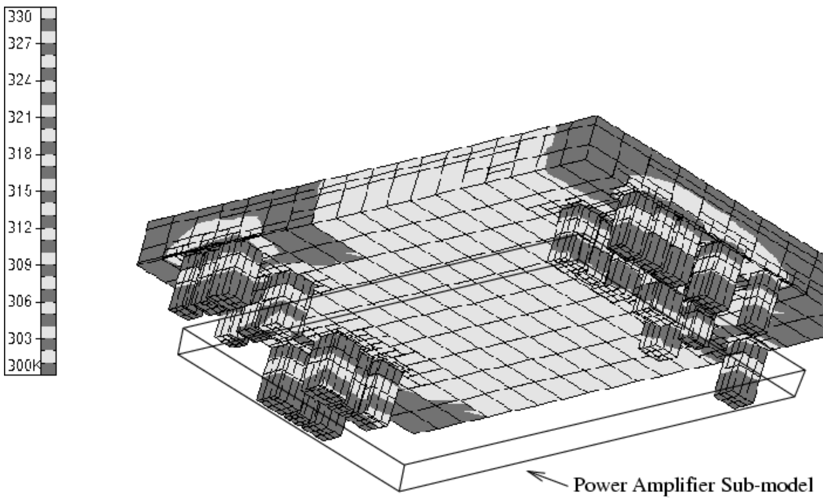


Base Model

- **Build each four finger transistor cell as sub-model**
- **Use 9 ports – one for each side and the metal connections.**
- **Base uses 10 transistor cells sub-models.**

Hierarchal Submodels — Power amplifier as a sub-model

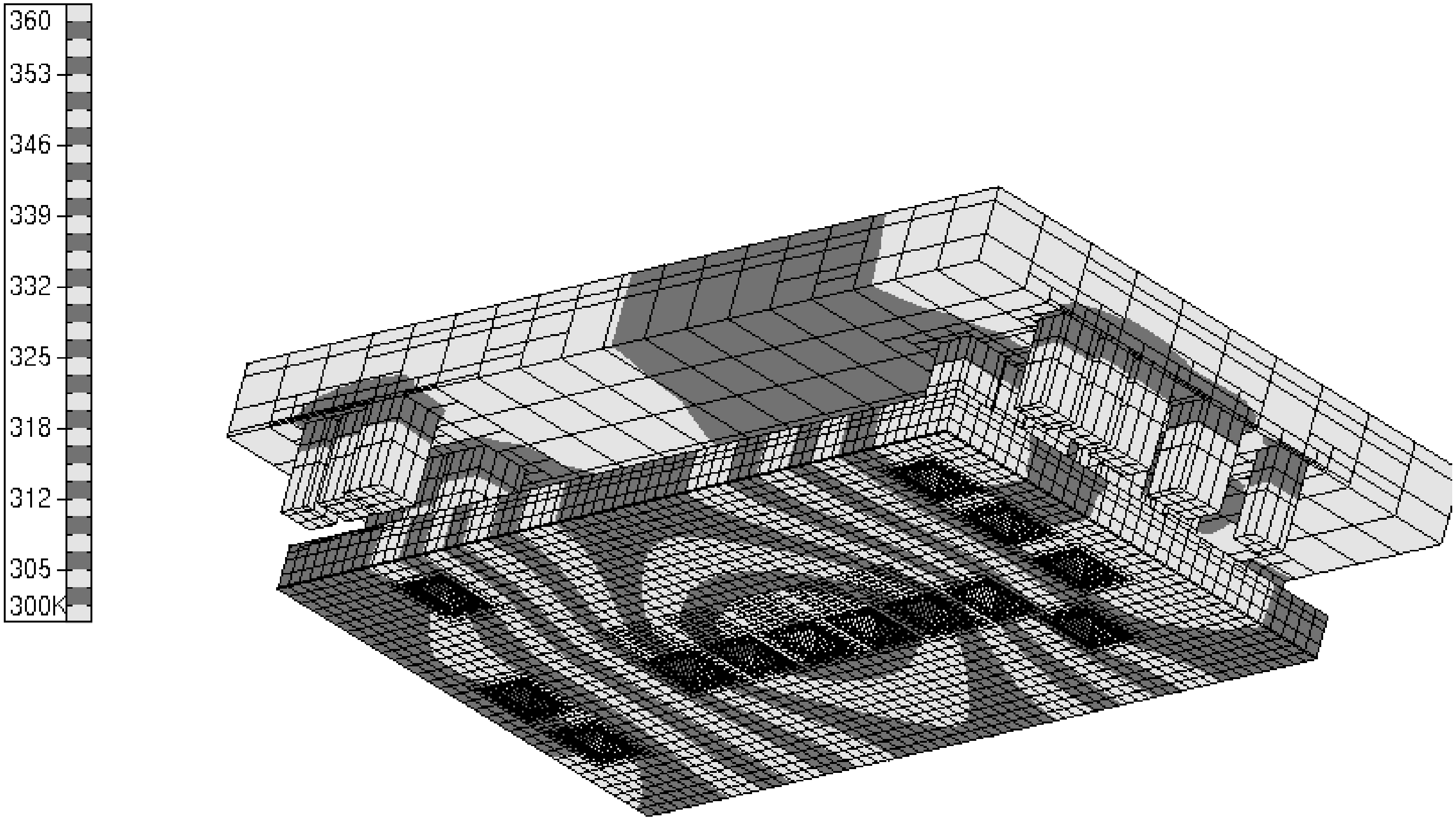




Detailed model of PA and InP Carrier **Base after solution**

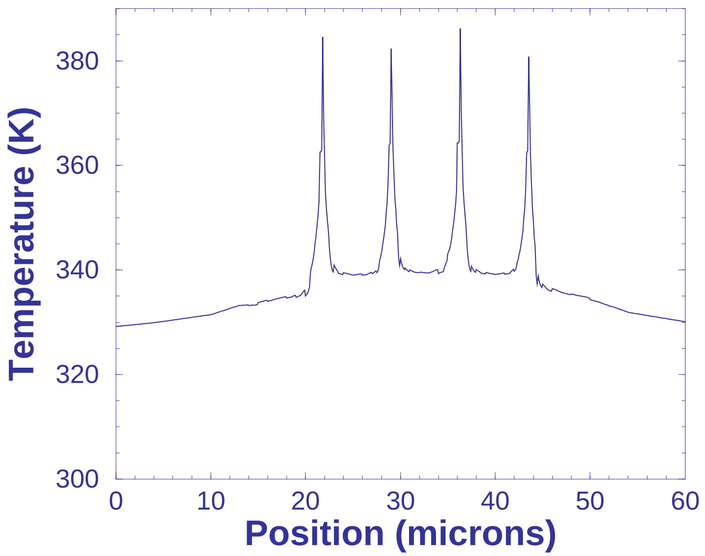
- **Build PA as a 12-port sub-model containing 10 transistor submodels**
- **Solve InP mixed-model with attached PA submodel.**
- **Calculate PA temperatures from port temperatures of the InP mixed model.**
- **Calculate transistor temperatures from port temperatures of the PA mixed-model.**

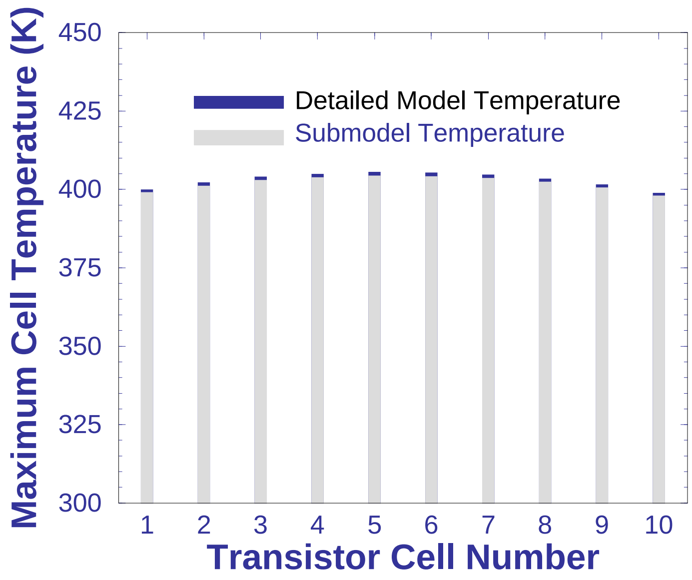
Temperature contours



- **Obtain all internal temperatures.**
- **PA sub-model contains heat flow paramater for backside flow.**

Internal Tempertures





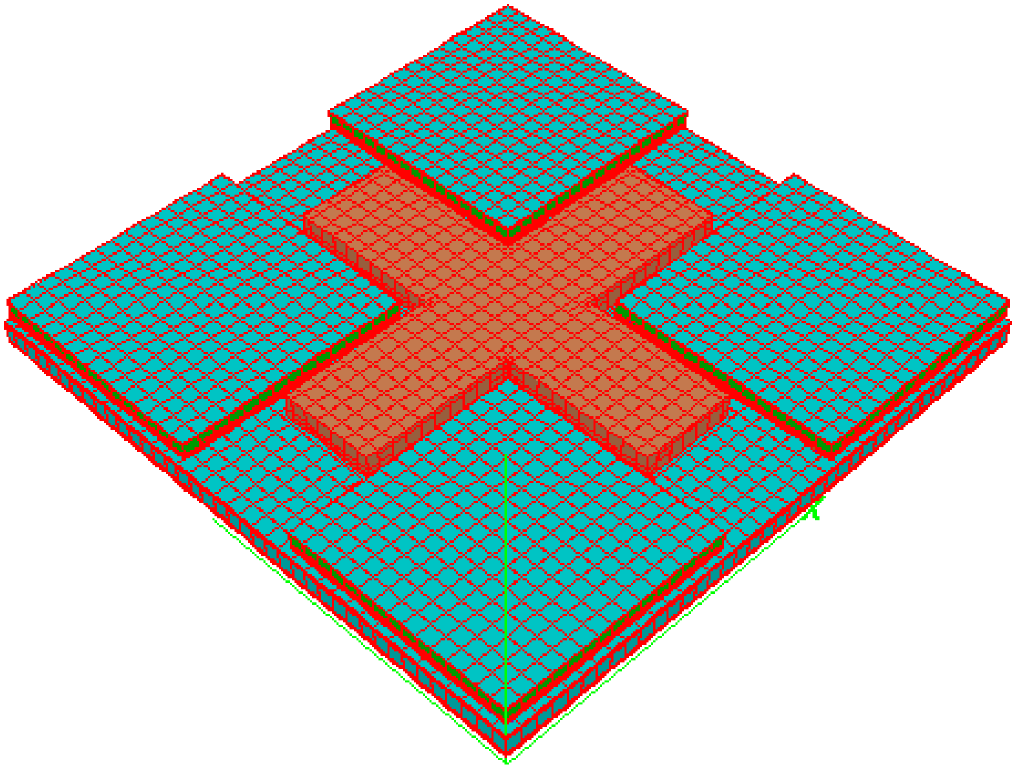
Finger temperatures

Junction Temperatures

- **Compare to “fully detailed” numerical model of all components.**
- **Accurate to better then 2%.**

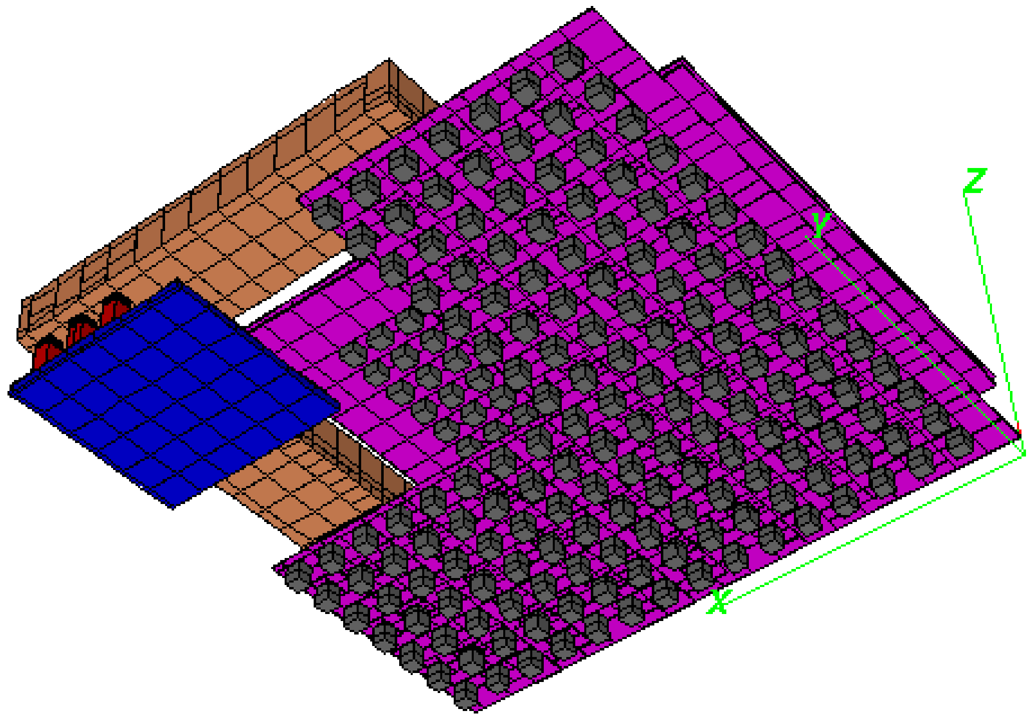
Example: ATI Technologies 216T9NFBGA13FH Processor

- **Working with DY4.**
- **Model based on Semiconductor Insights report.**
  - **PCB package substrate**
  - **ATI graphics chip**
  - **Four DDR SDRAM memory chips**



ATI Technologies 216T9NFBGA13FH Processor

- **Include lots of internal detail**
- **Base model plus 4 submodels for Memory and 1 for die**
- **Built reduced model for connection to a board.**
- **Paramaterized heat flow off cross and memory chips.**

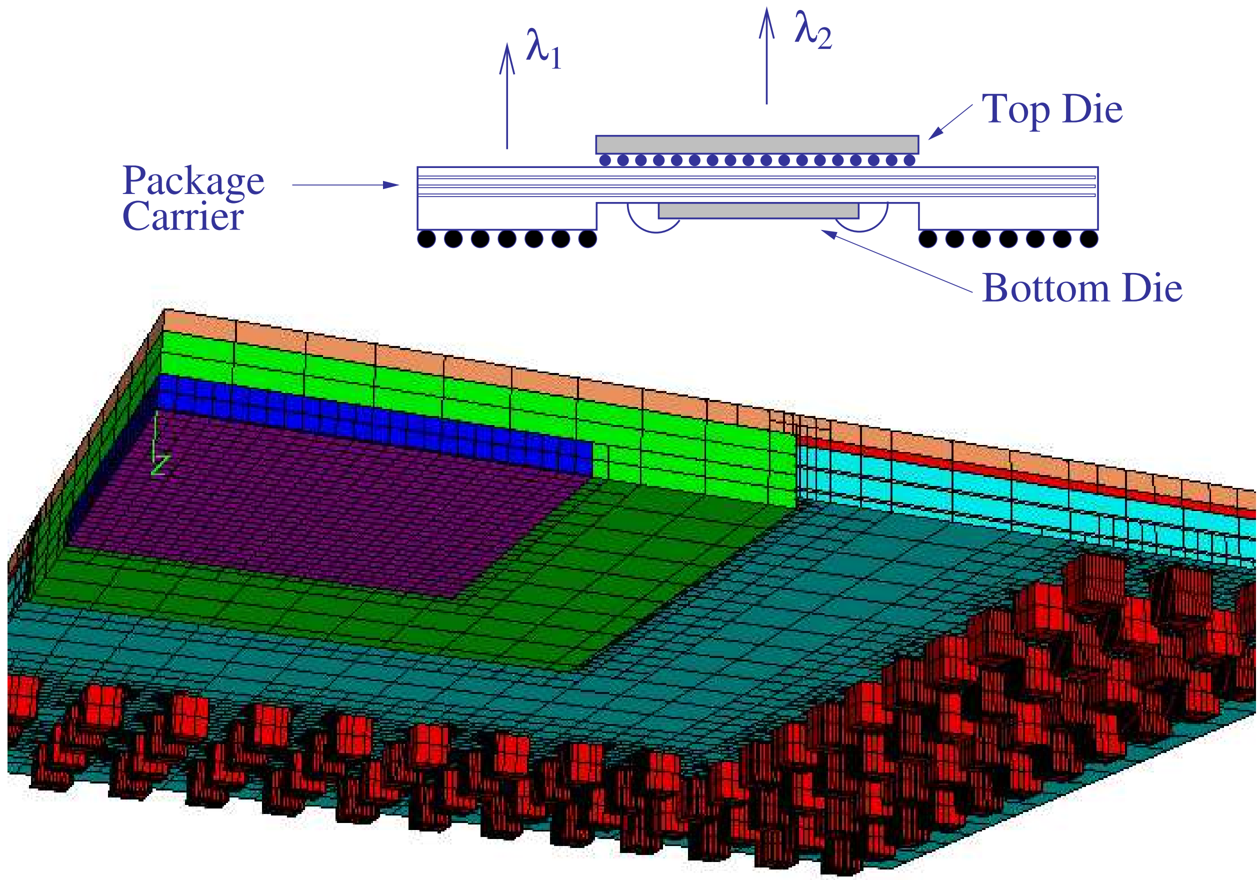


ATI Technologies 216T9NFBGA13FH Processor

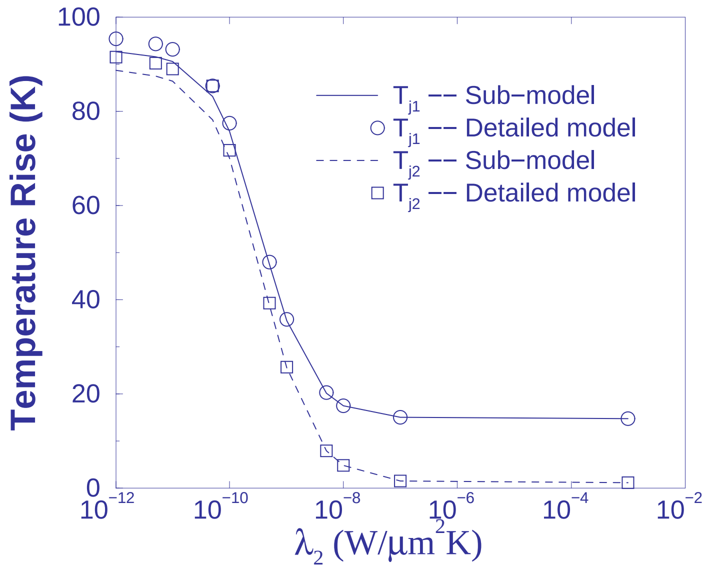
- **Preliminary results match reported θ_{JC} to within 5%.**
- **Future work will involve integration of module into cards.**

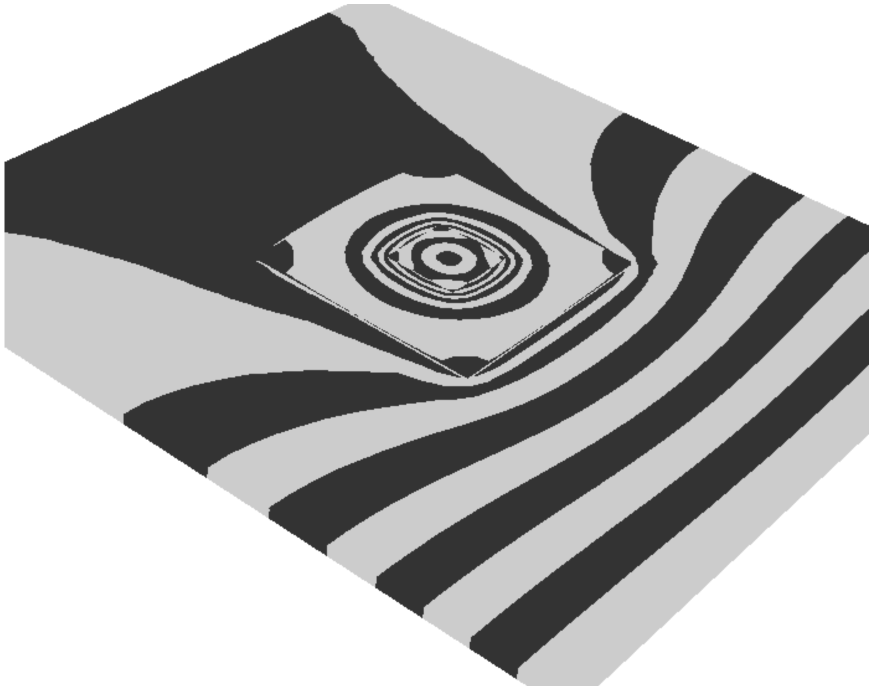
Second Example: MCMBGA

- **Large pinout multichip package**
- **Need a boundary condition independant model**
- **Paramaterize heat flow off top and sides of package.**



Attachment and boundary condition independance





Junction temperatures

Base and sub-model contours

- **Used models with 4 to 64 ports.**
- **Varied heat flow off the top and sides.**
- **Model reduction error less then 1%**
- **Error is primarily due to port configuration not model reduction.**

Model size and reduction time

Model	Detailed Size	Sub-model size		t_{red} (sec)
		Reduced	Attached	
PA				
Transistor	19,900	11×11	9×9	46
Die[1]	63,943	60×60	12×12	233
MCMBGA				
Package	73,129	32×32	4×4	415

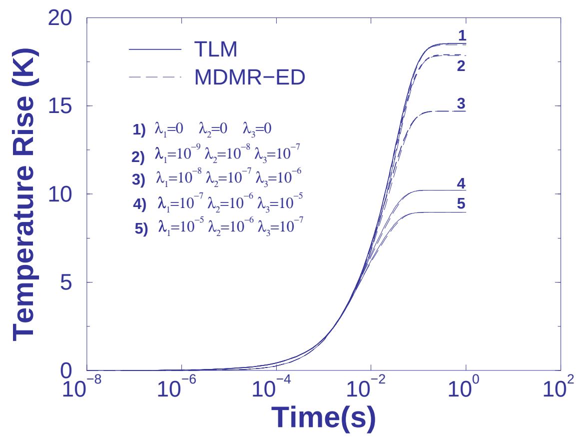
- **Model size and sub-model generation time for each component in PA and MCMBGA models**
- **Die model is formed out of a die substrate and 10 transistor sub-models**

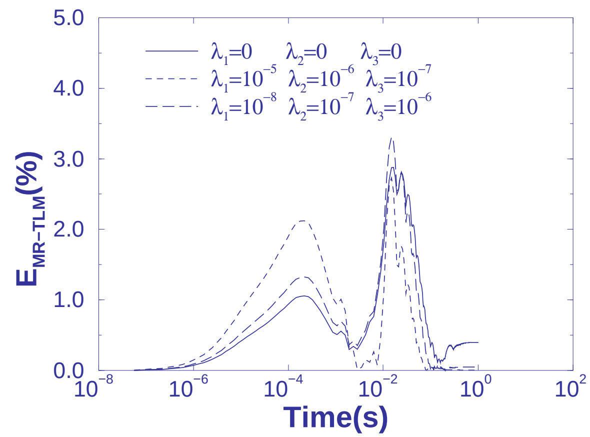
Model size, speed-up and accuracy

Model	Size	t_{sol} (sec)	T_j (K)
PA			
Detailed	269,547	768	105.4
InP+Die sub-model	1212	16	104.3
	Speed-up of 48		ΔT_j=1.0%
MCMBGA			
Detailed	77,929	213	95.4
PCB+package sub-model	4804	2.20	93.1
	Speed-up of 97		ΔT_j=2.5%

- **Solution time and junction temperature obtained from comparison of fully detailed solution of all components and a mixed-model using sub-models.**

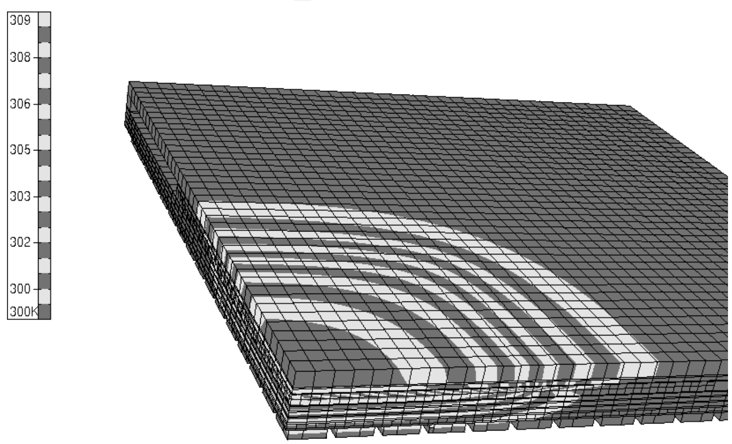
CBGA: Transient Simulations

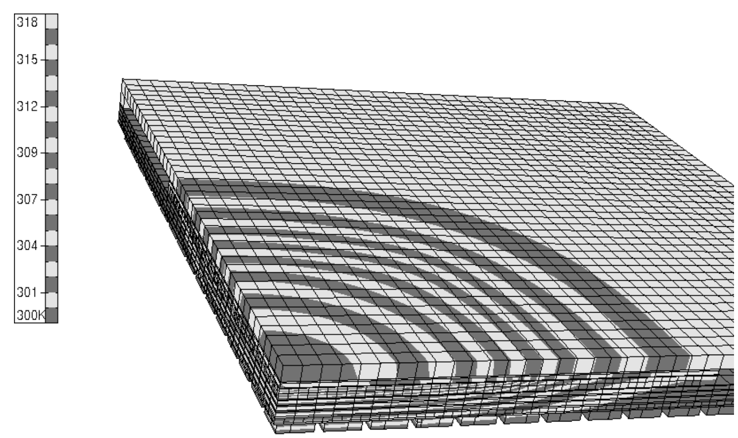




Temperatures

Errors

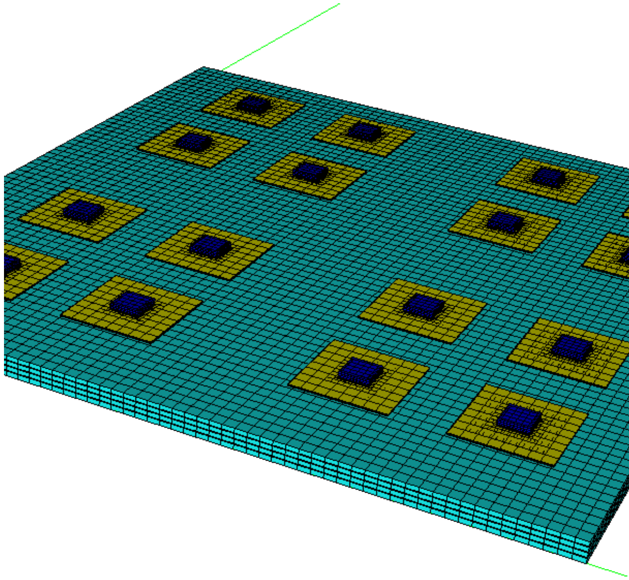


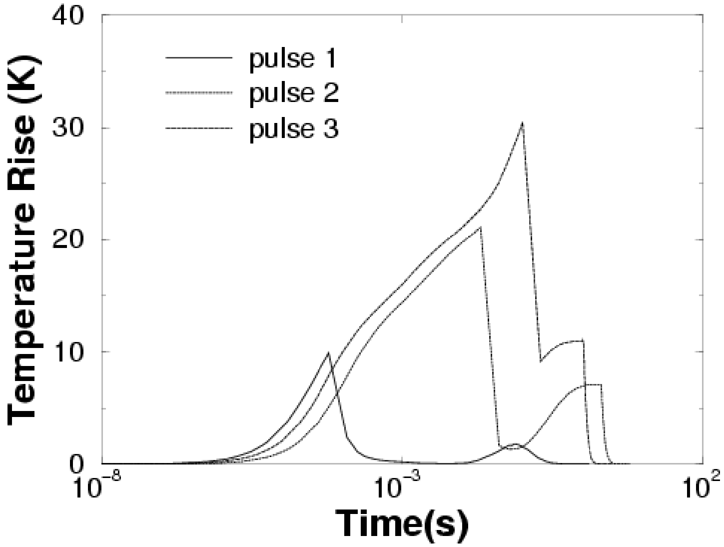


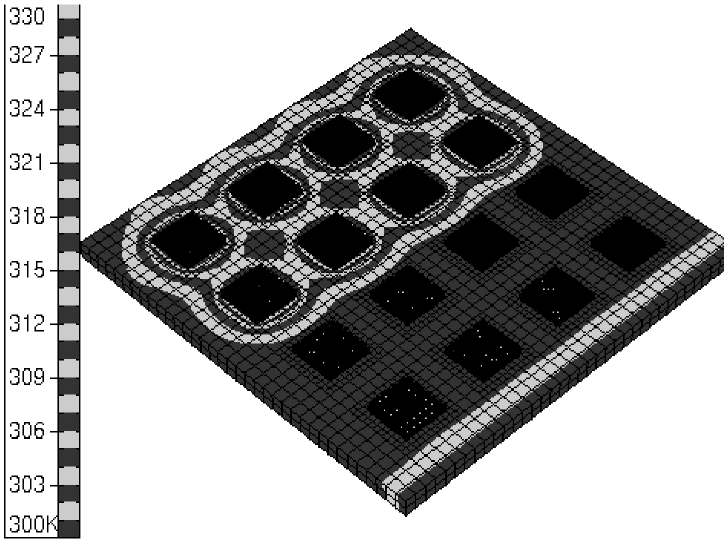
1/2 SS

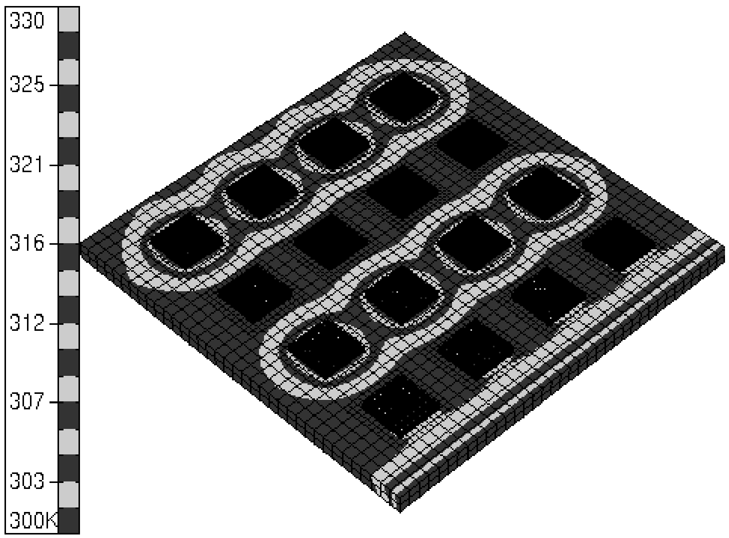
SS

Submodel: Transient Simulations









Future Work

- **Full System Modeling**
  - **Steady-state and transient – hiearcheal modeling, thermal libraries.**
  - **Convection models and boundaries.**
  - **Advanced technologies – heat pipes.**
- **Non-linear modeling (Convective BCs, K(T))**
- **Multiphysics**
- **Application Work**
  - **Higher level of integration (3D, SOC, SIP) – Chip/Package co-design**
  - **Heat Removal (Optimization, Heat pipes, others?)**
- **Making the work accessible.**
  - **Web based application server.**
  - **GUI for Atar/MR based analysis**
  - **Industrial inspired projects.**