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Material Issues in Thermal Management of RF Power Electronics

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? System Level ? Description of system(s) ? Thermal management issues ? Temperature gradients ? Absolute temperature levels ? Special array-level (AESA) problems ? Role of materials at the system level ? Component Level ? Primary source of thermal dissipation ? Unique thermal analysis aspects of RF components ? Role of materials at the component level

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Introduction

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- System Level
  - Description of system(s)
  - Thermal management issues
    - Temperature gradients
    - Absolute temperature levels
    - Special array-level (AESA) problems
  - Role of materials at the system level
- Component Level
  - Primary source of thermal dissipation
  - Unique thermal analysis aspects of RF components
  - Role of materials at the component level

Phased Array System Hierarchy

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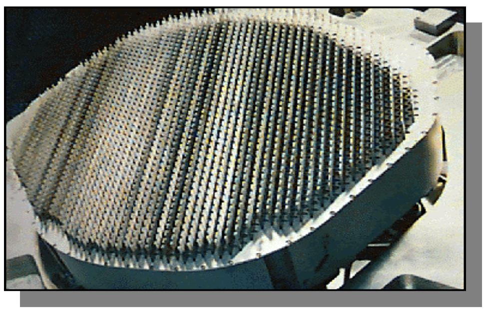
Phased array hierarchy	Physical dimensions, characteristics	Material issues	Thermal management issues
Active antenna	Meters, many elements	Structural support Thermal gradient	Coolant routing Heat absorption
Slat, Subpanel	Meter several elements	Interconnect, CTE, thermal	Packaging density
RF Module	Collection of MMICs and ICs	Dielectric, CTE, thermal, hermetic	Module attach thermal interface
Device	Power Amplifiers sub-micron active area	Semiconductor Thermal interfaces	Die attach FET layout

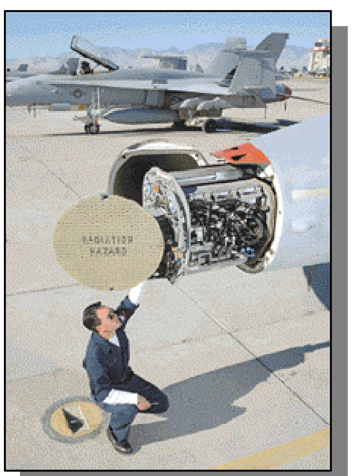
Typical RF Platforms / Systems
Airborne and Ground Systems

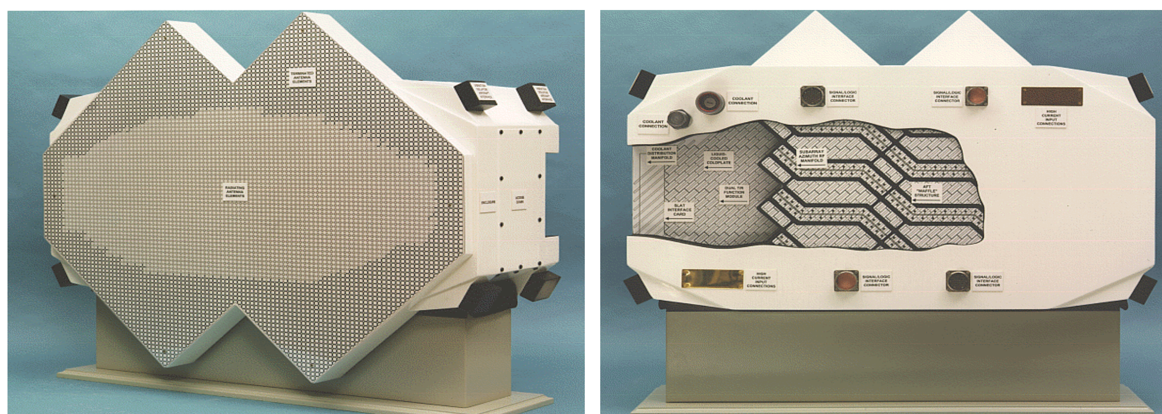
- Often require designs for continuous operation

Ground based



Airborne





Shipborne

Typical RF Platforms / Systems

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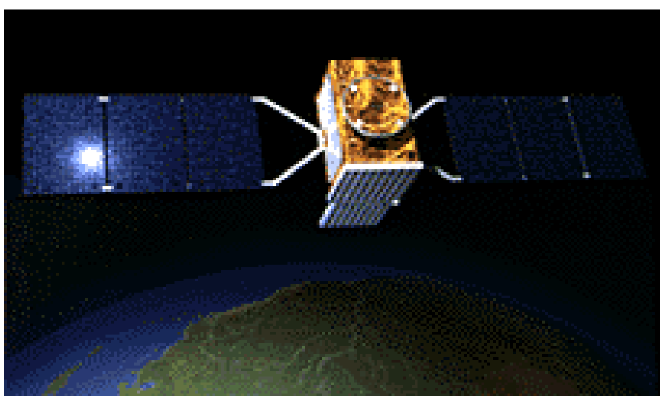
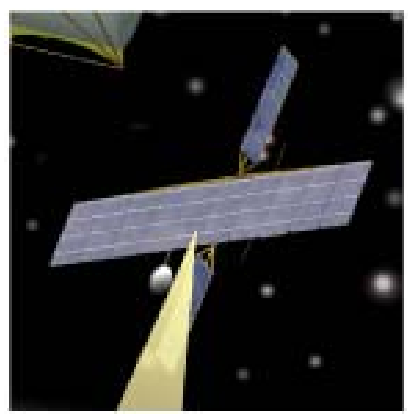
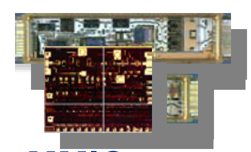
Satellite Systems

- Large antenna dimensions
- May have thousands of modules
- May have option of intermittent or short term operation

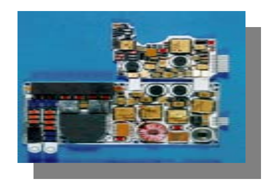




Modules



MMICs



Power Converter

Typical RF Platforms / Systems

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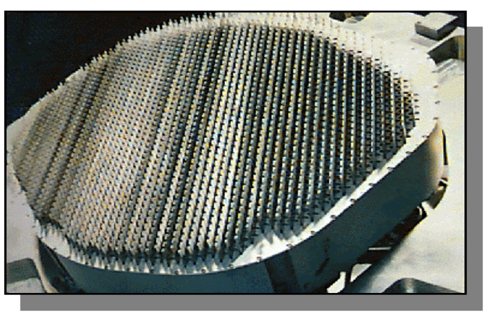
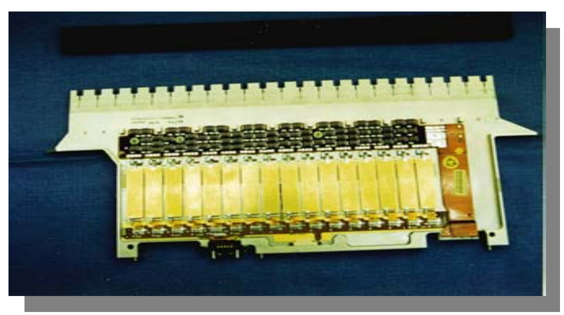
Phased-Array Radars

- Phased-array radars typically operate at frequencies from 1 to 30 GHz and dissipate from hundreds to tens of thousands of KW of waste heat
- Phased-array radars often contain many thousands of microwave modules as building blocks for AESA (***Active Electronically Steered Arrays)***
- Power dissipations of ground-based systems are typically higher than airborne systems because of physical size, but dissipation flux levels are comparable

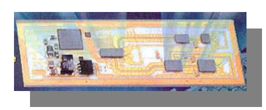


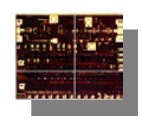
Active Array



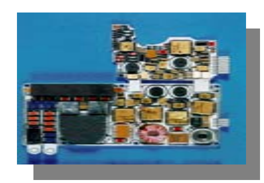
Subarray (Slat)

Modules





MMICs



Power Converter

Critical Thermal Management Issues
Related to Cold Plate Design

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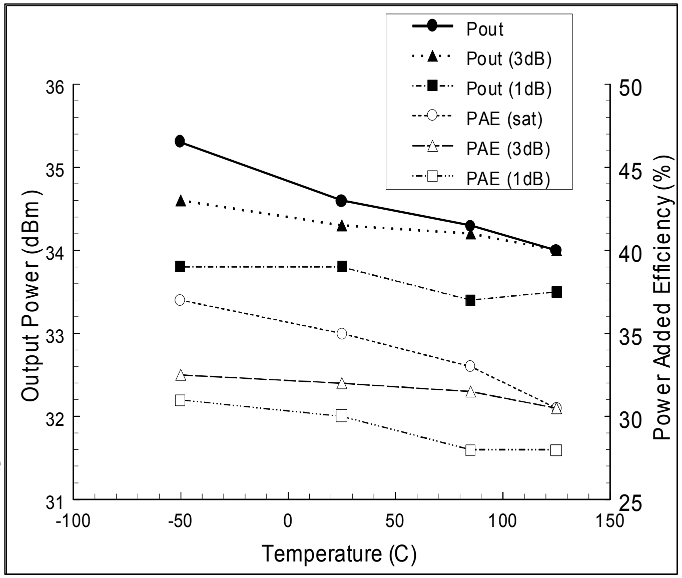
- Temperature Issues
  - Absolute temperature
    - Reliability
    - Electrical performance
    - Failure temperature limit
  - Temperature gradients
    - RF phase shift is temperature depende
    - Higher operating frequencies are more demanding
    - Gradients need to be constant over operating frequency range from a calibration standpoint



Operating Frequency of Phased-Array (GHz)	Maximum Allowable Temperature Difference Across Array (^{o}C)
5	20
10	10
20	5
40	2.5
80	1.3

Reliability Issue
Requires Use of Channel Temperature

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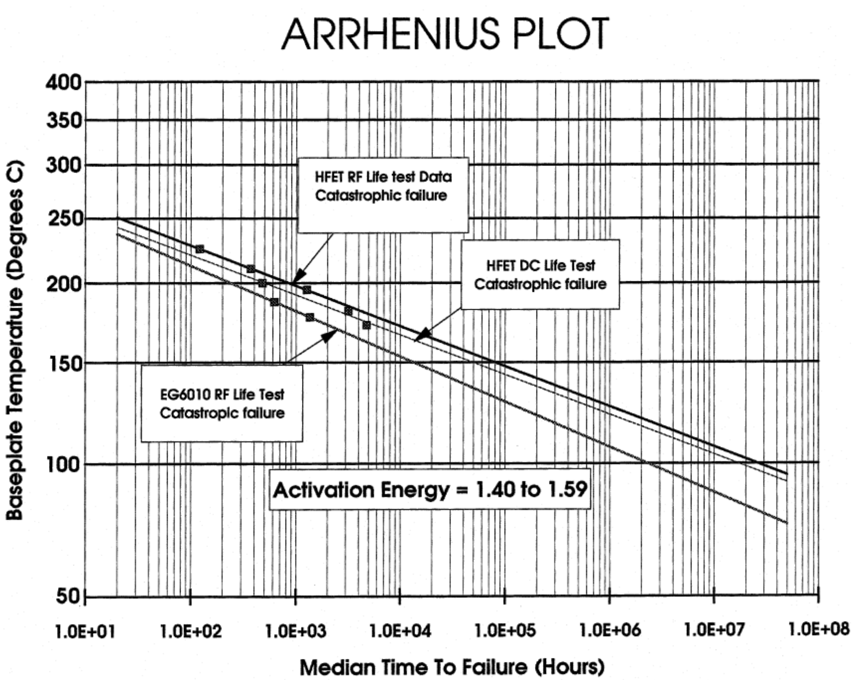

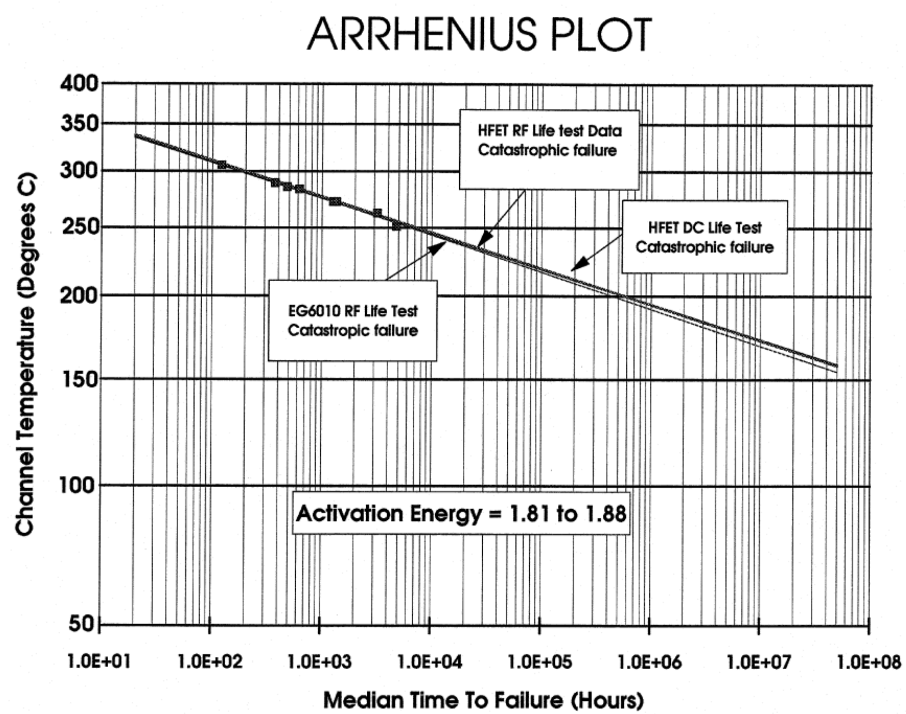

Same data plotted considering either base or channel temperature

Role of Materials
System Level

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- System usually employs cold plate structures which become the heat sink for the dissipating electronics
- Cold plate cooling methods
  - Forced fluid
  - Phase change material (both cyclical and expendable)
  - Heat pipes and capillary pump loops
- Thermal conductivity enhancements for cold plates in use
  - High conductivity graphite (TPG) for lateral conduction
  - Convection enhancement with compact finstock and aluminum foams
  - Phase change material conductivity enhancement with high thermal conductivity graphite foam (satellite and missile applications)

Role of Materials
System Level (continued)

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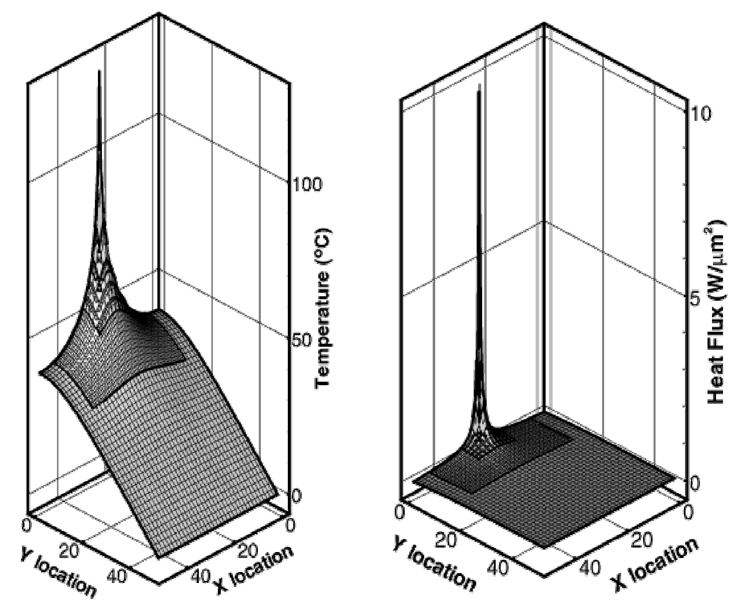
- Wide environmental operating range requires that coefficient of thermal expansion (CTE) differences be addressed
  - RF electronic package materials are set and not likely to change
  - Constrain the cold plates
    - Aluminum Silicon Carbide cold plates provide good match
  - Compliant bonds
    - Thermal concerns (this is often the weak link in the thermal design)
    - Good for repairability concerns
- Material compatibility (from the standpoint of galvanic corrosion) must also be considered
  - Long shelf life required
  - Usually solved by metal plating

Power Dissipation and Heat Flux Issues

	Typical Dissipation (Watts)	Typical Heat Flux (W/cm2)
FET	1 to 15	Order of 1E7 at junction
MMIC Several FETs	1 to 20	100 - 2000 (at base MMIC)
Module (several MMICs)	1 to 50	1 to 5
Coldplate (several modules)	10 to 2000	0.5 to 3
System (several coldplates)	100 to many kW	Order of 1



Concentrated heat flux at device junction

Outline
TR Module and MMIC Thermal Issues

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- TR Module and MMICs
  - Description
    - Materials
  - Analysis
    - Specialized techniques
    - Examples
  - Verification
    - IR imaging

Illustration of TR Modules

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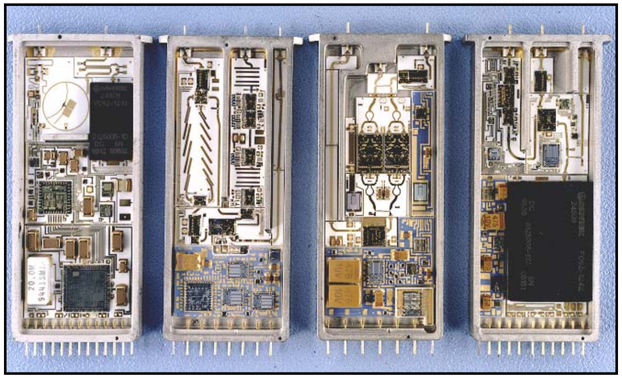
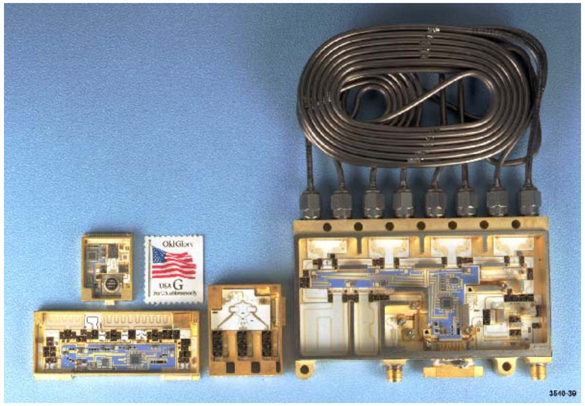
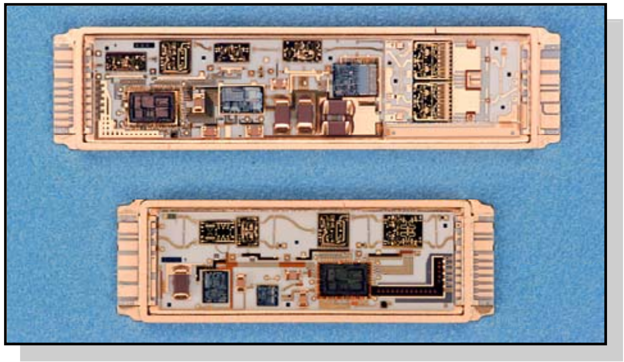
- TR modules are the basic building blocks of phased- array antennas
- Typically a single T/R channel

Towed Decoy



Space





Airborne Radar

Packaging of TR Modules

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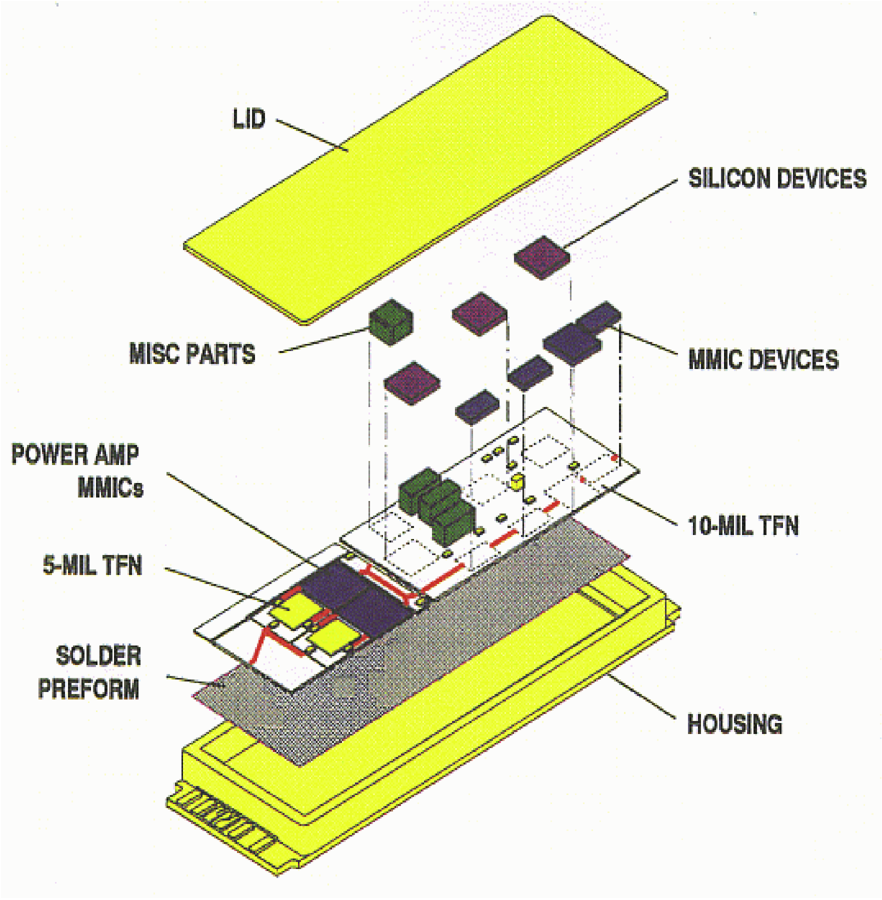
- Typically require hermetic sealing
  - Welded and brazed connections
- Built-in layers
  - Thermal interfaces are important for power devices
  - Require CTE matched materials



Role of Materials
Package Level

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- Dielectric substrates
  - Al_2O_3, BeO, AlN, thick film, some circuit board
- Heat spreaders for MMICs/Module base
  - Copper Moly, Copper Tungsten, Diamond, Molybdenum, Kovar, Titanium
- Die attach
  - Solders (AuSn, SnPb, Indium)
  - Silver-filled epoxy
  - Z-axis material and solders for flip chip
- Module attach
  - Compliant adhesives, filled epoxies, metal-metal
  - Ball grid array

Module/MMIC Thermal Analysis
Requirements for Numerical Solution

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- Numerically difficult
  - Large scale range
  - Non-linear material properties (GaAs, GaN, SiC, BeO)
  - Fully three-dimensional
  - Pulsed operation (transient analysis required)
- Often a majority of the total temperature rise from the junction to sink is in the module and MMIC
  - Thermal design of module/MMIC most important from an ambient-to-junction temperature rise perspective

Transition From System To Device

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Antenna Level

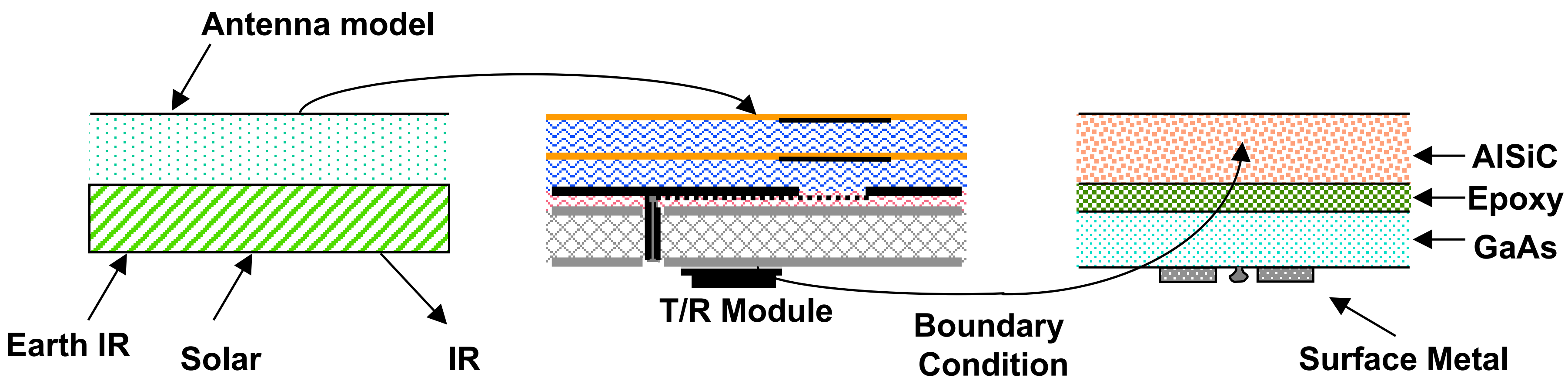
- Orbit environment or system level analysis
- Provide boundary condition for module model
- Time scale in minutes

Module Level

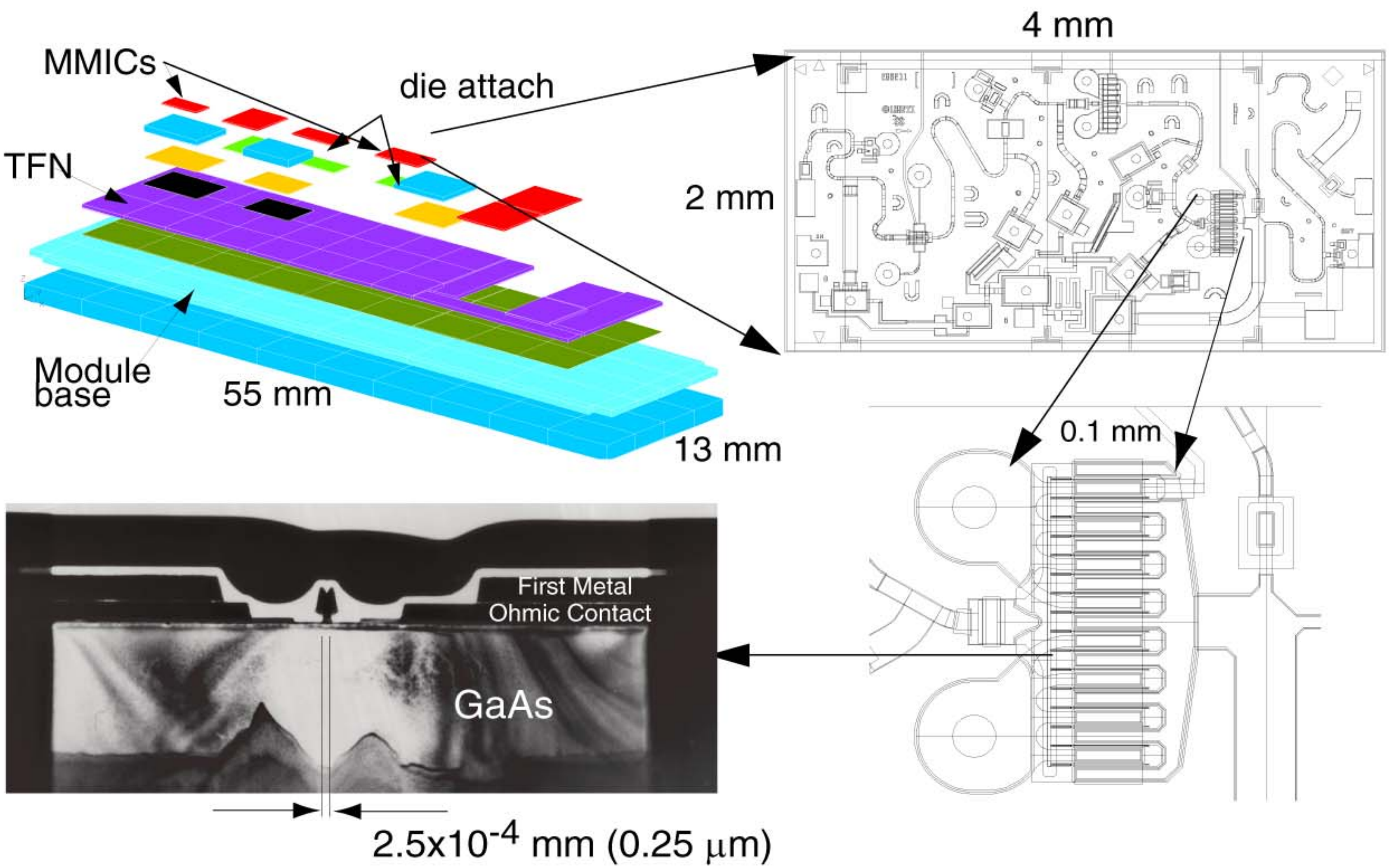
- Boundary condition from antenna model
- Predict module base temperature for operating conditions
- Time scale in seconds

MMIC Level

- Boundary condition from module model
- Junction temperature prediction
- Time scale in microseconds



Scale Variation
MMICs and Microwave Modules



5 to 7 orders of magnitude variation in both space and time scales

Power Amplifiers
Often Critical Component

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- RF Power Amplifiers
  - GaAs dissipation on the order of 1 W/mm
  - GaN currently at 5 W/mm, soon to be near 9 W/mm with process improvements
  - GaAs heat flux on the order of 1000 W/cm^2 at base of amplifier (several thousand for GaN/SiC)
  - Often operated in a pulsed mode
    - Duty-cycle (time-average) power will usually apply below MMIC base (assuming pulse width less than 1 msec)

Self Adaptive Thermal Modeling

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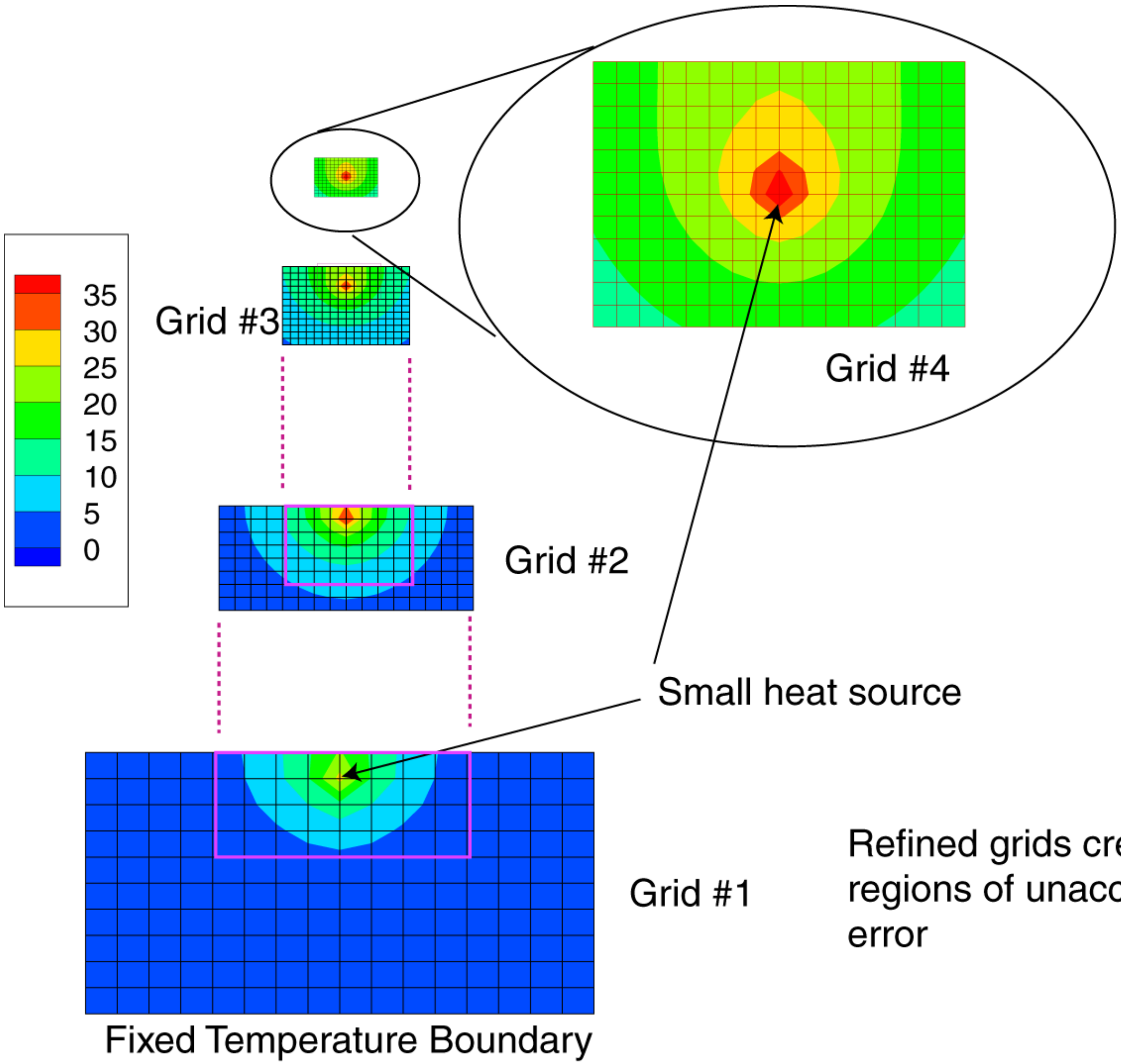
- Large scale range(s) require specialized approach for solving FET/MMIC time dependent thermal problems
  - Finite Difference Approximations
  - Uniform Grid Spacing
  - Control Volume Formulation
    - Effective thermal properties smeared across multiple materials
    - Arbitrary alignment between grid and physical geometry
  - Successive Refinement in space and time
    - Like graphics information transfer on internet

Steady-State Nesting



Refined grids created in regions of unacceptable error

Transient Nesting

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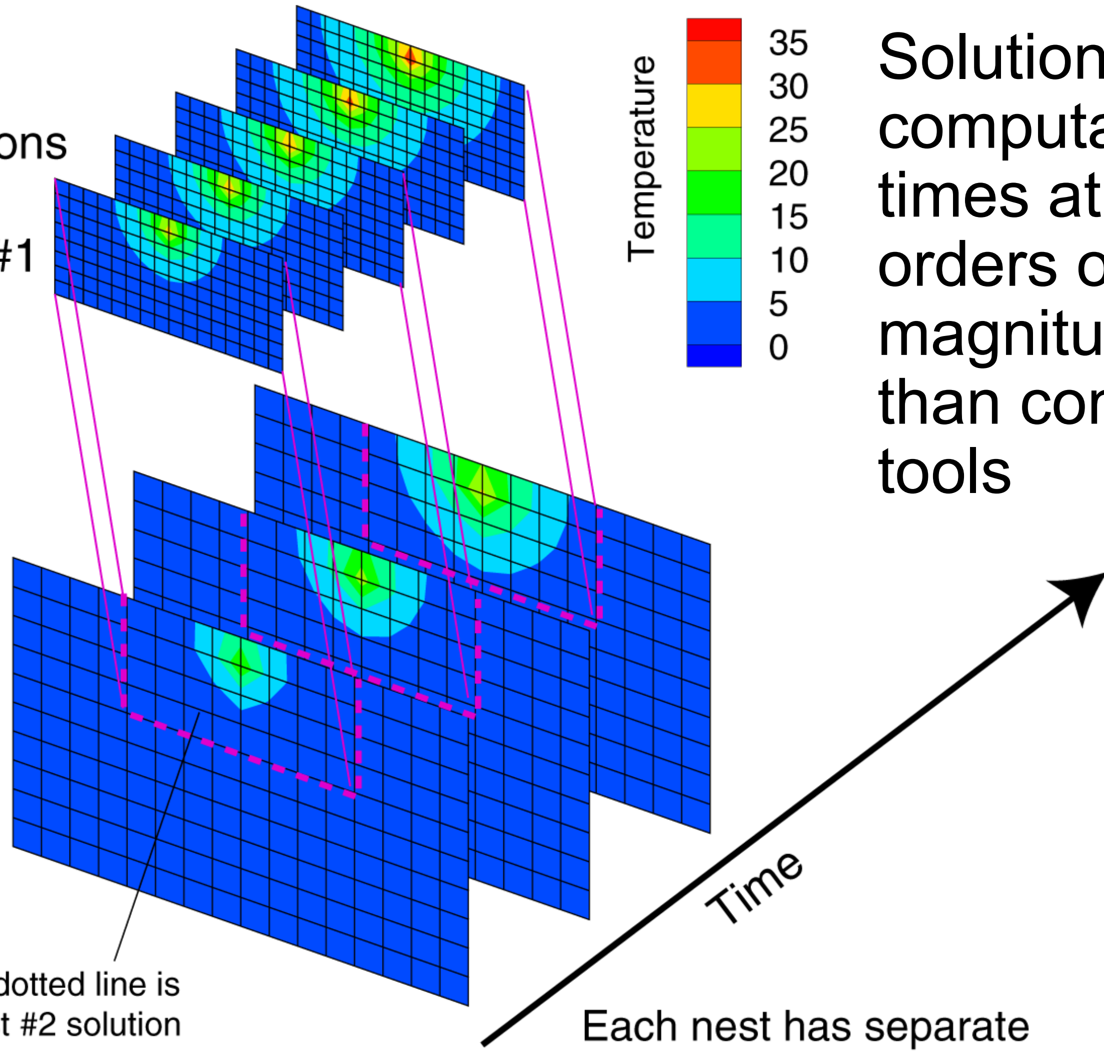
Nest #2

Boundary conditions on the edges come from Nest #1



Solution computational times at least two orders of magnitude faster than commercial tools

Nest #1

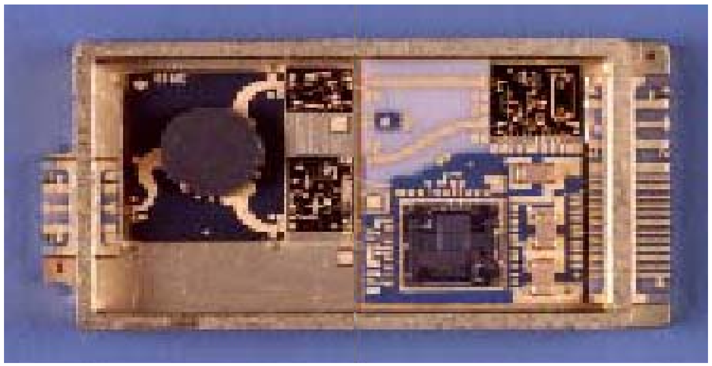
Solution inside the dotted line is replaced by the nest #2 solution

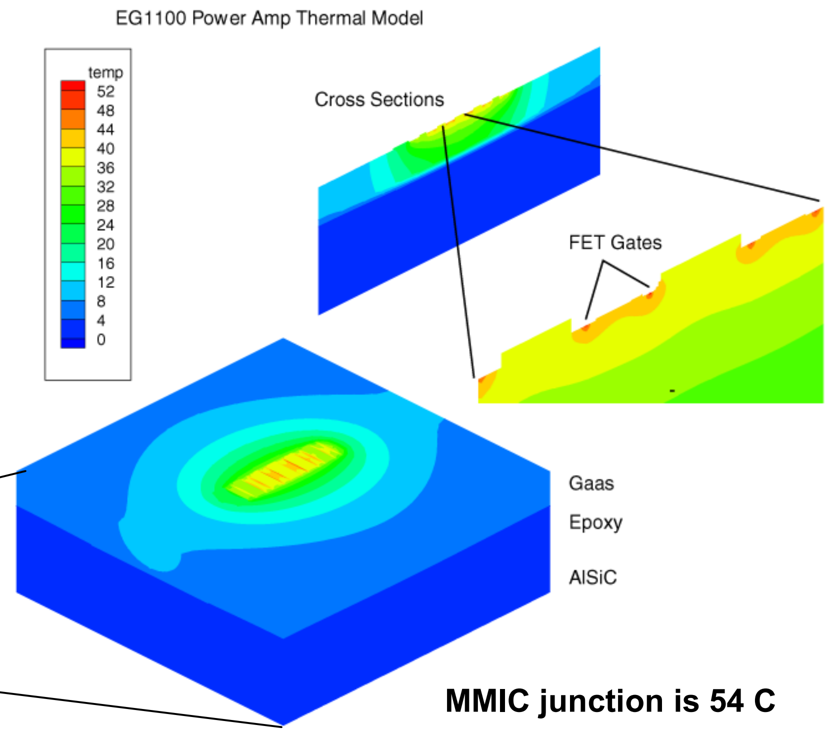
Each nest has separate spatial and temporal resolution

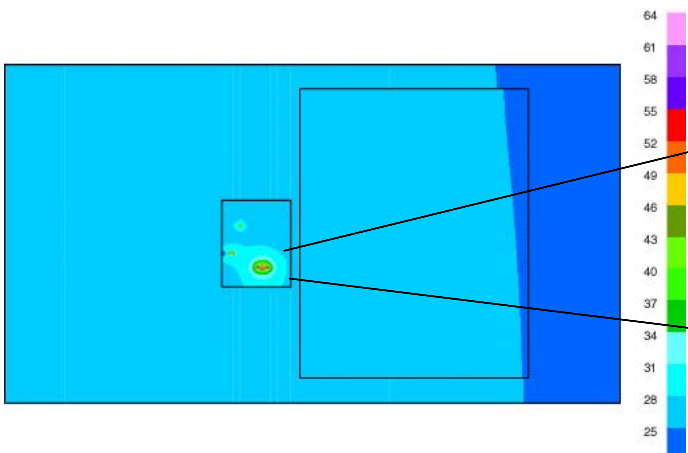
Example TR Module/MMIC Model Results

Significant portion of the rise in the GaAs

Future module packaging techniques (flip chip, BGA) still are on the order of 60 C rise







TR module thermal model

MMIC junction is 54 C above the module mounting surface (module rise is 4C)

50 C rise from AlSiC pedestal to junction (with CW power dissipation)

Thermal Model of GaN FET
1/4 Section Adaptive Mesh

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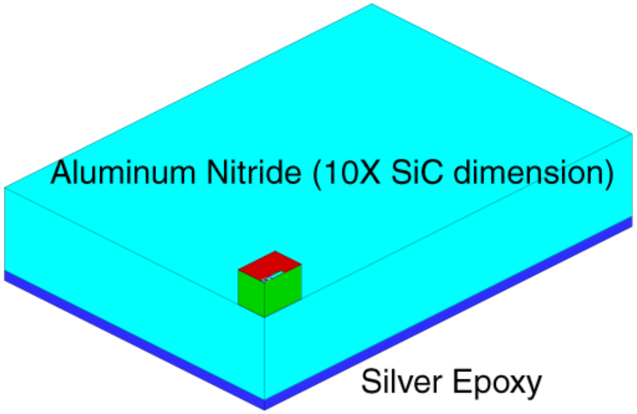
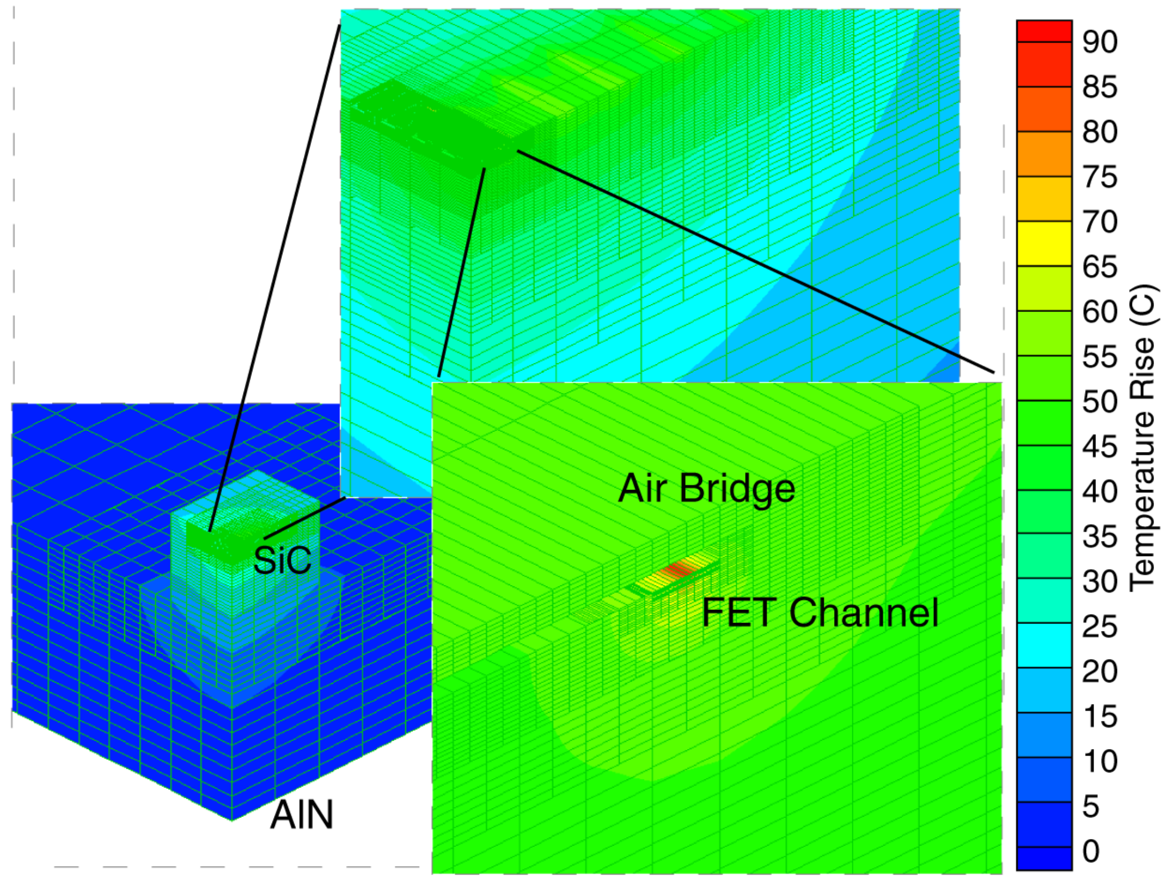


- **thermosonic die attach (5 um Au)**
- **4.5 W/mm dissipation**
- **50 um gate-gate**
- **10 fingers @125 um length**



Package Materials /Trades
Diamond Heat Spreader

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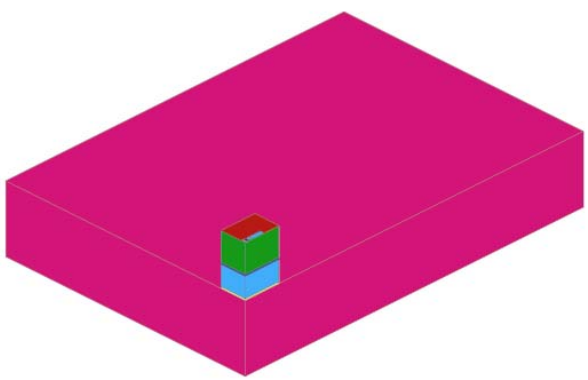
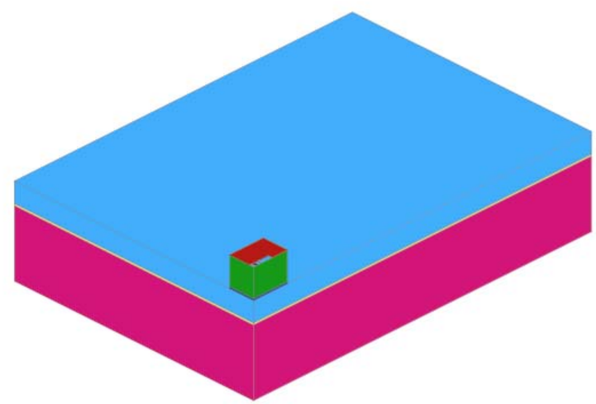
Evaluations at 4.5 W/mm dissipation

	SiC Thk (microns)	Diamond area	Temperature Rise (C)	Comparison case to one AuSn layer and same SiC thickness - no diamond
Thick Discrete	425	same as SiC	91.4	89.3
Thin Discrete	125	same as SiC	84.3	85.0
Thick MMIC	425	same as AlN	80.0	89.3
Thin MMIC	125	same as AlN	72.9	85.0



Diamond heat spreader same size as SiC



Diamond heat spreader same size as AlN

Benefit with diamond for MMICs but not for discrete FETs

GaN FET Channel Spacing Trade

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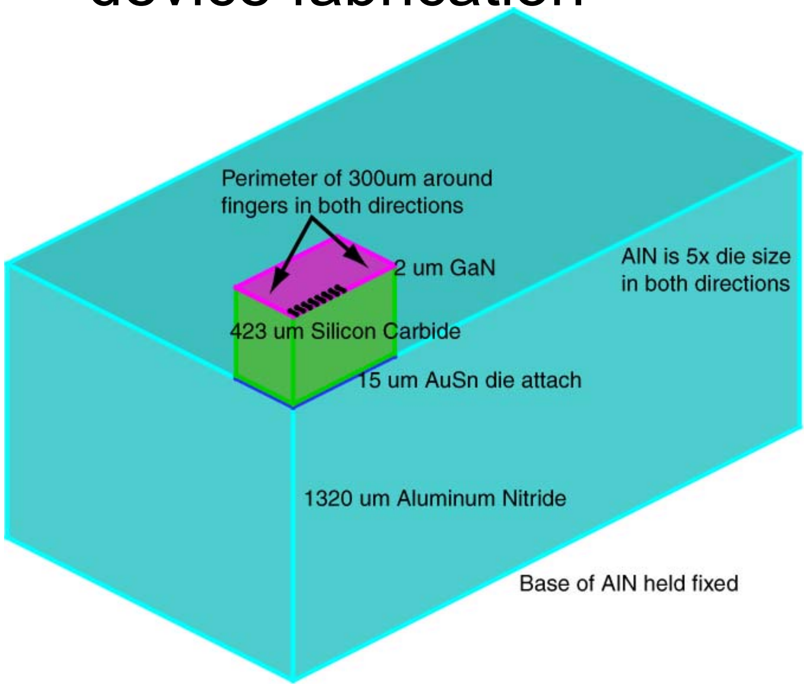
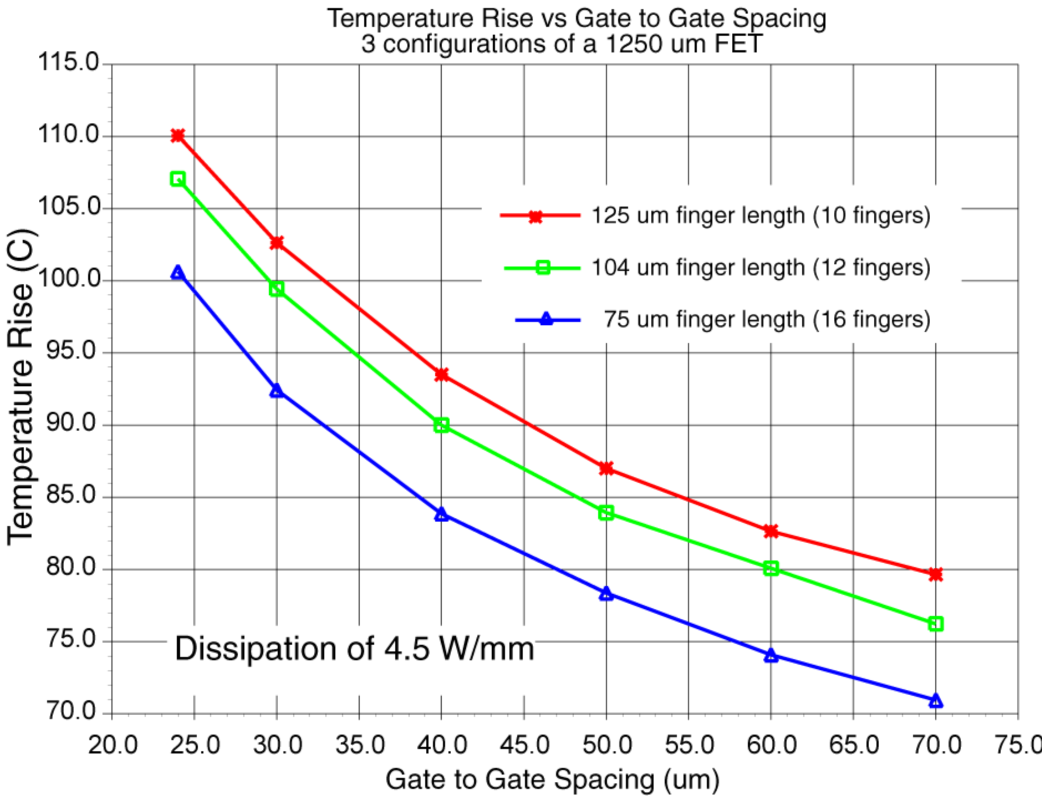
Rapid thermal analysis capability allows design trades prior to device fabrication





Transient Analysis at Pads

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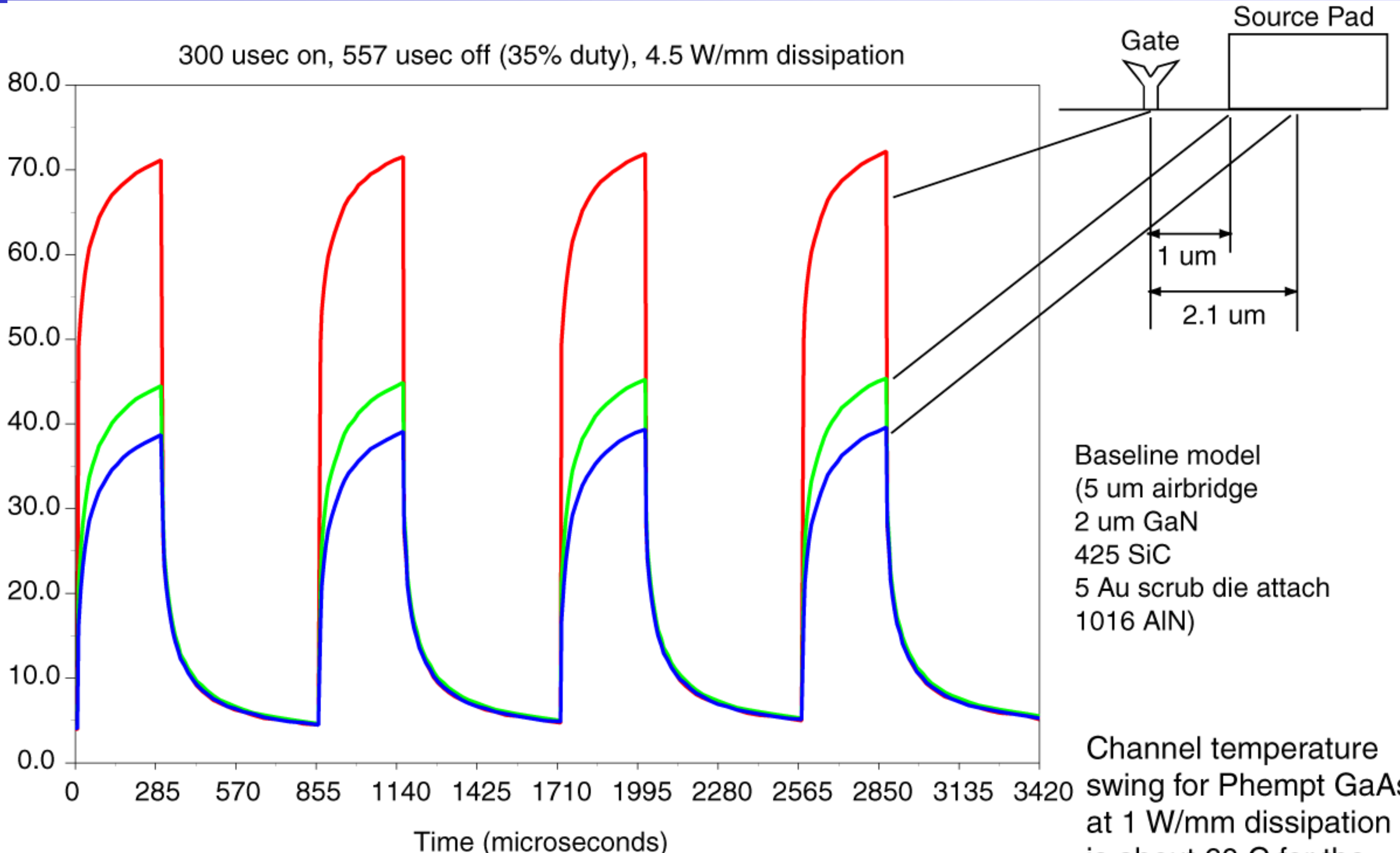

Baseline model
(5 um airbridge
2 um GaN
425 SiC
5 Au scrub die attach
1016 AlN)

Channel temperature swing for Phempt GaAs at 1 W/mm dissipation is about 60 C for the same pulse width and duty but temperature swings at pads are less

Transient Analysis

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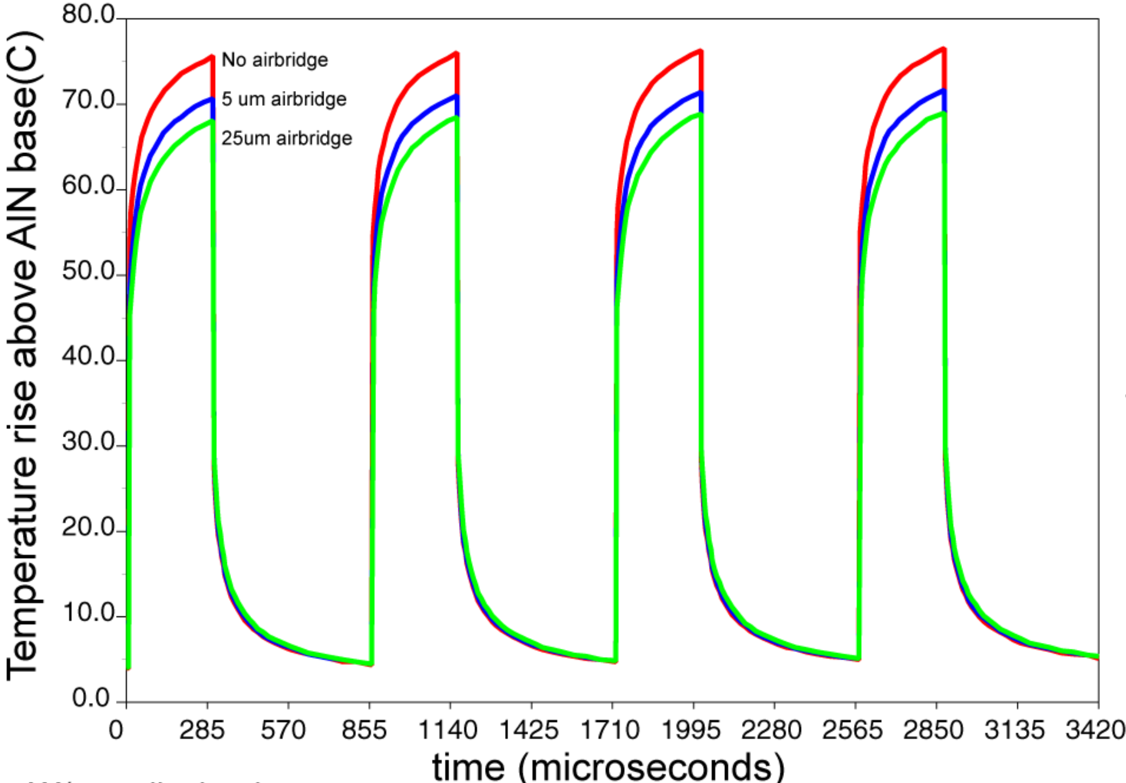

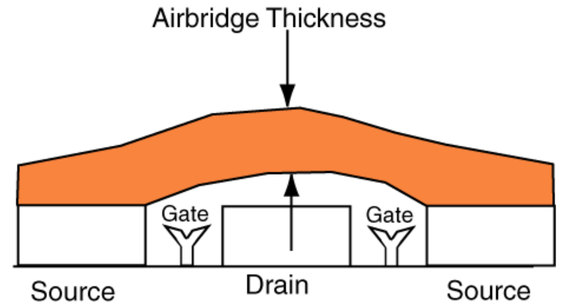

4.5 W/mm dissipation
base of AlN held fixed
SIC conductivity = 272 W/m-K
10 finger FET, 50 um g-g

On for 300 usec, off for 557 usec

2 um GaN
423 um SiC
5 um Au
1016 AlN

Model Verification with IR

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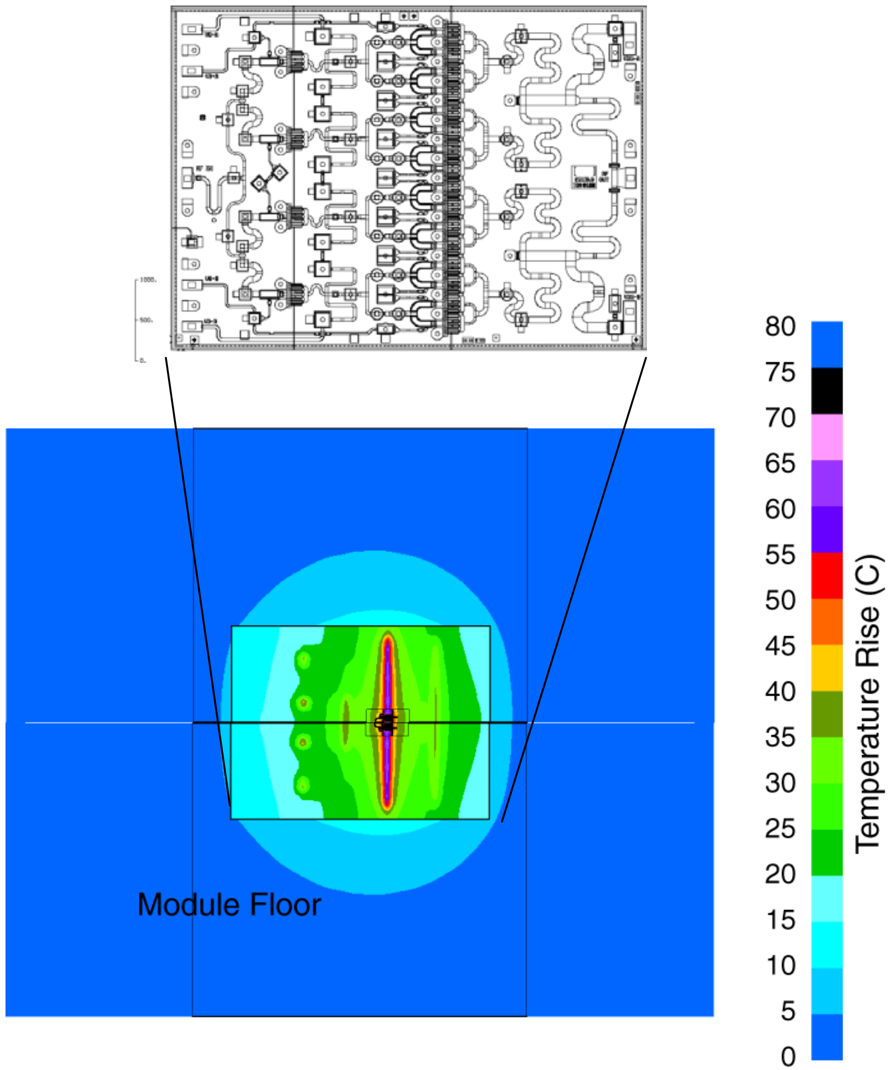
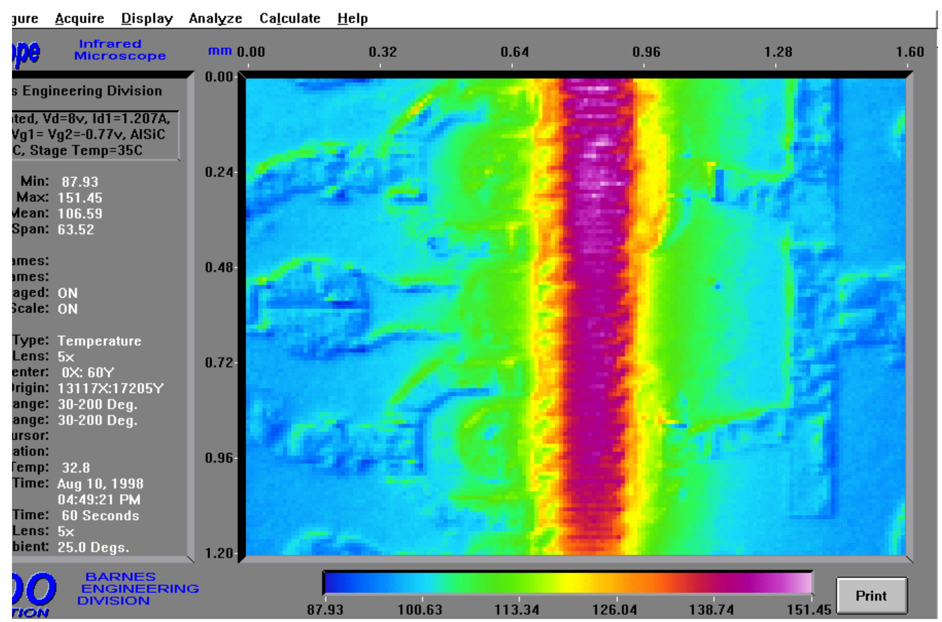


IR at 10 μm resolution

Test: 106 C rise

Model: 102 C rise



Thermal Interface for Die Attach

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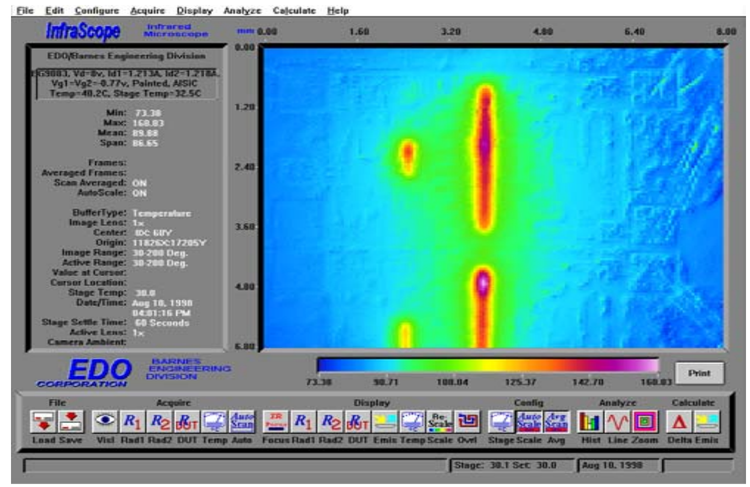
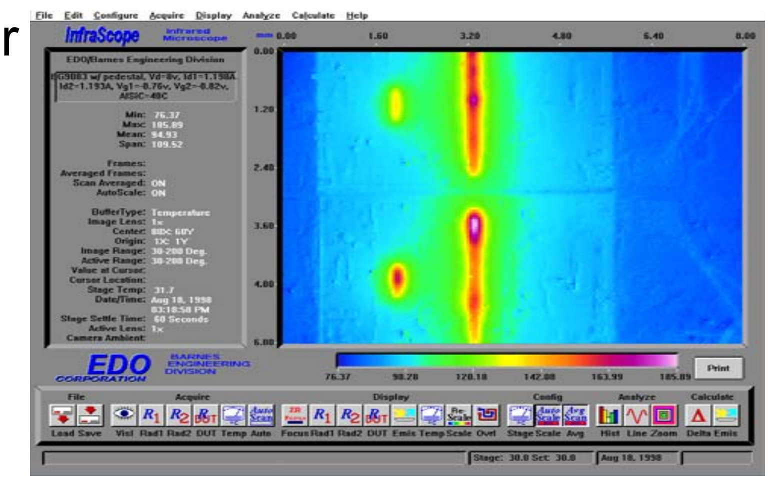
Repair and rework concerns favor the use of silver-filled epoxy to attach power amplifiers to module floors - (power amplifier is soldered to a heat spreader which is then attached with epoxy)

Direct Attach



Comparison of direct attach and spreader mounted power amps. Same DC power for both cases, IR images indicate about a 15 - 20 C junction temperature increase for the pedestal mounted part

Heat spreader (10 mil CM15 plus 1 mil epoxy)



Conclusions

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- Material interface issues very important
  - Module and die attach (heat flux high)
  - Compliant attach may be required because of CTE concerns
- Thermal analysis needs to be integrated into the power amplifier design process
- Material properties for “thin film” materials at device level are not well known (surface metalization)