ModSim Challenges in Co-Design of Embedded Cooling Solutions

A. Bar-Cohen, DARPA-MTO
K. Matin, SPC

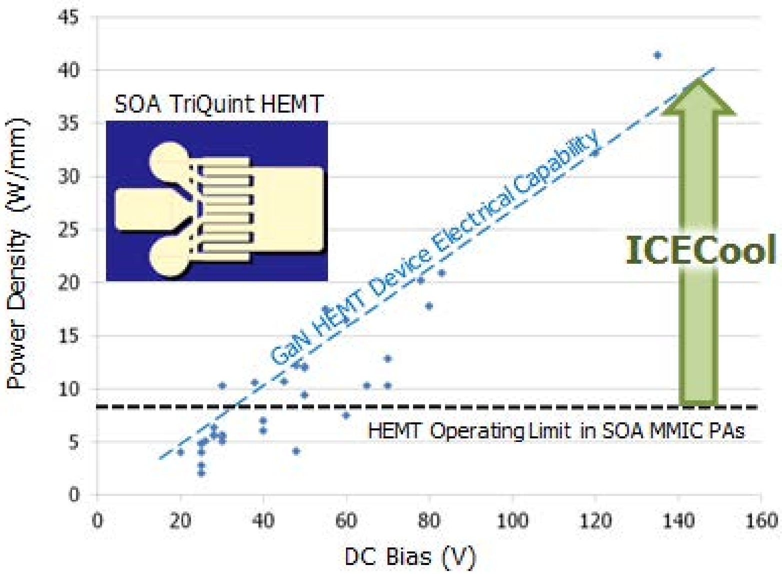
ModSim 2015 Workshop
Seattle, Wa
8/12/15 – 8/14/15

Presentation Roadmap

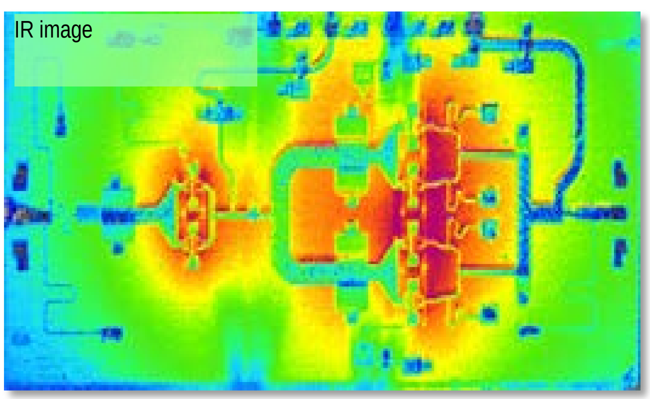
- Why Embedded Cooling?
- DARPA's ICECool Program
- Modeling and Co-Design Challenges in Embedded Cooling

Defense Electronics are Thermally Limited

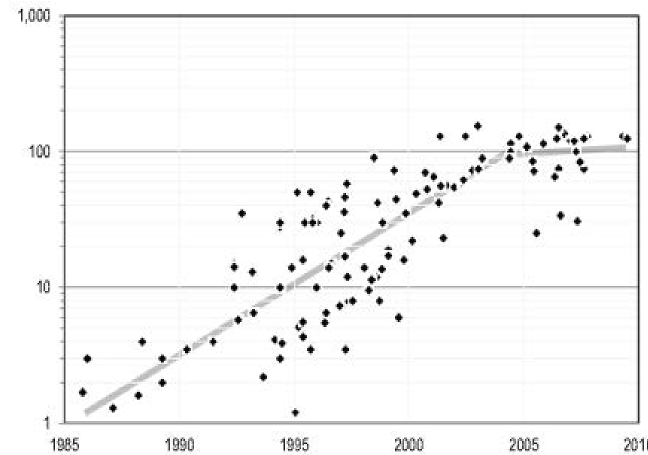
GaN Power Amplifiers



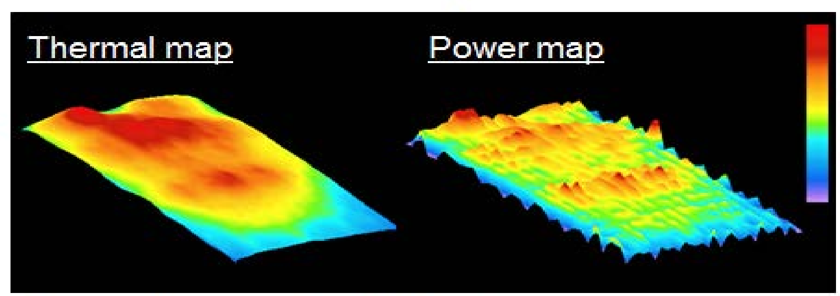
Infrared image of GaN PA MMIC



Silicon Microprocessors



The Thermal HotSpot Problem



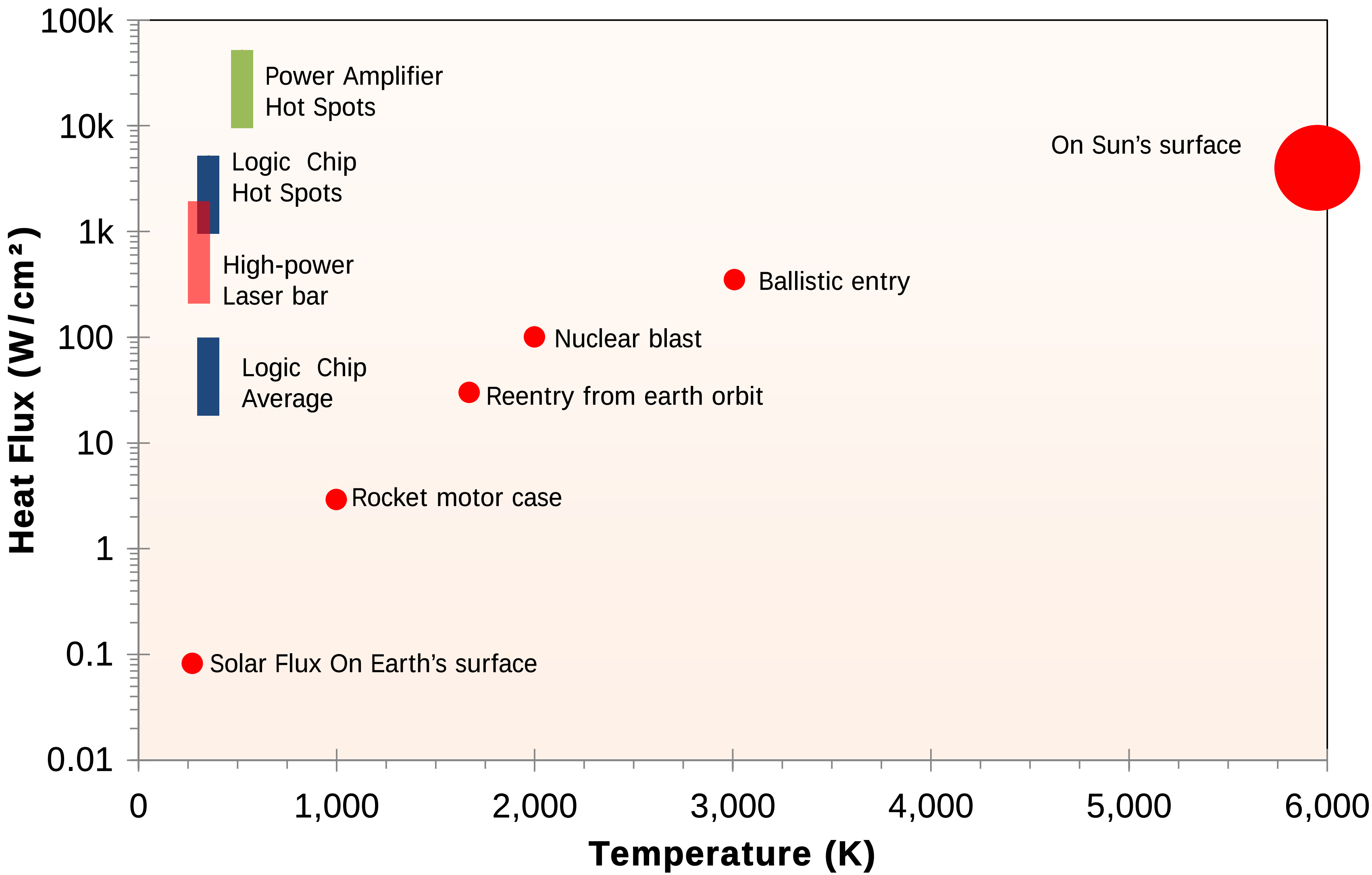
-50 different workloads for POWER5 imaged & analyzed
- •HotGen microbenchmark generator tool

- observed significant differences in circuit utilization

(H. Hamann et al., ISSCC-2006)

 14

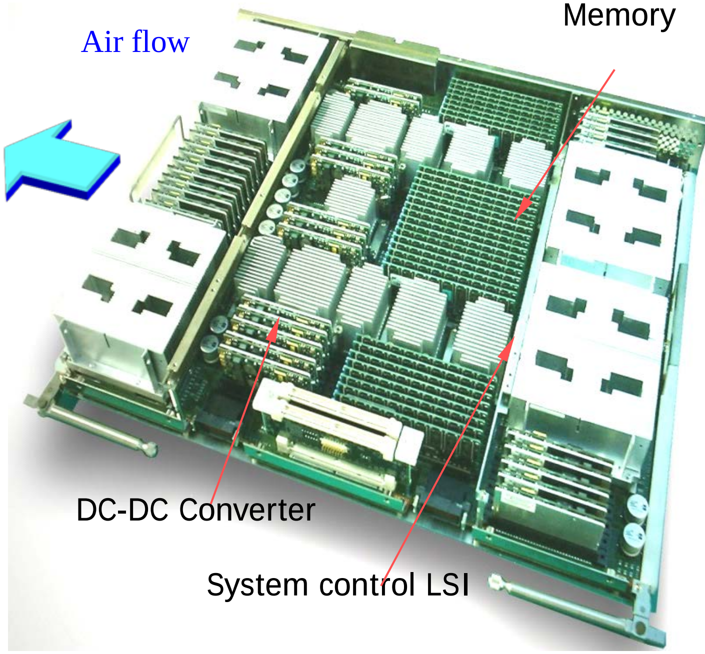
Heat Flux Thermal Challenge

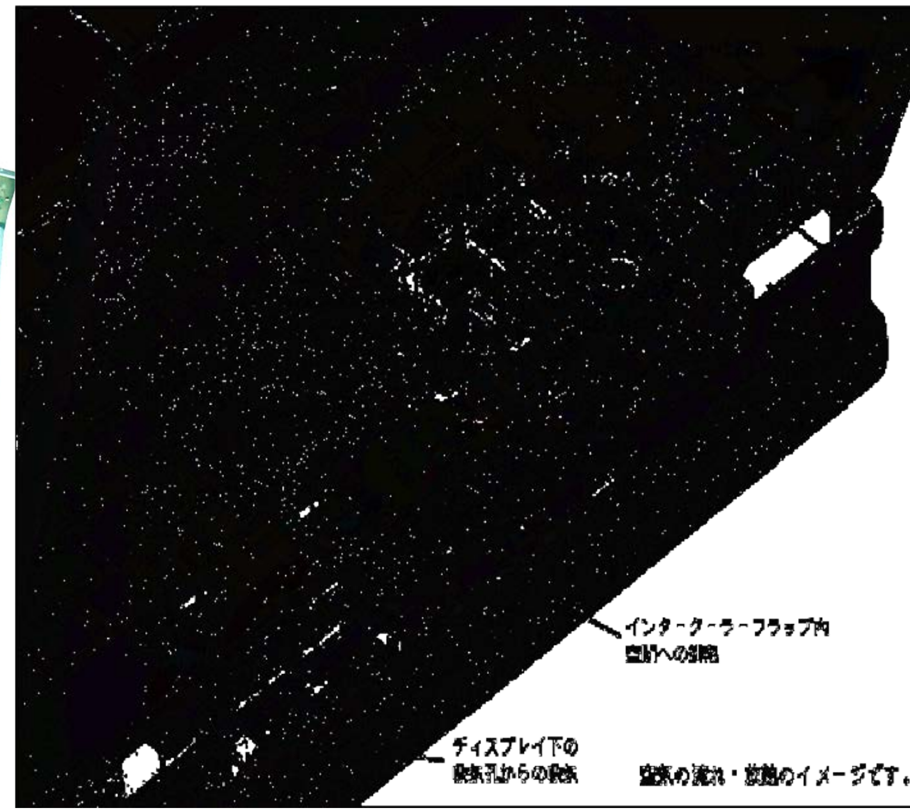


Air Cooling Servers - Notebooks

System-board

8CPU
470x580x80
1600W
Airflow～3.5 m/s

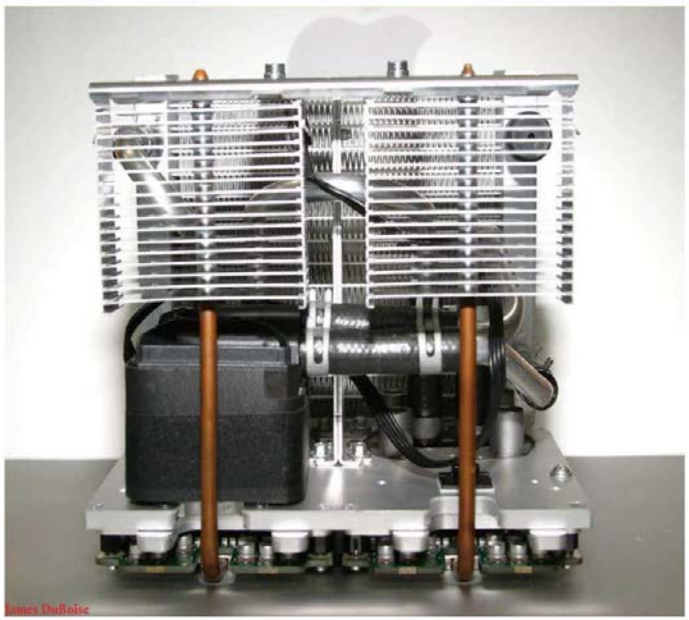




Sony PCGXG9 Intercooler

Water Cooled PC/MCM

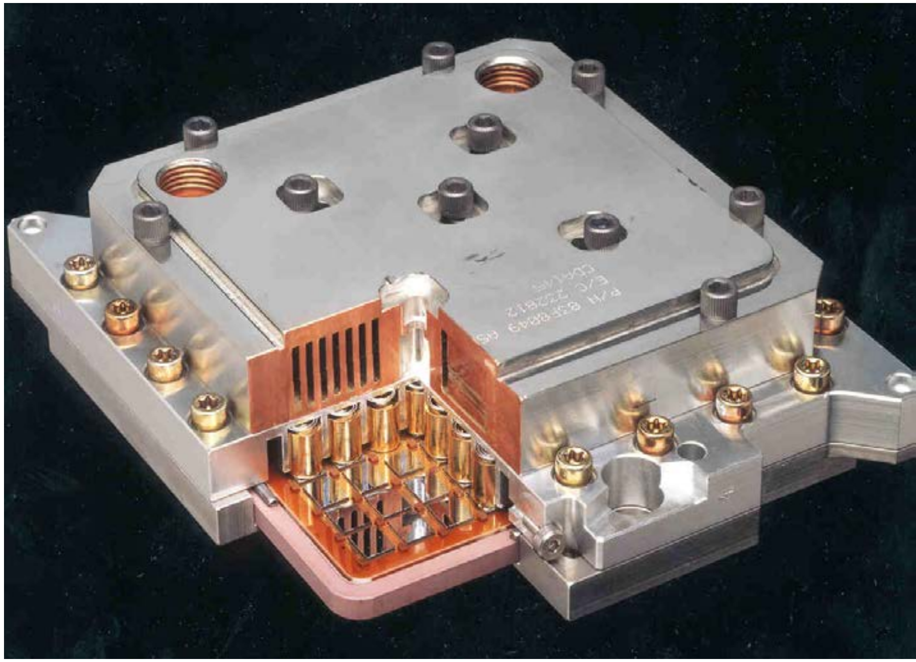
Apple G5 Liquid Cooling Hardware



Ref: http://homepage.mac.com/thunderaudio/PhotoAlbum1.html

6

AAVID THERMALLOY



IBM Thermal Conduction Module
Circa ‘03

Limitations of Remote Cooling

Remote cooling paradigm: Heat rejection to a remote fluid involving thermal conduction and spreading in substrates across multiple material interfaces with associated thermal parasitics

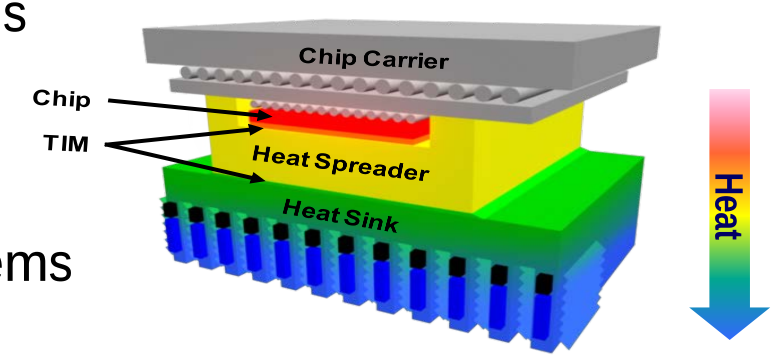
Limitations

Thermal Performance:

- Incapable of effectively limiting the "hot spot" temperature rise
- Can not extract heat efficiently from high heat density, 3D package

SWaP Goals:

- Accounts for a large fraction of SWaP-C of advanced high power electronics, lasers, and computer systems
- Frustrates attempts to reach SWaP-C targets for electronic systems
- Stymies attempts to port advanced systems to small form-factor applications



Promise of Embedded Cooling

Embedded cooling paradigm: Use of high conductivity substrates, thermoelectrics, and convective/evaporative microfluidics for on-site removal of kW-level heat fluxes and heat densities.

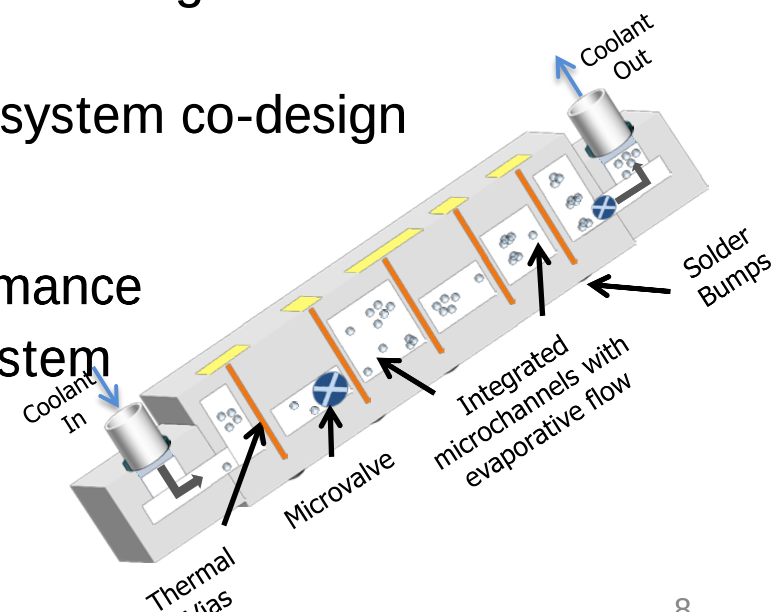
Promise

Performance:

- Allow electronic systems to reach material, electrical, optical limits
- Improve functional efficiency and reliability
- Place thermal management on an equal footing with functional design and power delivery
- Lead the way to integrated, intelligent system co-design

SWAP-C:

- Reduce SWaP-C for comparable performance
- Improve overall energy efficiency of system



Virtual Prototyping of Embedded Cooling

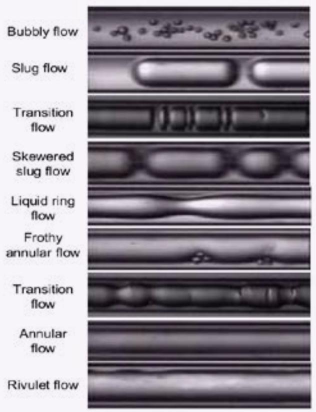
- Virtual Prototyping enabled by *“multi-physics”* co-simulation
- DoD Investment in Virtual Prototyping - “Innovation Engine”
  - **HPCMP** - High Performance Computer Modernization Program
  - **CREATE** – Computational Research and Engineering Acquisition Tools and Environments
- Extend to Thermal-Mechanical-Electrical interactions
- Apply sequentially to:
  - Virtual Proof of Concept
  - Detailed design
  - Functional and performance optimization
  - Physics of Failure and Reliability of components/system
  - Cost of usage and maintenance
  - Health Maintenance and End-of-Life

DARPA Embedded Cooling Technologies & Challenges

Integrated Microfluidics & Thermal Substrates/Interconnects

Evaporative Microfluidic Cooling

Evaporative Microchannel Flow



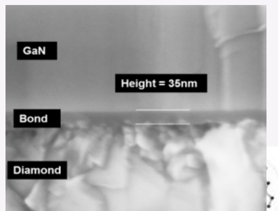
Serizawa and Feng (2001)

Challenges:

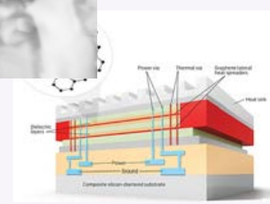
- > 90% vapor in exiting flow
- $\Delta T < 5\ ^0C$ across chip
- CoP > 30 (Coefficient of Performance)
- Pressure drop < 10% P_{sat}

CoP is defined as the ratio of heat removed to the power required to deliver the cooling.

Thermal Substrates, Vias and Integrated TECs



Epitaxial Transfer



Integrated high k vias

Balandin (1999)

Thin-film Thermoelectrics

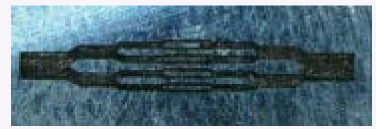
Source: Nextreme

Challenges:

- Highly conductive thermal vias
  - k > 1000 W/mK
  - n > 1000 temp cycles
- TECs for hot spot cooling
  - $\Delta T < 5\ ^0C$ rise
  - CoP > 2.5
  - n > 1000 temp cycles

Microchannels and Microvalves

SiC Microchannels



Carter et al(2009)

MEMS Valves

Source: Texas Tech

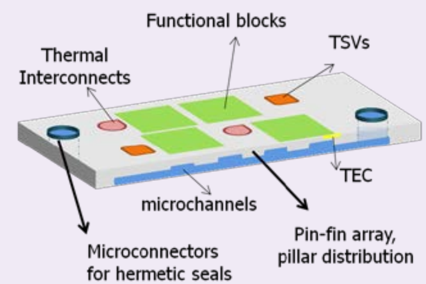
Challenges:

- Walls, channels in SiC and diamond
  - < 50 micron thick
  - >10:1 aspect ratio
- Microvalves:
  - 10% to 90% control of maximum flow
  - n > 1000 temp cycles

Thermal Co-Design

Design of ICECool Active Chips

ICECool Design Schematic



Challenges:

- Evaluate impact of ICECool techniques on device performance
- Optimize placement and efficiency of thermal and electronic/RF features
- Achieve 10x in MMIC and microprocessor performance

Hierarchy of Thermal-Electrical Co-Design

I. Passive "Thermally-Informed" Design

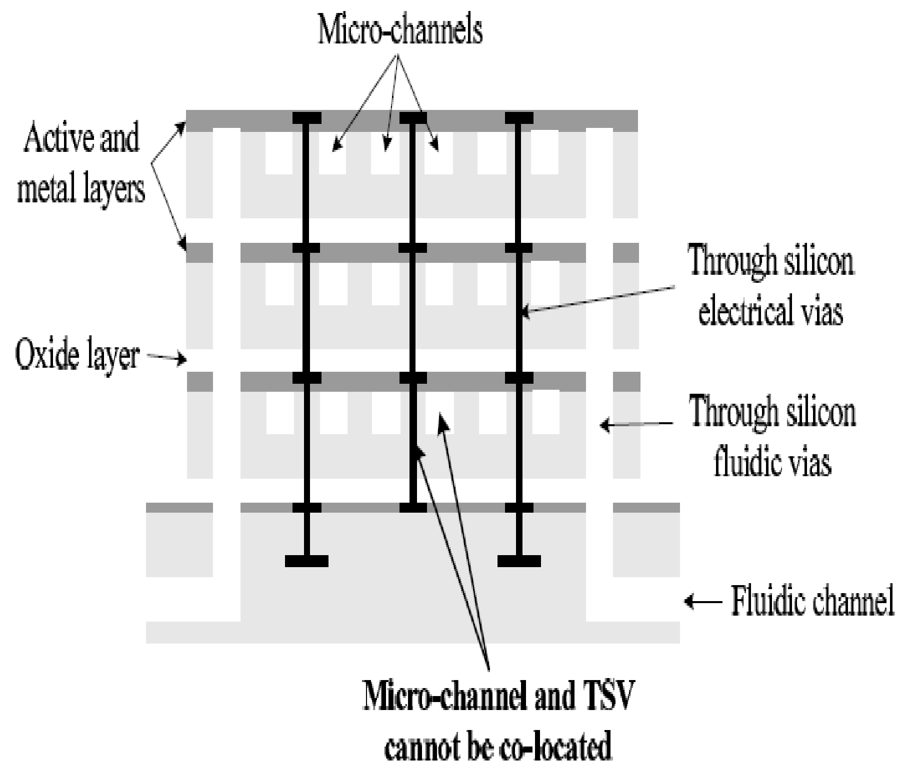
- Uniformly distribute functional tasks
- Avoid creating hot spots

II. Active Thermal Co-Design

- Functional blocks/paths and thermal elements placed in most favorable locations
- Functional blocks remapped to accommodate temperature effects

III. Fully-Integrated Thermal Co-Design

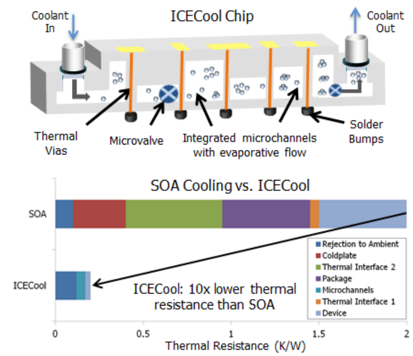
- Create passive/active thermal interconnect network
- optimize layout for energy consumption and functional performance



Source: B. Shi, A. Srivastava and A. Bar-Cohen, "Hybrid 3D-IC Cooling System Using Micro-Fluidic Cooling and Thermal TSVs ", To Appear ISVLSI, Aug 2012

Intrachip Enhanced Cooling (ICECool)

ICECool utilizes intrachip microfluidic and conductive cooling to provide up to a 10x gain in performance for digital and RF electronics



ICECool Applications (Apps)

Goals

- Near-term insertion of microfluidics
- 3x performance in GaN PA and HPC Modules

Program Challenges

- Functioning Electrical Demonstration Vehicles
- Drop-In Compatible with DoD Systems
- Hot spot flux (MMIC) >25kW/cm^2
- Reliability design and demonstrations
- Electronic-Thermal –Mechanical Co-Design

ICECool Fundamentals (Fun)

Goals

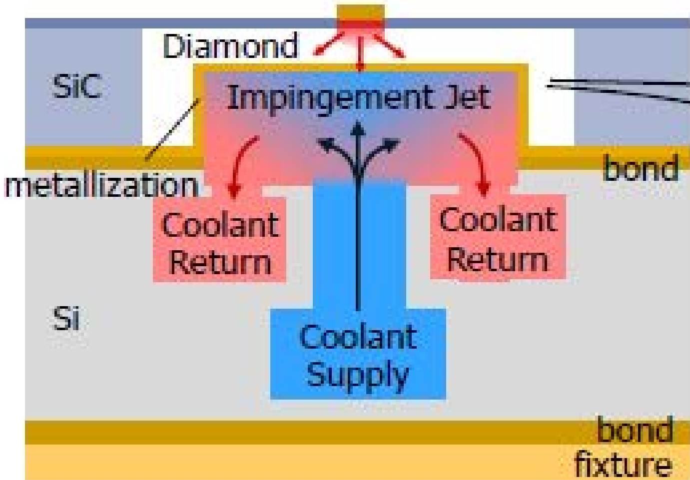
- Evaporative thermofluid building blocks
- 10x thermal performance

Program Challenges

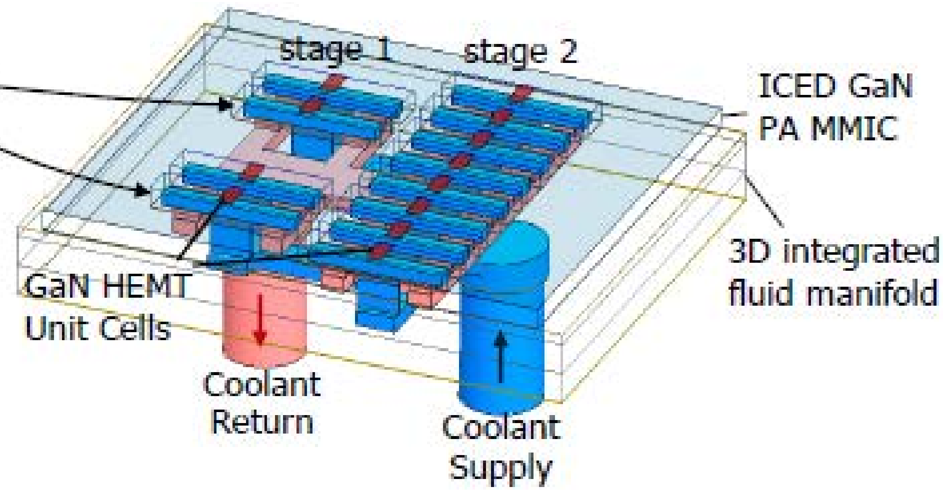
- Efficient Cooling, >90% vapor content
- Chip Heat Flux > 1kW/cm^2
- Hot Spot Heat Flux > 5kW/cm^2
- Validated Thermofluid Models
- Microchanneling SiC and Diamond

NGAS: Impingement Cooled Embedded Diamond (ICED)

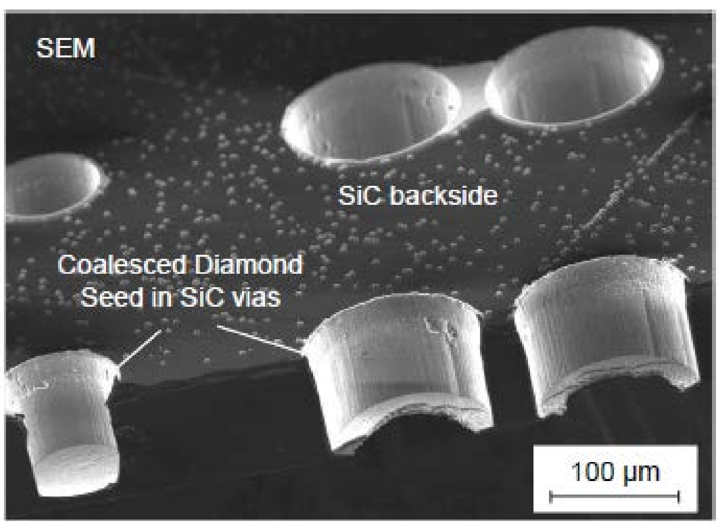
GaN HEMT on ICED Micro-Channel

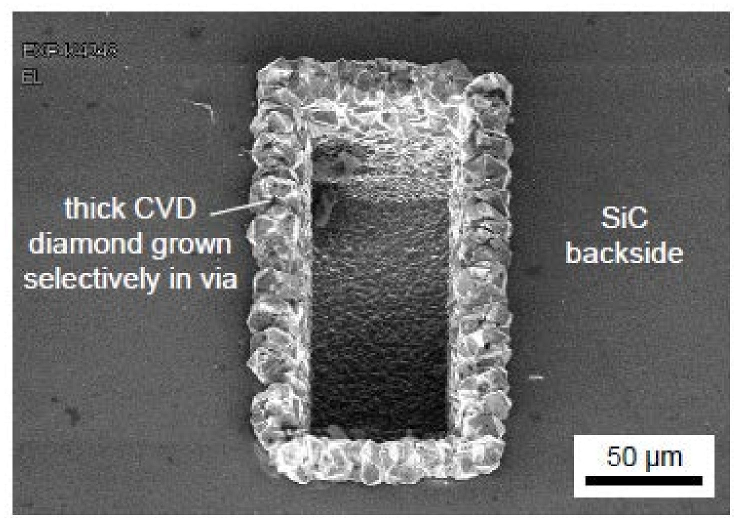


ICED 3D Integrated Fluid Manifold



Demonstration of Selective Diamond Growth – Done in Partnership with NRL and ADI



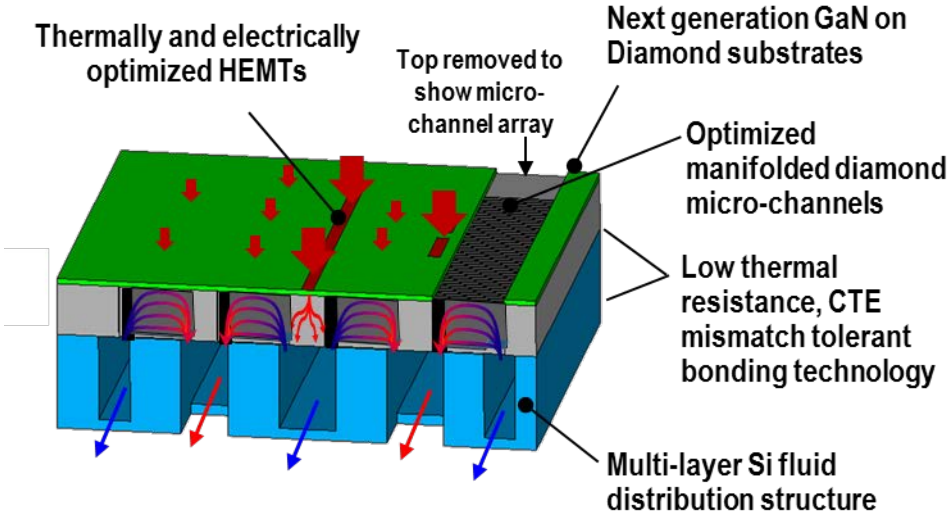


Slide Adapted from Gambin et al, iTHERM 2014

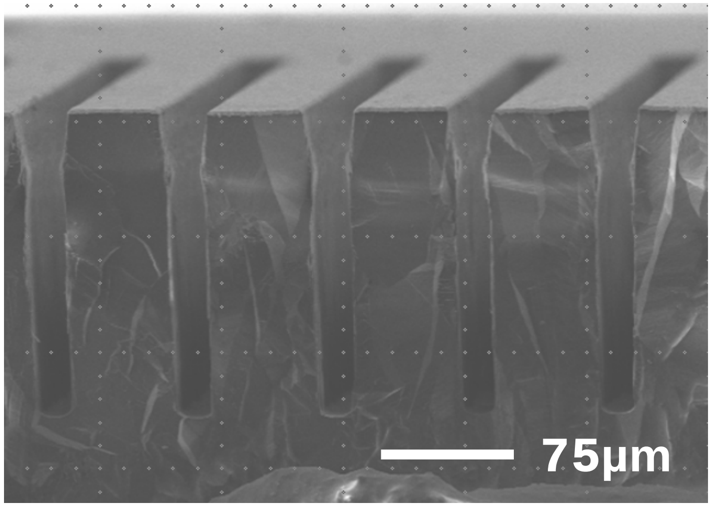
Raytheon: Integrated Circuit Enhancement through Microfluidic MMIC Intrachip Cooling (ICE MMIC)

- ICE MMIC focuses on an intra-chip cooling structure for GaN on Diamond substrate
- Diamond substrate has integral microfluidic channels fed by a Si fluid distribution manifold

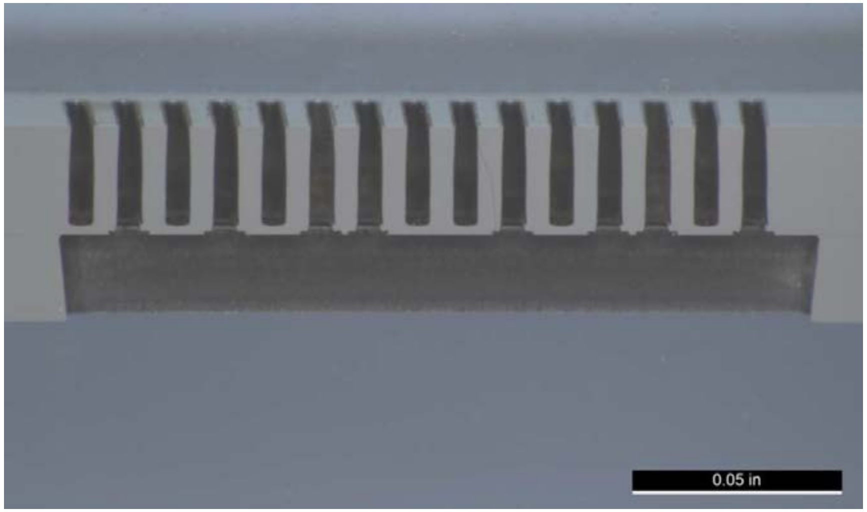
Images from Altman, Gupta, Tyhach InterPACK 2015



Micro-Channels Fabricated on GaN on Diamond Substrates



Cross-section of DRIE Etched and Oxide Bonded Multi-layer Si Manifold



Thermo-Mech-Fluid Modeling - ICECool

Phenomena

- Heat generation – joule heating, energy conversion
- Thermal diffusion – discrete and planar heat sources
- Convection – heat transfer, pressure drop
- Evaporation – thermodynamics, heat transfer, pressure drop
- Thermal stress – differential expansion/contraction
- Mechanical stress – clamping forces, fluid pressure
- Vibration – wave propagation, modes, resonances
- Particle flow – trajectories, erosion, deposits
- Corrosion/fouling – chemical reactions, deposition/removal

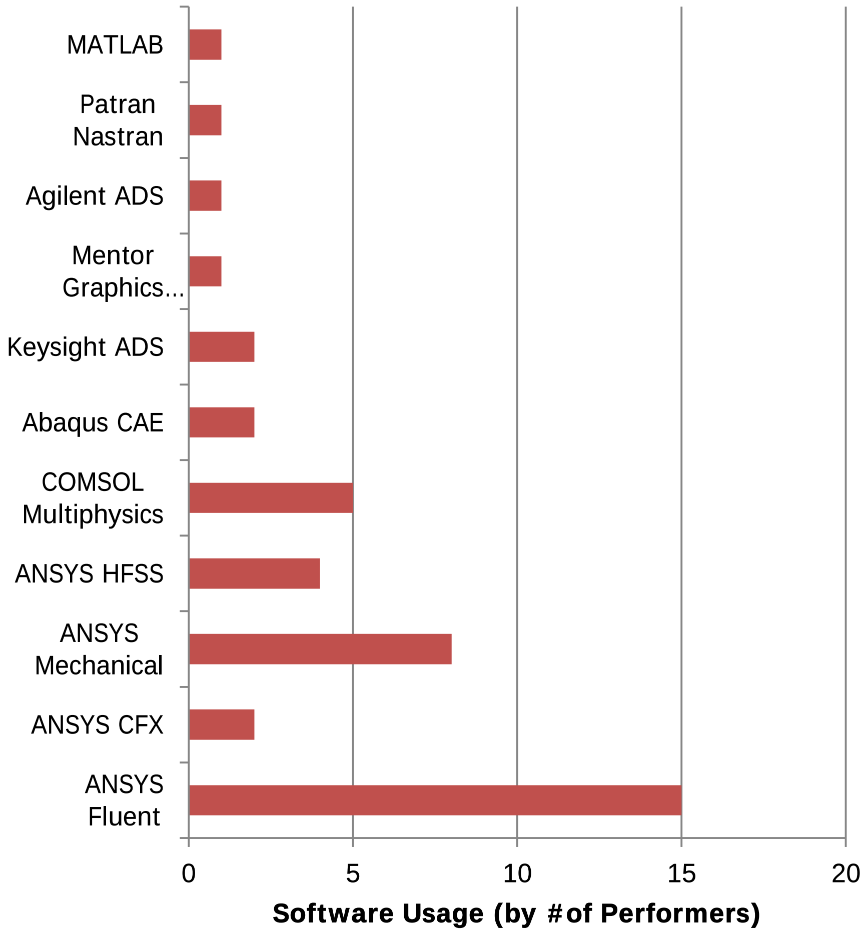
Tools

Analytical (1^{st} Principles) – Empirical Correlations

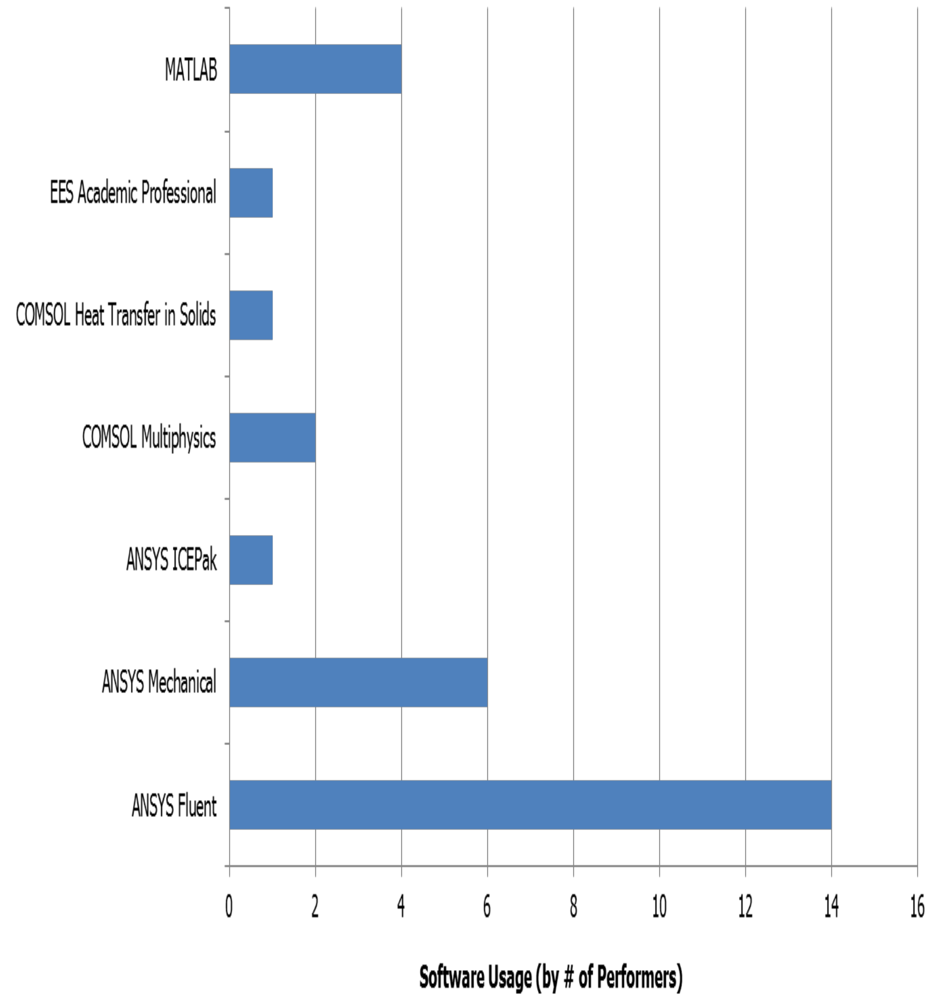
Resistance Networks – Reduced Order (Compact)

Finite Element – Finite Volume – Volume of Fluid

ICECool TMF Modeling Software



ICECool Apps



ICECool Fun

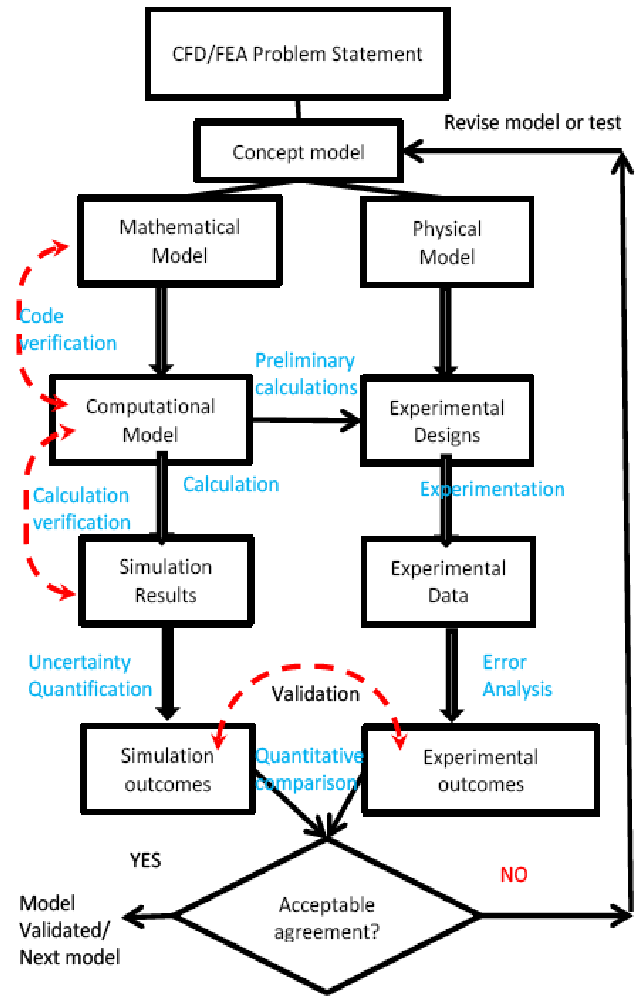
Predictive Failure Models - ICECool

- Modified failure rates/modes in the electrically active areas of the chip, substrate due to temperature, stress, electrical fields
- Modified failure rates/modes in electrically “stressed” conditions
- Failure rates/modes in “thermal solution”
    - Seals, Pumps, valves, sensors, actuators...
    - Erosion, corrosion, fouling in microgaps
    - Bond failures
- Impact of microfabrication and operation on the structural integrity of substrate and chip
- Bonding - chip-to-chip, wafer-to-wafer

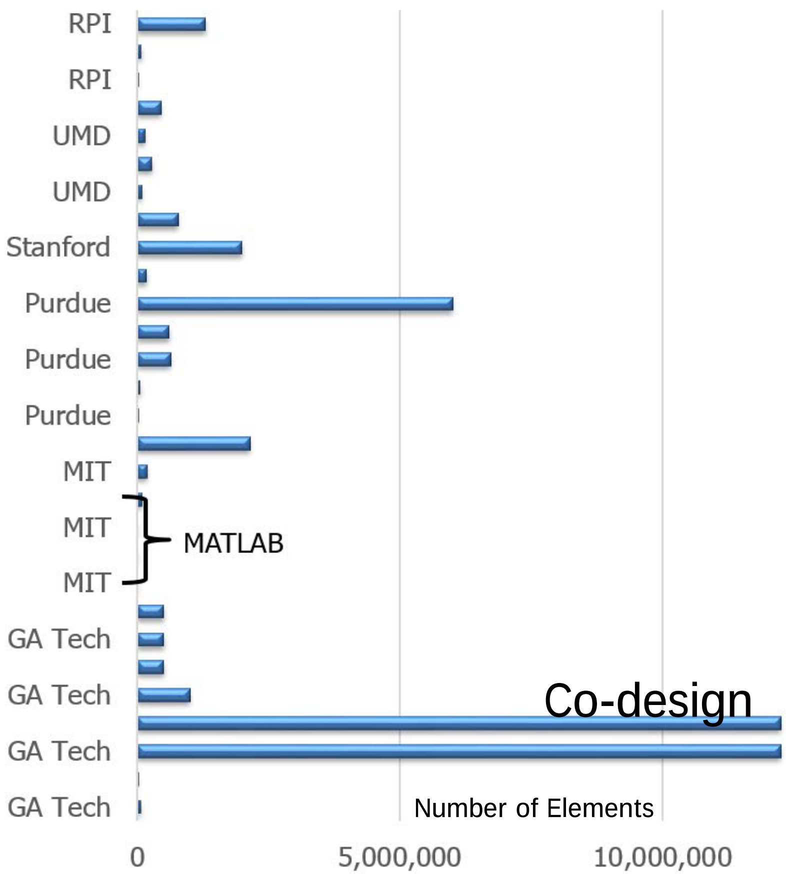
V&V and Uncertainty Quantification

Sources of uncertainty in physical models:

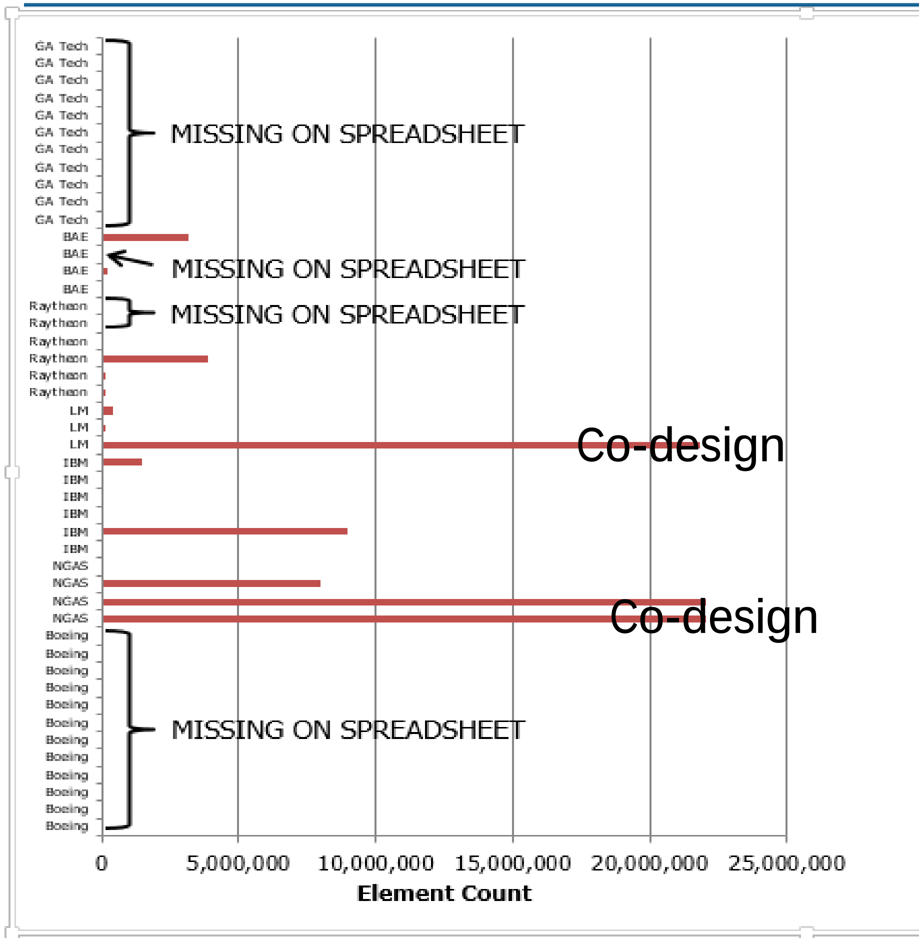
- Phenomenon is not thoroughly understood
- Uncertainty in the values of parameters used in the model
- Uncertainty introduced thru simplified – reduced order - models
- Experimental confirmation of the models is not possible or is incomplete.



ICECool Performers: Element Count



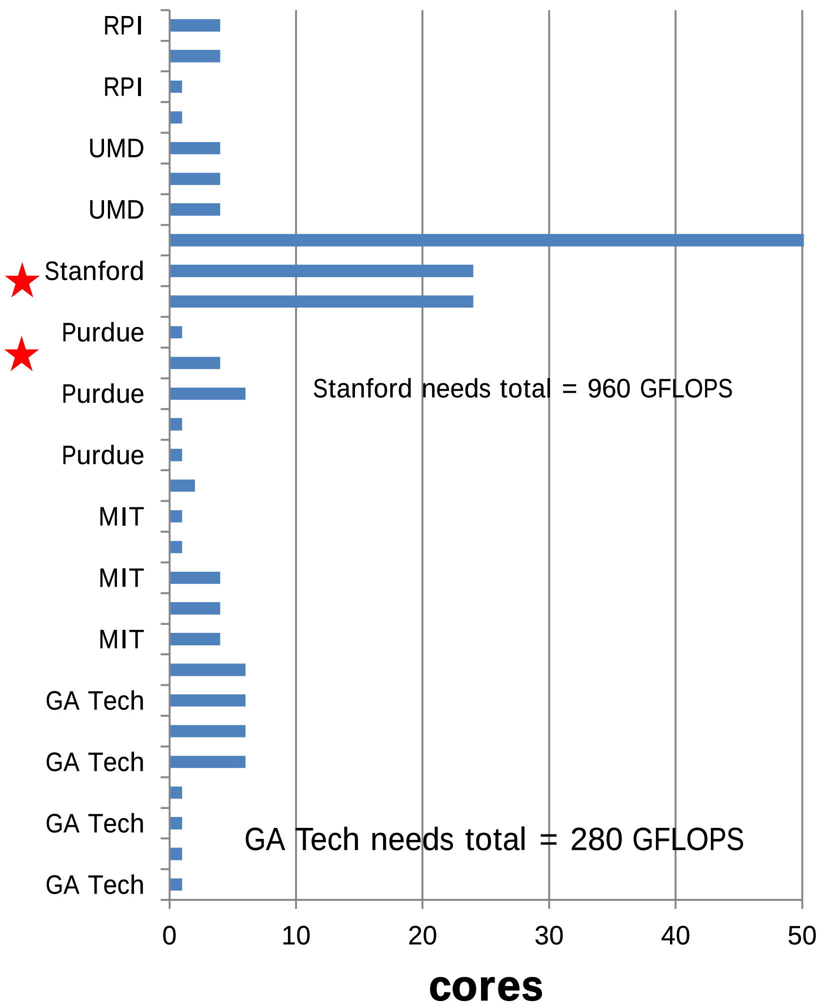
ICECool Fun



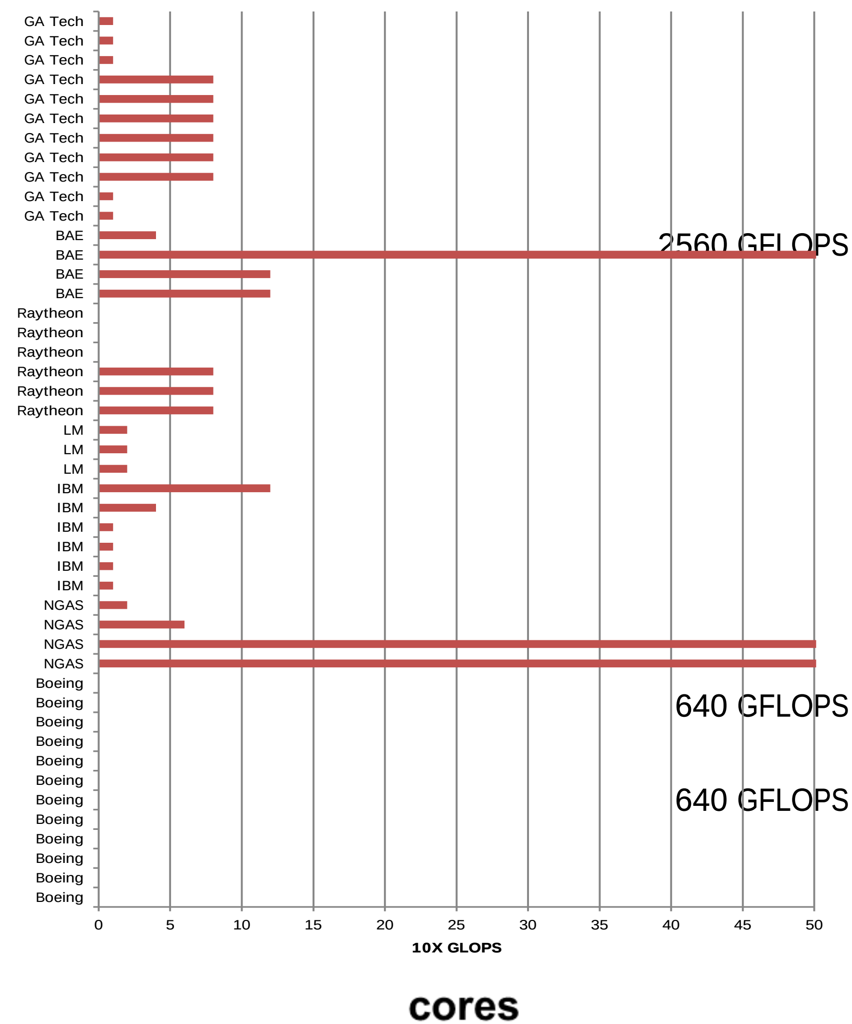
ICECool Apps

1 million elements in CFD typically requires 1 GB of RAM

ICECool Performers: Computing FLOPS



ICECool Fun



ICECool Apps

Solved on cluster ★

1 core (4FLOPS) * 2.5 Ghz Processor = 10 GFLOPS

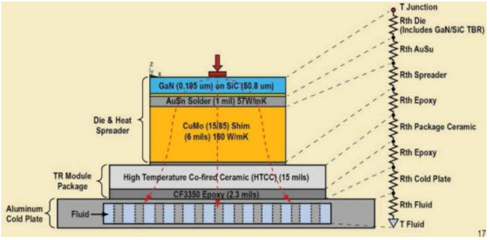
ICECool Applications: Lockheed Martin

Lockheed Martin / Qorvo / RPI

Embedded Microfluidic Cooling of High Heat Flux Electronic Components

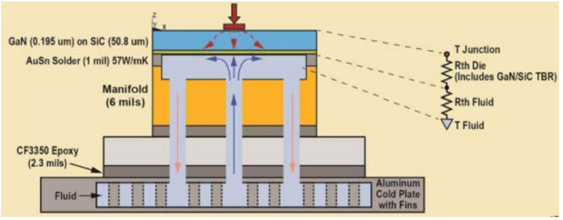
- The Performance of Many Modern Systems is Currently Limited due to the High Thermal Resistance of Conventional, Remote Cooling Techniques.
- LM's ICECool Approach Utilizes Direct Jet Impingement on the Back Side of the Die, Significantly Reducing Thermal Resistance and Improving System Level Performance.

Conventional (Remote) Cooling



Long, high thermal resistance path to cooling fluid

LMCO -- ICECool Embedded Cooling Approach

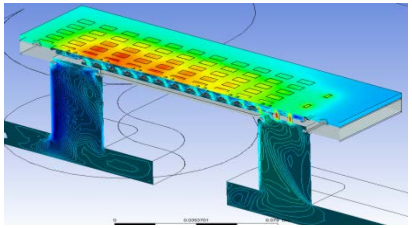


Short, low thermal resistance path to cooling fluid – Very high heat transfer coefficients

Key Accomplishments

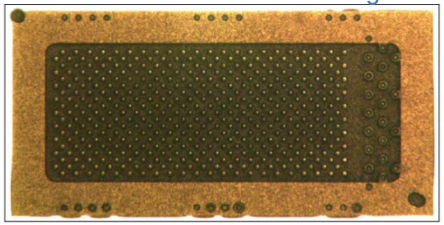
- ✓ Completed Design, Analysis and Fabrication of ICECool Optimized Microfluidic Manifold, MMIC Backside Features, and Modules.
- ✓ Implemented Multiphysics Co-Design & Simulation to Optimize Electrical, Flow, Thermal and Structural Performance.
- ✓ TDV Demo Supports ICECool Metrics of 1 kW/cm^2 Die-Level and 30kW/cm^2 HEMT-Level Flux.

Compact Microfluidic Manifold

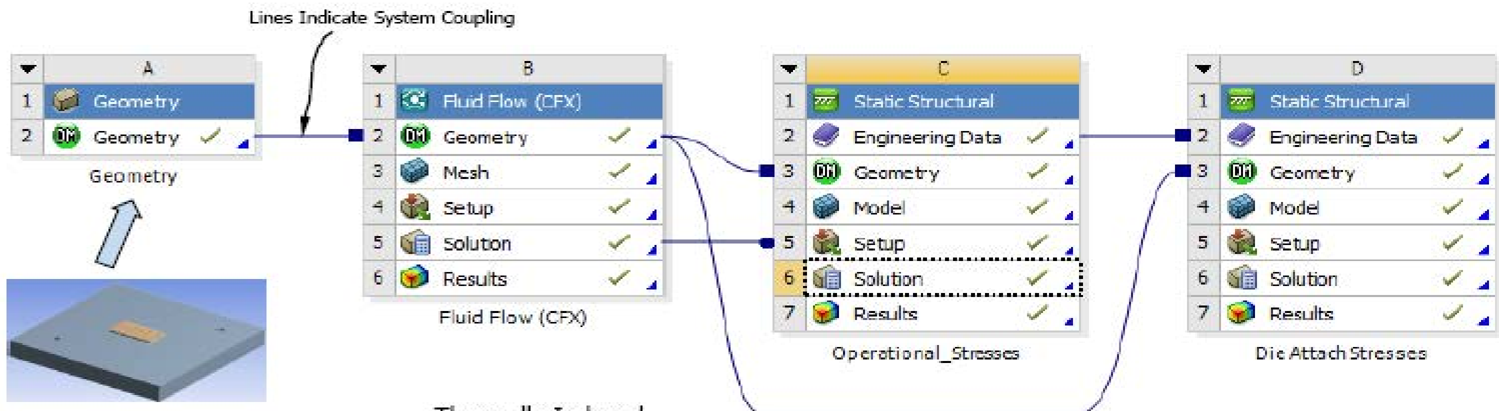


Co-Design & Simulation

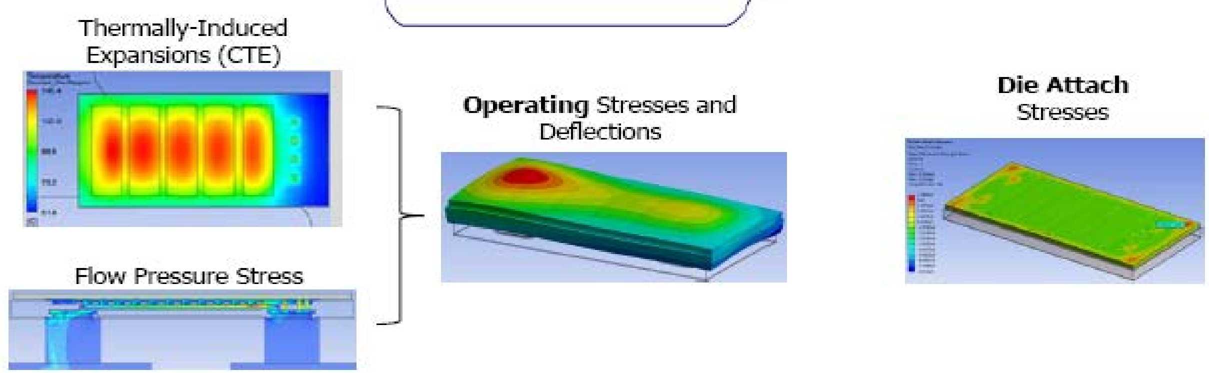
Die Back-Side Processing



Co-design done in ANSYS Workbench

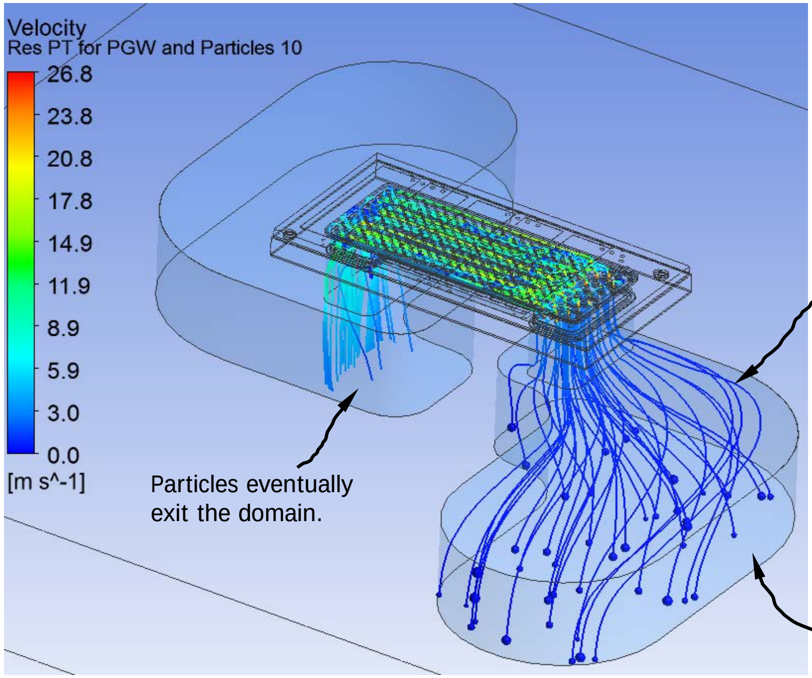


- FEA Model Imports the Same CAD Geometry Used to Fabricate the Parts (-> Accurate Representation)



Model size ~ 25 GB; ~ 90 Hours to solve on a 60 GFLOPS machine

Case Study: Erosion Modeling (LM) – Particle Tracking



Particle Trajectories are Influenced By Geometry and Fluid Flow. They are calculated by solving PDE's.

Particles of Varying Size are Injected at the Inlet of the Domain.

- **Lagrangian Particle Tracking is a Coupled-Field Simulation, Computing trajectory of particles**
- **orces Acting on the Particles are Inertia, Viscous Drag, Buoyancy, "Virtual Mass" and Pressure .**

Model size ~ 5 GB; ~ 15 Hours to solve on a 60 GFLOPS machine

Closure

- Why Embedded Cooling?
- DARPA's ICECool Program
- Modeling and Co-Design Challenges in Embedded Cooling

www.darpa.mil