ICECool Apps Proposers' Day Agenda

Time	Title	Presenter(s)
7:00 – 8:00 AM	Breakfast and Registration	Jeannie Osborne, SPC
	ICECool Applications BAA	
8:00 – 8:45 AM	Introduction and Overview	Avram Bar-Cohen, DARPA
8:45 – 9:15 AM	Overview of the BAA Process	Michael Blackstone, DARPA
	ICECool Needs	
9:15 – 9:35 AM	ICECool for WBG RF Systems	John Albrecht, Michigan State
9:35 – 9:55 AM	ICECool for Energy Efficient Computing	Paul Franzon, NC State
9:55 – 10:10 AM	AFRL MMIC Testing Capability	Dave Via, AFRL
10:10 – 10:30 AM	*Break*	N/A
10:30 – 10:40 PM	DARPA/MTO Program Manager Introduction	Avram Bar-Cohen, DARPA
	ICECool R&D Concepts	
10:40 – 11:00 AM	3D Stackable Evaporative Cooling of Microelectronics	Yogendra Joshi, Georgia Tech
11:00 – 11:20 AM	Integrated 3D Silicon Two Phase Cooling	Tim Chainer, IBM
11:20 – 11:40 AM	Microcooling for Intensely Concentrated Electronics – An Intrachip Approach	Suresh Garimella, Purdue
11:40 – 12:00 AM	Phase Separation Diamond Microfluidics for HEMT Cooling	Ken Goodson, Stanford
12:00 – 12:20 PM	Embedded Micro Thin Film Cooling for High Power Electronics	Michael Ohadi, U. Maryland
12:20 – 12:40 PM	Piranha Pin Fins: Voracious Boiling Heat Transfer by Vapor Venting from Microchannels	Yoav Peles, RPI
12:40 – 1:00 PM	Membrane-Enhanced Evaporative Cooling for High Flux Thermal Management	Evelyn Wang, MIT
1:00 – 2:00 PM	*Lunch (On Your Own)*	N/A
1:00 – 2:00 PM	Poster Setup	Poster Presenters
2:00 – 4:00 PM	**Embedded Thermal Management**	Poster Session and Coffee/Munchies
4:00 – 4:30 PM	Poster Breakdown	Poster Presenters
	Meetings	
1:30 – 7:00 PM	Meetings with PM (10 Minute Blocks)	Avram Bar-Cohen, DARPA
1:30 – 7:00 PM	Breakout Room Available for Teaming Meetings (10 Minute Blocks)	As Arranged

Intra/Inter Chip Enhanced Cooling Applications (ICECool Apps)

Dr. Avram Bar-Cohen, PM, DARPA/MTO

Briefing Prepared for ICECool Applications Proposers' Day

February 7, 2013

Distribution Statement A, Approved For Public Release, Distribution Unlimited

ICECool Applications BAA – Introduction and Overview

- DARPA and MTO Visions
- Thermal Management Technologies Program
- Thermally Limited Components and Systems
- Embedded Cooling Paradigm
  - Near Junction Thermal Transport
  - Intra/Inter Chip Enhanced Cooling – Fundamentals
  - Intra/Inter Chip Enhanced Cooling – Applications
- ICECool Applications BAA
  - Objectives
  - Structure
  - Technical Areas
  - Metrics
  - Deliverables

MTO leverages, counters, and transcends COTS to give the U.S. warfighter an Unlevel Playing Field

- ✓ Leverage COTS:
  Multiply power of COTS by aggregating, adapting and integrating components into networks and systems which benefit the warfighter
- ✓ Counter COTS:
  Defend against threats emerging from sustained advancements of cheap (i.e. consumer price-point), readily available technologies
- ✓ Transcend COTS:
  Develop high-risk, high-reward technologies outside and beyond the scope of commercial industry

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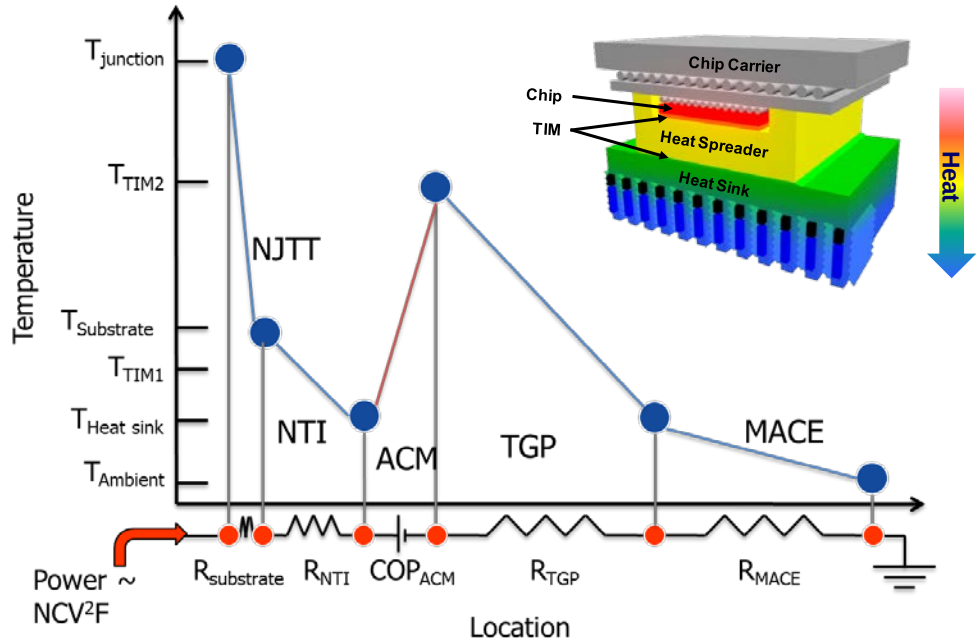
Thermal Management Technologies (TMT) Program Goals

- Leverage significant recent advances in nanostructured materials, active structures and integrated manufacturing
- Enhance performance of DoD systems through manipulation, transport and rejection of waste heat

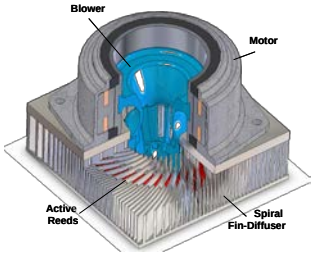


Task Areas :

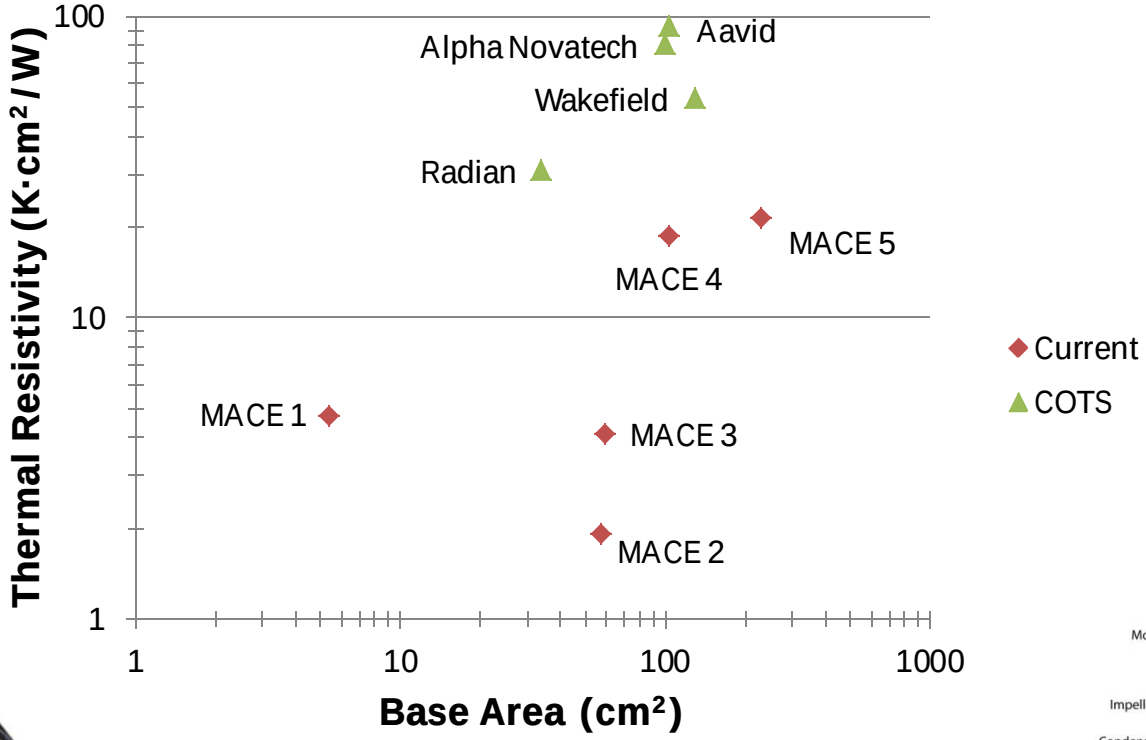
Microtechnologies for Air-Cooled Exchangers (MACE): Active surfaces and jets for enhanced heat sinks
Thermal Ground Plane (TGP): Nanostructured wicks and cases for 2-phase vapor chambers
Nano-Thermal Interfaces (NTI): Engineered, reworkable nanostructures for low resistivity TIMs
Active Cooling Modules (ACM): High COP cooler using novel TE materials and refrigeration concepts

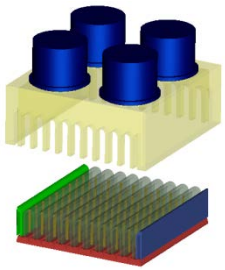
Goal: To deliver transformative thermal management technology that will reduce or remove thermal limitations on DoD platforms

MACE Approaches and Performance

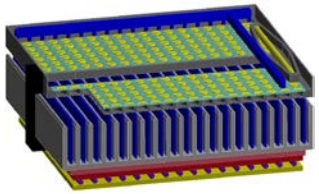


United Technologies Research Center: Integrated blower/heat sink with optimized fin geometry

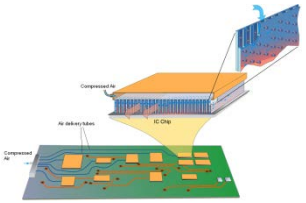




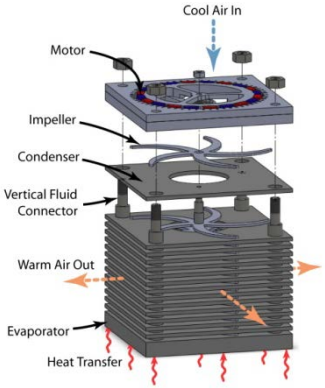
Raytheon: Micro/Macro Fin; Synthetic jets



Thermacore: 3D vapor chamber, vibrating elements

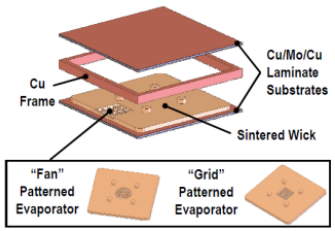


Honeywell: Jet-driven entrainment

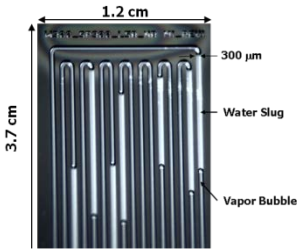


MIT: 3D vapor chamber; fan/fin integration

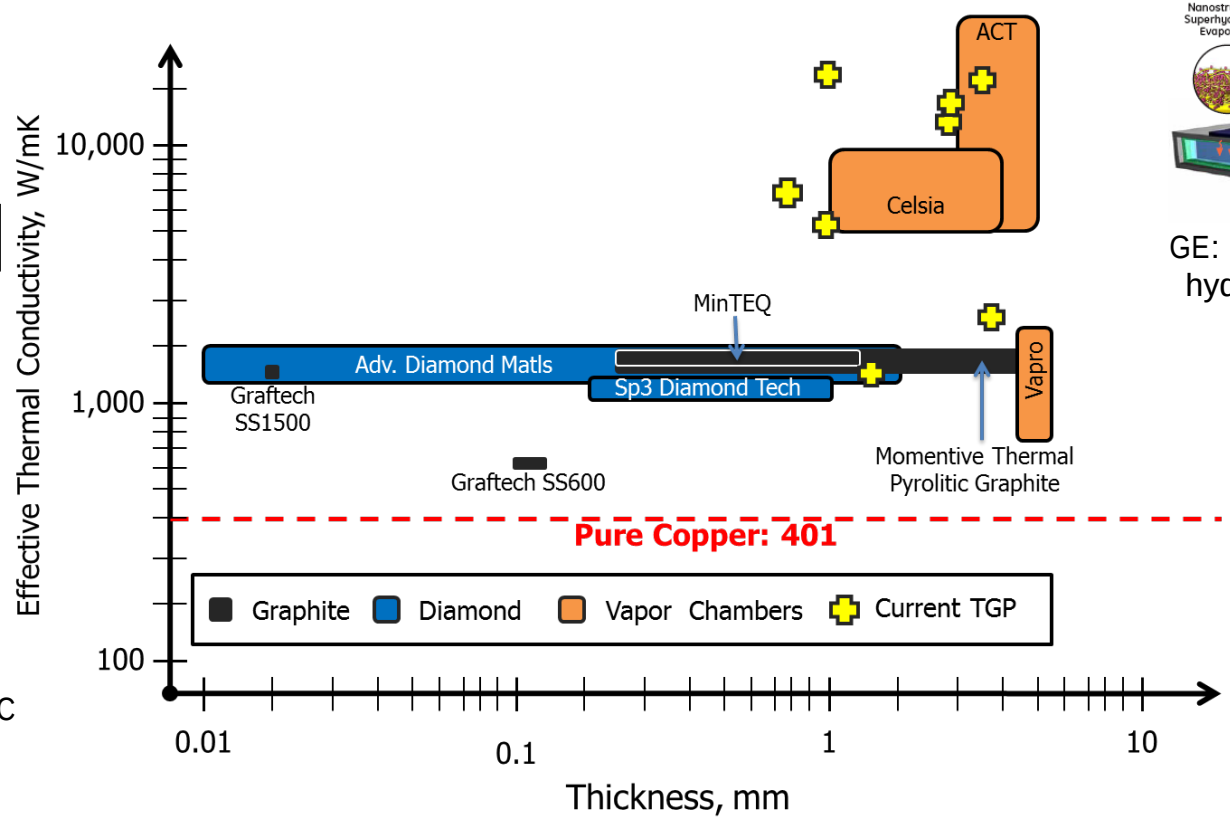
TGP Approaches and Performance

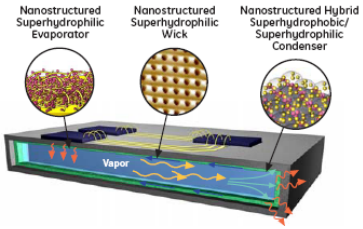


Raytheon: Patterned CNTs on Cu wick

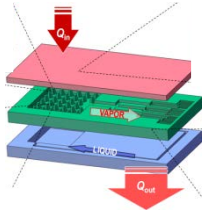


Northrop Grumman: SiC oscillating heat pipe

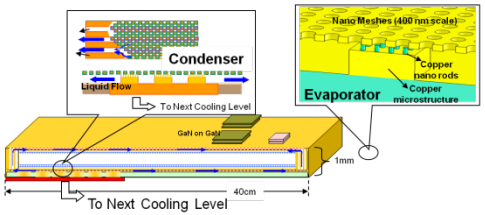




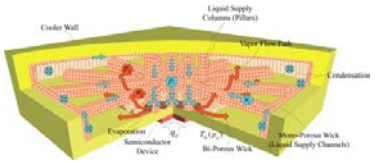
GE: nanostructured super hydrophobic/philic wick



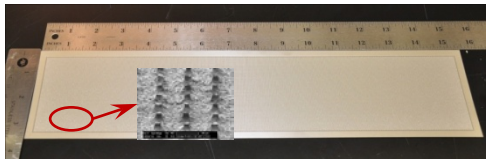
UC Berkeley: two phase flow with coherent porous silicon wick



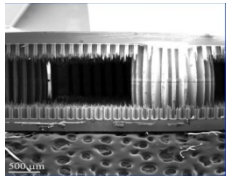
U Colorado: flexible/conformal case with Cu nanomesh wick



UCLA: metallic powder + biporous wick/posts

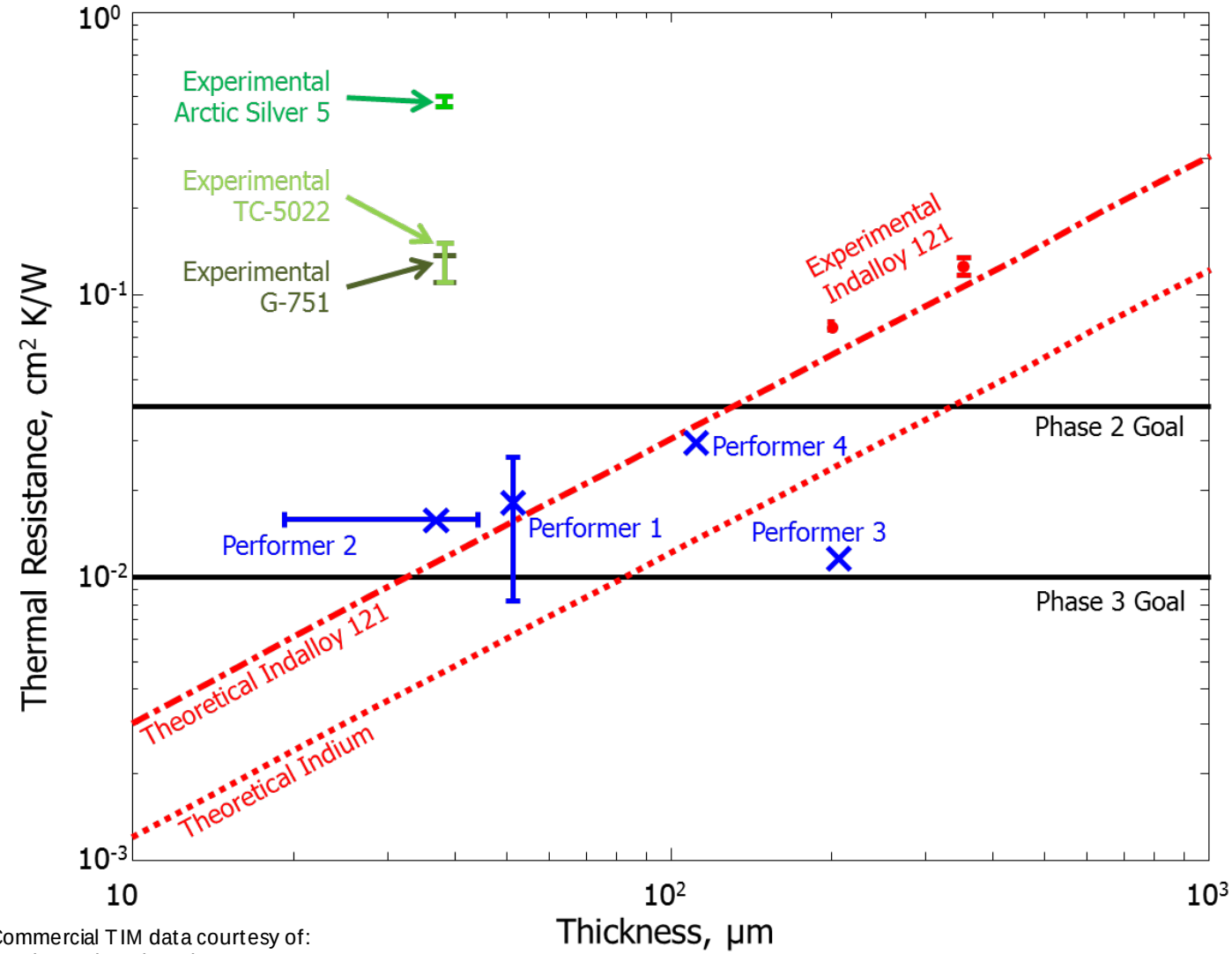


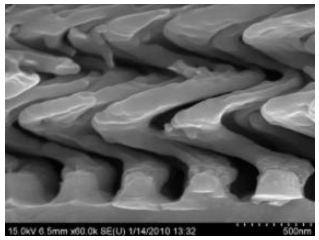
UC Santa Barbara: large scale titanium TGP



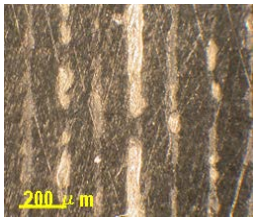
Teledyne: CNT/Si wick structures

NTI Approaches and Performance

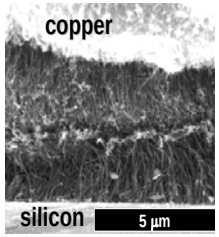




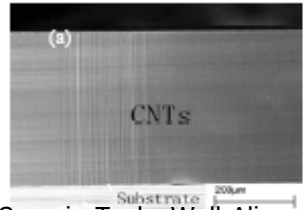
General Electric: Copper Nanosprings



Teledyne: Laminated Graphite and Solder



Raytheon: Double-sided Multi-walled Carbon Nanotubes



Georgia Tech: Well-Aligned Open-End Carbon Nanotubes

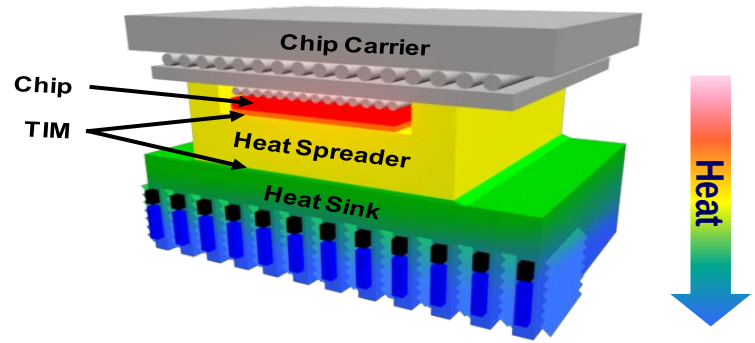
Commercial TIM data courtesy of:
D. Altman (Raytheon)
Y. Zhao (Teledyne)

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:

- Incapable of effectively limiting the device "junction" temperature rise
- Can not selectively target the thermally-critical devices
- Can not extract heat efficiently from 3D package
- Accounts for a large fraction of SWaP-C of advanced high power electronics, lasers, and computer systems
- Stymies attempts to port advanced systems to small form-factor applications
- Frustrates attempts to reach SWaP-C targets for electronic systems



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Defense Electronics are Thermally Limited

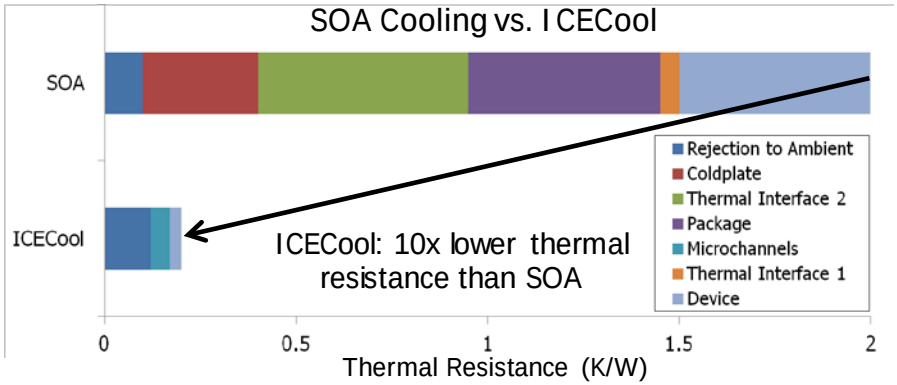
Problem: Defense Electronic Systems Fail to Reach Device Performance Limits Due to High Thermal Resistance

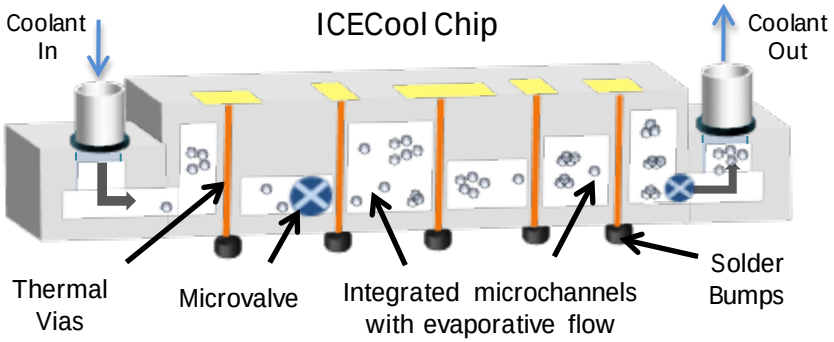
<u>Thermally-Limited DoD Systems</u>

RF systems
- Radar
- SATCOM
- ISR
- EW

Embedded Computers
- Processors
- Flight Computers
- Graphics Cards

Solid-State Lasers
- Laser Diode Bars



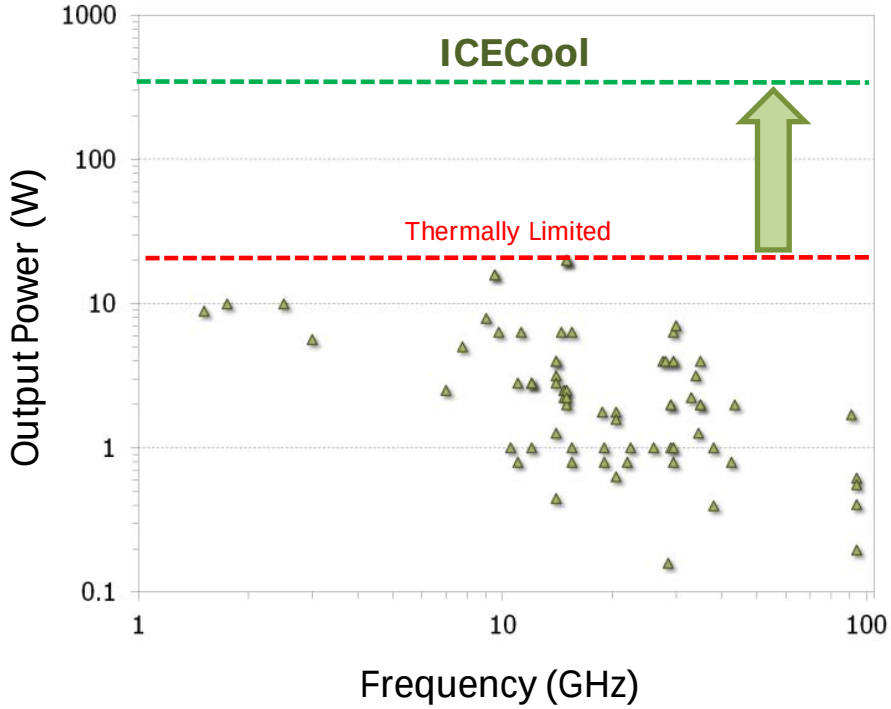


ICECool utilizes intra/interchip microfluidics to reduce thermal resistance by 10x

GaN MMIC PAs

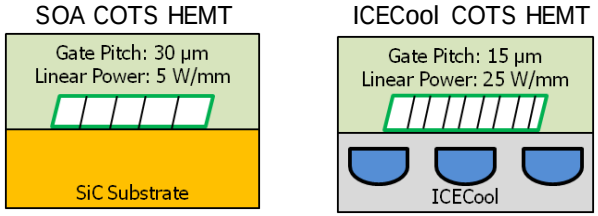
Solid State Sources (CW)

Plot adapted from: Crowe et al 2005



ICECool provides the 10x increase for MMICs by allowing designers to:

- Shrink transistor (HEMT) gate pitch by 2x
- Increase transistor linear power density by 5x



System Implications of PA with 10x P_{out}

Electronic Attack

- Range ~ $P_{out}^{1/2}$ (Free Space)
- 10x P_{out} → 3.1x Range

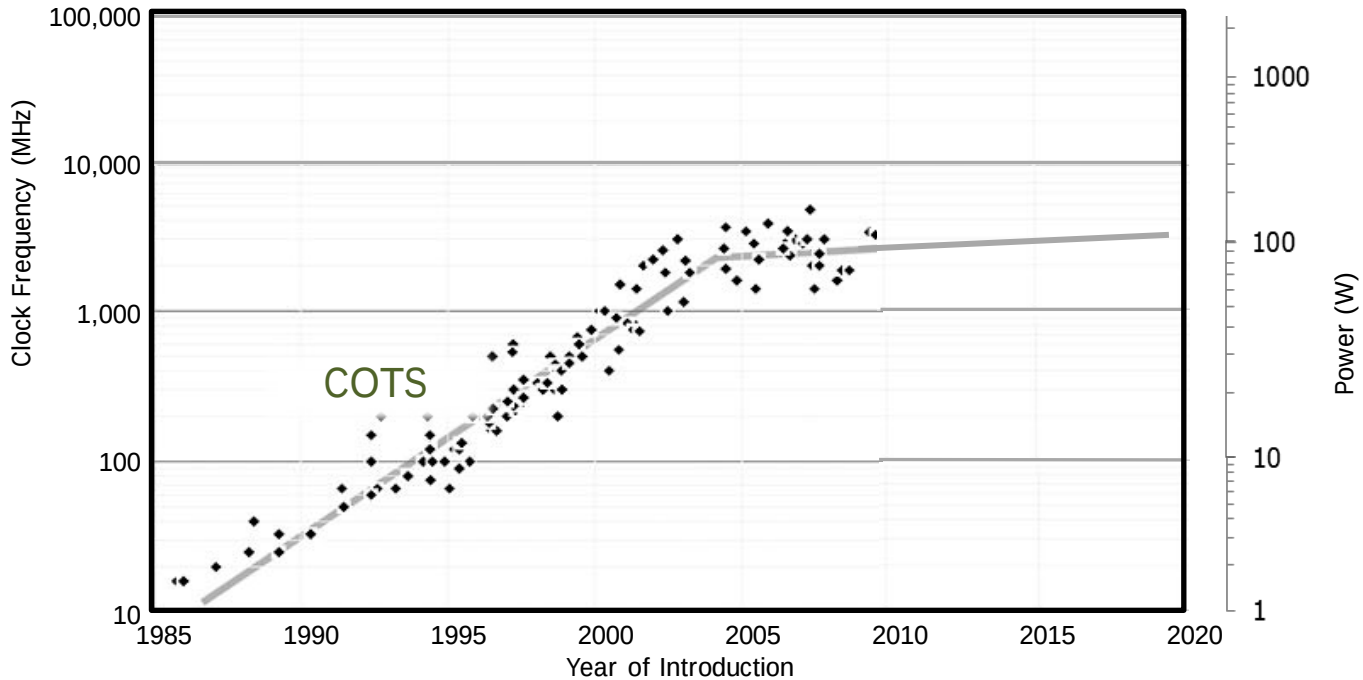
Radar

- Range ~ $P_{out}^{1/4}$ (Free Space)
- 10x P_{out} → 1.7x Range

ICECool GaN MMIC PAs provide a path for RF systems to increase their range by up to 3x

End of Moore's Law or Just Hiatus?

2011 NRC/CSTB Study: "The Future of Computing Performance"



Moore's Law progression stalled by voltage and feature size limits

Dennard's Equation:

$$f = \frac{P_{density}}{N_g C_{load} V^2}$$

$$f \propto P_{density}$$
$$f \propto heat$$

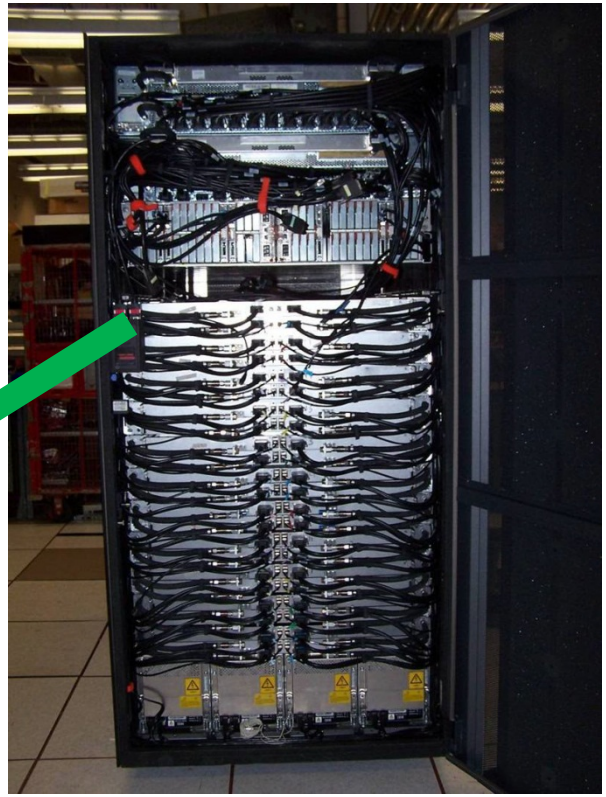
- N_g = CMOS gates/unit area
- C_{load} = capacitive load/CMOS gate
- V = supply voltage
- f = clock frequency

Enhanced cooling can restore chip frequency progression

Integral Cooling – High Performance Computing

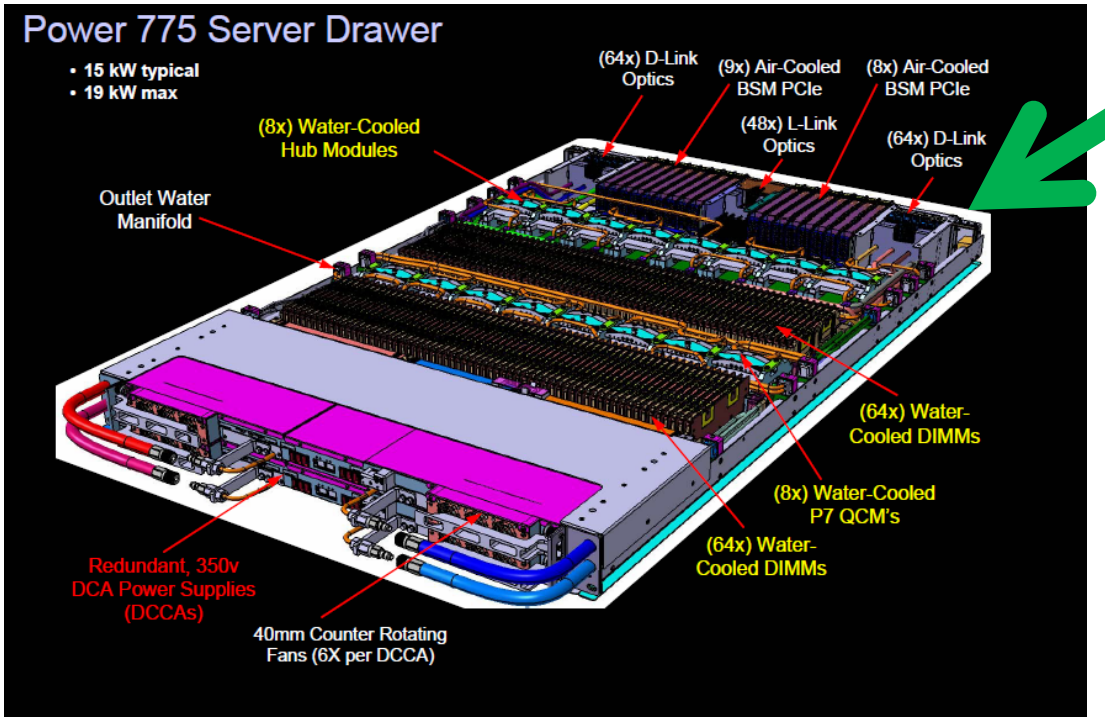
- IBM 775 is water-cooled supercomputer
- Capable of dissipating 19 kW heat load at the CEC level
  - Removes 100% of the heat load to the cooling water
  - Needs no help from HVAC
- 8 Tflops of peak compute performance at the CEC level
  - Future systems will require even more cooling to push performance higher

IBM 775



Images From Interpack, Ellsworth 2011

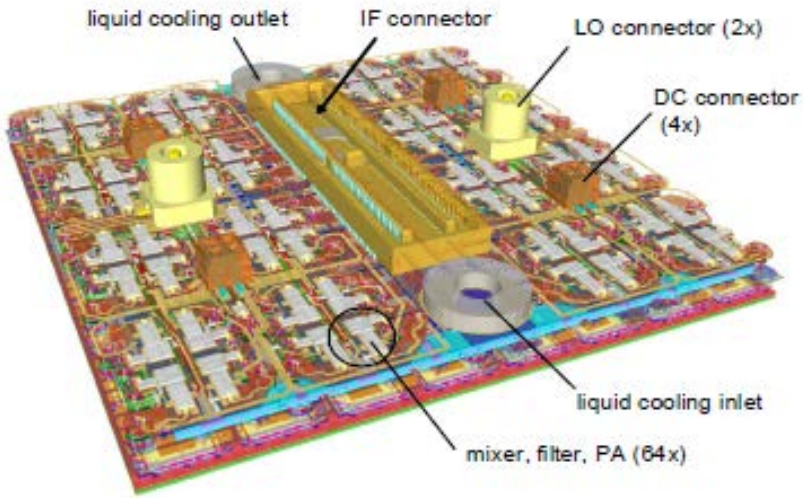
IBM 775 CEC



Integral Cooling – RF Systems

- RF arrays and sub-arrays are already manufactured with integral cooling
  - Fully functional Ka-band 8x8 array in LTCC
- Liquid cooling via a microchannel cooler has been shown to improve the performance at the MMIC level
  - 17 ^{0}C reduction in gate temperature at 5 W/mm heat dissipation

IMST Ka-band Tx Demonstrator



NRL GaN MMIC with Microchannel Cooler

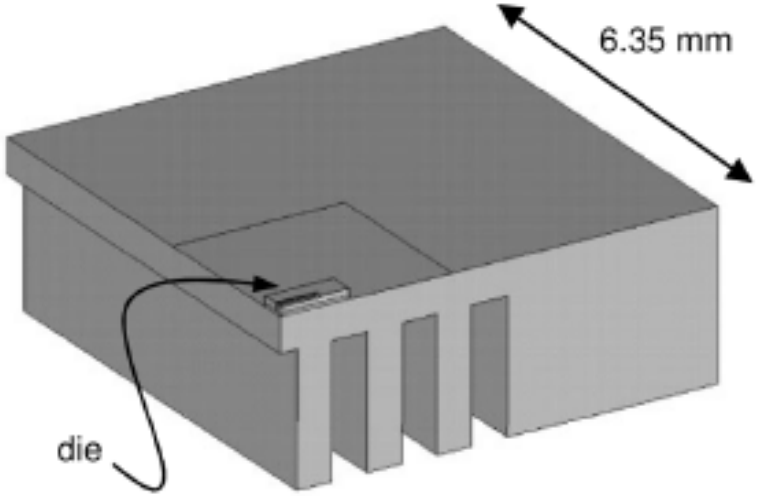
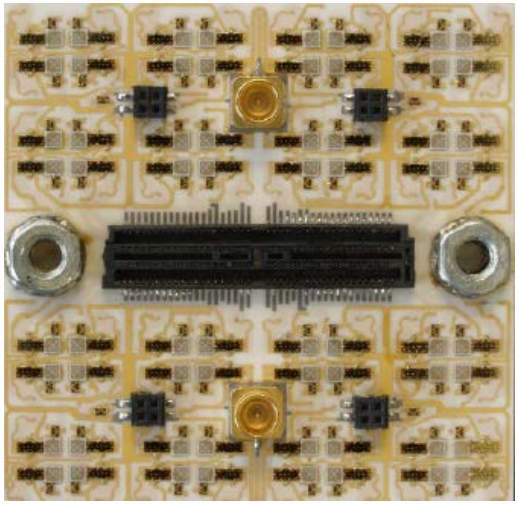


Image from IEEE Trans. On CPT, Garven and Calame, 2009.



Images from EuCAP, Holzwarth et al, 2010

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Towards Gen3 Thermal Packaging

Challenges:

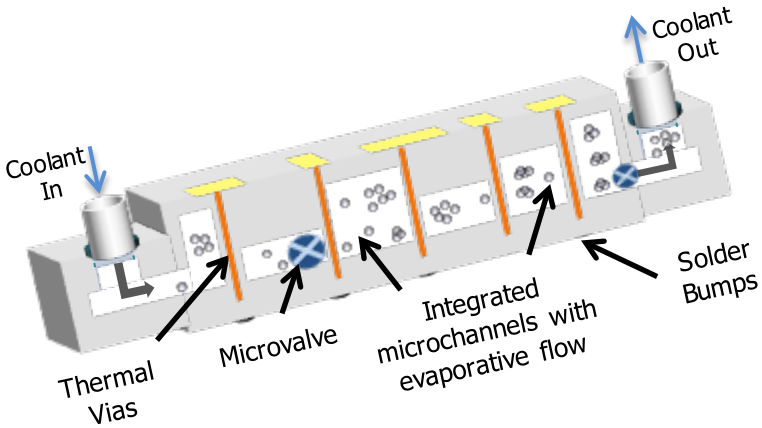
- Complete the Inward Migration of Thermal Packaging
- Extract heat directly from device, chip, and package
- Place thermal management on an equal footing with functional design and power delivery

Benefits:

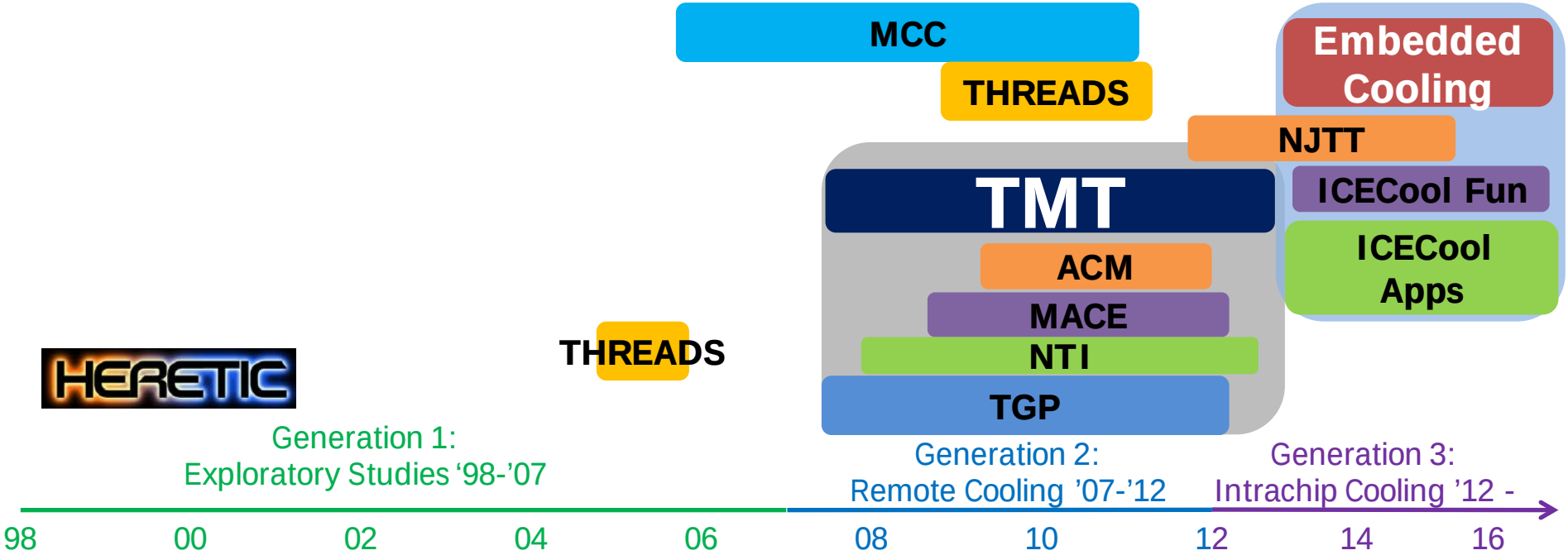
- Allow electronic systems to reach material, electrical, optical limits
- Reduce SWaP-C for comparable performance
- Lead the way to integrated, intelligent system co-design

Enabling Technologies:

- Microfluidics – convective and evaporative
- Thermal interconnects – active/passive
- Microfabrication – channeling, hermeticity
- Thermal Co-Design



DARPA Thermal Management Programs Timeline



Heat Removal by Thermo-Integrated Circuits (HERETIC)

- 1998: DARPA PM Towe
- 2001: DARPA PM Radack
- 2002: HERETIC ends

Technologies for Heat Removal in Electronics at the Device Scale (THREADS)

- 2005-2006: DARPA PM Rosker
- 2009-present: DARPA PM Albrecht

Micro Cryo Coolers (MCC)

- 2006-2011: DARPA PM Dennis Polla

Thermal Management Technologies (TMT)

- 2007-2010: DARPA PM Kenny
- 2010-present: DARPA PM Bar-Cohen

Embedded Cooling (NJTT and ICECool)

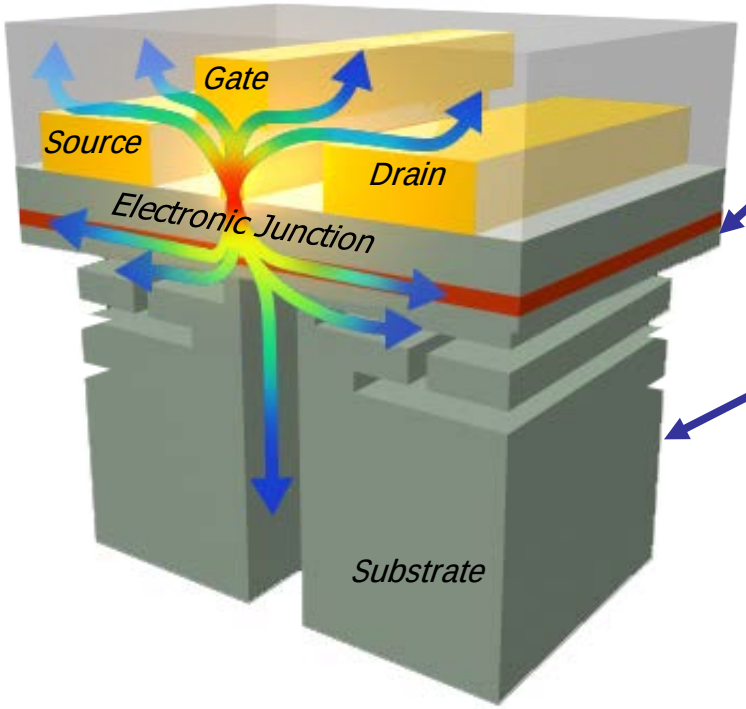
- 2011 - 2015: DARPA PM Bar-Cohen
- NJTT and ICECool explore novel, disruptive, chip/package level – embedded - thermal technologies in Si and non-Si electronics

Near-Junction Thermal Transport (NJTT)

DARPA's Near-Junction Thermal Transport (NJTT) is an effort inside DARPA's Thermal Management Technology (TMT) portfolio

- Start Date: Fall 2011
- Teams: TriQuint, BAE, Raytheon, RFMD, NGAS, GE

Schematic of NJTT HEMT Device



NJTT Approaches

Liquid Cooling

Team: General Electric

Challenge:

- Eliminate impact on device electrical properties due to time varying dielectric constant of liquid

High Thermal Conductivity Diamond

Teams: TriQuint, BAE, Raytheon, RFMD, NGAS

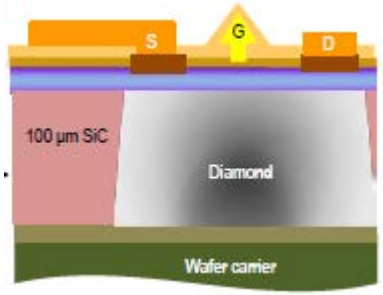
Challenges:

- Integrate lattice-mismatched heat spreaders
- Minimize thermal boundary resistance (TBR)
- Match coefficient of thermal expansion of electronic material

NJTT Vision: Provide localized thermal management within 100 µm of the device substrate to increase Output Power from GaN PAs by >3x

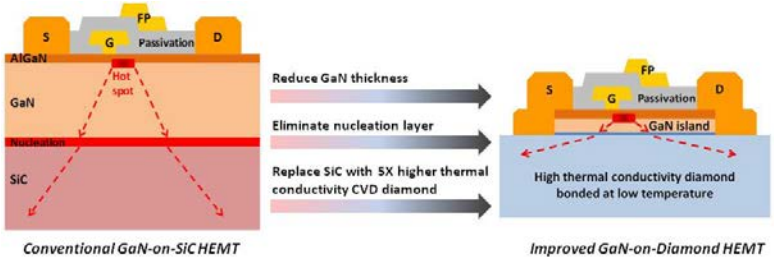
NJTT Performers

NGAS
NRL, ADI, Stanford



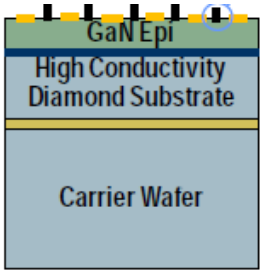
NGAS Approach: Utilize high k diamond vias in etched GaN on SiC

BAE
Group4, Stanford, IPG, IQE



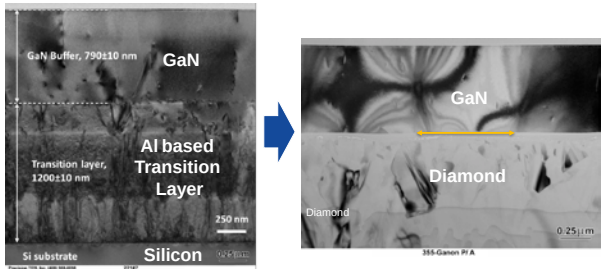
BAE Approach: High thermal conductivity diamond bonding at low temperatures (<200°C) on thinned GaN to minimize impact of CTE mismatch on device performance and reliability

Raytheon
Group4, Stanford, Georgia Tech



Raytheon Approach: Diamond Substrate achieves 3-5x reduced thermal resistance

TriQuint
Group4, Bristol, Lockheed Martin

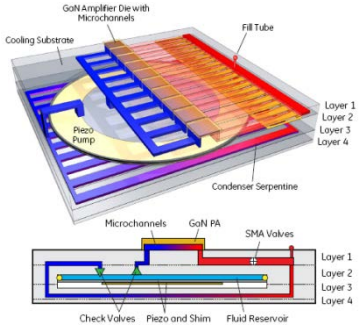


TriQuint Approach: Remove Si substrate and transition/buffer layers and bond diamond to AlGaN/GaN layers at optimized distance from device channel

RFMD
Group4, Stanford, Georgia Tech, Boeing

RFMD Approach: Remove transition layers, employ super-thin adhesive between GaN and Diamond, GaN thinned to sub 1 µm

GE
RFMD

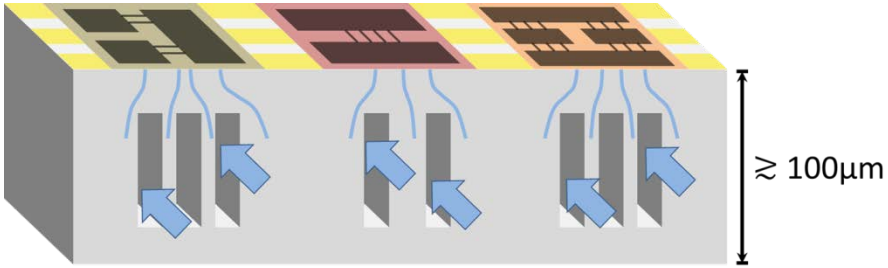


GE Approach: Cooling through autonomous fluid routing via shape-memory alloy valves

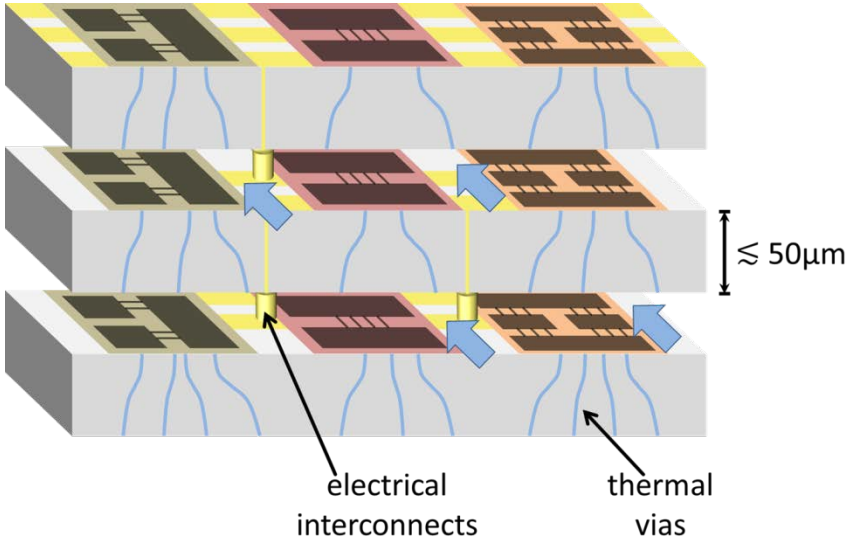
ICECool Fundamentals (ICECool Fun)

Program Objective: Provide the fundamental thermofluid building blocks for the utilization of Intra and Interchip **evaporative** cooling in DoD electronics

Intrachip: Flowing cooling fluid through microchannels fabricated directly into the chip



Interchip: Flowing cooling fluid through the microgap between chips in 3D stacks



ICECool Fun will kickoff in Spring 2013.

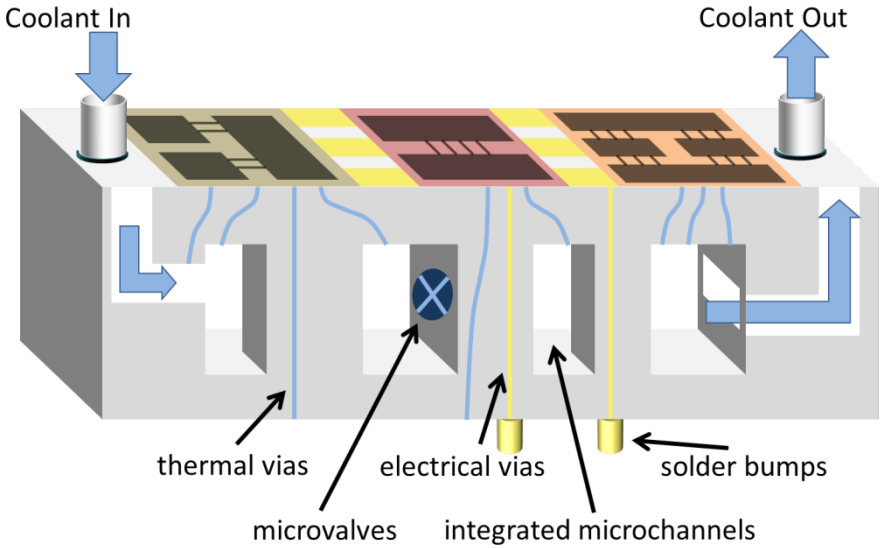
ICECool Applications BAA – Introduction and Overview

- DARPA and MTO Visions
- Thermal Management Technologies Program
- Thermally Limited Components and Systems
- Embedded Cooling Paradigm
  - Near Junction Thermal Transport
  - Intra/Inter Chip Enhanced Cooling – Fundamentals
  - Intra/Inter Chip Enhanced Cooling – Applications
- **ICECool Applications BAA**
  - Objectives
  - Structure
  - Technical Areas
  - Metrics
  - Deliverables

ICECool Applications (ICECool Apps)

Program Objective: ICECool Apps will enhance the performance of RF MMIC power amplifiers and embedded high performance computing systems through the application of chip-level heat removal with kW-level heat flux and heat density with thermal control of local submillimeter hot spots.

Conceptual ICECool Apps Wafer



ICECool Applications Program Structure

- ICECool Apps is broken into two technical areas
  - RF MMIC Pas; Embedded HPCs
  - Multiple awards anticipated in each area
  - Proposers can only address one technical area per proposal
- ICECool Apps will encompass two phases, 30 months
  - Phase 1 (12 months):
    - Design, fabricate, and demonstrate feasibility of ICECool concept with TDV
    - Establish through co-simulation performance enhancement in targeted electronic module
  - Phase 2 (18 months):
    - Implement and validate ICECool strategy in an operational EDV module
    - Demonstrate simultaneously meeting thermal and functional performance metrics
- ICECool Apps targets significant improvements in electronic/computing module performance through embedded thermal management
  - Proposals without both thermal and electrical/computing performance enhancements will not be reviewed favorably
- To support near-term system insertions, encouraged to apply "embedded" microfluidic thermal management techniques to existing liquid-cooled systems.

Technical Area I: RF MMIC PAs

- Microfluidic cooling for GaN RF MMIC PAs with operating frequencies at Q band and below (≤ 50 GHz)
- ICECool approaches are permitted to utilize GaN on a relevant "microchanneled" substrate (SiC, Si, sapphire, diamond, AlN, bulk GaN)
- GaN-on-SiC MMIC PAs should be utilized as the baseline part
- EDV should flow out of the baseline GaN RF MMIC PA and be a fixtured multi-stage (minimum 2-stage) or distributed PA with the appropriate embedded cooling features
- Not interested in major electrical changes to the SOA GaN PA architecture or extensive transistor development to improve PAE or output power
- Minor changes to device architecture needed to accommodate the higher output power enabled by ICECool are within scope
- The ICECool improvements in thermal transport within the EDV PAs must not interfere with the DC or RF operation of the MMIC

Technical Area I: Metrics

	Phase 1 Metric	Phase 2 Metric	Units
Thermal Metrics	***TDV Demonstrated***	***EDV Demonstrated***	
MMIC (die-level) heat flux	> 1	> 1	kW/cm^2
Heat density	> 2	> 2	kW/cm^3
Total heat	Proposer defined	Proposer defined	kW
HEMT "hot spot" flux	> 30	> 30	kW/cm^2
Thermal resistivity	Proposer defined	Proposer defined	cm^2K / kW
Thermofluid CoP	> 20	> 20	N/A
Electrical Performance Metrics	***Simulated***	***EDV Demonstrated***	
Output power	> 3x baseline	> 3x baseline	W
Reliability Metrics			
Design for MTTF	10^6	10^6	Hours
Demonstrated cycles	10^3	10^3	Cycles
Demonstrated lifetime	10^2	10^2	Hours
Hermetic connector leakage	< 1%	< 1%	% per year

Technical Area II: Embedded HPCs

- Develop microfluidic cooling for high performance integrated circuits, including CPUs, GPUs, and FPGAs, that would be utilized in an embedded high performance computing application
- Seeks to support the development of embedded, energy efficient computing devices and architectures a la DARPA's PERFECT program
  - Proposals that explore the use of embedded cooling techniques with current generation IC technology and architectures **ARE** also welcome and responsive
- Proposed approaches must be compatible with a 2.5D or 3D configuration
  - Teams are encouraged to propose TDV and EDV vehicles with the appropriate number of layers, including an interposer, if used, that are needed to demonstrate the thermal and functional benefits of ICECool architectures
- Approaches are permitted to use various thermal interconnect materials
  - However, baseline device performance should be harvested from the SOA copper Through Silicon Vias (TSVs) in silicon components
- The ICECool improvements in thermal transport within the EDV must not interfere with the electrical and functional characteristics of the IC

Technical Area II: Metrics

	Phase 1 Metric	Phase 2 Metric	Units
Thermal Metrics	***TDV Demonstrated***	***EDV Demonstrated***	
Heat flux	> 1	> 1	kW/cm^2
Heat density	> 5	> 5	kW/cm^3
Total heat	Proposer defined	Proposer defined	kW
Hot spot flux	> 2	> 2	kW/cm^2
Temperature rise of hot spot	$\Delta T < 5$	$\Delta T < 5$	K
ΔT across heated chip	$\Delta T < 10$	$\Delta T < 10$	K
Peak temperature rise above inlet	$\Delta T < 30$	$\Delta T < 30$	K
Thermofluid CoP	> 20	> 20	N/A
Computational Performance Metrics	***Simulated***	***EDV Demonstrated***	
Throughput efficiency	> 2x baseline	> 2x baseline	Throughput/W
Throughput density	> 3x baseline	> 3x baseline	$Throughput/cm^3$
Reliability Metrics			
Design for MTTF	10^6	10^6	Hours
Demonstrated cycles	10^3	10^3	Cycles
Demonstrated lifetime	10^2	10^2	Hours
Hermetic connector leakage	< 1%	< 1%	% per year

Instructions for Proposers

1. Proposals must detail the approach and provide quantitative predictions of embedded cooling of a specified electronic chip
2. Proposals must contain a comprehensive thermofluid and mechanical model for ICECool approach in TDV and EDV and an electrical/computational model for EDV.
3. Proposals must contain a thorough description of all relevant thermal and performance parameters of the baseline part.
4. The proposals must identify the relevant material set and properties.
5. Proposals must provide a clear description of the entire fabrication process
6. Proposers must describe the flow manifold and detail the microfluidic components in a microchanneled or microgap electronic chip or stack.
7. Proposals must describe the plan for hot spot mitigation.
8. Proposals must establish the reliability of the proposed cooling approach.
9. Proposals must clearly establish the plan for thermal-electrical-mechanical co-design.
10. Proposals must contain a detailed test plan for validating compliance against program metrics.

Deliverables

- Program Start (In first 120 days of Program)
  - 4 Baseline Test Modules provided to government for IT&V (AFRL)
    - Note: The cost for this task should be itemized separately
  - Thermal and Performance Model
    - Teams should also be prepared through the course of the effort to share details of their modeling with the government and provide full support to government verification of their modeling through independent validation
- Phase 1
  - 8 Operational TDVs, at least 4 TDVs to be provided to government for IT&V (AFRL)
  - 1 Demonstration Module for Embedded Cooling Showcase
  - 1 Desktop Module
  - Thermal and Performance Model
- Phase 2
  - 8 Operational EDVs, at least 4 EDVs to be provided to government for IT&V (AFRL)
  - 1 Demonstration Module for Embedded Cooling Showcase
  - 1 Desktop Module
  - Thermal and Performance Model

ICECool Apps Proposers' Day Agenda

Time	Title	Presenter(s)
7:00 – 8:00 AM	Breakfast and Registration	Jeannie Osborne, SPC
	ICECool Applications BAA	
8:00 – 8:45 AM	Introduction and Overview	Avram Bar-Cohen, DARPA
8:45 – 9:15 AM	Overview of the BAA Process	Michael Blackstone, DARPA
	ICECool Needs	
9:15 – 9:35 AM	ICECool for WBG RF Systems	John Albrecht, Michigan State
9:35 – 9:55 AM	ICECool for Energy Efficient Computing	Paul Franzon, NC State
9:55 – 10:10 AM	AFRL MMIC Testing Capability	Dave Via, AFRL
10:10 – 10:30 AM	*Break*	N/A
10:30 – 10:40 PM	DARPA/MTO Program Manager Introduction	Avram Bar-Cohen, DARPA
	ICECool R&D Concepts	
10:40 – 11:00 AM	3D Stackable Evaporative Cooling of Microelectronics	Yogendra Joshi, Georgia Tech
11:00 – 11:20 AM	Integrated 3D Silicon Two Phase Cooling	Tim Chainer, IBM
11:20 – 11:40 AM	Microcooling for Intensely Concentrated Electronics – An Intrachip Approach	Suresh Garimella, Purdue
11:40 – 12:00 AM	Phase Separation Diamond Microfluidics for HEMT Cooling	Ken Goodson, Stanford
12:00 – 12:20 PM	Embedded Micro Thin Film Cooling for High Power Electronics	Michael Ohadi, U. Maryland
12:20 – 12:40 PM	Piranha Pin Fins: Voracious Boiling Heat Transfer by Vapor Venting from Microchannels	Yoav Peles, RPI
12:40 – 1:00 PM	Membrane-Enhanced Evaporative Cooling for High Flux Thermal Management	Evelyn Wang, MIT
1:00 – 2:00 PM	*Lunch (On Your Own)*	N/A
1:00 – 2:00 PM	Poster Setup	Poster Presenters
2:00 – 4:00 PM	**Embedded Thermal Management**	Poster Session and Coffee/Munchies
4:00 – 4:30 PM	Poster Breakdown	Poster Presenters
	Meetings	
1:30 – 7:00 PM	Meetings with PM (10 Minute Blocks)	Avram Bar-Cohen, DARPA
1:30 – 7:00 PM	Breakout Room Available for Teaming Meetings (10 Minute Blocks)	As Arranged

List of Poster Presentations

Effort	Title	Presenter(s)
Seedling	Capacitive Deionization of Water Coolant by using Vertically Aligned Carbon Nanotubes	CP Wong, Georgia Tech
Seedling	Thin-Film Evaporation With Digital Microfluidic Coolant Delivery System For Embedded Thermal Management	S.M. You, UT-Dallas
Seedling	Galinstan-Based Liquid Cooling of Microelectronics	Marc Hodes, Tufts University
Seedling	CHF Enhancement of Dielectric Microemulsion Fluids in Pool Boiling and Flow Boiling	Bao Yang, University of Maryland
Seedling	Electro-Thermo-Mechanical Co-Design of Fluidically Cooled Integrated Circuits	Ankur Srivastava, University of Maryland
NJTT	Design of a Near Junction Thermal Transport Spreader	Stanton Weaver GE Global Research
NJTT	Thermally Enhanced Gallium Nitride	Steve Bernstein, Raytheon
NJTT	GaN-on-Diamond RF Power Technology	Rama Vetury, RFMD
NJTT	Next Generation GaN-on-Diamond RF Power Amplifier Device and MMIC Technology	David Fanning, TriQuint
NJTT	Low Temperature Bonding GaN-on-Diamond Technology	P.C. Chao, BAE Systems
NJTT	NJTT Diamond Vias	Randy Sandhu, NGAS
SBIR	Strain-Tolerant Organic-Ceramic Coatings for the Passivation of Laser Diodes	Tapan Desai, ACT
SBIR	Scroll Pump for Vapor-Liquid Refrigerant Mixtures	John Dieckmann, TIAX
SBIR	Pump for Mixed Phase Refrigerant	Jerry Wagner, Mainstream
YFA	Electrical and Microfluidic Interconnection Technologies for Computing Systems	Muhannad Bakir, Georgia Tech
YFA	Quantitative Nanoscale Thermal Imaging	Pramod Reddy, University of Michigan
Capability	Additive Manufacturing Process for Three Dimensional Microchannels	Ross Wilcoxon and Nate Lower, Rockwell Collins
Capability	Micro/Nano-Structured Surfaces for Thermal Management	Ronggui Yang, University of Colorado at Boulder

Happy Anniversary DARPA!

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