Thermal Sciences & Materials Research for Aerospace

Materials and Manufacturing Technology Directorate
Thermal Sciences and Materials Branch
(overview)

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Thermal Sciences and Materials Branch (RXBT)
Materials and Manufacturing Directorate

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"Thermal Sciences and Materials" (RXBT) branch Mission and Thrust Areas:

To solve Air Force thermal issues limiting today's and future warfighting capabilities through research, development and transition of innovative materials

- **Tailorable and adaptive thermal interfaces & coolants**
- **Directionally controlled thermal transport**
- **Thermal energy storage, rejection and harvesting**
- **Thermal load sensing and adaptive response**

Scientific Advisor: Timothy Fisher, timothy.fisher@wpafb.af.mil

Ongoing Programs:

Coolants for High Performance Heat Exchangers
(PM: John Jones, john.jones@wpafb.af.mil)

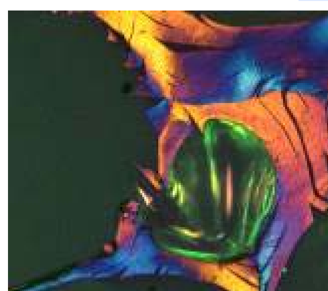
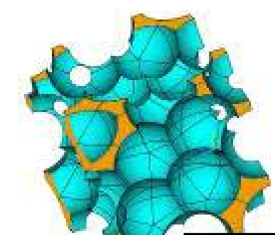
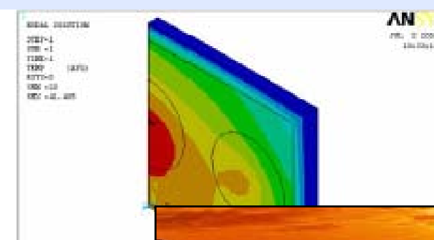
Thermal Interface Engineering Initiative
(PM: John Jones, john.jones@wpafb.af.mil)

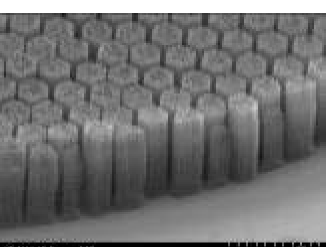
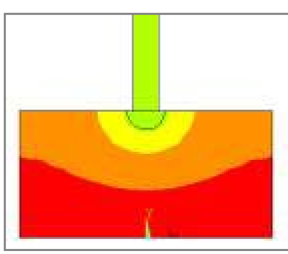
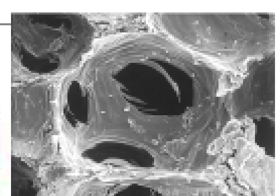
Directionally Tailored Thermal Management Materials
(PM: Karla Strong, karla.strong.1@us.af.mil)

High Temperature Mechanical-Chemical Interfaces
(PM: Pat Heinrichs, Pat.Heinrichs@wpafb.af.mil)

Thermal Transport Predictive Method Development
(PM: Pat Heinrichs, Pat.Heinrichs@wpafb.af.mil)

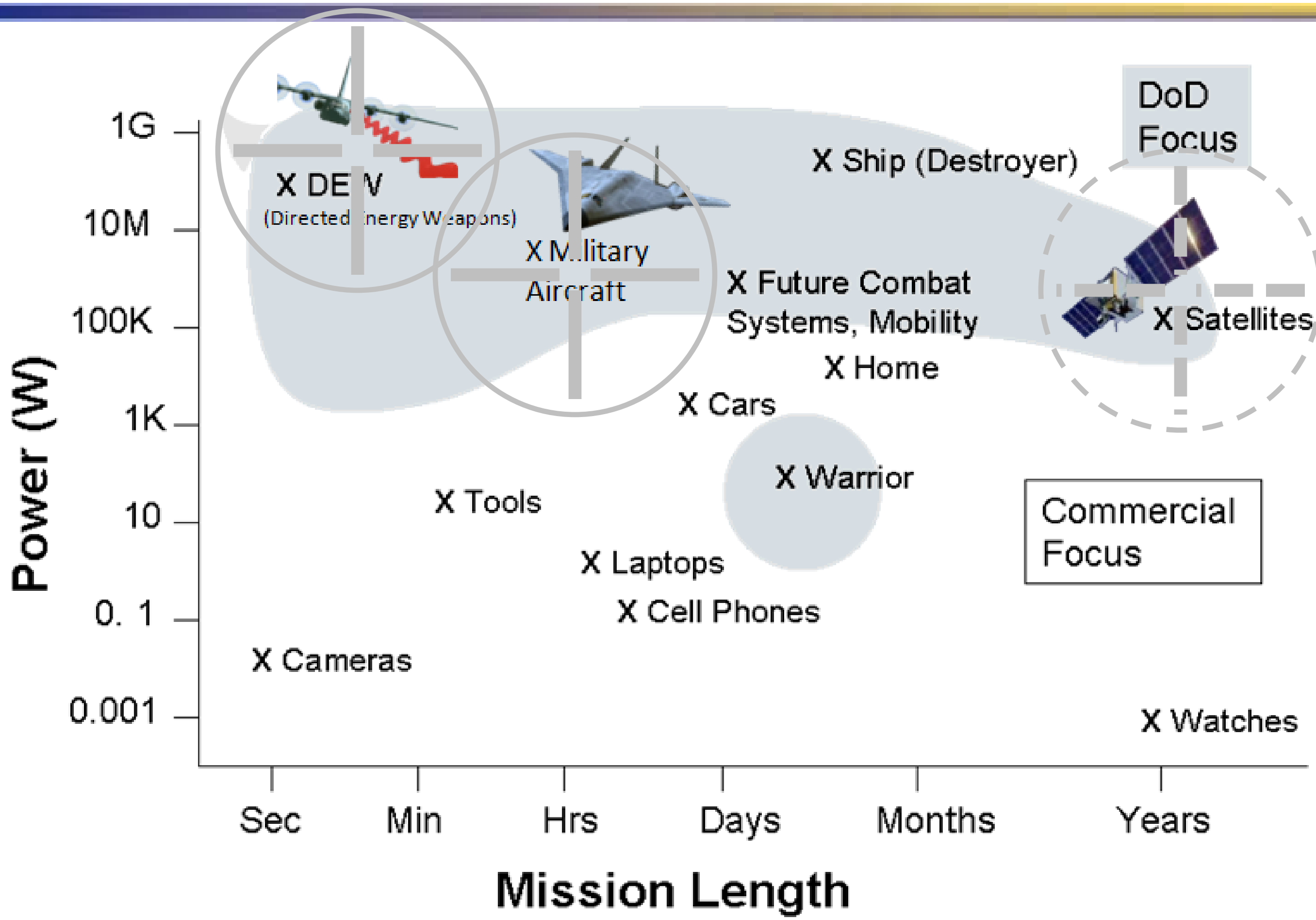
THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

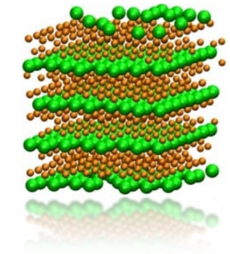




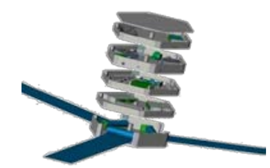


Unique AF Requirements and Impact on FLTCs





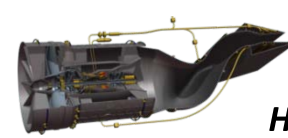
Thermal Sciences Fundamentals



TM for modular Satellites

TM for solid state lasers

Electric actuator for flight control



HEETE engine

THERMAL MANAGEMENT CRUCIAL TO CURRENT AND FUTURE AF CAPABILITIES!

- Thermal impact has become THE rate limiting step in AF capabilities today and will pace our technological advances

Mission Power… … Survivability… … Speed… … Engines… … Computation…

- **Higher-capability sensors/avionics**
- **Airborne directed energy systems**
- **Responsive space systems**

- **Fewer openings for ram air cooling**
- **Increased agility via thrust vectoring**

- **Increased skin aeroheating loads**
- **Increased ram air temperatures**
- **Increased sensor power requirements**

- **Higher compressor & turbine temps.**
- **Reduced fuel burn to absorb heat**

- **Super computer cooling**

We have hit the thermal wall!

System Design Alone Can No Longer Handle The Heat

Need New Materials Coupled with New Designs -- need to engage down to the molecules to manage waste heat

Courtesy of AFRL Thermal Steering Committee

Thermal Sciences and Materials Branch

Advances in thermal material sciences and technologies will transform thermal limitations into war fighting assets

VISION

Today

Waste Heat Limits AF Capabilities

Material design
Advanced coolants
Material integrated energy conversion
Adaptive thermal interfaces
High density storage
Sustained thermal stability

Heat capturing storing removing

Energy source for AF platform

In 5 years

System optimized thermal management

In 10 years

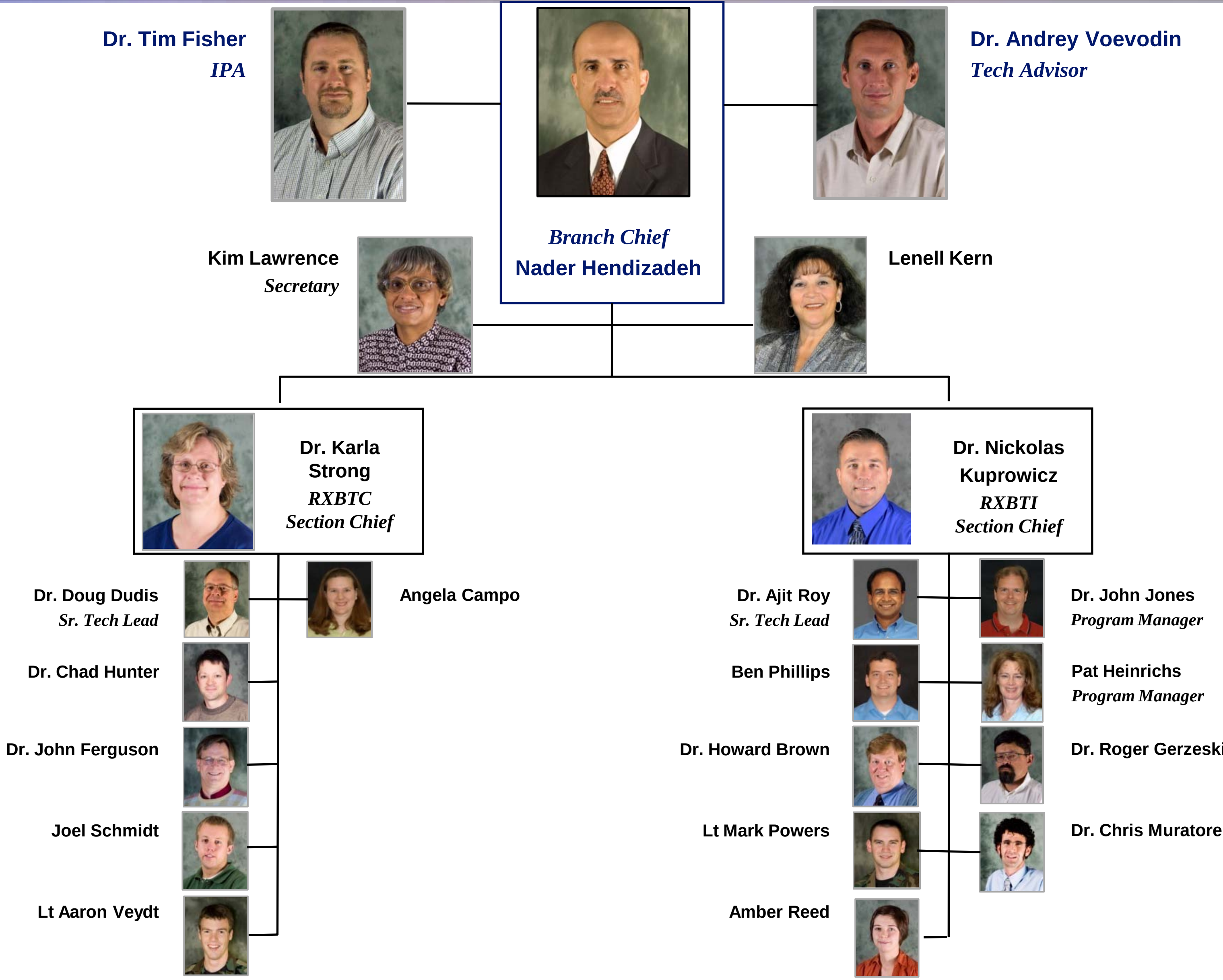
Warfighter additional reserve

In 15 years

New capabilities for AF

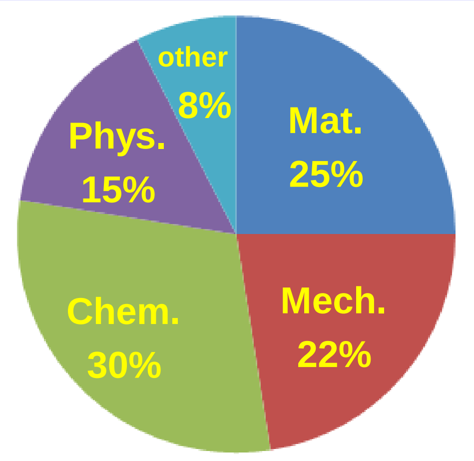
AFRL/RXBT Organization

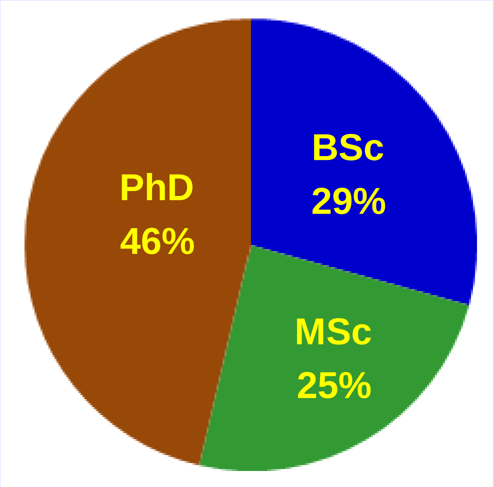
Updated 10/23/09



People Resources

- Over 50 highly skilled personnel
- High-level expertise via IPA
  Prof. T. Fisher
- Post-docs from leading
  thermal science academia groups
- State-of-the-art facility





Facilities

Added in 2008-2010

- **Multiscale Thermal Modeling:**
  - Molecular Dynamics and Wave Packets
  - Mesoscale particle based
  - Continuum modeling (FEM, BEM, FVM)

- **Thermophysical Characterization of solids:**
  - Laser Flash (Thermal Diffusivity &Thermal Conductivity)
  - IR Microscope (Thermal Diffusivity)
  - 3 Omega (Thin Film Thermal Conductivity)
  - Thermal AFM (Relative Thermal Conductivity @ nm)
  - Laser Pump Probe (Thermal Conductivity)
  - Guarded Hot Plate (Bulk Thermal Conductivity)
  - Dilatometer (Thermal Expansion)
  - Seebeck coefficient (Thermoelectric Power)
  - FIB based microheater
  - Photoacoustic Interface Resistance (incoming)
  - SFG for molecular level thermal analysis (incoming)
  - Seebeck microprobe surface mapping (incoming)
  - Transient hot-disk probe for Kz thermal conductivity (incoming)

- **Thermophysical Characterization of liquids:**
  - Coolant Loop Validation Test Bed
  - Pool Boiling Apparatus
  - IR and High Speed Camera for spray cooling & boiling
  - Laser pump probe cell
  - Hot Wire (Thermal Conductivity in Liquids)
  - Dielectric strength

- **Surface and Interface Analysis:**
  - XPS, imaging XPS, Auger Spectroscopy
  - Time of Flight SIMS
  - Inductively Coupled Plasma (ICP)
  - FTIR and Raman
  - Atomic Force Microscopy (AFM)
  - Scanning Tunneling Microscopy (STM)
  - FIB and HRTEM
  - Nano-Mechanical Characterization
  - High-temperature sliding interface testing
  - Optical and contact profilometery
  - Rheology

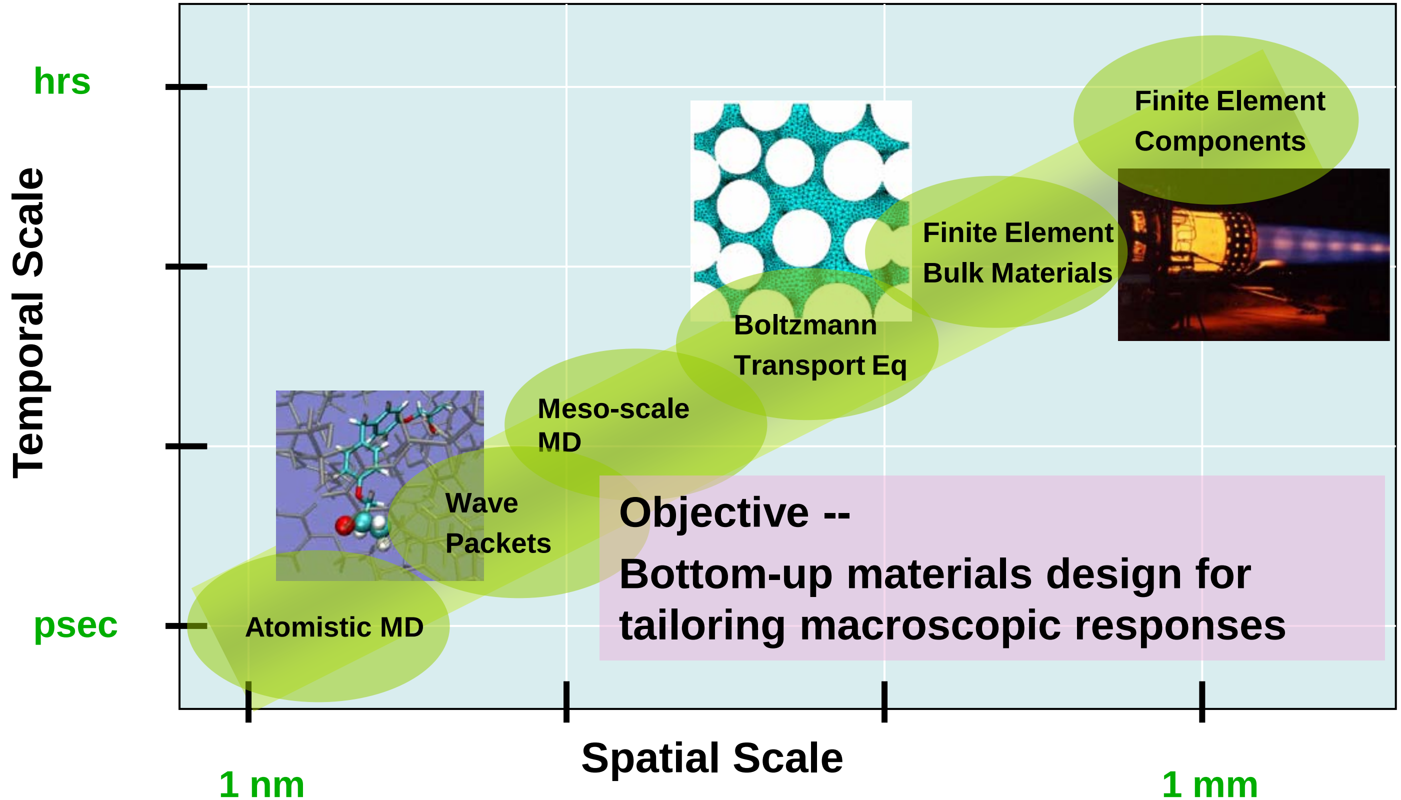
- **Thermal Analysis (DSC and GC)**

- **Thin Film Deposition:**
  - Sputtering, laser ablation, vacuum arc, ion beam
  - MAPLE (nanostructure depositions)

- **Chemical Synthesis and Coolant Formulation**

- **Microelectromechanical Systems (MEMS) Lab**

Multiscale Modeling Integrated with Experimental Characterization

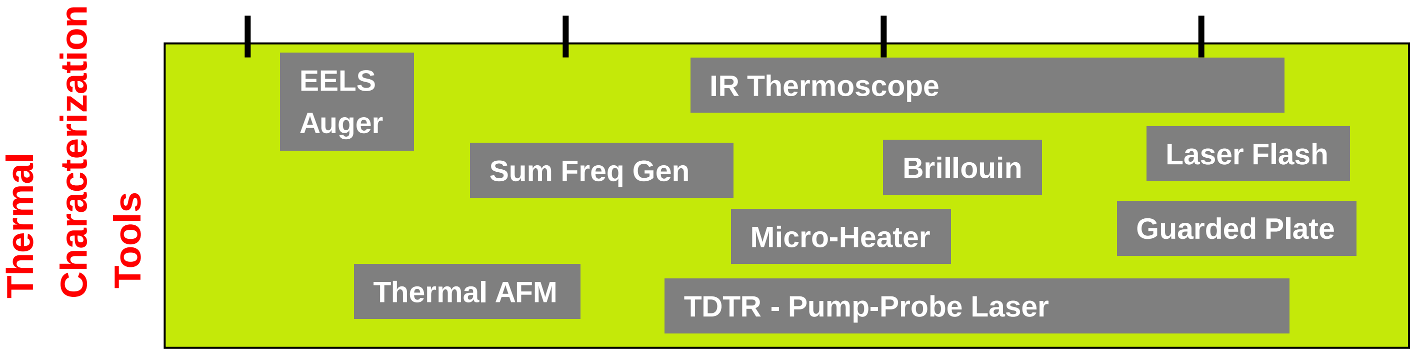


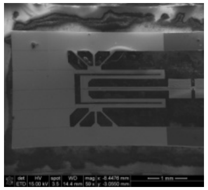
Materials Modeling

- Molecular Dynamics (MD) simulation of Epoxy cross-linking
- MD of thermal transport in cross-linked polymers
- MD of CNT-polymer interface
- MD Wave Packets across interface
- Molecular Mechanics for thermo-mechanical response

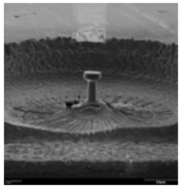
Materials Characterization

- CNT modified durable thermal interface (DTI)
- MEMS-based RTD micro heater design and testing
- FIB micro specimen fabrication and thermo-mechanical in-situ testing
- Thermal AFM, Laser Flash





MEMS RTD micro heater

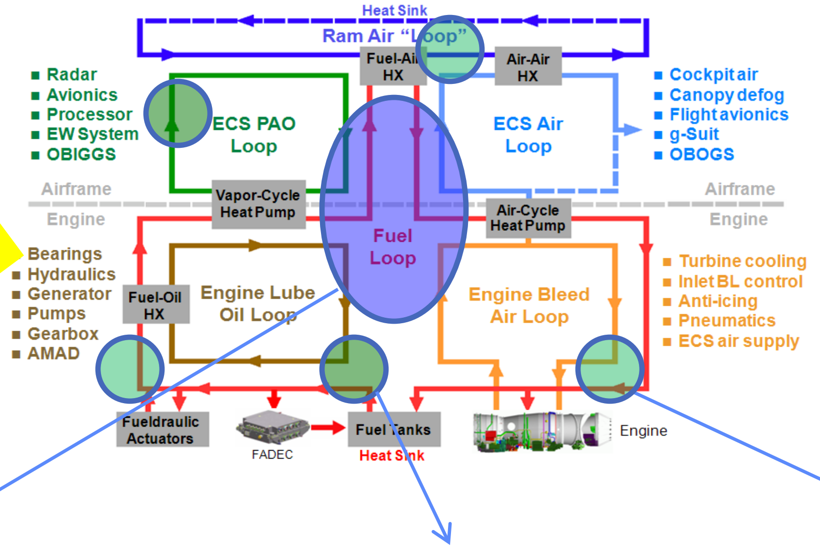


FIB Micro Spec

Strategic Thrusts: Materials to Enable Future AF System Level Thermal Management

Aircraft TM system example from 2007 SAB study

Tech Pull and Tech Push Balance

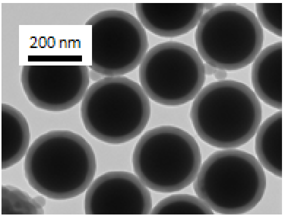


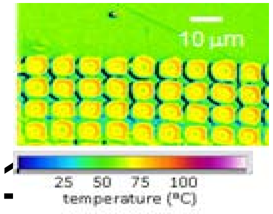
Near term: generate relevant data and help to chose from existing materials.

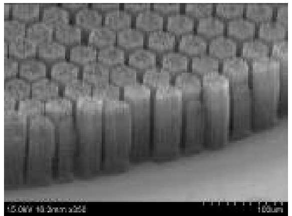
Mid term: support emerging designs (e.g. INVENT, DEW) by material tailoring.

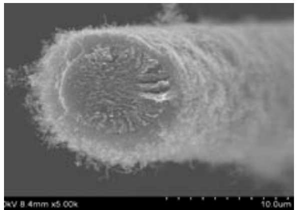
Long term: enable new designs and capabilities with conceptually novel materials.

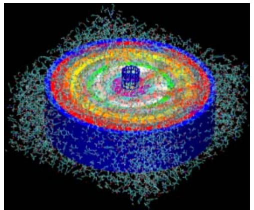
Goals:	Thermal Transport Thrust	Thermal Storing	& Conversion Thrust
Near	• Interfaces for 200-500 W/cm^2 • Solid/liquid interfaces and adaptive capacitance coolants	• Thermal storage materials for 0.5 MJ/kg capacitance	• Scalable Thermoelectrics (TE) tuned for efficiency above state of the art
Mid	• Composites with 600 W/mK • Interfaces for >1,000 W/cm^2	• Thermal storage materials for 1 MJ/kg and 500 W/cm^2 flux	• Two phase coolants and TEs (ZT>2) with wide temperature ranges
Far	• Solid state materials to actively regulate heat flow (e.g. thermal switch and thermal rectifier)	• Thermal storage coupled with energy conversion via multifunctional materials	• Thermal radiating materials with controlled angle and wavelength emission

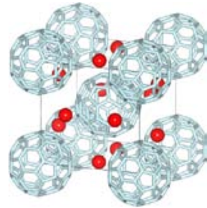








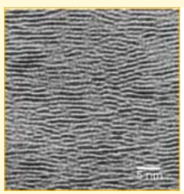


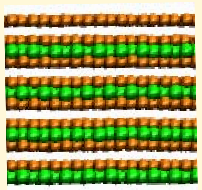


Thermal Response to Physical Properties at Interfaces

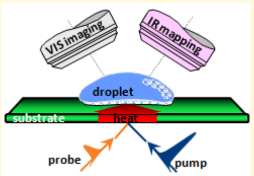
Interface

- **Solid-Solid**
  - Anisotropic crystals

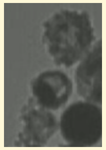


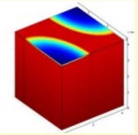


- **Solid-Liquid-Vapor**
  - Boiling phenomena
  - Droplet convection



- **Solid-Liquid**
  - Phase change material (PCM) nanofluids
  - Embedded PCM surfaces





Crystal orientation
Periodic order/disorder

Heat of vaporization
Surface energy

PCM architecture
PCM latent heat
PCM melting point

Response

- **Thermal Conductivity**
  - Phonon group velocities
  - Dominant vibrational modes
  - Phonon scattering

  Impact: Directed heat flow

- **Critical Heat Flux**
  - Bubble nucleation
  - Solid-vapor interface formation
  - Liquid replenishment at interface

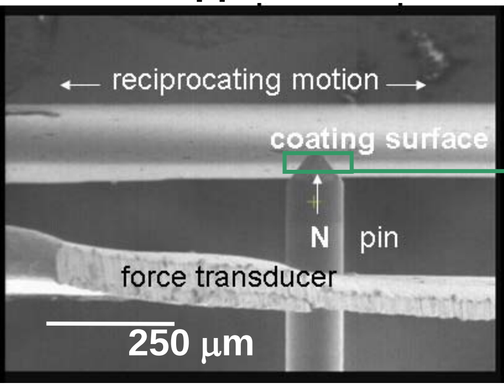
  Impact: Increased thermal limits of safe operation

- **Heat Capacity**
  - Dependence on phase change
  - Time constant limits on cycling

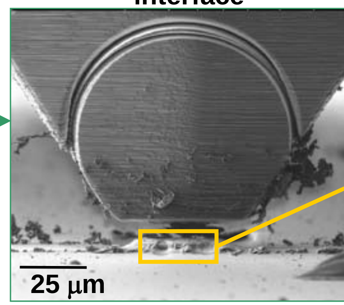
  Impact: Enhanced cooling at target temperatures

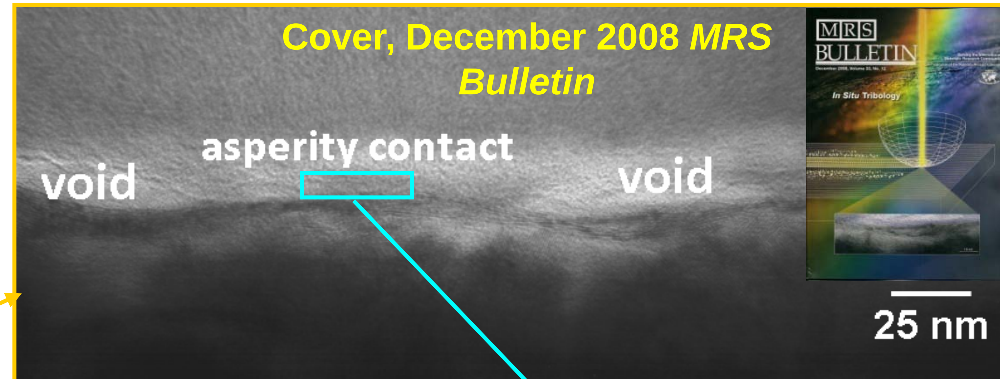
Solid-Solid Interfaces: Dissipation of Frictional Heat and Adaptive Behavior

Test apparatus

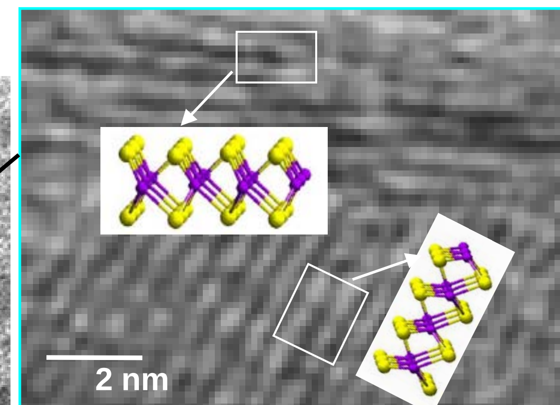


FIB welding of loaded interface

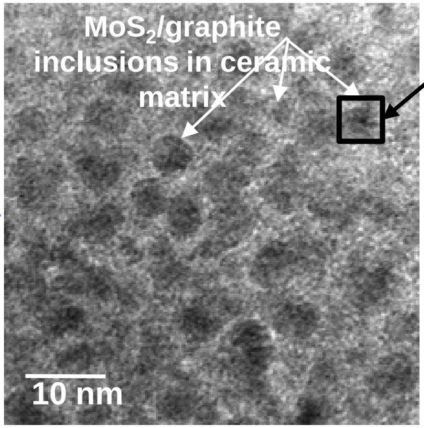




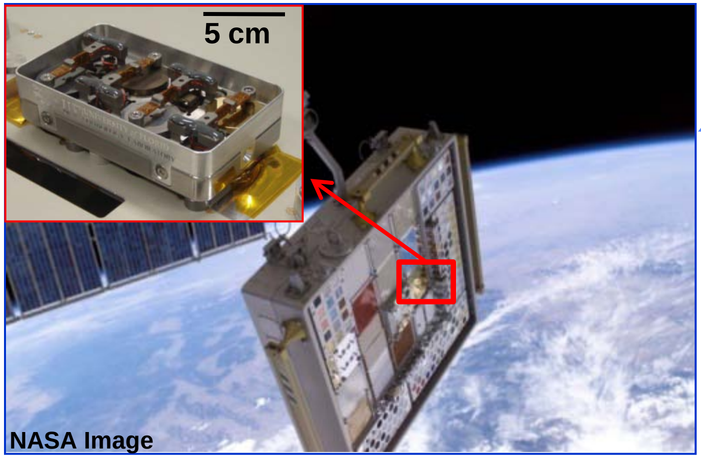
Atomic structure at contact interface



Demonstration of multi-phase nanocomposites for terrestrial & space applications (AFRL/AFOSR MURI/industry collaboration)



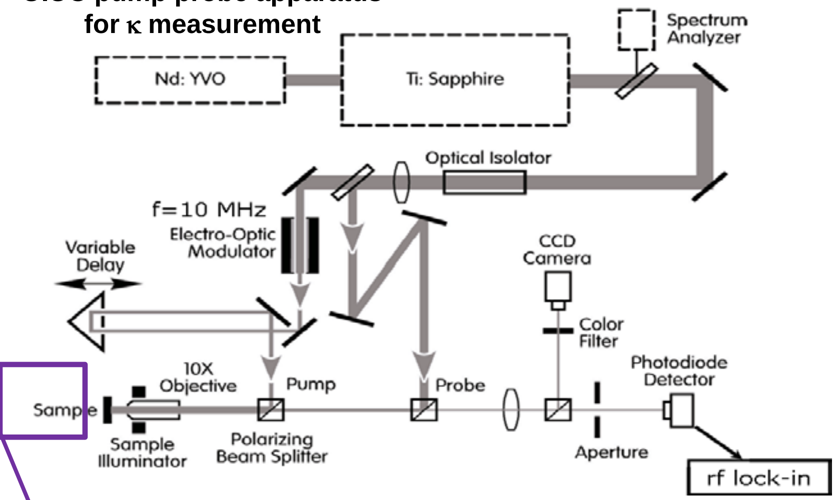
MISSE 7 test-bed

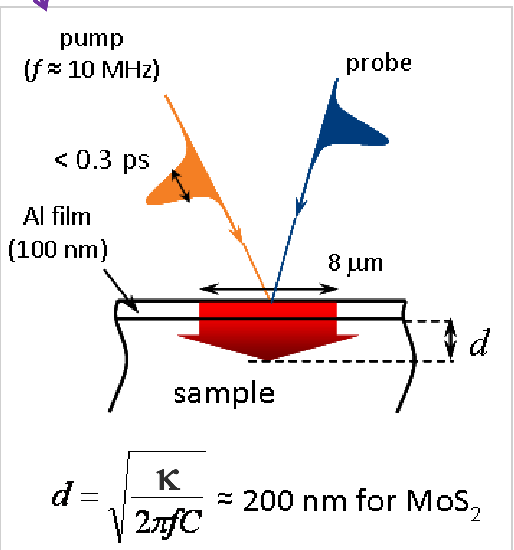


Obvious adaptation of mechanical properties—what about thermal properties of anisotropic crystals?

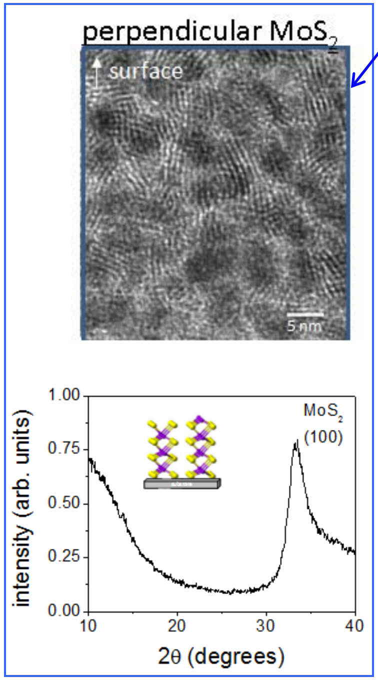
Crystal Anisotropy and Thermal Conductivity

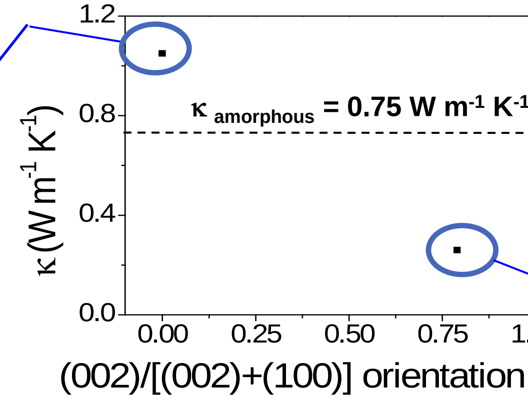
UIUC pump probe apparatus for κ measurement





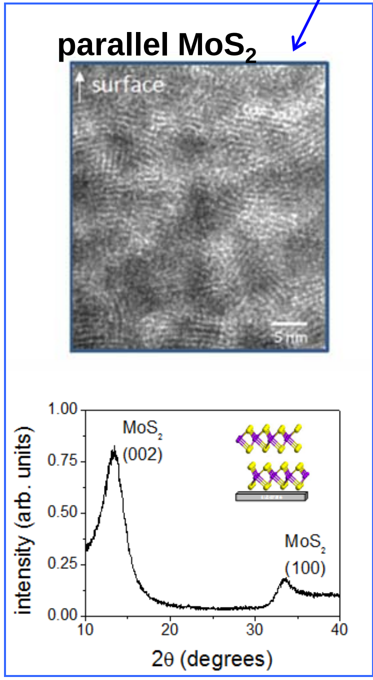
Time-domain thermal reflectance (TDTR) technique is well-suited for examination thin films and interfaces





data courtesy off B. King & D. Cahill at UIUC

Crystal anisotropy alters thermal conductivity and guides heat flow as predicted

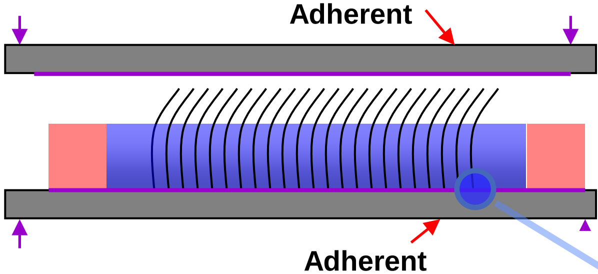


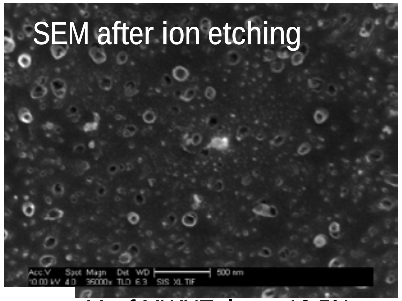
Studies of anisotropic crystals reveal the relationship between thermal conductivity and strength of inter- and intra-layer interactions

POC: Dr. Chris Muratore, RXBT

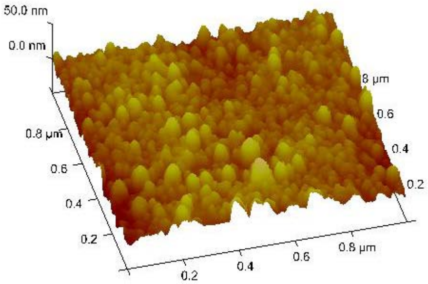
Through-thickness Thermal Conductivity (K_z) of Adhesive Interfaces

Press & Cure

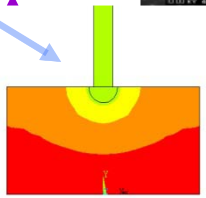




V_f of MWNT tips ~ 12.5%



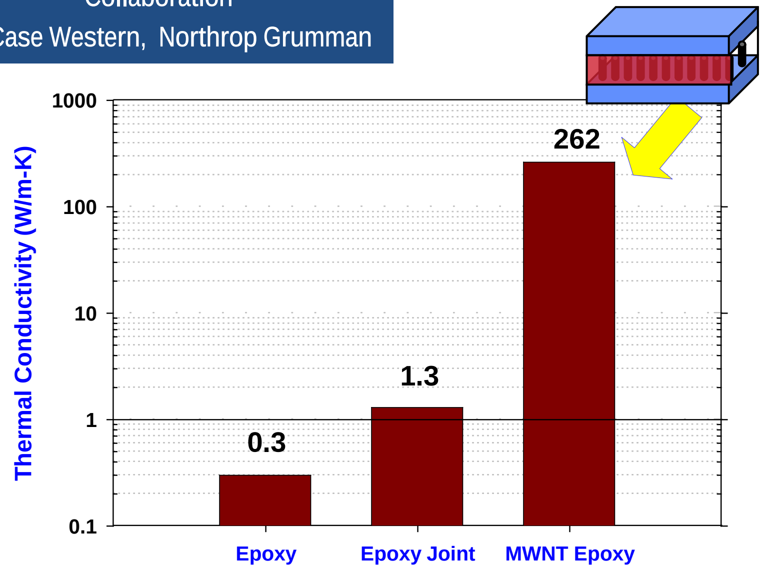
AFM image (peaks) revealing MWNT tips



FEM modeling revealed need for establishing a conductive transition zone between MWNT and adherents

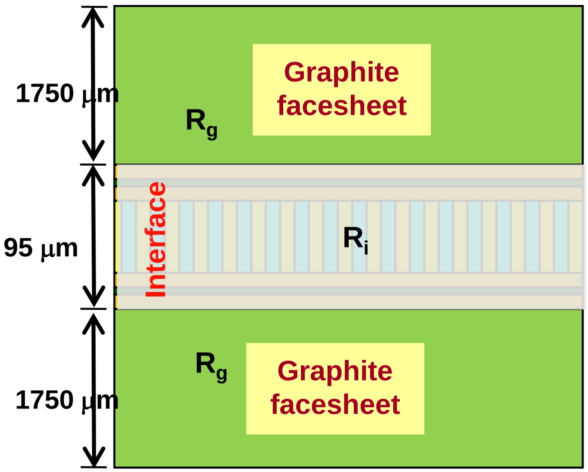
Collaboration
RZ, Case Western, Northrop Grumman

κ_z ~ 262 W/m-K



R_i from Measured κ_z

5.7 mm²K/W



Theoretical Limit

<1 mm²K/W

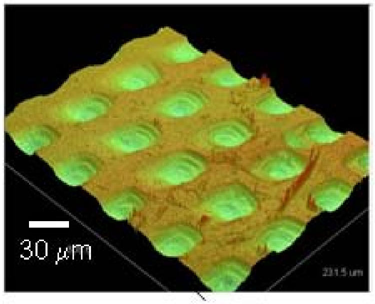
The further reduction of R_i requires understanding the physics of the interface thermal transport at the atomistic scale

Ganguli, et al, Nanoscience & Nanotechnology 2008

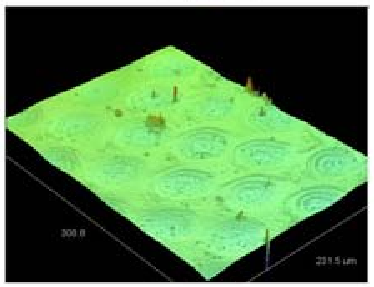
Sihn, et al, Comp Sci Tech, 2007

POC: Dr. Ajit Roy, RXBT

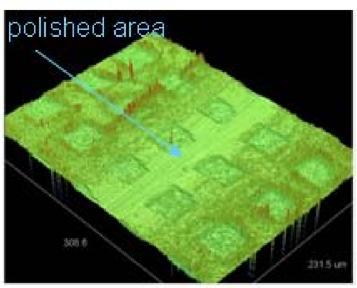
Patterned Phase Change Material (PCM) PCM Surfaces



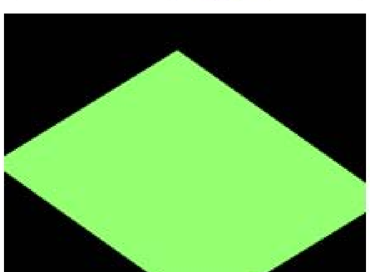
Etching of ceramic coating surface to create pores



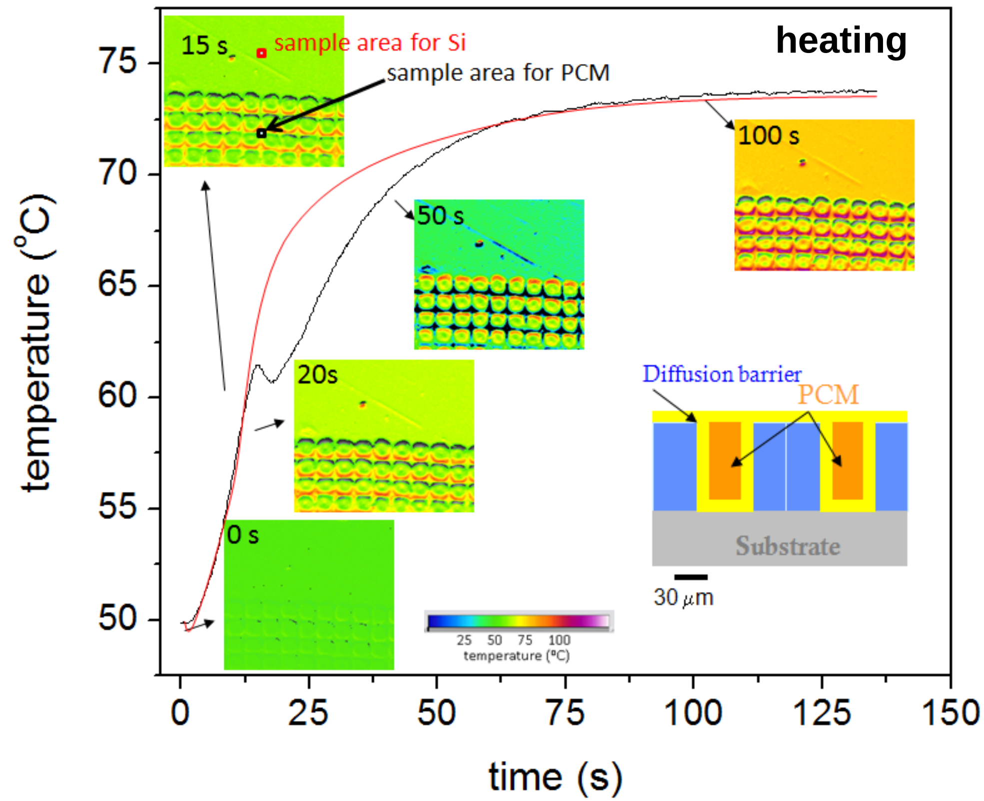
Deposit diffusion barrier followed by PCM



Polish away PCM from surface, leaving behind material in the pores

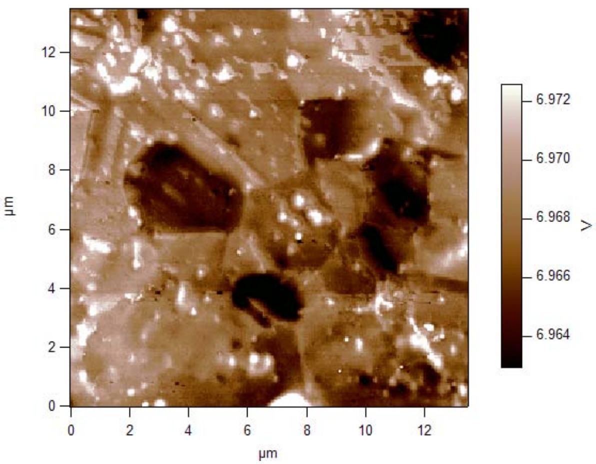


Cap with inert, high temperature diffusion barrier (i.e., HfN)

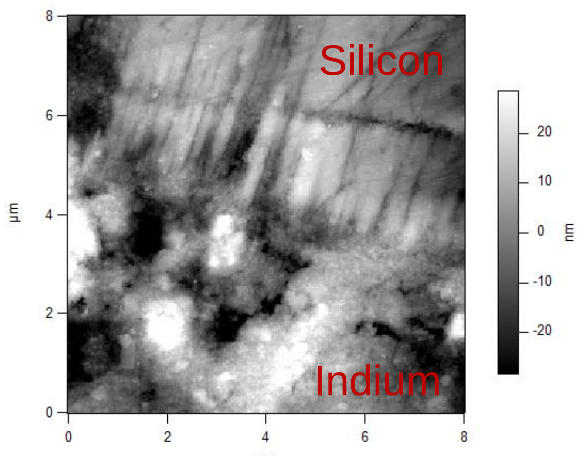


Proof of concept: laser processed 10 µm dimple pattern on a Si surface filled with wax is capable for a short time temperature stabilization.

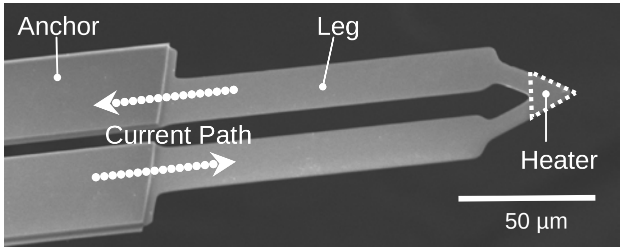
Surface Characterization by Atomic Force Microscopy: Probing Thermal, Electrical, and Mechanical Properties



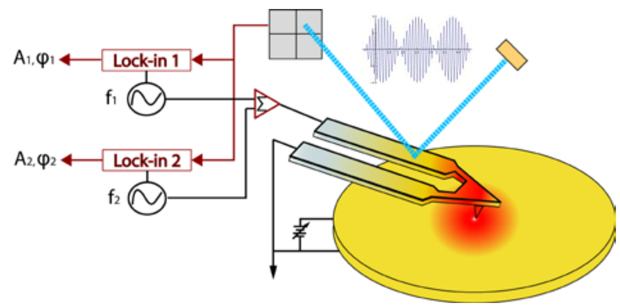
Thermal image of BiSbTe composite generated by continuous measure of cantilever resistance

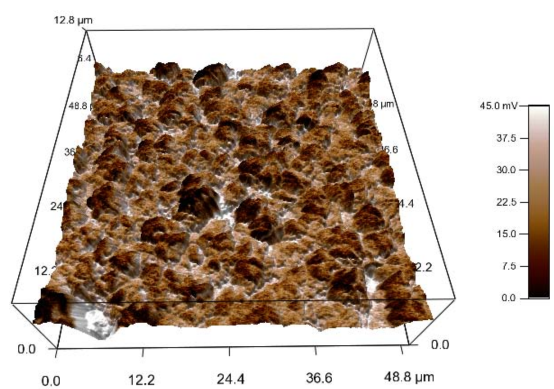


PCM Interface (Topography)



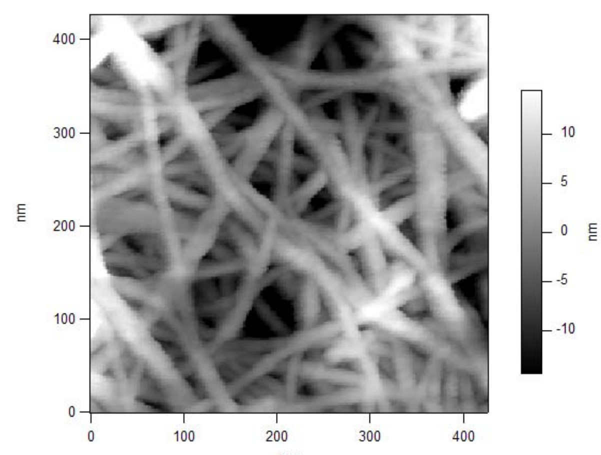
Multi-frequency AFM to study mechanical dissipation as a function of temperature (Local Thermal Analysis)





Surface Potential Map of Graphite Structures

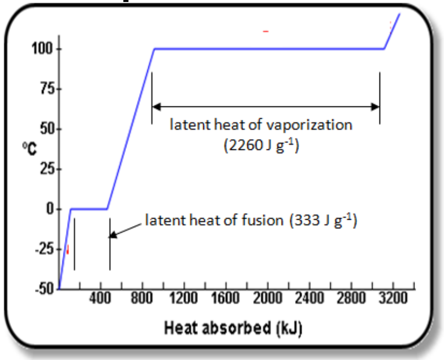
Courtesy Asylum Research



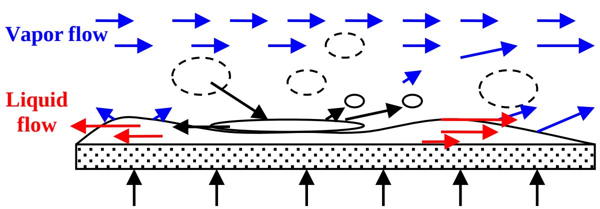
CNT Membrane (Topography)

Thermal Characterization of solid-liquid-vapor interfaces

Evaporative heat removal

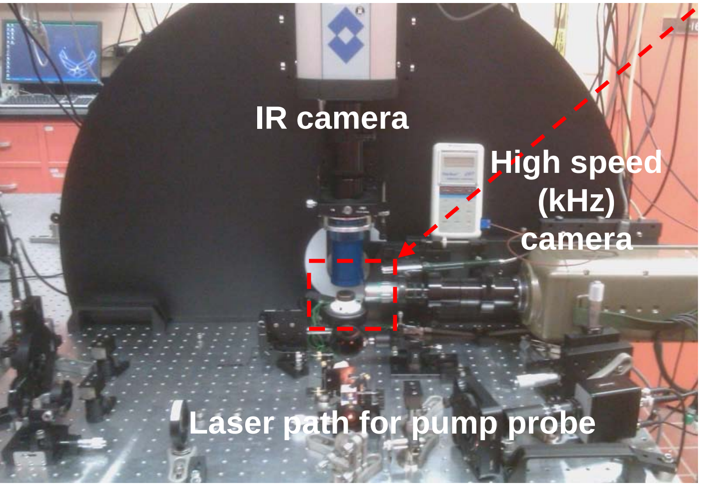


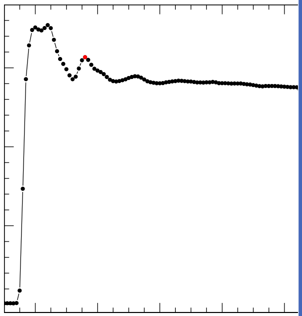
Droplet dynamics on heated surface



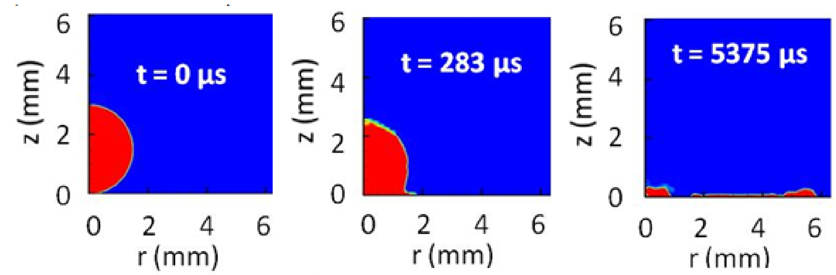
USAF Predator MQ-1 employs spray cooled electronics

Imaging & characterization apparatus

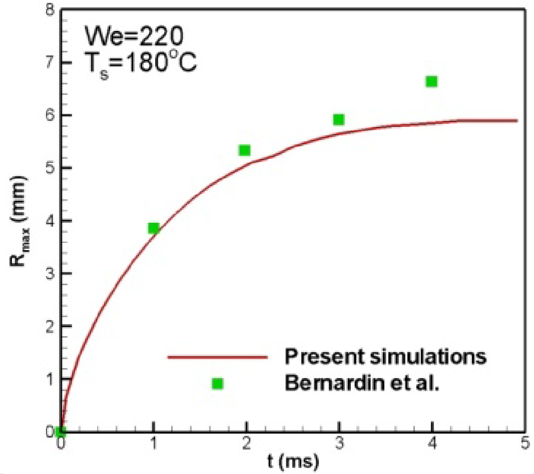




Droplet simulations (collaboration with AFRL Propulsion Directorate)



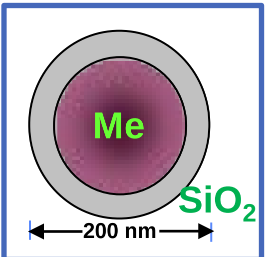
Relationship between drop inertia and surface tension dictates droplet morphology and cooling performance



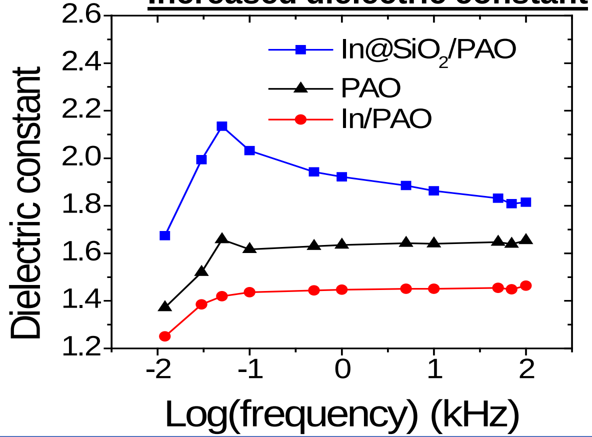
In situ **high-speed imaging, IR thermal mapping coupled with Time Domain Thermoreflectance (TDTR) for comprehensive studies of spray cooling at engineered interfaces**

Solid-Liquid Interfaces: Coolants with Multifunctional PCM Additives

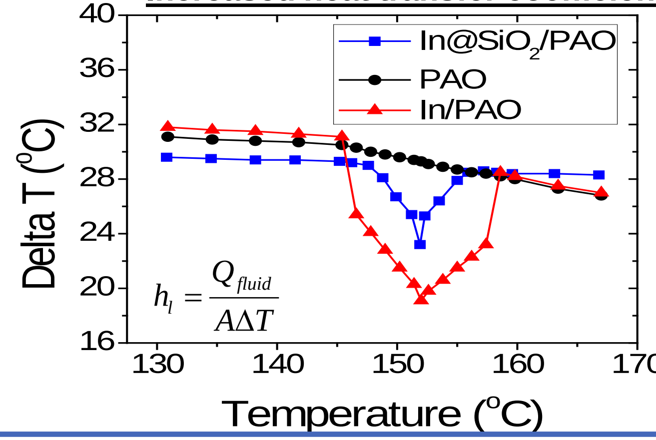
collaboration with
U. Central FL
ACS Nano, in press



Increased dielectric constant

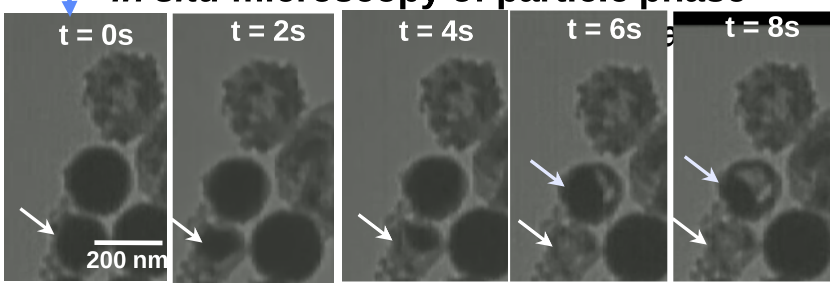


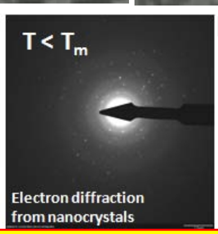
Increased heat transfer coefficient



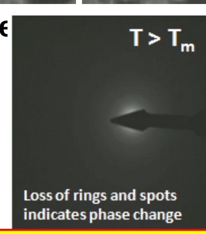
PAO -based coolant properties measured in heat transfer loop

In situ microscopy of particle phase



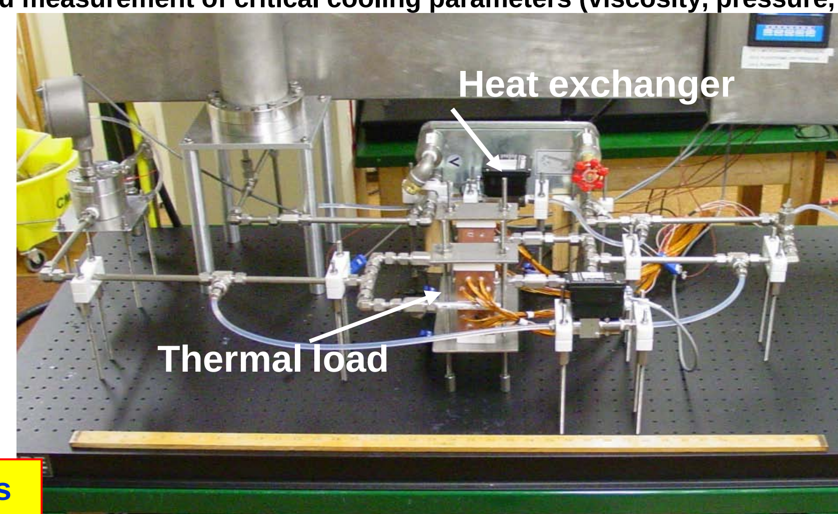


Reversible phase change in a single loop at flow rate of 0.3 ms^{-1}



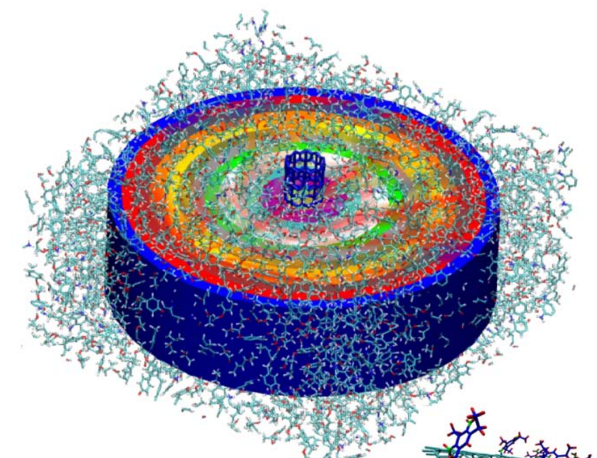
Avionics coolant simulator

-in situ measurement of critical cooling parameters (viscosity, pressure, etc.)

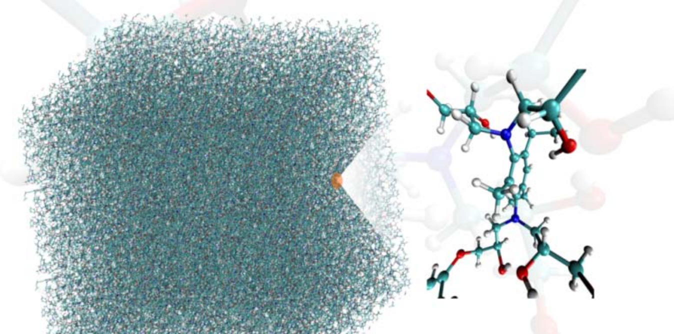


Addition of encapsulated PCM nanoparticles to standard coolants for increased dielectric strength and heat transfer coefficient

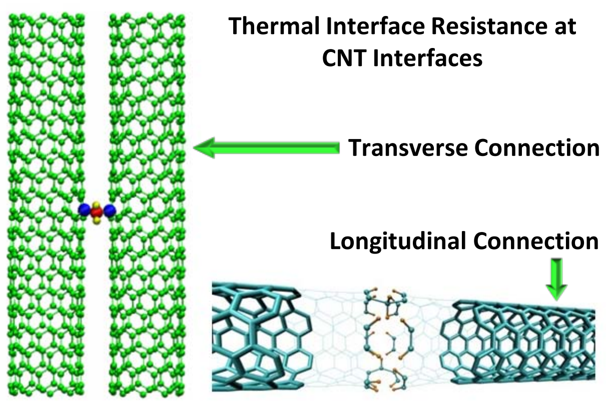
Various Thermal Transport Projects



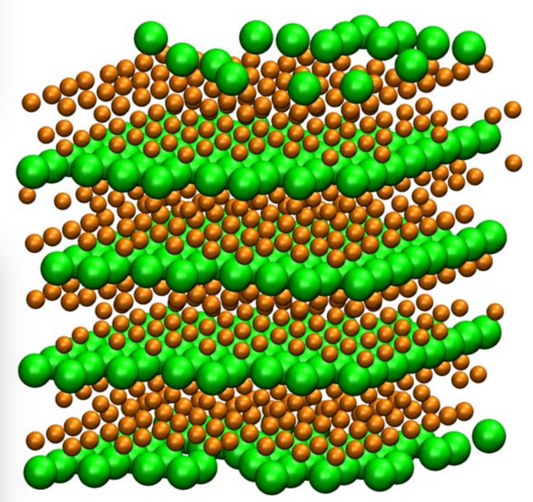
Thermal Interface Resistance at CNT/Matrix Interface



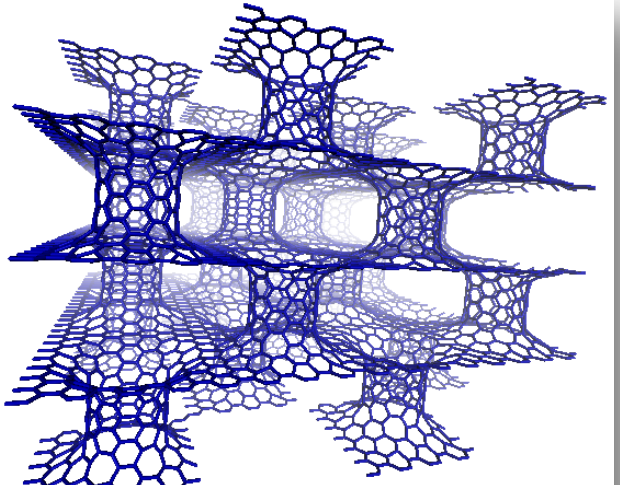
Thermal Transport in Epoxy Networks



Thermal Interface Resistance at CNT Interfaces



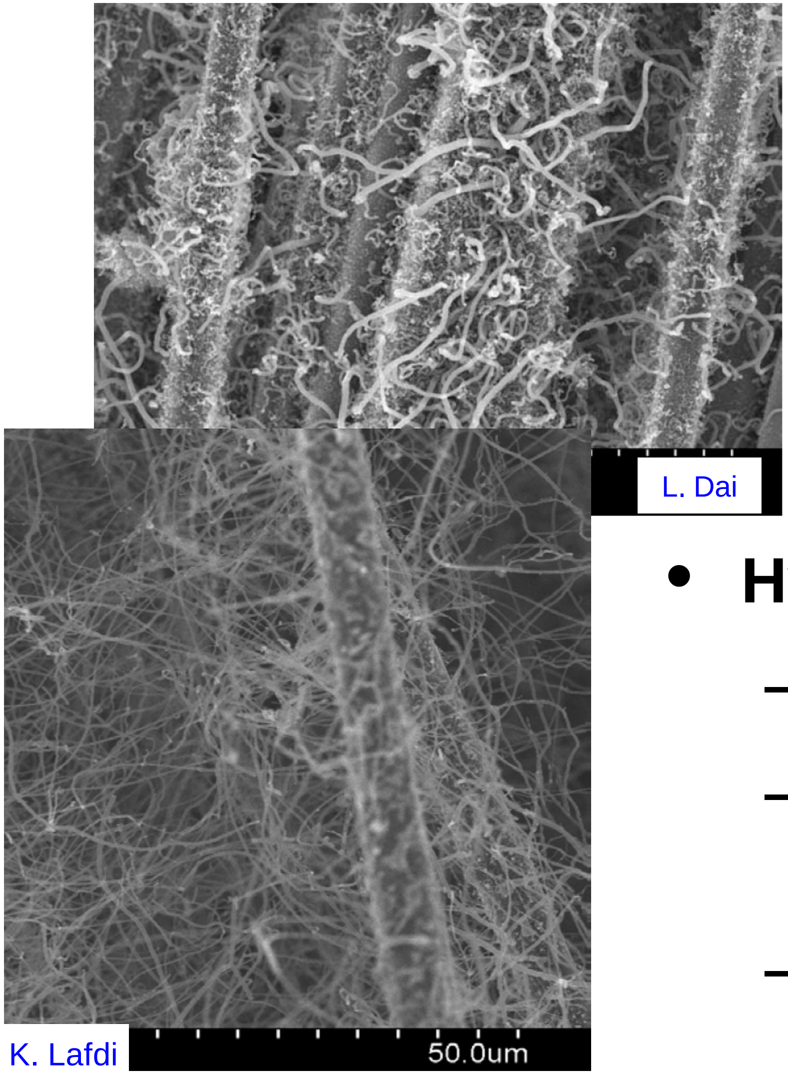
Thermal Transport in Layered Structures (MoS_2)

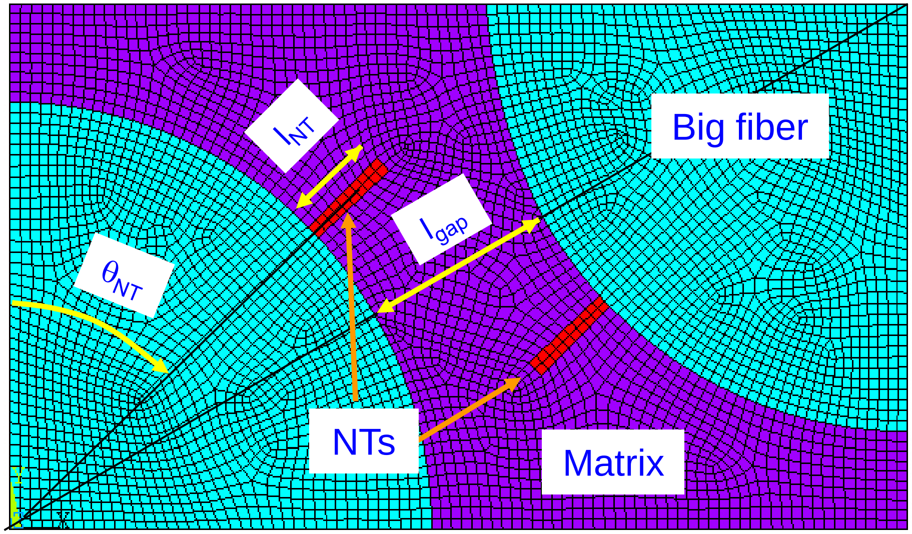


Thermal Transport in Pillared Graphene Structures

POC: Dr. Ajit Roy, RXBT

CNTs Grown on Big Fibers
Hybrid Carbon Fibers for Improved Thermal Transport

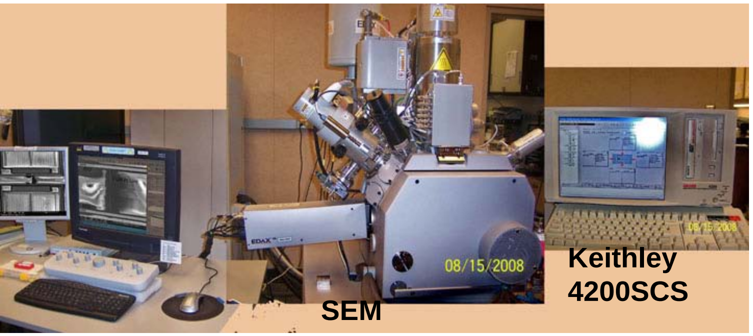




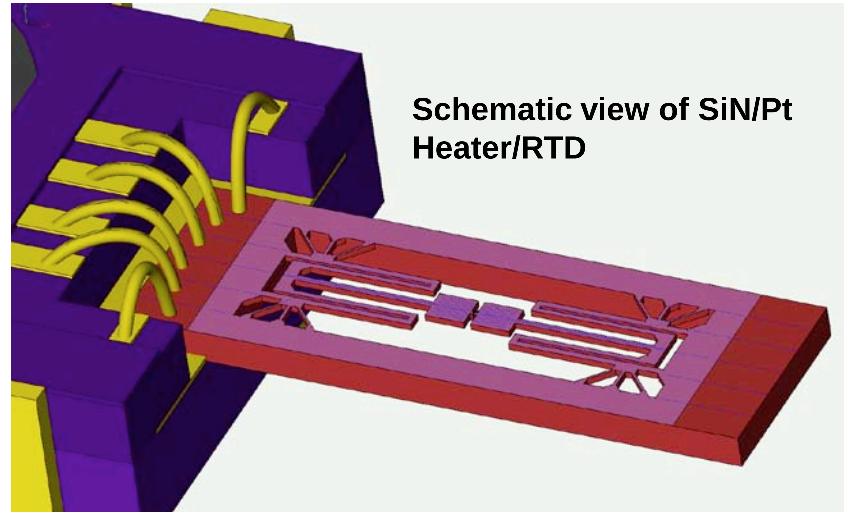
- **Hybrid carbon fibers**
  - **CNT grown on carbon fibers**
  - **CNTs to make contact with each other**
  - **To make pathways for thermal transport through the matrix**

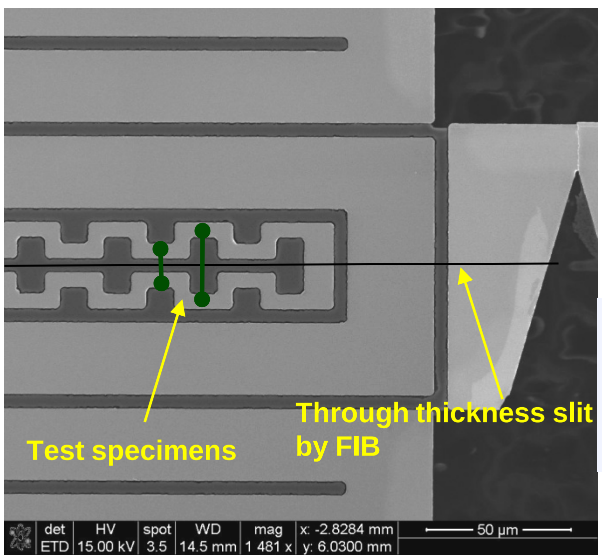
POC: Dr. Ajit Roy, RXBT

Sub-micron Scale Thermal Conductivity Measurement



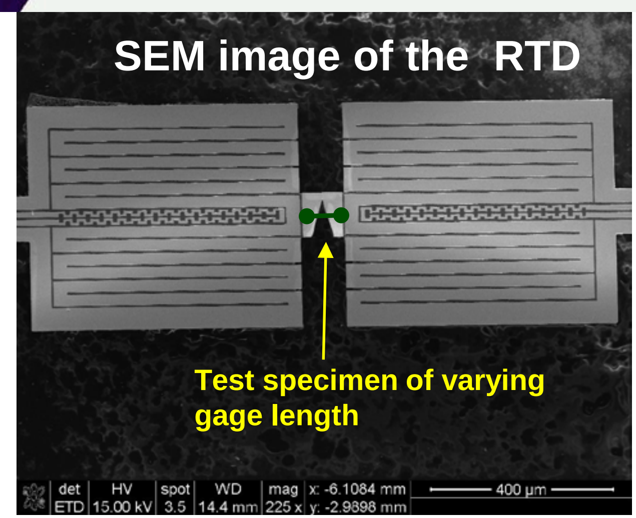
Resistance Temp Detector – RTD





Collaboration
Metal sub-CTC, Army, AFIT

Another test configuration using the RTD



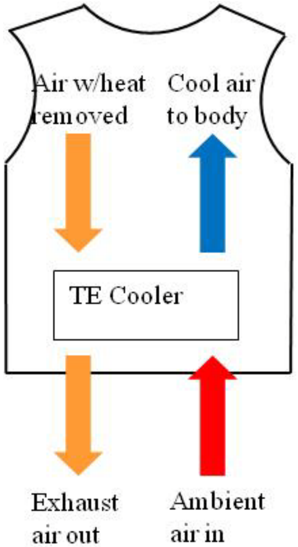
Versatile RTD design for nano- to sub-micron scale direct thermal conductivity measurement

POC: Dr. Ajit Roy, RXBT

Directionally Tailored Thermal Management Materials

- Develop condensed-phase materials to manage high thermal fluxes, control temperatures, harvest waste thermal energy, and enable real-time reconfigurable thermal management
- Improved thermal management materials will improve performance, reduce weight, reduce cost, and increase maintainability/ survivability of critical AF weapons systems
- Transition path to DEW and spacecraft applications through AFRL and external partners
- Focus on novel chemistries for:
  - Thermoelectrics
  - Thermal energy storage
  - Asymmetric heat transfer

Pilot Cooling Vest



Spacecraft

Directed Energy Weapon

New Thermoelectric Materials

Refrigeration, Heating, Heat Lift & Rejection, Energy Harvesting

AF Impacts	*Advantages*
Lasers	*Precision Temp Control*
Satellites	*Reconfigurable, Long Life, No Vibrations*
Pilot Suits	*Independent of Orientation & g-forces*
UAVs, Sensors	*Efficient for small applications*
Electronics	*Solid State, switchable*

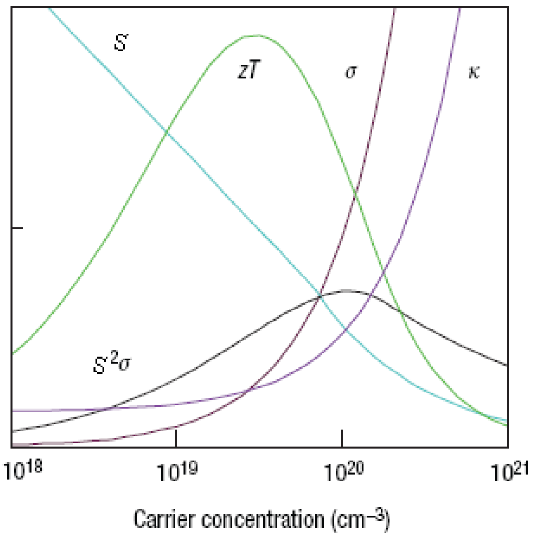
Material Challenges

- Efficiencies (high σ, Σ; low κ)
- Toxicity (Pb, Te)
- Brittle
- Heavy / High Density
- Rare & Expensive Elements
- Scalability

Figure of merit: ZT

$$ZT = \frac{\sigma S^2 T}{\kappa}$$

- σ Electrical conductivity (S/cm)
- S Seebeck coefficient (μV/K)
- T Temperature (K)
- κ Thermal conductivity (W/mK)

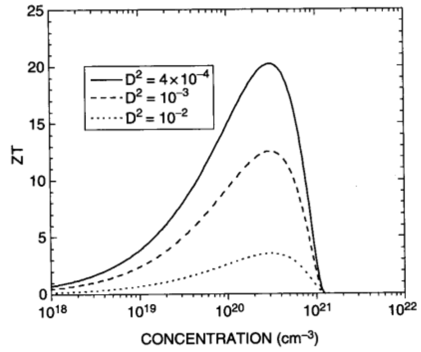


APPROACH: new material classes leading to *scalable*, lower density, lower cost, non-toxic, more efficient thermoelectric performance.

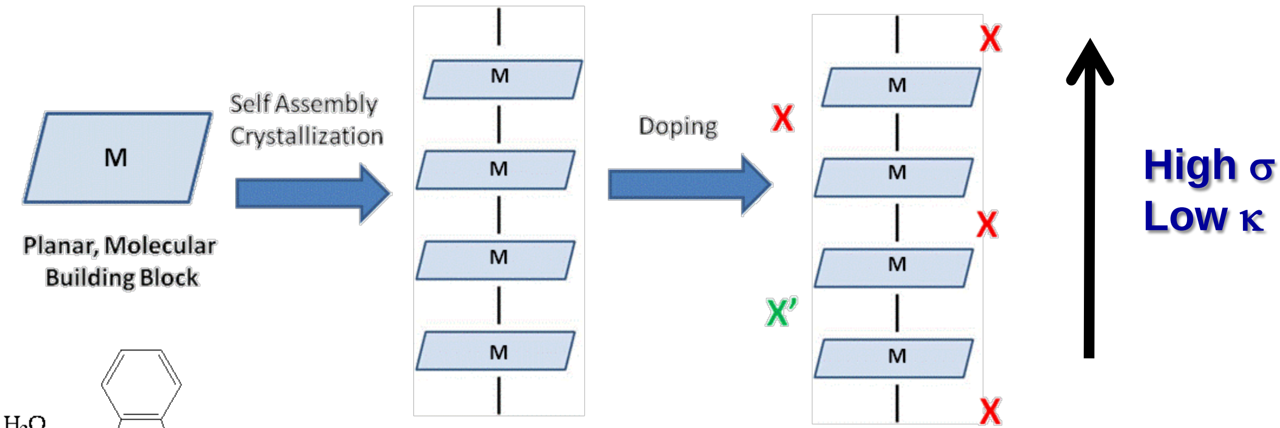
POC: Dr. Doug Dudis, RXBT

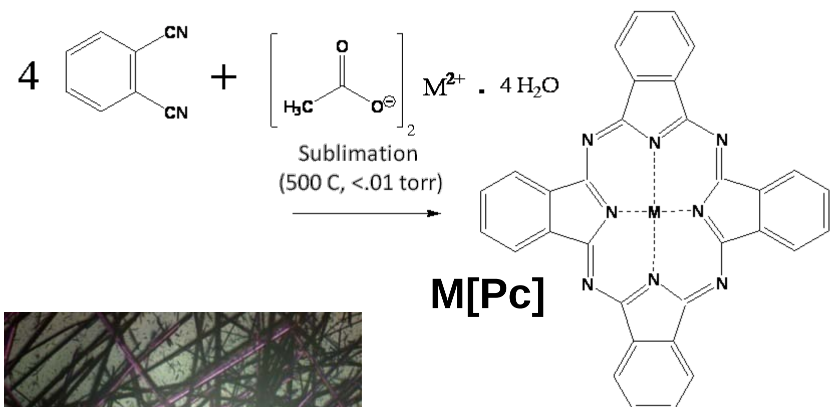
1-D Self-Assembled Charge Transfer Nanowires

Predicted ZT ~ 20
(Casian, 2006)

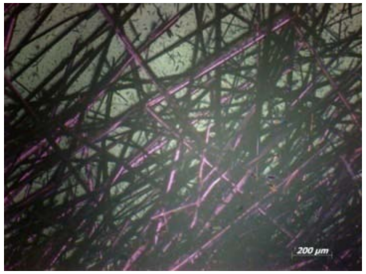


<u>Phthalocyanine Advantages:</u> High Purity, Thermally Stable
Wide choices of M (Cu, Co, Si, Pb, etc) & Dopants

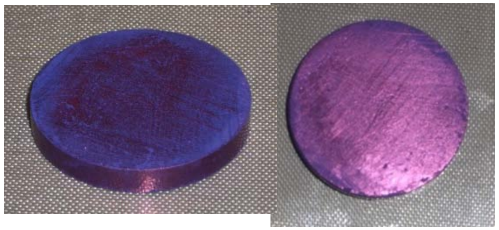




Dopants act as rattlers (phonon scatterers)
Mixed dopants lower κ by alloying effect
Seebeck (literature): 1 μV/K to 1 V/K



Grind
Compress



Thermal Conductivity: 0.3 W/mK
(~ 1/10 SOA TE Materials!)
Stable (600 C) Doping Achieved
(in vacuum; stable to solvents)

POC: Dr. Doug Dudis, RXBT

Ongoing Research Highlights

- ***advanced coolants*** **with extended temperature range and thermal capacity using single and two-phase operation, synthetic chemistry and nanoparticles;**
  (Dr. J. Jones, Dr. C. Hunter)

- ***tailored and adaptive thermal conductivity interfaces*** **using metal-ceramic multilayer thin films, carbon-nanotube (CNT) arrays, polymer-CNT structures, and micro-encapsulated phase change materials (PCMs);**
  (Dr. C. Muratore, Dr. J. Jones, Dr. A. Roy, Mr. R. Gerzeski)

- ***high and directional thermal conductivity materials*** **using CNTs and carbon fibers, carbon and metal foam structures;**
  (Dr. K. Strong, Dr. A. Roy)

- ***thermal energy conversion and storage materials*** **using PCMs and thermoelectric layered and composite structures;**
  (Dr. D. Dudis, Dr. K. Strong)

- ***high-temperature mechanical sliding interfaces*** **with adaptive tribological response and heat flow control using nanocomposites of ceramics, metals, dichalcogenides;**
  (Dr. C. Muratore)

- ***modeling of thermal flow in nanostructured materials*** **using multiscale MD and FEM computations for material designs**
  (Dr. A. Roy)