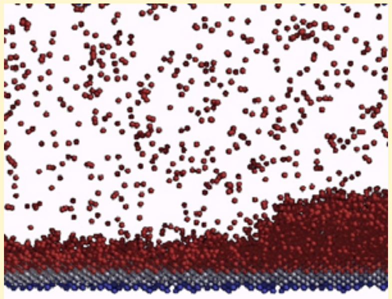
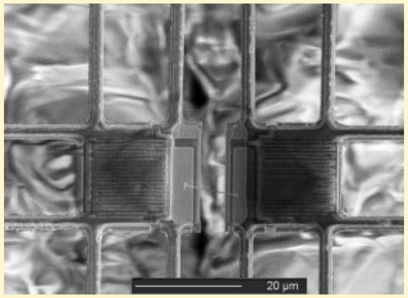
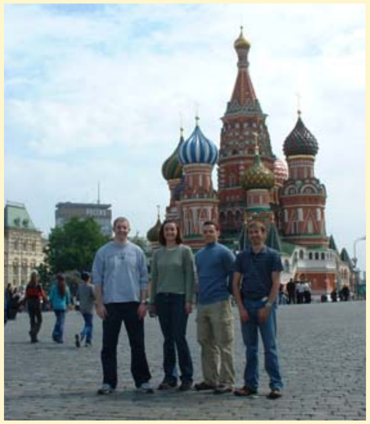
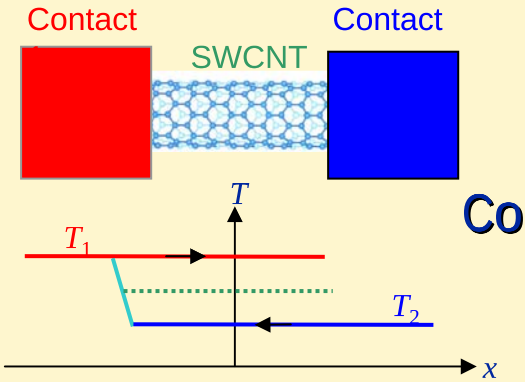
ITHERM 2006 San Diego, CA June 2, 2006

The Engineering of Small Scale Thermal Systems: A National Science Foundation Perspective









Alfonso Ortega

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The National Science Foundation
http://www.nsf.gov/eng/cts/presentations/

Outline

Research impact and the role of NSF

Small scale thermal systems—a contemporary driver for research in thermal transport

Examples of NSF supported research that impact thermal systems for electronics thermal management

Opportunities and Directions

The Nature of Engineering Research

All engineers work on the development of systems, in one way or another

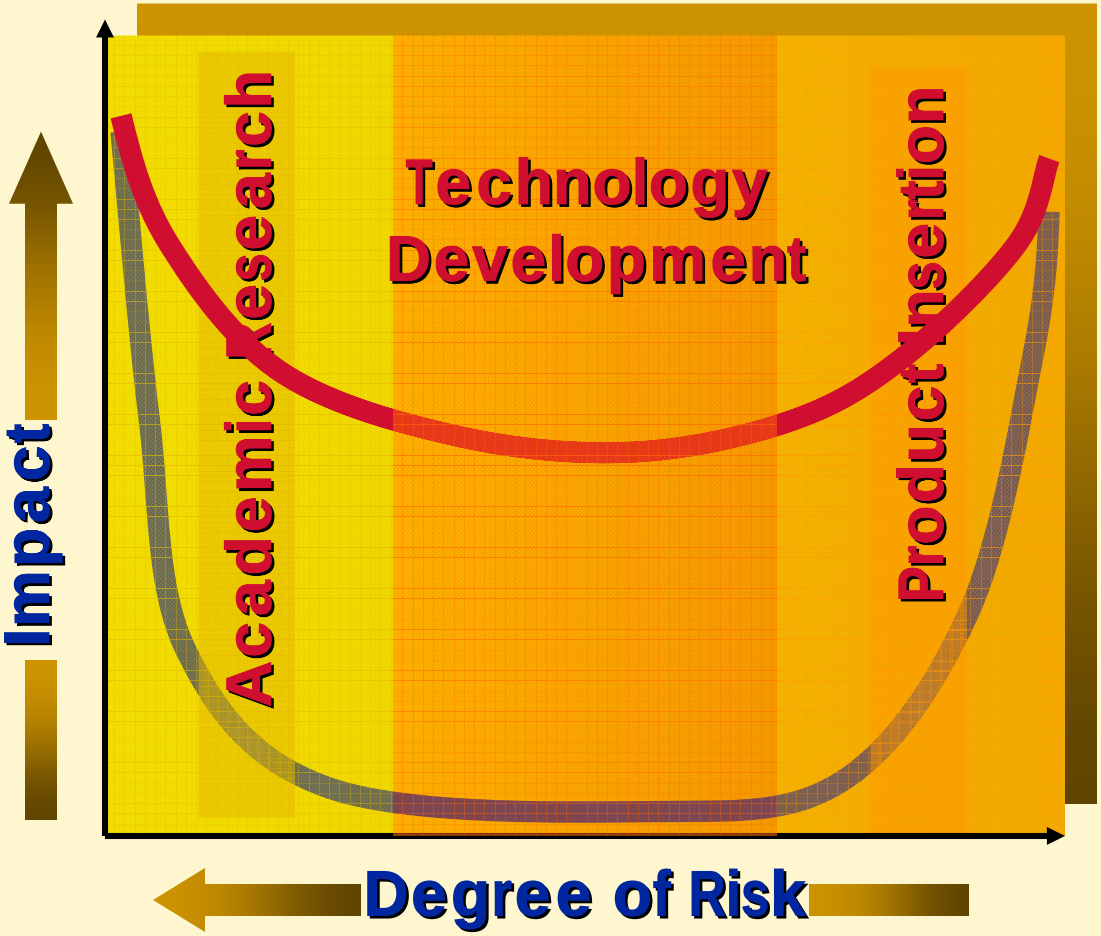
Fundamental engineering research is not system specific

Applied engineering research is system specific

Both are necessary for the development of useful systems

Engineers do not need to apologize for working on real systems. That’s what we are paid to do

The Impact of Research



Academic Research

Technology Development

Product Insertion

Impact

Degree of Risk

Very Fundamental

Very Applied

NSF's Role in Engineering Research

Very Fundamental

Very Applied

NSF's Role in Engineering Research

Enable Fundamental research

That is INNOVATIVE

That has IMPACT

Impact on Engineering Science

Impact on Technology and Society

Impact on People

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Opportunities and Directions

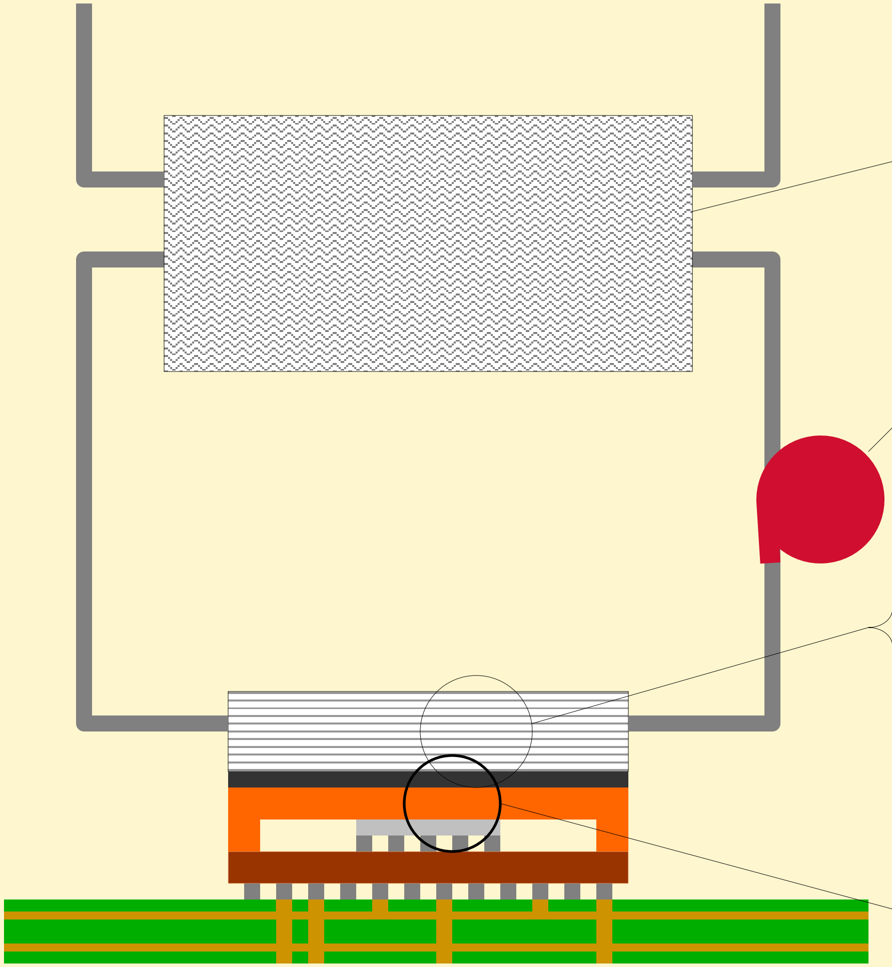
Technology Drivers for Research in Thermal Transport

Nuclear and conventional steam power generation has driven research in multi-phase flow and transport for 50 years

Terrestrial and aerospace propulsion has provided the technology driver for convective transport research for 60 years

Electronics thermal management is the single most important contemporary technology driver for thermal transport research

Small Scale Thermal Systems for Electronics Cooling



High efficiency highly compact heat exchangers: liquid to gas or liquid to liquid

Small scale low power pumping

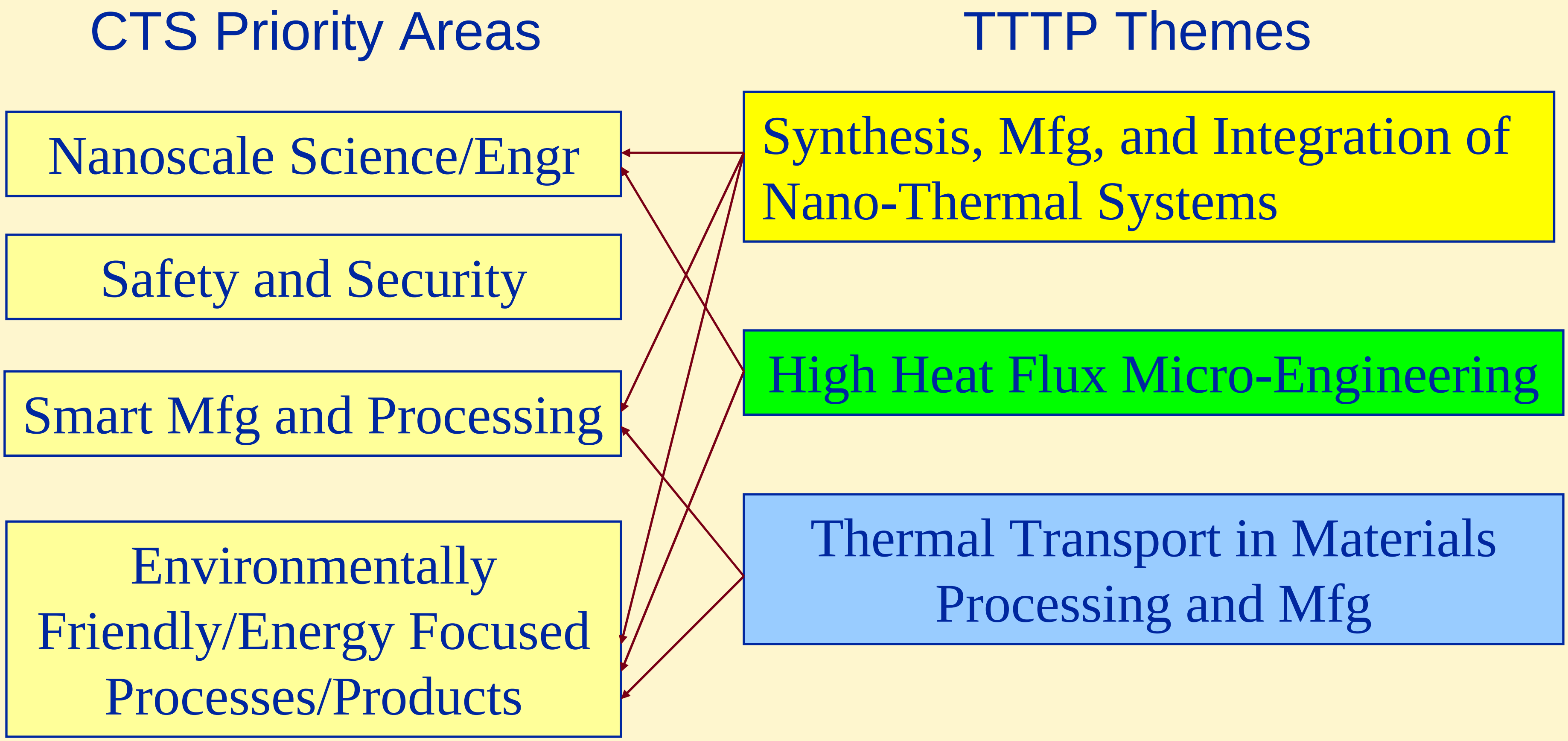
- Mini / micro-channel heat exchanger; single phase or multiphase
- Nanofluid heat exchange

- Non-continuum electron/phonon transport in thin films and solid-state devices
- Interfacial phenomena transport
- Thermoelectric heat pumping

NSF TTTP Program Scope

- Phase change (liquid/vapor; solid/liquid)
  - High speed annular flow; microscale condensation and evaporation; multi-component solidification; nano-enhanced boiling phenomena
- High heat flux applications, especially at small length scales
  - Microchannel flows; microelectronics cooling
- Complex flow processes (in terms of driving forces, geometry, etc.)
  - Turbulent combustion with radiation; turbulence with real surface roughness; magnetic and electric fields; building flow environments
- Manufacturing and materials processing
  - Laser materials interactions; optical fiber drawing; MEMS processing; crystal growth; thin film processing
- Nanoscale transport phenomena
  - Energy conversion devices; semiconductor devices; multiscale conduction; interfacial phenomena; sub-nano second thermal transport; nanoscale thermal instrumentation; nanofluids; nano-materials processing
- Properties
  - Thermal/electrical properties of nano-structures: Non-isotropic conductivity; thermal properties of thin films; shape memory alloys; high temperature gas radiative properties
- Design, control and optimization
  - Inverse design; 2nd Law optimization; active control of convection

TTTP Research Themes Relative to CTS Priority Areas



CTS Priority Areas

Nanoscale Science/Engr

Safety and Security

Smart Mfg and Processing

Environmentally Friendly/Energy Focused Processes/Products

TTTP Themes

Synthesis, Mfg, and Integration of Nano-Thermal Systems

High Heat Flux Micro-Engineering

Thermal Transport in Materials Processing and Mfg

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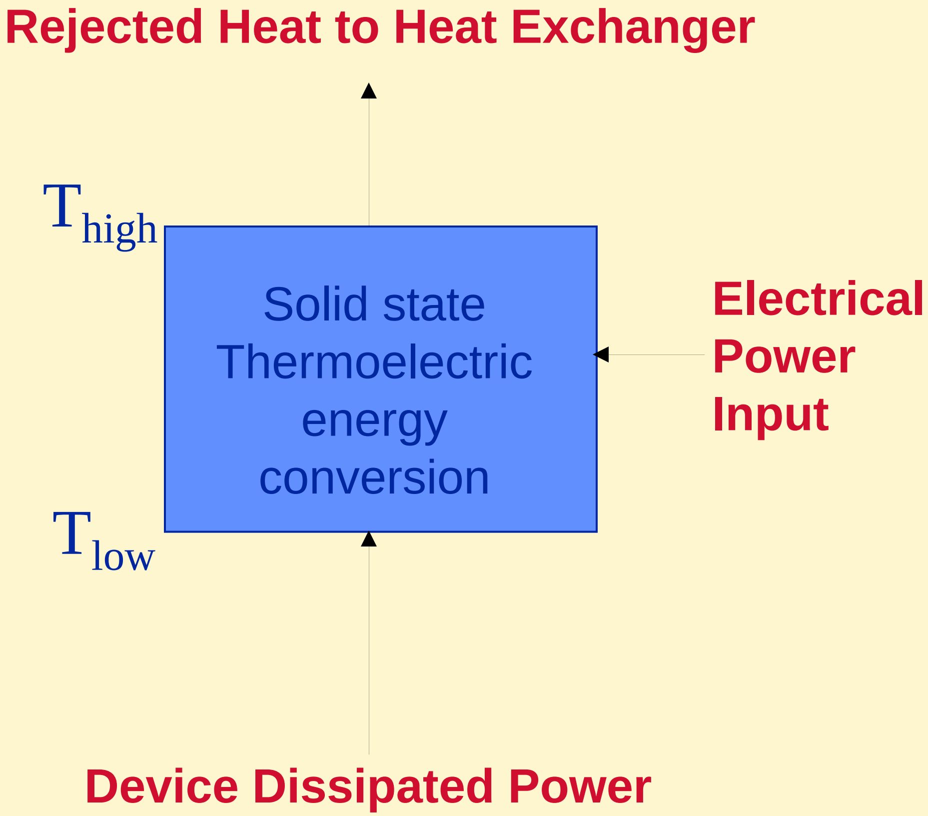
Opportunities and Directions

NSF Award 0506830 NIRT

Integrated Study of Thermoelectric Transport and Energy Conversion in Bismuth-Based Nanowires

Gang Chen et al. (MIT)



The use of thermoelectric energy conversion has been hampered by low efficiencies

The efficiency scales with the following figure of merit:

Joule Heating

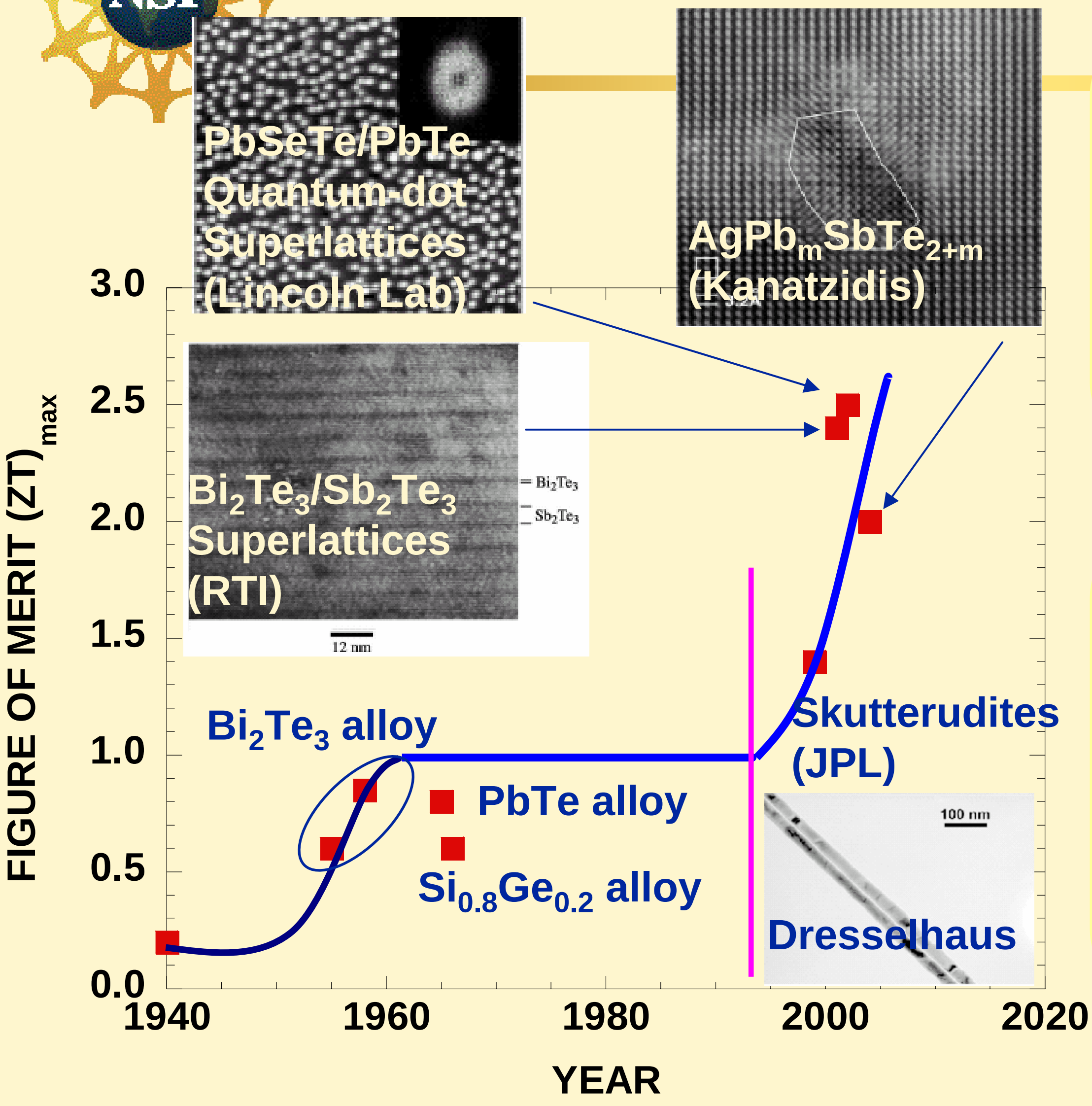
Seebeck Coeff. Electron Cooling

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

Reverse Heat Leakage Through Heat Conduction

The use of nanocomposites shows great promise for greatly improving efficiencies

State-of-the-Art in Thermoelectrics



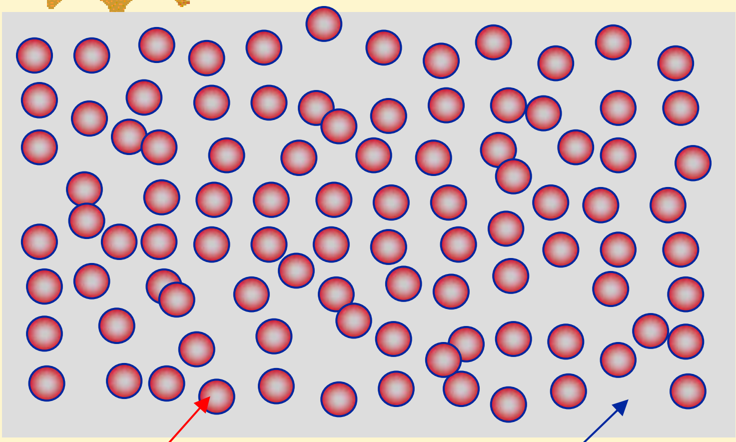
PbTe/PbSeTe	Nano	Bulk
$S^2\sigma$ (μW/cmK^2)	32	28
k (W/mK)	0.6	2.5
ZT (T=300K)	1.6	0.3

Harman et al., Science (2003)

Bi$_2$Te$_3$/Sb$_2$Te$_3$	Nano	Bulk
$S^2\sigma$ (μW/cmK^2)	40	50.9
k (W/mK)	0.6	1.45
ZT (T=300K)	2.4	1.0

Venkatasubramanian et al., Nature, 2002.

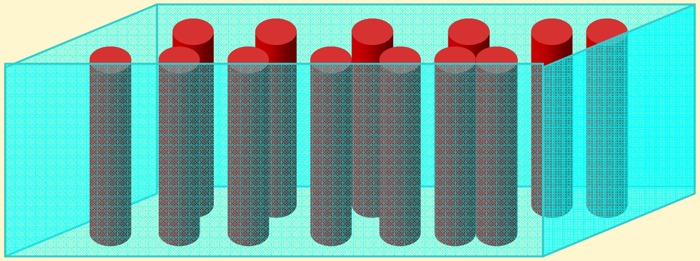
Transport in Nanocomposites



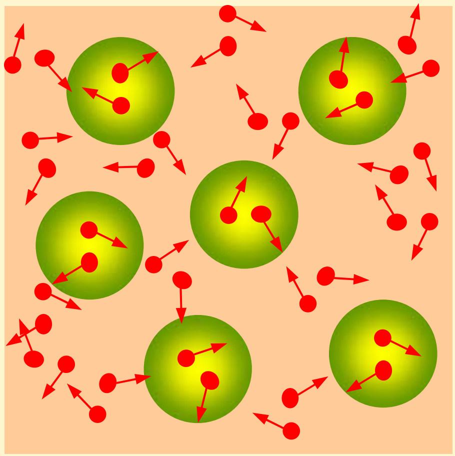
Si Nanoparticle Ge Host

- **Challenges:**

  Random structure
  Variable particle diameter
  Large computational power
  Phonon transport
  Electron transport



2D Period Structure



Monte Carlo Simulation

The promise of nanocomposites

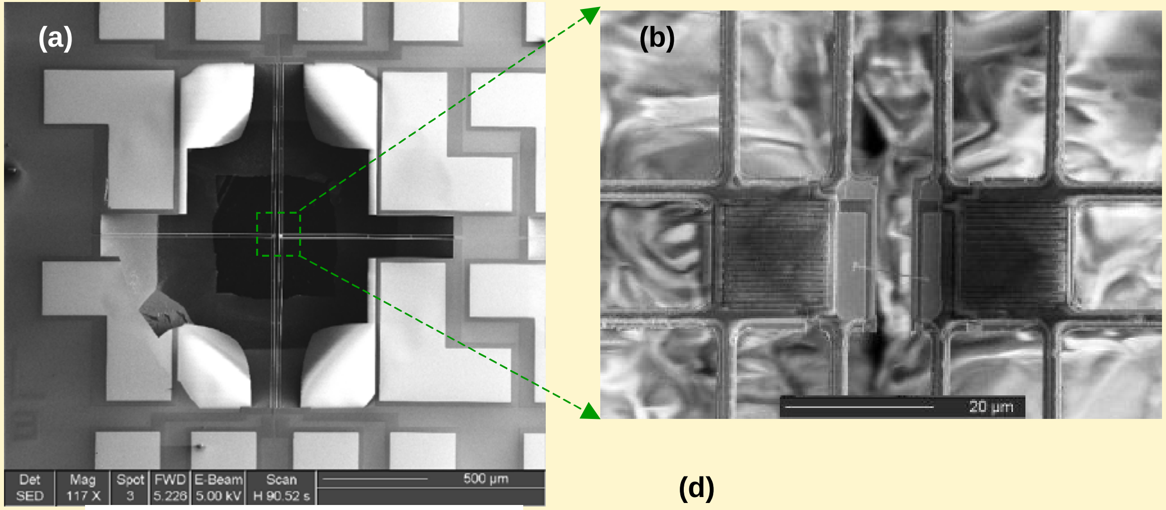
- Engineered nanomaterials hold great promise for energy conversion.
- Significant progress has been made in the ability to simulate thermal (phonon) and electrical (electron) transport
- Nanocomposites can improve thermoelectric figure-of-merit by reducing phonon thermal conductivity while increasing electron power factor.

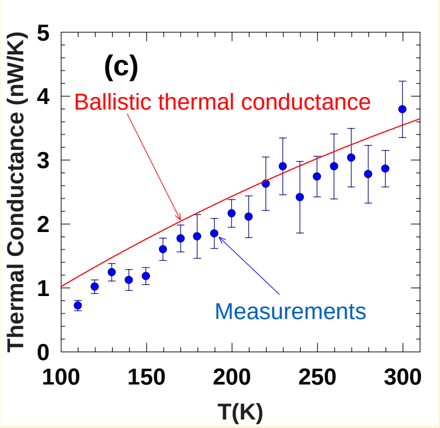
- The figure of merit has more than doubled in the past five years as a result of nanoengineering!

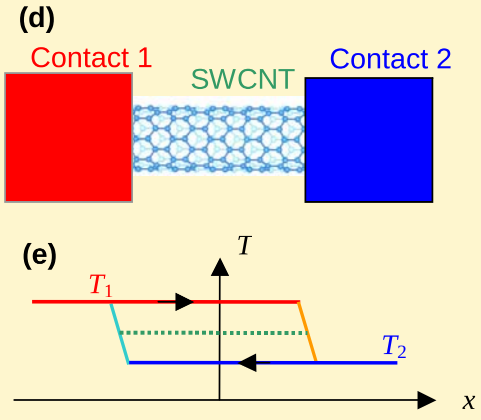
NSF Award CAREER 0239179

Thermal Transport and Thermoelectric Measurements of Nanotransistors, Nanowires, and Superlattices

Li Shi (U Texas)







(a-b) A micro-device for characterization of structure-thermal/thermoelectric property relationships of nanotubes and nanowires;

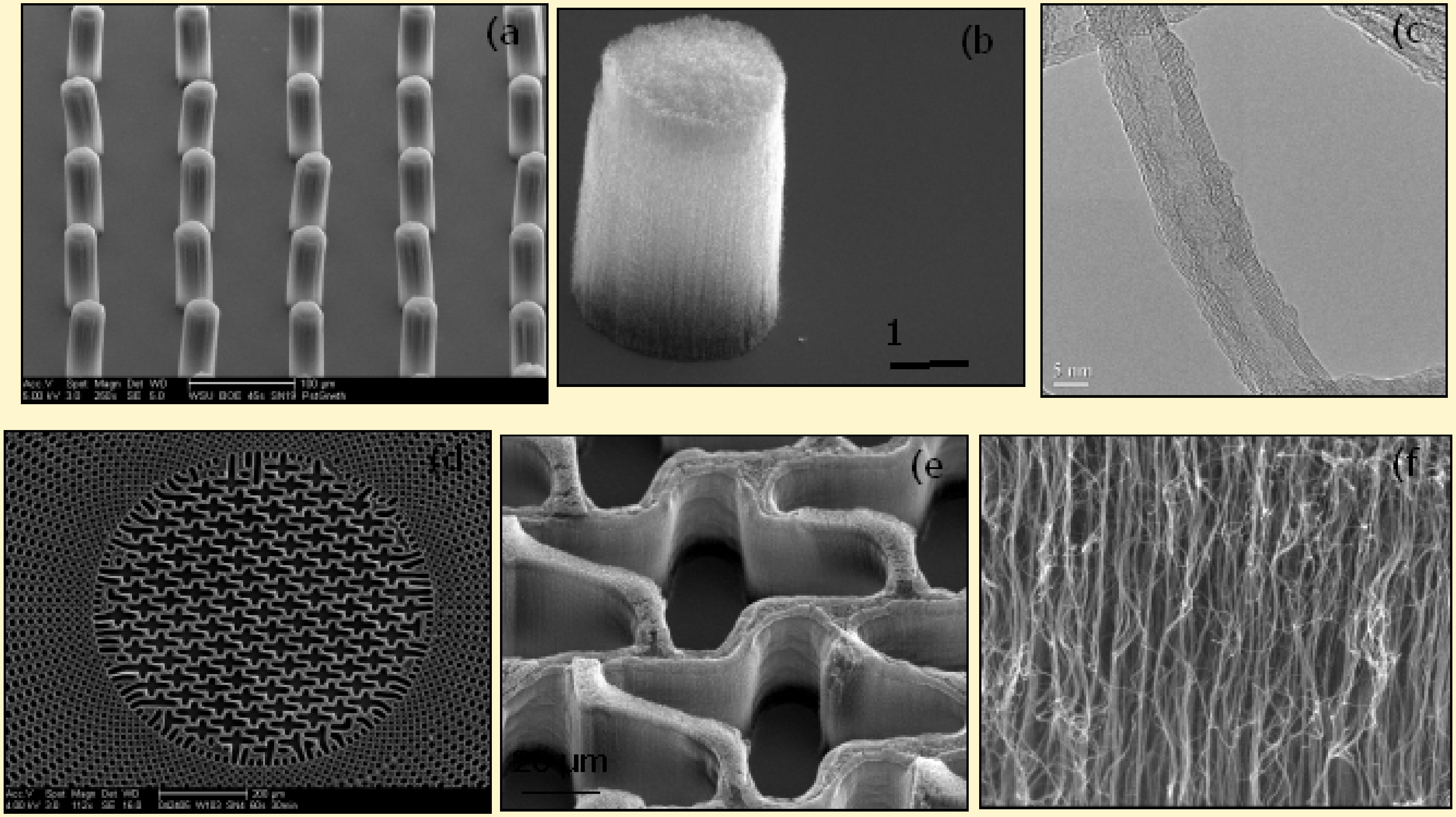
(c) The measurement results of the thermal conductance of a single-wall carbon nanotube (SWCNT) is very close to the calculated ballistic thermal conductance of a 1-nm-diameter SWCNT;

(d-e) Schematic showing two opposite phonon flows at different temperatures transported ballistically in a SWCNT.

NSF NIRT Award Number: 0238888

Nanotube based structures for high resolution control of thermal transport

Cecilia Richards et al., Washington State



Images of patterned vertically aligned carbon nanotube turf

NSF NIRT Award Number: CTS-0404370

Nanotube based structures for high resolution control of thermal transport

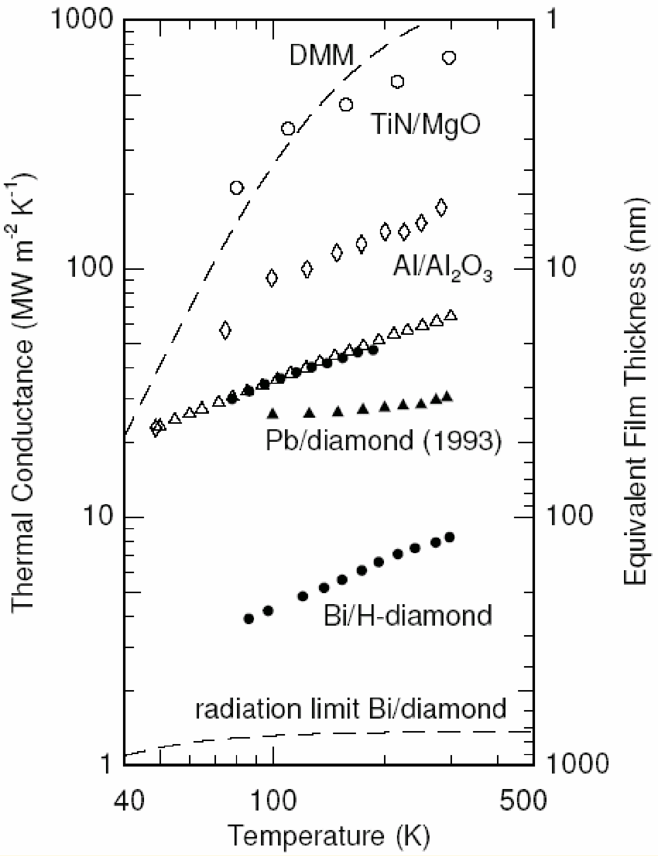
Cecilia Richards et al., Washington State

- Carbon nanotubes are incorporated into microscale composites to create a new kind of mesoscale device, a thermal switch
- Arrays of thermal switches will then be produced in batch to create sheets with spatially and temporally controllable “digital” thermal conductivity
- Carbon nanotubes (CNT’s) bridge scales from nanometers to micrometers, and MEMS techniques bridge scales from micrometers to millimeters
- Manufacturing across six orders of length scales from nano to meso is made possible by utilizing the mixed-scale architectures of high aspect ratio CNT’s and two-dimensional lithographic-based low-aspect ratio MEMS fabrication techniques.

NSF NIRT Award Number: CTS-0404370

Thermal conductance of solid-solid interfaces

David Cahill, Univ Illinois Urbana-Champagne

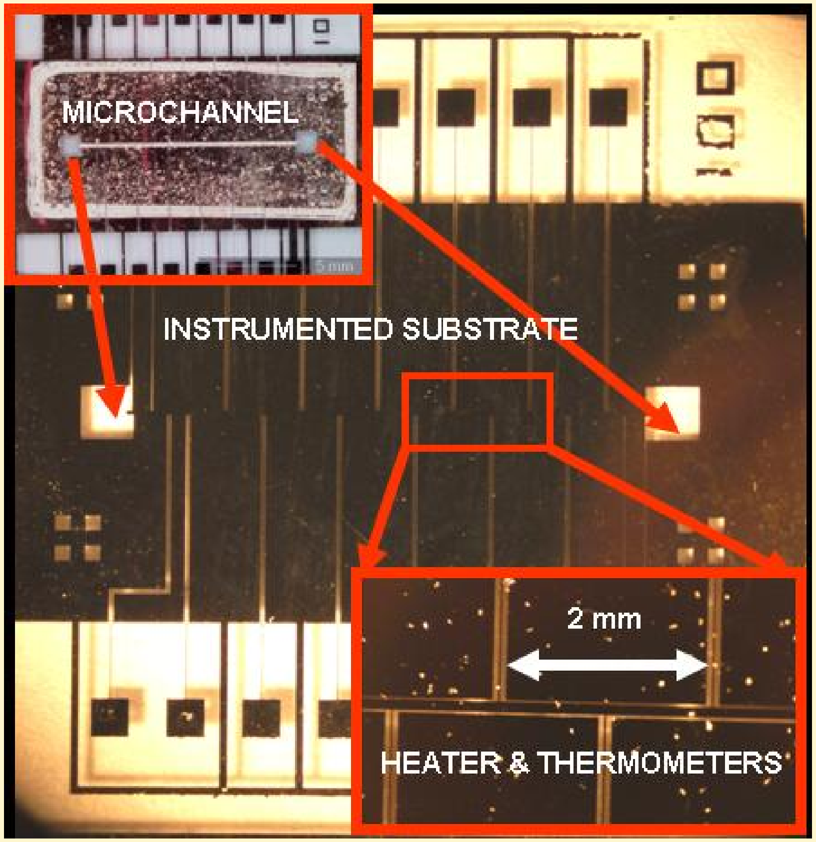


- The time-domain thermoreflectance (TDTR) technique for measuring the temperature of interfaces was greatly improved
- The technique was used to measure the heat conduction in thin films and across interfaces
- Data for these interfaces between materials with highly dissimilar spectra of lattice vibrations were used to test current theoretical and empirical understanding of interfacial heat transfer
- The established theories for the thermal conductance of interfaces become increasingly unreliable as the Debye temperature of the substrate increases

NSF Award Number: CTS-0245642

The Critical Heat Flux Condition in Micro-Channels

Jensen, M and T. Borca-Tasciuc, RPI; Kandlikar, S. RIT



Test-chip designed to investigate two-phase flow and boiling phenomena in microchannels

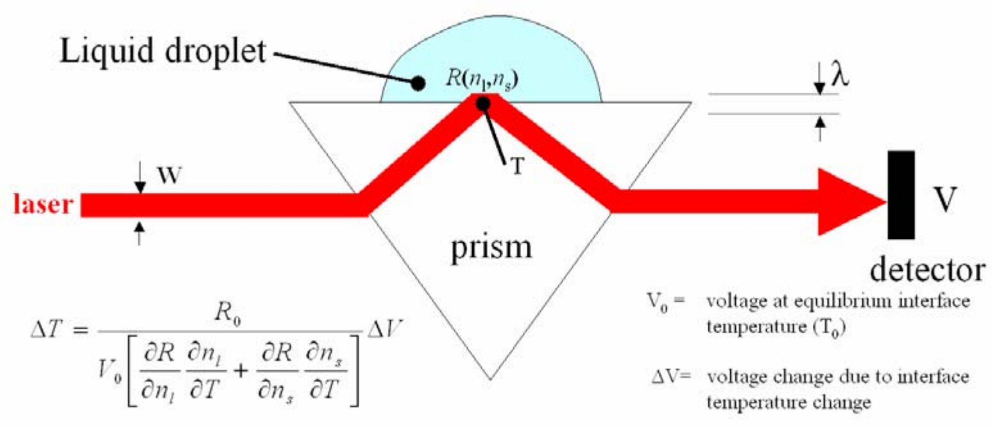
- The primary project objective is to develop a better quantitative and qualitative understanding of and prediction capabilities for the CHF condition in single and multiple parallel micro-channels
- The CHF condition with water and R123 in single metal tubes and single microfabricated channels is being investigated at RPI
- The local boiling phenomenon in multiple parallel channels with R123 in large monolithic metal blocks is being investigated at RIT

NSF Award Number: CTS-0336757

Coupling the High Resolution of Laser Measurements and Finite-Element Simulations to Understand Transport Phenomena during Microdroplet Deposition

Daniel Attinger *,Jon Longtin **

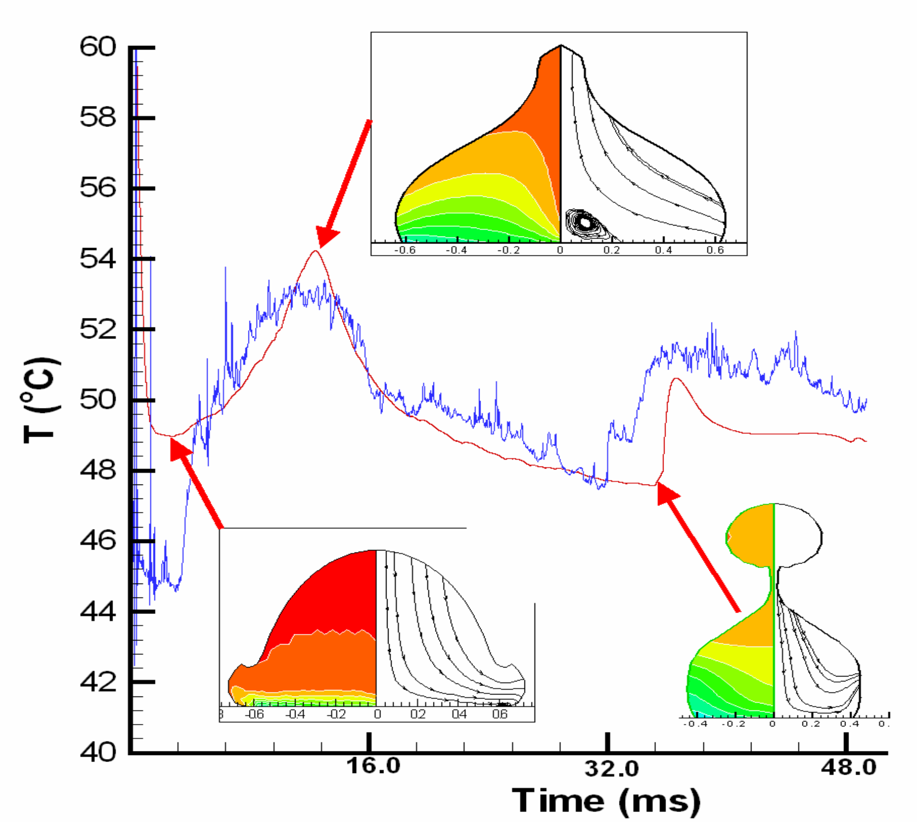
Columbia University*, State University of New York at Stony Brook**



$$\Delta T = \frac{R_0}{V_0\left[\frac{\partial R}{\partial n_l}\frac{\partial n_l}{\partial T} + \frac{\partial R}{\partial n_s}\frac{\partial n_s}{\partial T}\right]}\Delta V$$

V_0 = voltage at equilibrium interface temperature (T_0)

ΔV= voltage change due to interface temperature change



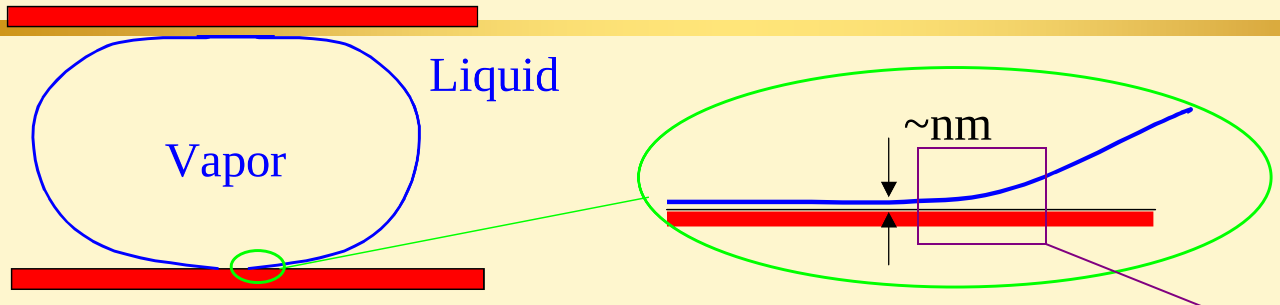
The temperature under a single impinging droplet was measured using a new thermoreflectance technique

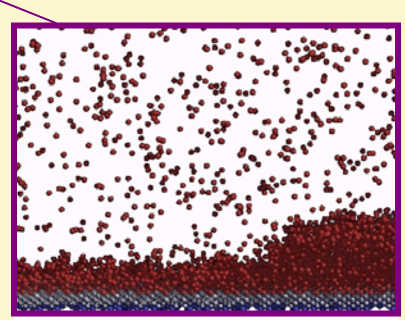
The agreement with the finite element simulations was excellent

NSF Award Number: CTS-0245642

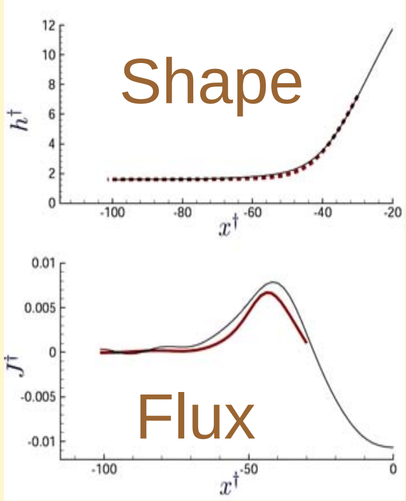
Atomic Detail of an Evaporating Meniscus

Jon Freund, Univ Illinois Urbana Champagne



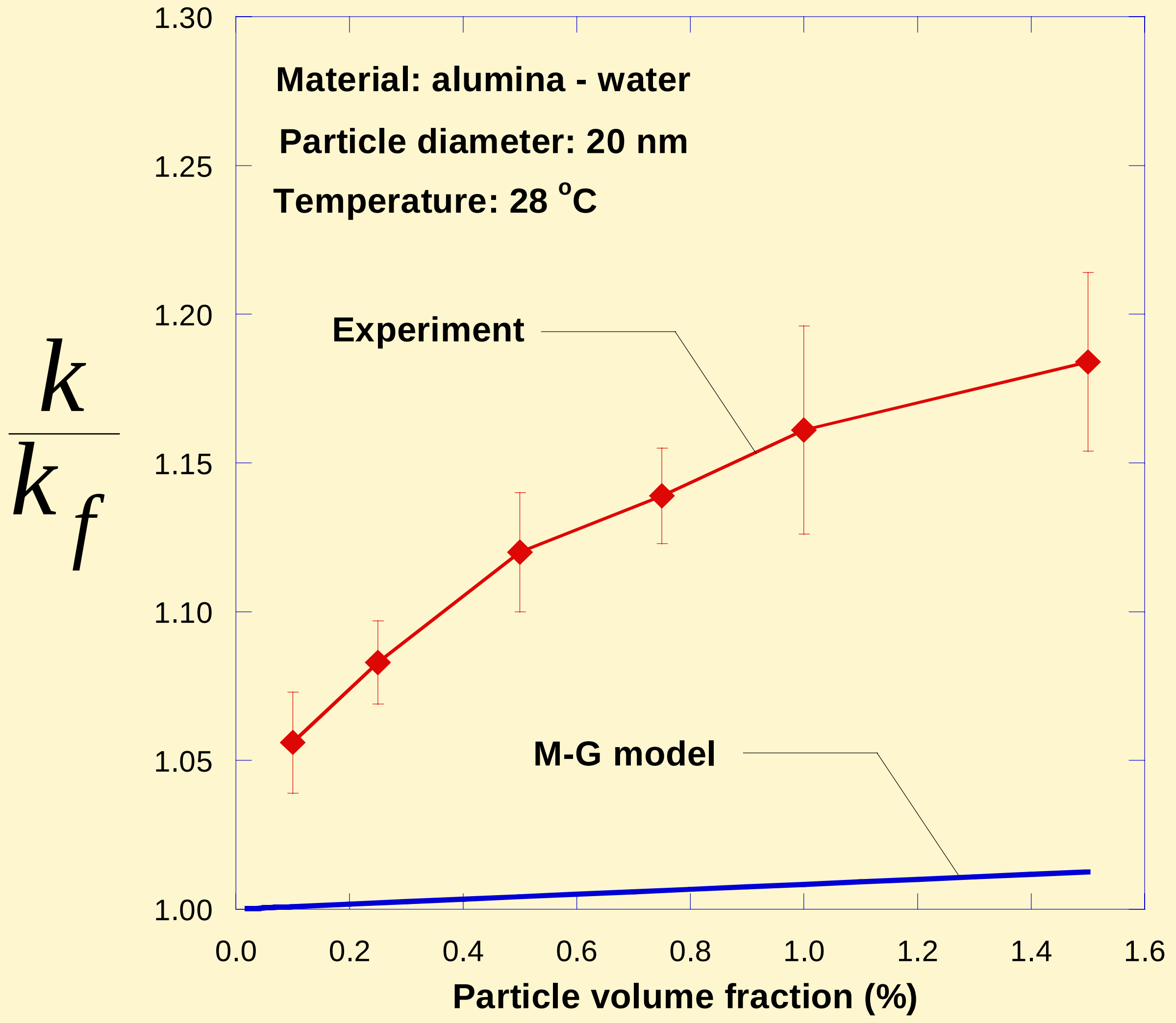


- Micro-fluidic actuation, nucleate boiling, heat pipes, etc.
- Coupled evaporation kinetics, viscous flow, surface tension, heat conduction, non-local influence of the wall
  - effect of atomic granularity?
  - proposed continuum models [e.g. Ajaev & Homsy, 2001]
- Studied with MD using simple fluids (for now)
- Findings
  - Kapitza resistance important at wall-liquid boundary
  - weakly wetting: good agreement with asymptotic model
  - strongly wetting: failure of Newtonian constitutive model
- Freund, *Phys. Fluids* (2005)



NSF GOALI: Nanofluids

P. Phelan, ASU

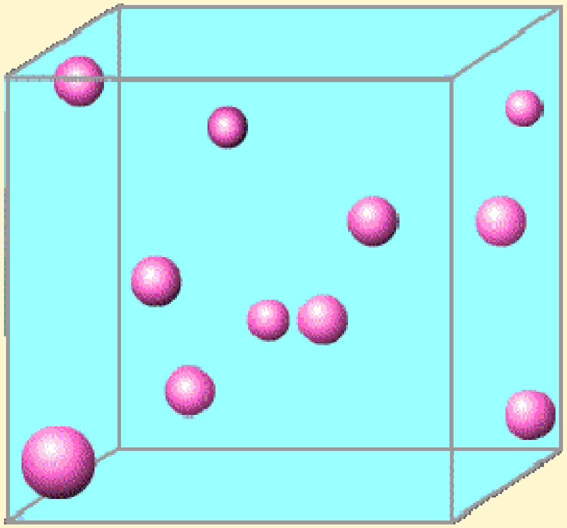


Enhanced thermal conductivity is greater than what is predicted by conventional theory

k = nanofluid thermal conductivity

k_f = thermal conductivity of base fluid

Convection Induced by Brownian Motion



- Effects of Brownian motion characterized through a "Brownian Reynolds Number."
- Brownian motion causes enhanced convection, as well as enhanced stirring

T = temperature

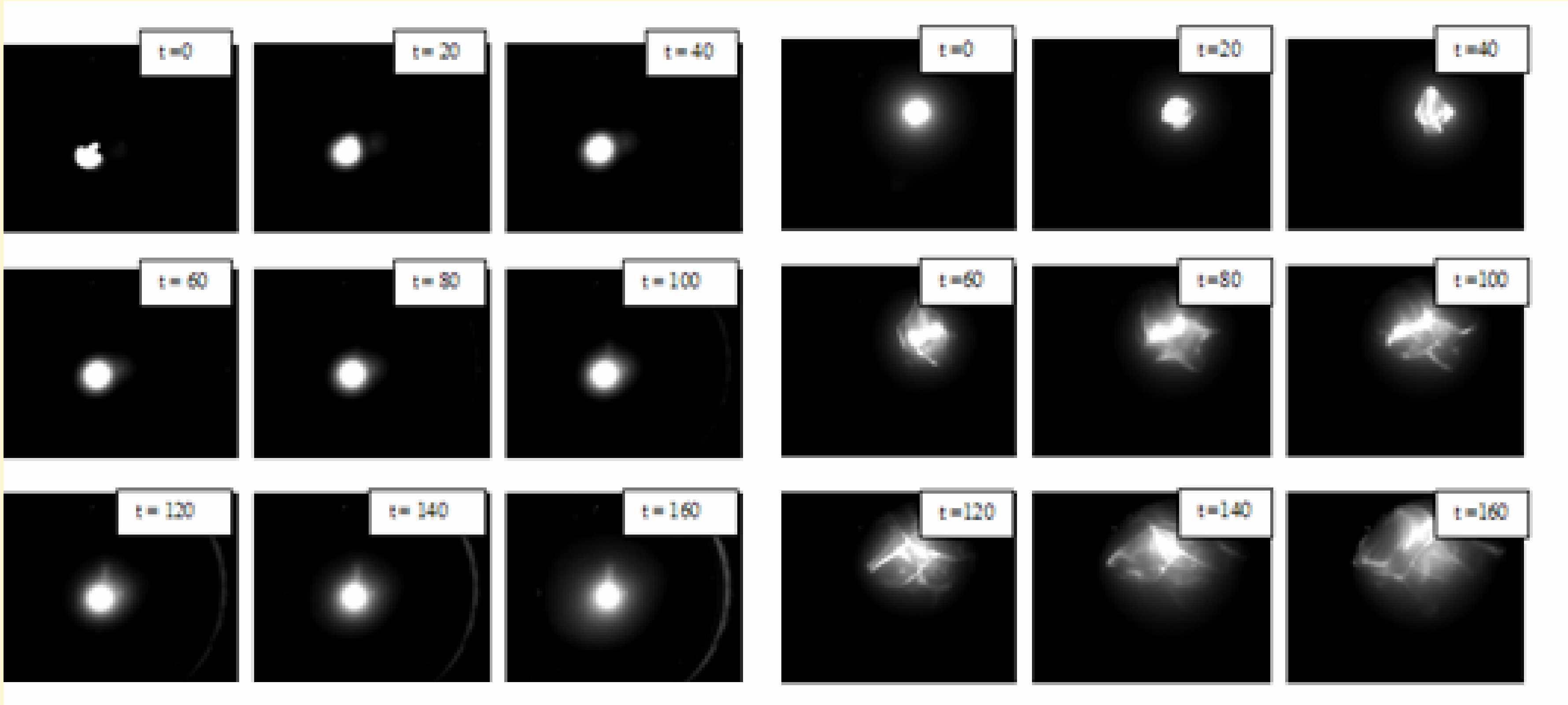
ρ_n = nanoparticle density

d = nanoparticle diameter

ν_f = fluid viscosity

$$\mathrm{Re} = \frac{1}{\nu_f}\sqrt{\frac{3k_bT}{m}} = \frac{1}{\nu_f}\sqrt{\frac{18k_bT}{\pi\rho_n d}}$$

Spread of the Fluorescent Dye in Water and in Nanofluid



Deionized (Pure) Water

1% 20-nm Al_2O_3 Nanofluid

Nanofluid Characteristics in Pool Boiling

Ranganathan Kumar
University of Central Florida

Supported by NSF NER Award No. 0404174

Modification of Boiling Curve due to Nanoparticle additives

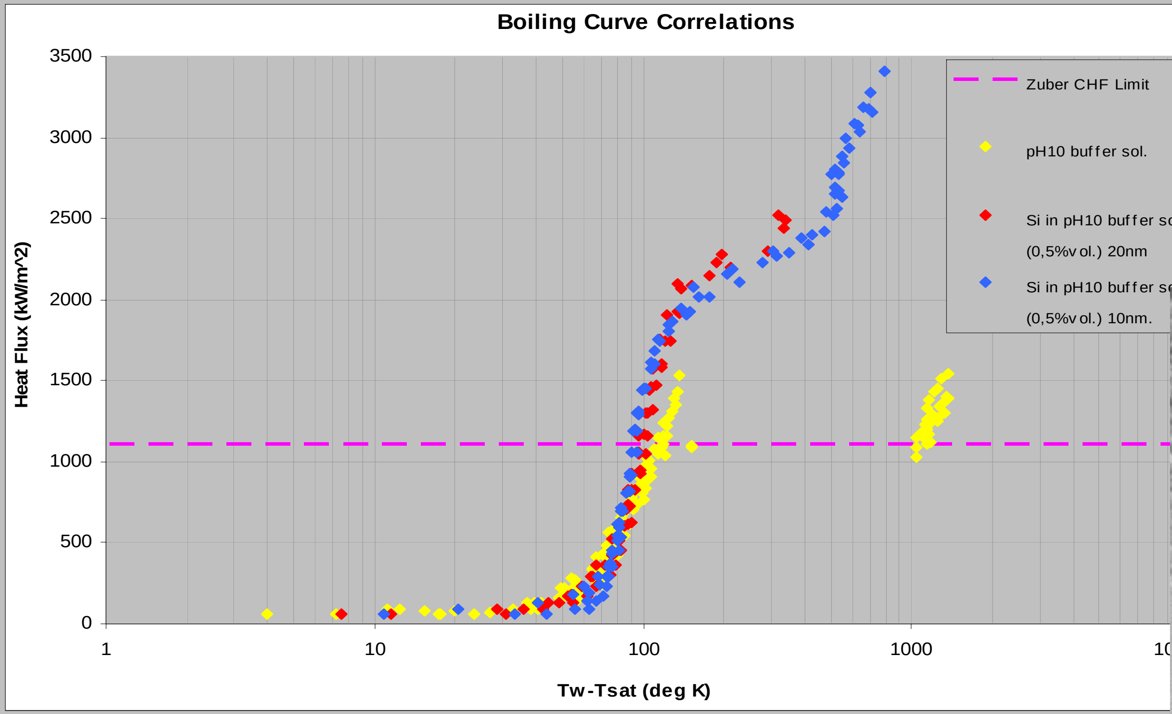
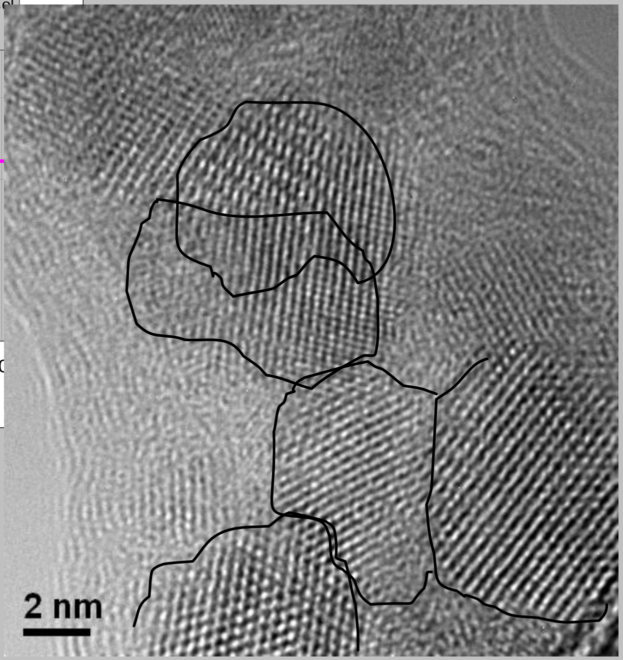


Figure 1. Modification of Boiling Curve due to Nanoparticle additives

Figure 2. High resolution TEM micrograph
3-8 nm nanoceria particles added to fluid



High resolution TEM micrograph
3-8 nm nanoceria particles
added to fluid

Metal Based Micro Heat Exchangers

W. Meng, S. Ekkad, LSU

Three Main Areas:

- Focus on fabricating microchannels in metals like Cu and Al.
- Reactive joining to enclose microchannels
- Thermal testing of micro heat exchanger performance

Microfabrication

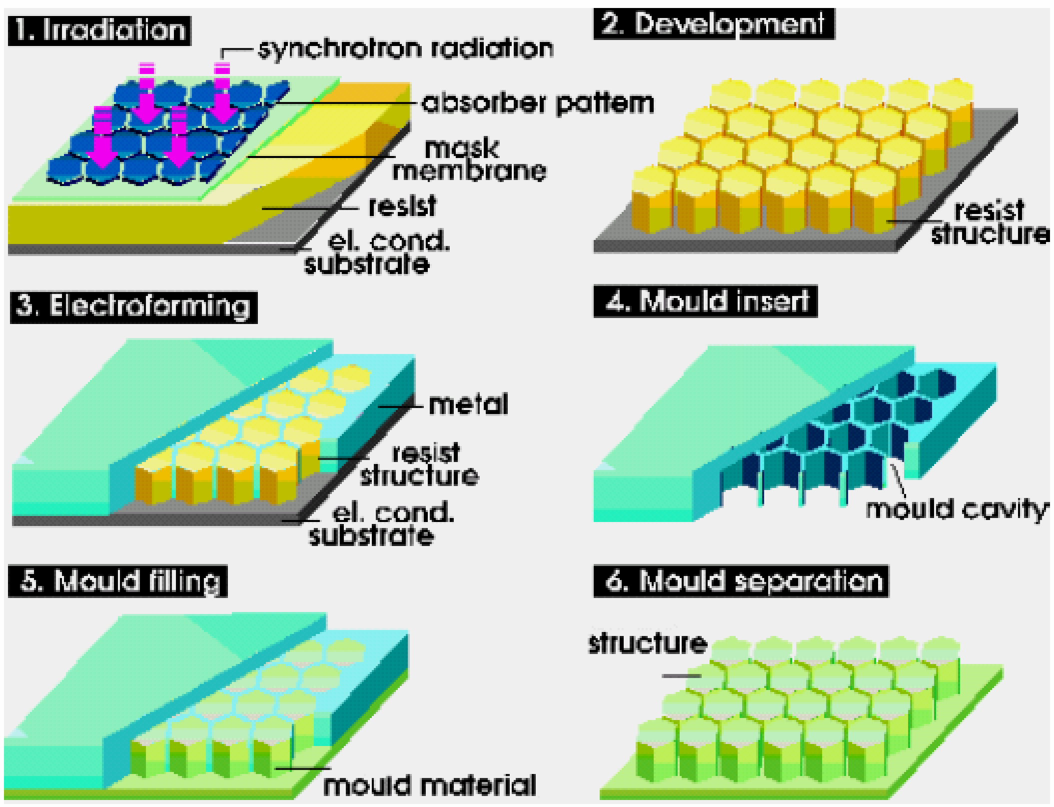


Figure 1. Schematic of the conventional LiGA microfabrication process steps: 1) the primary pattern is generated in polymeric resists by deep X-ray/UV lithography, 2) resist development, 3) metal electrodeposition into developed resist recesses, 4) dissolution of remaining resist, yielding an electrodeposited metallic HARMS, 5-6) compression molding with the electrodeposited primary HARMS insert followed by demolding yields the replicated HARMS. Economic mass fabrication of microparts hinges on the molding replication step.

Microfabrication

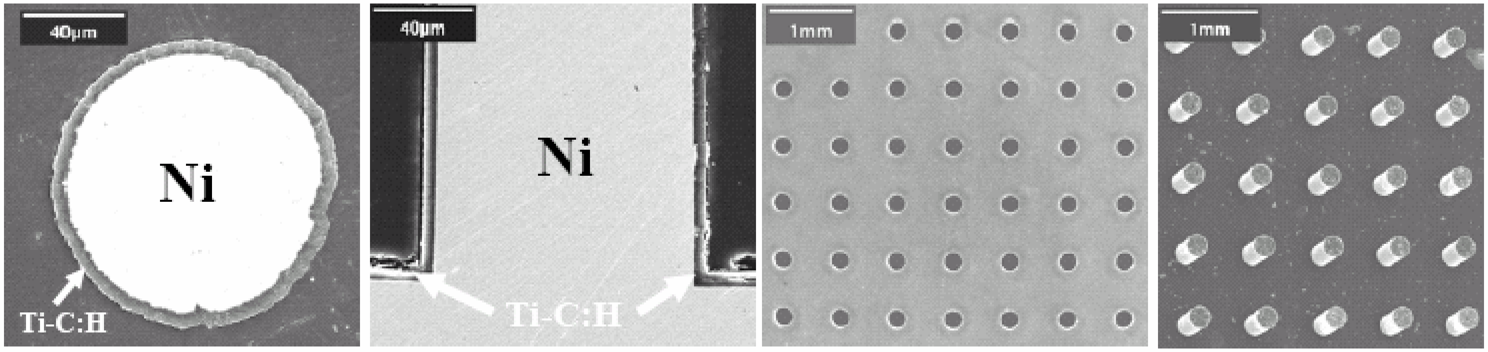


Figure 2. Surface engineering of a Ni microscale mold insert with an array of Ni microposts ~400µm in height by conformal deposition of a Ti-C:H nanocomposite coating: (left) cross-section perpendicular to a Ni micropost; (left middle) cross-section parallel to a Ni micropost; (right middle) an array of molding replicated microholes in an Al plate with depths ~400µm; (right) the surface engineered mold insert consisting of an array of Ti-C:H coated Ni microposts after multiple molding replication runs at ~460°C.

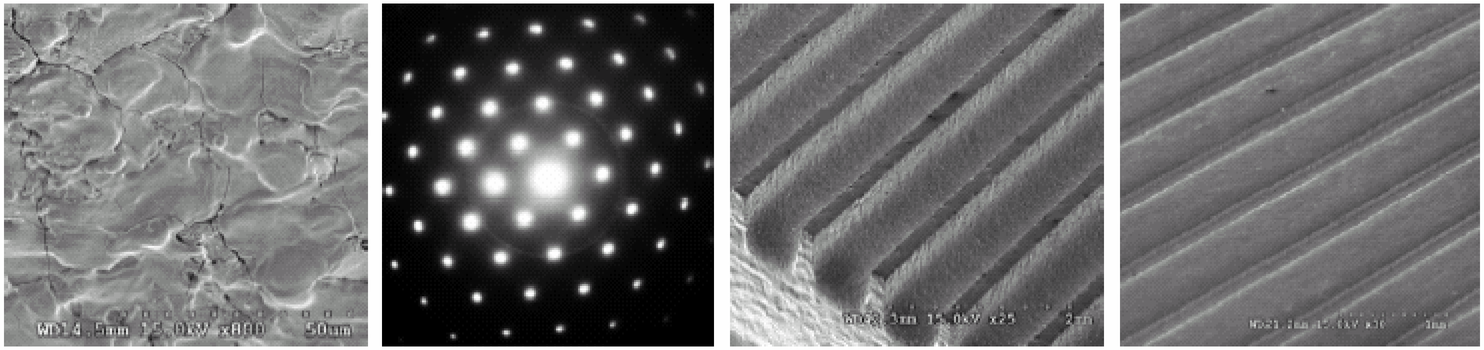


Figure 3. Hybrid fabrication and application of microscale Ta mold inserts: (left) morphology of as-µEDMed Ta surface showing the existence of the ASL with nodules and cracks; (left middle) cross-sectional electron diffraction pattern showing that the structure of ASL is B1-TaC rather than A2-Ta; (right middle) overview of surface engineered Ta HARMS insert consisting of an array of rectangular micro-protrusions fabricated by µEDM followed by ECP and conformal Ti-C:H deposition; (right) an array of Cu microchannels replicated at ~500°C from the Ta insert by molding. The width and depth of the Cu microchannels are ~160µm and ~220µm, respectively.

Microfabrication

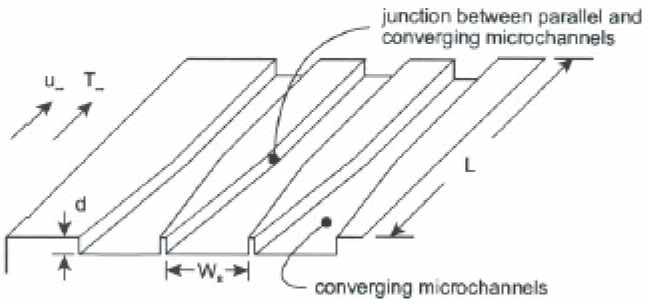


Figure 8. Need for microchannels with geometrically complex patterns: a schematic of converging microchannels from Ref. 72.

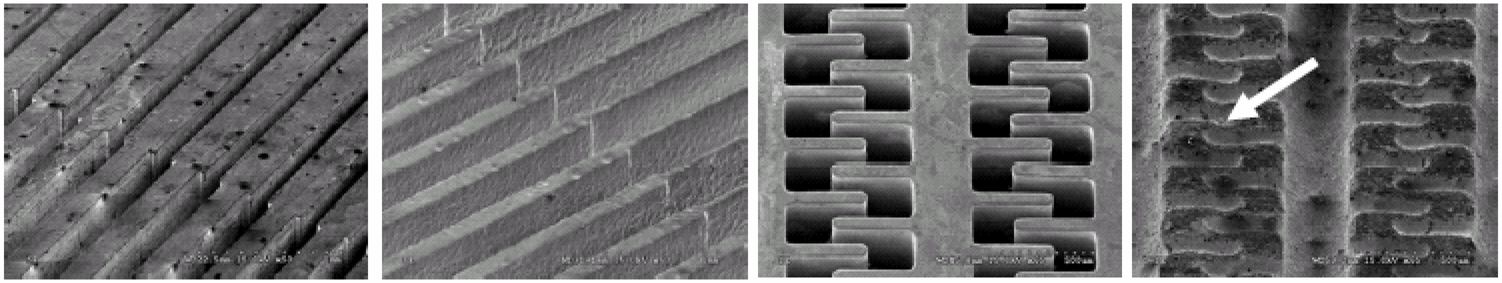


Figure 9. Feasibility of and challenges for pattern transfer with parallel µEDM: (left) an array of electrodeposited Ni rectangular protrusions with widths of ~185µm and ~276µm; (left middle) corresponding structures transferred onto a Ta insert blank by parallel µEDM, after the removal of the ASL by ECP. The depth of the transferred Ta HARMS is ~400µm; (right middle) electrodeposited Ni interdigitated structure. The widths of the long-ridges and short-fingers are respectively ~330µm and ~80µm. The height of the Ni HARMS is ~1200µm; (right) corresponding transferred structures on a W plate. The arrow indicates one example of excessive erosion on W due to interactions between primary Ni microfeatures in close proximity during µEDM.

Where are the frontiers?[1]

TTTP Looking Forward

- Challenges remain in continuum level phenomena that will continue to nurture mature fields at a lower level
  - Multi-phase, multi-component, high turbulence, coupled reacting flows with heat transfer, but
- Micro and Nano-scale Engineering will continue to be the dominant driver of modern Thermal Science
  - High heat flux, small scales, convective and nanoscale interfacial phenomena driven by emerging integrated electronics, future nanoelectronics, and bio-interfaces
  - Synthesis, characterization and modeling of nanomaterials and nanostructures and integration into nanosystems; motivates research in nano-manufacturing
- Rapid transition of ideas, measurements, and modeling to two emerging, transcendant areas:
  - Sustainable energy (Hydrogen, Nano-photovoltaics)
  - Cellular and Molecular engineering

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[1]"Frontiers in Transport Phenomena Research and Education: Energy Systems, Biological Systems, Security, Information Technology, and Nanotechnology" a NSF/ TTTP Funded Workshop, scheduled for March 2007