NSF/DOE Thermoelectrics Partnership: An integrated approach towards efficient, scalable, and low cost thermoelectric waste heat recovery devices for vehicles

Scott Huxtable[1]
Srinath Ekkad[1]
Shashank Priya[1,2]
Daniel Inman[1]
Andrew Miner[3]

Center for Energy Harvesting Materials & Systems
[1]Department of Mechanical Engineering
[2]Department of Materials Science
Virginia Tech

[3]CEO and founder, Romny Scientific

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Our project addresses 5 key elements towards realization of TEGs for vehicles

1. **Materials** (Romny, Priya)
   - Our materials efforts focus on rapid, low cost, and scalable fabrication techniques
   - Isostatic pressing of appropriately scaled materials
   - Development of a 3D aerosol deposition system
2. **Thermal management** (Ekkad, Huxtable)
   - System level models and experiments to maximize temperature gradient across device
3. **Heat exchangers** (Ekkad)
   - Experiments and models of efficient heat sinks using, e.g., minichannels and swirl jet impingement
4. **Interfaces** (Inman, Huxtable)
   - Measurements of adhesion, electrical and thermal transport through interfaces and methods for improvement
   - Effects of vibration, thermal cycling on adhesion & transport
5. **Metrology** (all)
   - Complete nano-macro TE and structural characterization (HRTEM, TDTR, XPS, Auger, XRD, laser flash, etc.)
   - System level models and measurements on a prototype

Romny Scientific will focus on low cost, high volume, and scalable production of TE elements

The approach is to …

(a) take advantage of nanostructured effects in macroscale elements, and
(b) fabricate elements at optimum sizes and shapes

We will create powders of high quality TE materials starting with Mg based silicides through pulverization processes in inert environments

Powders are then pressed into elements that are the optimum shape and size for the particular application

While this approach will not result in a breakthrough in a material ZT, it limits waste, maximizes device ZT for a particular material by fabricating at the optimum geometry for the particular application, and is adaptable to many material systems

Andy Miner, CEO and founder of Romny, will speak on Wednesday at 10:20 am.

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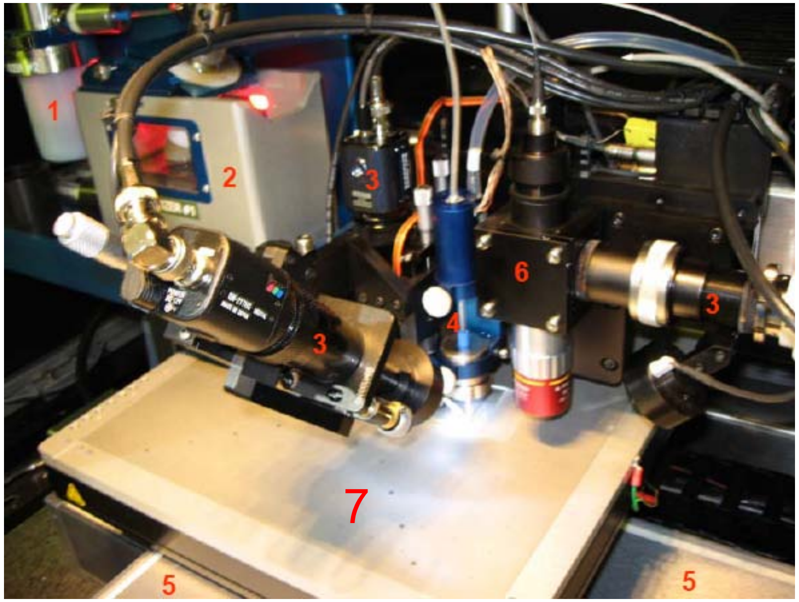
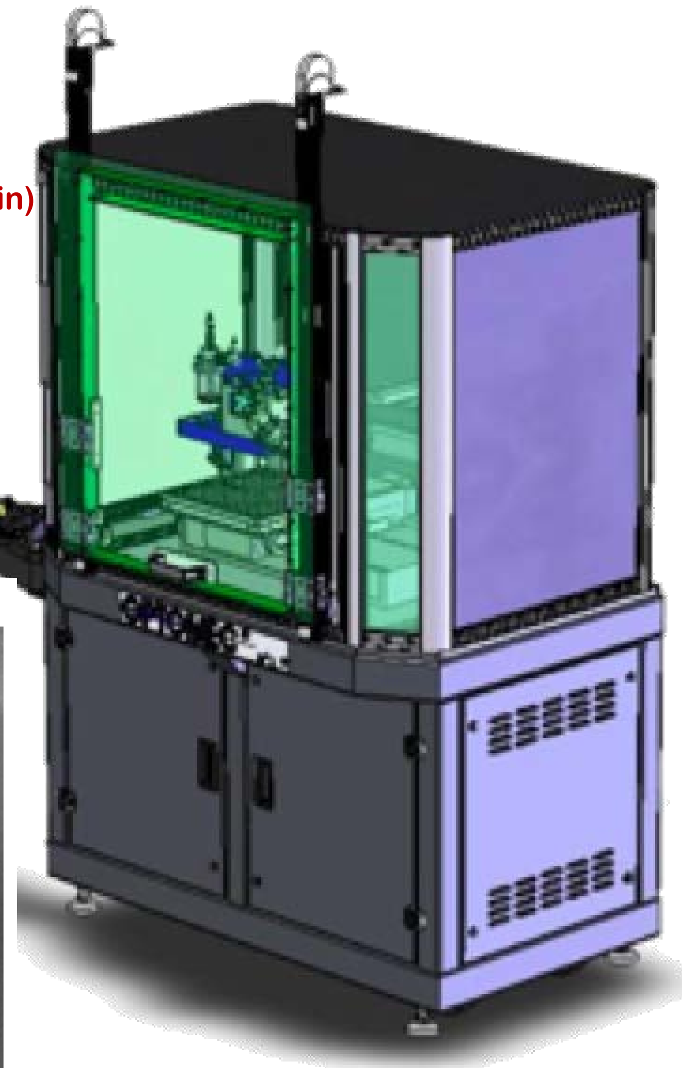
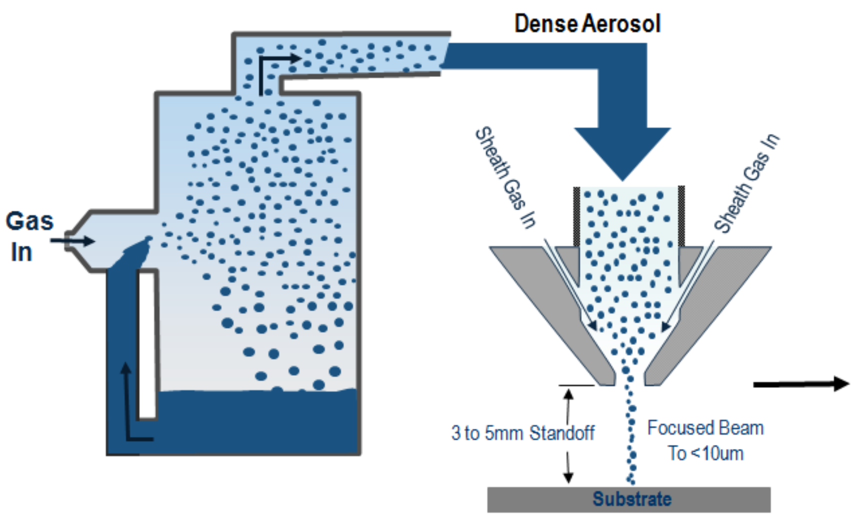
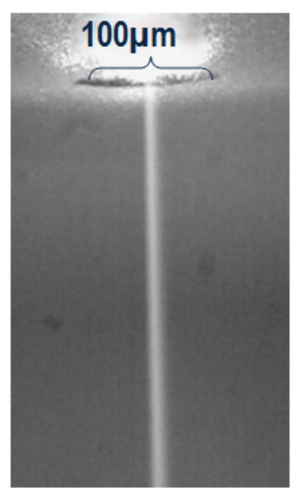
Priya's group at VT will examine the growth of TE materials through 3D aerosol printing



1- Pneumatic atomizer
2- Ultrasonic atomizer
3- Digital cameras
4- Deposition module
5- Translation stage
6- Diode laser module
7- Sample Platen (12x12in)





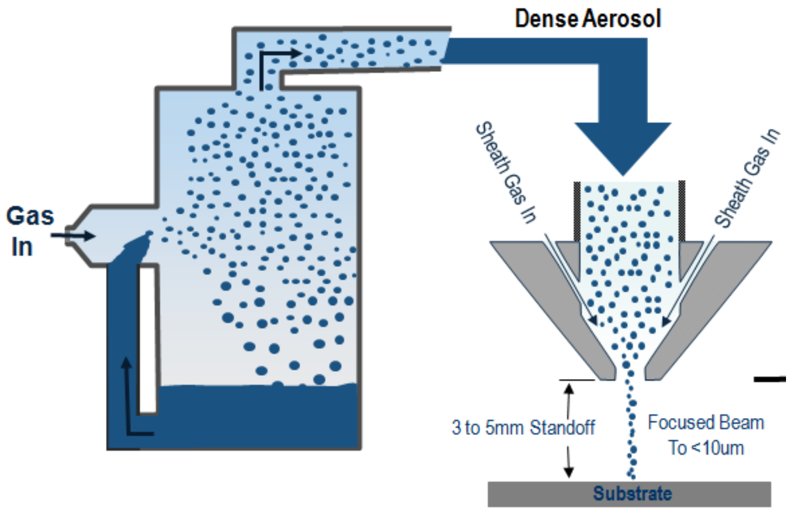


Focused Material Beam

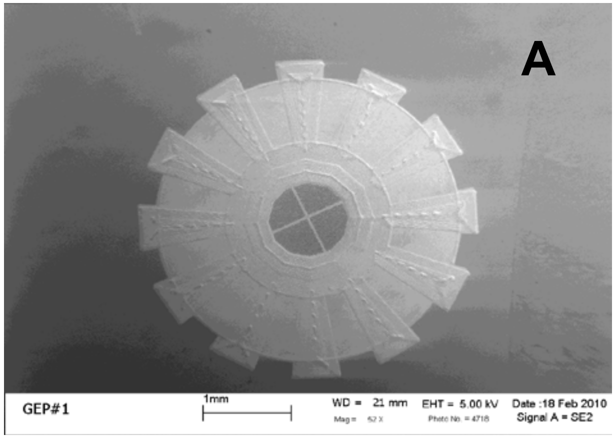
Aerosol deposition has several key features that make it attractive for TE materials growth

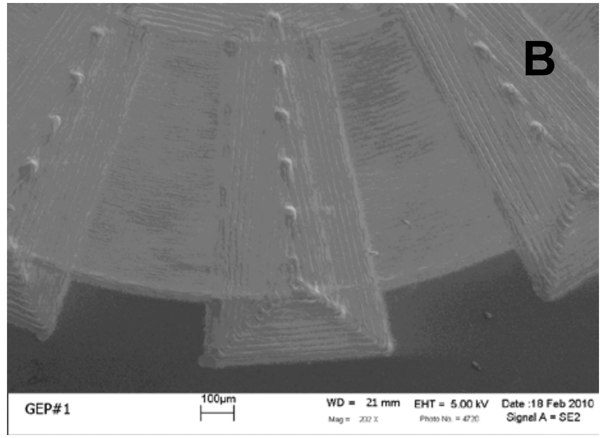
Key features of our aerosol deposition system include…

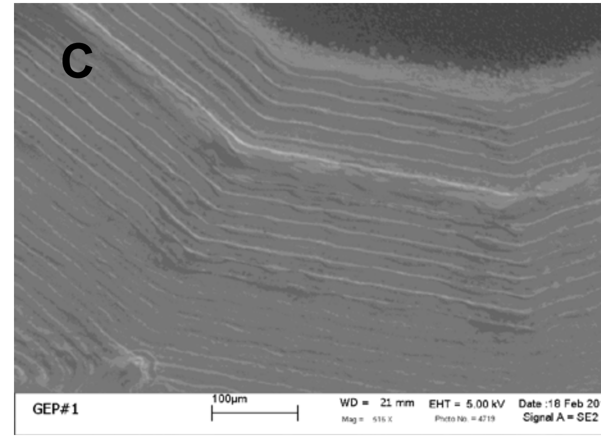
- Deposition rates up to ~10 μm/sec, with resolution of ~1 μm in the X and Y direction
- Thicknesses up to ~10 mm on a 6 x 6 in^2 substrate
- Easy to include dopants
- Potential to tailor microstructures with characteristic texture and nanoscale interfaces
- Potential to co-synthesize materials and structures
- Potential to grow graded structures
- Deposition possible on non-planar structures
- Adaptable to many materials systems

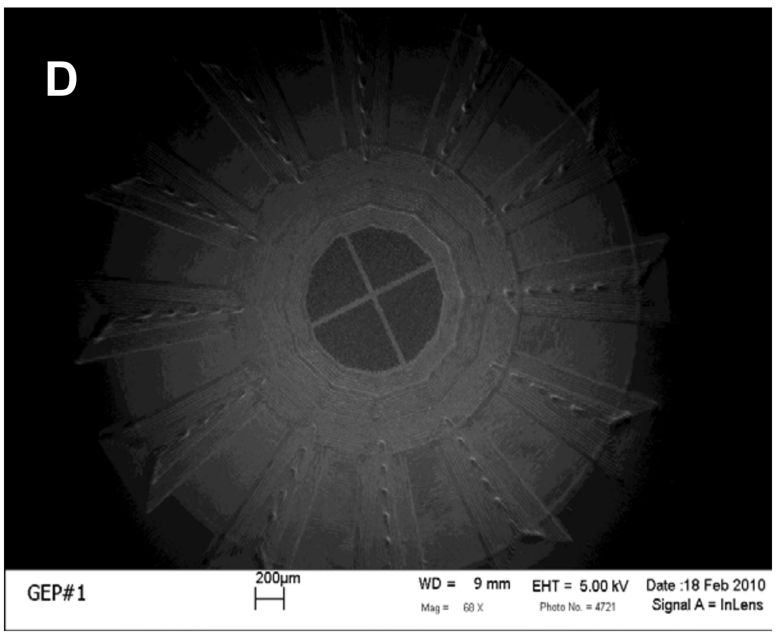


Priya's group has used aerosol deposition to create 3D silver structures









Bevel gear of ~5 mm size made of silver

(A) full size gear made of Ag dispersion ink on alumina substrate heated to 80 °C while deposition was in progress.
(B) gear tooth and the material build up from the outside to the inside as layer depositions increase.
(C) inside of the gear, the layers can be differentiated, the line thickness was roughly 20 µm.
(D) the gear with shading according to the layer increments towards the center.

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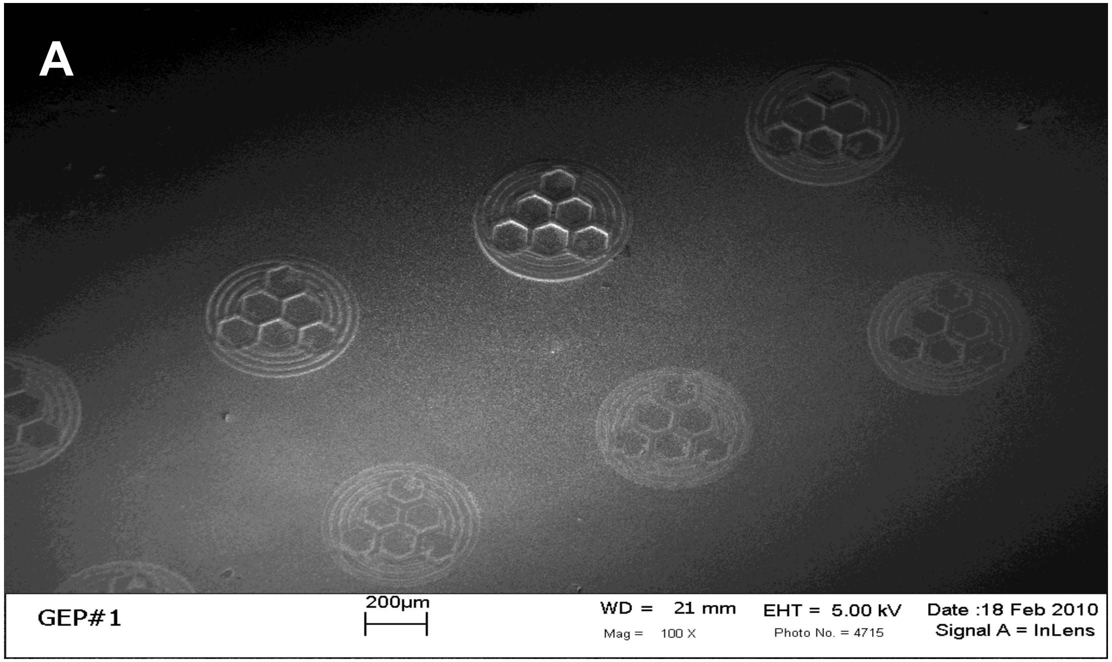
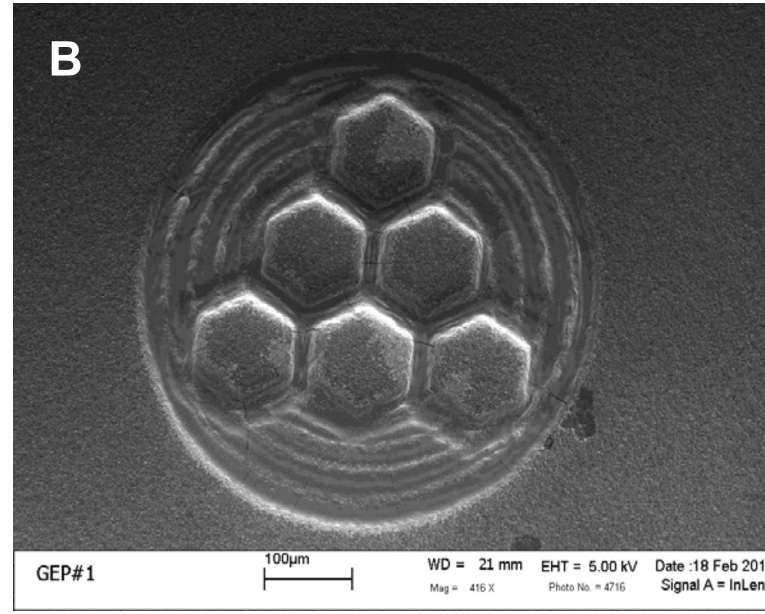
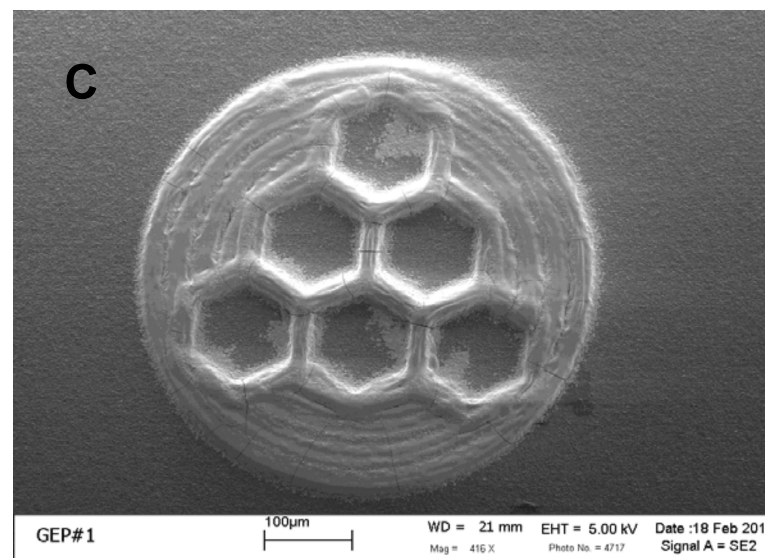
Large scale patterns of complex structures have also been grown with aerosol deposition



Silver honeycomb structure inside a series of concentric circles; the outer circle measures ~500 µm.

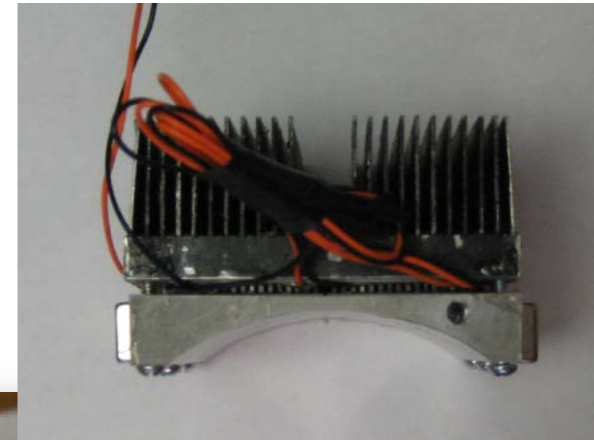
(A) arrays with varying deposition parameters.
(B) & (C) single structures where the best settings (for test purposes) have been found and repeated deposition several times.





Inman's group will examine vibrations and thermal cycling through models & experiments

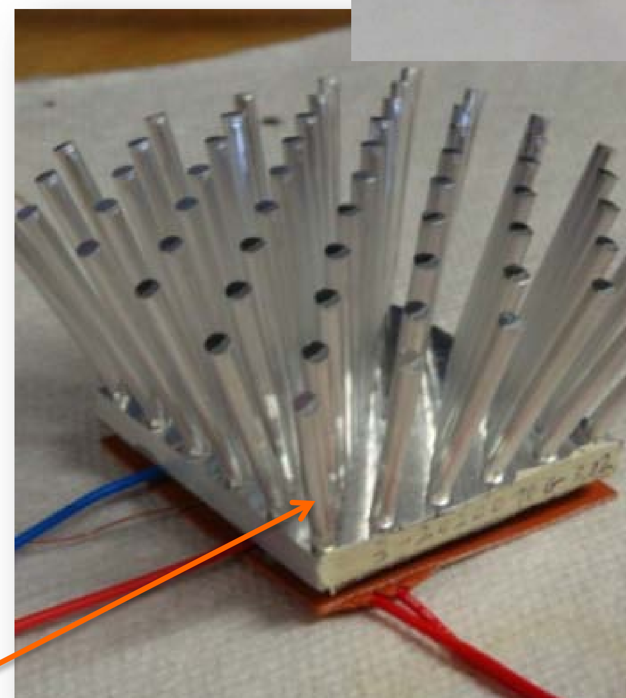
We will examine the effects of vibrations, shock, and thermal cycling on the TE elements, heat sinks, interfaces, and entire system.



Dynamic Modeling of TEG Components and System

Use of Lagrange Methods to formulate vibration models for each component

Use of substructure methods to produce a combined model



Preliminary studies were done on a prototype heat sink mounted on a TEG

Preliminary dynamic testing of TEG systems performed on vehicles and laboratory shakers

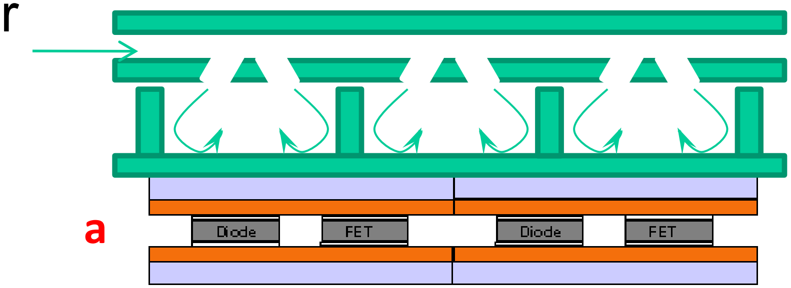
Vibration testing of TEG system mounted on a vehicle

Vibration testing of TEG and heat exchanger

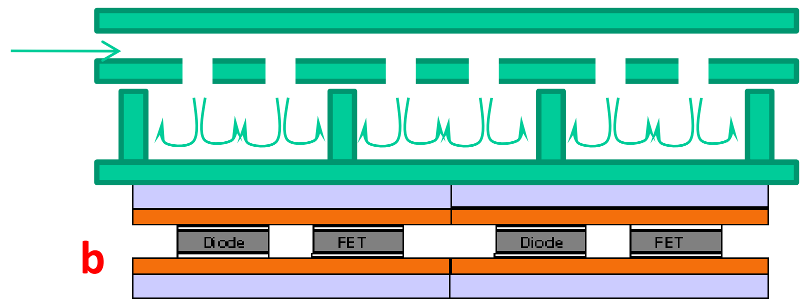
Ekkad and Huxtable's groups will evaluate various heat sink designs

Ekkad recently examined several schemes for cooling power electronics on hybrid vehicles

a. Swirl – Impingement – Fin (SIF) cooling
b. Jet impingement on a finned plate
c. Conventional jet impingement cooling
d. Conventional pin-fin/mini-channel cooling
e. Jet Impingement on angled walls.



a



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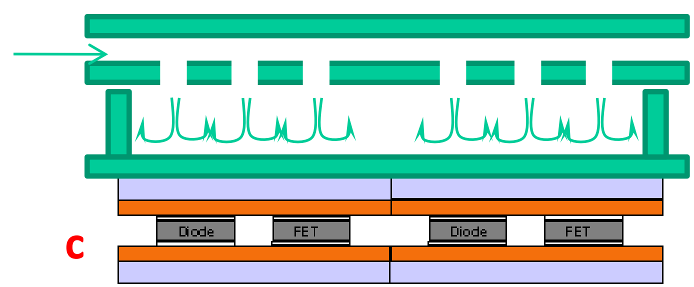

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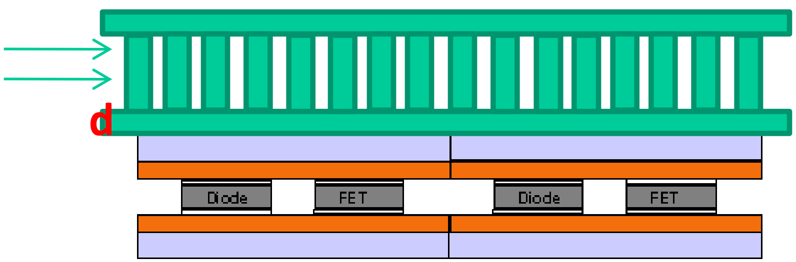

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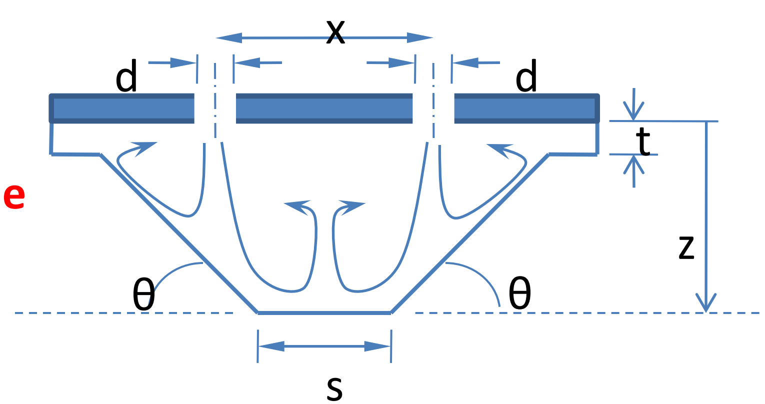

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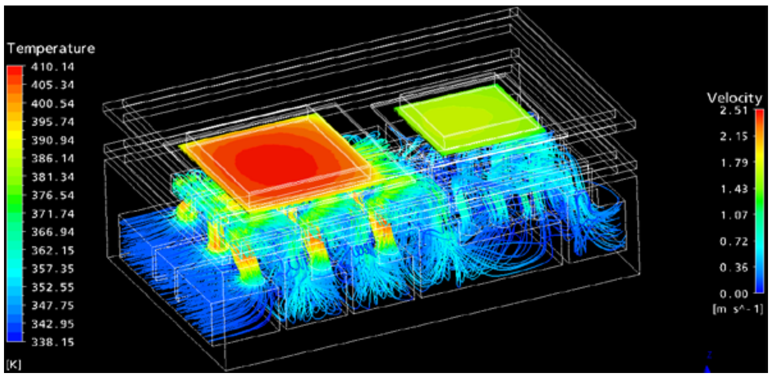
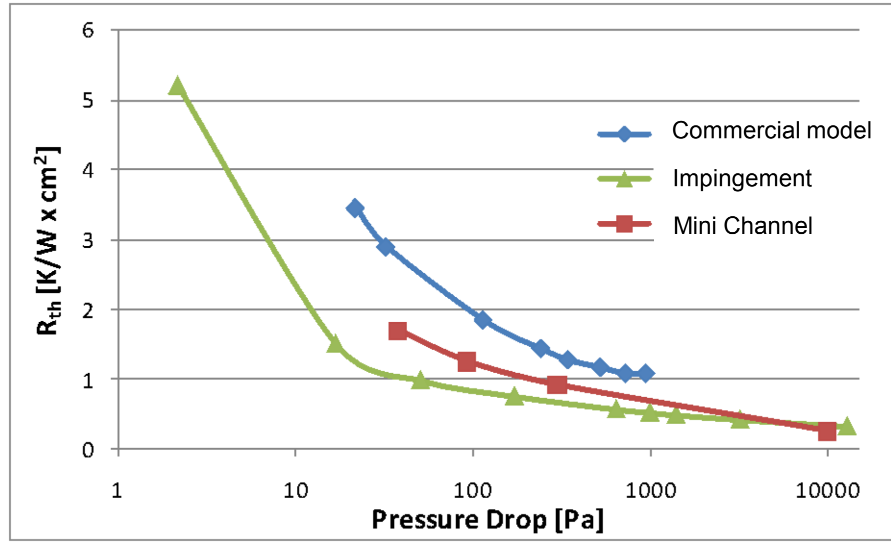
Prototype heat exchangers are modeled, designed, fabricated, and tested at VT

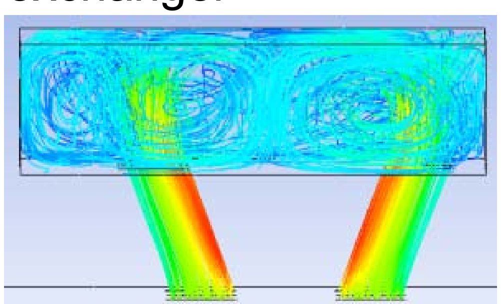
We have existing computational tools and experimental facilities used for evaluation of heat transfer in gas turbines and power electronics.



Comparison of preliminary heat exchanger designs with commercial model



CFD model for swirl impingement flow heat exchanger



Example of mini-ribbed heat exchanger design (A) & prototypes (B & C) made through metallic molds. Prototypes are ~ 20 x 60 x 5 mm

Our metrology efforts span from nano to macro scale measurements

In addition to the previously mentioned metrology efforts we also will perform careful structural and thermoelectric measurements on the materials at the new VT Nanoscale Characterization and Fabrication Lab (NCFL)

Structural measurements include

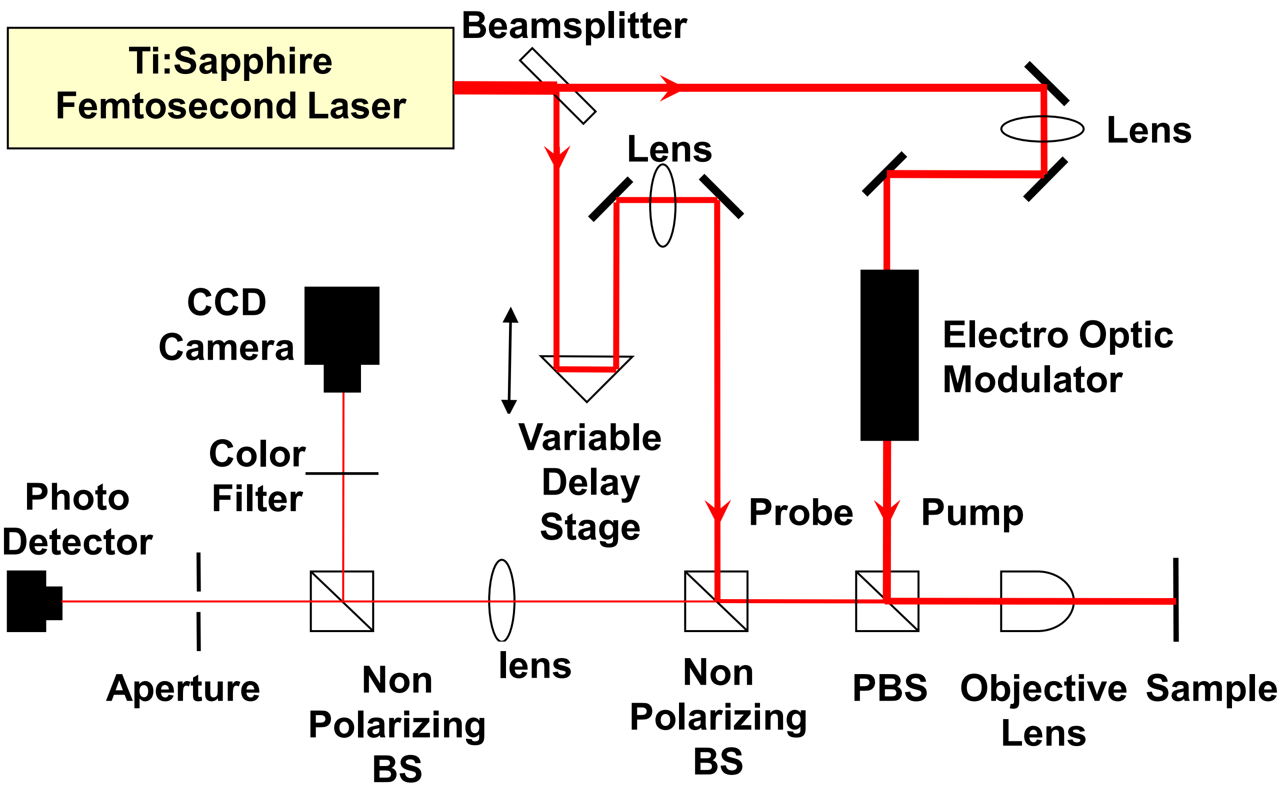
- High resolution TEM
- Energy dispersive X-ray spectroscopy
- XPS
- Auger electron spectroscopy
- Raman spectroscopy

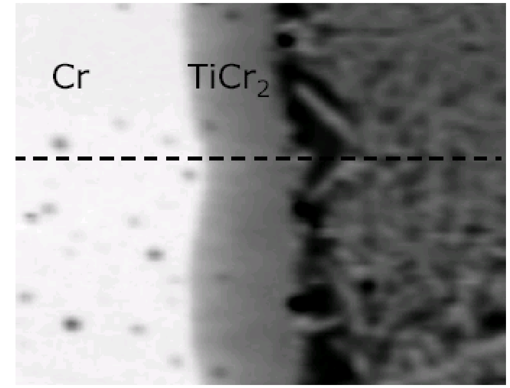
TE and system measurements include

- Electrical, thermal, and Seebeck measurements at VT and Romny
- Full instrumentation (vibration, strain, temperatures, power, etc.) on table-top and in-vehicle prototypes

The structural analysis of the materials will be used to correlate with the mechanical, thermal, and electrical behavior. Combined, all of these experimental results will help in establishing the structure – property relationship for the thermoelectric materials developed in this work

Thermal conductivity is measured with time-domain thermoreflectance (TDTR)





Thermal conductivity image from TDTR of a Cr-Ti interface with ~3 μm resolution (image is ~ 100 x 100 μm)

Additional thermal measurements are done with an Anter Flashline 3000 laser flash system and a home built 3-omega system

With TDTR we can simultaneously extract thermal conductivity *and* interface thermal conductance.

We can also map thermal conductivity with ~3 μm resolution. This can be useful for measuring local conductivity on cross-sections of graded materials, and thermal interface materials

Finally, we will also work closely with our local automotive experts at VTTI

The Virginia Tech Transportation Institute (VTTI) conducts applied research to develop new techniques and technologies to study transportation challenges from various perspectives: vehicle, driver, infrastructure, and environment.

VTTI is the largest research center at VT (200+ faculty, staff, and students)

2.2 mile “smart road” with weather making capabilities, lighting, embedded sensors, etc.

Key to us is the expertise at VTTI in automotive instrumentation and systems integration within vehicles.

In summary, our team will take an integrated approach towards developing TEGs for vehicles

In summary, our work will focus on…

- Developing high quality, low cost, thermoelectric materials of appropriate shapes & sizes
- Thermal models and experiments, from micro to system level, to maximize temperature gradient across the device
- Modeling, design, fabrication, and testing of efficient heat sinks that involve staggered fins, minichannels, and jet impingement
- Measurements of adhesion, and electrical and thermal transport through interfaces, and methods for improving
- Effects of vibration, thermal cycling on adhesion & transport
- N ano-macro thermoelectric and structural characterization including system level models and measurements on a prototype

We gratefully acknowledge support from NSF and DOE