NSF-DOE Thermoelectrics Partnership:

Automotive Thermoelectric Modules with Scalable Thermo- and Electro-Mechanical Interfaces

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Stanford University

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Department of Physics  
University of South Florida

Dr. Boris Kozinsky  
Energy Modeling, Control, & Computation  
R. Bosch LLC

ACE067

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Overview

Timeline
- Start – January 2011
- End – December 2013
- ~40% complete

Budget
- $1.22 Million (DOE+NSF)
- FY12 Funding = $423K
- Leveraging:
  - ONR (FY09-11)
  - Fellowships (3 NSF, Sandia, Stanford DARE)

Barriers (2.3.2)
- Thermoelectric Device/System Packaging
- Component/System Durability
- Scaleup

Partners
- K.E. Goodson, Stanford (lead)
- George Nolas, USF
- Boris Kozinsky, Bosch
Relevance: Addressing Key Challenges for Thermoelectrics in Combustion Systems

*Improvements in the intrinsic ZT of TE materials are proving to be very difficult to translate into efficient, reliable power recovery systems.*

**Major needs include…**

...Low resistance interfaces that are stable under thermal cycling.

...High-temperature TE materials that are stable and promise low-cost scaleup.

...Characterization methods that include interfaces and correlate better with system performance.
Relevance: Thermoelectric Interface Challenge

- Combustion TEG systems experience enormous interface stresses due to wide temperature spans.
- Thermal cycling degrades interface due to cracks, delamination, reflow, reducing efficiency.
- Our simulations show importance of thermodynamic stability (chemical reactivity, inter-solubility, etc.) and elastic modulus.


Gao, Goodson et al., Journal of Electronic Materials, 2010

Technical Accomplishment 2011 (Bosch)
Research Objectives & Approach

OBJECTIVES

Develop, and assess the impact of, novel interface and material solutions for TEG systems of particular interest for Bosch.

Explore and integrate promising technologies including nanostructured interfaces, filled skutterudites, cold-side microfluidics.

Practical TE characterization including interface effects and thermal cycling.

APPROACH

Multiphysics simulations ranging from atomic to system scale.

Advanced materials development including CNT and metal nanowire TIMS, and high temperature thermoelectrics.

Photothermal metrology including Pico/nanosecond, cross-sectional IR. MEMS-based mechanical characterization.
### Research Approach

Additional Faculty & Staff beyond PIs
- Prof. Mehdi Asheghi, Stanford Mechanical Engineering
- Dr. Winnie Wong-Ng, NIST Functional Properties Group
- Dr. Yongkwan Dong, USF Department of Physics

**Stanford Students:**
- Michael Barako, Yuan Gao (NSF Fellow), Lewis Hom (NSF Fellow), Saniya Leblanc (Sandia Fellow), Woosung Park, Amy Marconnet (NSF Fellow), Sri Lingamneni, and Antoine Durieux

<table>
<thead>
<tr>
<th>Area</th>
<th>Specifics</th>
<th>Source</th>
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<tbody>
<tr>
<td>Interfaces</td>
<td>Nanostructured films &amp; composites, metallic bonding Ab initio simulations and optimization</td>
<td>Stanford Bosch</td>
</tr>
<tr>
<td></td>
<td>(ZT)$_{eff}$ including interfaces, thermal cycling</td>
<td>Stanford USF/NIST</td>
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<td></td>
<td>High temperature ZT</td>
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<tr>
<td>Materials</td>
<td>Filled skutterudites and half Heusler intermetallics Ab initio simulations for high-T optimization</td>
<td>USF Bosch</td>
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<tr>
<td>Durability</td>
<td>In-situ thermal cycling tests, properties Interface analysis through SEM, XRD, EDS</td>
<td>Stanford Bosch</td>
</tr>
<tr>
<td>Heat sink</td>
<td>Gas/liquid simulations using ANSYS-Fluent Novel cold HX using microfluidics, vapor venting</td>
<td>Bosch Stanford</td>
</tr>
<tr>
<td>System</td>
<td>System specification, multiphysics code Evaluation of research impacts</td>
<td>Bosch Stanford</td>
</tr>
</tbody>
</table>
Approach: Thermal & Mechanical Properties of CNT Interface Films

Cross-sectional IR Microscopy with in-situ Thermal Cycling

Mechanical Characterization

Four Separate Papers at IThERM, May 2012
Marconnet, Panzer, Godson, et al. ACS Nano (2011)
Panzer, Murayama, Goodson et al. Nano Letters (2010)
**Approach: Nanostructured Interfaces**

**Nanostructured Interfaces**

- **Carbon Nanotube**
- **Copper Nanowire†**
  - xGNPs: 25 µm || ~10 nm ⊥
  - 1 µm

**Thermal Resistivity (m K / W)**

- *Elastic Modulus (MPa)*
  - Greases & Gels
  - Phase Change Materials
  - Indium/Solders
  - Adhesives
  - Nangels
  - Greases & Gels

**GOAL**

- Life time thermal cycling

**Year 2 DOE-NSF Project**

**Our Latest CNT Data**


†In collaboration with group of Prof. Fritz Prinz, Stanford

‡www.xgsciences.com
Approach: Bulk TE Materials for Vehicles

Lamberton, G.S. Nolas, et al APL 80, 598 (2001)

- Skutterudites with partial filling using heavy, low valence “guest” atoms

Heavy-ion Filling Yields Lower Thermal Conductivity. Low Valence Filling Facilitates Optimization of Power Factor.

Partial Filling – Optimization of Power Factor & Thermal Conductivity

George S. Nolas
Department of Physics,
University of South Florida
Approach: Materials Computation

- Predictive computations of TE materials
  - Electronic conductivity
  - Seebeck coefficient
  - Thermal conductivity

- Understanding of transport mechanisms on atomic level and composition trends from ab-initio

- Composition screening in skutterudites
  - Several new compositions predicted with higher Seebeck than base-line CoSb$_3$

- Trade-offs with conductivity investigated

- Collaborative work with Nolas group focuses on Yb and Eu-filled skutterudites
**Approach: Interface Optimization**

- **Thermal characterization** focuses on interface engagement, nanotube wetting, and stability
- **Mechanical modeling** of interfaces allows screening of compositions to improve thermo-mechanical stability
  - Chemical reactivity at interfaces considering phase stability
  - Ab-initio computations and measurements of modulus, CTE
  - Q1/2011: Analysis of mechanical stresses at interfaces – in-plane stress limitations using computed and measured CTE
  - Q1/2011: Cross-section of leg found to be related to the critical stress, strong implications for materials strength for cost reduction
- **Electronic transport across contacts**
  - Work function and barrier calculations set up and calibrated
  - Key numerical screening criteria identified: Fermi level and band offsets, Schottky barrier heights

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**Technical Accomplishment Q1 2011**

Panzer, Goodson et al., *Nanoletters* (2010)
Technical Accomplishment: Publications

5 Full-Length Papers Accepted, after review, for ITERM 2012


7 Archival Journal Papers Appeared or were Accepted
Technical Accomplishments: Stanford Overview

**ThermoElectric Module/Pellet**

- Thermal Cycling

**Nanostructured Interfaces**

- Solder-Bonded Nanotube Thermal Interface Materials

- Thermal Cycling


Gao, Panzer, Goodson et al., J. Electronic Materials, 2010

High Temperature IR Imaging & Characterization

Electrodeposited Metal Nanowire TIMs

Michael Barako, Unpublished research

Nanoscale Conformable Coatings for Enhanced Thermal Conduction of CNT Films

Resistances for 1.5, 2.5, and 40 micron thick CNT films varied between 0.035 and 0.055 cm$^2$ °C/W, with evidence of decreasing engagement with increasing film thickness.
Technical Accomplishment: Mechanical Characterization of CNT Films


<table>
<thead>
<tr>
<th></th>
<th>Thickness (μm)</th>
<th>Modulus (MPa)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWCNT Top</td>
<td>1</td>
<td>600</td>
<td>110</td>
</tr>
<tr>
<td>SWCNT Middle</td>
<td>0-25</td>
<td>0.5</td>
<td>95</td>
</tr>
<tr>
<td>MWCNT Top</td>
<td>0.4</td>
<td>300</td>
<td>40</td>
</tr>
<tr>
<td>MWCNT Middle</td>
<td>0-150</td>
<td>10</td>
<td>29</td>
</tr>
<tr>
<td>Polysilicon</td>
<td>5.8-8.7</td>
<td>155e3</td>
<td>2330</td>
</tr>
</tbody>
</table>

With W. Cai Group, Stanford

\[ E (\text{MPa}) \] vs. CNT thickness (μm)

- Maruyama Lab Samples (SWNT), 95 kg/m³
- Monano Samples (MWNT), ~30 kg/m³
- Wardle Lab Samples/MIT (MWNT), 45 kg/m³

Crust Model

Zipping/Velcro Model
Technical Accomplishment: Infrared Thermometry Failure Analysis of TE Modules

A modified Harman technique was developed to measure the TE figure of merit $ZT$ and the electrical resistance $R$. 

Thermal conductivity and Seebeck coefficient remain relatively stable. Reduction of electrical conductivity and $ZT$. 

Before Cycling

Optical

Infrared

40°C

70°C

100°C

After 45,000 Cycles

SEM courtesy of Yuan Gao

45,000 Cycles

SEM

50 μm

Fracture

Optical
Technical Accomplishment: CNT-Indium Bonding

• Indium (In) foil† is obtained (25 μm thick).
• Cleaned and etched using:
  1. Acetone
  2. Isopropyl alcohol
  3. Deionized water
  4. Solder flux 5R

• The foil is compressed between the CNT film and the glass substrate with light pressure
• The stack is placed on a hot plate at 180°C for one minute. This melts and bonds the indium to the adjacent surfaces. \( T_{\text{melt}} = 156.6^\circ \text{C} \)

† Indium foil by Indium Corp.
Technical Accomplishment: CNT Nanofoil Bonding


• Nanofoil‡ (NF) is a 40μm Al/Ni superlattice which ignites and exothermically alloys to adjacent surfaces

• NF is placed between two gold surfaces. Pressure is applied and the NF is ignited, bonding the two surfaces

• Sn-plated NF bonds Au surfaces (forming Sn-Au bonds). The resulting intermetallic is stable up to 1000°C

1. NF is placed between CNT and adjacent surface

2. NF alloys to form Sn-Au bonds to adjacent surfaces

‡ Nanofoil® by Indium Corp.
Thermal Conductivity

Using conservation of energy, Fourier’s Law, and neglecting convection/radiation, we get:

\[
\frac{k_{\text{sample}}}{k_{\text{ref}}} = \frac{dT}{dx}_{\text{ref}} \quad \frac{dT}{dx}_{\text{sample}}
\]

Thermal Boundary Resistance

Using the temperature drop at the interface and Fourier’s Law

\[
R_{\text{CNT-ref}}^{\prime\prime} = \frac{\Delta T_{\text{int}}}{q''} = \frac{\Delta T_{\text{int}}}{k_{\text{ref}} \frac{dT}{dx}_{\text{ref}}}
\]

Technical Accomplishment: Pressure-Dependent Infrared Thermometry of CNT Interfaces

Compressive Measurement Apparatus
Technical Accomplishment: Pressure Dependence Before Bonding

1. CNT-CNT Boundary Resistance
2. CNT-metal Dry Contact
3. Variation in CNT Heights

Marconnet, Wardle, Goodson, et al., ACS Nano (2011)
For constant $q''$, the interfacial temperature drop is reduced by an order of magnitude through solder bonding.

Indium wets to CNTs and engages more CNTs in conduction, increasing the bulk thermal conductivity of the film.

**Technical Accomplishment:** Pressure Dependence After Bonding
Technical Accomplishment: Total Thermal Resistance (S1-CNT-S2)
Technical Accomplishment: *Intrinsic* Thermal Resistance

If the CNT-Substrate/metalization interface resistance could be reduced, the intrinsic thermal resistance of the CNT films would outperform solders.

The blue arrow shows the magnitude of $R_{S1-CNT}$ and $R_{CNT-S2}$.

The green data points indicate the magnitude of the intrinsic $R_{CNT}$.

**Thermal Greases (E~1 GPa)**

**Alloys (E~10 GPa)**

**Ideal CNT Film (3% Dense)**

---

- Tong *et al.* (2007)
- Tong *et al.* (2006)
- Pal *et al.* (2008)
- Son *et al.* (2006)
- Xu *et al.* (2006)
- Zhang *et al.* (2008)
- Xu *et al.* (2008a)
- Xu *et al.* (2008b)
- Cola *et al.* (2008)
- Hodson *et al.* (2011)
- Cola *et al.* (2007)
- Aradhya *et al.* (2008)
- Cross *et al.* (2010)
- Panzer *et al.* (2008)
- Hu *et al.* (2006)
- Gao *et al.* (2010)
- Barako *et al.* (2012)
- Marconnet *et al.* (2011)
- Marconnet *et al.* (2012)
Technical Accomplishment: Impact of CNT Volume Fraction on Intrinsic Thermal Conductivity

![Graph showing the impact of CNT volume fraction on intrinsic thermal conductivity.](image)

- **RCNT-S2**, **RCNT**, and **RCNT-S2** represent different configurations or materials.

- **Yang et al. (2002, 2004)**
- **Tong et al. (2007)**
- **Tong et al. (2006)**
- **Pal et al. (2006)**
- **Son et al. (2008)**
- **Xu et al. (2006)**
- **Zhang et al. (2008)**
- **Xu et al. (2006a)**
- **Xu et al. (2006b)**
- **Cola et al. (2008)**
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- **Cola et al. (2007)**
- **Aradhya et al. (2008)**
- **Cross et al. (2010)**
- **Panzer et al. (2008)**
- **Hu et al. (2006)**
- **Gao et al. (2010)**
- **Barako et al. (2012)**
- **Marconnet et al. (2011)**
- **Marconnet et al. (2012)**
Technical Accomplishment: Electrodeposited Metal Nanowire TIMs

In collaboration with Prinz group, Stanford

Nominal geometry:
- Cylindrical NWs
- 10 μm film thickness
- 200 nm diameter

a) Polycarbonate membrane is etched to create cylindrical pores
b) Catalyst Pt/Pd is deposited on one side of the membrane
c) Metal is electrodeposited into the pores
d) Membrane is etched away, leaving freestanding nanowires

Thermal Conductivity vs. Volume Fraction

- Picosecond thermoreflectance technique.
- Uncertainty is due to current sample preparation techniques.
Technical Accomplishment 2011: Nanoscale Conformable Coatings for Enhanced Thermal Conduction of CNTs

A custom-fabricated vacuum enclosure with integrated heat exchanger will be built to achieve >500 °C temperature gradient across a TE sample and facilitate simultaneous electrical and optical measurements.
Technical Accomplishment:
Bulk TE Materials for Automotive Applications

- p-type partially filled and Fe-substituted Skutterudites: $Yb_xCo_{4-y}Fe_ySb_{12}$
- Double filled and Fe-substituted Skutterudites: $Ba_xYb_yCo_{4-z}Fe_zSb_{12}$
- n- and p-type Half-Heusler alloys

Yb-filled Fe-substituted CoSb$_3$ by solid state reaction

- Bi$_2$Te$_3$-alloys for High Resolution IR Thermometry (in collaboration with Marlow Industries, Inc.)
- Survey of other material systems with potential for enhanced thermoelectric properties

ZrNiSn by Arc Melting

Thermopower of hot pressed $Yb_{0.4}Co_3FeSb_{12}$ ~ 60µV/K at room temp.

In collaboration with GM R&D for melt-spun processing in investigating amorphous and fine-grained Half-Heusler alloys.
Technical Accomplishment: Bulk TE Materials for Automotive Applications

Prof. G. Nolas, Dr. Yongkwan Dong, University of South Florida

Glen Slack initiated PGEC concept with skutterudites:
✓ Fillers should be loosely bonded to the cage-forming atoms.
✓ Fillers should have large atomic displacements.
✓ Fillers act as independent oscillators ("rattlers").
✓ Interaction of rattlers with the normal modes should lower lattice thermal conductivity.
✓ Phonon-scattering centers ("rattlers") should not greatly affect electronic properties.

- Ytterbium (Yb) partially-filled skutterudites
  - Partial filling optimizes lattice thermal conductivity reduction\(^1\)
  - Yb intermediate valence in CoSb\(_3\) maximizes filler concentration while minimizing added carriers\(^2\)
- P-type partially filled skutterudites (high temp measurements at NIST & Clemson U.)
- Amorphous intermetallic alloys\(^3\) (in collaboration with General Motors)
- Bi\(_2\)Te\(_3\)-alloys for High Resolution Infra-Red Thermometry (in collaboration with Marlow Ind.)
- Survey of other material systems with potential for enhanced thermoelectric properties

Technical Accomplishment: Bulk TE Materials for Automotive Applications

Thermal Conductivity of Yb-filled Skutterudites

Partial filling optimizes lattice thermal conductivity reduction


Increasing Yb concentration

Increasing Ba concentration

Partial filling optimizes lattice thermal conductivity reduction

Technical Accomplishment:

The effect of filling distorts the structure *locally*.
- Soft Sb rings accommodate the distortion.

Electrons from filler open *band gap*, while volume expansion closes the gap.
- Band gap is also sensitive to local distortion

→ Filler vibration is localized and strongly hybridized with Sb atoms. Effect of *force constants* more important than filler mass.

\[
M_{Ba} > M_{Sr} > M_{Ca}, \quad \text{but} \quad \omega_{Ba} > \omega_{Sr} > \omega_{Ca}.
\]
Ternary-substituted skutterudites may hold more potential for n-type

$$XCo_4B_{12} \quad B = Sb \rightarrow (Ge,Sn)/(S,Se,Te)$$

Higher Seebeck coeffs than $CoSb_3$

Filling of ternary skutterudites weakly affects the Seebeck maxima

Changes the carrier concentration significantly

### Seebeck coeff

<table>
<thead>
<tr>
<th>$\mu$ (Ry)</th>
<th>$S$ (µV/K)</th>
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<tbody>
<tr>
<td>0.5</td>
<td>-5.00E-04</td>
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<tr>
<td>0.55</td>
<td>-0.50E-04</td>
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<tr>
<td>0.6</td>
<td>0.00E+00</td>
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<tr>
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<td>5.00E-04</td>
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<td>0.7</td>
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<td>0.75</td>
<td>1.50E-03</td>
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<td>0.8</td>
<td>2.00E-03</td>
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<tr>
<td>0.85</td>
<td>2.50E-03</td>
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<tr>
<td>0.9</td>
<td>3.00E-03</td>
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</table>

### Power factor

<table>
<thead>
<tr>
<th>$\mu$ (Ry)</th>
<th>$\sigma$ (W/mK²)</th>
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<td>0.5</td>
<td>5.00E-04</td>
</tr>
<tr>
<td>0.55</td>
<td>4.50E-04</td>
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<tr>
<td>0.6</td>
<td>4.00E-04</td>
</tr>
<tr>
<td>0.65</td>
<td>3.50E-04</td>
</tr>
<tr>
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<tr>
<td>0.75</td>
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<tr>
<td>0.9</td>
<td>1.00E-04</td>
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</table>
Technical Accomplishment: Nanostructure Design for Thermal Transport

- New method developed for ab-initio thermal conductivity prediction
  - Grain boundary scattering term included in thermal conductivity
- Effect of scattering noticeable at 300K for 500nm grains
- Grain boundary scattering much less effective at high T for skutterudites

\[ \frac{1}{\tau} = \frac{1}{\tau_{ph-ph}} + \frac{v(q,n)}{d} \]
Accomplishment: Outreach & Engagement

Industry Initiatives in Science and Math Education (IISME) – Summer 2011

*Mentorship of a public high school teacher for summer research experience and curriculum development using thermoelectrics*

- Designed engineering course which is now taught at a public high school
- Experienced first-hand application of thermoelectric modules

Undergraduate Thermoelectrics Lab – Fall Quarter

*Stanford’s heat transfer course (ME131A) includes a thermoelectrics laboratory experience.*

- Designed in conjunction with IISME teacher
- Lab exercise uses infrared microscopy with thermoelectric modules

K-12 Educational Outreach – Fall 2011-present

*We are now partnered with a public high school to provide materials and mentors for a TE design lab*

- Introduces high school students to thermoelectric modules and their applications each semester
- Hands-on design lab to engage students in engineering
Collaboration & Coordination

Samples

Stanford
• Prepares CNTs samples on TE materials
 • Transport property measurements of CNT-TE pellet combination, thermomechanical reliability tests on interface (300-800 K)
 • Process development for CNT TIM tape

Bosch
• Ab-initio simulations of transport properties of TE materials and interfaces.
 • System-level simulation and optimization

USF
• Develops high-T, high efficiency TE materials
 • Transport properties (\(\rho\), \(S\) and \(\kappa\)) and Hall measurements (10 - 300K)
 • Structural, morphological and thermal (DTA/TGA) analyses

NIST
• Transport properties (\(\rho\), \(S\) and \(\kappa\)) and Hall measurements (1.8-390K)
 • Specific heat, Power Factor measurement at 300 K.
 • Custom-designed precision TE properties measurement system (300 – 1200 K)

Information

Samples

1, 3, 4, 6

1, 2, 3, 5

4, 6
Proposed Future Work

- **Bulk TE Materials**: Develop p-type partially/double filled Fe-substituted Skutterudites, n- and p-type half heusler alloys for melt-spun processing, thermal stability tests of materials and joints.

- **CNT Thermal Tape Development and Characterization**: Bonding extension to 600°C, thermal stability investigation.

- **Nanostructured Metal Thermal Interface Materials**: Investigate thermal, mechanical, and electrical properties of metal nanowires and meshes, optimization of materials, geometries, and surface treatments for operation at 600°C.

- **High-T (ZT)$_{eff}$ Characterization Facility Implementation**: Vacuum chamber development with IR transparent window, validation using Bi$_2$Te$_3$-alloys

- **Ab-Initio Simulations**: Band gap calibration for skutterudite and half-Heusler families, focussed computatios on phase stability, Seebeck coefficient, and transport properties.
With this award, DOE & NSF are enabling an academic-corporate team to focus on the key practical challenges facing TEG implementation in vehicles: interfaces, system-relevant metrology, and materials compatibility.

We are developing metrology for fundamental properties of nanostructured interfaces, as well as $(ZT)_{\text{eff}}$ metrology for half-Heusler and skutterudite thermoelectrics considering interfaces. Simulations include atomistic and ab initio results for TE materials and interfaces, and system & heat exchanger level optimization with the corporate partner.

Key 2011 results include: (a) process development of CNT tape and several bonding options (Stanford) (b) detailed mechanical characterization of CNT films (Stanford), (c) IR characterization of TE pellets and corresponding interfaces under thermal cycling (Stanford), (d) interface modeling & optimization (Bosch) and (e) process development (arc melting, melt spun) for bulk TE materials (USF).
Technical Backup Slides
• Bonding the CNT films to relevant substrates is a major challenge as not all materials are compatible with the CNT growth procedure.

• Recent progress utilizing a combination of metallizations allows CNT films grown on sacrificial silicon wafers to be successfully transferred to a range of substrates using thin indium foils as binding layers.

• This is a key step towards developing the free standing CNT tape for thermal interface applications.
Technical Accomplishment: CNT Bonding Procedure

1) SAMPLE PREPARATION
   a) Evaporate Au/Ni/Cr on CNT and glass substrates

   b) Clean indium foil or apply flux

   Au/Ni/Cr
   CNT
   Si
   Glass

2) THERMAL BONDING

   Hotplate
   Si
   CNT
   Glass
   Indium
   CNT film bonded to glass, before removal of Si substrate
Technical Accomplishment: CNT Bonding Procedure

3) CNT FILM RELEASE

CNT bonded to Si

CNT bonded to glass

Original CNT substrate, with no CNT remaining

CNT (side is covered with Au from metallization)
Relevance: Effect of Interface Resistances on Thermoelectric Device Properties


<table>
<thead>
<tr>
<th>Interface Material</th>
<th>$R''_{\text{th}}$ [W/m²K]</th>
<th>$R''_{\text{e}}$ [Ω m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solders And Ideal CNT</td>
<td>$\sim 10^{-7}$</td>
<td>$\sim 10^{-12}$</td>
</tr>
<tr>
<td>High Quality CNT</td>
<td>$\sim 10^{-6}$</td>
<td>$\sim 10^{-10}$</td>
</tr>
<tr>
<td>Lower Quality CNT</td>
<td>$\sim 10^{-5}$</td>
<td>$\sim 10^{-8}$</td>
</tr>
<tr>
<td>Thermally &amp; Electrically Conductive Grease</td>
<td>$\sim 3\times 10^{-6}$</td>
<td>$\sim 3\times 10^{-9}$</td>
</tr>
<tr>
<td>Thermal Conductive Grease</td>
<td>$\sim 8\times 10^{-6}$</td>
<td>$\sim 3\times 10^{-7}$</td>
</tr>
<tr>
<td>Electrically Insulating Grease</td>
<td>$\sim 8\times 10^{-6}$</td>
<td>$&gt;10^{-5}$</td>
</tr>
</tbody>
</table>
“...Stanford is also working with the National Science Foundation (NSF) on a project with the Department of Energy Partnership on Thermoelectric Devices for Vehicle Applications. Here, the nanotape will facilitate the recovery of electrical power from hot exhaust gases using thermoelectric...”