NSF-DOE TE Partnership: Integrated Design and Manufacturing of Cost-Effective & Industrial-Scalable TEG for Vehicle Applications

Lei Zuo, Jon Longtin, Sanjay Sampath and Baosheng Li
State University of New York at Stony Brook

Qiang Li
Brookhaven National Lab

2011 DOE Thermoelectrics Workshop, Jan 3-6th, San Diego, CA
Thermoelectric Waste Heat Recovery

- **Traditional TEGs**
  - Material synthesis ➔
  - Module assembly ➔
  - Subsystem integration ➔
  - Vehicle Integration

**Challenges**
- Multiple-step assembling
- Interface and durability (soldering, clamping)
- Considerable vehicle modification
- Materials (cost, toxicity, synthesis time)
Integrated Design and Manufacturing
Integrated Design and Manufacturing

- Abundant low-cost feedstock
- Direct fabricate on exhaust pipes
- Non-equilibrium synthesis for improved ZT
- Industrial progress: thermal spray and laser micromachining
- Reliable interface and durability without soldering or clamping

Exhaust pipe with heat sink fins
Bottom electrical insulation layer
Bottom electrical conductor strips
TE layer inducing diffusion barrier
Top electrical conductor strips
Coolant liquid
Cooling jacket
Exhaust pipe with heat sink fins
Bottom electrical insulation layer
Top electrical insulation layer
Integrated Design and Manufacturing

System-Level Approach

Design
- Mechanical and Thermal Manufacturing

Materials
- Metal Silicides
- Skutterudites

Process
- Nonequilibrium Synthesis
- Thermal Spray

Integration
- Direct-to-part Fabrication
- Laser Micro Machining
Metal Silicide (Mg$_2$Si)

- Metal Silicides: slightly lower $ZT$, but abundant, inexpensive, no toxicity.
- $ZT \approx 1.1$ near 800K (Mg$_2$Si$_{1-x}$Sn$_x$), Bi/Al doped

Source: Tokyo University of Science
R. Szczech and Song Jin 2008 and references therein
V. K. Zaitsev et al, 2006, Physical Review B
Metal Silicide (FeSi$_2$)

- $\beta$-FeSi$_2$ has TE properties. N-type doping with Co, p type with Mn or Al
- $ZT \sim 0.06$–$0.15$ at $400$ – $600$ °C
- Process Study: Thermal Spray used to synthesize bulk $\beta$-FeSi$_2$
- $ZT$ can be higher than by hot pressing!

Filled Skutterudites

- Fill the void with low-coordination ion: phonon scattering to reduce thermal conductivity
- $ZT = 1.4$ reported

Co-PI Qiang Li at BNL2009
Integrated Design and Manufacturing

System-Level Approach

Design
- Mechanical and Thermal Manufacturing

Materials
- Metal Silicides
- Skutterudites

Process
- Nonequilibrium Synthesis
- Thermal Spray

Integration
- Direct-to-part Fabrication
- Laser Micro Machining
Non-Equilibrium Synthesis Method

Rapid solidification starting materials into near amorphous ribbons in seconds → Direct conversion and densification under high pressure in minutes

Dr. Q. Li (co-PI), Head of Advanced Energy Materials Group, BNL
Non-Equilibrium Synthesis Method

Conventional TE Synthesis

- High pressure densification
- Powdering, sintering (days to weeks)
- Advantage of Non-equilibrium Synthesis
  - Reduced processing time from days to minutes
  - Higher density and mechanical strength
  - More control of micro- to nano-structure

Non-equilibrium Synthesis Techniques (e.g., Melt-Spinning)

- Rapid solidification into amorphous ribbons (few seconds)
- High pressure densification

Advantages:
- Reduced processing time
- Higher density and mechanical strength
- More control of micro- to nano-structure
Practical Non-Equilibrium Synthesis: Thermal Spray

Melt spinning

- High pressure
- Industrial-scalable non-equilibrium synthesis
- Rapid quench

Hot press

- High pressure
- $10^7 K/s$
What is Thermal Spray?

100-1000 m/s

Protective Coating ➔ Electronics and Sensors

Thermal Spray: Non-Equilibrium Processing

*Melting, quenching and consolidation* **in single process**

*Splat based build-up and state induced properties***

High velocity, $T$ *(melting/softening)* → Impact, rapid solidification → Quenching *(10^7 K/s)*

*Layered and graded architectures through successive splat quenching***

Interfaces and Adhesion

Micro Features and Phases

Layered Thick Films

Graded Porosity
**Past Work: Thermal Spray of Iron Silicide in Japan and Germany**


*Figure 2* SEM of shrouded plasma spray (SPS)–formed iron disilicide: (a) as sprayed; (b) after 100 h heat treatment at 800 °C.
TE Properties of FeSi₂: Thermal spray vs. hot pressing

Seeback coefficient $S$ almost the same

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

Figure of merit ZT increased by 30-60%! 
Center for Thermal Spray Research at SBU

Atmospheric Plasma Spray System
Sulzer Metco F4

Consortium for Thermal Spray Technology

High Velocity Oxy-Fuel System
Sulzer Metco Diamond Jet (DJ-2600)

In Situ Curvature Sensor

Spray Stream Guillotine

3D Particle In Flight Diagnostics
Integrated Design and Manufacturing

System-Level Approach

Design ➔ Materials ➔ Process ➔ Integration

- Mechanical and Thermal Manufacturing
- Metal Silicidies
- Skutterudites
- Nonequilibrium Synthesis
- Thermal Spray
- Direct-to-part Fabrication
- Laser Micro Machining
Integrated Design and Manufacturing

(a) Start with exhaust pipe with heat sink fins (Mo-Cu or Al alloy)

(b) Coat electric insulation layer using thermal spray

(c) Pattern electric conductor strips using thermal spray and laser cutting

(d) Spray n and p type TE rings and diffusion barriers using direct thermal spray (Mg2Si or filled Skutterudites)

(e) Cut the TE rings into thermal couples using laser

(f) Gap filling and top electric conductor strips to form thermal piles

(g) Coat electrical insulation layer using thermal spray

(h) Add cooling jacket outside
Short-Pulse Laser Micromachining

Amplified Ti:sapphire laser beam,
\( \lambda = 790 \text{ nm}, \tau_p \sim 150 \text{ fs}, \ E_p \sim 1.2 \text{ mJ} \)

NiCr

Al₂O₃
Prior Work and Resources

Past Research: Thermal Spray of TE materials (Japan, Germany)

Center for Thermal Spray Research at SBU

Non-equilibrium TE Synthesis at BNL

Pulse Laser Micro Machining

Vehicle Energy Harvesting

Cost-Effective and Industrial Scalable TE for Vehicles
Summary

• *Systems-driven* approach to practical TE devices for vehicles

• *Non-equilibrium* synthesis of abundant, low-cost TE materials

• Integrated *direct-to-part* fabrication on exhaust pipe components using thermal spray and laser micromachining

• High-throughput, low-cost scalable manufacturing process
Lei Zuo (PI)
Mechanical Eng
lei.zuo@stonybrook.edu

Jon Longtin
Mechanical Eng

Sanjay Sampath
Material Science

Qiang Li
Material Science

Baiosheng Li
Mineral Physics