Environment and Natural Resources Trust Fund
2016 Request for Proposals (RFP)

Project Title: **ENRTF ID:** **151-E**

Waste Heat Recovery with Efficient Thermoelectric Energy Generators

Category: E. Air Quality, Climate Change, and Renewable Energy

Total Project Budget: $ 404,427

Proposed Project Time Period for the Funding Requested: 3 years, July 2016 to June 2019

Summary:

Almost 55% of energy consumed in the US is discharged as waste heat. We propose transforming waste heat into electricity through thermoelectrics to ameliorate climate change and reduce air pollution.

Name: Uwe Kortshagen

Sponsoring Organization: U of MN

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Minneapolis MN 55455

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Email kortshagen@umn.edu

Web Address

Location

Region: Metro

County Name: Statewide

City / Township:

Alternate Text for Visual:

The chart describes the integrated approach of thermoelectric materials synthesis, device fabrication, and characterization.

_____ Funding Priorities _____ Multiple Benefits _____ Outcomes _____ Knowledge Base

_____ Extent of Impact _____ Innovation _____ Scientific/Tech Basis _____ Urgency

_____ Capacity Readiness _____ Leverage _______ TOTAL ______%

PROJECT TITLE: Waste Heat Recovery with Efficient Thermoelectric Energy Generators

I. PROJECT STATEMENT

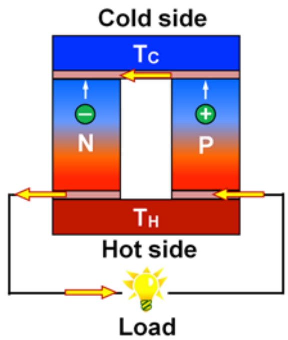


Figure 1. Schematic of a TE device for power generation

The U.S. used ~97 quadrillion BTU of energy in 2011, of which 55.6 quadrillion BTU were emitted as "waste heat" (rejected energy).[1] Tapping into this reservoir of waste heat would allow lowering the consumption of fossil fuels and reducing greenhouse gas emissions and air pollution.

Thermoelectrics (TE) seeks to harvest waste heat and transform it into useful electrical energy. The **objective** of this project is to develop **novel thermoelectric energy generators** based on high-performance TE materials that combine high electrical conductivity with low thermal conductivity. The waste heat entering a TE generator (Figure 1) pushes negatively charged electrons and their positive counterparts (holes), to the cold side of the device, where they neutralize each other. This transport of electrons and holes causes a lack of these species at the hot side, which generates a TE voltage that provides electricity to drive external loads.

This project will focus on producing more efficient "nanograined" TE materials and devices thereof utilizing a unique materials synthesis technique that was developed at the University of Minnesota. This synthesis technique will enable us to produce materials based on silicon and germanium with more sophisticated control over TE properties and better scalability than other known approaches. Through combining materials synthesis with thermal and electrical characterization and device fabrication, we will develop novel TE energy generators that improve the efficiency of thermal power systems, reduce the consumption of fossil fuels, and ameliorate air pollution and the emission of greenhouse gases.

II. PROJECT ACTIVITIES AND OUTCOMES

The best TE materials must combine seemingly paradoxical properties: excellent electrical conductivity with extremely poor thermal conductivity. Usually, these two properties are coupled such as in metals, which are good electrical and thermal conductors, as everyone knows who has stirred hot tea with a silver spoon. Recently, researchers found that fabricating TE materials from nanometer-sized grains can significantly enhance their performance. In such "nanograined" materials, the carriers of electrical energy, electrons and holes, can travel largely unimpeded by the nanometer-sized grain structure, but the carriers of thermal energy (heat), so called phonons, are strongly hindered in their motion by the many boundaries between the nanometer-sized grains. Compounds of silicon and germanium are known as excellent TE materials for high-temperature applications, such as for waste heat recovery from the exhaust of automotive engines or power plants. In order to harvest the full potential of such materials, they must be produced from grains as small as few nanometers. Professor Kortshagen's group at the University of Minnesota developed a novel synthesis plasma technique for nanograined materials in 2005, which is covered by three US patents and was licensed to companies including DuPont-Innovalight and Dow Corning, having generated, to date, royalty income for the University of Minnesota exceeding $700k. Due to its novelty and scalability, this technique offers our group competitive advantages compared to approaches used by other research groups and may lend itself to large scale commercialization.

Activity 1: *Nanograined Materials Synthesis* **Budget: $159,180**

Silicon and germanium nanograins will be produced using Professor Kortshagen's plasma synthesis approach, which produces nanograins from atomic precursors within a few milliseconds. The nanograins will be deposited through impaction from the gas phase. By rapidly modulating the deposition of silicon and germanium nanograins, the materials structure can be controlled with nanometer accuracy, different from competitors who

[1] Report by Lawrence Livermore National Laboratory: https://www.llnl.gov/news/americans-use-more-efficient-and-renewable-energy-technologies

use methods such as day-long ball milling to break down bulk materials into nanograins. The nanograin deposits will be transformed into dense scalable TE materials through thermal sintering.

Outcome	Completion Date
1. Construct deposition reactor	*Dec 31, 2016*
2. Produce TE materials through deposition and sintering	*June 30, 2017*

Activity 2: *Materials Optimization* **Budget: $121,371**

Professor Xiaojia Wang's custom-built ultrafast-laser based time-domain thermoreflectance system is a noninvasive, accurate, and high-throughput test rig for probing the thermal properties of TE materials. In particular, it is by far the only technique which can directly capture the information on the optimized "nanograin" size to decouple electrical and thermal energy carriers. Using information from her thermal characterization and electrical characterization to be performed by Prof. Kortshagen, we will optimize the thermoelectric properties through optimizing the layering of silicon and germanium and through optimizing electrical conductivity through a process called doping.

Outcome	Completion Date
1. Optimize boron-doped silicon/germanium TE materials	*Dec. 31, 2017*
2. Optimize phosphorous-doped silicon/germanium TE materials	*June 30, 2018*

Activity 3: *TE Device Development* **Budget: $123,877**

Optimized boron and phosphorous-doped silicon germanium TE materials will be integrated into TE energy generators and their efficiency will be characterized

Outcome	Completion Date
1. Develop TE energy generators from optimized materials	*Dec. 31, 2018*
2. Characterize device efficiencies	*June 30, 2019*

III. PROJECT STRATEGY

A. Project Team/Partners

Professor Xiaojia Wang is an expert in analyzing the thermal properties of materials. As a junior faculty member, she has published 14 journal articles in the area of micro-nanoscale thermal transport. Her time-domain thermoreflectance system is equaled only by a few similar systems in the country. Professor Kortshagen brings unique expertise in materials synthesis and electrical characterization. Since joining the University of Minnesota in 1996, he has directed research on grants exceeding $25M, including large research groups around nanograin materials, which has led to over 100 research papers, three patents and two technology licenses to DuPont-Innovalight and Dow Corning.

B. Project Impact and Long-Term Strategy

This proposed work improves the energy conversion efficiency of thermoelectric devices, and subsequently reduces the usage of fossil fuels to ameliorate air pollution and the emission of greenhouse gases. It leverages upon research which is performed by the "Sustainable Nanocrystal Materials" group (directed by Kortshagen) of the National Science Foundation-funded University of Minnesota Materials Research Science and Engineering Center, a $17.8M federal grant. If successful, the outcomes of this work will contribute to the scientific knowledge base, but also hold great prospect for commercialization.

C. Timeline Requirements

The project will require 36 months to complete with milestones explained above.

2016 Detailed Project Budget

Project Title: Waste Heat Recovery with Efficient Thermoelectric Energy Generators

IV. TOTAL ENRTF REQUEST BUDGET: 3 Years

BUDGET ITEM	AMOUNT
Personnel:	
Uwe Korthagen PI (2 weeks (.06FTE) + fringe 33.8% fringe) for 3 years.	$ 35,948.00
Xiajia Wang (2 weeks (.06 FTE) + fringe 33.8% fringe) for 3 years.	$ 19,564.00
2-Graduate Research Assistant 50% FTE (fall & spring include 16.6% fringe plus $17.84/hour tuition, summer 16.6% fringe only) for 3 years	$ 278,915.00
Equipment/Tools/Supplies:	$ 40,000.00
Lab Supplies	$ 30,000.00
TOTAL ENVIRONMENT AND NATURAL RESOURCES TRUST FUND $ REQUEST =	$ 404,427

V. OTHER FUNDS

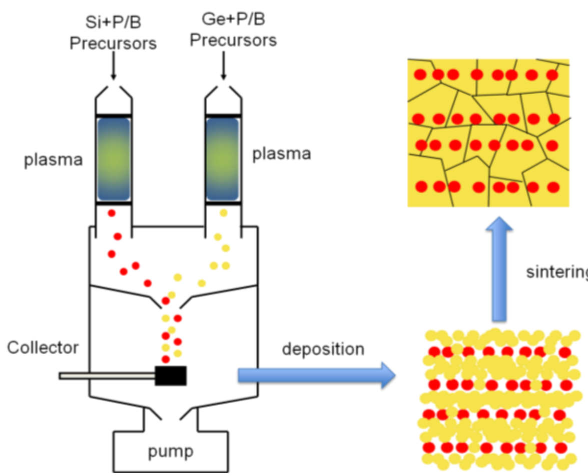
SOURCE OF FUNDS	AMOUNT	Status
Other Non-State $ To Be Applied To Project During Project Period:		
Other State $ To Be Applied To Project During Project Period: *N/A*		
In-kind Services To Be Applied To Project During Project Period: *N/A*		
Funding History: *Minnesota private company funds for development of graphene sensors*		
Remaining $ From Current ENRTF Appropriation: *N/A*		

Kortshagen & Wang, University of Minnesota

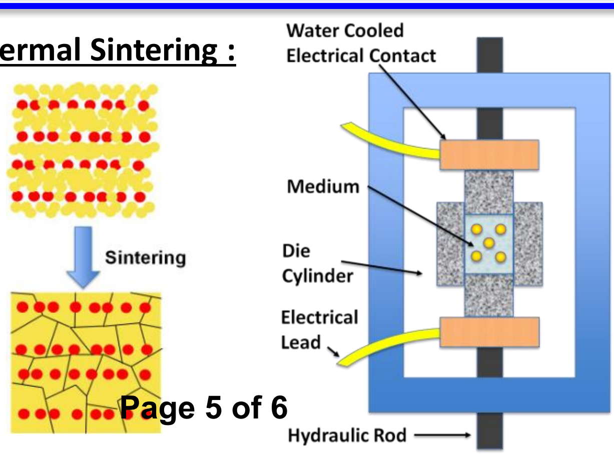
Waste Heat Recovery with Efficient Thermoelectric Materials

Growth of Si-Ge Nanoparticles

- Novel nanoparticle synthesis
- Control of the nanograin size and doping level
- New insights into the growth mechanisms

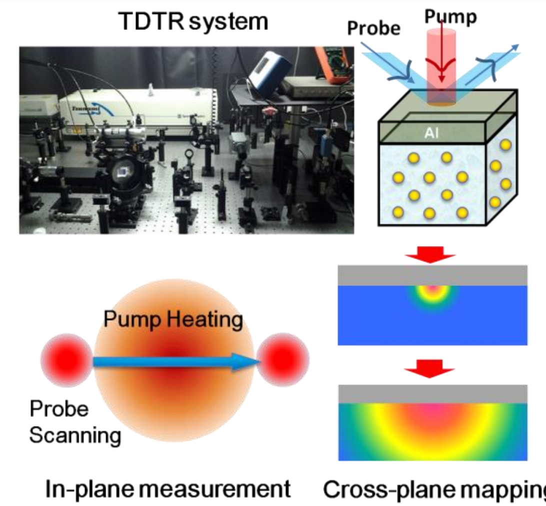


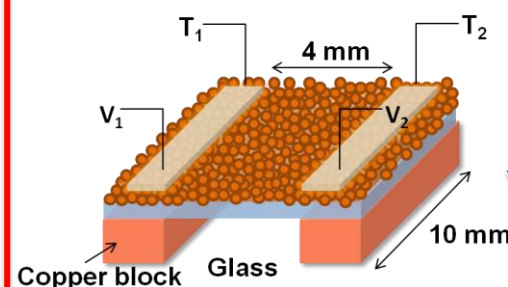
Thermal Sintering :



Thermal Properties:

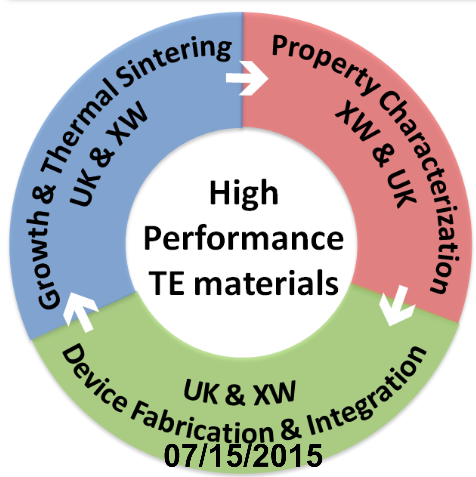
- Accurate, high-throughput, and noninvasive ultrafast optical approach
- Characterization of the thermal properties in both the in-plane and cross-plane directions
- 3D thermal mapping with micron scale resolution





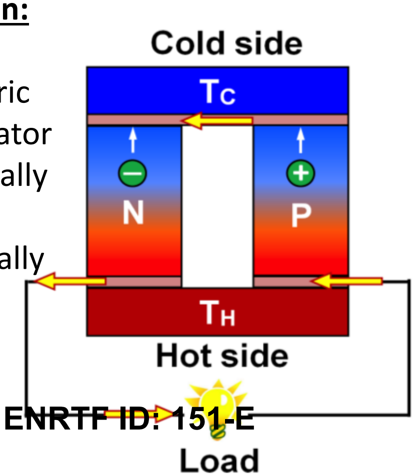
Electrical Properties:

- Deposition of fine metal lines
- Characterization of Seebeck coefficient and electrical conductivity



Device Fabrication:

- Thermoelectric power generator
- No mechanically moving parts
- Environmentally friendly



Project Manager Qualifications & Organization Description

Uwe Kortshagen is Distinguished McKnight University Professor and Head of the Department of Mechanical Engineering at the University of Minnesota, and a member of the graduate faculties of Physics, Chemical Engineering and Materials Science, and Nanoparticle Science and Engineering. He earned his Diploma degree in Physics in 1988, and his Ph.D. in Physics in 1991 from the University of Bochum, Germany, under Hans Schlüter. He came to the U.S. in 1995 with an Alexander von Humboldt Fellowship and spent a year at the University of Wisconsin-Madison. He earned the Habilitation in Experimental Physics at the University of Bochum in 1995. In 1996, he joined the Department of Mechanical Engineering at the University of Minnesota as Assistant Professor, where he was promoted to Associate Professor in 1999, and to Full Professor in 2003. He served as President of the International Plasma Chemistry Society and is a Fellow of the American Society of Mechanical Engineers, the Institute of Physics (IOP, London, UK), and the International Plasma Chemistry Society. He was awarded the 2005 Institute of Technology-George Taylor Award for Distinguished Research, and was named Distinguished McKnight University Professor of the University of Minnesota in 2007. His work is in the area of kinetic theory of plasmas, nonthermal plasmas at atmospheric pressures, and in the plasma synthesis and functionalization of nanomaterials. His work has been published in more than 140 articles in peer-reviewed journals and received more than 5,000 citations with an H-index of 39.

Xiaojia Wang is an assistant professor in the Department of Mechanical Engineering at the University of Minnesota. She received her Ph.D. in Mechanical Engineering from the Georgia Institute of Technology in 2011, and her M.E. in 2007 and B.E. in 2004 from Xi'an Jiaotong University, China, all in Mechanical Engineering. She was a postdoctoral research associate in the Department of Materials Science & Engineering at the University of Illinois, at Urbana-Champaign till 2014. Her research focuses on the fundamental mechanisms of thermal transport in micro/nano-engineered structures for energy conversion and harvesting, by utilizing the ultrafast pump-probe technique and other optical spectroscopic approaches. She received the Innovation Award for poster competition at ASME 2009 IMECE and the Outstanding Reviewer Award for the *Journal of Quantitative Spectroscopy and Radiative Transfer* in 2014. Her work on the optical properties of inclined silver nanorods was featured on the issue’s cover of *Nanoscale and Microscale Thermophysical Engineering* in 2012. She is currently a member of ASME Heat Transfer Division K9 Committee on Nanoscale Thermal Transport.

Uwe Kortshagen is the PI of this proposed work, and he will be responsible for the overall management of this project and the status reports of project update. He has directed research on grants exceeding $25M. For this project, he will be working on the synthesis of silicon-germanium nanoparticles with precisely controlled sizes and doping levels. In addition, he will characterize the electrical properties of scalable thermoelectric materials from thermal sintering of nanoparicles. **Xiaojia Wang**’s expertise lies in the heat transfer in micro- and nano-scale using novel ultrafast optical characterization techniques. She will be in charge of the thermal sintering of nanoparticles and she will also investigate the thermal properties of the proposed thermoelectric materials and correlate the material thermoelectric performance to their property characterization. Two PIs will coordinate with each other to experimentally develop and characterize new thermoelectric energy generators and to theoretically explore and validate the relation between the device design and property performance.