Environment and Natural Resources Trust Fund
2017 Request for Proposals (RFP)

Project Title: **ENRTF ID:** **145-E**

Novel Nanocomposite Materials for Thermal Management and Energy Conversion/Storage

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

Total Project Budget: $ 256,112

Proposed Project Time Period for the Funding Requested: 3 years, July 2017 – June 2020

Summary:

This proposal focuses on fabricating novel nanocomposite materials for better thermal management in operating devices, as an enabling technique that will improve the efficiency for energy conversion and storage.

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Sponsoring Organization: U of MN

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Location

Region: Statewide

County Name: Statewide

City / Township: Minneapolis

Alternate Text for Visual:

The map illustrates a schematic of the novel nanocomposite structure and its great potential for improving the efficiency of thermal energy conversion and storage in numerous applications.

_____ Funding Priorities _____ Multiple Benefits _____ Outcomes _____ Knowledge Base

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

_____ Capacity Readiness _____ Leverage _______ TOTAL ______%

PROJECT TITLE: Novel Nanocomposite Materials for Thermal Management and Energy Conversion/Storage

I. PROJECT STATEMENT

According to the US Department of Energy, more than half of the energy consumed in the state of Minnesota is lost as waste heat resulting from operating devices in transport, industry, residential and commercial services.[1] Such a large amount of waste heat, if not adequately removed, will reduce both the performance reliability and lifetime of the devices. One solution to address this issue is to develop materials that allow better removal or redistribution of heat in device operation (the so-called **thermal management**) to improve the device reliability and lifetime. For example, a 10^{o}C reduction in the temperature of an LED light module would make the difference in energy efficiency in light output and more than twice in useful life of the LED. Ultimately, products/devices made from materials with high performance of thermal management will lower the consumption of fossil fuels and reduce greenhouse gas emissions. This is a strategy in clear alignment with Minnesota's energy policy - Balancing the state's need for affordable energy with the **environmental** and **economic** needs of the state.[2]

The ***goal*** of this proposal is to design, fabricate, and characterize novel nanocomposite materials for better thermal management in devices, as an enabling technique that will improve the efficiency for energy conversion and storage. Such novel materials could be readily applied to existing devices in industry, solar cell panels, power plants, electrical car engines, computers, and hand-held electronics (i.e., tablets and smart phones). There have been attempts on the composite approach to synthesize thermal interface materials for better heat dissipation in microelectronics packaging, which involve embedding fillers (good thermal conductors) into flexible host media to improve the overall performance of heat removal. Unfortunately, thermal resistance at the interfaces between the fillers and host media results in rather modest gains to the overall performance of these composite materials, regardless the high thermal conductivities and/or enormous amounts of fillers added. For example, the highest reported thermal conductivity (indicating a material's capability to conduct heat) of composites with alumina particles (fillers that are good thermal conductors) loaded in polymers (one type of host media used for 3M thermal tape to enhance the material flexibility) is only one tenth of the intrinsic thermal conductivity of alumina. This leads to emerging challenges in thermal management for numerous applications wherever heat dissipation is crucial, especially in modern electronic systems with increasing circuit density and dimension miniaturization.

The proposed work will be achieved by designing and characterizing special materials that better couple the fillers with the host medium to reduce the dominant thermal resistance at the interfaces. Professor Wang will integrate the expertise of her group at the U of M with that of the group led by Dr. Jeremy Higgins, a senior material chemist at 3M (see details in the support letter by Dr. Higgins). The proposed work is of mutual interest for 3M's research and development, as 3M is in the business of thermal management with current product lines and future product development, including solutions to enhanced heat removal and redistribution (i.e., heat spreaders, thermal tapes/pads/gels, and LED cooling) and phase change materials for energy conversion/storage (i.e., thermally adaptive smart clothing). Thus, outcomes from this work hold great prospect for direct commercialization, which will potentially create job opportunities and benefit the state economy.

II. PROJECT ACTIVITIES AND OUTCOMES

This proposal will focus on engineering the interfaces between the nanoparticle fillers and the host medium by designing special linking layers, which will bridge fillers and the host medium with strong chemical bonds through a process of surface functionalization. This will assure fillers to well adhere to the host medium, which will not only enhance the overall thermal performance of the nanocomposites but also improve the material's mechanical performance for device integration. Experimental validation of the thermal enhancement will be performed to prove that the nanocomposites work as designed for further incorporation into device or product fabrication.

Activity 1: *Nanoparticle Synthesis and Linking Layer Development for Nanocomposites* **Budget: $84,093**

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[1] http://www.districtenergy.org/blog/2013/05/23/minnesota%E2%80%99s-new-waste-heat-recovery-law/
[2] https://ballotpedia.org/Energy_policy_in_Minnesota

Nanoparticles that are already adopted in 3M products will be used as fillers as a good start, including boron nitride nanoplates, alumina and silica nanospheres. Professor Wang will work with Dr. Higgins to systematically alter the chemical recipes of the linking layers for different types of nanoparticles to be loaded into polymer host media. Other unique nanoparticles involving metals and semiconductors will be also be synthesized and surface functionalized for further attempts of enhancing energy transfer at interfaces.

Outcome	Completion Date
1. Linking layer development and structure characterization of commercial nanoparticles	*Dec 31, 2018*
2. Synthesis and characterization of metallic and semiconducting nanoparticles	*June 30, 2018*

Activity 2:*Thermal Performance Optimization of Nanocomposites* **Budget: $85,268**

As yet, experimental probe of interfacial thermal transport remains a pervasive bottleneck, mainly due to the low measurement sensitivity. The custom-built ultrafast-laser based pump-probe system in Wang's group enables accurate, noninvasive, and high-throughput measurements for probing the thermal properties of nanocomposites. This is currently the only technique which can directly capture the information about thermal transport across interfaces within nanocomposite materials. The interfacial thermal properties extracted from experiments will guide the material design in an iterative manner for performance optimization.

Outcome	Completion Date
1. Iterative optimization of linking layers for commercial nanoparticles	*Dec. 31, 2018*
2. Iterative optimization of linking layers for metallic and semiconducting nanoparticles	*June 30, 2019*

Activity 3: *Nanocomposite-Based Thermal Interface and Energy Storage Materials* **Budget: $86,751**

Upon the completion of design and optimization of nanocomposite materials, Professor Wang will work on demonstrating the potential for commercialization of nanocomposite-based materials with the assistance of Dr. Higgins. These materials can be readily incorporated into existing 3M products such as thermal tapes and gels.

Outcome	Completion Date
Prototype of novel nanocomposites in commercially host media	*Dec. 31, 2019*

III. PROJECT STRATEGY

A. Project Team/Partners

Professor Wang is an expert in thermal energy transport, especially in analyzing the thermal properties of materials at the microscale and nanoscale. She has successfully demonstrated her leadership in the area of micro/nanoscale thermal transport by conducting many groundbreaking experiments in the field and the results are published in high-profile scientific journals. She also has proven records of collaborating with researchers from several Minnesota-based companies including Seagate and 3M. Her custom-built pump-probe system is equaled only by very few similar systems in the country. Dr. Higgins will provide research samples that are directly relevant to 3M product lines and technical assistance with optimizing the linking layers (chemical surface functionalization). This collaboration between Professor Wang and Dr. Higgins well reflects the theme of 3M–Science Applied to Life.

B. Project Impact and Long-Term Strategy

If successful, the results of this work hold promise in basic scientific foundation and commercialization, as readily seen from the direct involvement of industrial company. The novel nanocomposites will significantly advance the development of commercial products for thermal management and energy conversion/storage. This proposal will also motivate the team to seek for federal funding resources that require participation of industrial partners (i.e., NSF-Goali) for supporting continued efforts on this topic. In the long run, this proposal will benefit the environmental and economic systems in the state of Minnesota.

C. Timeline Requirements

The completion of this project will require 36 months starting from July 01, 2018 to June 30, 2020, in three stages as detailed in Section II.

2017 Detailed Project Budget

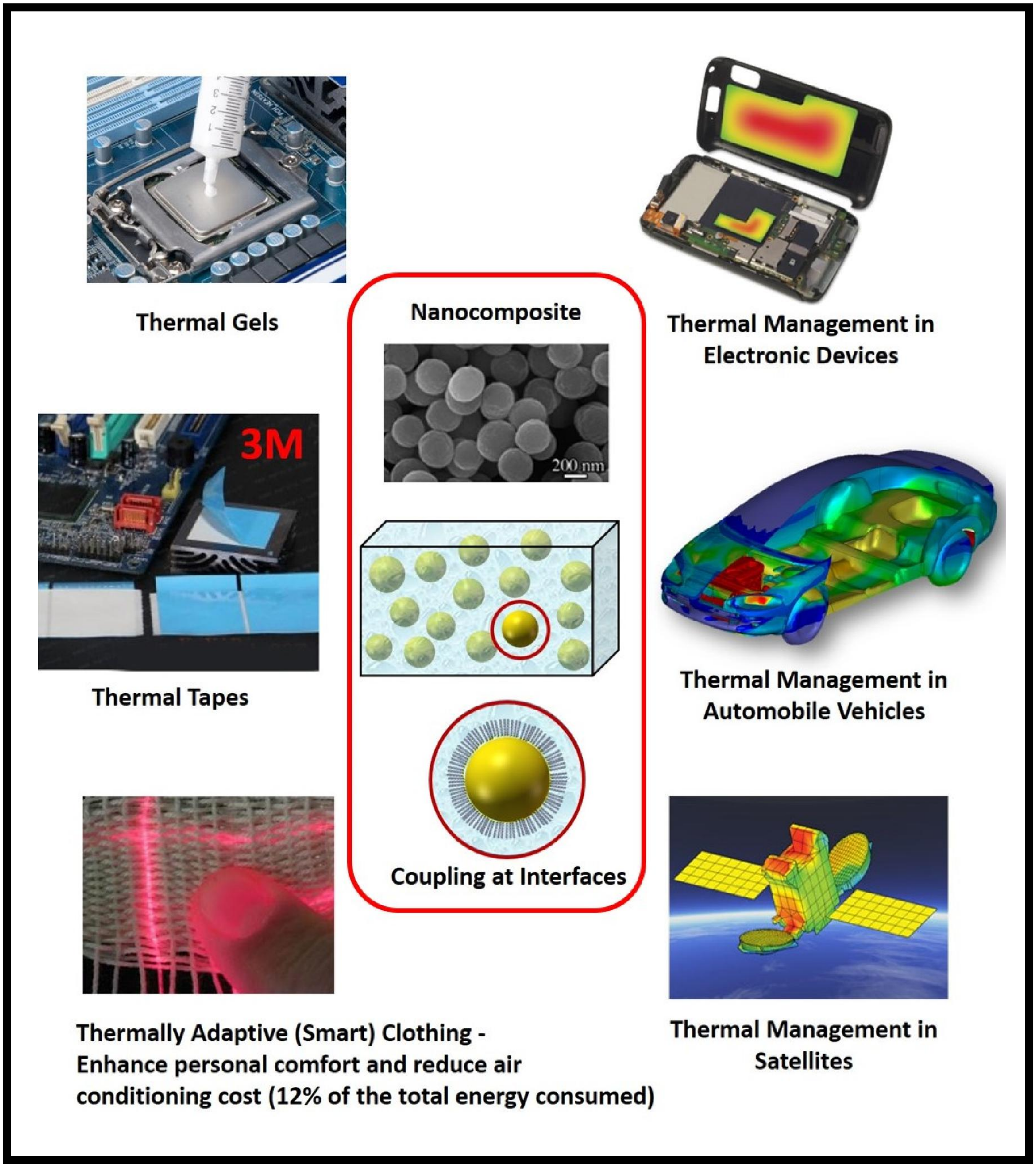
Project Title: Novel Nanocomposite Materials for Thermal Management and Energy Conversion/Storage

IV. TOTAL ENRTF REQUEST BUDGET: 3 Years

BUDGET ITEM		AMOUNT
Personnel:	**$**	**229,111.65**
Dr. Xiaojia Wang , PI, (2 weeks (.06 FTE) + fringe 33.8% fringe) for 3 years ($ 4975 + $ 5124 + $ 5278)	$	20,574.75
1 postdoctoral research associate ($ 22,000 for 6 months each year and last for 3 years)	$	66,000.00
1-Graduate Research Assistant 50% FTE (fall & spring include 16.6% fringe plus $17.84/hour tuition, summer 16.6% fringe only) for 3 years	$	142,536.90
Lab Supplies/User Fees	**$**	**24,000.00**
Cost for purchasing chemicals and containers for nanoparticle synthesis ($250*3=$750) and surface functionalization ($250*3=$750)	$	1,500.00
Purchasing reference materials for validation thermal measurements, including bare silicon wafers ($200*3=$600), silicon dioxide wafers ($200*3=$600), and sapphire wafers (aluminum oxide, $300*3 = $900) for extracting transducer properties.	$	2,100.00
User fees for rental and usage of facilities at the campus Characterization Facility Center (CharFac) for nanoparticle, surfactant coating (linking) layer, and reference film sample structural/property characterization (4-point probe electrical conductivity, atomic force microscopy, Raman spectroscopy, tunneling electron microscopy, and ellipsometry, $4300*3=$12900) and user fees for facility at the Minnesota Nano Center (MNC) for thin-film deposition and nanoparticle synthesis ($2500*3=$7500). Detailed information about the facility at the U of M CharFac and MNC are listed in the file of Project Manager Qualifications & Organization Description.	$	20,400.00
Travel cost	**$**	**3,000.00**
Travel cost for broader dissemination of the outcomes from this proposal at conferences, workshops, and seminars. Mainly for the in-state travel expense for communications between the PI and collaborators at 3M.	$	3,000.00
TOTAL ENVIRONMENT AND NATURAL RESOURCES TRUST FUND $ REQUEST =	$	256,112

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*		


Thermal Gels
Nanocomposite
200 nm
Thermal Management in Electronic Devices
3M
Thermal Tapes
Thermal Management in Automobile Vehicles
Coupling at Interfaces
Thermally Adaptive (Smart) Clothing - Enhance personal comfort and reduce air conditioning cost (12% of the total energy consumed)
Thermal Management in Satellites

Project Manager Qualifications & Organization Description

A. Project Manager Qualifications

Xiaojia Wang is an assistant professor in the Department of Mechanical Engineering at the University of Minnesota starting in the fall of 2014. 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 from 2012 to 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.

B. Organization Description

(1) Micro/Nanoscale Thermal Transport Laboratory, Directed by the PI (Wang)

Both the spectroscopic characterization of nanoparticles and nanostructures and the ultrafast transient absorption measurements of probing thermal interfaces will be performed at the University of Minnesota (UMN) in the PI's **Micro/Nanoscale Thermal Transport Laboratory (MNTTL).** Figure 1 depicts (a) the optical layout of the functional custom-built pump-probe system, (b) accessories for ultrafast transient absorption measurements on nanoparticles.

<u>*Instrument for ultrafast transient absorption measurement*</u>

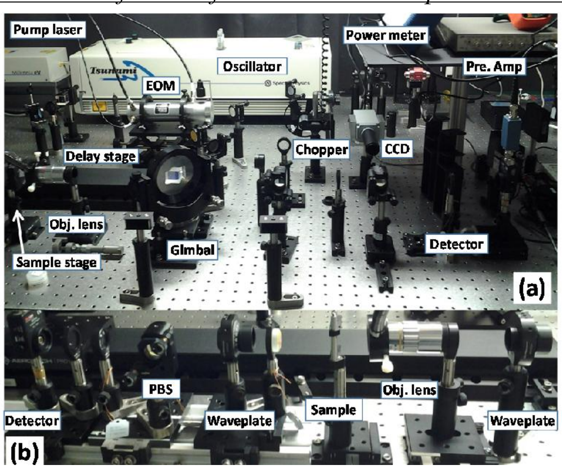


Figure 1. (a) Optical layout for the functional TDTR system in MNTTL at UMN. Several major parts are labeled for better illustration; (b) accessories for ultrafast transient absorption measurements.

Wang's lab has also been upgrading facilities for controlling the sample environments from low (a liquid nitrogen cryostat, down to 80 K) to high (up to 1000 K) temperatures.

<u>*Instrument for spectral characterization of nanoparticles and nanostructures*</u>

- Double monochromator (Newport, MS257™, 0.2 – 2 μm)
- Fourier Spectrometer (Oriel FTIR, MIR8025™, 0.7 – 25 μm)
- UV/Vis/NIR spectrophotometer (PerkinElmer, LAMBDA 1050, 0.175 – 3.3 μm)
- Microscopes (AmScope, SM-1TSZZ-144S-3M, 3.5X-180X; T690C-DK-PL, 40X-2500X)

(2) Campus Facilities

<u>*Minnesota Nano Center (MNC)*</u>

The Minnesota Nano Center (MNC, http://www.nfc.umn.edu/) offers state-of-the-art facilities for interdisciplinary research in nanoscience and applied nanotechnology. The labs and tools of the MNC are open to all qualified users. The MNC is composed of two main facilities, located in Keller Hall and in the new Physics and Nanotechnology (PAN) building. Recently, the MNC opened one new research laboratory, the Nanomaterials Lab that offers researchers capabilities for nanoparticle synthesis and analysis. The Nanomaterials Lab features particle analysis tools for measuring the size distribution, morphology, and ionic properties of particles ranging from a few nanometers to thousands of microns in size. It also offers apparatus for synthesizing particles using wet chemistry, tools and techniques for particle surface modification, separation, and filtration. It enables lab users to safely work with chemicals in proximity to facilities for fabricating micro-devices and for making nanoparticles.

Characterization Facility (CharFac)

The Characterization Facility (CharFac, http://www.charfac.umn.edu/) is a multi-user, shared instrumentation facility at UMN. Analytical capabilities at CharFac include microscopy via electron beams, atomic force probes and visible light, including cryogenic methods; elemental and chemical imaging including depth profiling; elemental, chemical and mass spectrometry; atomic and molecular structure analysis via X-ray; ion or electron scattering; and other tools for particles, surface, and thin-film metrology.

Table 1 on the next page lists several major instruments as shared facilities that are available in the MNC and CharFac to be used for this project.

Table 1. List of campus shared facilities to be used in this proposed project

Equipment	Brand/Model	Functionality
Tunneling Electron Microscopy	Tecnai T12	Size and structural characterization of nanoparticles
Dynamic Light Scattering	Microtrac NanoFlex	Size characterization of nanoparticles and surfactants
Atomic Force Microscopy	JSM-6610LV	Characterization of composite dimensions and compositions
Four-Point Probe		Characterization of electrical properties
Confocal Raman	Witec Alpha 300R	Linking layer characterization
Sputtering	AJA I, AJA II	Thin-film deposition for reference samples
Ellipsometry	VASE	Thickness measurement of reference samples