REPORT DOCUMENTATION PAGE

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Stanford University 3160 Porter Drive Suite 100 Stanford, CA 94304 -8445	
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Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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RPPR Final Report
as of 09-Mar-2021

Agency Code:

Proposal Number: 75149MSII **Agreement Number: W911NF-19-1-0358**

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DUNS Number: 009214214 EIN: 941156365
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Final Report for Period Beginning 06-Jun-2019 and Ending 30-Sep-2020
Title: Physical Properties of Materials: Phonon Localization via Defect Engineering in Low-Dimensional Boron Nitride
Begin Performance Period: 06-Jun-2019 **End Performance Period:** 30-Sep-2020
Report Term: 0-Other
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:** 2

Major Goals: Heat conduction in non-metals occurs via propagation of waves of lattice vibrations energy, whose quanta are called phonons. Because phonons undergo several types of de-phasing scattering, it has been difficult to use phase-coherent interactions for controlling heat conduction, thereby relying largely on manipulating phonon diffusion to minimize heat propagation. Phase-coherent interactions across the whole blackbody spectrum of phonons could presumably exhibit Anderson location, but this has never been experimentally observed. The goal of this high-risk high-reward project is to explore Anderson localization of broadband phonons in 1-D and 2-D boron nitride (BN), which could potentially offer the opportunity to create ultralow thermal conductance via defect engineering in materials

Accomplishments: While the original goal was to explore localization of phonons in hexagonal boron nitride (hBN), we found as a first step it would be easier to study localization of photons, since it is much easier to excite photons in a spectrally selective manner. Furthermore, atomic scale defects in hBN are known to be single-photon emitters with a localized photoexcited state. To study this, we have constructed a specimen holder with a fiber optic feedthrough that can be inserted into any compatible transmission electron microscope (TEM) to photo-excite materials and simultaneously image with electrons. We are currently optimizing our light injection and data processing methodology to overcome light induced specimen motion due to thermal expansion, which limits the resolution of our technique. These methodologies include manipulating the polarization of light to study polarization dependent absorption, using interference patterns to spatially scan the laser beam, and sub-pixel drift correction.

Training Opportunities: Nothing to Report

Results Dissemination: Nothing to Report

Honors and Awards: The PI (Arun Majumdar) was elected to the US National Academy of Sciences.

Protocol Activity Status:

Technology Transfer: Filing of US Patent "Photoabsorption Microscopy Using Electron Analysis," No. US 2021-0066030A1

PARTICIPANTS:

Participant Type: PD/PI
Participant: Arun Majumdar
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: Y
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Ze Zhang
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Joel Martis
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

PROJECT REPORT

Project Title: Phonon Localization via Defect Engineering in Low-Dimensional Boron Nitride
Funding Agency: Army Research Office
Grant #: W911NF1910358
Grantee: Stanford University
PI: Professor Arun Majumdar, Department of Mechanical Engineering
Start Date: 06/01/2019
Duration: 1 year
Graduate Students Supported: Joel Martis, Ze Zhang

Project Goals

The goal of this high-risk high-reward project is to explore Anderson localization of broadband phonons in 1-D and 2-D boron nitride (BN), which could potentially offer the opportunity to create ultralow thermal conductance via defect engineering in materials.

Project Execution

Atomic-scale defects in BN offer the opportunity to explore new scientific phenomena. Since BN is a wide-bandgap semiconductor, electron transport can be minimized thereby allowing the study of study phonon localization, which is the goal of the project. However, these defects are also known to be single-photon emitters, with photoexcited states falling inside the bandgap of BN. Such single-photon emitters are considered to candidates for quantum entanglement and information processing. While the goal of this project was to phonon transport, we develop the basic tools to investigate the effects of atomic scale defects in BN for other excitations as well, including photoexcitations.

Probing defects in 2D materials at the atomic scale

Atomic defects in 2D materials such as hBN [Fig 1] have garnered enormous interest within the scientific community because of their unique properties such as single photon emission [1-3]. These defects have been investigated optically (absorption/emission spectrum) but their structural origin remains unknown because the spatial resolution of optical imaging/spectroscopy is limited by the Abbe diffraction limit. To overcome this limit, we recently proposed using a transmission electron microscope (TEM) coupled with photoexcitation to image optical effects at the atomic scale [4]. To this end, we have constructed a specimen holder with a fiber optic feedthrough that can be inserted into any compatible TEM [Fig 2] to photo-excite materials and simultaneously image with electrons. We are currently optimizing our light injection and data processing methodology to overcome light induced specimen motion due to thermal expansion, which limits the resolution of our technique. These methodologies include manipulating the polarization of light to study polarization dependent absorption, using interference patterns to spatially scan the laser beam, and sub-pixel drift correction.

Figures:

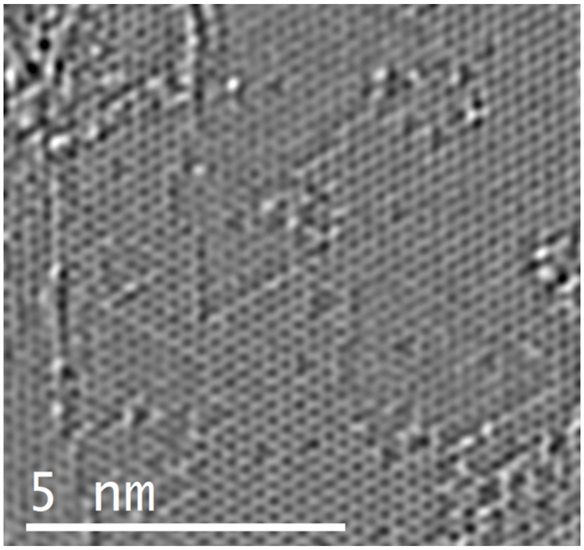

Fig 1: hBN imaged at Stanford showing several kinds of atomic defects.

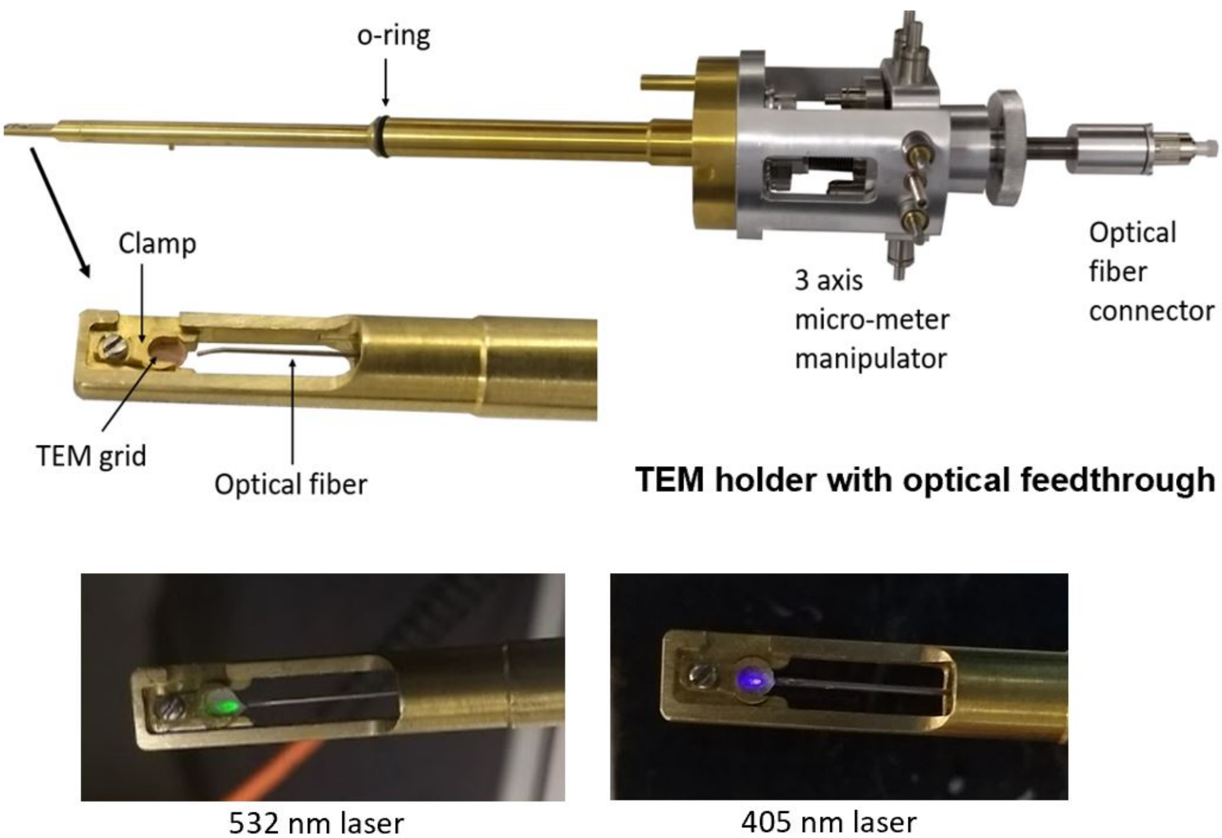

Fig 2: (top) TEM holder with an optical feedthrough and 3-axis micrometer stage; (bottom) top view of the tip of the holder showing laser beams of various wavelengths incident on the substrate.

References:

[1] Tran, T., Bray, K., Ford, M. *et al.* Quantum emission from hexagonal boron nitride monolayers. *Nature Nanotech* 11, 37–41 (2016). https://doi.org/10.1038/nnano.2015.242

[2] Srivastava, A. et al. Optically active quantum dots in monolayer WSe2 . *Nat. Nanotech.* 10, 491–496 (2015).

[3] Koperski, M. et al. Single photon emitters in exfoliated WSe2 structures. *Nat. Nanotech.* 10, 503–506 (2015).

[4] Zhang, Z.; Rayabharam, A.; Martis, J.; Li, H.-K.; Aluru, N. R.; Majumdar, A. Prospects for sub-nanometer scale imaging of optical phenomena using electron microscopy. *Appl. Phys. Lett.* **2021**, *118* (3), 033104, DOI: 10.1063/5.0029979