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University of Texas at Austin
101 East 27th Street
Suite 5.300
Austin, TX 78712 -1532

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RPPR Final Report
as of 13-Aug-2018

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Proposal Number: 70054ELRIP

Agreement Number: W911NF-17-1-0190

INVESTIGATOR(S):

Name: Keji Lai
Email: kejilai@physics.utexas.edu
Phone Number: 5124759128
Principal: Y

Organization: **University of Texas at Austin**
Address: 101 East 27th Street, Austin, TX 787121532
Country: USA

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Final Report for Period Beginning 15-Apr-2017 and Ending 14-Apr-2018

Title: Cryogenic Microwave Impedance Microscope with Pulsed Laser Stimulation for Studying Phase Transitions

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Submitted By: Keji Lai

Email: kejilai@physics.utexas.edu
Phone: (512) 475-9128

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STEM Degrees: 0

STEM Participants: 3

Major Goals: The objective of this DURIP award is to develop a cryogenic microwave impedance microscope (MIM) with broadband and pulsed laser illumination for the study of phase transitions.

Accomplishments: With the DURIP support, we have acquired a professional scanning probe microscopy controller, a number of CW and pulsed lasers, a white-light source, and various optical components. The system is now fully up and running in the PI's laboratory. Preliminary data on low-dimensional materials have been achieved and a manuscript is being prepared to disseminate the results.

Training Opportunities: Two graduate students and one undergraduate student (all personnel supported by other funding sources) in the PI's group have been involved in the construction and operation of the system. They will have the opportunity to learn the basic microwave network analysis, transport and optical measurements, and scanning probe skills in the laboratory. The interpretation of the real-space conductivity images under strong electromagnetic radiation requires a thorough understanding of the relevant physics on complex quantum materials, which are of great interest to the DoD.

Results Dissemination: Manuscript in preparation (ARO support acknowledged in the paper)
1. Zhaodong Chu, Ali Han, Chao Lei, Sergei Lopatin, Peng Li, David Wannlund, Di Wu, Kevin Herrera, Xixiang Zhang, Allan H. MacDonald, Xiaoqin Li, Lain-Jong Li, Keji Lai, "Energy-resolved Photoconductivity Mapping in a Monolayer-bilayer WSe_2 Lateral Heterostructure", to be submitted to Nature Communications.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Zhaodong Chu
Person Months Worked: 6.00

Funding Support:

Project Contribution:
International Collaboration:

International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: David Wannlund
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Kevin Herrera
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Final Report: Cryogenic Microwave Impedance Microscope with Pulsed Laser Stimulation for Studying Phase Transitions

Defense University Research Instrumentation Program (DURIP)

Army Research Office Grant # W911NF-17-1-0190

PI: Keji Lai, University of Texas at Austin, Department of Physics, Austin, TX 78712

List of illustrations:

Statement of the Problem

The objective of this DURIP award is to develop a cryogenic microwave impedance microscope (MIM) with broadband and pulsed laser illumination for the study of phase transitions. Different from the thermally driven phase transitions, the photo-induced phase transition illustrated in Fig. 1 is initiated by the photo-excited carriers that redirect the system to a new stable or metastable phase. Owing to the intricate interplay among disorders, electron-electron interactions, and competing orders, electronic inhomogeneity with different spatial configurations is ubiquitously observed in semiconductors, complex oxides and other functional materials. Before our work, however, mesoscopic phase separation has not been addressed for the light-driven phase transitions observed in advanced materials. It is our goal to combine the MIM with nanoscale imaging capability and laser excitation to study the microscopic details of these processes.

This program is the continuation of a prior DURIP Grant # W911NF-16-1-0276, which allowed the PI to obtain an optical table, cryogenic stepping/scanning stages, and MIM electronics. With the current support, we have acquired the remainder of the setup, including a professional scanning probe microscopy controller, a number of CW and pulsed lasers, a white-light source, and various optical components. The system is now fully up and running in the PI's laboratory.

The MIM is a powerful technique to spatially resolve the mesoscopic (10 ~ 100 nm) electrical properties without the need of contact electrodes. This novel apparatus will be the first scientific instrument that offers mesoscopic conductivity information with CW or pulsed laser excitations under variable temperatures (10 – 300 K). The research to be conducted based on this platform will provide significant amount of new knowledge on many advanced materials that are important for military applications in photo sensing and data storage.

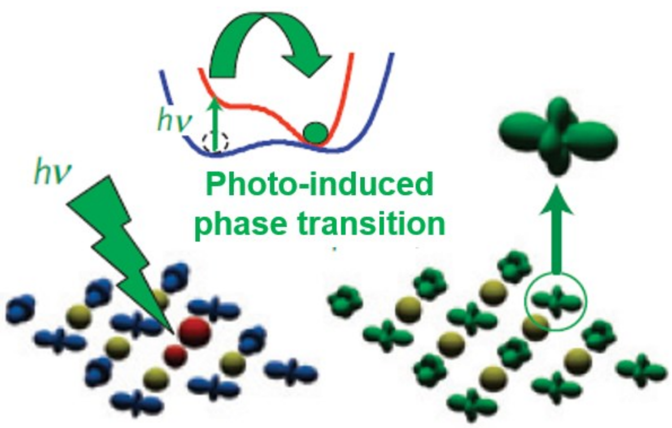

Fig. 1. Schematic of the photo-induced phase transition in complex systems, where the system is redirected to a stable or metastable by photo-generated carriers.

Summary of Key Results

Fig. 2a illustrates the configuration of the cryogenic light-stimulated MIM setup. A photo of the completed system is shown in Fig. 2b. Specifically, we have acquired the following components for the proposed experiments.

a. A professional scanning probe microscopy controller Nanonis BP5 from SPECS Surface Nano Analysis GmbH.

b. A wavelength-tunable light source TLS-55-X300 and peripheral optics from ScienceTech Inc.

c. A set of CW and pulsed laser sources and controllers from Thorlabs.

d. Piezoelectric positioning stages and other optical components (high-NA objectives, high-end CCD camera, mirrors, lenses).

e. Other electronics (lock-in amplifiers, microwave components, etc).

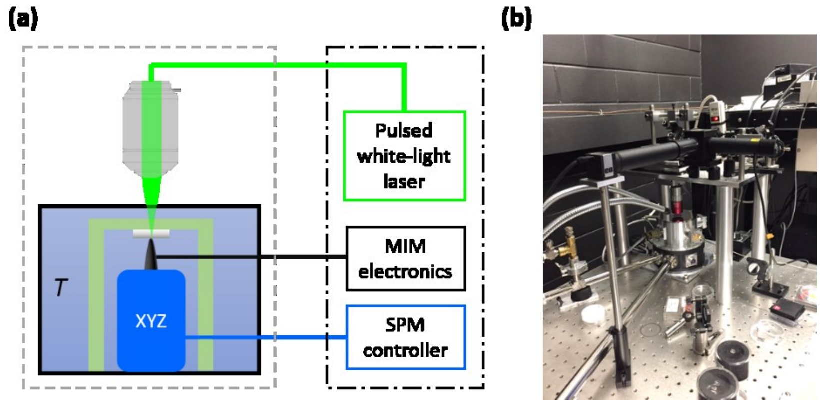

Fig. 2. (a) Schematic of the low-temperature MIM system with CW/pulsed laser stimulation. (b) Photo of the system currently under final construction and testing.

The PI's lab has been renovated to accommodate the requirement of laser optics for this system. We started to integrate all components earlier this year and the system is fully functional at the time of this report. The first experiment using multiple diode lasers to study the energy-dependent photoconductivity of a monolayer-bilayer WSe_2 heterostructure is completed. A manuscript is being prepared to disseminate the results. Another exciting experiment to investigate the carrier diffusion in 2D materials is currently in progress. Other innovative experimental investigations enabled by this instrument in the near future (3 ~ 5 years) include:

- Nanoscale coexisting phases in chalcogenide glasses. The new instrument will allow us to study the microscopic origin of phase transitions in these materials, which are attractive for rewritable data storage and photo-sensing applications.
- Light-driven versus temperature-driven phase separation in transition metal oxides. If the sizes, shapes, and dynamics of the competing metallic and insulating states differ drastically in the two experiments, the result may imply very different physical mechanisms.
- Spatial distribution of photo-induced hidden states associated with charge-density waves. By tracing the formation and melting processes in the real space, we expect to shed some light on the dynamics and possible phase competition in these materials.

To summarize, thanks to the DURIP support, the PI's group has constructed a new tool for probing light-driven phenomena in novel quantum materials at the nanoscale. The work will establish a new research direction and augment existing DoD programs at UT-Austin. The research is of fundamental importance for Army applications of photosensitive materials in future sensing and data storage devices.