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University of Michigan - Ann Arbor
3003 South State Street

Ann Arbor, MI 48109 -1274

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14. ABSTRACT

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as of 04-May-2021

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Proposal Number: 75467ELII
Agreement Number: W911NF-20-1-0196

INVESTIGATOR(S):

Name: Parag B Deotare
Email: pdeotare@umich.edu
Phone Number: 7346473119
Principal: Y

Organization: **University of Michigan - Ann Arbor**
Address: 3003 South State Street, Ann Arbor, MI 481091274
Country: USA
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Submitted By: Parag Deotare
Email: pdeotare@umich.edu
Phone: (734) 647-3119
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STEM Degrees:
STEM Participants:

Major Goals: The goal of this STIR program is to demonstrate the feasibility of a room temperature excitonic device for on-chip optoexcitonic devices. The two vital goals under the proposed STIR program are:
(i) Directional exciton energy transport
(ii) Spatial control of exciton energy transport

Accomplishments: A pdf document has been uploaded.

Training Opportunities: Nothing to Report

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Che-Hsuan Cheng
Person Months Worked: 2.00
Funding Support:
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Kanak Datta
Person Months Worked: 1.00
Funding Support:
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Zidong Li
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: PD/PI
Participant: Parag Deotare
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Parag B Deotare
Signature Date: 5/3/21 10:22PM

FINAL REPORT

Award ID: AWD015339

P/G #: F057382

Award Ref No: W911NF2010196

Project Title: 001200-Towards Room Temperature Optoexcitonic Devices For Data Communication and Processing.

Project Period: 06/05/20 - 02/04/21

Project Director: Parag B. Deotare

Statement of the problem studied:
The work focuses on preparing a platform for manipulating optically active excitonic states to demonstrate control over exciton flux. Such control is important for demonstrating a platform for next generation integrated optoexcitonic devices. Our aim is to create an energy gradient using the shift in energy bands associated with bathochromic effect due to the presence of external strain. Such energy gradient can enable controlled exciton drift towards lower energy states. The STIR program explored the feasibility to demonstrate a room temperature proof-of-concept device based on strain engineering, in a transition metal dichalcogenide (TMD) monolayer material system. By first converting a photon into an exciton that is two orders of magnitude smaller in size, and then manipulating the excitonic energy in space before remitting the photon, the work lays out an optoexcitonic device platform for next generation on-chip communication and processing.

Summary of the most important results:

- Demonstrated > 4μm exciton drift in monolayer TMDs.
- Streamlined the nanofabrication process (three overlay process).
- Demonstrated control over exciton flux with an extinction ratio of ~72 %.

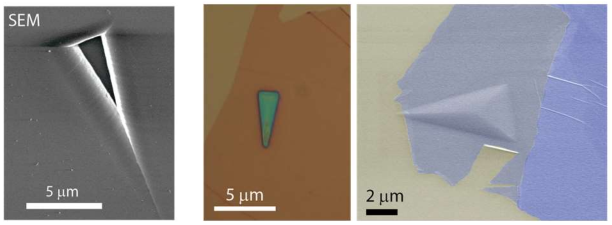

Figure 1: SEM and brightfield images of the nanowedges used to induce strain gradient in the TMD monolayers.

Large exciton drift in monolayer TMDs: We had proposed to use nanowedges as shown in Figure 1 as a platform for generating strain gradient. Strain reorients the crystal structure, resulting in local shift in the energy bands. Thus, by spatial engineering of the strain in the TMDs, we were able to generate exciton energy gradient to achieve directional transport of excitonic energy. The local yet controlled tensile strain in the monolayer generated by tapered nanowedges drives the excitons down the energy gradient in space. Tapered nanowedges were fabricated by over etching a wedge pattern in buffered oxide etch solution. Figure 1 shows a SEM and brightfield images of a representative nanowedge with monolayer transferred over it. The strain induced in the material is a function of the aspect ratio of the nanostructure, with higher aspect ratio leading to larger strain values. However, transfer of monolayers on high aspect ratio patterns without damaging the layer is challenging. Nevertheless, we were able to transfer monolayers by optimizing the process parameters.

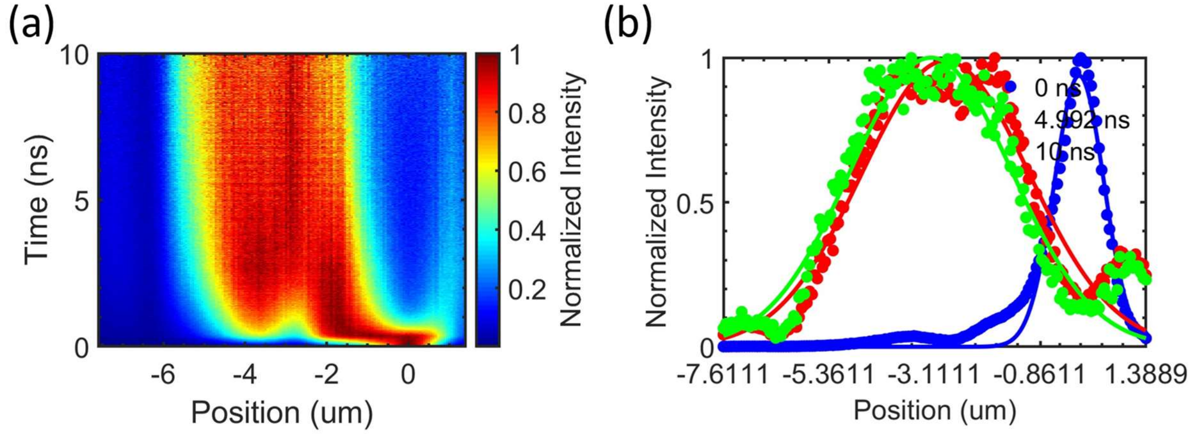

Figure 2: (a) Drift of exciton distribution on WSe_2 monolayer strained using a nanowedge. (b) Normalized exciton distribution profiles at three instances.

The exciton drift under external strain gradient was analyzed using the diffusion imaging microscope developed in our lab. The spatiotemporal map generated using the measurement technique is shown in Figure 2. Diffusion is driven by exciton density while drift is the motion of the whole exciton distribution in space and is driven by energy gradient. The time evolution of the normalized exciton density distribution along the nanowedge shows that the exciton distribution move towards the left (the most strained region along the nanowedge). The results show nearly 4 μm drift length which is ~100 % improvement compared to the preliminary data. Such spatial motion is sufficient to demonstrate control over the exciton flux.

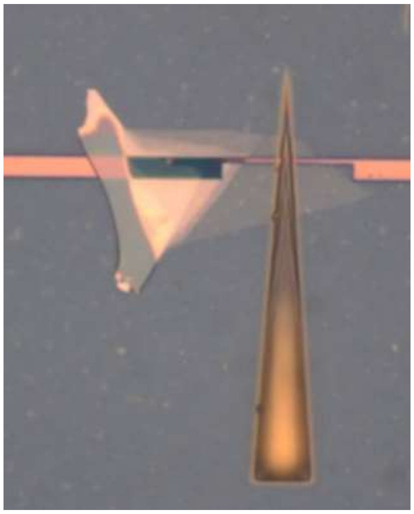

Figure 3: Brightfield image of the nanofabricated device with lateral gate electrodes.

Developed nanofabrication process: One of the challenges for the STIR program was to develop a robust nanofabrication process for overlaying the control electrodes across the nanowedges. The electrodes were necessary to achieve spatial control over the drifting excitons. The principle was based on changing the potential of the exciton dipole in an external electric field. The dipole potential varies according to $\vec{p}.\vec{E}$, where $\vec{p}$ is the dipole moment and $\vec{E}$ is the external field. The field generated by the control electrode (gate) would manipulate the exciton potential in the channel. The creation of a barrier by gate electrodes controlled the exciton flux. Since we propose to work with monolayers, the control field needs to be along the plane of the monolayer. Figure 3 shows a nanofabricated device with lateral gate electrodes patterned along the nanowedges to control the exciton flux.

A thin layer of hafnium oxide was deposited using atomic layer deposition to electrically isolated the monolayer from the electrodes. However, we observed breakdown through the layer even for 60 nm of hafnium oxide at voltages much below the reported breakdown voltages. This raised concerns on the quality of the deposition. Hence, we decided to add a thin layer of mechanically exfoliated hexagonal boron nitride (h-BN). The h-BN layer prevented the breakdown for voltages as high as 40 V, which is much larger than the levels needed to control the exciton flux.

Control of exciton flux:

Figure 4 shows our preliminary results demonstrating control over the exciton flux. The data shows photoluminescence (PL) over time as gate voltage is changed. We observe nearly 72% extinction with application of control voltage. The high electric field causes exciton dissociation. The dissociated carriers shield the electric field that results in the rise of the PL. Upon further increasing the voltage by 2V we observe similar trend. Thus, a 2V swing results in a greater than 72% extinction. The results are vital and validate the proposed scheme for next generation communication and processing devices based on excitons that utilize strain engineering to create exciton drift and control the flux via quantum confined stark effect. The results are a major breakthrough for the future of room temperature optoexcitonic devices.

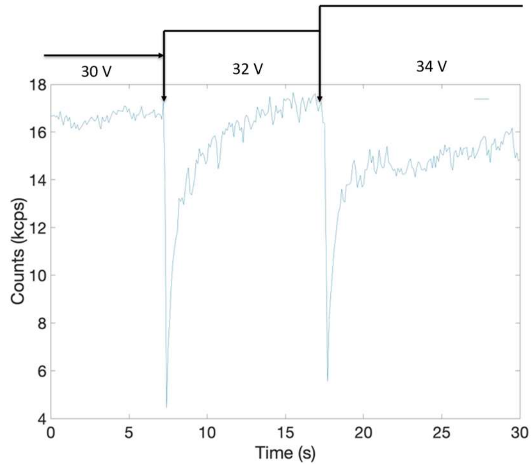

Figure 4: PL over time for different gate voltages. Nearly 72% extinction is observed with application of control voltage. The high electric field causes exciton dissociation. The dissociated carriers shield the electric field that results in the rise of the PL.

The use of excitons for information processing has been proposed for over a few decades [1–4]. However, this goal has thus far been difficult to achieve due to lack of appropriate material systems that can support room temperature excitons with good mobility. Our results from the STIR program demonstrates a potential pathway to address the challenge. Further research based on the ground work from this program will eventually establish a platform for next generation integrated nanophotonic circuits for data communication and processing. Such circuits would result in higher computer central processing unit clock speeds (that has remained stagnant for more than a decade), enhanced data processing capabilities and longer battery life for portable devices, all of which are vital to Army's needs.

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