II. Accomplishments:

A. The major goals of the project are to demonstrate multifunctional zero-standby power sensing and reconfigurable photonic integrated circuits by integrating ***vanadium dioxide (VO_2)***, ***Micro-electromechanical systems (MEMS)***, electronic ***integrated circuits (ICs)***, and ***photonic integrated circuits (PICs)***. Two objectives to achieve extremely low-power solutions for NASA missions are proposed:

O1: Develop scalable near zero-standby power VO_2 switches. Multifunctional optical-to-electric switches with near zero-standby power will be developed. These switches can serve as event-driven power switches for electro-optical sensors, communication units, and even the main switch of a whole space probe system in a deep-space exploration mission.

O2: Develop a versatile reconfigurable photonic integrated circuits sensor system with near zero-standby power and low-operation power. By incorporating near-zero-standby power switches for sensor awaken and VO_2 reconfigurable components for fast and frequent signal processing, the proposed PICs sensor system significantly reduces power consumption for signal processing and for optical-to-electrical conversion by units such as detectors and optical amplifiers.

To realize the proposed objectives, we will perform the following thrusts:

Thrust 1: Develop scalable near zero-standby power VO_2 switches (Sci-I Wang)
Thrust 2: Develop key elements of reconfigurable photonic integrated circuits (Sci-I Wang and Co-I Saxena)
Thrust 3: Demonstrate an integrated spectrometer and small-scale optical neural networks (Co-I Saxena and Sci-I Wang)

This proposed work will advance the state-of-the-art low-power technology in optoelectronic switches and reconfigurable PICs. Successful completion of this work will lead to scalable near-zero-standby power switches, which may be used in several application scenarios from single waveguides, single devices, to chips, and eventually a whole space probe system. By combining these switches and other VO_2 reconfigurable components, PICs that consume very low power will be achieved and fit in ultracompact systems such as space probes driven by laser sails or solar sails. Through our proposed efforts, we expect to bring this technology from TRL1 to TRL4. Furthermore, in addition to the space application, the developed low-power components will advance other PICs applications, such as deep neural network architectures, which are scalable to real-world architectures using benchmarking datasets.

B. We have successfully fabricated initial switches actuated by free space excitation in Year 1. To further improve the yield and enhance endurance during switching, we need to modify our design and fabrication procedures. First, we introduced ruthenium (Ru) as the material for movable electrodes attached at the bottom of cantilevers. The Ru tip was selected for its advantageous material properties, such as low contact resistance, minimal material transfer during cycling, resistance to carbon contamination, and excellent mechanical and thermal stability under both hot and cold switching conditions. These properties collectively enable reliable and repeatable contact performance over extended operation. In our earlier switches, we tested contact materials such as Al, Au, and Pt. However, these exhibited issues like contact welding, degradation, and sticking failures, particularly under prolonged or harsh switching conditions. These problems were significantly mitigated by incorporating a Ru move electrode at the contact interface. Second, we optimized the fabrication procedures to fully eliminate the need for hydrofluoric acid

(HF) etching. This step supports a more environmentally sustainable approach. Most importantly, the developed Ge-based sacrificial layer isotropic dry etching process avoids the capillary forces often encountered in wet etching release methods that can lead to stiction or gap variation. The total fabrication yield reached above 90%. The performance of fabricated VO_2 switches has been characterized under a probe station and laser excitation. Power-dependent switching behavior has been verified.

Additionally, by changing the active layer from VO_2 to palladium, a hydrogen sensing material, we have successfully designed and fabricated zero-standby power hydrogen sensing using event-driven micromechanical switches. We demonstrated that the bistable micromechanical switch-based sensor generates a wake-up signal with activation time depending on hydrogen concentration in the target environment while consistently remaining active for events without any standby power consumption under normal conditions. The hydrogen adsorption-induced subsequent switching of the multi-cantilever-based switch configuration on the sensor resulted in the quasi-quantification of hydrogen concentrations. Both hydrogen and VO_2 switches can be utilized in various application scenarios, ranging from single alarms and individual devices to chips and, ultimately, an entire space probe system. They will provide extremely low-power solutions for NASA missions in space exploration.

The second goal in Year 2 is to develop the integration procedures to combine VO_2 and PICs to achieve reconfigurable PICs. Simulation results show that if the thickness of the VO_2 layer is too thick, the performance of PICs will significantly degrade due to loss. Therefore, after careful analysis and numerical simulations, we decided to deposit a 30 nm-thick layer of VO_2 on PICs, followed by nanofabrication patterning. However, since our current standard deposition procedures were optimized for a VO_2 thickness of 120 nm, we need to modify the pulse laser deposition (PLD) recipe to maintain good quality VO_2 at a thickness of 30 nm. During this process, we have also been working to reduce the grain size to approximately 30 nm to ensure good fidelity. Originally, depositions were performed at a temperature of 650 °C, an O_2 pressure of 9 mTorr, a pulse rate of 23 Hz, and a thickness of 120 nm. However, after a failure in a clip holding the sample stage and the replacement of a broken bulb, an adjustment of the recipe was necessary. This adjustment reduced the temperature to 600 °C and then later to 550 °C after characterizing deposited films by resistance-temperature measurement and SEM images. Eventually, the temperature will be raised as more material is deposited onto the shield of the heater. From this point, we began to adjust the recipe to obtain a smaller grain size. We started by eliminating the post-deposition thermal soak and adjusting the deposition pressure, discovering that both increasing and decreasing the pressure from the original 9 mTorr resulted in a reduced grain size, with a more significant difference at 6 mTorr and 20 mTorr, where we began to approach the 30 nm grain size. This change in pressure increased the formation of other vanadium oxides, such as V_2O_3 and V_2O_5, substantially altering the resistance change of the film from 30 °C to 90 °C. Therefore, we only performed a minor adjustment in pressure (from 9 mTorr to 10 mTorr) and deposited 30 nm-thick films without post-deposition thermal soak. We successfully obtained VO2 films with grain sizes of about 40 nm. The resistance-time measurements indicated that the films exhibited a smaller drop in resistance change during the hysteresis (originally a change of 3-4 orders of magnitude for a 120 nm-thick film, now 2 orders). We believe this phase-transition behavior is sufficient for reconfigurable PICs due to their confined modes.

The third goal in Year 2 is to simulate, design, and tape-out a test PIC using CMC-AMF foundry process. To investigate the optical modulation behavior of VO_2, we designed a silicon waveguide integrated with a 30 nm-thick layer of VO_2 deposited on its top surface. The structure was simulated under two distinct material phases of VO_2: the low-loss insulating phase and the high-loss metallic phase. In the insulating state, VO_2 exhibits low optical absorption, allowing the guided optical mode to propagate predominantly through the silicon waveguide with minimal loss. In contrast, the metallic phase introduces significant absorption, resulting in severe attenuation of the guided mode due to strong optical field confinement and loss within the VO_2 region. To evaluate the impact of VO_2 length on transmission, we varied the VO_2 segment from 2 μm to 5 μm and observed the resulting transmission through the waveguide. When a 2 μm-long VO_2 segment was used, approximately 94% of the input light was transmitted in the insulating phase, compared to only 40% in the metallic phase. As the VO_2 length increased to 5 μm, the transmission dropped to around 50% in the insulating state and to nearly 10% in the metallic state. These results confirm the strong absorption contrast between the two phases and demonstrate the potential of VO_2 as a compact and efficient material for tunable photonic devices. The tape-out is scheduled at the end of June 2025.

To demonstrate resonance-based modulation, a VO_2-integrated micro-ring resonator was designed. The device was analyzed under both insulating and metallic phases of VO_2. In the insulating state, VO_2 exhibits low optical absorption, enabling strong resonance buildup and deeper transmission notches due to near-critical coupling. In contrast, the metallic state introduces higher absorption and refractive index change, disrupting the resonance condition and reducing extinction. In the insulating phase, a resonance dip of approximately −22 dB is observed at 1550 nm, with a free spectral range (FSR) of ~5.79 nm. Upon switching to the metallic phase, the resonance shifts by ~3.23 nm, and the minimum transmission increases to around −18 dB. Reducing the VO_2 length to 1 μm results in lower absorption and reduced extinction contrast: the resonance depths vary between −12.3 dB (insulating) and −13 dB (metallic), with a smaller wavelength shift of ~1.3 nm.

C. In total, six graduate students have participated in work supported by or related to this award. All graduate students have been trained in experimental techniques, data analysis, and scientific writing. They participate in weekly meetings within the Wang and Saxena groups. Additionally, we hold biweekly joint meetings for this project, providing students exposure to further theoretical and experimental techniques and practice presenting their work to scientists outside their direct research area. The primary students working on this project are Kyle Laskowski, a junior graduate student, and S M Jahadun Nobi, a senior graduate student, both advised by Wang, as well as Noor Afsary, a PhD candidate advised by Co-PI Saxena. Kyle was trained in relevant experimental techniques by senior students Zhixiang Huang and S M Jahadun Nobi in the Wang group, and he became involved in the deposition of VO_2. S M Jahadun Nobi joined the project this year to significantly enhance non-HF etching techniques and the fabrication and characterization of zero-standby power sensors. The graduate student under Co-PI Saxena, Noor, is trained in PIC design through internal and external courses from UD and AIM Photonics, respectively. He has also been exposed to PIC characterization from senior PhD students in the Saxena group. Two undergraduate researchers from minority backgrounds were supported by Co-I Saxena on summer research aligned with this project. They helped build an optical alignment setup to test PICs fabricated on this project. Their story was covered by our UD Daily.

D. Sci-I Wang gave a talk at MRS Fall 2024, Boston, MA, USA, which included the optimized fabrication procedures of high-quality VO_2 films. Sci-I Wang will give an invited talk at META 2025, Malaga, Spain, which included optimized fabrication procedures of high-quality VO_2 films and non-HF nanofabrication of VO_2 nanostructures. S M Jahadun Nobi will give two talks at SPIE Optics + Photonics 2025, San Diego, CA, USA. One talk focuses on zero-standby power hydrogen sensing, and the other focuses on non-HF nanofabrication of VO_2 nanostructures. A manuscript describing the optimized PLD recipe is under review. A manuscript describing the zero-standby power hydrogen sensor is under minor revision.

E. The plan during the next reporting period includes: 1) complete the development and characterization of VO_2 switches designed for various stimuli; 2) optimize and improve the consistency of VO_2 integration on PICs; 3) demonstrate key elements of reconfigurable PICs. We plan to file a no-cost extension request due to the lack of students in Year 1, resulting in the delay of the PICs design.

III. Products:

A. List Journal publications – Please only list papers that have been published. **Please do not remove the table; or alter columns, add additional rows as required.**

Date Published	Published Paper (APA format)
	None to report

B. List Conference Papers – Please only list papers that are included in conference proceeding. **Please do not remove the table; or alter columns, add additional rows as required.**

Conference Date	Conference Paper (APA format)
	None to report

C. List Conference Presentation – Please list conference presentation. **Please do not remove the table; or alter columns, add additional rows as required.**

Conference Date	Presentation Topic (APA format)
Dec. 1-6, 2024	**Hunag, Z., Ji, J., Ma, K., Herrmann, E., Yahiaoui, R., Jahadun Nobi, S., Ding, F., Jepsen, P., Searles, T., Zhou, B., Chase, Z., Wang, X. (2024, Dec. 1-6) Switchable Terahertz Beam Steering with Nearly 100% Ordinary Transmission. MRS Fall 2024, Boston, MA, United States**

D. List Books and/or other Publications – Please include explanations, help us to learn about your accomplishments. **Please do not remove the table; or alter columns, add additional rows as required.**

Date	Explanations (APA format -Book, Newspaper Op-Ed, …)
	None to report

E. List talk/presentation/event/outreach activity – Please include explanations, help us to learn about your accomplishments. **Please do not remove the table; or alter columns, add additional rows as required.**

Date	List talk/presentation/event/outreach activity (APA format if applicable)
June-Aug 2024	Two undergraduate researchers from minority backgrounds were supported by Co-I Saxena on summer research aligned with this project. They helped build an optical alignment setup to test PICs fabricated on this project. Their story was covered by our UD Daily. URL: https://www.udel.edu/udaily/2025/april/summer-scholars-photonics-research-collaboration/

F. List of new or updated Website(s) or other Internet site(s). **Please do not remove the table; or alter columns, add additional rows as required.**

URL	Short description of purpose of site
None to report	

G. Technology/Technique – **Please do not remove the table; or alter columns, add additional rows as required.**

Technology/Technique	Short description of technologies or techniques
PIC PDK for AMF	A custom PDK for the AMF photonic foundry was developed for Klayout. The PDK uses components from AMF and AIM available under and NDA. The PDK is for internal use of Saxena group at PDK for taping out the PICs using AMF's active silicon photonic process.

H. List patent – Please include Patent Number/Patent Title/ Patent Abstract (or link to it). **Please do not remove the table; or alter columns, add additional rows as required.**

Date Patent Issued	Patent Number/Patent Title/ Patent Abstract (or link to it)
	None to report

I. List Inventions – Please include Invention Title, List of Inventor(s) and Description. **Please do not remove the table; or alter columns, add additional rows as required.**

Invention Title	List Inventor(s)	Invention Description
Zero-Standby Power Hydrogen Actuated Micro-Electro-Mechanical Switches for Wide-Range Hydrogen Sensing	**Xi Wang, S M Jahadun Nobi**	**We developed a zero-standby power, maintenance-free, low-cost hydrogen sensor capable of detecting hydrogen in a wide range of concentrations. The sensor employs a micromechanical design actuated by chemical interactions between hydrogen and sensitive active materials within the structure. Operating as a passive switch, the sensor generates a wake-up signal only when hydrogen concentration reaches a specific threshold. This design offers significant energy efficiency, cost-effectiveness, and reliability advantages for long-term hydrogen monitoring across various applications. A provisional patent application has been filed.**

J. List Licenses – Please include license issued, Invention Title, List of Inventor(s) and Description. **Please do not remove the table; or alter columns, add additional rows as required.**

Date License Issued	License Assignees	License Title
	None to report	

K. List New/Revised Courses – Please include new/revised courses. **Please do not remove the table; or alter columns, add additional rows as required.**

Course Number	Course Name/Title	Offering Institution
	None to report	

L. Others: List Databases, Physical collections, Audio or video products, Software or NetWare, Models, Instruments or equipment, Data & Research Material (e.g., cell lines, DNA probes, animal models) related to your EPSCoR research. **Please do not remove the table; or alter columns, add additional rows as required.**

Accomplishments title	Short Description of accomplishments
None to report	

IV. Participants & Other Collaborating Organizations:

A. University Research Team Members (do not include names of minors). **Please do not remove the table; or alter columns, add additional rows as required.**

Name	Project Role	Nearest person month worked	Contribution to Project	Funding Support
Xi Wang	Science PI	2	Oversee the entire project. Lead the development of VO_2 switches and individual reconfigurable components of PIC.	
Vishal Saxena	Co-I	2	Lead the integration of individual components into a PIC, and design and characterization of integrated devices.	
Kyle Laskowski	Grad Student	6	Fabricate VO_2 films and cantilevers. Develop new release methods. Perform simulations for VO_2 on silicon waveguide.	UD's teaching assistant
Zhixiang Huang	Grad Student	6	Fabricate VO_2 films and structures.	This award
S M Jahadun Nobi	Grad Student	12	Develop new release methods and fabricate zero-standby power sensor.	This award

Noor Afsary	Grad Student	12	Designed photonic chip with programmable optical devices	This award

B. NASA Collaborators. **Please do not remove the table; or alter columns, add additional rows as required.**

Name	Title	NASA Center	Nature of the Collaboration
Mark Stephen	Research Engineer	GSFC	Technical Monitor. Provide feedback and develop research goals and tasks for future applications.

C. Industry Collaborators. **Please do not remove the table; or alter columns, add additional rows as required.**

Name	Title	Industry/Company Name	Nature of the Collaboration
None to report			

D. New non-EPSCoR grants. **Please do not remove the table; or alter columns, add additional rows as required.**

Funding Entity	Award Name	Value of New Grant
None to report		

E. Other Organizations Involved as Partners. **Please do not remove the table; or alter the columns, add additional rows as required.**

Organization	Nature of the Collaboration	Benefit of Collaboration	Additional Information
None to report			

V. Changes/Problems

A. Changes in approach and reasons for change.

none

B. Actual or anticipated problems or delays and actions or plans to resolve them.

In Year 1, there was a delay in recruiting a graduate student for photonic integrated circuit (PIC) design under the advice of Co-PI Saxena. Noor joined us in UD in Fall 2024 and has been working on PIC tape-out. There has been a delay associated with the photonic foundry (AMF), where they postponed the tape-out date due to a smaller number of riders. All our designs have been done for CMC-AMF. Also, the alternative foundry, AIM Photonic, raised its fabrication prices by 50%, so we will stick to CMC-AMF.

C. Changes that have a significant impact on expenditures.

none

D. Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards.

none

E. Change of primary performance site location from that originally proposed.

none

VI. Impact: Stimuli article, a high-resolution photo, and a one line caption. ***See Instructions.*** Obtain permission to publish photo from any recognizable person. ***Do not*** *include photos of minors.*

NASA's missions to explore the solar system, the universe, and deep space require extended travel time before and between events recorded by various types of detectors and sensors carried by satellites and space probes. However, space probes cannot carry large loads or travel far enough within a reasonable time frame. Therefore, smaller and lighter sensors with lower energy consumption are of particular interest. While developing sensors with reduced operational power consumption is important, sensors with ultralow standby power are particularly suited for long-standby-time missions, such as planetary exploration and space sensing. Unlike conventional sensors that continuously drain power to detect signals, these sensors consume nearly zero power until an event of interest activates them, significantly extending their lifespan during missions. However, the standby power of current sensors is not optimal; motion or light sensors in conventional LED bulbs consume between 0.1W to 1W while on standby. In this project, we aim to create electronic switches and sensors with zero standby power. We demonstrated a hydrogen sensor that activates only when hydrogen concentrations exceed its flammability limit. The transition of the sensor from off to on, facilitated by a physical gap between electrodes, ensures minimal to no power consumption when inactive. It can be utilized for future deep space explorations and various other real-world applications in energy, safety, and environmental monitoring with an extended operational lifespan.

Photo: Schematic of a hydrogen sensor featuring a zero-standby power switch. The SEM image of the fabricated microcantilever switch is displayed on the left.