Executive Summary

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1. Title of the Project: IoT enabled 2D Materials functionalized AlGaN/GaN transistor for water quality monitoring

2. Date of Start of the Project: 01/10/2022

3. Aims and Objectives:

   The main objective of this proposal is to develop a heavy metal ion detection system (Hg+ and Pb+) using a novel high-electron-mobility transistor (HEMT) that can form a distributed sensor network. The specific aims are:
   (i) Procurement of AlGaN/GaN epitaxial wafers and fabrication of electrodes using Photolithography.
   (ii) Synthesis of 2D materials such as MoS_2, WS_2, $MoSe_2$, hBN, g-C_3N_4 using hydrothermal, and layers transferred methods.
   (iii) Selectivity and sensing measurements applying a constant voltage between source and drain.
   (iv) Demonstrate integration, packaging, and electronic interface of multiple ion sensing devices and characterize selectivity over other interfering ions.
   (v) Demonstrate wireless, portable heavy metal ion sensors for real-time water quality monitoring.

4. Significant achievements (not more than 500 words to include a List of patents, publications, prototype, deployment, etc)

In the past three years, we worked on development and fabrication of AlGaN/GaN HEMT based sensors as well as successfully synthesized the MoS_2 and g-C_3N_4 for detecting the Hg^{2+} and Pb^{2+} ions. We have reported the enhanced sensing response of the fabricated AlGaN/GaN HEMT functionalized with the hybrid 1T and 2H MoS_2 and after applying the external gate bias demonstrated changes in the surface potential over the gate electrode surface and solution interface, which helps in the modulation of the drain current thereby resulting in enhanced sensitivity in comparison to the HEMT without applying external bias. For the Pb^{2+} ions detection, we successfully synthesized g-C_3N_4 nanostructures by the single-step combustion process and later used it to functionalize the gate region of the fabricated AlGaN/GaN HEMT sensor to study the Pb^{2+} ion sensing properties across the entire test range of solutions. The electrical response shows the responsivity of the g-C_3N_4 functionalized sensor toward the Pb^{2+} ions across the entire test range. The improved sensing performance of the g-C_3N_4 sensor could be attributed to the formation of numerous binding sites that provide strong complexation between the g-C_3N_4 and Pb^{2+} ions. Moreover, the sensing was also performed on the Kaylana lake water in Rajasthan after taking water samples to confirm the applicability of the sensor for the onsite monitoring of the water. Further, we are currently working on developing an Internet of Things (IoT) prototype for a time domain analogue front-end system for real-time water quality monitoring system. This system will simultaneously detect Hg^{2+} ions that takes advantage of High-electron-mobility transistors (HEMTs) while transmitting on a single frequency band. The Hg^{2+} information modifies the oscillator's centre frequency, and a delay line controls the oscillator's ON/OFF state. Depending on the present operating voltammetric range, a power amplifier (PA) that transmits a signal to an antenna can choose between three distinct power supplies with variable output swing. The obtained essential information about Hg^{2+} ion detection will facilitate the invention of sensing systems and the processing of novel GaN HEMT based sensors in the near future. Following are the publications which were reported in the last year.

- Sharma, Nipun, Adarsh Nigam, Surani Bin Dolmanan, Ankur Gupta, Sudhiranjan Tripathy, and Mahesh Kumar. "1T and 2H heterophase MoS_2 for enhanced sensitivity of GaN transistor-based mercury ions sensor." *Nanotechnology* 33, no. 26 (2022): 265501.
- Sharma, Nipun, Arun Kumar Sakthivel, Subbiah Alwarrapan, Ankur Gupta, Ahmed S. Razeen, Dharmraj Subhash Kotekar Patil, Sudhiranjan Tripathy, and Mahesh Kumar. "Ultrasensitive real-time detection of Pb^{2+} ions using gC_3N_4 nanosheets." *IEEE Sensors Journal* (2023).
- Real-time wireless monitoring of Arsenic ions detection using SnS_2 active layers on AlGaN/GaNHEMT for water quality monitoring, IEEE, Internet of Things Journal (under review)
- MoS_2@MWCNT Modified Glassy Carbon Electrode for Electrochemical Mercury (II) Ion Sensor, Journal of Material Chemistry C (In Press)

5. Concluding remarks

- The development of AlGaN/GaN HEMT sensors has expanded the application of III nitride-based devices for sensing applications apart from high-frequency and high-power operations. It presents a new approach that involves reference electrode-free sensing operation which opens new avenues for miniaturization of the detection devices with shorter response periods and greater stability. The successful fabrication of AlGaN/GaN HEMT based sensors and detection of toxic heavy metal ions such as Hg^{2+}, $Pb^{2+,}$ and As^{3+} using different 2D materials (MoS_2, g-$C_3N_{4,}$ and SnS_2) on miniaturized devices is summarized in this report. All these studies involve the development of a comprehensive platform for ion detection and necessitate collaboration across various interdisciplinary domains, aligning with the objectives of the interdisciplinary research program (IDRP) at IIT Jodhpur. This work encompasses electrochemistry, device physics, micro and nanofabrication, integrated circuit (IC) design, firmware development (specifically for the microcontroller and wireless module), and system integration. The AlGaN/GaN HEMT sensor exhibits a highly favorable property in terms of its size, response time, measured in seconds, and reference electrode-free approach. The sensors exhibit quick sensing response in detecting heavy metal ions and necessitate minimal voltage for detection. Therefore, it is possible to conduct the on-site detection of heavy metal ions using battery-operated systems with little power consumption for a prolonged duration. The devices provide several desirable characteristics that make them very suitable for next-generation heavy metal ion sensing for onsite detection. These include a low power demand, high stability, rapid response time, high sensitivity, and exceptional chemical inertness of the GaN surface. In our next year plan, we aim to integrate multiple ion sensors on a single platform, and the contacts of each sensor will be flip-chip or wire bonded and eventually develop a prototype device. The commercialization of these sensors for early-stage detection still has a significant journey ahead, despite the presence of current technologies. Therefore, in our next phase of work, we are working towards fabricating a single chip module connected with a different array of sensors for the simultaneous detection of different heavy metal ions. After enabling it with AI/ML assisted models and developing app-based connected interface for real-time effective continuous monitoring using a wireless network without any human intervention.