Executive Summary

<<Prof. Mahesh Kumar>>
<<Indian Institute of Technology Jodhpur>>

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 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 a wireless, portable heavy metals ion sensors for real-time water quality monitoring.

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

In the first year, 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).

5. Concluding remarks

The successful fabrication of AlGaN/GaN HEMT based sensors and detection of toxic heavy metal ions using 2D materials and miniaturized devices is summarised in this report. The complete portable ion sensor requires the work under interdisciplinary areas which satisfies the goal of interdisciplinary research program at IIT Jodhpur as it includes electrochemistry, device physics, micro and nanofabrication, integrated circuit (IC) designing, firmware development (for the microcontroller and wireless module), and system integration which we are doing with our collaborator from University of Edinburgh, UK.These materials and devices improve sensing behaviour and generate a detectable signal, paving the way for the development of portable sensors. 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 to develop a prototype device. For the onsite monitoring we will take samples from different water sources (e.g., tap water, lake water, river water, and pond water) will be transported to the functionalised region of each sensor through the test strip. The sensing results will be amplified and displayed on the LCD screen and transmitted over Wi-Fi. The response time (in seconds) of the AlGaN/GaN HEMT sensor is one of the most advantageous properties of the proposed device. We expect these would be one of the fastest sensors for heavy metal ion detection and would also require very low voltage for sensing analysis. Thus, the onsite detection of heavy metal ions can also be performed with very low power in battery-operated systems for an extended period of time (e.g. months). The low power requirement, high stability, rapid response time, high sensitivity, and excellent chemical inertness of the surface of GaN will make these devices an excellent candidate for next-generation heavy metal ion sensing for onsite detection.