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Conclusion and Future Work

8.1 CONCLUSION

In this thesis, a brief study about the III-N materials, simulation of AlGaN/GaN HEMTs, and their fabrication of AlGaN/GaN HEMT was carried out. The AlGaN/GaN HEMTs were then utilized to detect toxic heavy metal ions, including cadmium, lead, and mercury in the aqueous media. Starting with the brief study of the III-N semiconductor device followed by the idea of AlGaN/GaN heterostructure and the concept of 2DEG gives the realization of the AlGaN/GaN HEMT device. Thus, the AlGaN/GaN HEMT was discussed with the material characteristics of III-Ns. Furthermore, the layer by layer discussion along with the choice of substrate for the fabrication of AlGaN/GaN HEMT was also described. In this work, the HEMT is utilized for heavy metal ion sensing; thus, the different heavy metal ions, sources, and toxicity were also discussed. Subsequently, the various parameters that decide the quality of an ion sensor, such as sensitivity, selectivity, response time, the limit of detection, and many more were also explained in chapter 1.

Chapter 2 reveals the inside device physics of AlGaN/GaN HEMT by performing device simulation on the Sentaurus TCAD simulator tool. The Sentaurus TCAD utilizes the basic charge transport equations like Poisson's and continuity equations along with various device models such as mobility, piezoelectric, tunneling, bandgap, thermodynamic, and generation and recombination to solve in order to determine the behavior of the device. This process is utilized for the comparative analysis of the obtained simulated results with experimental one to validate simulated data with experimental results indicating the racialization of the device characteristics and simulated device represents itself as the real-time fabricated device. The simulated work was further extended towards the analysis of the self-heating issue in the AlGaN/GaN HEMT during high biasing conditions. The observed results indicate that at the higher electric field, the self-heating effect significantly affects the electrical characteristics of the device.

The task of fabrication and characterization of AlGaN/GaN HEMT cannot be accomplished by the proper utilization of the microfabrication and characterization systems. Thus, in chapter 3, the techniques utilized from the beginning of the fabrication to the electrical characterization were explained. It includes MOCVD, thermal evaporation system, RF sputtering, photolithography, XRD, SEM, AFM, AAS, ICP-MS, FESEM, and many more.

In chapter 4, the process flow of the growth and fabrication AlGaN/GaN HEMT was explained. In this work, the fabrication of AlGaN/GaN HEMT was specifically performed for heavy metal ion sensing applications. By using the combination of the thermal evaporation, RF sputtering, and optical lithography processes, the fabrication of AlGaN/GaN HEMT was accomplished. Moreover, its contact and sheet resistance were also observed using the TLM approach. The contact resistance and sheet resistance were calculated by the TLM process as 0.03457 Ω.mm and 230.88 Ω/□ respectively.

Since the HEMTs are normally-on devices due to the availability of two-dimensional electron gas (2DEG) at the heterointerface of AlGaN and GaN, which provides a conducting channel without applying any gate voltage. Thus, it eliminates the requirement of a reference electrode, reduces the complexity of the sensor. Using these excellent properties, the AlGaN/GaN

HEMTs were used in different ion sensing applications without employing any reference electrode. After the fabrication of the AlGaN/GaN HEMT for the sensing application using the process flow given in chapter 4, it is utilized for the detection of Cd^{2+} ions in the aqueous solution in chapter 5. In this perspective, the gate region was functionalized using MPA and GSH layers. The combination of these layers detects the cadmium ions during the sensing operation, and correspondingly the drain to source current varies. Utilizing the AlGaN/GaN HEMT sensor for Cd2+ ion detection, a good sensitivity of 0.241 μA/ppb, and an excellent response time of ~3 seconds was achieved. Further, the sensor exhibits a limit of detection around 0.255 ppb, which is less than the drinking water standards of the WHO (3 ppb). The sensor also possesses good selectivity over other heavy metal ions such as Cr^{3+}, Ni^{2+}, and Zn^{2+} metals and shown good repeatability and reproducibility.

The results of AlGaN/GaN HEMT for the Cd^{2+} ions are motivating and exciting, which encourages us to carry forward this work towards other heavy metal ion detections. In this regard, a sensor was developed to detect toxic Pb^{2+} ions and was explained in chapter 6. Here the DMTD layer was functionalized over the gate region of AlGaN/GaN HEMT. The developed sensor showed a high sensitivity of 0.607 μA/ppb and a rapid response time of ~ 4 seconds. The observed detection limit is around 18.41 ppt, an extremely low concentration of Pb^{2+} ions detected by the AlGaN/ GaN HEMT sensor. The sensor also showed highly selective behavior towards Pb^{2+} ions. These results make the DMTD functionalized AlGaN/GaN HEMT sensor a promising candidate for ultra-low-level detection of Pb^{2+} ions.

Further, the AlGaN/GaN HEMT was also utilized for the determination of toxic Hg^{2+} ions. For this work, the 2D material, MoS_2, was functionalized over the Au-gated AlGaN/GaN HEMT. In this work, a simple hydrothermal synthesis was carried out for the preparation of MoS_2. Furthermore, this hydrothermally prepared flower-like structure MoS_2 was drop cast on the gate region of AlGaN/GaN HEMT to use it as a functionalizing material to sense Hg^{2+} ions in aqueous solutions. The device shows a rapid response time of 1.8 s and an excellent detection limit of 11.52 ppt. Hence, a simple, novel, highly sensitive, and selective MoS_2 functionalized AlGaN/GaN HEMT sensor was developed for Hg^{2+} ions detection without the need for the reference electrode. By considering all the applications of the AlGaN/GaN HEMT for the heavy metal ion sensing application, it can be said that the AlGaN/GaN HEMT devices have a vast potential for next-generation ion sensing applications.

8.2 FUTURE WORK

The Simulation of AlGaN/GaN HEMT can be continued for the analysis of passivation by different materials. Additionally, the realization of MOS-HEMT can also be performed using high-K materials such as BST, BZN, PZT, and many more. The III-N materials are still comparatively new than Si and GaAs. Thus, it requires considerable work because the built-in data in TCAD is mostly for Si and GaAs. Due to this problem, the researcher needs to obtain data from the fabrication processes. In addition, the TCAD device modeling of the AlGaN/GaN HEMT can also be export as a complete device that can be utilized for SPICE circuit-level simulation programs.

By the encouraging results from the developed AlGaN/GaN HEMT heavy metal ion sensor for Cd^{2+} Hg^{2+} and Pb^{2+} ions, the investigation can be further carried out to detect various other heavy metal ions. Further, these developed sensors can be integrated on a single chip to perform the simultaneous detection of heavy metal ions. In addition, the simulation studies for the surface analysis can also be performed for AlGaN/GaN HEMT based heavy metal ion sensors. Since the AlGaN/GaN HEMTs are also utilizing in the high frequency and wireless applications, hence this property of AlGaN/GaN HEMT can also help to develop the wireless sensors and further can be employed in the internet of things (*IoT*) applications. Furthermore, in the future, the back-gate designing for the AlGaN/GaN HEMTs for heavy metals can also be performed to analyze dynamic characteristics of the AlGaN/GaN HEMT sensor. This technique would also be helpful for the analysis and control of the possible threshold voltage shift [Mahaboob *et al.*, 2019]. Moreover, the photoelectrochemical approach can also be utilized for the threshold voltage shift of AlGaN/GaN HEMT. By this process, the threshold voltage of AlGaN/GaN HEMT can be shifted to the desired level where the transconductance is maximum, which would help in the enhancement of the sensitivity of AlGaN/GaN HEMT based sensors [Xue *et al.*, 2020].

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