Chapter 7

Summary and Future scope of Research

In this thesis, I have successfully demonstrated the design, fabrication, and characterization of organic thin-film transistor (OTFT) based ammonia sensor utilizing polythiophene derivative PBTTT-C14 or PBTTT-C14 based nano-composite as the active semiconducting material. The fabrication of the sensing layer is done by an inexpensive and simple technique named FTM method. The integration of PBTTT-C14 a conducting polymer with notable charge transport properties and high environmental stability, with OTFT technology provides a promising platform for the detection of NH_3 in various applications, ranging from industrial safety to environmental monitoring. Additionally, photo-sensitivity of the devices is also investigated in some studies.

The outcomes verified that the ammonia-sensing capabilities of PBTTT-C14 based hetero-junction and homo-junctions OTFTs appeared promising. The current-voltage parameters of the OTFTs changed significantly in the presence of NH_3 gas, suggesting a noticeable ammonia response at lower concentrations in both accumulation and depletion modes. This performance was illustrated as a result of NH_3 molecules interacting with the polymer/nano-composite surface, which changed the concentration of charge carriers in the active channel. With a detection limit in the low parts per million (ppm) ranges, the sensor showed a significant improvement in sensitivity with rising NH_3 concentration, qualifying it for use in gas detection applications. The current-voltage parameters of the OTFTs changed significantly in the presence of NH_3 gas, suggesting a detectable ammonia response. The primary objective was to explore the sensitivity, selectivity, and stability of sensors in response to ammonia gas. In photo-sensitivity investigations of both the ON and OFF currents of the fabricated device show larger variation due to the enhancement in channel conductivity.

7. 1. Key Contributions:

7.1.1. Design and Fabrication: Along with the unique conjugated structure, PBTTT-C14 also exhibits excellent electrical conductivity and good stability, which are essential for the reliable operation of OTFTs in sensing applications. Its tunable properties through doping and processing conditions make it a promising candidate for detecting gases like ammonia.

For the fabrication of the π-conjugated polymers based organic electronic devices, FTM is an efficient process which offers a thinner layer of the active materials and improves the possibility of gas interaction at the dielectric-semiconductor interface for the aim of enhanced gas sensitivity.

7.1.2. Performance of the sensor: PBTTT-C14 based heterojunction or homo-junction OTFT sensor offers higher sensitivity as they displayed a significant change in drain current (I_D) even at low ammonia concentrations by a distinct shift in its electrical characteristics as threshold voltage, charge carrier mobility in the presence of NH_3 at varying concentrations, which indicates its potential for detecting trace amounts of NH_3. Both accumulation and depletion modes provide significant change in drain current, which is linear with the gas concentrations.

For the selectivity, these OTFT sensors demonstrated selective sensitivity towards NH_3 over other common environmental interfering gases confirming its utility in selective gas detection. Other key performance metrics such as response time, recovery time, and detection limit were evaluated, showing that OTFT sensors are competitive with other conventional sensor technologies.

7.1.3. Sensing Mechanism: The OTFT sensor operates through a change in the electronic conductivity of the active polymeric layer in response to NH_3 gas exposure. The interaction between ammonia and the sensor's surface modifies the charge distribution in the active layer, leading to a measurable change in drain current, which can be correlated with NH_3 concentration. Additionally, in our study we have examined accumulation and depletion mode operations with NH_3 concentration and found that the OFF current variation is much higher than the ON current variation. A comparative device performance of the NH_3 sensors that I developed is listed in Table 7.1.

Table - 7.1. Represents the Comparative performance of the fabricated sensors

Material	**NH_3 Concentration**	**Response**	**Detection limit**	**Off- current factor**
PBTTT-C14	0 ppm - 50 ppm	35.6%	0.82 ppm	~1.98
PBTTT-C14/MoS_2-QDs	0 ppm - 50 ppm	84.66%	0.317 ppm	~$3X10^3$
PBTTT-C14/WS_2-QDs	0 ppm - 10 ppm	50%	0.44 ppm	~10^3
Fibrillar PBTTT-C14	0 ppm - 5 ppm	74.8%	0.67 ppm	~10^2
Fibrillar PBTTT-C14 (Low operating voltage, <2 V)	0 ppm - 20ppm	69.04%	0.41 ppm	-

This thesis works demonstrated that the developed sensor exhibited a high sensitivity and selectivity towards NH_3 gas, with a wide detection range and a fast response time. The sensor's capability to operate at room temperature and its potential for real-time monitoring of ammonia concentration make it an attractive solution for applications in environmental monitoring, industrial safety, and agricultural practices. Moreover, the results showed good reproducibility and stability, which are crucial for practical deployment.

7.1.4. Real-World Application Scenarios: Ammonia (NH_3) is a toxic, pungent gas prevalent in agriculture, industry, and the environment. It poses serious health and environmental risks, contributing to pollution when released in large amounts. While vital in fertilizer production and promising as a hydrogen carrier, its hazardous nature makes effective detection crucial for safety and regulatory compliance. Ammonia detection has a wide range of potential applications across environmental, medical, industrial, and consumer sectors.

1. **Environmental NH_3 Detection in Agriculture -** In agriculture, real-time monitoring of ammonia emissions is critical, particularly in livestock farms and areas with heavy fertilizer use. Excessive ammonia not only poses health risks to farm workers and animals but also contributes to environmental issues like soil acidification and eutrophication. Integrating NH_3 sensors into farm management systems can enable precision agriculture practices, optimize fertilizer application, and improve air quality control within animal housing.
2. **Medical Diagnostics (Kidney & Liver Function Monitoring) -** In the medical field, elevated levels of ammonia in breath, sweat, or bodily fluids can serve as non-invasive biomarkers for diagnosing conditions such as liver dysfunction (e.g., hepatic

encephalopathy) and kidney disease. Wearable or portable ammonia sensors could offer real-time patient monitoring, aiding early intervention and disease management.

3. **Food Spoilage Monitoring -** Another important application of ammonia sensors is in food safety, where ammonia is a byproduct of protein decomposition. Smart packaging equipped with NH_3 sensors can indicate spoilage in meat, fish, and dairy products, improving supply chain transparency and reducing food waste.
4. **Industrial Safety and Workplace Exposure -** Industrial environments also benefit from ammonia detection, as it is commonly used in refrigeration and chemical processes. Detecting leaks quickly is vital to ensure worker safety and comply with health regulations. Finally, in urban settings, ammonia contributes to air pollution and the formation of fine particulate matter (PM2.5). Deploying NH_3 sensors across cities can help monitor air quality, inform public health policies, and support the development of cleaner, healthier environments.

In summary, the rising need for reliable ammonia detection—driven by environmental, industrial, and safety concerns calls for cost-effective, portable sensors with high sensitivity and selectivity. This study addresses that need by focusing on the detection of low airborne ammonia concentrations, essential for protecting both human health and the environment.

7.2. Future Directions:

Future work can focus on optimizing the sensor's performance further, exploring the use of additional functionalization strategies and offering a cost-effective, flexible, and scalable solution for environmental and industrial monitoring. Researchers are working to overcome the limitations of OTFT ammonia sensors by Nano-structuring the polymer to increase surface area and improve gas adsorption, hybridizing polythiophene with inorganic nano-particles or metal oxides to enhance sensitivity and selectivity, developing more stable materials to improve the longevity of the sensors.

An alternative organic semiconductors and dielectric combinations may be used to compare the performances of a gas sensor. As the carrier transport is confined in between the OSC and dielectric, it also plays the major role during sensing measurement. The successful realization of an OTFT sensor by using appropriate surface treatment of dielectric may be used to tune the sensor response. The solution-processable low voltage working OTFT may be used to design flexible sensors. Further, the impact of mechanical deformation on the OTFTs built on the flexible substrate may also be analyzed.

Additionally, as the demand for advanced, real-time, and highly selective gas detection systems increases especially in domains like environmental monitoring, healthcare diagnostics, and industrial safety, future research is likely to focus on the integration of thin-film gas sensors with machine learning, which offers a promising path for enhancing gas detection through advanced pattern recognition and multiplexed sensing. Machine learning can improve selectivity, compensate for cross-sensitivity, and enable accurate classification of gas types and concentrations based on sensor response patterns. When organized into sensor arrays, thin-film platforms can detect multiple analyte simultaneously, forming the basis of compact, high-performance "electronic nose" systems. These platforms are ideal for applications in environmental monitoring, industrial safety, and medical diagnostics.

Overall, future efforts may explore miniaturized, low-power systems compatible with flexible or wearable electronics, as well as edge computing for real-time decision-making. The convergence of advanced materials, scalable fabrication techniques, and adaptive AI models holds the potential to revolutionize gas sensing across numerous domains.