Chapter 8

Conclusion, Challenges and Future Work

Abstract This chapter gives the conclusion of the work done on the fabrication and implementation of printed flexible sensors for different applications. It also showcases the challenges faced by the current sensors along with some of the remedial solutions for them. It also explains some of the possible uses of the developed sensors along with the market survey for the MEMS-based and printed flexible sensors for the upcoming years.

8.1 Conclusion

The work showcased in the preceding chapters involves the fabrication of different flexible sensors via printing technology and employing them for various applications. Four different types of sensor prototypes were designed, developed, characterized and utilized for environmental (taste, salinity, nitrate sensing), healthcare (monitoring of physiological movements and respiration) and industrial (tactile sensing, robotic arm) applications.

The CNT-PDMS sensor prototypes were based on nanocomposites where the electrodes were carved out of the top nanocomposite layer. This layer was developed by mixing MWCNTs and PDMS at an optimized proportion with a trade-off done between the conductivity and flexibility of the resultant sensor patches. The characterization was done regarding their frequency response and stress-strain behavior. Then they were employed for monitoring physiological movements and respiration, and for tactile sensing.

The Al-PET sensor prototypes were fabricated from a single material using metallized polymer films. The electrodes were carved out from the Al side of the polymer films with an optimized electrode finger width. Then the prototypes were characterized, determining their responses towards changes in frequency and stress. The sensor prototypes were then utilized for tactile measurements for measuring the pressure on the patches on different portions of an arm.

The graphene-PI sensor patches were prototypes from laser induction of commercial polyimide films. Optimization was done on the laser parameters to achieve proper induction process. The sp^3 hybridized carbon atoms of the polymer films were photothermally converted into sp^2 hybridized carbon atoms of the laser-induced graphene. The sensor patches were then characterized by CNLS software to determine their passive electrical parameters consisting of it, followed by utilizing them for different industrial applications like salinity, taste and nitrate sensing.

The graphite-PDMS sensor prototypes were developed from the casting of graphite followed by PDMS on 3-D printed molds of specific dimensions. The depth developed of the trenches of the 3-D printed molds was optimized to obtain a trade-off between the electrical conductivity and critical volume fraction of the graphite powder present on the channels to form the electrodes. The sensor patches were then characterized to determine their frequency response and stress-strain behavior, followed by their implementation in monitoring the physiological strain-induced body movements and force sensing.

8.2 Challenges of the existing work

Even though a substantial amount of work has been done with printed flexible sensors till date, there are still some glitches that need to be addressed. Researchers are trying 24/7 to fabricate sensors with better performances regarding their sensitivity and sustainability in comparison to the existing ones, have easier fabrication process with multiple applications for ubiquitous monitoring purposes. There are still some loopholes and bottlenecks that exist in the current technologies that need to be addressed to optimize them for better use in the future. None of the current printing technologies has been able to print flexible sensor prototypes with a resolution in nanometres range. The nanowires used for forming the electrodes of flexible sensors via nanocomposites, thus compromising on electrical, mechanical and thermal characteristics while building them by mixing the nanofillers with the polymer matrix. The formation of the nanocomposites is another issue that needs to be addressed to further optimize them to minimize the reduction in electrical conductivity and achieve proper alignment of the nano-fillers in the polymer matrix. The spreading of the conductive inks and shadow effects during the offset printing, and hydrophobic problems in contact printing are some other drawbacks that need to be resolved among the current issues. The sensor prototypes fabricated with printing technology need to be scaled down regarding their dimensions while keeping consistency in their efficiency and sensitivity. The utilization of the sensor prototypes for a range of applications, especially in wearable sensing systems, needs to be improved to reduce the overall cost of the equipment. Sensor prototypes possessing multifunctional operating principles should be developed more to address the applications in a much more dynamic way. For example, sensors possessing electrochemical, strain and electrical sensing characteristics can be developed with multiple layered structures.

The enormous data generated by the wearable sensing systems makes it difficult to handle, store and process them. It also becomes a tedious job for the system and its operator to classify out the significant data among the huge database obtained for future analysis. Due to the huge amount of transferred data, there needs to be an authorized security system to avoid any mishandling and misuse of the received data. Time-varying traffic is another important issue that occurs during data transmission from a set of sensor nodes in a real-time topological system. This causes a delay in the data reception in the monitoring unit, thus reducing the efficiency of the system. It is also possible that some of the significant information might get lost due to the high traffic generated by AAL applications. The transmission of data via a central coordinator system in Wireless Sensor Networks (WSNs) should be operated properly to reduce the traffic and the data loss. The connectivity and interoperability of the embedded sensing systems should be significant in order to reduce the power and data loss. From a patient's point of view, he should not be facing any kind of discomfort while wearing the sensors for monitoring purposes. There should not be any breach of privacy for him in the monitoring duration. The embedded sensing systems attached should not be loosely attached to the body or clothes worn by the patient, as this could cause glitches during the data collection.

There is also a substantial risk of thermal effects of the embedded sensors on the tissues of the patient. Some of the factors contribute to this thermal effect (Bagade et al. 2015) like the total number of operated sensors and the positioning of the sensors on the body. The sensitive frequencies of the sensing systems should be as low as possible. Input power to the WFSs is another significant demerit that needs to be addressed by the current researchers. Sensors like SHIMMER, Telos having low input power should be considered for monitoring purposes to reduce the overall power consumption of the sensing systems. The continuous input supply of power to the system is another issue that needs to be discussed for future operations. The system should be designed and developed for on-node processing and reduce the effects of motion artifact and distributed interferences.

8.3 Future work

There is a considerable amount of work that can be done with the continuation of the presented work. The sensor prototypes can be deployed for some other applications in addition to the ones that are shown in the preceding chapters. For example, the prototypes can be implemented as temperature and humidity sensors in concurrence with other applications. For example, the results from the graphene-PI sensor patches towards a range of temperature and humidity values are shown in Figures 8.1 and 8.2. The changes in phase angle (Φ) concerning frequency was changing symmetrically for temperature values ranging between 30 °C and 50 °C. Even though the frequency sweep was done from 1 Hz to 10 kHz, the operating frequency was obtained between 100 Hz and 5 kHz, where the differences in the phase angle values can be seen. The operating frequency range for the humidity values ranging between 60% RH and 80% RH, was lower than that for the temperature values. Only a specific range of frequency between 600 Hz and 930 Hz out of the entire frequency sweep was capable of clearly differentiating the experimental humidity values. It can be obtained from these figures that the developed sensor prototypes can be deployed for other multiple applications, validating their multifunctionality.

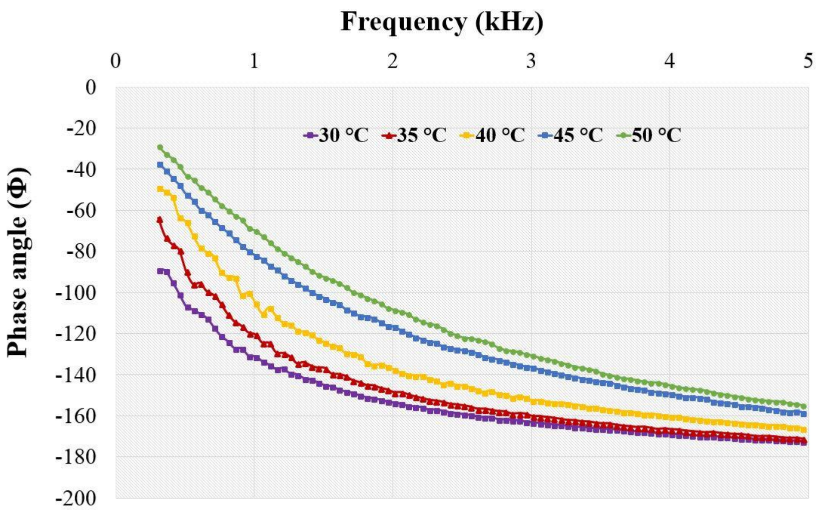

Figure 0.1 Response of the graphene – PI sensor patches towards different temperatures values ranging from 30 °C to 50 °C.

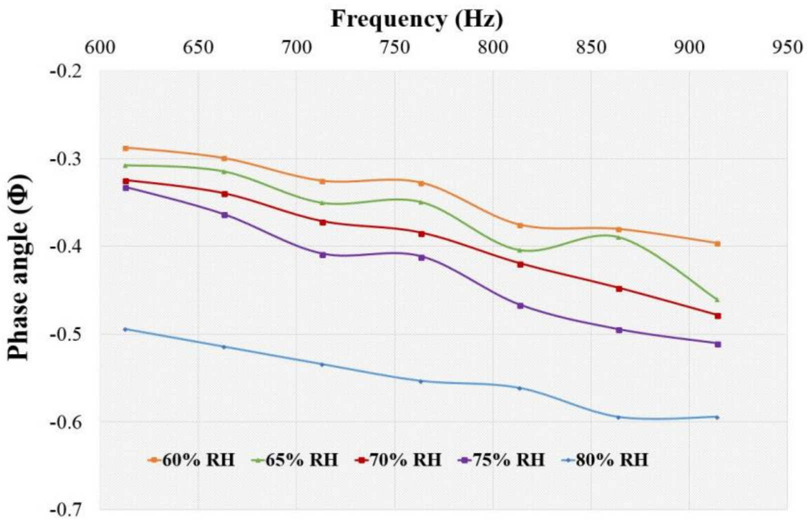

Figure 0.2 Response of the graphene – PI sensor patches towards different humidity values ranging from 60% RH to 80% RH.

There are some other suggestions that can be worked with to achieve better responses. Firstly, the developed sensor prototypes can be enhanced to develop new prototypes which are better than the current ones regarding dimensions, robustness, efficiency, sensitivity, reproducibility, and dynamic nature. Printing technology holds a pivotal role in future for the fabrication of new and enhanced sensor prototypes that can be considered for multifunctional applications. Secondly, the processed materials to form the sensor prototypes can be modified regarding functionalization to form advanced prototypes. For example, since the selectivity of a material to any particular analyte holds a pivotal role in sensing applications, porous materials like graphene that are considered to form the electrodes, can be made selective to a target molecule in other applications. The selectivity of the electrodes can be considered with a range of techniques like molecular imprinted polymer (MIP), non-imprinted polymer (NIP) and ion-imprinted polymer (IIP). The selectivity of the sensing systems can also be done in a way to ensure the reusability and repeatability of the sensors. The modification of the raw materials can also be done by the functionalization of the substrate and electrode materials to contain increased attributes as sensing prototypes. Thirdly, as with the fabricated sensor prototypes were related to printing technology, sensing prototypes formed with direct printing of nanocomposites can be considered on flexible substrates to obtain optimized electrical and mechanical properties in comparison to the manual mixing of nano-fillers to the polymer matrix to develop the nanocomposites. The direct printing of the nanocomposites on the flexible substrates can be obtained with certain techniques like ink-jet printing and screen printing, where the ink droplets that are dribbled on the substrate or template are made into nanocomposites which will serve as electrodes or conductive part for the flexible sensors. Sensors with multi-structured layers can be also be considered with different polymers and conductive materials to form a compact, yet multifunctional sensing prototype. The polymer materials in conjunction with the electrodes can be positioned on top of one another to obtain amalgamated attributes of the individual materials.

There is a prominent future for flexible electrical and electronic systems in wearable sensing based on its market opportunities (Flexible Smart Sensors and the Future of Health). The market values of printed and flexible electronics are predicted to be over 75 billion USD by 2025 (The State of Flexible and Printed Electronics). The estimated figures for the consideration on flexible sensing systems for the next 10-15 years have been considered along with the challenges that the flexible sensing systems fabricating companies need to address currently. There is a substantial opportunity to develop these flexible systems for monitoring health and physiological parameters. The estimated cost of WFSs by 2020 is more than 3 billion USD (2016-2026: Market Forecasts), and a substantial rise over 40 billion USD with more than 240 million annual unit shipments by 2025 (The Wearable Technology Ecosystem: 2016 - 2030 - Opportunities, Challenges, Strategies, Industry Verticals, And Forecasts). The current challenges for the companies are to develop the sensing systems to reduce complexity and overall fabrication cost. One of the possible ways for this is to consider cheap, safe and biocompatible materials for their design and fabrication. FlexEnable, a UK-based company, has estimated rise in the organic electronics among WFSs (Organic Electronics Will Play a Key Role in Increasing the Utility of Wearables). With the growing interest of present consumers, the companies should design systems which will not only serve the people but also meet the application purposes at low cost. The systems should be made cost-effective so that they can be used to address a wider community in the society. The scope of research work that can be done on this topic is increasing every day with its growth in its market value. The growth in MEMS along with Nanoelectromechanical (NEMS) technology is expected to reduce the overall cost of fabrication of the flexible sensing systems, thus leading to a wider range of applications soon. The uses of the existing fabricating techniques along with the upcoming ones will help in developing new sensing systems and should assist people to have a better quality of life.

8.4 References

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