ABSTRACT

KEYWORDS: Piezoelectric Energy Harvesters/Sensors, Triboelectric Energy Harvesters/Sensors, Photopatternable Nanocomposites, Self-Powered Sensing, Hybrid Energy Harvesters/Sensors, Machine learning

The dawn of the Internet of Things (IoT) represents a monumental shift in the way we connect and interact with devices and the environment around us. One pivotal factor in the rapid growth of IoT is the significant contribution of low-power electronics. These energy-efficient components enable the deployment of IoT devices that can operate on minimal power resources, enhancing their reliability and scalability. As a result, IoT applications have flourished across various sectors, from smart homes and cities to industrial automation and healthcare, ushering in a new era of connectivity and data-driven insights that continue to reshape our world. However, the surge in IoT nodes has exponentially increased the number of wireless, remotely placed "IoT nodes" that should operate independently with minimal maintenance. The dependence on batteries is not feasible for the predicted growth of IoT technologies as it limits its multi-domain expansion.

Since sensors are a vital component of IoT node, transforming the passive-energy consuming sensors into active-self powered sensors (or harvesters) provides a suitable solution and creates a transformative shift towards a greener world. Tapping the "always available" mechanical energy in the form of biomechanical and ambient vibrations opens up new avenues for self-powered sensing. The low-frequency (< 200 Hz) vibrational energy can be efficiently harvested using a flexible piezoelectric, and triboelectric harvesters built from a diverse set of materials, including polymer nancomposites and nano-filler combinations.

The majority of the published research on piezoelectric or triboelectric harvesters discusses the methodologies that are CMOS incompatible, expensive, complex, single transduction, and restricted to a small area harvesting/sensing. However, there are no reported studies on the development of novel material and their optimization as a CMOS compatible, simple, low-cost, dual transduction, and large area harvester/sensor that is suitable for self-powered IoT nodes.

This thesis explores a series of research works associated with dual transduction nanocomposites and their process optimization to develop energy harvesters/sensors for extracting ambient and biomechanical energy. This thesis uncovers the possibility of dual transduction in photopatternable and non-photopatternable nanocomposites with applications in energy harvesting, impact loss compensation, machine learning integrated sensors, etc.

This thesis reports the following significant findings:

1. The optimization of photopatternability and piezoelectricity in %weight ratio varying ZnO/SU-8 and BTO/SU-8 nanocomposites. The thesis uncovers the optimum weight ratio value of 15% and 20% for ZnO/SU-8 and BTO/SU-8 nanocomposites, respectively. At these values, they show optimum results with good piezoelectric response and UV transmittance, allowing reliable lithography of the nanocomposites. This optimization allows the

development of flexible biomechanical energy harvesters with output power of 223µW and 642µW for ZnO/SU-8 and BTO/SU-8, respectively.

2. The exploration of inherent triboelectric nature of BTO/SU-8 nanocomposites and the effect of %weight ratio on its triboelectric transduction. The performance enhancement techniques on the form of UV exposure and graphene doping are also presented. The 1% graphene doped 20% BTO/SU-8 shows a high triboelectric shift with a charge retention measure of 85mV that enables the design of a dual transduction energy harvester with a power density of 0.65µW/cm^{-2} at 0.75g acceleration amplitude.

3. The development of a novel pixelated tactile pressure sensor with dual transduction capabilities using the optimized 20% BTO/SU-8 composites as the active layer. The sensor shows a sensitivity of 34 mV kPa−1 for deep linear region and 2.7 mV kPa^{-1} for the linear region over a pressure range of 0–170 kPa. The sensor shows a negligible hysteresis with an average deviation of 2.7%. A sensor-ML integration is also presented that allows effective utilization of this sensor for hind foot deformity detection, activity monitoring and grip strength assessment with 98.5%, 98.3% and 93.75% model accuracy, respectively.

4. The concept of dual transduction in a single thin film is presented as a possible solution to impact losses in impact driven piezoelectric energy harvesters. The proposed impact driven energy harvesters is capable of compensating impact-induced energy loss by a 100% power integral recovery at < 1.5g acceleration amplitude by suitably designing the device that incorporates a dual piezoelectric/triboelectric transduction-based nanocomposite as the active layer. This hybrid design demonstrates 3.3 times power gain and the bandwidth broadening of 5.4Hz at 1g.

5. The exploration of dual transduction in BTO/P(VDF-TrFE) and the effect of %weight ratio on the β-phase as well as triboelectric shift. 15% weight ratio of BTO in 20% P(VDFTrFE) nanocomposites film shows the highest piezoelectric co-efficient of 0.58nm/V. The addition of BTO in 20% P(VDF-TrFE) results in a triboelectric shift from a tribonegative to tribopositive nanocomposite. The surface potential shifts from -382.5mV to 495 mV in 20% P(VDF-TrFE) and 15% BTO/20% P(VDF-TrFE). The charge retention metric ΔV_{200} also decreases from 150 mV to 60 mV in 20% P(VDF-TrFE) and 15% BTO/20% P(VDF-TrFE), indicating the improvement in charge retention in 15% BTO/20% P(VDF-TrFE).