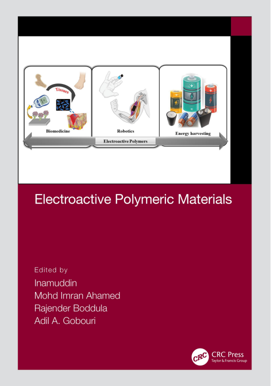

Electroactive Polymeric Materials

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Systematic Investigation of the Revolutionary Role of Electroactive Polymers in Modifying Microelectromechanical Systems

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7 Systematic Investigation of the Revolutionary Role of Electroactive Polymers in Modifying Microelectromechanical Systems

Shaan Bibi Jaffri and Khuram Shahzad Ahmad

CONTENTS

7.1 INTRODUCTION

A myriad of materials have been synthesized and others are emerging with time, which are aimed at the welfare of humans by revolutionizing several domains in human life. The scientific community has been actively engaged in the development of novel materials that have varied compositions, for example, oxides, sulfides, tellurides, selenides, polymeric substances, and composite materials (Afsheen et al., 2020; Ahmad and Jaffri, 2018; Ijaz et al., 2020a). They are employed in a variety

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of applications that range from biomedical to photovoltaic applications, which depend on the characteristics required. Among different materials, polymeric substances have gained special attention for many decades due to their characteristics (Bonneaud et al., 2021; Nenna et al., 2021). Today, there are no areas of life where the utilization of polymers and polymeric composites has not been implemented. The field of polymers has grown considerably over time and a significant amount of research has been conducted to resolve the concerns raised against polymers for their persistence and stability in environmental matrixes that negatively affect life (Forouzanfar et al., 2021; Hafner et al., 2021). Polymers can be broadly categorized in different classes depending upon their composition, nature, type of application, and other characteristics. Electroactive polymers (EAPs) are the major class of polymers and polymeric substances that are known for their feature of undergoing change in their size ranges, morphology, and volume when they come into contact with an electrical field of higher strength (Peng et al., 2021; Marín et al., 2021). They are one of the active polymeric materials, such as magnetostrictive materials, piezoelectrics, alloys, and polymers that have shape memory, and thermoelastic polymers These active materials are mainly marked by their remarkable active disfiguration capacity, higher speed of response, lower density, and upgraded resilience. In addition, EAPs are remarkably lightweight materials that have good fracture tolerance and compliance. Furthermore, they are economically viable (Bar-Cohen, 2004). This category has grown into a large number of polymeric materials that are highly responsive toward electric field application.

Synthetic EAPs emerged in the 1990s and since then, they have been inspiring the scientific community and engineering, which has led to their application in wider spectrums that encompass biomedical and other microelectromechanical systems (MEMs). For instance, they have similar aspects with the muscles, and therefore, they have been seen as artificial muscles based on their mode of action (Sarikaya et al., 2021; Rohtlaid et al., 2021). In addition, the softer and robust EAPs are associated with the provision of the larger strains compared with traditionally employed piezoceramics. Such features advocate their utilization in a wide range of applications. The literature is indicative of the larger number of publications that report the utilization of EAPs in actuators and sensors (Takagi et al., 2021; Yang et al., 2021; Rivkin et al., 2021). Of note, most actuators were developed previously using ceramic piezoelectric substances. Ceramic piezoelectric materials can withstand larger forces that are exerted on them and the consequent deformation in them is very minimal. However, with the development of EAPs, they can withstand 380% strain. Therefore, they have exceeded the ceramic piezoelectric materials to be considered in actuators. Of interest, these EAPs undergo greater deformation although they support large forces (Surmenev et al., 2021).

EAPs have undergone rapid transformation from their previous forms to their present form. Electromechanical coupling is usually carried out in EAPs to use them in actuation in addition to other applications of chemical sensors and mechanical stimuli. EAPs represents a unique category of materials that are known for their potential to conform to the surface regions of varied morphologies. These characteristics renders them suitable for applications in sensors and actuators (Minaian et al., 2021). EAPs are usually categorized into two classes that consider the major types of charge carriers in them (Bar-Cohen 2004) and this system of categorization is often referred as the Yoseph Bar-Cohen classification of EAPs. The classes of EAPs are ionic and electronic. Ionic EAPs include polymeric gels, carbon nanotubes (CNTs), conducting polymers (CPs), and ionic polymer–metal composites (IPMC) and the electronic EAPs include dielectric elastomers (DEs), liquid-crystal polymers, and piezoelectric polymers (PE) (Wang et al., 2016). EAPs is a generally used term and includes lightweight, flexible, and organic materials that are highly responsive to electrical stimuli. Ionic polymers usually function based on the migration of ions in the polymer matrix, and electronic polymers are functional after activation by an extrinsic electrical field. Electronic polymers usually required a higher voltage of >100 V, which exhibit shorter responsive durations.

MEMS signify the advanced systems that consist of smaller scale electrical and mechanical constituents and are used for specialized purposes. The translation of MEMS into specialized systems was carried out by the incorporation of electromechanical components and since then the boundaries of MEMS has been extended to include various devices, for example, nano, optical, and radio–frequency. Therefore, MEMS-based devices are known by various names that depend on the type of application and device where they are employed. For instance, optical applications make use of micro–optoelectromechanical systems (MOEMS) (Hillmer et al., 2021; Busurin et al., 2021), radio–frequency constituents and applications make use of radio–frequency MEMS (RF–MEMS) (Iannacci et al., 2021; Shanthi et al., 2021), and nano systems and devices have one dimension <1 µm that make use of nanoelectromechanical systems (NEMS) (Auciello & Aslam, 2021; Song et al., 2021). In addition, MEMS are used in biological domains for the detection of a desired target or for the manipulation of the cells. These biological systems that incorporate MEMS are often referred to as bioMEMS (Espinosa-Hernandez et al., 2021; Garcia-Ramirez & Hosseini, 2021). MEMS in a general sense are known by different names in different parts of the globe. For instance, they are referred to as microsystems technology (MST) in European countries and in Japan they are known as micromachines. In brief, MEMS can be used to describe smaller machines that are composed of a set of electrical and mechanical constituents that aim to achieve a specific purpose. According to the requirements of specific devices, other components can be added to the MEMS device, for instance, reflective surficial components used in micrometers. The components of MEMS are between 1 and 200 µm with an overall size approximately <1 mm.

The features of polymers that have been used in MEMS are given in Table 7.1. Different types of EAPs have been utilized in different kinds of microdevices. For instance, CPs have expressed

TABLE 7.1
Utilization of different types of EAPs for development into MEMS

Name of EAP (pristine or modified)	Role	Type of MEMS	References
Poly(2,2-dimethyl-3,4-propylene-dioxythipohene) (PProDOT-Me2)	Polymeric electrodes	Supercapacitor modules	Liu & Reynolds (2010)
Polyhydroquinone–graphene hydrogel composites	Electrode material	Supercapacitor	Chen et al. (2015)
Polyaniline and carbon fiber graphene oxide	Electrode material	Supercapacitor	Gandara & Gonçalves (2020)
ligninsulfonate/single-wall carbon nanotube film/holey reduced graphene oxide (Lig/SWCNT/HrGO)	Film for energy storage	Wearable supercapacitors	Peng & Zhong (2020)
Poly(vinyl alcohol)-PANI nanofiber/graphene hydrogel	Energy storage	Coin Cell Supercapacitor	Joo et al. (2020)
Polyaniline/$Ti_3C_2T_x$ composites (i-PANI@$Ti_3C_2T_x$)	Wearable energy storage	Flexible all-solid-state supercapacitors	Zhou et al. (2020)
Nitrogen-doped ordered mesoporous carbon, in which g-C3N4	Mesoporosity provisioning	Volumetric supercapacitor	Xie et al. (2021)
Palladium oxide-polypyrrole (PdP)	Active electrode material	Supercapacitors	Jose (2021)
PEDOT:PSS/PPy	Electrode material	Flexible fiber-shaped supercapacitor	Teng et al. (2020)
Silsesquioxane -containing graphene oxide (SSQ-GO)	Energy storage	Supercapacitor	Ajdari et al. (2020)
PEDOT nanotubes	Energy storage	Supercapacitor	Hryniewicz et al. (2020)
Pyrolyzed polyacrylonitrile particles	Energy storage	Supercapacitor	Abalyaeva et al. (2020)

(*continued*)

TABLE 7.1 (Continued)
Utilization of different types of EAPs for development into MEMS

Name of EAP (pristine or modified)	Role	Type of MEMS	References
PVDF–PZT nanohybrid	Nanogenerator	Energy harvesting applications	Wankhade et al. (2020)
Contact-type (CT)	Dielectric elastomer generator	CT energy harvesting	Zhang et al. (2020)
Poly(ε-caprolactone) (PCL) membranes	Nano harvester	Energy harvesting	Sencadas (2020)
PVDF	Effective energy harvesting	Light detection	Si et al. (2020)
VHB elastomer	Dielectric elastomer generator	Energy harvesting	Jiang et al. (2020)
Poly(vinylidene fluoride-co-hexafluoroproplyene) (PVDF-HFP)	Energy harvesting	Energy harvesting	Ponnamma et al. (2020)
PVDF and trifluoroethylene (P(VDF-TrFE))	Piezoelectric medium	Energy conversion and sensing	Jiang et al. (2020a)
Ionic polymer–metal composite (IPMC)	Ionic medium	Wearable sensors	Patel & Mukherjee (2020)
Nafion IPMC	Porous media	Energy harvesting	Kweon et al. (2020)
β-PVDF/rGO	Piezoelectric nanogenerators	Energy harvesting	Ongun et al. (2020)
Terpolymer P(VDF-TrFE-CFE)/diisononyl phthalate (DINP)	Actuation	Optical applications inside Live Mirror	Thetpraphi et al. (2020)
HNTs/P(VDF-CTFE) nanocomposite	Capacitance	Dielectric capacitor	Ye et al. 2020
Ferroelectric copolymer P(VDF-TrFE)	Actuation	Dielectric material and actuators	Thuau et al. 2020
Poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate) (PEDOT:PSS)	Electrode material	Linear actuators	Nguyen 2020
IPMC	Actuation	Actuators	Chang et al. 2020
Poly(ethylene glycol) diacrylate-poly(acrylic acid)	Electroactive scaffold	Excitable tissues	Gupta et al. 2021

remarkable performances in different for their potential for energy storage, sensing ability, and actuation. In addition, they are preferred because they are compatible with biological environments that have higher levels of moisture. MEMS-based devices made using EAPs can be further engineered for their speed by their enhancement at macroscale, because the ionic transfer paths are smaller, and the surface areas are relatively larger. Furthermore, a myriad of patterning methods are available and suitable for EAPs, which ensures their utilization in microfabrication (Spinks et al., 2007). The micro robots prepared with EAPs are based on a number of actuators that are marked by their movements that mimic the motion of elbows, wrists, and fingers.

The utilization of EAPs in different types of MEMS are in development and considers the suitability and end products prepared. In different types of MEMS, EAPs are used as integral components and some studies have suggested the advantages and disadvantages associated with them. A lot of data has been published that describes the use of EAPs in different types of MEMS; however, the utilization of these polymers in energy system is gaining considerable attention due to the present status of energy demand on a global scale. Research has been carried out on single EAPs and MEMS in addition to the utilization of these polymers in MEMS. However, to the best of our knowledge, no work has provided a comprehensive overview of the utilization of EAPs in MEMS.

In particular, there is limited literature on comprehensive reviews that cover energy systems based on EAPs. Therefore, this chapter will, for the first time, study the utilization of EAPs in MEMS, which specifically targets EAPs in energy systems. This chapter will focus on EAPs, their various types in ionic and electronic polymers, MEMS, the commercially significant uses of MEMS, and EAP-based energy MEMS will be discussed. In addition, this chapter will present some significant future considerations and challenges that are associated with the utilization of EAPs in different types of MEMS.

7.2 METHODS

7.2.1 Search Strategy

This chapter has adopted a literature survey on previous years to compile a brief review that considers the favorability of EAPs in MEMS. Therefore, the literature studied was from published items that included research articles, book chapters, short communications, reviews, perspectives, and reports. The published items were selected from authentic publishers, such as Taylor & Francis, Elsevier, Springer, Springer Nature, JStore, Science direct, and IEEE. In general, the literature studied included articles from 2005 to 2021; however, considering the relevance of the topics and the space requirements, the selected papers were from 2010 to 2021. Different types of search engines were used, specifically Google scholar and the terms used to search different databases were varied, such as: [“polymers”, “electroactive polymers”, “microelectromechanical systems”, “MEMs”, “EAPs classes”, “MEMS types”, “electroactive polymers and MEMS”, “electroactive polymers and energy harvesting”, “Issues of electroactive polymers”].

7.3 BROAD CATEGORIZATION OF ELECTROACTIVE POLYMERS

EAPs have a significant position as polymers, and they are employed in a wide range of devices. EAPs are a very large family of polymers that have been further divided into the major groups of ionic and electronic EAPs according to Yoseph Bar-Cohen classification as shown in Figure 7.1. The categorization of EAPs is carried out based on their actuation. Specifically, the ionic EAPs are include materials that function as a result of the motion or diffusion of ions. Electronic materials are the EAPs that provide a mechanical response toward the Coulombic forces or other types of electrical fields. Recently, EAPs have emerged due to the favorable results and prompt reaction toward electrical stimulation with the following transformations in their morphology. These features have prompted the scientific community since the 1990s to explore EAPs and their use in different types of devices, especially MEMS (Defaz et al., 2021). Therefore, they have been used in increasing applications with time. Robust polymers are known for providing larger strains compared with other conventional materials.

7.3.1 Ionic Electroactive Polymers

Ionic EAPs include a wide range of materials, which differ based on different factors. In addition, they are further classified into polymeric gels, CPs, CNTs, and IPMC. In all these ionic EAPs, the major mechanism of functionality is via electrically triggered ionic diffusion that occurs inside the material in bulk. The following section will discuss these types of ionic EAPs.

7.3.1.1 Polymeric Gels

Polymeric gels are a widely investigated type of EAP. Among the different types of polymeric gels, a highly advanced form of polymeric gel has been studied, which has been modified by metallic cross-linkers to improve the characteristics. Researchers have been using metal cross-linkers to modify

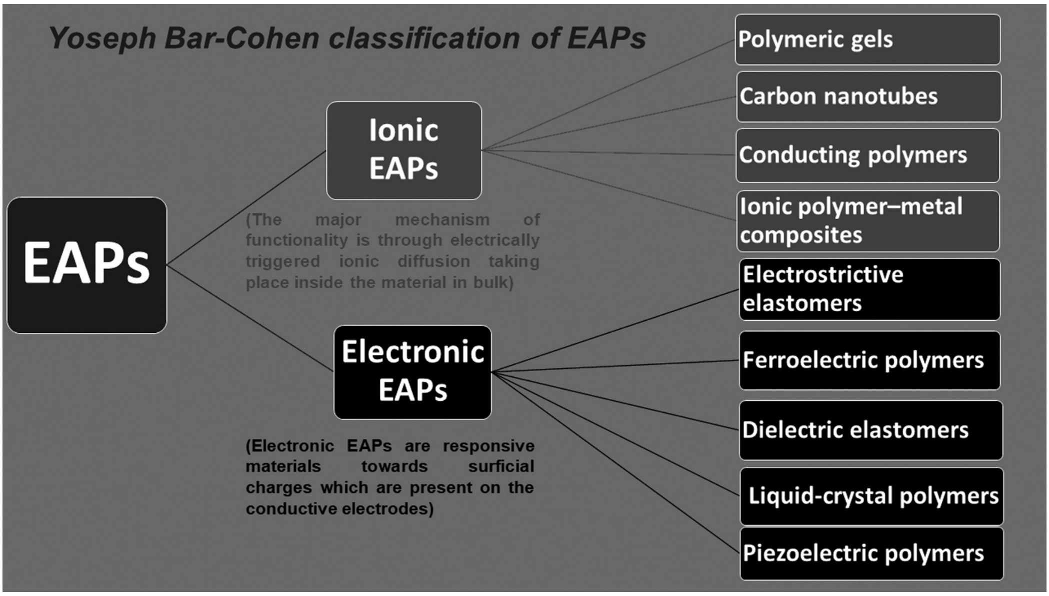

FIGURE 7.1 Yoseph Bar-Cohen classification of EAPs in sub-classes.

polymeric gels to overcome different limitations. For instance, such modification has been carried out to resolve in situ monomeric units and polymeric gels for stability in varying thermal conditions, plugging potential, and viscoelasticity (Boakye & Mahto, 2021). In 1990, the first polymeric gel was fabricated, investigated, and modified by the used of metallic cross-linkers. It was referred to as HPAM/Cr(III) (Karimi et al., 2016). Based on the cross-linkers used, polymeric gels can be further categorized into organically and inorganically cross linked polymeric gels. Organic cross-linkers include phenolics and polyethyleneimine (PEI) (Zhu et al., 2016). An organic cross linked polymeric gel was formed using hydroquinone (HQ) and hexamethylenetetramine (HMTA) that had amazing strength at 120°C (Sengupta et al., 2017). Inorganically cross linked polymeric gels include metallic ions, for example, Zr, Al, and Cr (Jia & Chen, 2018). Zhao et al. (2013) prepared an inorganic polymeric gel using HPAM and a zirconium salt (i.e., acetate). Rheological measurements in this inorganic polymeric gel indicated the division of the gelation process in three stages: induction, quicker mode cross-linking, and stabilization (Zhao et al., 2013).

7.3.1.2 Conducting Polymers

CPs are the fourth generation of polymeric materials (Ke et al., 2021). This class of EAPs is important for energy, because the final physicochemical characteristics of CPs can be altered positively compared with conventional polymeric substances through the combination of the remarkable electrical conductivity of the metals with polymers (Ibanez et al., 2018; Swager et al., 2017). In addition to the utilization of CPs in energy associated MEMS, which is due to their favorable electrical and electronic features, CPs have been employed in biomedical fields. Their use in biomedical applications is attributed to their responsive chemistry toward electrical fields (Llerena Zambrano et al., 2021). Since 1980, polymer and synthetic scientists have been synthesizing novel combinations of CPs that possesses favorable characteristics. Since then, a large number of CPs have been synthesized, in addition to their derivatives. However, some of the CPs have been developed based on their favorable features (e.g., polyaniline, polyacetylene, polypyrrole, polythiophene, and poly[3–ethylenedioxy)thiophene]) (Alipour et al., 2021; Boswel et al., 2021; Synodis et al., 2021)

7.3.1.3 Carbon Nanotubes

CNTs are the stiffest anthropogenic material with elevated strength. In addition to this, CNTs have significant electrical conductivity, and therefore, they are gaining a significant place in different types of electrical devices and applications in of communications. However, the favorable features of CNTs can only be employed in practical applications if care is taken due to their smaller size and embedding is carried out meticulously inside light weight matrixes in a homogenous manner (Spitalsky et al., 2010). CNTs are a type of ionic EAPs that has great flexibility, lower mass density, and a larger aspect ratio that is typically >1,000. In addition to this, experiments carried out with CNTs indicated their higher strengths and tensile moduli. CNTs are further categorized into different types, for example, single-walled carbon nanotubes (SWCNTs) and multi-walled CNTs (MWCNTs) (Yoo et al., 2021). These types can be metallic or semiconducting. In semiconducting CNTs, they have potential for the transport of electronic species over a range of longer lengths. There is no interruption in this electronic transferal, which makes them highly conductive compared with copper.

7.3.1.4 Ionic Polymer–Metal Composites

IPMCs are another significant type of EAPs that are available in composite forms of some conductive media, for instance, metals. IPMCs expresses a larger dynamic disfiguration during its development into electrode material in an electric field that varied as a function of time (Washington et al., 2021; Olsen et al., 2021). Typical sensors and actuators that use IPMCs are composed of a thinner layer of polyelectrolyte membrane*,* for example*,* Nafion, Flemion, or Aciplex, which is plated over the surface of the noble metal (Jamil et al., 2021). The noble metal is often platinum (Pt) or gold (Au) or Pt with top finishing layer of Au to improve conductivity. They are neutralized using different counter ions, and the balancing occurs for the anions that have been covalently bonded onto the membrane backbone. Sulfonates are typical anions in Aciplex and Nafion, and carboxylates are the major anions in Flemion (Sanginov et al., 2021; Taufiq Musa et al., 2021).

7.3.2 ELECTRONIC ELECTROACTIVE POLYMERS

Electronic EAPs are responsive toward the surface charges that are present on the conductive electrodes. They are often bulk insulators. The surface charges over the conductive electrodes are known for the application of Coulombic forces over the materials that causes stress and strain in them. Electronic EAPs have further been categorized in different types. The following section gives a brief description of these types.

7.3.2.1 Electrostrictive Elastomers

Electrostrictive elastomers are electronic EAPs that are characterized by their light weight, flexibility, and economic viability and they are especially considered for their potential toward morphological molding into the desired shapes (Diguet et al., 2021). Furthermore, their mechanical energy density is remarkable compared with piezoelectric single crystals. Electrostrictive elastomers and piezoelectric EAPs are still emerging, and research is continuing in new areas in polymers. Compared with electroactive ceramics, electrostrictive elastomers are gaining attention, which could be attributed to their characteristics of responsiveness to electrical fields. Research in the field of electrostrictive elastomers led to the development of poly(vinylidene fluoride) (PVDF or PVF2) in 1969 (Su & Tajitsu, 2016).

7.3.2.2 Ferroelectric Polymers

Ferroelectric polymers and ferroelectret polymers are important types of electronic EAPs that are used in a wide range of applications (Mi et al., 2021). However, there is a fundamental difference between ferroelectric and ferroelectret EAPs due to the larger elastic anisotropic features of ferroelectret EAPs. They are prone to deformation due to compression and expansion. Ferroelectric EAPs are often incompressible that leads to stronger coupling. This type of coupling often develops between longitudinal piezoelectricity that occurs in the thick direction and transverse piezoelectricity. The latter piezoelectricity is often known for coupling the crosswise elastic disfiguration with transformation of the perpendicular electric polarization. Ferroelectric EAPs are used in a wide range of commercial applications, for example, piezoelectric ignition systems, hydrophones, and clamp-on transducers (Bauer & Bauer, 2008).

7.3.2.3 Dielectric Elastomers

DEs are a unique class of electronic EAPs that consist of longer chains of monomeric units, and they have the potential for larger disfiguration ≤300%. When subjected to higher voltage ranges, DEs undergo deformation and convert electrical energy into mechanical energy. Similar to other electronic EAPs, DE have been used in a variety of appliances, for example, valves, robotics, pumps, prosthetic devices, and medical implants. These applications mainly includes DE actuators with various configurations (Ni et al., 2021). On exposure to a constant voltage, DEs produce an augmented electrical field that leads to a further thinning of the film and instability in DE actuation. Therefore, further research is needed to resolve the issue of electromechanical instability that is encountered in DE-based actuation.

7.4 MICROELECTROMECHANICAL SYSTEMS AS REVOLUTIONIZERS

Currenlty, there has been in increase in the fabrication of new materials in different applications (Ijaz et al., 2002b; Iqbal et al., 2019; Jaffri & Ahmad 2018, 2018a). A lot of materials have been synthesized (Ahmad & Jaffri, 2002a; Ijaz et al., 2020a), which were aimed at utilization in MEMS. MEMS-based devices and structures that have smaller mechanical and electromechanical constituents are adding value to human life due to their development into different types of applications, which have been generated via microfabrication techniques. The revolutionary role of MEMS could be understood from the large number of polymer and other chemical constituent-based MEMS-based devices that are available on a commercial scale. In addition, research is being carried out to optimize the results for different types of MEMS (Gupta et al., 2021; Nguyen et al., 2020). One typical example of MEMS is a micromirror, which is used for the transmission and display of desired information. Other examples of MEMS include pressure sensors, gyroscopes, digital micromirror devices, and accelerometers that have industrial significance (Ye et al., 2020; Thuau et al., 2020; Ren et al., 2012). These devices have been commercialized and are being utilized in a wide range of applications that benefit humans. Despite the benefits that MEMS offer to humans, there is an ongoing debate about MEMS on the consolidation of the softer, cheaper, and efficient materials in operationally active MEMS that does not impact their functionality. The synergistic mixture of microelectronics and mechanical structures of micron sizes leads to the development of MEMS, which has gained interest due to the favorable results (Tiliakos, 2013).

7.5 MICROELECTROMECHANICAL SYSTEMS: COMMERCIALLY SIGNIFICANT APPLICATIONS

7.5.1 MICROCOOLING

Microcooling is a type of fluid acceleration. MEMS-based micro heat pipes (MHPs) are an emerging technology aimed at cooling heat pipes and they have acquired a significant place in thermal managerial strategies. The best use of this MEMS-based technology is carried out in microelectronic circuits packing, laser diodes, and concentrating photovoltaic cells. MHPs have often been employed as thermal spreaders that are the best technology the removal of heat directly from devices made from semiconductors. The fabrication and integration of the MHPs can be achieved by the electronic or optoelectronic chips over the MEMS surface. Research has been carried out to improve thermal conductivity and to augment heat transferal (Qu et al., 2017). In a recent report by Sun et al. (2017), an investigation was carried out on a MEMS-based micro oscillating heat pipe (micro-OHP) to determine the characteristics of the flow and thermal functionality using the working fluid, for instance, a dielectric liquid HFE-7100. The integration of the micro-OHP was carried out on a silicon wafer that had trapezoidal channels 357 μm of the hydraulic diameter (Sun et al., 2017). In another report, a feasibility study was conducted for a liquid microthruster that was based on channels with regenerative microcooling. The microthruster was based on the materials that were thermally fragile (Huh et al., 2017).

7.5.2 MICROELECTROMECHANICAL SYSTEM-BASED MICROSCOPY

MEMS have had an impact on all fields of human life including science, technology, and engineering. Microscopic techniques have acquired an important place in science for the detection of morphology and dimension-based measurements. Microscopy depends on the use of MEMS for proper functionality. Recently, in a microscopy-based report, an array of a single-chip atomic force microscope (sc-AFM) was reported for the first time, which could capture a lot of images of the target sample simultaneously (Olfat et al., 2017). Another report based on an AFM that was modified by MEMS demonstrated the use of a MEMS-based probe scanner. The device was composed of a stage (in place) that was equipped with electrostatic actuators and sensors for electrothermal displacement. For implementation, a microfabrication procedure was used, which was based on a reference silicon-on-insulator (Maroufi et al., 2019). Sun et al. (2020), used a MEMS-based multiprobe scanning probe microscope (SPM) that was developed to improve the efficiency of the images of target samples. The developed SPM was based on seven MEMS probes that had identical features. Each MEMS probe was integrated over the displacement sensor and actuator's *z*-axis (Sun et al., 2020).

7.6 ELECTROACTIVE POLYMER-BASED MICROELECTROMECHANICAL SYSTEMS AND ENERGY HARVESTING

Energy is an integral factor for the progress of any nation. Therefore, energy is considered to be one of the Sustainable Development Goals (SDGs) (Jaffri &Ahmad 2020, 2020a). The achievement of a cheap and clean energy resource would fulfill our energy needs and would protect future generations from insufficient energy. Fossil fuels are exhaustible energy resources; therefore, the development of novel energy resources highlighted by sustainability and SDGs is urgent. Therefore, a large number of materials have been synthesized and used and further research is ongoing to achieve the most suitable energy sources that have the capacity for replenishment through anthropogenic means. A number of researchers have reported the use of various types of EAPs in MEMS, which are aimed at development into energy systems (Sunithamani et al., 2020; Yang et al., 2017; Wang et al., 2018). For instance, a recent report used microturbines to extract wind energy, which was different to traditionally used batteries and other techniques at the microscale and provided the power to microsystems that operated without any batteries. In brief, the experiment designed, developed, and tested microturbines composed of 160 μm blade lengths. This type of the microturbine-based MEMS were developed using EAPs that is known as polysilicon surficial micromachining silicon technology (PolyMUMPs), which is known for the effective transformation of wind kinetic energy into torque to drive electric generators. Furthermore, PolyMUMPs are associated with the provision of direct power. This system could be a future candidature for commercialization, since compared with the traditionally employed batteries that cannot be scaled down effectively to a microscale, these MEMS-based polymeric systems are characterized by the potential to scale down in addition to the extension of the operational range of the appliances that run on conventional batteries (Visconti et al., 2020). There is increased demand to provide power for sensors and other types of sensing devices that are present at distant locations. Therefore, research is being carried out on harvesting vibrational energy as an effective substitute for batteries. This research into harvesting vibrational energies at the microscale has carried out over the last two decades. In particular, significant recognition has been given to the use of mechanical nonlinearity for the dynamic response of the structure that has piezoelectric power generation. This is considered to be one of the promising solutions for the problem of vibrations with lower frequency that are used in ecospheric applications. To combat these issues, a vibrational energy harvester based on a nonlinear MEMS-scale was developed and tested for efficiency (Derakhshani et al., 2018).

EAPs have emerged as a promising component of MEMS applications that are aimed at energy systems, which could be attributed to the favorable features of these EAPs for strain rate, rapid responsiveness, compliance, and higher mechanical flexibility, although they are manufactured through harder synthetic routes (Bashir & Rajendran, 2018; Guo et al., 2019). In a previous study carried out with poly(vinylidenefluoride-co-trifluoroethylene) (P(VDF-TrFE)), which are piezoelectric polymers, the focus was on harvesting the mechanical energy. The study highlighted the possible use of electrostrictive materials for energy harvesting since they are operational at lower voltages and have promising electromechanical characteristics (Liu et al., 2005). Therefore, studies carried out with electrostrictive materials produced interesting results for functionality in harvesting vibrational energy by generating 1.5 $\mu W/cm^3$ of the power density. The material specifically used was polyaniline (PANI), which has significant conduciveness articulated in a polyurethane (PU) matrix at a considerably lower percolation threshold (Jaaoh et al., 2016). Other research investigated the use of an electrostrictive terpolymer, for instance, P(VDF-TrFE-CTFE). Here, the power generation capacity was higher and produced 7.2 $\mu W/cm^3$ on the application of a 5 V/μm of polarization field (Cottinet et al., 2011).

Design modifications have been carried out for the incorporation of the EAPs into MEMS. For instance, in a recent report, researchers integrated electrostrictive nanocomposites inside the matrix of microcantilever resonators with an organic composition, which was designed to harvest the mechanical energy produced from environmental vibrations. Specifically, the dispersion of the nanocomposite material that had considerable strain sensitivity, for instance, reduced graphene oxide (rGO) was carried out inside polydimethylsiloxane (PDMS). This type of EAP embedded MEMS is a cost-effective and eco-friendly procedure that combined printing techniques and xurography (Nesser et al., 2018). In another study on the use of nanoscale materials in MEMS, ternary composites were synthesized for higher density high density polyethylene (HDPE)/boron nitride (BN)/CNTs via melt blending and hotter sheets were obtained. This studied signified the development of polymeric composites that possess super thermal conductivity (Che et al., 2018). The demonstration of the synergistic impacts of the use of CNTs and graphene nanoplatelets (GNPs) has been studied for energy harvesting via the construction of a hybrid filler inside PVDF composites inside a thermal conduction network (Xiao et al., 2016). In a recent report, PDMS-rGO/C hybrid membranes were used for self-charging supercapacitors (PSCS) that had flexible piezoelectric characteristics (Lu et al., 2020).

A significant amount of work has been carried out using different types of EAPs in MEMS for the harvesting of the different types of energies (Cao et al., 2019; He et al., 2021; Mariappan et al., 2019). In a report on the harvesting of electrochemical energy, a powder of carbyne and N-doped carbyne polysulfide was synthesized by a mechanochemical procedure (Liu et al., 2017). Similarly, the preparation of carbyne polysulfide was carried out by combining carbyne (i.e., dehydrochlorination of polyvinylidene chloride) and sulfur in elemental form using coheating. The final product was then used as a cathodic material for use is a lithium-sulfur (Li/S) battery (Duan et al., 2013). Furthermore, a carbyne-rich carbon film has been utilized as an electrode material in supercapacitor MEMS (Bettini et al., 2016). In a recent report, the energy storage capacity of the chemically synthesized carbyne was carried out for electrochemical energy. A carbon film enriched with carbyne was used as a MEMS for harvesting the energy, and it produced 72 nW/cm^2 energy density instantly in addition to exhibiting promising electromechanical stability (Krishnamoorthy et al., 2019). A polymeric composition-based composite matrix based on PVDF was shown to be a self-charging system that was designed by embedding PVDF/sodium niobate, which behaved as an energy harvester, and PVDF/rGO SSC behaved as an energy storage unit (Pazhamalai et al., 2020). Other advances have improved the functionality of EAP-based MEMS aimed at harvesting different types of energy (Sunithamani & Lakshmi, 2015; Deng et al., 2018; Mangaiyarkarasi et al., 2019).

7.7 CHALLENGES AND CONCLUSIONS

The promising characteristics associated with different types of EAPs means that they are suitable candidates for use in different types of MEMS, which are aimed at applications in different domains of life. In particular, they are appreciated for their remarkable actuation strains and comparatively elevated energy densities compared with other materials. In addition, they have other favorable features, such as lighter weight, noiseless, economic viability, and remarkable tolerance toward damage. The first interest in this field occurred in 2000 and, since then, a significant amount of research has been carried out by altering the types of EAPs through rigorous experiments and optimization. In addition to this, their use in different types of MEMS has been attempted from different perspectives. EAPs were finally commercialized in 2011. Since then, many market-based products have been released to ease human life in different ways.

The favorable features associated with the use of EAPs in MEMS has revolutionized human life. However, some of the challenges associated with these polymeric substances cannot be overlooked. First, the persistence of all polymeric substances including EAPs and their derivatives in the ecosphere pose a threat to the environment and the inhabitants from microbial species that reside inside hydrospheric bodies to the top predators in the food chain that are the residents of the lithosphere. Therefore, the complete commercialization, synthesis, and design of these polymeric substances that does not consider the environment and biotic health could be devastating. Although the world has benefited from EAPs; however, some ares have suffered because of their persistence, which has led to harming the precious biota in the oceans. In addition, EAPs can exist in the soil for millions of years. Therefore, these challenges need to be resolved by the development of more eco-friendly plastics, especially those that can be easily biodegraded by microbial consortia. In addition to this ecospheric perspective, there are some technical problems associated with the use of EAPs in MEMS. For instance, the electrical responsiveness of EAPs is remarkable; however, on a practical scale, this responsiveness can only be obtained by the application of higher operational voltages, especially if a larger response is required. Therefore, their practical implementation in different types of MEMS requires further research and development to obtain maximum benefit.

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