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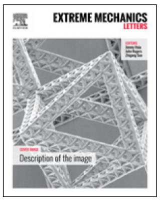

Recent progress in flexible and stretchable piezoelectric devices for mechanical energy harvesting, sensing and actuation

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ABSTRACT

Recent advances in materials science and mechanical engineering enable the realization of high performance piezoelectric systems in soft, flexible/stretchable formats, with unique opportunities for use in bio-integrated applications, from mechanical energy harvesting to sensing and actuation. This article highlights the essential mechanical to electrical conversion processes in devices and systems of this type, along with key considerations in their designs. Quantitative, experimentally validated mechanics models provide guidelines in the selection of optimized configurations and materials choices. The former focuses on thin geometries, neutral mechanical plane construction and controlled buckling. The latter includes options such as organic polymers, inorganic nanomaterials and various types of composites. Concluding sections summarize representative applications in biomedicine, ranging from devices for mechanical energy harvesting from natural motions of internal organs to sensors and actuators for the skin.

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1. Introduction

Recent developments in materials science, mechanics and manufacturing now enable the construction of piezoelectric devices in formats that are thin, flexible and, in some cases, mechanically stretchable. The results allow straightforward miniaturization of lightweight, compliant electromechanical systems suitable for mounting on nearly any type of surface, with performance characteristics that can match those of conventional, rigid devices. Such technologies leverage the ability of piezoelectric materials to interconvert mechanical and electrical forms of energy [1]. Electrical power can be generated from vibrations associated with operating machinery, movements of the human body and environmental sources, such as waves, wind, and others. Similarly, application of electric fields to piezoelectric materials yields well-controlled mechanical forces for actuation in robotics, biomedical devices and metrology tools. These dual functions in piezoelectrics, together with an increasingly broad set of material choices [2–12] and device designs, provide the foundations for numerous applications [13–15] of growing interest, particularly in wearable or implantable systems. Here, recent capabilities in rendering piezoelectric devices in thin, mechanically 'soft' formats are critically important. Specific examples include sustainable power sources in consumer electronics [13] and sensors for blood pressure measurements [16].

Various options can be considered for the use of piezoelectric materials in such contexts. Established strategies to deploy the highest performance, inorganic piezoelectric materials rely on methods adopted from the semiconductor industry. Planar, high modulus substrates serve as supports for two dimensional device architectures that follow from high temperature growth/deposition processes and lithographic patterning. The resultant technologies are mechanically hard and brittle, with limited capabilities for biocompatible integration with the soft surfaces of the human body. Advances in fabrication techniques [17–21] and device designs [8,20,22–25], together with the recent emergence of high performance inorganic piezoelectric materials that have the mechanical attributes of plastics, create opportunities in piezoelectric devices with form factors and characteristics that are dramatically different from those previously attainable. Research over the last several years demonstrates possibilities in highly efficient and/or sensitive piezoelectric energy harvesters/sensors/actuators, with particular relevance in biomedical applications [20,26–32] and wearable electronics [33–37]. Furthermore, the discovery of high-performance, lead-free piezoelectric materials suggests bio/eco-compatible options that will further enhance opportunities [38–43].

This review highlights these advances, with an emphasis on underlying concepts in mechanics and associated engineering strategies in device construction. A short initial section summarizes the dual operating mechanisms of piezoelectrics. The content that follows highlights key design strategies for piezoelectric devices that adopt unusual mechanical attributes (flexible, stretchable) by virtue of optimized mechanical configurations (membrane strain engineering, wavy/buckled configurations), material chemistries (organics, inorganics and composites) and/or geometrical features (nanostructures, thin films). Component examples and system level demonstrators illustrate these ideas in mechanical energy harvesters, sensors and actuators. The collective results suggest a promising future for the combined use of piezoelectric materials and unusual mechanics concepts across a range of fields, particularly those in biomedical engineering.

2. Discussion

2.1. Coupled mechanical and electrical behaviors in flexible piezoelectric systems

The ability of piezoelectric materials to generate electrical power from mechanical deformations, and vice versa, originates from direct and indirect piezoelectric effects, respectively [1]. Bulk samples or thin films of piezoelectric materials typically serve as active components in rigid devices, for systems that exploit such effects in mechanical energy harvesting, sensing and actuation. The operating principles and design guidelines in flexible devices are different from those of conventional, rigid technologies. The essential mechanics concepts are most easily examined in device architectures that combine thin piezoelectric films on sheets of plastic. One recently reported example involves nanoscale ribbons (∼200 nm thicknesses) of PZT (lead zirconate titanate) created on a silicon wafer and then released by undercut etching of a sacrificial interfacial layer to allow integration onto thin flexible polyimide (PI) substrates with thicknesses of 75 μm by transfer printing [20]. In this type of system, the electromechanical behavior can be described via an analytical model in which compression by a distance ΔL at the ends leads to a curved shape (Fig. 1(a)) with an out of plane displacement given by $w = A\left[1 + \cos(2\pi x_1/L)\right]/2$, where A is the amplitude and L is the initial length of the device. The bending moment (M) is related to the curvature $\left(w''\right)$ as