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INTRODUCTION

Consider the following: writing (and reading) ferroelectric memories without applying voltage;[1–3] piezoelectric-like transduction without piezoelectric materials;[4–6] bone remodeling[7] and mammalian hearing;[8,9] asymmetric fracture toughness;[10] and bulk photovoltaic effects in non-polar materials.[11] What do these apparently disparate phenomena have in common? Flexoelectricity.

Flexoelectricity is defined as a coupling between dielectric polarization and strain gradient. Although discovered in the late 1960s,[12–16] the field of flexoelectricity in solid materials lay relatively dormant and understudied for decades and studies on flexoelectricity mostly focused on liquid crystals.[17] This situation changed in the early 2000s, with a series of reports from Cross[18] showing that the flexoelectric coefficient in materials with high dielectric constants could have rather large flexoelectric coefficients — sufficiently large to make piezoelectric-like transducers with decent performance using non-piezoelectric materials.[18]

Piezoelectricity, the linear coupling between polarization and strain, is still the most direct, and generally stronger, form of electromechanical coupling, and entire journals have been dedicated to their study. Unfortunately, nature has not been very kind to us in terms of giving us many piezoelectric materials and, even worse, the best ones we know tend to contain toxic lead. By contrast, flexoelectricity couples electrical polarization to strain gradients through a fourth order material property tensor. Symmetry tells us that fourth order tensors are universal and thus all dielectrics possess flexoelectricity. This is the key advantage of flexoelectricity. All insulators (and, as recently discovered, also semiconductors), will electrically polarize if subjected to non-uniform deformation, and this is true also for biomaterials. The challenge of generating electricity from mechanical pressure thus changes from being a chemical one, focused on the synthesis of asymmetric materials, to a structural one, focused on the generation of non-centrosymmetric deformations.

The flexoelectric effect tends to be rather weak for most materials; in bulk ceramics, piezoelectricity wins over flexoelectricity in terms of the ability to convert mechanical stress into voltage. A further breakthrough, however, came with the realization that at the nanoscale strain, gradients can be much larger than at the macroscale, and, therefore, the importance of flexoelectricity grows with miniaturization.[19–24] With the coming of age of nanotechnology, the development of advanced materials characterization methods, and commensurate developments in theoretical and computational materials science, we have seen an explosion of literature on flexoelectricity. Flexoelectricity has now permeated into wide-ranging topics: smart material design,[25–28] sensors and actuators,[29–31] MEMS/NEMS and memory devices,[31,2,32] soft robotics,[33] energy harvesting,[34,11,35–37] 2D materials and domain walls,[6,38–40] and understanding of biological phenomena. Much of these developments have been summarized in review articles.[24,23,38]

Flexoelectricity started out as a proposed replacement of piezoelectricity, with disadvantages in terms of magnitude that were partially compensated by its universality and larger magnitude at small scales. This "poor man's piezoelectricity" status, however, is being reassessed. Not only can flexoelectricity be an adequate alternative (or, in some cases, the only alternative) to piezoelectricity but it can also be a complement to piezoelectricity (the two are not mutually exclusive), and, excitingly, it can generate novel physical responses that would NOT be possible by piezoelectricity alone, such as asymmetric mechanical responses, mechanical reading and writing of ferroelectric domains, or bending-induced bulk photovoltaic effects. By enabling new physical phenomena, flexoelectricity emerges from under the shadow of piezoelectricity as an exciting research subject in its own right; hence the title of this Editorial.

SUMMARY OF AREAS COVERED

The articles in the "Trends of Flexoelectricity" Special Topic Collection in *Journal of Applied Physics* reflect the diversity and the breadth of the emerging field. The collection covers a wide variety of topics ranging from the application of flexoelectricity in flexible electronics,[41] sensing,[42] energy harvesting,[43,44] semiconductors,[45,46] to actuators utilized in structural health monitoring.[47] We also see the prospects of using flexoelectricity for mechanical reading of memory devices[3] and topics underpinning the theory of flexoelectricity.[48,49] An extensive and detailed overview of the mathematical and computational modeling of flexoelectricity is presented in Ref. 50.

Possible approaches of enhancing flexoelectric properties are discussed in polymers,[51,52,44,53] ceramics,[54–57] ferroelectrics,[58–62] and two-dimensional (2D) materials.[63,62] There is also an intriguing proposal regarding flexoelectricity in metals.[42] The role of surfaces on flexoelectricity is elaborated in Ref. 64 and the origin of flexoelectricity from a quantum mechanics point of view is discussed in Ref. 65.

CONCLUDING REMARKS

The "Trends of Flexoelectricity" Special Topic illustrates the emancipation of flexoelectricity, with articles covering many of the new possibilities enabled by this phenomenon. Current research topics reflect the diversity in this field and range from theoretical developments, novel devices that exploit flexoelectricity, novel physical phenomena, and investigations in soft matter and biology. It is a timely endeavor to collect advances in the finally flourishing field of flexoelectricity and its emergence from the shadows.

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