

# Nanotechnology Application to Optimize Piezoelectric Metamaterials for Highly Sensitive Transducers and Energy Harvesting

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iezoelectric materials are defined as those that produce a linear electrical output in response to a mechanical input and vice versa. The most common piezoelectric materials are crystals or ceramics, both of which are thought to operate by straining of dipole

moments. Using this formal definition of piezoelectricity, electret materials are a class of piezoelectric elements.

Most microphones in the world today are electret microphones. Modern electrets were first described and demonstrated by Sessler and West.<sup>1</sup> Electret materials are monopole dielectrics capable of permanently retaining a charge. They typically are used as one plate in a parallel plate capacitor with the polarization replacing the battery normally found in condenser transducers.

Recently, there has been some interesting work on piezoelectricity in polypropylene foam, also called cellular polypropylene (PP), or voided low-density polypropylene (LDPP). The new material consists of air bubbles introduced into polypropylene. This sheet of voided material is then biaxially stretched to elongate the voids (Fig. 1). After this material is stretched, a strong electric field is applied via a corona that exceeds the dielectric breakdown strength of the air inside the voids. The charges are forced to the polymer frame by the electric field, and the temperature is cooled, thus creating permanent electric charges along these boundaries. Because the sides of the voids have opposite charges, the charged voids become synthetic macroscopic dipoles. When an external force is applied to

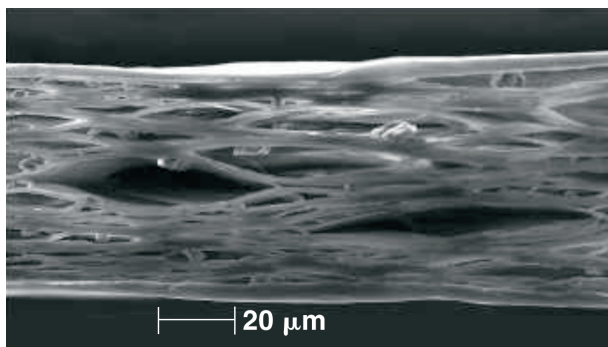


Figure 1. Cross-section of voided LDPP.

this material, the voids are narrowed, causing stronger dipole strength, and produce a compensating charge on the electrodes at the extreme boundaries of the material. It also is believed that there is an additional redistribution of the charges along the voids as well. This hypothesis was put forth to explain measurements of the material's piezoelectric constant and stiffness (Fig. 2). Busch-Vishniac, West, and Wallace<sup>2</sup> applied these polymer transducer materials in an array of designs and other applications.

Polymer piezoelectric materials offer lower density and more flexibility than piezoelectric ceramics

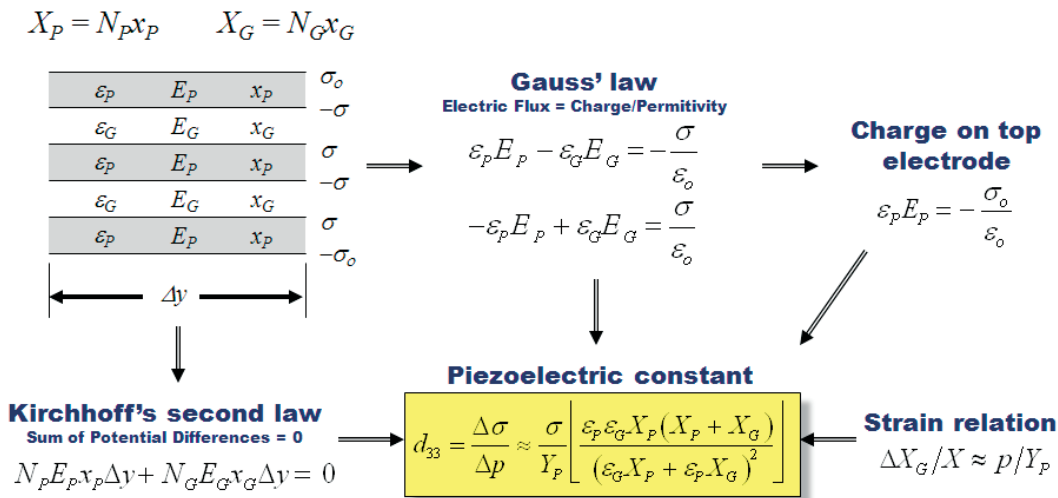


Figure 2. Analytic model of the voided polymer.

for applications where rugged and lightweight acoustic sensors are required. Constraints are imposed by material stiffness and dielectric constants. We derive a generalized closed-form solution for optimizing charged foamed polymers. Optimized solutions are reached in the limits of very large and small void fraction and permittivity ratios. The permittivity ratio is the ratio of the dielectric constants of the polymer and the material that fills the voids. Demonstrations indicate that, in the oblique asymptote, the optimized void fraction becomes equivalent to the permittivity ratio (Fig. 3).

Metamaterials have been developed to exhibit a negative effective permittivity through the formation of a crystal lattice with nanotechnology. Therefore, the denominator of the piezoelectric constant may become nearly zero when a carefully designed lattice structure is introduced in the piezoelectric polymer. A loss mechanism may impose an upper constraint, but the resulting sensitivity may be high enough for energy harvesting by sensing ambient noise.

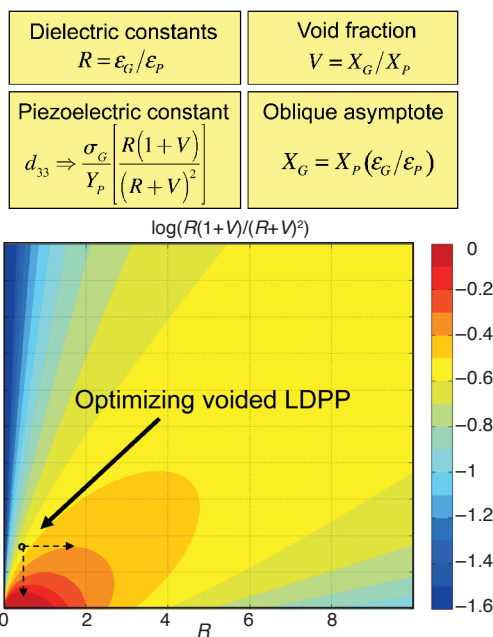


Figure 3. Optimized LDPP is possible if the void fraction is decreased [thin voids (via stretching film)] and the permittivity ratio is increased (larger gas dielectric constant).

For further information on the work reported here, see the references below or contact [juan.arvelo@jhuapl.edu](mailto:juan.arvelo@jhuapl.edu).

- <sup>1</sup>Sessler, G. M., and West, J. E., "Self-Biased Condenser Microphone with High Capacitance," *J. Acoust. Soc. Am.* 34, 1787–1788 (1962).
- <sup>2</sup>Busch-Vishniac, I. J., West, J. E., and Wallace, R. L., "A New Approach to Transducer Design Applied to a Foil Electret Acoustic Antenna," *J. Acoust. Soc. Am.* 76, 1609–1616 (1984).
- <sup>3</sup>Paajanen, M., Wegener, M., and Gerhard-Mulhaupt, R., "Understanding the Role of the Gas in the Voids During Corona Charging of Cellular Electret Films—A Way to Enhance Their Piezoelectricity," *J. Phys. D Appl. Phys.* 34, 2482–2488 (2001).
- <sup>4</sup>Shelby, R. A., Smith, D. R., and Schultz, S., "Experimental Verification of a Negative Index of Refraction," *Science* 292, 77–79 (2001).
- <sup>5</sup>Fang, N., Lee, H., Sun, C., and Zhang, X., "Sub-Diffraction-Limited Optical Imaging with a Silver Superlens," *Science* 308, 534–537 (2005).
- <sup>6</sup>Arvelo, J. I., Biermann, P., Farrar, D., Busch-Vishniac, I. J., West, J. E., and Yu, M., "Polymer Piezoelectric Materials for Lightweight, Rugged, and Inexpensive Transducers," U.S. Navy Workshop on Acoustic Transduction Materials and Devices, State College, PA (9–11 May 2006).
- <sup>7</sup>Arvelo, J. I., "Optimizing Voided Piezoelectric Polymers for Acoustic Sensors," in *Proceedings of the National Society of Black Physicists*, H. M. Oluseyi (ed.), American Institute of Physics, CP1140, pp. 148–155 (2008).
- <sup>8</sup>Zhang, S., Yin, L., and Fang, N., "Focusing Ultrasound with an Acoustic Metamaterial Network," *Phys. Rev. Lett.* 102, 194301 (2009).