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13. ABSTRACT *(Maximum 200 words)*

Electrostriction is the elastic deformation of a material caused by an electric field. Achievable deformations can be much larger than those of piezoelectric polymers and inorganic materials. Our research has focused on understanding electrostriction in thin polymer films — determining the underlying mechanism or mechanisms and the properties that control observed behavior. We have shown that experimental observations can be described as elastic deformation due to electrostatic forces. Critical to this conclusion has been correctly identifying the dielectric properties that govern electrostriction, and developing techniques to measure them. We have also developed a microscopic model for electrostriction of amorphous, polarizable solids. Model predictions agree very well with measured electrostriction parameters for a variety of polymer films.

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FINAL REPORT

"Electrostrictive Mechanisms in Polyurethane and Other Polymer Films"

by

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Electrostrictive Mechanisms in Polyurethane and Other Polymer Films

FINAL REPORT

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1 Research Summary

Electrostriction is the elastic deformation of a material caused by an electric field. Achievable deformations can be much larger than those of piezoelectric polymers and inorganic materials. Our research has focused on understanding electrostriction in thin polymer films — determining the underlying mechanism or mechanisms and the properties that control observed behavior.

We have shown that experimental observations can be described as elastic deformation due to electrostatic forces. Critical to this conclusion has been correctly identifying the dielectric properties that govern the electrostatic stress. and developing techniques to measure them.

We developed a linear theory for simple materials which introduces five material parameters governing electrostriction: the relative dielectric constant, ϵ^0, two derivatives of the dielectric tensor with respect to strain components. a_1 and a_2, Young's modulus, E_y, and Poisson's ratio, ν. Knowledge of these parameters and appropriate boundary conditions allow one to predict field-induced deformations.

Of these parameters, a_1 and a_2 had not previously been measured for systems of interest. We have developed several techniques to measure these parameters, based on the simultaneous measurement of deformation and permittivity in thin polymer films. One experimental apparatus, shown schematically in Figure (1), consists of a

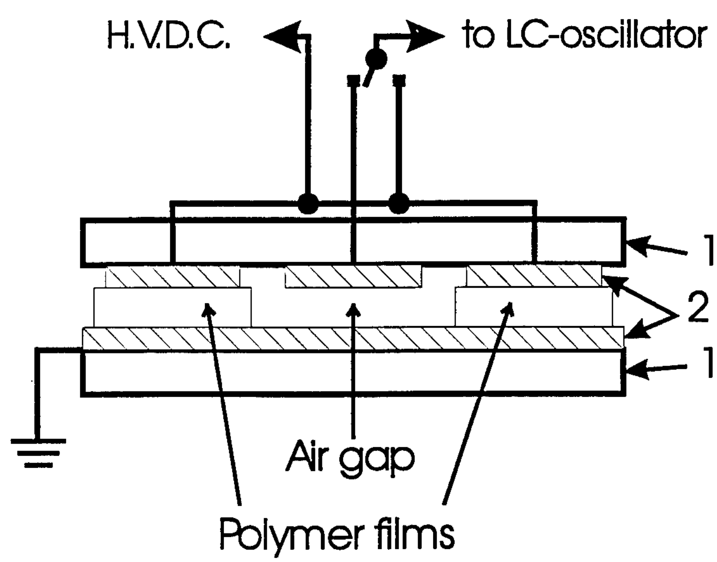

Figure 1: Schematic diagram of the polymer-air-polymer capacitor assembly. The electrodes are glued to the glass slides. The two polymer films, obtained by cutting a single film in half, act as a spacer for center air-gap capacitor.

polymer-film capacitor integrated with an air-gap capacitor. Deformation induced by an applied field is determined from the change in capacitance of the air-gap capacitor, while the electrostriction parameters are determined by the change in capacitance of the polymer-film capacitor.

We have also developed a microscopic model for electrostriction of amorphous, polarizable solids. The electrostriction parameters are predicted to be functions of only the dielectric constant of the nondeformed solid, ϵ^0,

$$a_1 = -\frac{2}{5}(\epsilon^0 - 1)^2, \tag{1}$$

$$a_2 = -\frac{1}{3}(\epsilon^0 - 1)(\epsilon^0 + 2) + \frac{2}{15}(\epsilon^0 - 1)^2. \tag{2}$$

The measured parameters agree very well with this microscopic model, as illustrated in Figure (2). The electro-

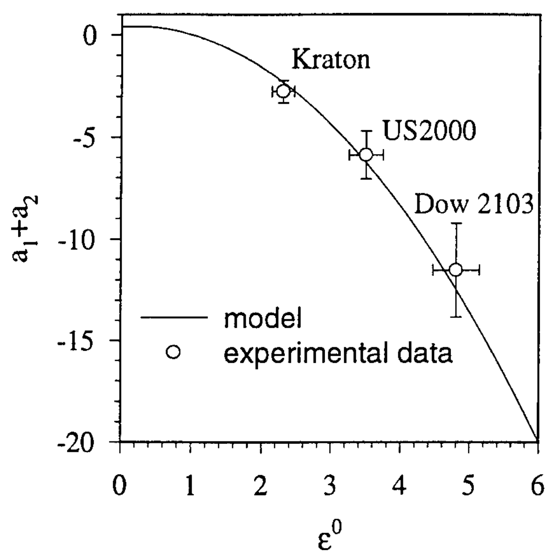

Figure 2: Sum of electrostriction coefficients, $a_1 + a_2$, as a function of the polymer dielectric constant. The solid curve is the prediction from the microscopic model, and the symbols are experimental data for a Kraton (SIS, Shell) and two polyurethane elastomeric films.

static stress driving the deformation contains two contributions—the Coulombic attraction between the bounding electrodes, and "pure electrostriction" which is linear in the quantity $-(a_1 + a_2)$. The measured parameter values indicate that the deformation arising from pure electrostriction is $> 10\times$ that arising from Coulombic attraction for polyurethane elastomers. Thus, understanding the relationships between a_1, a_2 and material chemistry is crucial for future development of electrostrictive materials.

2 Personnel

Name	Classification
Eric Ding (Wisc.)	Graduate Student
Yuri Shkel (Wisc.)	Postdoc
Kristen Hartley (Wisc.)	Undergraduate
Alastair Steel (Wisc.)	Undergraduate
Phil Jackson (Del.)	Graduate Student
Saumitra Bhargava (Del.)	Graduate Student
George A. Cragg (Del.)	Undergraduate
Laura L. Zeafla (Del.)	Undergraduate

3 Publications and Presentations

1. "Electrostriction of Polarizable Materials. Comparison of Models with Experimental Data," Y. M. Shkel and D. J. Klingenberg, *J. Appl. Phys.*, submitted (1997).

   The significance of this publication is that we relate dielectric properties that govern electrostrictive stresses to other, more common properties, namely the dielectric constant of nondeformed medium. We also show that a simple microscopic model agrees very well with experimental data.

2. "Material Parameters for Electrostriction," Y. M. Shkel and D. J. Klingenberg, *J. Appl. Phys.*, **80**, 4566–4572 (1996).

   In this paper, we outline a linear continuum theory for electrostriction, whereby deformation of an elastic medium in an electric field is caused by electrostatic stresses. The stress magnitudes are determined by two material parameters. We describe an experimental technique for measuring these parameters, and present the first experimental data for these parameters for polyurethane elastomers.

3. "Electrostatics at Rough Interfaces," D. J. Klingenberg and S. L. Cooper, *J. Electrostatics*, **35**, 339–348 (1995).

   This paper describes how interfacial roughness can alter the electrostatic field and the resulting stresses at interfaces. Interfacial roughness can have a large impact on force magnitudes, but determining this contribution requires measuring roughness on all length scales.

4. "Dielectric Parameters for Electrostatic Forces in Solids," Y. M. Shkel and D. J. Klingenberg, American Physical Society Meeting, Kansas City, MO, Mar. 17-21, 1997.

5. "Material Parameters for Polymer Electrostriction," Y. M. Shkel and D. J. Klingenberg, Society of Rheology Meeting, Galveston, TX, Feb. 16-20, 1997.

6. "Measurement of Electrostrictive Properties of Polymers," Y. M. Shkel, E. R. Ding, K. L. Hartley, A. G. Steel, and D. J. Klingenberg, American Institute of Chemical Engineers Annual Meeting, Chicago, IL, Nov. 11-15, 1996.

7. "Electrostriction in Polymer Films," Department of Chemical Engineering, University of Michigan, Ann Arbor, September 19, 1996.

8. "Overview of Research Projects," presented to S. C. Johnson Wax, Madison, WI, Jan. 23, 1996.

9. "Electrostrictive Polyurethane Films," D. J. Klingenberg, ONR Program Review, Rutgers University, NJ, May, 1995.

10. "Electrostatics at Rough Surfaces," D. J. Klingenberg and S. L. Cooper, ONR Workshop on Transducer Materials and Transducers, State College, PA, April, 1995.

11. "Electrostriction of Polyurethane Films," D. J. Klingenberg, S. L. Cooper, and M. J. Winokur, ONR Transducers and Transducer Materials Workshop, University Park, PA, April 10-13, 1994.

12. "Maxwell Stress Calculations in Heterogeneous Materials," Philip L. Jackson, APS Meeting, San Jose, CA March 23, 1995.

13. "Maxwell Stresses in Heterogeneous Materials," Philip L. Jackson, ONR Program Review, Rutgers, May 17, 1995.

14. "Electrically Induced Stress and Strain in Block Copolymers," Philip L. Jackson, APS Meeting, Pittsburgh, PA, March 24, 1994.

4 Interactions

We have had one significant scientific interaction with Dr. Ed Balizer from the Naval Surface Warfare Center in Bethesda, MD. The objective of this interaction was to use our experimental techniques to measure electrostriction parameters of films prepared by Dr. Balizer. The two main conclusions from this interactions are (1) that different polyurethane elastomers appear to have similar values for the electrostriction parameters a_1 and a_2, and (2) that field-induced deformations are also sensitive to differences in the mechanical properties of the films (Young's modulus and Poisson ratio).