

The evolution of the dielectric constant in various polymers subjected to uniaxial stretch



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ABSTRACT

Dielectric elastomers (DEs) are materials that deform in response to electric excitation, an attractive feature that deems them suitable for various actuation-based devices. The growing interest in these materials leads to many intriguing questions regarding the origin of the electro-mechanical coupling and its relation to the dielectric constant. This work examines the coupled response of four dielectrics: VHB 4910, Polytetrafluoroethylene (PTFE), High-density polyethylene (HDPE) and Low-density polyethylene (LDPE). We demonstrate the substantial dependence of their dielectric constants on the deformations. These findings are compared to a recent statistical-mechanics based model which takes into account the structure of the dielectric. A good agreement is found between the theoretical model and the experimental measurements.

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1. Introduction

Dielectric elastomers (DEs) are materials capable of undergoing large deformations as a result of electrostatic excitation [1,2]. Due to attractive properties such as light weight, fast response and flexibility, these materials hold promise for a wide range of applications. Roughly speaking, the actuation is due to the attraction of two oppositely charged flexible electrodes that are adhered to a thin DE layer. The electrical forces compress the DE layer and, due to the Poisson's effect, the layer expands in the transverse plane. The recent increased interest in these materials raised a few questions concerning the coupling between their electrical and mechanical responses. This work is dedicated to an experimental study of some aspects of this intriguing electro-mechanical coupling.

Nowadays, quite a few actuation-based devices are utilizing VHB 4905/10, which is a commercially available acrylic elastomer produced by 3M [3–6]. The electrostrictive properties of this DE have been intensively investigated over the past 15 years [7–11]. Kofod et al. [12] and Di Lillo et al. [11] measured the change in permittivity under biaxial extension and found that the variations are negligible. However, several works contradicted their conclusion and measured substantial variations of the permittivity with deformation. The measurements of Choi et al. [8] revealed an initial

relative permittivity $\epsilon_r = 4.4$. Subjected to an area stretch of 9, this value dropped to $\epsilon_r = 2.25$. Wissler and Mazza [9] measured the values $\epsilon_r = 4.68$ and $\epsilon_r = 2.62$ at the reference and under an area stretch of 25, respectively. McKay et al. [10] examined the influence of different electrodes on the variations in the relative permittivity of VHB 4910. Using Nyogel electrodes, the measured relative permittivities were $\epsilon_r = 4.59$ and $\epsilon_r = 3.75$ before and after a biaxial stretch of 16. Qiang et al. [13] also measured a decrease under a planar stretch of 16. Specifically, the relative permittivity dropped from $\epsilon_r = 4.36$ to $\epsilon_r = 2.44$.

Characterizations of the electrostrictive properties of silicone based polymers [14–16] and natural rubber ZruElast A1040 from Zrunek rubber technology [17] were also carried out. These experiments demonstrated the expected quadratic dependency of the mechanical deformation on the electric field. Interestingly, these experiments also revealed that the dielectric constant depends on the deformation in the silicone based polymers and is independent of the deformation in the natural rubber.

Moreover, Zhao and Suo [18] realized the possible impact of the deformation on the polarization of elastomers and developed a systematic model for implementing this dependency on the basis of experimental measurements. The model was used to determine the coefficient of electrostriction of VHB 4910 that corresponds to a two fold decrease of the dielectric constant. These works suggest that the premise that VHB 4910 does not exhibit electrostriction is disputable.

The aim of this work is to investigate the effect of the mechanical deformation on the electrostatic response of various polymers.

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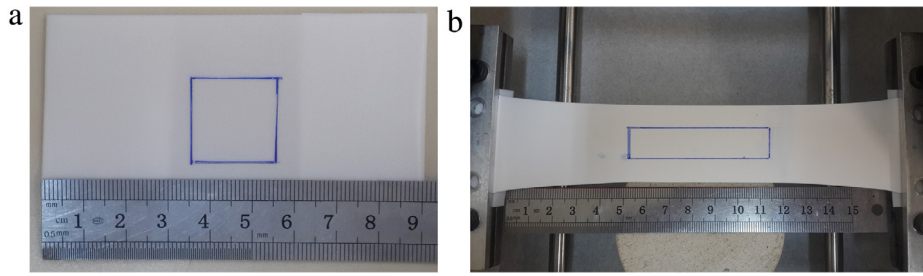


Fig. 1. A PTFE sample (a) before and (b) after a 200% uniaxial deformation.

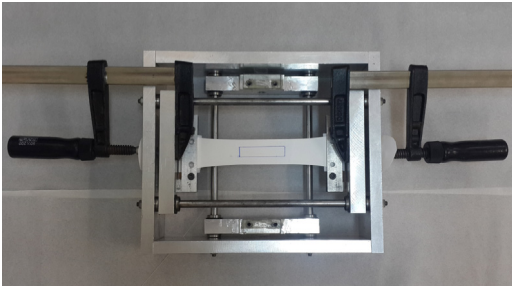


Fig. 2. A self-constructed stretching apparatus used to uniaxially stretch the polymer samples.

To this end we measured the variations of the dielectric constant of four polymers at different levels of uniaxial stretches:

1. VHB 4910 (by 3M).
2. Polytetrafluoroethylene (PTFE), also known as Teflon (by Fluorseals).
3. High-density polyethylene (HDPE) (by Polimeri Europa).
4. Low-density polyethylene (LDPE) (by Carmel Olefins).

These materials are of interest due to their flexibility, light-weight and ubiquitous use in current applications.

The experimental findings are compared to the predictions of the novel statistical mechanics based model of Cohen et al. [19], where the microscopic model parameters are adjusted to the experimental findings.

2. Experimental set-up

Ten rectangular samples of each of the four chosen polymers were cut out of the provided films and 20×20 [mm] squares were drawn on their surfaces, as shown in Fig. (1a). The samples were then stretched (Fig. 1b) using a self constructed stretching apparatus comprised of two movable grippers. The motion of the grippers is controlled with the aid of two auxiliary clamps that generate the required tension in the sample, as shown in Fig. 2.

To measure the permittivity of the deformed samples, we employed the parallel plate capacitor set-up using the C-shaped clamp shown in Fig. 3. The ends of the C-clamp are mounted with two insulating perspex disks and two circular copper plates with a 30 [mm] diameter (see Fig. 3). The experimental procedure was as follows. The sample was firmly attached to the movable grippers with the drawn square at the center between the grippers (see Fig. 4). With the aid of the tension screws (of the auxiliary clamps) the sample was slightly tensed. The thickness of the sample was measured at a few points with a micrometer to ensure the homogeneity of the deformation. Next, the C-clamp was gently attached to the sample such that the copper cheeks are centered around the

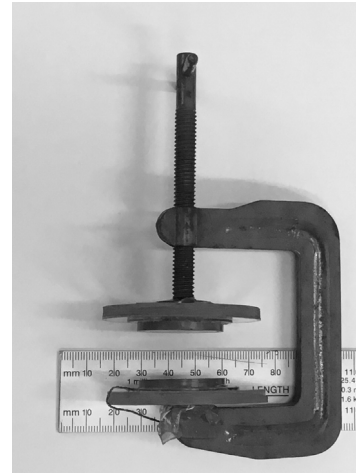


Fig. 3. The C-clamp used as a parallel plate capacitor. The tightening screw is tightened such that the two copper disks sandwich the sample.

drawn square (see Fig. 4). The capacitance C of the film trapped between the copper cheeks was measured with an Agilent U1701A capacitance meter. Subsequently, the C-clamp was removed and, with the aid of the tensile screws, the sample was stretched to the first stretch ratio at which we measured the capacitance once again. This was done with the C-clamp as described in the referential measurement. The sample thickness was again measured at several points. This process was repeated until we completed 4 to 5 measurements for each sample. We observe in Fig. 2 two large clamps that are horizontally attached to the grippers. These auxiliary clamps were used to reinforce the tension screws during the experiments.

We point out that to ensure a proper measurement of the capacitance, we confirmed that the entire area of the copper cheeks (of the C-clamp) was in contact with the polymer sample. It is also noted that due to the advantageous structure of this device, the two circular copper plates are concentric and parallel.

The relative permittivity of each sample was determined via

$$\varepsilon_r = \frac{C d}{\varepsilon_0 A}, \quad (1)$$

where $\varepsilon_0 = 8.85 \cdot 10^{-12}$ [F/m] is the permittivity of vacuum, A is the area of the copper plates, and d is the thickness of the sample.

To accurately compute the relative permittivity, the incompressibility assumption was not used. Rather, the thickness of the prestretched sample was measured at different locations with a micrometer. The volume of the stretched sample was then determined from the measured thickness and area of the drawn quadrangle (see Fig. 1). We point out that all the experiments were conducted at room temperature to avoid thermal effects. Furthermore, the polymers were quasi-statically stretched to avoid the effects of strain-rate.

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