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Improving the electromechanical performance of dielectric elastomers using silicone rubber and dopamine coated barium titanate

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ABSTRACT

In this work, a new soft dielectric elastomer (DE) was fabricated from dopamine coated barium titanate particles and silicone rubber (SR). The results showed that the barium titanate ($BaTiO_3$, BT) was coated by dopamine and the coated particles were highly compatible with SR. In order to achieve a maximum voltage-induced deformation, the minimum secant moduli of DEs were obtained in experimentation at a stretch ratio of approximately 1.6 by applying equi-biaxial tensile strain using the bubble inflation method. Additionally, it was found that the addition of DP-BT into SR led to an increased dielectric constant and decreased dielectric loss tangent for the matrix by comparison with SR/BT composites. Furthermore, the electromechanical properties of the SR/DP-BT composites were greatly improved in terms of voltage-induced deformation (s_a), electromechanical energy density (e) and coupling efficiency (K^2). A maximum actuated area strain of approximately 78%, which was 30% larger than that of the SR/BT composites, was achieved for the sample having a DP-BT content of 20 wt.%. This strain corresponded to a low dielectric strength of around 53 V/μm, the composite exhibited a maximum energy density of 0.07 MJ/m^3 and coupling efficiency of 0.68.

1. Introduction

DEs belong to a family of smart materials, having compliant electrodes sprayed on their surfaces, that can respond to electrical stimulus by changing their shapes [1]. The effective compressive stress (σ_v) is created by applying a high voltage between the top and bottom surfaces of the DE and complies with Eq. (1).

$$\sigma_V = \varepsilon' \varepsilon_0 (\phi/z)^2 = \varepsilon' \varepsilon_0 \varphi^2 \quad (1)$$

where ε' is the relative permittivity or the dielectric constant of the DE material, ε_0 is the permittivity of the free space (8.85×10^{-12} F/m), and φ is the electric field which equals the applied high voltage (Φ) divided by the thickness of the DE (z).

To date, both VHB acrylics [2,3] and SR [4,5] have been regarded as good candidates for DEs because they have provided the best characteristics when actuated. Hence, they have a large number of biomimicry applications such as refreshable braille devices [6], hand rehabilitation splints [7], microfluidic devices [8,9] and wearable tactile interfaces [10,11]. However, SR has begun to attract more interest as the DE matrix, because it does not have certain intrinsic limitations possessed by VHB acrylics such as low thermal stability, widely varying modulus with temperature change and high viscoelasticity [12,13]. Furthermore, SR has superior biocompatibility to most carbon based polymers [14]. It has been proven that voltage-actuated strain can be increased by increasing the dielectric constant of a composite while decreasing the elastic modulus (E) of the DE [15,16]. The relation between dielectric constant and elastic modulus is described by Eq. (2), when a constant elastic modulus exists for small strains (<20%) and free boundaries are assumed [1,17].

$$s_z = \varepsilon' \varepsilon_0 \varphi^2 / E \quad (2)$$

Further, in order to investigate the relation between voltage and strain, numerous hyperelastic strain energy functions, such as the Neo-Hooken [18], Mooney-Rivlin [19], Ogden [20], Yeoh [21] and Gent [22,23] models have been widely used to mathematically simulate DE behaviour. As the volume of a DE is assumed to be constant (Poisson's ratio $\nu \approx 0.5$) irrespective of whether a high voltage is applied or not, the area strain (s_a) has a simple relationship with the thickness strain as given by Eq. (3).

$$s_a = 1/(1-|s_z|)-1 \quad (3)$$

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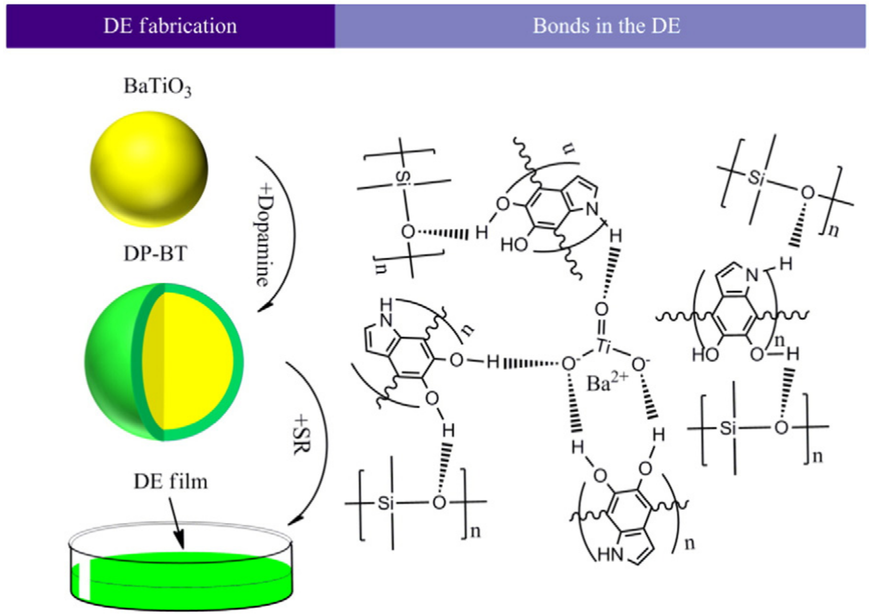

Fig. 1. Schematic of the fabrication of SR and dopamine coated BT composites.

Therefore, high dielectric fillers with soft SR matrices offer the possibility of achieving large voltage-induced deformations. It has been reported that SR containing BT particles can produce a large area strain of around 30% [24,25] under a high voltage. Nevertheless, BT has a high dielectric loss tangent and poor compatibility with SR and these disadvantages prevent its further application in soft actuators. To negate this limitation, researchers focused on doping to modify BT [26,27]. Dopamine, which can interact strongly with metal oxides by forming hydrogen bonds [4], was considered an effective chemical with which to modify the surface of BT particles [26,28]. Moreover, both the aromatic group and the hydrogen bond are of high polarizability [29, 30] which is propitious to the enhancement of the dielectric constant.

The key to develop large strains in DE composites has been shown to be the application of pre-stretch [31–33]. Additionally, pre-stretch can reduce viscoelastic effects, thus improving mechanical efficiency and response time accompanied by a marginal decrease in the dielectric constant [34]. In elastomers, the mobility of molecular chains can be restricted by intermolecular interactions [35]. However, the intermolecular interactions can be reduced by stretching and this change is characterized by a reduction in elastic modulus. It was reported that a low

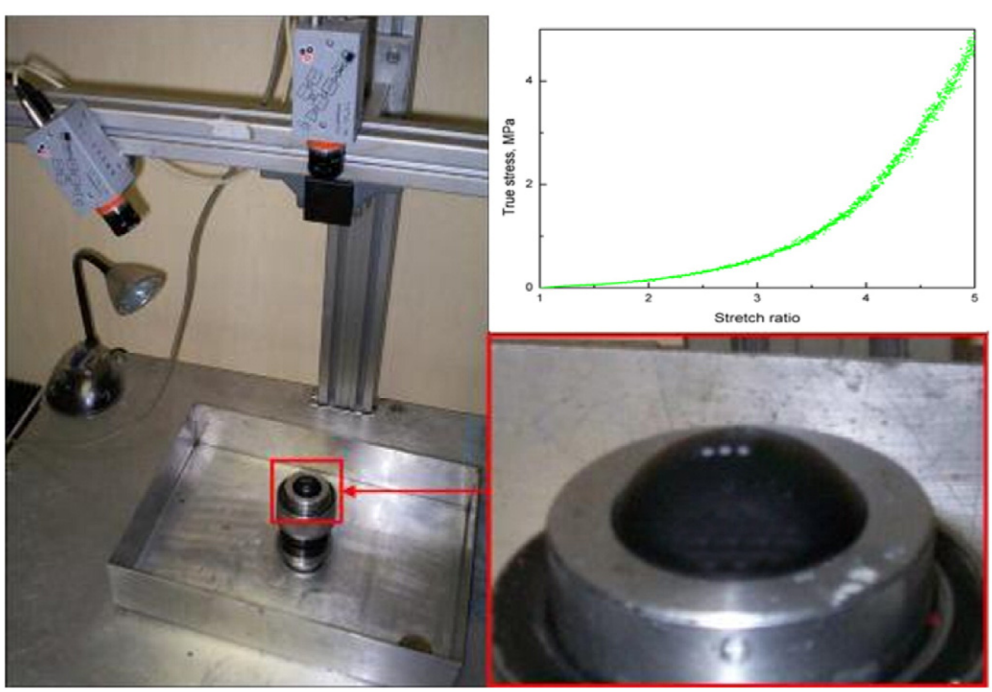

Fig. 2. A sample under test in the bubble inflation test system.