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<td><strong>Author(s)</strong></td>
<td>La, Thanh-Giang; Lau, Gih Keong</td>
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Very high dielectric strength for dielectric elastomer actuators in liquid dielectric immersion

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Very high dielectric strength for dielectric elastomer actuators in liquid dielectric immersion

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This letter reported that a dielectric elastomer actuator (3M VHB), which is immersed in a liquid dielectric bath, is enhanced tremendously in dielectric strength up to 800 MV/m, as compared to 450 MV/m for the actuator operated in air. The bath consists of silicone oil (Dow Corning Fluid 200 50cSt), which is 6.5 times more thermally conductive than air, and it is found able to maintain the actuator at a stable temperature. As a result, the oil-immersed dielectric elastomer actuator is prevented from local thermal runaway, which causes loss of electrical insulation, and consequently avoids the damage by electromechanical instability. © 2013 AIP Publishing LLC.

Dielectric elastomer actuators (DEAs) can produce large deformation under Maxwell stress, which is proportional to the square of the electric field. As a soft capacitor, DEA is liable to breakdown that limits the ultimate actuation strain. Dielectric elastomers without pre-stretch usually have a low dielectric strength, for example, 34 MV/m for the no-strained acrylic foam tape (VHB 4905). Pre-stretch was shown to help VHB dielectric elastomer increase substantially the dielectric strength to 300-400 MV/m. Such enhancement is attributed to air void suppression and dielectric stiffening of the pre-stretched dielectric elastomer that avoids premature failure. Yet, the pre-stretched DEAs are still prone to failure by electromechanical or pull-in instability. When activated by voltages.

According to Stark-Garton theory, softened polymer at elevated temperature may fail by mechanical collapse when stressed electrically. The theory predicts a critical dielectric strength of \( E_c = \sqrt{\frac{Y}{\varepsilon_r \varepsilon_0}} \), in which \( Y \) is the Young’s modulus and \( \varepsilon_r \) is the relative permittivity of the electrically stressed polymer slab, and \( \varepsilon_0 \) is the air permittivity. The value for critical strength is calculated to be 275 MV/m for VHB 4905 foam tape by using the properties: \( Y = 1.8 \, \text{MPa} \) and \( \varepsilon_r = 2.68 \), given by the 3 M datasheet (see supplementary material). If the pull-in instability can be avoided, DEA is believed to be able to sustain an even higher dielectric strength for producing higher actuation stress. As silicone oil is 6.5 times more thermally conductive than air (with a thermal conductivity of 0.024 Wm⁻¹K⁻¹), it can convect more heat than air following the law of heat transfer. 

The immersion is in a bath of silicone oil (Dow Corning Fluid 200 50cSt), which has a boiling point of 65 °C, a thermal conductivity of 0.155 Wm⁻¹K⁻¹, and a specific heat of 1473 Jkg⁻¹K⁻¹ according to the datasheet (see supplementary material). As silicone oil is 6.5 times more thermally conductive than air (with a thermal conductivity of 0.024 Wm⁻¹K⁻¹), it can convect more heat than air following the law of heat transfer. The immersion is expected to prevent partially discharge breakdown because the silicone oil is reported to have dielectric strength of 400 V/mil (Ref. 18) (or 15.7 MV/m) and a dielectric constant ranging from 2.72 to 2.75, which are greater than 3 MV/m dielectric strength at one atmospheric pressure and a unit dielectric constant of air, respectively.

In this work, samples of DEA were prepared from a 200% bi-axially pre-stretched VHB 4905 foam tape, which has a thickness of 55.0 μm as measured after pre-stretch. Borders of the pre-stretched dielectric film were supported on a square acrylic frame (60 mm × 60 mm). Graphite powders (TIMREX KS6) were applied by brushing on the pre-stretched dielectric film to form a pair of 15 mm diameter circular compliant electrodes, which has a surface resistivity measured to be 600kΩ/□. During actuation test, DEA samples were completely immersed in the silicone oil bath as shown in Fig. 1. For comparison, samples of the same prepared DEAs were also tested in the usual condition, i.e., in air.

The DEA was activated using a high voltage supply (Spellman’s CZE1000R). When the DEA is activated at an electric field \( E' \), its electrodes expand from an initial area \( A_0 \) to the activated area \( A' \) and the dielectric film reduces from an initial pre-stretched thickness \( t_{pre} \) to an activated thickness...
t'. The areal strain is measured as $s_A = A'/A_0 - 1$, while the activated thickness is calculated as $t' = t_{pre}/(s_A + 1)$, on the assumption that the dielectric film is incompressible. In turn, the true electric field is calculated as $E' = V/t'$, according to Ref. 7. As the voltage was ramped up during DEA activation, leakage current was monitored continuously using a digital multimeter (Agilent 34410A) and a NI data logger while photographs for the activated DEA were captured using a digital camera.

Electromechanical or pull-in instability of DEAs is often accompanied by thinning down in thickness and severe wrinkles\textsuperscript{8,9,14,24,25} that indicate the loss of tension in the prestretched dielectric film. Such pull-in instability was also observed in our test of DEA samples. The DEA sample, which was tested in air, nearly failed at 11 kV and it exhibited a distorted electrode shape and irregular-pitch wrinkles near the defective spot as shown in Fig. 2(a) (image\textsuperscript{1}). On the other hand, the DEA sample, which was tested in the liquid dielectric bath, did not fail at 11 kV while mild wrinkles appeared on the dielectric film (see image \textsuperscript{2} in Fig. 2(b)). Interestingly, as driving voltage went beyond 11 kV, the oil-immersed DEA continued to work even though the wrinkles turned from mild (see image \textsuperscript{3} at 15 kV) to severe (see the image \textsuperscript{4} at 18 kV).

Figure 2(b) showed actuation of the DEAs as a function of the applied electric field. A similar trend of actuation was observed for both samples tested in either air or oil immersion. The areal actuation strains increase at a decreasing rate with respect to the applied electric field. The areal actuation strains are almost independent of the increasing electric field above 400 MV/m because the active dielectric film, which was pre-stretched, lost tension and buckled into wrinkles that were accompanied primarily by thickness reduction but little areal expansion. Similar observation on how wrinkles affect the areal actuation of dielectric elastomer was previously reported.

![FIG. 2](image2.png) Electromechanical activation of DEAs in either the air or the oil immersion: (a) Photographs showing electrode expansion for a DEA when tested in air. Wrinkles and sparks at spot were observed on dielectric film when the DEA breaks down at 11 kV (or 450 MV/m). (b) Photographs showing electrode expansion for a DEA when tested in the silicone oil immersion. Wrinkles appear changing from mild to severely undulated and sagging as the driving voltage increases from 11 kV to 18 kV, but the oil immersed DEA did not break down. (c) A graph showing areal strain of the activated DEAs as a function of electric field until breakdown.
Despite the similar actuation trend, the oil-immersed DEA can sustain a much higher voltage, 18 kV as compared to 11 kV of the DEA operated in air. The oil immersed DEA achieved a dielectric strength of 800 MV/m, as calculated from the 142% areal strain at 18 kV. On the other hand, the DEA operated in air achieved a dielectric strength of 450 MV/m, as calculated from the 125% areal strain at 11 kV. In short, the immersion in silicone oil enhanced the dielectric strength of DEA by 70% more than that in air.

When a dielectric film breaks down, corona discharges (sparks) are observed to happen at local spots over the wrinkled regions. The spots are believed to collapse under excessive Maxwell stress, which is induced by increased electric field. At the same time, leakage current may accelerate the collapse because it resistively heats up and softens the spots. To monitor the temperature at the defective spots, thermograms of the DEA were captured using an infrared camera (NEC Thermo Shot F30W) with a pixel size of 156 μm × 156 μm).

When broken down in air at 11 kV, the DEA sample is punctured at a defective spot, which coincides with the hot spot in the thermogram in Fig 3. The defective spot underwent a drastic temperature rise from 31.6 °C to 53.5 °C, as shown in Fig. 4(a), as the driving voltage was increased towards 11 kV, at which terminal failure happened. The transient corona discharge at the puncture is expected to be higher in temperature, but not captured by the thermogram. Joule heating at the puncture is indicated in Fig. 4(b) by a current surge that remains high at 120 μA, which is the current limit of the high voltage supply.
resistivity reduces substantially with temperature rise according to Refs. 26 and 28 and our recent measurement of VHB bulk resistivity.

In this work, we measured the bulk resistivity from a VHB sample, which consists of a 200% bi-axially pre-stretched VHB film and is configured into a capacitor by cladding the VHB film with a pair of copper foil electrodes (with an electrode area of $A = 15 \text{ mm} \times 15 \text{ mm}$). During measurement, the elastomeric sample was subjected to an elevated temperature $T$ in a furnace and its leakage current $I(T)$ under a constant voltage $V_{dc} = 100 \text{ V}$ was measured using a picoammeter (Keithley 6485). The bulk resistivity is calculated as: $\rho = V_{dc}/I(T) \times A/t$, in which $A$ is the cross section area of the capacitor and $t$ is its thickness.

Fig. 5(a) showed that bulk resistivity of pre-stretched VHB4905 is strongly dependent on temperature. The measured bulk resistivity decreases exponentially from $1.2 \times 10^{12} \Omega \text{m}$ to $1.5 \times 10^{8} \Omega \text{m}$, which amounts to a 4-order drop, when the VHB temperature rises from 25°C to 200°C. Hence, this leads us to believe that thermal runaway happens because resistivity reduces with temperature rise at the pull-in hot spot, in addition to the effect from electric field.27

In addition, the silicone oil bath is expected to have some effect on electrode resistance. Fig. 5(b) showed graphite electrode resistance as a function of uni-axial stretch. The presence of oil did not change the initial resistance (10.5 MΩ) of the unstretched electrode, but it affected the apparent resistance of the stretched electrode. For example, the oil-immersed electrode, which was uniaxially stretched 1.58 times (corresponding to 150% areal strain), exhibited 20% more resistance than that in air. This resistance increment in the presence of oil is attributed to oil seepage between the dislocated graphite particles. However, the effect of silicone oil on the stretched electrode resistance is not as dominant as its effect on the dielectric temperature, which in turn greatly influences the bulk resistivity and electrical breakdown of the dielectric elastomer.

Table I lists the reported dielectric strengths for VHB acrylic elastomers. The reported strengths vary substantially because of the different conditions of pre-stretch, dielectric film thickness, and compliant electrode materials. A high dielectric strength as much as 412 MV/m was reported for a bi-axially prestretched $(4 \times 4)$ VHB DEA with conductive grease electrodes. Recently, a 500 MV/m strength was also demonstrated for a pre-stretched VHB film, which was clamped between two stiff plastic layers.9 However, the

![Figure 5](image_url)

**FIG. 5.** (a) Temperature dependence of volume (or bulk) resistivity of a 200% biaxially pre-stretched VHB 4905 film (with a 55 μm pre-stretched thickness). (b) Surface resistance of graphite powder electrodes as a function of uniaxial stretch ratio.

When tested in the silicone oil bath up to 18 kV, the DEA sample is maintained a rather stable temperature and minimal leakage current. As a result of oil immersion, terminal failure of the DEA is deferred from 11 kV to 19 kV. The minimal leakage current. As a result of oil immersion, terminal failure of the DEA is deferred from 11 kV to 19 kV. The oil-immersed DEA survived the nearly pull-in state which is influenced the bulk resistivity and electrical breakdown of the dielectric elastomer.

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<th>TABLE I. Breakdown strength of VHB films or DEAs.</th>
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<td>Work</td>
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<tr>
<td>Shankar et al.6</td>
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<td>Pelrine et al.7</td>
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clamped VHB film cannot actuate. In comparison, a very high dielectric strength 800 MV/m is demonstrated by our silicone-oil-immersed VHB DEA.

With such high dielectric strength, the oil-immersed DEAs can not only operate reliably at high electric fields but also offer the benefit of higher force generation. According to the electrostatics formula, the induced Maxwell stress at the 800 MV/m is calculated to be as much as 12.7–13.3 MPa, based on the reported dielectric constant 4.5–4.7 for the pre-strained VHB 4905/4910 tape. In future, such oil-immersed DEAs can be configured to work against an even higher preload or external load, for example, in a cylindrical shape for lifting a heavy deadweight.

In conclusion, this work showed that silicone oil immersion can prevent thermal runaway, which causes loss of electrical insulation at defective spots, from damaging dielectric elastomer actuators. As a result, the oil-immersed DEAs demonstrated a large actuation at a very high dielectric strength 800 MV/m, even in the presence of severe wrinkles that indicate imminence of pull-in instability. This work showed that the oil-immersed DEAs have potential to sustain a very high Maxwell stress.

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18. See supplementary material at http://dx.doi.org/10.1063/1.4806976 for given material properties of 3M VHB Adhesive Transfer Tapes and Dow Corning 200 Fluid 50cs (now known as Xiameter PMX-200 Silicone Fluid 50cs).