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# Very High Breakdown Field Strength for Dielectric Elastomer Actuators Quenched in Dielectric Liquid Bath

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## ABSTRACT

Dielectric elastomer actuators (DEAs) are prone to failure by pull-in instability. However, this work showed that DEAs, which were immersed in a silicone oil bath (Dow Corning Fluid 200 50cSt), can survive the pull-instability and operates beyond the pull-in voltage. Membrane DEAs (VHB 4905), which were pre-stretched bi-axially at 200% strain and immersed in the oil bath, survived a very high field strength (>800 MV/m) and demonstrated areal strains up to 140%. The dielectric strength, achieved in the immersion, is approximately two times larger than that in the air (450 MV/m). This is achieved because the dielectric liquid bath helps to quench the localized electrical breakdown, which would have discharged sparks and burnt the dielectric film in the air.

**Keywords:** Dielectric elastomer actuator, breakdown, dielectric liquid, silicone oil

## 1. INTRODUCTION

Dielectric elastomer actuators (DEAs) are very promising for wide applications[1] because they can generate a large actuation strain when subjected by a high electric field.[2,3] The electromechanically induced strain is proportional to the electric field and inversely proportional to the Young's modulus of elastomer.[4] Thus, dielectric elastomers need to have a high breakdown field strength and a small Young's modulus in order for ultimately large actuation strain. However, DEA as a soft capacitor is prone to failure which limits its reliable operation. For instance, a non-pre-stretched VHB 4905 dielectric elastomer membrane (Young's modulus of 1.8 MPa[5]) exhibits low performance at which a low breakdown strength of 34 MV/m induced an area strain of 12.4%.[6] If a very high breakdown field can be achieved, DEA is believed to operate reliably at higher actuation strain.

Recently, pre-stretch was demonstrated to help VHB acrylic elastomer raise the breakdown field strength to 300–400 MV/m,[3,7–9] consequently the actuation strain increase to >100%.[3] Reasons for enhanced dielectric strength by pre-stretch are explained by: i) suppression of air void in the polymer film,[10] ii) stiffening of the dielectric film.[11] However, DEA even with pre-stretch is still liable to breakdown by electromechanical or pull-in instability.[12–15] It is believed if the pull-in instability can be overcome, DEA can achieve the high performance. In recent report of Keplinger et al.,[16] charge-sprayed electrodeless DEA was shown to eliminate the electromechanical instability. Nevertheless, such actuator is subjected to the practical problem that charges are not completely removed upon de-activated.[17] This hinders cyclic operation of electrodeless DEA by charge control activation. Usually, DEA with electrodes was not experimentally reported to survive the electromechanical or pull-in instability. In short, the pull-in instability still remains as a problem to the DEA under voltages control activation.

Dielectric oil is shown to raise the dielectric strength of power capacitors by impregnated in polypropylene film to fill the air gap between layer interfaces.[18] The enhancement was explained by that dielectric oil helps to eliminate the electrically localized breakdown. More recently, Yuan et al.[19] presented that a thin layer of dielectric oil, which was coated on each single-walled-carbon-nanotube (SWCNT) electrodes in a 5 layered DEA stack, can quench corona discharge at air gap and consequently extends the lifetime of pre-stretched DEA. According to the study,[19] partially premature breakdown was also prevented by dielectric oil quenching.

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However, quenching by dielectric oil was not reported to enhance dielectric strength to a particularly high value at 250 MV/m.[19] Thus, the question is if the dielectric oil can raise the dielectric strength even higher to survive pull-in instability.

In this work, we shall show that DEAs can achieve a very high breakdown field strength (up to 800 MV/m), which is beyond the electro-mechanical strength of dielectric elastomers (300–500 MV/m),[3, 7, 8, 12] and comparable to the field strength of hard plastics.[20]

## 2. OBJECTIVE AND SCOPES

Electrically localized breakdown affects high-actuation and reliable performance of DEAs. Its mechanisms need to be fully understood to aid the design for high-performance DEAs. The electromechanical or pull-in instability is usually attributed as the determining factor to electrical breakdown of dielectric elastomers.[11] If the dielectric elastomer can avert electrical breakdown, DEA is believed to sustain a very high field strength and consequently produce high actuation stress. This motives the present study to develop a method to avert electrical breakdown from damaging DEA. Dielectric liquid immersion was investigated to quench localized electrical breakdown which would have discharged sparks and burnt the dielectric film in the air. This work shall evaluate the enhancement of dielectric oil by silicone oil and how the immersion helps to avert electrical breakdown of DEA.

## 3. MATERIALS AND SAMPLE PREPARATIONS

Samples of DEA were prepared from a 200% bi-axially pre-strained VHB 4905 foam tape, which has a thickness of 55.0 $\mu$m as measured by a micrometer after pre-stretch. Borders of the pre-stretched dielectric film is supported on a square acrylic frame (60 mm×60 mm). Graphite powders (TIMREX KS6) is applied by brushing on the pre-stretched dielectric film to form a pair of 15mm diameter circular compliant electrodes, which has a surface resistivity measured to be 22 K$\Omega$/$\square$.

These DEA samples were prepared for two tests, such as actuation test and temperature test. In these tests, the samples were totally immersed in the silicone oil bath as shown in Fig. 1. The silicone oil is selected as the dielectric liquid for quenching in the study. The oil of Dow Corning Company (Fluid 200 50cSt) has a boiling point of 65°C, a thermal conductivity of 0.155 Wm$^{-1}$K$^{-1}$, and a specific heat of 1473 Jkg$^{-1}$K$^{-1}$ according to product datasheet.[21] In addition, the electrical properties of such oil were reported to have dielectric strength of 400 V/mil (or 15.7 MV/m) and a dielectric constant 2.72–2.75.[21] For comparison, samples of the same prepared DEAs were also tested in the usual condition, i.e. in the air for actuation test and temperature test.

## 4. TESTS FOR DIELECTRIC LIQUID QUENCHING

A few tests are designed to investigate effects of dielectric liquid immersion on DEA performance. For details, these are three tests: 1) actuation test to evaluate areal strain for DEA samples immersed in a silicone oil bath, 2) monitor of leakage current during the voltage activation, 3) monitor of DEA surface temperature measurement so as to understand the oil quenching of localized breakdown for DEA.
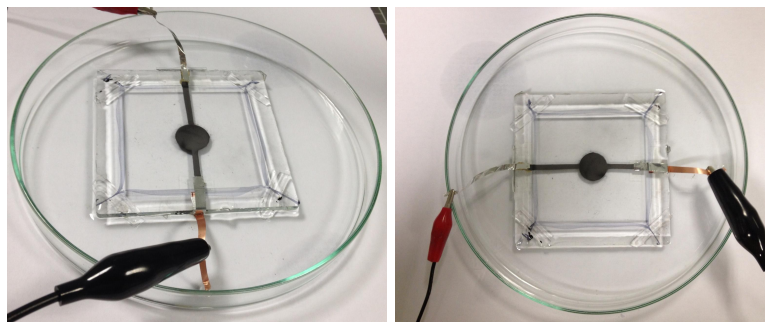


Figure 1. Photographs in side and top view of the experimental setup, which has a DEA sample completely immersed in a silicone oil bath while the DEA is activated by high voltage.

## 4.1 Breakdown field strength

In the test for electric field actuation, DEA samples, immersed in a silicone oil bath, are activated by incrementally increasing voltages up to the breakdown. The driving voltage is provided by a high voltage supply (Spellman's CZE1000R). The activated DEA has the electrodes expanded from an initial area $A_0$ to the activated area $A'$ at the electric field $\widetilde{E}'$. The areal strain is measured as $s_A = A'/A_0 - 1$. The true electricfield is the ratio of the applied voltage $V$ to the thickness$t'$, which is determined indirectly on the assumption that the dielectric elastomer is incompressible. As such, the true electric field is given by $\widetilde{E}' = V/(t_{pre}/(s_A + 1))$,[8] in which $t_{pre}$ is the initial thickness of the pre-stretched dielectric film. In the event of electrical breakdown of DEA, a current surge[22] is typically detected, in addition to the observation of puncture in the dielectric film. Hence, leakage current through the DEA was also continuously monitored using a digital multimeter (Agilent 34410A) and a data logger (NI).

## 4.2 Leakage current and Temperature monitoring

When the localized breakdown occurs, the leakage current typically surges and induces spark at a spot. It may cause 'thermal runaway' at the spot leading to localized breakdown of plastic insulating slab.[23] Thus, for DEA, temperature is measured in order to detect if the local thermal runaway happens at breakdown event. DEA temperature is monitored by an infrared camera (NEC Thermo Shot F30W) with a pixel size of 156 $\mu$m$\times$156 $\mu$m) to capture thermograms of the DEA, which was driven by increasing voltages. The temperature will be shown as a function of applied voltages up to the DEA breakdown event.

# 5. RESULTS AND DISCUSSIONS

Experimental results for DEA tested in oil immersion are shown and discussed below.

## 5.1 High electric field with electromechanical instability

DEA samples, tested in usual condition, i.e. in air, failed with localized breakdown at a moderate voltage. Fig. 2 shows that two DEA samples were suffered from electrical breakdown at a spot when tested in air. Sample 1 achieved the maximum area strain at 8 kV, but it broke down at 9 kV. As a result of burning by electrical spark, a pinhole was formed in the dielectric film as seen in Fig. 2(a). On the other hand, Sample 2 also broke down at 9 kV but the pinhole was hardly seen due to its small size as seen in Fig. 2(b). Locally joule heating, or partially discharged defects are attributed to localized breakdown in these DEA samples.

Fig. 3(a) showed the actuation strains of the two tested-in-air DEA samples. Sample 2 produced a larger area strain as much as 140%, which is greater than the maximum strain of 120% of Sample 1, at 8 kV, beyond which both samples broke down. Monitor of leakage current as in Fig. 3(b) shows that leakage current surges up to 25 $\mu$A and subsides when Sample 1 was activated below 9 kV. Likewise, as shown in Fig. 3(c), Sample 2 is also subjected to surge and subsides in the leakage current up to 15 $\mu$A. The instantaneous surge in leakage current, which dies off shortly, indicates that the partially premature breakdown occurs. However, when DEA samples terminally broke down at 9 kV, the leakage current remained high at 120 $\mu$A and did not die off.

However, when immersed in silicone oil, the DEA samples survive a very high voltage up to 18 kV (Fig. 4). At that high driving voltage, severe wrinkles are observed over the activated DEA samples. At 17 kV, Sample 3 and Sample 4 has broadened wrinkles on their dielectric films as shown in Fig. 4(a),(b). But, there was little wrinkles observed over the Sample 5 (see Fig. 4(c)) at the same driving voltage of 17 kV . When the driving voltage is increased to 18 kV, the wrinkles in the Sample 3 and Sample 4 turned into a broaden band of sagging over the whole electrode as seen in Fig. 4(a),(b)). After all, all threee 18kV-activated DEA samples demonstrated a large areal strain up to ~140%. This samples suriviv a very high electric field of beyond 800 MV/m, which was estimated from the nominal driving voltage and the areal strain by assume incompressible dielectrics.

On the other hand, another three DEA samples were tested in the silicone oil immersion, are shown in Figure 5 (Sample 3, Sample 4, and Sample 5). Figure 5(a) compares the actuation performances in the silicone oil immersion for the three samples. The maximum area strain is ~140% for the three samples at a very high applied voltage of 18 kV. Figure 5(b),(c),(d) show that all three samples did not fail up to 18 kV. The leakage
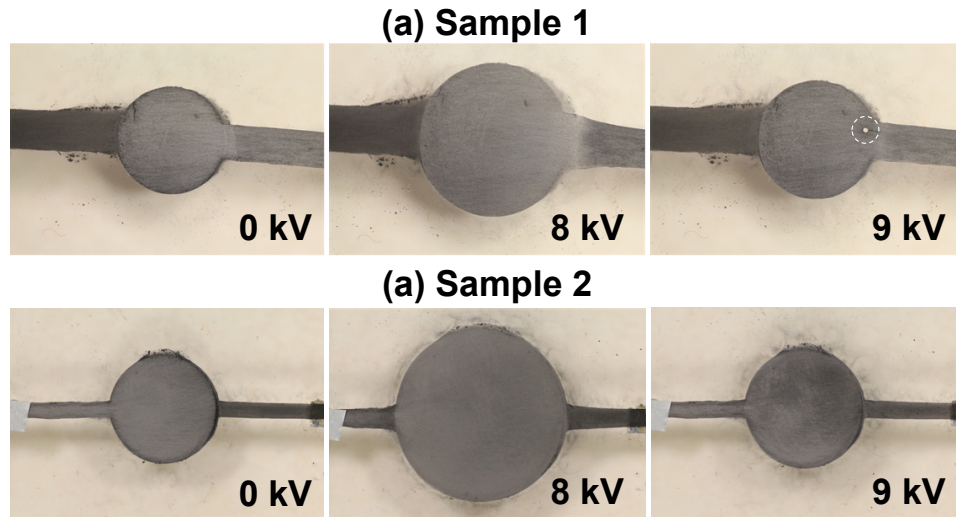
Figure 2. Photographs showing electrode expansion for two DEA samples when tested in the air. (a)Sample 1 was breakdown at 10 kV with a pinhole formed. (b) Sample 2 exhibits the large actuation at 9 kV before suffered permanent breakdown at 10 kV.
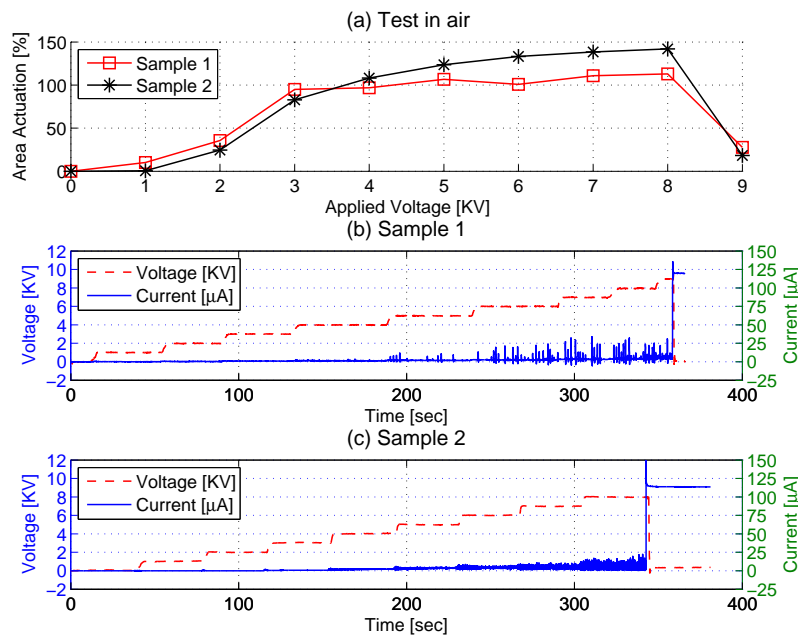


Figure 3. (a)Area strains of tested-in-air DEA samples as the functions of the applied voltage. (b), (c) Time histories of voltage and leakage current of two samples (Sample 1 and Sample2).

current, which induces the breakdown of DEA samples, did not surge when the driving voltage reached to 18 kV at which Sample 4 stands at a very high electric field to produce areal strain of 140%. In comparison to test in air, the immersion in silicone oil clearly prevented the DEA from early breakdown and thus improve the dielectric strength (>800 MV/m) beyond the limit by the electromechanical instability.
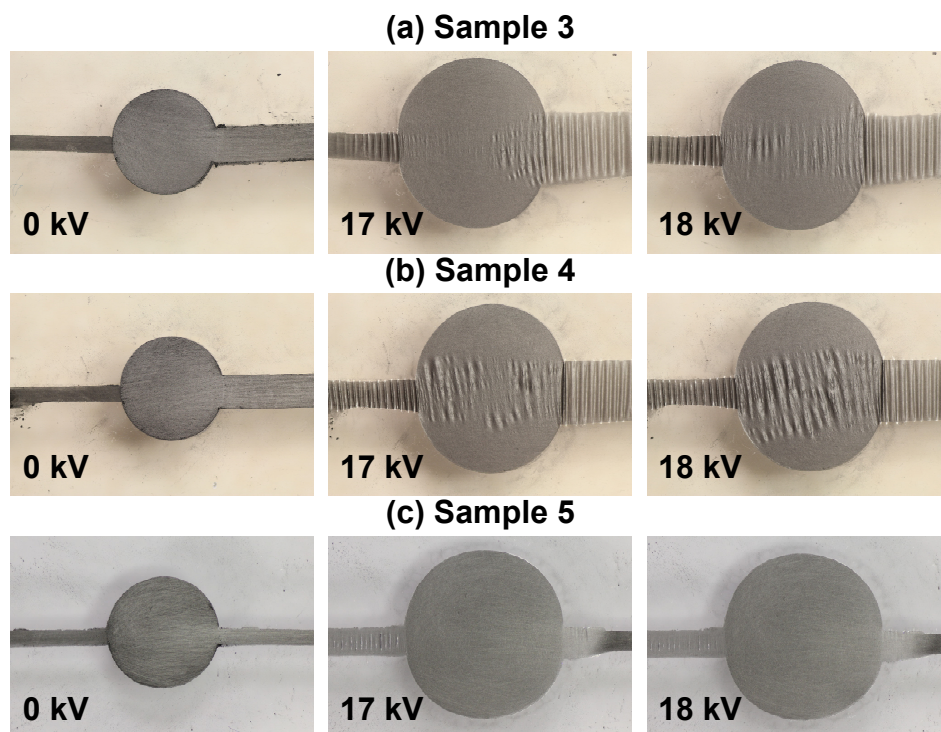
Figure 4. Photographs showing electrode expansion for three DEA samples when tested in silicone oil: (a)Sample 3, (b) Sample 4, and (c) Sample 5.

## 5.2 Temperature measurement at breakdown

When a dielectric film breaks down, corona discharges (sparks) were observed to happen to localized spots at the wrinkled regions, which are believed to collapse under excessive Maxwell stress. The pull-in spots are subjected to increased electric field and leakage current.[12, 23, 24] Consequently, the spots are prone to resistive heating by leakage current, and may undergo a drastic temperature rise, which softens the spots.[23]

When tested in air at 11kV, the DEA sample is punctured at a spot, which coincides with the hot spot in the thermogram in Fig. 6. The spot undergoes a drastic temperature rise from 31.6°C to 53.5°C as the driving voltage is increased from 10kV to 11kV, as shown in Fig. 7. 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 may be created by a current surge that remains high after breakdown seen in Fig. 3(b),(c).

These experimental results showed that the oil immersed DEA survived the nearly pull-in state which is indicated with severe wrinkles, but the DEA tested in the air did not. This suggests that the pull-in instability might not caused terminal failure to a DEA. Instead, 'thermal runaway' may have 'killed' the DEA. This is supported by the fact that temperature of the punctured spot rises drastically with respect to the driving voltage whenever DEA breaks down in either air or silicone oil. The observed thermal runway in the DEA is similar to those reported for plastic capacitor.[23] It was attributed by Joule's heating at the defective spot by leakage current, which further increases with the increasing conductivity as the local temperature rises.[23, 25]
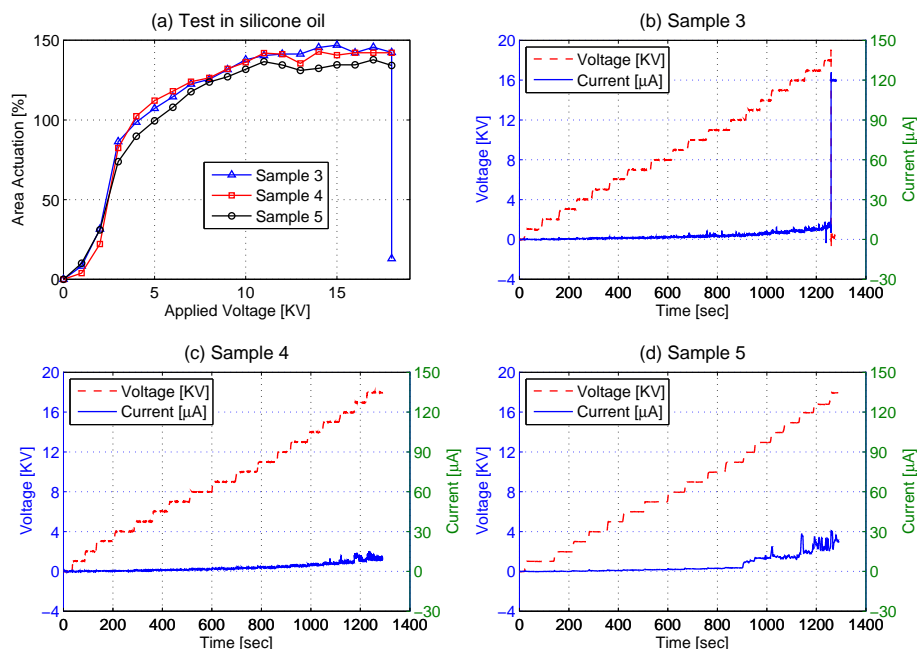
Figure 5. Electromechanical activation of DEAs in the silicone oil immersion for three samples. (a) A graph showing areal strains of the activated DEAs as a function of driving voltage until breakdown. (b), (c), and (d) Time histories of voltage and leakage current of Sample 3, Sample 4, and Sample 5 respectively.

## 5.3 Comparison to reported works

Various dielectric strengths were reported for VHB 4905 acrylic elastomers, as listed in Table 1. The variations were associated with the pre-stretch condition, dielectric film thickness, and compliant electrode materials. A high dielectric strength as much as 412 MV/m was reported for VHB DEA under a 4×4 pre-stretch. Recently, a high dielectric strength as much as 500 MV/m was also demonstrated by a pre-stretched VHB film, which was clamped between two stiff plastic layers to prevent necking.[9] However, the clamped VHB film cannot be actuated. In this work, we showed that liquid dielectric immersion enables VHB DEA to function up to a very high dielectric strength 800MV/m and produce a large areal strain of 140%.

## 6. CHALLENGES IN DIELECTRIC LIQUID IMMERSION

The immersion in silicone oil is contributed to increase the dielectric strength. The oil is observed to maintain DEA at low temperature even with very high electric field activation. It may indicate that the silicone oil helps to stop 'thermal runaway' to avert the surge of current. It is also known that thermal runaway much depends on

Table 1. **Breakdown strength of VHB films or DEAs**

| Work | Compliant electrode | Dielectric elastomer | Pre-stretch ratio (x,y) | Breakdown strength (MV/m) | Area strain (%) |
|---|---|---|---|---|---|
| Shankar et al.[6] | Ag grease | VHB 4910 | (0,0) | 34 | 12.4 |
| Pelrine et al.[3] | Carbon grease | VHB 4910 | (4,4) | 412 | 158 |
| Kofod et al.[8] | Brass plate | VHB 4910 | (6,6) | 218 | 0 |
| Huang et al.[9] | Copper wires | VHB 4905 | (6,6) | 500 | 0 |
| Yuan et al.[22] | SWCNTs | VHB 4905 | (4,4) | 340 | 140–160 |
| Low et al.[26] | Electro-less silver | VHB 9473PC | (2.5,2.5) | 350 | 50 |
| Current work | Graphite powder | VHB 4905 | (3,3) | >800 | 142 |
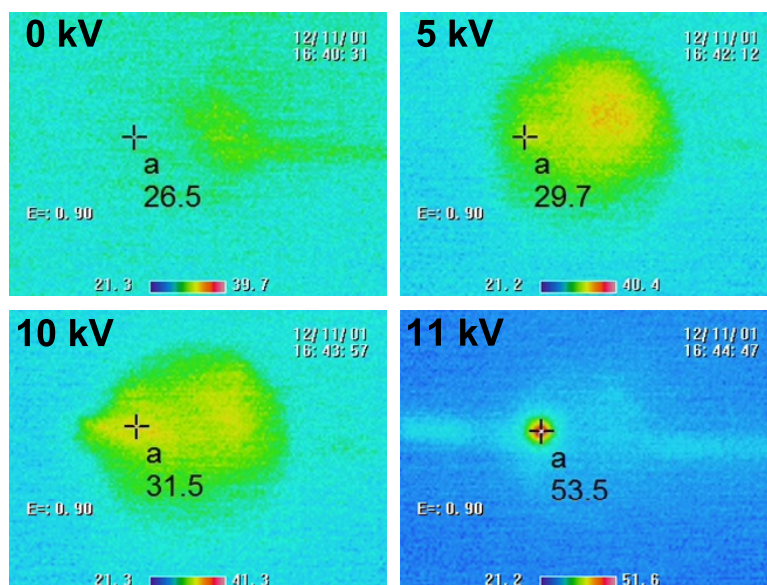
Figure 6. Thermography of the activated DEAs: four thermograms of a DEA sample in air at 0kV, 5kV, 10kV, and 11kV respectively. The right-bottom thermogram showed that a hot spot occured at the puncture when the DEA in air breaks down at 11KV. It indicates Joule's heating at the puncture of DEA, which breaks down at 11kV.
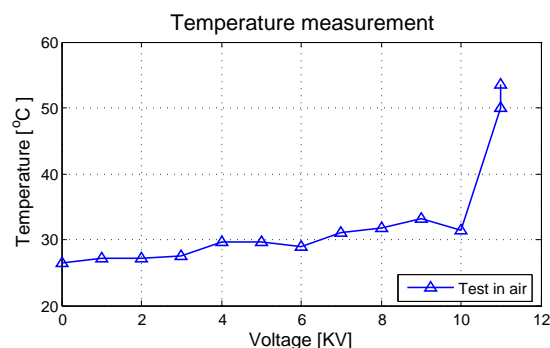


Figure 7. Monitor of temperature for DEA sample, which was activated by increasing voltages in air. A graph showing temperature as a function of driving voltage at the punctured region of DEA sample.

electrical and thermal properties of the dielectric elastomer slab. Thus, there is still a question if the dielectric liquid immersion can work with the combination of other elastomers and liquids. In addition, the observed area strain of immersed DEAs is in the same range of reported works even with very high electric strength as shown in Table. 1. It indicates the amount of the biaxial pre-stretch has significant effects on the actuation strain. The DEA has to be pre-stretched with the optimal amount to achieve ultimate actuation strain. Moreover, the immersion works when all electrodes are completely covered in the dielectric liquid. Therefore, there is a requirement of properly design for applying the dielectric immersion on roll and stacked dielectric elastomer actuators.

## 7. CONCLUSIONS

This work showed that stable temperature control by using liquid dielectric immersion can greatly increase the dielectric strength of operating DEA, well beyond the limit by pull-in instability. A very high dielectric strength of 800MV/m is demonstrated and it is good for producing high actuation stress. Even with wrinkles, the DEA

sample can produce areal strain of 140% in the silicone oil immersion. Future works will further investigate the effect of other coolants for better DEA performance as well as develop an approach to apply for roll or stacked DEAs.

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