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Inhibiting electro-thermal breakdown of acrylic dielectric elastomer actuators by dielectric gel coating

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Electrical breakdown of dielectric elastomer actuators (DEA) is very localized; a spark and a pinhole (puncture) in dielectric ends up with short-circuit. This letter shows that prevention of electrothermal breakdown helps defer failure of DEAs even with conductive-grease electrodes. Dielectric gel encapsulation or coating (Dow Corning 3-4170) helps protect acrylic elastomer (VHB 4905), making it thermally more stable and delaying its thermal oxidation (burn) from 218 °C to 300 °C. Dielectric-gel-coated acrylic DEAs can withstand higher local leak-induced heating and thus achieve higher dielectric strengths than non-coated DEAs do. © 2016 AIP Publishing LLC.

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Dielectric elastomer actuators (DEAs) can generate large voltage-induced actuation to drive soft robotic grippers.^{1–4} Their force-generation capacity is however limited by ultimate electric breakdown field of soft dielectric elastomer. Acrylic dielectric elastomer (3M VHB, a trademark for 3M high-strength bonding tape), which is commonly used to make DEAs, can sustain very high electric fields when pre-stretched.¹ This enhanced dielectric strength of pre-stretched VHB membrane is attributed to suppression of air voids from partial discharges^{5,6} and avoidance of electromechanical instability^{7,8} up to a higher electric field. Ultimate breakdown of the pre-stretched acrylic DEAs is mainly due to local thermal runaway^{9,10} and electronic avalanche¹¹ at a defective spot. The ultimate breakdown is harbingered by an exponential rise of leakage current,^{9,12} which causes excessive resistive heating at the defective spot (i.e., a hot spot^{9,10}). This agrees with Klein's model,^{13,14} which correlates the exponential rise of dielectric conductivity with a temperature rise $\Delta T = T - T_o$, following:

$$\sigma = \sigma_o e^{\alpha \Delta T}, \quad (1)$$

where σ_o is the conductivity at temperature T_o , σ is the conductivity at the defective spot, and α is a constant. Thermal instability (i.e., thermal runaway) could happen due to positive feedback of localized temperature rise, which leads to increased conductivity and thus higher leakage current, producing excessive heating beyond the capacity of heat dissipation.¹⁴

The critical electric field of thermal instability was expected to be very high even for soft dielectric elastomer.¹⁵ However, acrylic DEAs with carbon-grease compliant electrodes often break down at a moderate electric field (300–400 MV/m).¹⁶ Such premature breakdown could be initiated by gas discharges.^{5,6,17} A pinhole or puncture is usually formed at the defective spot^{11,18} as a result of electro-mechanical instability, local burning by thermal runaway, and electronic avalanche (see Figures 1(a) and 1(b)).

Flow of conductive grease across the puncture ends up with a permanent short-circuit between opposite electrodes of the DEA. In contrary, immobilized self-clearable compliant electrodes make DEAs more fault tolerant (against pinhole),^{19–21} whereas oil immersion or coating helps cool down the DEAs, preventing thermal runaway.^{10,22,23} If acrylic dielectric elastomer can withstand higher temperature, it could make DEAs tolerate higher leak-induced heating and avoid dielectric puncturing. However, dielectric oil immersion does not help carbon-grease-electroded DEAs because it becomes conductive upon dissolving the conductive grease.

It was reported that acrylic polymer is thermally more stable in nitrogen than in oxygen.²⁴ Depletion of oxygen by some kind of barrier coating could possibly make acrylic dielectric elastomer thermally more stable. Silicone dielectric gel is commonly used to insulate high-voltage electronics or power cables.²⁵ It is a soft cross-linked polymer network that retains extender liquid,^{25,26} but does not flow freely. It was reported to act as a tight seal over power electronic to bar moisture, suppress flash-overs, and resist flame.^{25,26} Its better-than-air dielectric properties (2.85 dielectric constant and 20 MV/m strength²⁷) could help suppress flash-over. So far, silicone dielectric gel has yet been applied to protect DEAs and its effect is not clear.

This letter reports the use of silicone dielectric gel (Dow Corning 3-4170) as coating or encapsulation to protect acrylic DEAs (VHB 4905) with carbon-grease electrodes, inhibiting electrothermal breakdowns as shown in Figure 1(c). This very soft gel exhibits higher thermal stability than acrylic dielectric elastomer (VHB) does. Subsequent paragraph will report that silicone-gel coating makes acrylic DEAs thermally more stable and electrically stronger.

First, material characterization was conducted to study the effect of temperature on bulk electrical resistivity and thermal stability of VHB 4905. Bulk resistivity of VHB 4905 was measured from ten samples of capacitor which consists of 3.5×3.5 -times equi-biaxially pre-stretched VHB membrane sandwiched by 15 mm $\times$ 15 mm copper foil electrodes, similar to Ref. 10. During testing, a VHB capacitor is subjected to a voltage ramp using a high-voltage supply

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FIG. 1. (a) and (b) Schematic to illustrate the hypothesized breakdown mechanism of the uncoated DEA; and (c) schematic to illustrate the barrier effect of the gel coating to suppress the DEA breakdown. (d) The measured volume resistivity ρ of VHB4905 as function of temperature. (e) Thermal gravimetric analysis of VHB4905, silicone gel, and gel-encapsulated VHB4905 in flow of air and nitrogen (N_2).

(Spellman CZE 1000R) and the leakage current is measured using a multimeter (Agilent 34410A). Temperature of the capacitor under test is controlled by a hotplate and measured using a thermocouple. Next, we used thermogravimetric analyzer (NETZSCH STA 409) to measure weight loss of VHB upon temperature rise towards its degradation. Degradation temperature is marked as the temperature at which 2% weight of VHB sample is lost. Two types of VHB samples were tested, namely, non-coated VHB (6–7 mg) and silicone-gel encapsulated VHB (9–10 mg). Thermogravimetric analysis was conducted in either air or nitrogen flow at 45 ml/min. A slow temperature ramp of 20 °C/min ensures uniform heating of the lightweight sample, even for the gel-encapsulated VHB core.

Encapsulation of VHB core in silicone gels was done in steps by casting and heat curing of liquid pre-polymer, which was mixed from 1 part of pre-polymer resin and 1 part of hardener (Dow Corning Dielectric Gel Kit 3–4170, Ref. 27). First, an underlying gel layer is cast and cured on a Mylar substrate. Second, VHB core was placed on the underlying gel layer before being over-coated by another gel layer. Prior to heat curing at 80 °C for 60 min, each liquid gel coating was degassed for 30 min. The cured gel overcoat or undercoat was measured to be 0.2–0.3 mm thick and estimated with a heat diffusion time constant of 0.02 s.

Figure 1(d) shows that the measured bulk electrical resistivity of VHB 4905 decreases exponentially with temperature rise. As the temperature of VHB substrate rises from room temperature 26 °C to 200 °C, its bulk electrical resistivity $\rho = 1/\sigma$ decreases for 4 order. This temperature dependence can be fitted well using Klein's model in Equation (1). Thermo-gravimetric analysis (TGA) in Figure 1(e) shows that VHB in nitrogen is thermally more stable than that in air flow. Thermal oxidation (burn literally) of VHB in air starts at 218 °C, whereas its thermal degradation in inert nitrogen flow starts at 300 °C. Interestingly, the silicone gel-encapsulated VHB in air becomes thermally as stable as the non-coated VHB in nitrogen, thanks to flame-resistant silicone gel which serves as barrier coating of moderate permeability²⁸ to delay burn of VHB. Silicone gel itself can withstand higher temperature up to 466 °C in air before its decomposition.

Second, we study the effect of silicone gel on acrylic DEAs' dielectric strength and maximum actuation. DEA samples were prepared following the process steps shown in

Figure 2. An acrylic dielectric elastomer tape (VHB 4905) was equi-biaxially pre-stretched for 3.5 × 3.5 times the initial dimensions and kept taut on a rigid annular frame with an 80 mm inner diameter. Subsequently, carbon greases (MG Chemicals 846–1P) were brushed to form 15 mm diameter circular compliant electrodes (with 62 kΩ/□ sheet resistance) on both sides of the pre-stretched VHB membrane. Finally, liquid prepolymer (0.1 ml) is cast through an 80 μm-thick Mylar stencil and heat cured on the DEA, forming a solid gel coating over the compliant electrodes. Figure 2(c) shows a circular sample of pre-stretched acrylic DEA with silicone gel coating, in contrast to a non-coated sample in Figure 2(b). The heat-cured silicone gel coating (with 85 g gel hardness²⁷) slightly softens the acrylic elastomer substrate (see Supplementary Figure S1 in Ref. 29) but has not adverse impact on electromechanical performance of DEAs.

During electromechanical testing, a high-voltage supply (Spellman CZE 1000R) is used to activate DEAs at a 160 V/s voltage ramp towards the breakdown voltage. Current limit of the high-voltage supply is 300 μA. A hot plate is used to control substrate temperature of DEAs. During the activation by the voltage ramp, leakage current across DEA was monitored continuously using a digital multimeter (Agilent 34410A) and a data logger (National Instruments CompactDAQ), while videos for the activated DEA were captured using a digital camera. The areal actuation strain s_A is calculated as $A_a/A_o - 1$, where A_a and A_o are the activated and initial electrode areas, respectively. The true thickness t_{true} of the dielectric membrane

FIG. 2. Fabrication steps for silicone-gel coated acrylic DEA (VHB). Angle-view photographs of: (a) a non-coated carbon-grease compliant electrode (with striation from brushing) on VHB and (b) silicone gel coating over a carbon-grease compliant electrode on VHB.

under activation is: $t_{\text{true}} = (t_{\text{pre}} A_o) / A_a$, where t_{pre} is the pre-stretched membrane thickness. Hence, the true electric field across the activated DEA is $E = V / t_{\text{true}}$. An infrared camera (NEC Thermo Shot F30) is used to capture DEAs' thermogram during their breakdown.

Figure 3 shows the effect of silicone-gel coating on electro-mechanical actuation of acrylic DEAs. The maximum voltage-induced areal expansion occurs at the ultimate breakdown voltage, beyond which the DEAs cease to actuate due to permanent short circuit. The silicone gel-coated acrylic DEAs can sustain very high electric field of up to 532 MV/m (6492 V) at room temperature (26 °C), producing a large ultimate area strain of up to 228% (see Figures 3(a)–3(c) (Multimedia view)). In comparison, non-coated acrylic DEAs broke down at a moderate electric field of 315 MV/m (4402 V) at room temperature and produced less ultimate areal strain of 189% before the ultimate breakdown ends up with membrane puncture and even rupture (see Figures 3(d)–3(f) (Multimedia view)).

FIG. 3. DEA's electromechanical actuation at room temperature (26 °C): (a)–(c) Photographs showing a gel-encapsulated DEA (the best performing sample) at 0 kV and its activated state at 6492 V; (d)–(f) photographs showing a non-coated DEA (the best performing sample) at 0 kV and its activated state at 4402 V; (g) the actuated areal strain as a function of true electric field (E); and (h) the leakage current as a function of voltage ramp (Multimedia view). [URL: <http://dx.doi.org/10.1063/1.4939550.1>] [URL: <http://dx.doi.org/10.1063/1.4939550.2>]

Once a local breakdown of DEA starts (by transient spark), arcing and flame continue and spread. The flame spread around the defective spot is fueled by burning of acrylic elastomer and carbon grease, in addition to resistive heating at the supply's current limit. For example, during 4402 V breakdown of non-coated DEA, the breakdown spot (with yellowish flame) grows from 0.27 mm to 1.34 mm diameter at 7 s later (see Supplementary Figure S2 in Ref. 29). In contrary, the bluish flame on the gel-coated DEA does not spread much (from 0.22 mm to 0.28 mm) during the 6492 V breakdown. This suggests that flame resistance of silicone gel coating could have helped contain the spread of arcing and flame. Moderate permeability²⁸ of silicone gel coating may help bar oxygen from fueling thermal oxidation of acrylic elastomer and carbon grease. It is also possible that silicone gel coating helps trap vapor emission (from local burning within) such as carbon dioxide which in turn helps extinguish arcing.³⁰

Figure 3(g) shows the acrylic DEAs' areal strains as a function of the driving electric field, whereas Figure 3(h) shows the DEAs' I-V curves (i.e., the leakage current during voltage ramp) up to the breakdown voltage V_b . When activated in the 0–3.5 kV range, acrylic DEAs behave almost like a ideal capacitor with low current leakage (at a 0.89 $\mu\text{A/kV}$ slope) and its areal strain increases quadratically with increasing voltage. Above a threshold voltage, the slopes of I-V curves become steeper up to 87.58 $\mu\text{A/kV}$, while the rate of areal increment decreases. This reduced dielectric resistance could be attributed to a weak spot with locally increased conductance. The ultimate breakdown of DEA is marked by a current surge to the supply's current limit. While the breakdown persists with leakage current hitting the supply's current limit, the supply voltage could fall below the first breakdown voltage V_b . The maximum ohmic leakage current I_b right before the current surge indicates DEA's thermal stability. It is found that gel-coated DEAs can withstand higher current leak before succumbing to thermal runaway, as compared to the non-coated ones.

Dielectric strengths of acrylic DEAs depend strongly on temperature. Here, acrylic DEAs were also tested at elevated temperatures of up to 94 °C. Twelve samples were prepared for each type of DEAs (either non-coated or gel-coated) at each testing temperature. Figure 4(a) shows that breakdown strengths of acrylic DEAs decrease exponentially with increasing temperature. For example, the dielectric strength of a non-coated DEA decreases from 303 MV/m to 139 MV/m when the substrate temperature rises from 26.3 °C to 94.1 °C, whereas a gel-coated VHB DEA has its dielectric strength decreased from 528 MV/m at 26.2 °C to 245 MV/m at 94.3 °C. This trend agrees with temperature-dependence of dielectric strength for DEAs^{15,31,32} and plastic capacitors.³³ The elevated substrate temperature energizes electrons in the dielectrics, leading to increased electrical conductivity and requiring less field-induced resistive heating to reach VHB's degradation temperature. Despite decreasing with temperature rise, dielectric strengths of the gel-coated DEAs are higher than those of non-coated DEAs. Weibull plot can well show distribution of breakdown.^{34–37} Figure 4(b) shows that the silicone gel coating clearly increases dielectric strength of acrylic

FIG. 4. Effect of silicone gel coating on dielectric strength of VHB4905 DEAs (12 samples for each types of DEAs at each temperature): (a) dielectric strength (E_b) as a function of temperature and (b) the cumulative probability of failure against applied electrical field for non-coated and gel-coated DEAs at either 26°C or 94°C.

DEAs at the high confidence level. Failure probabilities of DEAs at a temperature increase with electric field.

Thermograms in Figure 5 show that a hot spot is developed on a DEA subjected to ultimate breakdown. The hot spot is induced by shorting through a defective spot, with high leakage current and excessive resistive heating. Temperature in the thermogram was derived using a common 0.9 emissivity, and it was not corrected to account for the emissivity difference among VHB, carbon grease, and

silicone. Due to different emissivity, material boundaries are distinguishable, even at a uniform temperature. Surprisingly, the hot spot temperature of the gel-coated DEAs appears lower than those of the non-coated DEAs, despite the former withstanding a much higher electric breakdown field than the latter do. This lower apparent hot-spot temperature is an artefact due to low emissivity of transparent gel coating, beneath which small sparks flash, and heat diffuses through it.

Typically, a hot spot has a small radius r_{hot} and it is subjected to much higher temperature, i.e., the breakdown temperature T_{hot} , than its surrounding dielectric. Following Equation (1) of Klein's model, dielectric resistivity at the hot spot is expected to be much lower than the bulk resistivity at substrate temperature. As the local shorting happens, the voltage supplied V_b drops primarily across the hot spot dielectric where nearly all current I_b leaks through. Meanwhile, there is only minor voltage (10–30 V) drops across the carbon-grease electrodes (of 100–200 kΩ resistance). Hence, shorting resistance V_b/I_b can be used to estimate dielectric resistivity ρ_{hot} at the hot spot following $\rho_{\text{hot}} = (V_b \pi r_{\text{hot}}^2) / (I_b t_b)$, where t_b is the minimum dielectric thickness right before the breakdown. Following Klein's model,^{13,14} the maximum shorting temperature T_b at the hot spot is derived to be

$$T_b = -\frac{1}{\alpha} \ln \left(\frac{\rho_{\text{hot}}}{\rho_o} \right) \quad (2)$$

using the following parameters which were extracted from experimental correlation: $T_o = 0$ K, $\rho_o = 1.822 \times 10^{19} \Omega \text{ m}$, and $\alpha = 5.431 \times 10^{-2} / \text{K}$ for VHB4905 (see Figure 1(d)). According to calculation based on this model (see Supplementary Table S1 in Ref. 29), the hot spot temperature is estimated to be 307–316°C during 532 V/m breakdown of gel-coated DEAs at room temperature. In comparison, the estimated temperature is lower to be 261–269°C during 305 MV/m breakdown of non-coated DEAs at room temperature. This analysis shows that silicone gel coating helps acrylic DEAs withstand higher leak-induced heating.

FIG. 5. Thermo-grams of DEAs during persistent electrical breakdown at different substrate temperatures (T_s).

In short, this investigation found that silicone gel coating helps suppress electrothermal breakdown of acrylic DEAs with carbon-grease compliant electrodes. The silicone gel coating or encapsulation makes acrylic DEAs thermally more stable and tolerant of higher leak-induced resistive heating before dielectric puncturing. Dielectric strength of the silicone-gel coated pre-stretched acrylic DEAs is enhanced up to 532 MV/m at room temperature, higher than 315 MV/m of non-coated DEAs. The enhanced dielectric strength of DEAs is good for generating higher Maxwell stress. In future, these silicone-gel coated DEAs will be stacked into multiple layers to make stronger artificial muscles.

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- ¹R. E. Pelrine, R. D. Kornbluh, Q. B. Pei, and J. Joseph, *Science* **287**, 836–839 (2000).
- ²S. Shian, K. Bertoldi, and D. R. Clarke, *Adv. Mater.* **27**, 6814–6819 (2015).
- ³J. Shintake, S. Rosset, B. E. Schubert, D. Floreano, and H. Shea, “Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators,” *Adv. Mater.* (published online 2015).
- ⁴G. Kofod, W. Wirges, M. Paajanen, and S. Bauer, *Appl. Phys. Lett.* **90**, 081916 (2007).
- ⁵D. P. Muffoletto, K. M. Burke, and J. L. Zirnheld, *Proc. SPIE* **8340**, 834021 (2012).
- ⁶D. Muffoletto, A. Martinez, K. Burke, and J. Zirnheld, *IEEE Trans. Dielectr. Electr. Insul.* **22**, 1756–1762 (2015).
- ⁷G. K. Lau, J. F. L. Goosen, F. Van Keulen, P. J. French, and P. M. Sarro, *J. Micromech. Microeng.* **16**, S35 (2006).
- ⁸X. Zhao and Z. Suo, *Appl. Phys. Lett.* **91**, 061921 (2007).
- ⁹I. A. Anderson, T. A. Gisby, T. G. McKay, B. M. O’Brien, and E. P. Calius, *J. Appl. Phys.* **112**, 041101 (2012).
- ¹⁰T.-G. La and G.-K. Lau, *Appl. Phys. Lett.* **102**, 192905 (2013).
- ¹¹M. Kollasche, J. Zhu, Z. Suo, and G. Kofod, *Phys. Rev. E* **85**, 051801 (2012).
- ¹²T. Lu, Z. Shi, Z. Chen, H. Huang, and T. Wang, *Appl. Phys. Lett.* **107**, 152901 (2015).
- ¹³N. Klein and E. Burstein, “Electrical pulse breakdown of silicon oxide films,” *J. Appl. Phys.* **40**, 2728–2740 (1969).
- ¹⁴L. Dissado and J. Fothergill, *Electrical Degradation and Breakdown in Polymers* (Peter Peregrinus Ltd., 1992).
- ¹⁵S. Zakaria, P. H. Morshuis, M. Y. Benslimane, K. V. Gernaey, and A. L. Skov, *Proc. SPIE* **9056**, 90562V (2014).
- ¹⁶P. Brochu and Q. Pei, *Macromol. Rapid Commun.* **31**, 10–36 (2010).
- ¹⁷W. Yuan, P. Brochu, S. M. Ha, and Q. Pei, *Sens. Actuators, A* **155**, 278–284 (2009).
- ¹⁸S.-H. Low and G.-K. Lau, *Smart Mater. Struct.* **23**, 125021 (2014).
- ¹⁹W. Yuan, L. Hu, Z. Yu, T. Lam, J. Biggs, S. M. Ha, D. Xi, B. Chen, M. K. Senesky, G. Grüner *et al.*, *Adv. Mater.* **20**, 621–625 (2008).
- ²⁰G.-K. Lau, S. C.-K. Goh, and L.-L. Shiau, *Sens. Actuators, A* **169**, 234–241 (2011).
- ²¹S. H. Low, L. L. Shiau, and G.-K. Lau, *Appl. Phys. Lett.* **100**, 182901 (2012).
- ²²T.-G. La, G.-K. Lau, L.-L. Shiau, and A. W.-Y. Tan, *Smart Mater. Struct.* **23**, 105006 (2014).
- ²³G.-K. Lau, D. D.-T. Tan, and T.-G. La, *Smart Mater. Struct.* **24**, 045025 (2015).
- ²⁴V. V. Krongauz and M. T. Ling, *J. Therm. Anal. Calorim.* **96**, 715–725 (2009).
- ²⁵H. Yaworski and R. Bukovnik, in *IEEE/PES Transmission and Distribution Conference and Exposition* (2001), Vol. 2, pp. 837–842.
- ²⁶G. Finis and A. Claudi, *IEEE Trans. Dielectr. Electr. Insul.* **14**, 487–494 (2007).
- ²⁷See <http://www.dowcorning.com/DataFiles/090276fe8018f8f3.pdf> for the Dow Corning Dielectric Gel Kit 3–4170 product data sheet (accessed August 2015).
- ²⁸M. Velderrain, *Proc. SPIE* **8280**, 82800O (2012).
- ²⁹See supplementary material at <http://dx.doi.org/10.1063/1.4939550> for Figures S1 and S2, and Table S1.
- ³⁰C. Wadhwa, *High Voltage Engineering* (Electric Insulators and Insulation, 2007).
- ³¹L. Liu, H. Chen, J. Sheng, J. Zhang, Y. Wang, and S. Jia, *Proc. SPIE* **9056**, 905634 (2014).
- ³²L. Liu, H. Chen, B. Li, Y. Wang, and D. Li, *Appl. Phys. Lett.* **107**, 062906 (2015).
- ³³M. Ieda, M. Nagao, and M. Hikita, *IEEE Trans. Dielectr. Electr. Insul.* **1**, 934–945 (1994).
- ³⁴F. Carpi, I. Anderson, S. Bauer, G. Frediani, G. Gallone, M. Gei, C. Graaf, C. Jean-Mistral, W. Kaal, G. Kofod *et al.*, *Smart Mater. Struct.* **24**, 105025 (2015).
- ³⁵M. Kollasche and G. Kofod, *Appl. Phys. Lett.* **96**, 071904 (2010).
- ³⁶W. Weibull, *J. Appl. Mech.* **18**, 293–297 (1951).
- ³⁷L. Dissado, *J. Phys. D: Appl. Phys.* **23**, 1582 (1990).