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DIELECTRIC ELASTOMER ACTUATOR: NEXT GENERATION FUNCTIONAL MATERIALS FOR INNOVATIVE ROBOTICS

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ABSTRACT
Conventional actuators based on metal and ceramics face challenges in utilizing them for service and welfare robots, which should work cooperatively with human workers. Dielectric elastomer actuators (DEAs) are a promising alternative to the conventional hard actuators, because they can realize motions which more resemble those of human muscles. Our research aimed at developing a DEA for applications in handling robotic arms and gripper hands for service/welfare robots. To this end, the elements of soft actuator ought to be fabricated and integrated into a large-scale array. Design of the actuator need to be optimized using computational dynamics and Finite Element Analysis (FEA). The application of DEA in robotics is expected to create a drive for the practical realization of reliable and functional DEAs. It could also promote commercialization and tap into the vast potential service/welfare robotic market.

Keywords: DEA, FEA, Polymer, Robot.

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INTRODUCTION

Dielectric elastomer actuators (DEAs) are polymeric/elastomeric mechanical transducers that convert electrical energy to mechanical energy. They also function as sensors and convert mechanical energy to electrical energy. DEAs are important transducers in devices such as orthotics (Kurian, 2016) and portable force feedback sensors (Kadooka, 2016)

The working principle of a dielectric elastomer actuator is shown in Figure 1. When a high DC voltage (kV) is applied on a set of compliant electrodes sandwiching the dielectric elastomer expands in planar directions and compressed in thickness direction. When the voltage is removed, the DEA retains its shape (Asaka, 2014).

Assuming constant volume Maxwell tensor or Electrostatic Pressure *U:*

$$U = 0.5\, e_0 * e_r * V^2/d^2 \qquad (1)$$

Where e_0 is the permittivity in vacuum e_r is the permittivity of the dielectric, V is voltage applied and d is the gap (Carpi, 2008).

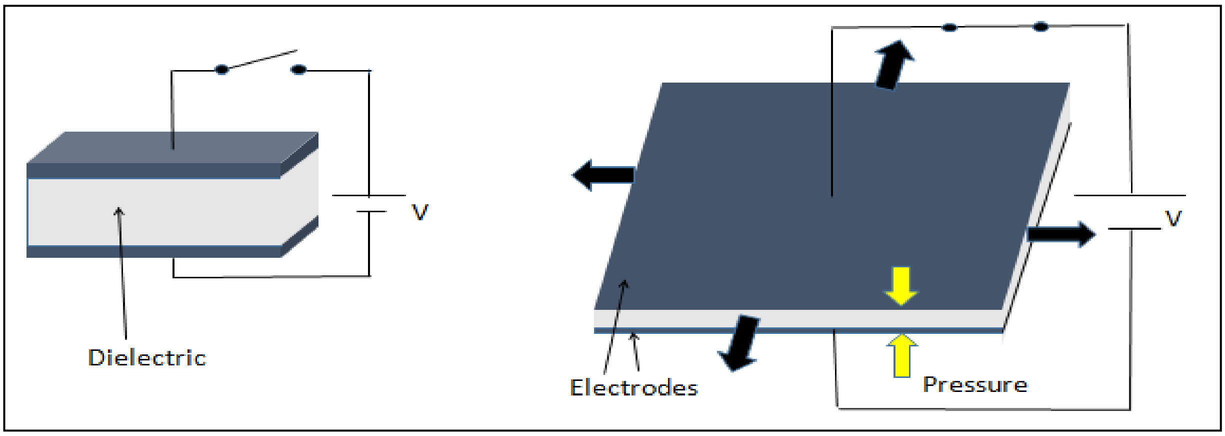


Figure 1: Working principle of dielectric elastomer actuator.

High voltage requirement (< 2.5 KV) is the major challenge associated with DEA application (Bar-Cohen, 2004). For instance, this limits the DEA application in medical field gadgets which have a voltage requirement of 24V due to safety reasons. Therefore, based on the mathematical formulation on Maxwell pressure, reducing the dielectric thickness or gap d would lower the voltage V requirement. Recently, research efforts towards decreasing the gap have been conducted (Poulin *et. al.*, 2016). They fabricated a 3 µm dielectric film and lowered the actuation voltage to 300 V. Based on this principle; we propose to fabricate thinner films to achieve lower actuation voltages until we attain 24V. Also, to achieve large deformation, we propose to stack more thin layers of dielectric elastomers and electrodes, as demonstrated by Carpi et al (2007).

Our overall NEDO project scope involved research and development of soft actuators, specifically DEA, for practical application in the soft gripper hands of welfare and service robots. This integrated project was supported by New Energy and Industrial Technology Development Organization (NEDO) in Japan. NEDO is a governmental agency for addressing energy and global environmental problems, and enhancing industrial technology. The primary focus is the development of ultra-thin dielectric to enable lowering of high voltage requirement of the DEA. We also sought to increase the overall deformation of the soft actuators. Precision control design and algorithms would also be developed to enable the

DEA to function as self-sensing actuators. Gifu University and VR Techno Inc. collaborate to achieve the practical application and commercializing of the DEA soft actuator.

This paper presents achievements towards the overall project scope. A finite element model of a multilayer stack DEA was developed and the deformation behavior due to applied voltage is discussed. With the FEM, the proof of concept about how the decreasing the thickness and the increasing the layers of stacks could lower the working voltages and increase the overall deformation, respectively, is discussed. The development of a stack dielectric elastomer actuators based on multiwalled carbon nanotubes (MWCNT) mixed in polydimethylsiloxane (PDMS) is presented. Molding and spin coating fabrication techniques are described and a side by side comparison of the outcome of the two methodologies is presented.

FINITE ELEMENT ANALYSIS OF THE DIELECTRIC ELASTOMER ACTUATOR

Design for proof of concept.

If the research is undertaken in a specific area, then some mention should be made about the study area. What are its unique features and their relevance to the study? Figure 3 shows a 3D isometric view of a stack actuator prototype. *H* is the overall height of the stack actuator while *L* and *W* are the length and width respectively. The black and white regions represent the compatible electrodes and the dielectric elastomer respectively. This example of stack shown in Figure 3 comprises of two layers of stacked DEA.

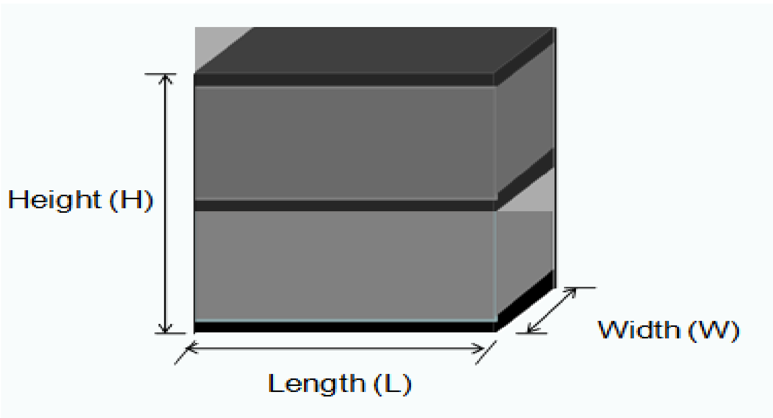
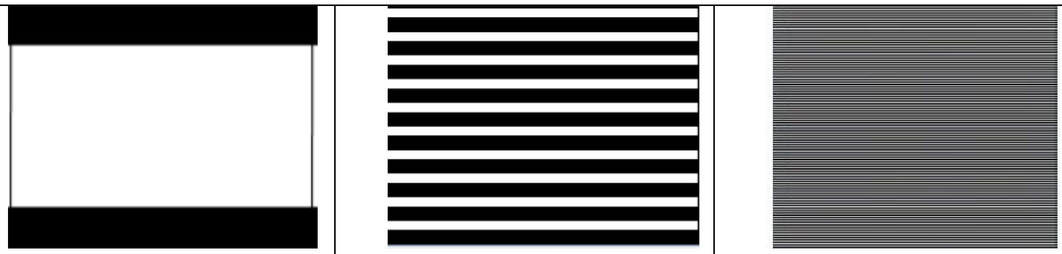


Figure 3: 3D isometric view of a stack actuator prototype.

Figure 4 shows the front views of the three proposed designs of stack actuator for the demonstration of concept of NEDO project described in section 1. For ease of comparison of the results, all the DEA stacks have equal length (L), width (W) and height (H) of 0.25mm, 0.25mm and 1mm respectively. Figure 4 a. shows a stack design of only one layer. Figure 4

b. shows a stack of 10 layers where each layer is 100µm thick. Figure 4 c. shows a stack of 100 layers where each layer is 10µm thick. A description of the development of the Finite Element analysis of the three stacks is presented in the next section.

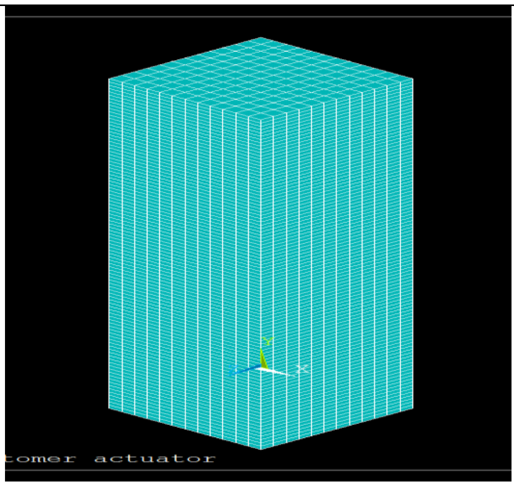


a. 1 layer, 1mm	b. 10 layers, each layer 100µm	c. 100 layers, each layer 10µm

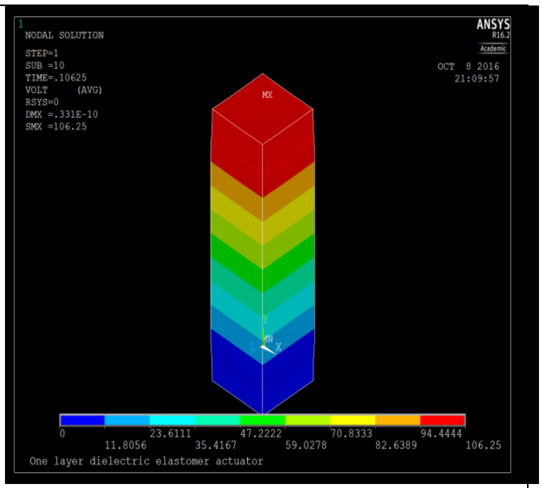
Figure 4: The front views of the three proposed designs of stack actuator.

Finite Element formulation

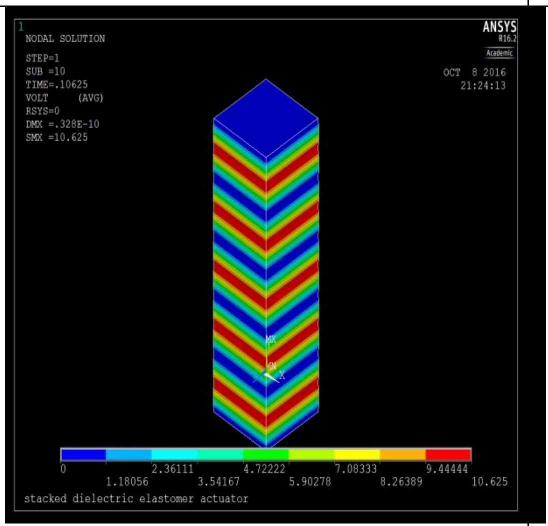
To simulate the deformation behavior of stack DEA actuators with applied voltage, a finite element model was developed in ANSYS mechanical software. This software utilizes coupled simulations of structural mechanics and electric fields. The models described in section 2.1 were drawn in ANSYS command. To model the electrode, planes of 0.25mm x 0.25 mm were centered between the layers. The planes had a thickness of 0.1mm, 0.01mm and 0.001mm for the designs of Figure 4a, 4b and 4c respectively. The material properties of the electrodes were modeled same as for the dielectric elastomer. Thus, the influence of the electrode on the mechanical behavior is not modeled here, but can be neglected due to its small thickness in comparison to the dielectric elastomer film thickness. Fine rectangular elements were selected for good computation results as shown in Figure 5 a.
The material chosen for the simulation was Solid 226 and it had electro-elasticity capability. The material parameters for the DEA were obtained from the Slygard 184 manual of the elastomer. The Young's Modulus was 1MPa, the relative permittivity was 2.65 and the Poisson's ratio was 0.48. An electric potential of 100V was assigned to every even number set of electrodes, while the remaining odd number set of electrodes were grounded. The electric fields are shown in Figure 5 b, 5c, and 5d.



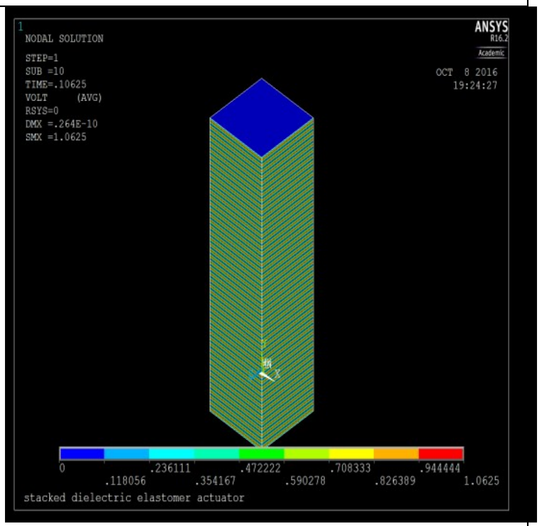
(a) Fine meshing



(b) 1 layer



(c) 10 layers



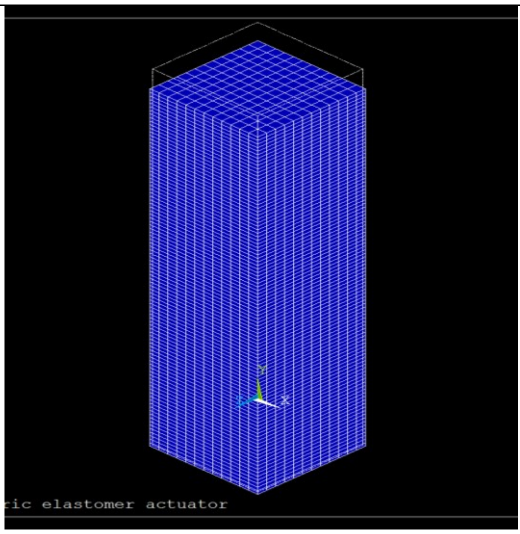
(d) 100 layers

Figure 5: Meshing and electric field.

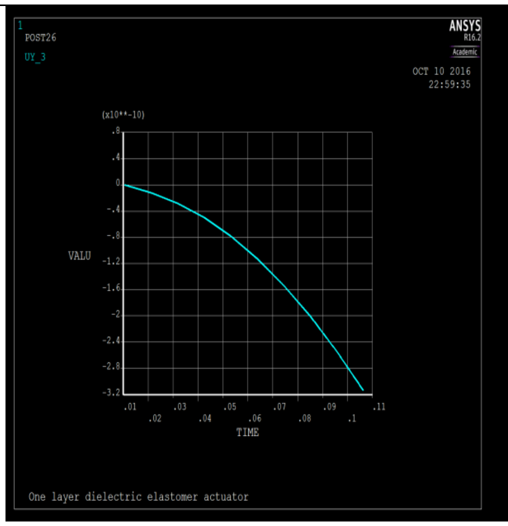
Finite element analysis deformation results.

This section describes the FEA Simulation results for the stack DEA after a DC electric field of 100v was applied gradually. Figure 6a shows the shape of deformation of the DEA model. It comprises of a deformed state with a comparison to the non-deformed state. Applied DC voltage causes the DEA to compress on Y direction and elongate on X and Z direction. This behavior agrees with experimental results of Carpi (2008).

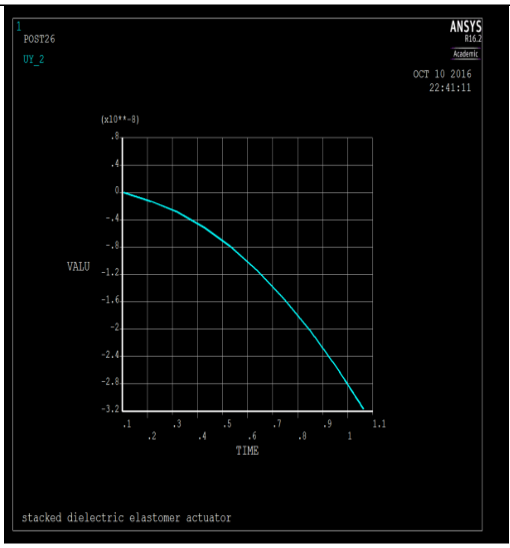
Figure 6b, 6c and 6d shows the graphs of the DEA elongation along Y direction in meters, as voltage is increased from 0v to 100V. The stack with one layer, as shown in Figure 6b, has an elongation of -2.8E-10m at 100V. The stack with ten layers, as shown in Figure 6c, has an elongation of -2.8E-8m at 100V. The stack with one hundred layers, as shown in Figure 6d, has an elongation of -2.3E-6m at 100V. The stack DEA with thinnest layer showed more deformation than the other stacks for the same applied voltage of 100 V.



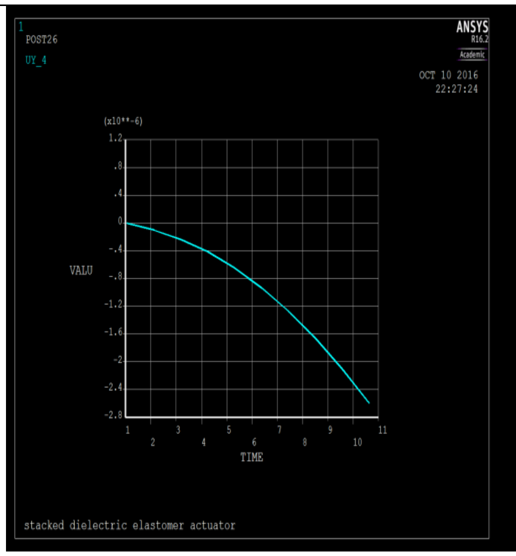
(a) Deformed and non-deformed shape



(b) One-layer stack with elongation of -2.8E-10m at 100V



(c) Ten-layer stack with an elongation of -2.8E-8m at 100V



(d) Hundred-layer stack elongation of -2.3E-6m at 100V

Figure 6: Deformation of the DEA stacks.

Figure 7 shows the variation percentage strains at 100V for the different thickness of layers of the stack DEAs. For the same stack height, higher strains can be obtained by decreasing the thickness of layers. This simulation result proves the concept described in section 1.

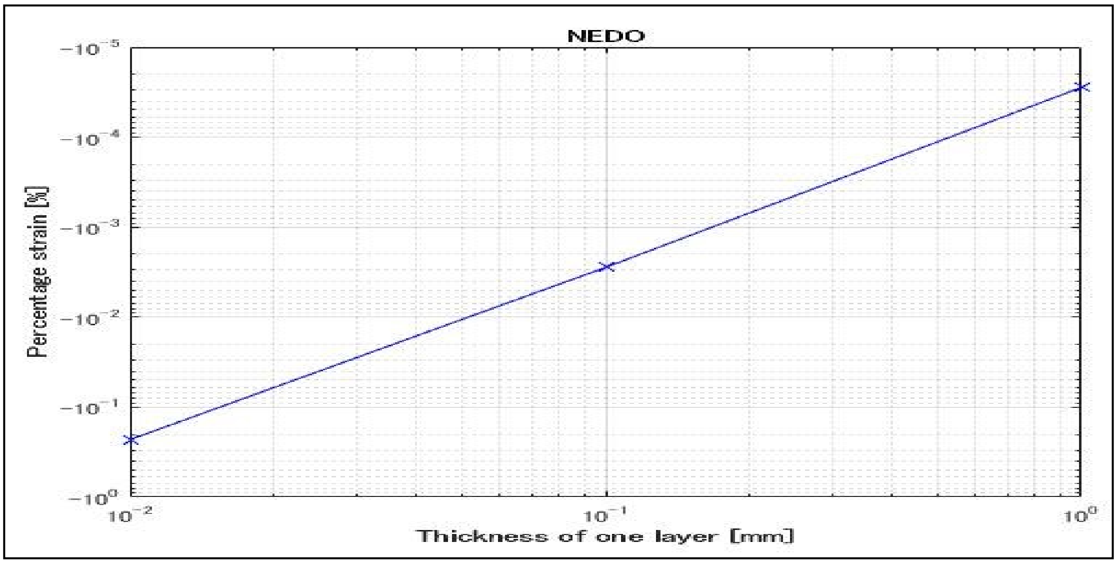


Figure 7: Variation of percentage strains at 100V for the different thickness of layers of the stack DEAs

Figure 8 shows the variation of percentage strains at 100V for the different thickness of layers of the stack DEAs. This figure shows a comparison with the FEA model which used Yeoh's hyper-elasticity model and material parameters obtained from the experimental data by Carpi (2008).

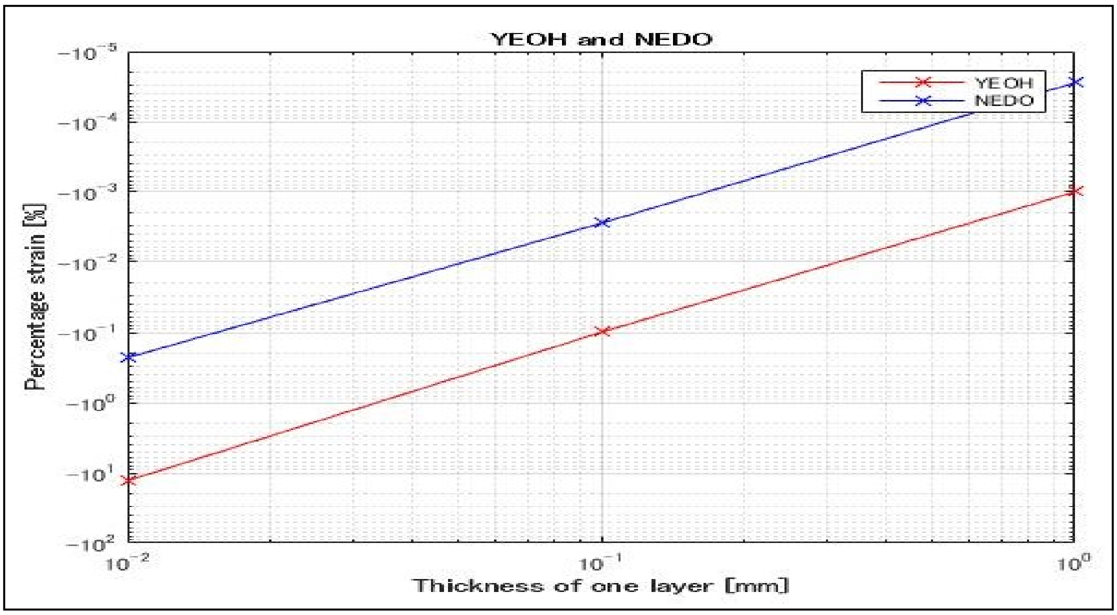


Figure 8: Comparison of variation of percentage strains at 100V for the different thickness of layers of the stack DEAs.

FABRICATION OF DEA STACKS

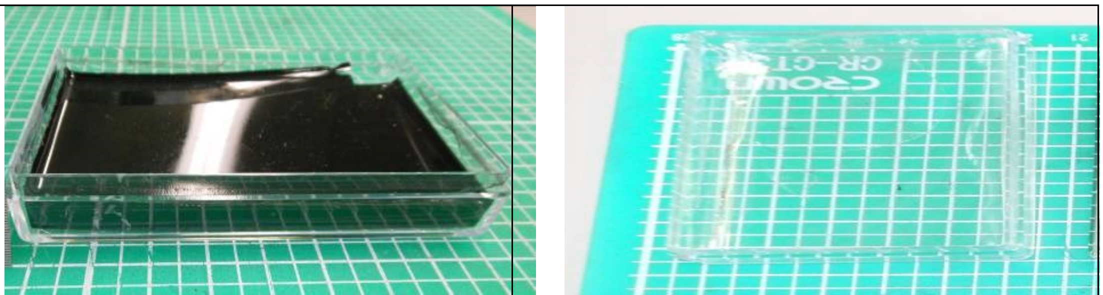
Materials

The materials used for fabrication of the DEA were PDMS (Slygard 184 elastomer Kit) purchased from Dow Corning which consisted of a base elastomer and a curing agent. The MWCNT was purchased from Sigma Aldrich item number 773840-25G with a purity of 98%.

Molding fabrication technique.

The process described here for the fabrication of the electrodes is similar to the method by Khosla (2009). Here, 3% weight to volume ratio of MWCNT to 97% of prepolymer PDMS was used. The mixture was sonicated with a frequency of 42 KHz for one hour. Curing agent was added in the ratio of 10: 1 as specified in Slygard 184 user's manual. The resulting mixture was poured into a petridish, degassed and cured at 125^{o}C for 1 hour. The cured electrode is shown in Figure 9a.

For the fabrication of the dielectric layer, the process described here follows Slygard 184 user's manual (Corning, 2014). PDMS base elastomer was carefully measured and the curing agent was added in ratio of 10:1 (10 parts of base polymer and 1 part cutting agent). The mixture was poured to petridish, degassed and cured. Figure 9b shows a sheet of cured PDMS dielectric in a petridish.

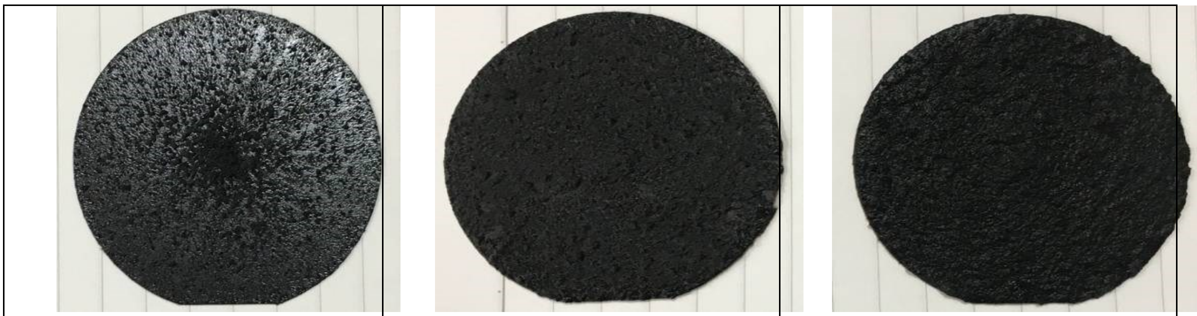


(a) Cured MWCNT/PDMS electrode	(b) Cured PDMS dielectric

Figure 9: Molded electrode and Dielectric

Spin coating fabrication technique

The spincoating machine used for this experiment was Mikasa Opticoat MS B100. Initially a water soluble sacrificial layer of Polyvinyl Alcohol (PVA) solution was spin coated onto silicon wafers. Then, the silicon wafers were spin coated with PDMS and cured. The electrode mixture was prepared, spincoated and cured on top of the earlier cured PDMS. Spin coating was carried out for different speeds and the cured samples are shown on Figure 10. This figure indicates that high spincoating speeds results in thin film fabrication.



(a) 200 microns, 2000rpm	(b) 400 microns, 1000rpm	(c) 600 microns, 500rpm

Figure 10: Spin coated electrodes and dielectric film obtained for different spin coating speeds. (a) 200 microns thick, spin coated at 2000 rpm (b) 400 microns at 1000 rpm and (c) 600 microns at 500 rpm.

Stack actuator assembly

Several equal rectangular strips were cut off from both the dielectric and electrode sheets. The strips were then stacked one on top of another. PDMS was used as an adhesive for joining the strips. The stack setup was then heat cured. The stacking assembly process is demonstrated in Figure 11.

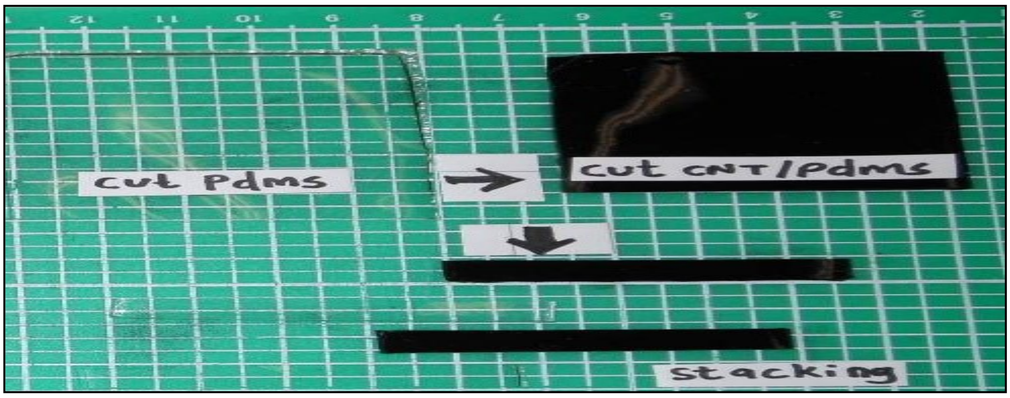


Figure 11: DEA stack assembly process.

Comparison between molded and spincoated stacks.

The samples were arranged side by side for ease of comparison as shown in Figure 12. The samples are both 1.5 mm thick and four layers stack in height.

(a) Spincoated DEA	(b) Molded DEA

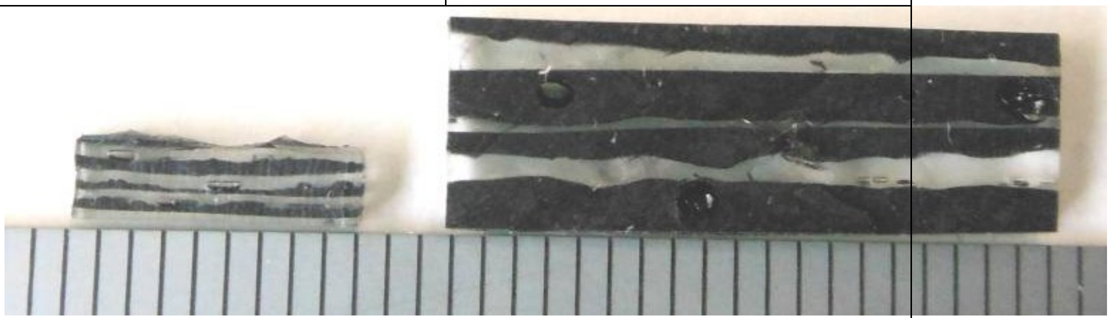


Figure 12: Lateral cross sections of spin coated DEA versus molded DEA

In both cases, it can be observed that there is lack of uniformity of the thickness of the dielectric and the electrodes. This could impact on the reliability, functioning and durability of the actuator due to short circuiting of current. This lack of uniformity is common in DEA and was also reported by Poulin *et al* (2016). The uniformity can be improved through better dispersion methodologies for the MWCNT/ PDMS mixture. Improvement of the dispersion will for basis for further research.

CONCLUSION

We have demonstrated the development of stack dielectric elastomer actuators from multiwalled carbon nanotubes (MWCNT) mixed in the polymer matrix polydimethylsiloxane (PDMS). We found that by increasing spin coating speeds, thin films could be obtained.

Through FEA, we showed that decreasing the thickness and the increasing the layers of stacks can lower the working voltages and increase the overall deformation, respectively. The proposed method could be useful when making low voltage driven DEA's that have large deformation.

ACKNOWLEDGEMENT

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REFERENCES

Khosla, B. L. (2009). Preparation, characterization and micromolding of multiwalled carbon nanotubes polydimethylsiloxane conducting nanocomposite polymer. *Materials Letters*, Pages 1203-1206.

Khosla, D. H. (2011). Large scale micropatterning of multiwalled carbon nanotube/polydimethylsiloxane nanocomposite polymer on highly flexible 12*24 inch substrates. In m. A. Maher (Ed.), *SPIE*, *7926.*

Poulin, A., Rosset, S., .& Shea, H.. (2016). Fully printed 3 microns thick dielectric elastomer actuator. *Electroactive Polymer actuators and Devices (EAPAD) 2016* (p. volume 9798). Las Vegas: SPIE.

Susan, A., & Kurian, T. G.-S. (2016). Printing of CNT/silicone rubber for a wearable flexible stretch sensor. *SPIE 9798, Electroactive Polymer Actuators and Devices (EAPAD)* . Las Vegas: SPIE.

Susan, A., K. T. (2016). Printing of CNT/silicone rubber for a wearable flexible stretch sensor. *Electroactive Polymer Actuators and Devices (EAPAD). 9798.* Las Vegas: SPIE.

Bar-Cohen, Y. (2004). *Electroactive Polymer Actuators as Artificial Muscles.* Washington: SPIE.

Carpi, C. A. F. (2007). Folded dielectric elastomer actuators. *Smart Materials and structures, 16*, S300-S305.

Federico Carpi, D. D. (2008). *Dielectric Elastomers as Electromechanical Transducers.* Netherlands: Elsevier.

Kadooka K., I. H. (2016). Tactile sensor integrated dielectric elastomer actuator for simultaneous actuation and sensing. *Electroactive Polymer Actuators and Devices (EAPAD). 9798.* Las Vegas: SPIE.

Kadooka, H. I. K.(2016). Tactile sensor integrated dielectric elastomer actuator for simultaneous actuation and sensing. SPIE 9798, Electroactive Polymer Actuators and Devices (EAPAD) . Las Vegas: SPIE.

Asaka, H. O. K. (2014). *Soft Actuators.* Tokyo: Springer.