Dielectric Elastomer for Energy Harvesting: Simulation of Different Electrodes

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***Abstract*—This paper discussed the simulation of the dielectric elastomer as electroactive polymer (EAP) where it can exhibit to certain expansion area. The dielectric elastomer (DE) as theoretically is a capacitor where it can function as the energy harvester and has been developed as a material in which can adapt with many application such as sensors , actuators and generators. DE is the type of polymer in which it can be expanded by injecting voltage toward it. The behavior of DE is simple as it can be strained or deformed to certain condition from existence of electric field flow through the structure. In order for the elastomer to expand to its full potential the suitable electrodes are required within the geometry. The electrodes function to transfer the voltage supply toward the elastomer of nonmetal material. The combination of the elastomer and electrode best explain as it sandwiched where the elastomer is placed between the terminal electrode and ground electrode. As the DE function to expand the need, a better study on the properties in terms of its deformation area is made. From this research, the simulation is made in determining the electrode material and the parameters that improve the performance in strain condition. COMSOL Multiphysics is used to simulate several different types of electrode tested on DE structure.**

***Index Terms*—Dielectric Elastomer; Electric Field; Electrodes; Strain.**

I. INTRODUCTION

Nowadays the dielectric elastomer (DE) is widely used in many industrial areas to help ease of mankind. DE is a class of EAP where it has good potential to be functional as active structures when the large deformation is needed. The DE work as it transforming the electrical energy into mechanical work. The force attraction between the electrodes squeezes the incompressible soft polymer film DE thereby causing the change in area and thickness.

The DE can function well with the aid of good and compliant electrode. The electrode is used to attach the DE and act as the role for the electromechanical performance of the elastomer [1]. The electrode that is used must typically have very good compliance so that it can make the DE can undergo a very large strain toward the DE [2].The surface conductive of the electrode is needed for large area strain such that it could make the charge flow onto the electrode and maintain the deformation of the dielectric film.

The compatibility of the electrode also plays a big role in the performance of the DE. In order to make the DE can overcome the large deformation during actuation the electrode should deform without imposing any restraint while maintaining the conductivity. The ideal electrode must have high conductivity, perfect compliant and patternable thus allowing uniform charge distribution over the surface of the film under an electrode.

The electrode is defined as the connector to link between nonmetallic parts in a circuit which best explains as a conductor. Table 1 shows various types of electrodes that were used in developing the technology of the actuator based on the elastomeric polymer. The best electrode item should have the good retain in conductivity with strain, should be low cost and low conductivity. From this research there are some best electrodes that have been selected for its properties to carry out in differentiating its performance in COMSOL. The selected electrode in this research is the graphite, carbon powder and carbon grease.

Table 1
Characteristic of Electrodes

Properties	Carbon Powder	Carbon Grease	Graphite Powder
Appearance	Black powder	Black Grease	Black Powder
Physical State	Powder	Paste	Nano powder
Density	2.267 g/cm3	2.7 g / ml	2.26 g/cm3
Boiling Point	4200 °C/7592°F	200°C/392°F	4027 °C/7280.6°F
Melting Point	3652 - 3697 °C	-	3550 °C
Thermal Conductivity	119-165 W/m/K	-	6.0 W/m-K
Appearance	Black powder	Black Grease	Black Powder

S. Michel explains that many types of electrodes that have been used in research toward developing many application such as transducer and sensor [8]. The number of electrodes being used are various and some are carbon nanotubes, metal electrodes and graphene to conduct the best stretchable electrode. Then for the application of the transducer in DE where functioning to convert from one form energy to another the common electrodes being used is the carbon blacks to act as the grease. Nevertheless, the performance of the electrode depends on the suitability of the application needed [5].

The experiment is conducted to show the effect of the electrode resistance to endure the elastomer under strain [9]. The resistance is the important module which can affect the performance of the DE. The graphite electrode is one the electrode being tested which give the different behavior as compared with others electrode which are the carbon conductive grease, silver conductive grease and conductive rubber. Graphite electrode gives the best actuation force toward the DE.

Through the entire connection whenever the input connected with the DE there is such energy and signal consideration. One of it is the strain ability of the elastomer can hold up whenever conducting with different types of electrodes. There is also some others consideration toward the flow of the charge from the input supply with the electrode and how it relates to the formation of the DE. Next, knowing that any motion required force thus making that the number of force encountered by the elastomer film needs to be studied and understand before further application required. Then from here the study on a parameter that affects the deformation is needed in study toward the properties within electrode and elastomer.

Regarding strain capacities and vitality thickness, the qualities of DE are like those of regular muscles, and they both react to electrical boost by an adjustment fit as a fiddle. Thusly, DE is once in a while nicknamed as artificial muscles [10]. Their vast strains and constrain capacities, coupled to their inborn direct movement and low weight, make DE extremely fascinating contender to an expansive scope of utilization.

Generally, the elastomer material is chosen from the acrylic material in which the VHB 4910 type was specified in membrane state. This types of elastomer give the best and suitable actuation strain almost up to 200% [11]. This material is widely being used by many manufacturers for large area present application nowadays.

Nevertheless, the electrode has to endure the expansion where it needs to have a stress-strain condition where it has to follow the DE as it sticks together. The greater part of the macroscale DE have electrode made of conductive carbon particles (carbon black), O'Brien [12] tried three distinctive strategies to make carbon-based electrode for self-detecting applications. The electrode having the resistance-strain conduct of free carbon powder, silicone-bound carbon powder and carbon oil. Free powder was found to be the best arrangement in term of electric properties, with low commotion and nonappearance of hysteresis. Be that as it may, it experiences exceptionally poor attachment of the powder on the elastomer. Thus, suspension of powders in oil or silicone are for the most part favored, as it stays conductive everywhere strains and offers better grip to the elastomer.

A straightforward capacitor comprises a dielectric medium sandwiched between two terminals which is the input and the ground electrode. At the point when a voltage is connected over the terminals an electric field is made that causes the collection of charged particles on either side of the DE. The electric field is guided from the decisively charged plate to the adversely charged plate. The most straightforward geometry of a capacitor is the parallel-plate capacitor where the cathodes are accepted to have a rectangular shape. The capacitance C is utilized to measure how well a capacitor can store charged particles [13]:

$$Q = CV \tag{1}$$

where Q = charge exerted on the elastomer storage.
C = capacitance value
V = potential difference

From Equation (1) it shows that the charge is the result of the capacitance with the volume of the DE stick electrodes. Application of a voltage prompts to a charge Q on the electrodes. The time rate of progress of Q relates to the present current I. Charge Q on the terminals and voltage are connected. Most vitality observations in writing are detailed by either a consistent voltage or a steady charge [14].

No current will flow through the dielectric material at the point voltage is connected, yet there will be a partition of charged particles. The positively charged particles will move toward the electric field while negatively charged particles will move the other way. Therefore, there will be gathered of inverse charges on either side of the DE. The oppositely charged particles will involve each other and so forth charges on every electrode will repulse each other. This brings about Coloumbic forces that pack the elastomer in the thickness heading and extends the film in the planar course. Since elastomers are almost incompressible the compression in thickness will likewise prompt an important development in DE.

An electric field is characterized as space (field) in which if there is put a little positive test charge, there will be a drive applied on this test charge. The extent of the electric field quality is given by the proportion of Equation (2) ,

$$\vec{E} = \frac{\vec{F}}{q} \tag{2}$$

where E = electric field
F = repulsive / attractive force
q = magnitude of charge

The electric field is the vector quantity in which is taken in becoming the direction that leads the small positive charge will flow. The charge distribution or other charges are needed in producing the electric field, where inside the structure of the DE the charge in which accumulated both the electrodes will create the electric field.

At the point when an electric field is connected over the electrodes, the columbic force creates the stress called Maxwell stress [16] that pulls in different electrodes together and presses the sandwiched DE layer. Thus, the in-plane extension of DE can be seen because of elastomer incompressibility.

$$P = \varepsilon_0 \varepsilon_r E^2 \tag{3}$$

where ε_0 = permittivity of the free space
ε_r = permittivity of dielectric
E = is the electric field encounter in the DE.

As shown in Equation (3), both electrodes attracted from the electric field based on the Maxwell stress in the elastomer

Examining the electric field appropriation in the DE material gives a more prominent comprehension of how the profile of the compliant metal terminal may possibly impact the electrical breakdown properties [4]. The enhancement of an electrostatic force and the gathering of charge on the electrodes are drawn in each other proportional to the area of the consistent metal electrodes. The attributes of the electric field are different layers of the DE material, too the impact of conceivable manufacture absconds (infiltration of the metal electrode into the elastomer body and the nearness of air rises in the elastomer [15].

Electrostatic force emerges just at the interface between the electrodes and the elastomer. The elastomer acts as an uninvolved layer and no immediate collaboration happen between electrical field and its mechanical properties. This reality was affirmed tentatively by [9], who exhibited that electrostrictive impacts are unimportantly little for VHB 4910. In this way, the constitutive model of the elastomer incorporates just simply mechanical equation while the electromechanical coupling is considered through active limit conditions speaking to the electrostatic force. At the point when an electrical voltage is connected between the cathodes, an electrostatic field happens and the electrostatic powers from the charges on the anodes press consistently the (incompressible) elastomer film. Subsequently, the polymer material is extended flexibly in the plane (Maxwell push). When the voltage is turned off and the cathodes are short-circuited the capacitor contracts back to its unique shape. The watched reaction of the polymer film is brought on basically by the collaboration between the electrostatic charges on the terminals. In light of the standard of operation of delicate DE, basically two headings to perform conflict with outer burdens are conceivable:

- Work in planar headings (growing actuator): Under electrical initiation of a DE essential unit the film extends in planar bearings and can consequently conflict with outside weight stacks in both planar headings.
- Work in thickness heading (contractive actuator): Under electrical enactment the anodes press the DE film in thickness course. Therefore, the actuator can conflict with outside elastic burdens acting in thickness heading.

It ought to be noticed that the electrostatic weight of a DE is double the one of a parallel-plate capacitor, because of the commitment to the change in electrostatic vitality. Physically, this is clarified by the reality that on a terminal, the charges repulse each other and tend to expand the electrode's zone, which adds to the disfigurement. In spite of the fact that this sidelong constrain is additionally present in parallel plate capacitors, it cannot add to the distortion in light of the unbending electrodes [17]. For consistent charge operation, spreading the charges of the same sign (expanding the region) and bringing inverse charges nearer (diminishing the thickness) both add to the lessening of electrostatic vitality.

II. Methodology

A. Experimental Method

Different types of electrode are being used in this experiment to measure the effect of stress and strain on the elastomer. These subjects were the three types of the electrode, elastomer, and the input supply. In many situations, the usually experimental method was adapted rather than software simulation. Nevertheless, using software sometimes give a better and responsive toward the idea and expected result.

The elongation of the elastomer as the main objective in developing the experimentation. The strain will remain conductive based on few characteristic for what is relates which are the types of the materials used, the conductor within it and the input supply. As the types of materials needed for the application is the elastomer in the class of polymer. Acrylic VHB 4910 is chosen to act as DE.

Table 2
Characteristic of acrylic polymer VHB 4910

Properties	Acrylic VHB4910
Adhesive type	Clear firm adhesive
Tape Thickness	1.0mm
Color	Clear
Temperature Resistance (Minutes Hours)	149°C
Temperature Resistance (Days Weeks)	
Min surface temperature	10°C
Maximum Operating Temperature	93.33°C
Young’s modulus (kPa)	220
Shear modulus (kPa)	73
Strain at failure (%)	860

B. Electrostatic Pressure

When the voltage arises at the DE, it will act to strain the elastomer mechanically. This occurs immediately as the electrode which act as conductor encounter force with the aid of electric field on it. The electrostatic force that ascends is only between the electrode and elastomer. Then, this force is being produced as the voltage give the roles onto the electrodes. The electrostatic force equation described in Equation (4).

$$p = \varepsilon_{\circ}\varepsilon_r \frac{U^2}{z^2} \quad (4)$$

where: p = electrostatic pressure,
U = voltage applied,
z = the thickness of elastomer,
ε_o = permittivity of free space
ε_r = permittivity of DE.

The electrostatic pressure is calculated from this simulation requirement. When electrostatic occur in the structure of the elastomeric polymer between the electrodes, the force enables the DE to strain. This condition leads the DE to change in the thickness where it becomes thinner but expand in size.

In many literatures, the value for the permittivity of free space $\varepsilon_{\circ}$ is given as $8.85\text{x}10^{-12}$ F/m while the relative permittivity of the DE for the acrylic polymer is 4.7. F/m In order to calculate for the electrostatic pressure, the value of input voltage is taken in example 3 kV and the thickness z of the DE is 60μm. From all those value obtain and following the formula the electrostatic pressure will be 104 kPa approximately.

C. Physics in COMSOL

In this software the main part to be set are the physics. This element needs to set up before conducting the simulation. From this experimental, the required physics used are electrostatic and also structural physics. First, the electrostatic physic used to determine the terminal, ground and also the electric potential flow through the material of the union combination DE.

Next, the structural physics are functioning in developing the stress-strain occur within the material. By using Von Mises stress the study is focusing on the load toward the DE behavior. The load here refer to the voltage apply toward the terminal part of DE. Whenever both physics are combined in the simulation it collaborates in determining the deformation of the DE based on the types of electrodes being used.

D. Geometry

Referring to the simulation software, the geometry that been design refers to 4 part of the material. There are the electrode, elastomer and also fixed material as a base. All those material are connected together through union function to make sure each part of the component sticks together.

The size geometry of the electrode refers to the compatibility of many references from research before is both are having 25mm width and 0.5mm height. The DE is 25mm width and 1mm height. The DE refers to the acrylic VHB 4910 geometry appendix which having 1mm thickness. Another part of the geometry is the fixed material which functions as a base for the material sizing in 30 mm width and 0.25mm height.

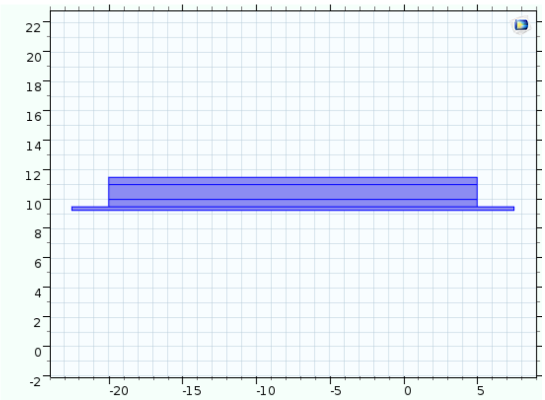

Figure 1: Geometry design of 2D DE

E. Properties of Materials

The benefits of this software are it has many types of materials that can be chosen inside the materials library. Once the material has been selected, the properties of materials also can be set up on which value to be used. The selected value also can be select either the one from the original or even defined by the user based on the requirement needed. In the electrodes section, there are three types of electrodes being used which are the carbon powder, carbon grease and graphite. Each of the element has its own specific types where the graphite electrode, carbon powder and carbon grease are taken from the Graphite Merck 4206, Ketjenblack 300 J and Nyogel 456G respectively. The materials properties needed in the formation of DE is presented in Table 3. The difference in properties will leads to the different behavior of dielectric deformation and its ability to strain.

Table 3
Properties of electrodes use in COMSOL

Electrodes	Relative Permittivity	Young modulus	Poisson Ratio
Ketjenblack EC 300J	7	$5.5x10^9$ Pa	0.4
Graphite Merck 4206	16	$10.5x10^9$ Pa	1
Carbon Grease Nyogel 756G	9	$7x10^9$ Pa	0.6

III. RESULT AND DISCUSSION

A. Electric potential through elastomer

The electric potential is the main toward the DE behavior. In any condition of the elastomer to react such as expand or elongate the first things to be discussed is about its capability. From this simulation, applying voltage on the structure giving the range of voltage potential that can pass through the connection between the elastomer and the electrodes.

Figure 2 shows the result of electric potential that occurs on DE. By applying 2 kV on this geometry structure the deformation takes place.

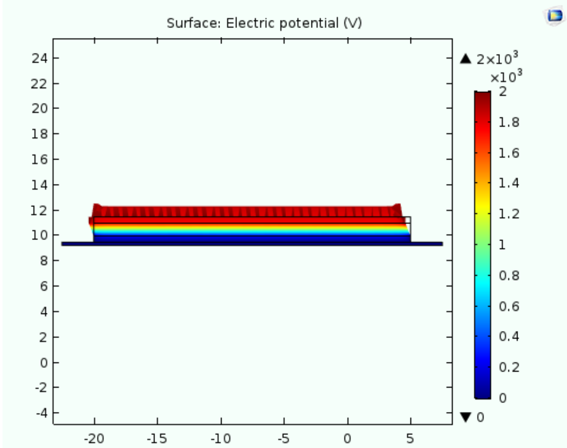

Figure 2: DE expansion with graphite electrodes

The graph in Figure 3 was obtained by using graphite electrode describe from Table 3 for an approximate result. In contrast, the expansion of the elastomer can be seen from Figure 4 where the structure expanded from its original shape.

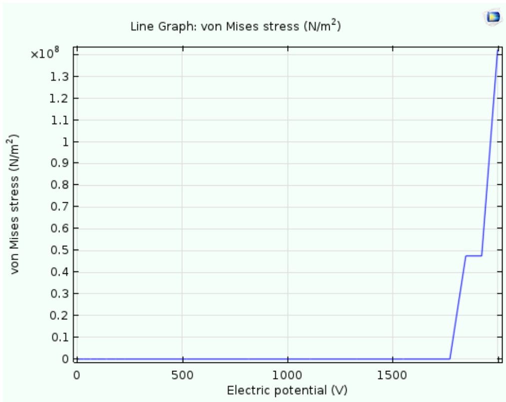

Figure 3: The stress versus electric potential for graphite electrodes graph.

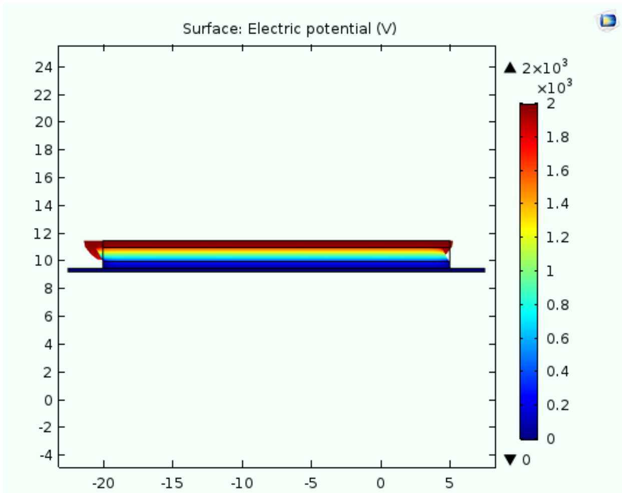

Figure 4: DE expansion with carbon grease electrodes

As the voltage starts from 1.75 kV the stress starts to appear increasing steadily until reaching 0.05G N/m^2 from Figure 3. The stress then achieves its final strain about 1.45 GN/m^2 with electric potential at 2 kV. This result shown that the relationship of electric potential and stress behavior when using graphite electrode are better. This shown when, the linear and steady increasing of the data tendency whenever electric potential are applied toward the dielectric elastomer.

The use of carbon grease electrodes shown the result of the terminal electrode having the highest electric potential about 2 kV and the elastomer of acrylic received the middle amount of electric potential, 1.2 kV. From this simulation, shown that the DE skewed to the left of the geometry structure.

Figure 5 shows the graph that describes the natural behavior and the tendency to expand which are the higher, lower and middle condition occur in the graph. From here, the stationary state is between 0 and 1.750 kV. At 1.750 kV, the stress increases to 1.5 MN/m^2 before staying constant until 1.85 kV. The highest stress was achieved at 4.75 MN/m^2 where the applied voltage is 2 kV. The final stress carbon grease electrodes can withstand much lower than graphite electrode can exhibit.

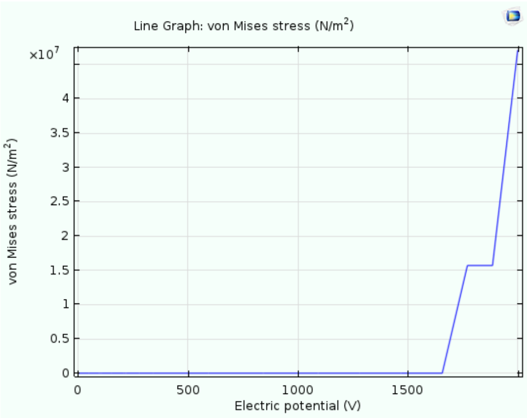

Figure 5: The stress versus electric potential for carbon grease electrodes graph.

Figure 6 shows the used of carbon powder as an electrode in the formation of DE. It can be described that, the value of electric potential or electric field occur on the structure are different compared with other electrodes. This showed that the flow on the terminal of the carbon powder is about 1.7 kV and the value decreases until reaching the ground electrode.

The deformation of the DE is expanding but in the condition of sliding. The expansion still exists in where it helps the elastomer to expand even as not expected.

Carbon powder as electrode result is shown in Figure 7. The relationship between the stress and electric potential shown not a good connection. The behavior of the dielectric elastomer shown much different as compared to others electrode. At the beginning of the graph shows the decreasing and fluctuating trend when the voltage flow through it. This demonstrates the unstable condition of the carbon electrode due to the scattered particles with the difference in distance.

The deformation of this dielectric is poor to withstand at higher electric potential. Referring to the deformation of the dielectric elastomer by using carbon powder, the elastomer expands but lower than carbon grease.

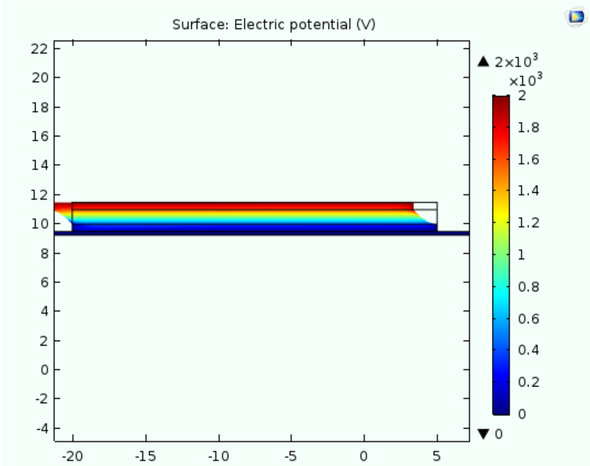

Figure 6: DE expansion with carbon powder electrodes.

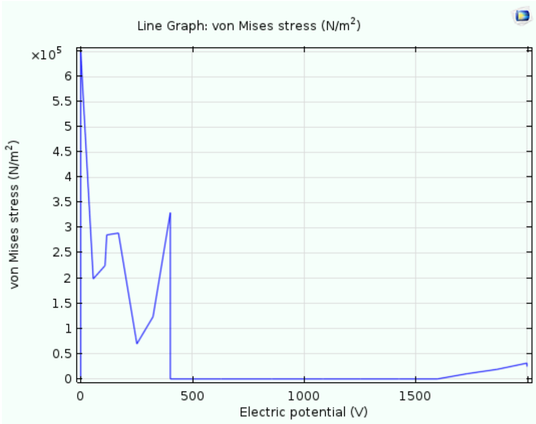

Figure 7: The stress versus electric potential for carbon powder electrodes graph

IV. Conclusion

Simulation of DE by using COMSOL Multiphysics has met the objectives where the deformation of DE by using different types of electrodes has shown its performance. In this work, three types of electrodes have been chosen wherein types of graphite, carbon grease and also carbon powder. The electrodes have been chosen from research made of the previous study.

From the results, the graphite electrode gives the best result. The shear stress showed the highest value at 2 kV. This best performance of graphite electrode indicates that the conductivity value and high of dielectric permittivity number will give the best output.

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