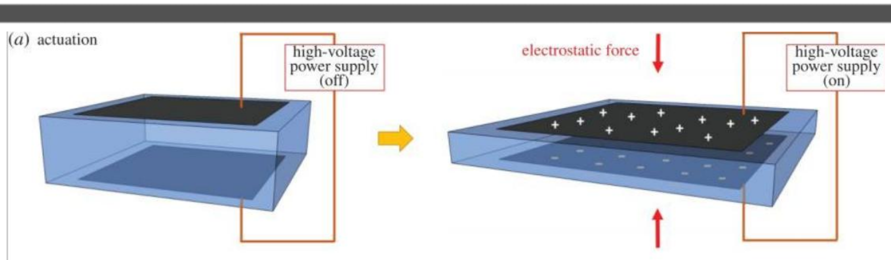
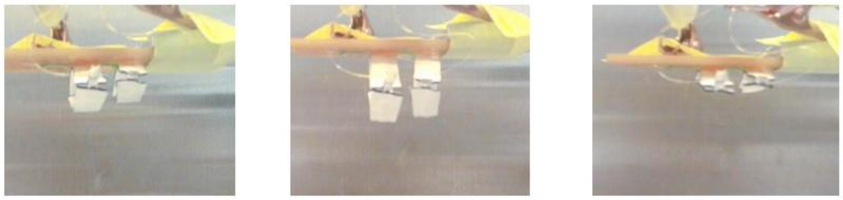
ELECTRO-ACTIVE POLYMERS

By Owen Brady



Electronic electroactive polymer in action [5]

Ionic electroactive polymers displaying bi-directional movement. [10]



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Introduction

Electroactive polymers are defined by their ability to change shape when stimulated by an electrical charge. Specifically, it is their ability to uniformly expand or bend bi-directionally that classifies these materials. The first electroactive material was discovered in 1880 by Wilhelm Roentgen, where he observed a rubber band change length when subjected to an electric field [1]. In modern times, electroactive polymers (EAP's) are sought after for a variety of reasons, such as their large strain, relatively low manufacturing costs, fast response times, and elastic energy density [2]. Furthermore, EAP's can be used as actuators, sensors, or generators [2]. They also have a wide variety of detailed applications such as artificial muscles, supercapacitors, or biomedical drug release agents [2]. There are two main types of EAP's, namely electronic and ionic. Electronic EAP's decrease their thickness to expand uniformly in the other two directions, whereas ionic EAP's can bend in opposite directions based on the input voltage.

Electronic Electroactive Polymers

Electronic EAP's are materials that change their thickness when subjected to electrical charges. They consist of three layers of specific materials, all of which act together to convert electrical energy into mechanical motion. Electronic EAP's are divided into different classification depending on their overall design [2]. The list of common electronic EAP's contains the following classes:

- Dielectric Elastomers
- Ferroelectric Polymers
- Electro Restrictive Graft Elastomers
- Liquid Crystal Elastomers

Material Structure and Properties

The electronic EAP is generally conceptualized as a polymeric film sandwiched between two conductive electrode layers. An example of this can be seen in figure 1, where the light blue layer is the polymeric film, and the grey layers are the two electrodes [3].

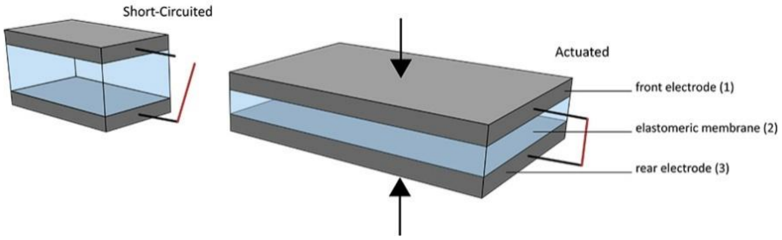

Figure 1: An electronic EAP in its before and after state. [3]

Firstly, the EAP starts with a good quality polymer middle. A good candidate will be incompressible, meaning instead of increasing its density, when an external force is applied it will redistribute its mass and shape to maintain the same volume. Furthermore, a good polymer candidate will be able to provide values of up to 380% linear strain [3, 4]. Three materials that stand out as exceptional options are silicones, polyurethanes, and acrylic based polymers [3]. Silicones can be operated in a wide variety of temperatures while maintaining fast activation responses [3, 5]. Polyurethanes have a larger force output than either silicones or acrylics, while the latter option provides a great dielectric strength [3].

Secondly, the EAP must have electrodes with specific qualities as well. Due to the extreme actuation of the polymer middle, the electrodes must have similar elastic properties and conduct efficiently when under extreme tensions. Furthermore, they must also be super thin and contain great bonding capabilities [3]. Therefore, materials such as metal, carbon black, or graphite powder are ideal candidates [3].

Operation

The two electrode layers maintain a neutral state until they are connected to a DC circuit, where they pick up opposite charges. This results in a coulomb force, an attraction of particles due to the difference in electric charge between the two electrodes [2, 6]. When a large enough force is applied, the two electrode layers press in towards each other, which compresses the middle layer. It is this action that causes the EAP to actuate, for as the thickness decreases the area increases equivalently. The expansion comes from the fact that the polymeric film is incompressible. The only two axis it has left to redistribute its volume, instead of compressing, is along the planar face of its orientation, perpendicular to the force acting upon it, as shown in figure 1.

The force applied over the material area is known as the Maxwell Stress [2]. This stress can be calculated using the following formula.

$$\sigma_{Max} = \epsilon_0 \epsilon_r E^2$$

Where ϵ_0 is the vacuum permittivity,ϵ_r is the relative permittivity, or the dielectric constant of the polymer, and $E^2$is the square of the electric field, which is calculated by $E = \frac{V}{t}$, where V is voltage and t is thickness [2].

While current draw is low for electronic EAP's, the operating voltage is high. For dielectric elastomer types, this voltage can be anywhere between 1-10kV [2]. This means that any electronic circuit where it is integrated needs to be designed with this in mind. High voltages can be dangerous when dealt with incorrectly, which leads to a greater risk of safety. This has been the focus of scientific studies surrounding electronic EAP's, where ongoing studies are trying to reduce the overall operating voltages.

The electronic EAP can be used as either an actuator, sensor, or generator. Firstly, the main purpose is to act as an actuator, which is a device that converts electrical energy into mechanical motion in one or more directions. Secondly, due to its design, any pressure or alteration of its shape will result in a varying level of resistance across its two electrodes. This property can be measured to create reliable flexible sensors, as seen in figure 2. Furthermore, the change in shape results in electron movement around the material, which can be collected as electrical energy. This means that electronic EAP's can also be used as electrical generators.

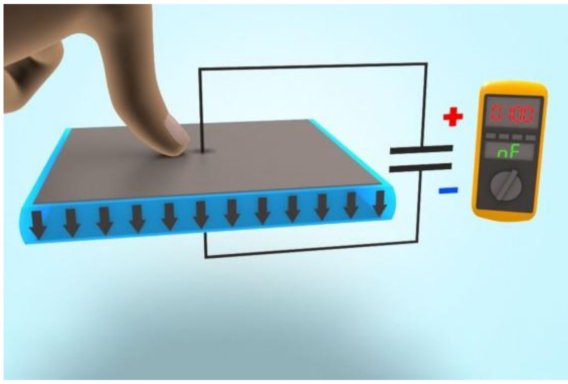
Figure 2: An example of an electronic EAP sensor [9]

Ionic EAP's

Ionic EAP's are characterized by the mobility of ions inside their structure [1, 2, 3]. They are generally conceptualized by two electrodes surrounding an ionic-liquid-carrying polymer. Ionic EAP's are divided into different types depending on the carrier polymer in the center [2]. The list of common ionic EAP's contains the following:

- Carbon Nanotubes
- Ionic Polymer Gels
- Ionic Polymer-Metal Composites
- Conducting Polymers

Material Structure and Properties

Ionic EAP's consist of three main layers, which are two electrode layers surrounding a liquid-based polymer. Figure 3 shows an example of an ionic EAP, where the two green layers are the electrodes, and the blue center layer is the polymer.

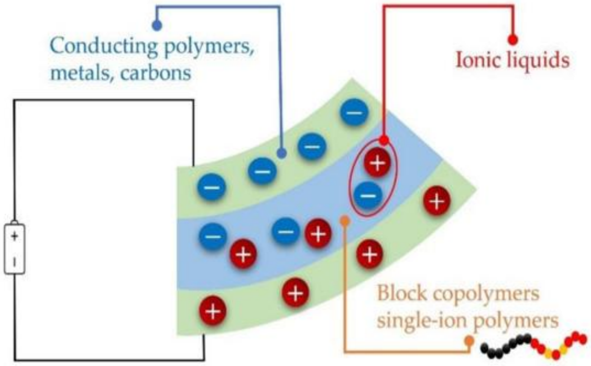

Figure 3: An ionic electroactive polymer [8]

Firstly, the electrode layers should have the similar characteristics to the ones in the electronic EAP. A good electrode candidate will be flexible, super thin, and be able to attach firmly to the polymer center. Ionic polymer-metal composites undergo a specialized process to attach their electrodes. Theses processes involve using electroless plating, electroplating, direct assembly, or sputtering depositions to form the electrode layers that surround the polymer [7]. The materials often selected are platinum, gold, silver, or copper [7]. Other common types of ionic EAP's aim to simplify this process by using different materials for their electrodes such as conductive polymers [7].

Secondly, the polymer membrane in the middle must be specialized to carry or diffuse ionic molecules. The four types of common ionic EAP's are defined by their polymer center [7]. Carbon nanotubes are carbon tubes measured on the range of .4 nm -100 nanometers in diameter, depending on if the tubes are single-walled or multi-walled [2]. They contain an electrolyte in the middle and only require 1 volt to cause strains from 0.1% -1% along the length of a single nanotube [2]. Ionic polymer-metal composites use an "ionomeric membrane $\leq 100\ \mu m$ thick" [2]. This membrane contains a randomized mixture of free-flowing cations and electrons [2, 7]. Ionic polymer gels contain an "ionic liquid in a solid matrix" [8]. They do not contain water, which makes them more ideal candidates for open-air solutions than other ionic EAP's. Conducting Polymers are formed with a membrane in the middle surrounded by two conductive polymers acting as the electrodes. Four common conductive polymers are polypyrrole, Polyaniline, Polythiophene, and polyacetylene [2].

Operation

Ionic EAP's use the location of ions inside its structure for their actuation. A voltage in the range of 1-10V is required to attract the cations and electrons to the oppositely charged electrodes [2, 7]. This relocation results in the cathode side expanding due to the cationic migration [2]. When the voltage stops being applied, the cations and electrons diffuse back to a randomly mixed state [2, 7, 8]. This results in the EAP resetting back to its initial state. A reversal of the electrode charge would result in the cations migrating to the opposite side, which means that ionic EAP's are bi-directional.

On the other hand, the migration of ions inside a polymer membrane is not as fast as the applied electric fields of electronic EAP's. Migration takes up a longer period of time and is often measured in the range of seconds [2, 8]. Furthermore, as long as voltage is being applied, cations will continue to migrate to the cathode side of the EAP [4]. This will result in a continuous bending motion until the voltage is disconnected.

Additionally, conductive polymers have some downsides as well. Due to their malleable nature, it runs the risk of delaminating or deteriorating over periods of extended use [7, 8]. Also, if the voltage level is too high, electrolysis can cause permanent damage to the EAP [4].

Ionic EAP's re-orient their electrons when under mechanical deformation [8]. This means they can be used as either an actuator or a sensor.

Electronic vs Ionic EAPs

The debate on when to use either an electronic or ionic EAP comes down to the specific use case. If a bending motion is required, ionic is the better option. If bending is not the main priority, then an electronic EAP may be the way to go. Table 1 is a list of advantages and disadvantages of both the electronic and ionic EAP's [1].

Table 1: Comparison of the Two EAP Types. Adapted from [1]

EAP Type	Advantages	Disadvantages
Electronic	-Long actuation time in room temperature conditions -Fast actuation response time -Large actuation forces -Maintains shape under DC voltage -High mechanical energy density	- Requires high voltages - Same output direction regardless of voltage polarity.
Ionic	-Large bend angles -Requires low voltage -Bi-directional based on voltage polarity	-Requires an electrolyte -Requires a *protective* layer in open air conditions -Does not hold strain under DC voltage -Slow response times -Low actuation forces

Electronic EAP's offer large actuation forces, high mechanical energy density, and the ability to hold its shape under load, but come at the cost of high voltage operations, and unidirectional movement regardless of input voltage polarity. Ionic EAP's offer large bending angles, a lower voltage range, and bi-directional controllability but do so at the cost of extra requirements and slow response times. Ionic EAP's also differ in that they do not operate well in dry conditions. This is due to their need for an electrolyte to function.

Engineering Applications

The vast applications for EAP's stems from its simple ability to convert electrical energy into mechanical motion, and mechanical motion back into electrical signals. This opens the market to practically any engineering project that moves.

Figure 4: Electronic EAPs in a heel [4]

Electroactive polymers are already integrated in quite a variety of concepts. These concepts range from artificial muscles for soft robotics, to portable electric generators tucked in the heels of army soldiers' shoes [4]. Furthermore, the research and design of these materials are always being worked on, so new possibilities are increasing every day.

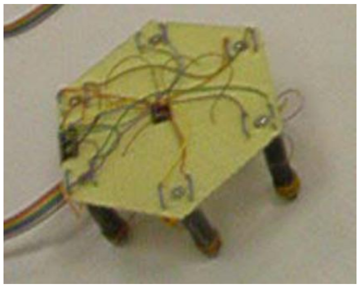

Figure 5: Walking Robot using Ionic EAP's [10]

Conclusion

In summary, there are two main types of electroactive polymers. These two are *electronic electroactive polymers* and *ionic electroactive polymers*. Both types are actuators that extend when under an electric voltage.

Electronic electroactive polymers reduce their thickness due to the applied maxwell stress of layered electrodes. The reduction in thickness is accounted for by an expansion in the planar face perpendicular to the applied force. This actuation mechanism defines them as unidirectional, which means their extension direction can not be controlled.

Ionic electroactive polymers, on the other hand, are bi-directional. Ionic EAP's take advantage of ionic migration to oppositely charged electrodes for their actuation technique. Two electrodes house an electrolyte in the middle, which contain an ionic liquid. The liquid separates when an applied voltage is given to the electrodes, where the EAP will bend in whatever direction has the positive voltage.

The potential applications for both electronic and ionic are quite limitless. Electronic EAP's can be used as actuators, sensors, or generators. Ionic EAP's can only be used as actuators or sensors but offer bi-directional capabilities as well. This opens them up to pretty much any type of engineering application.

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