Pedro Miguel Sá Marques Rocha

IMPLEMENTATION OF A DIELECTRIC ELASTOMER ACTUATOR (DEA) FOR ROBOTICS APPLICATION

Thesis submitted to the University of Coimbra for compliance with the requirements for the degree of Master in Biomedical Engineering under the scientific supervision of PhD Mahmoud Tavakoli (UC).

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UNIVERSIDADE DE COIMBRA

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Integrated Master in Biomedical Engineering

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Author:

Pedro Miguel Sá Marques Rocha

Supervisor:

PhD Mahmoud Tavakoli

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Collaborators

Carnegie Mellon | PORTUGAL

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Face

Fears

First

Agradecimentos

Aos meus pais que sempre me apoiaram e são a base de quem eu hoje sou. Aos meus irmãos pelas brincadeiras e dos quais sinto falta. À minha família pelo apoio que me dão. À Sara Anjo pelo amor e por me acompanhar em muitos momentos do meu percurso. Aos meus amigos pelos momentos que tivemos e teremos. Ao meu orientador Mahmoud Tavakoli pelos conselhos e compreensão. Ao pessoal do laboratório pelo companheirismo e por poder praticar um pouco de italiano. Aos meus professores que em muito contribuíram na minha formação pessoal e académica. Ao DL-LIP, em especial ao Luís e ao Américo pela disponibilidade e amabilidade.

Abstract

Machines in engineering are made out of rigid parts, while the biological systems are made of soft materials. Such conspicuous mismatch is the main motivation for the new area of soft robotics and soft electronics. Applications include soft mobile robots, soft grippers and novel soft human machine interfaces and multimedia devices, e.g. a mobile phone that can bend. Soft robotics and wearable computing require new classes of soft and elastically deformable electronics. The soft-matter electronics must be flexible and/or stretchable in order to accommodate the large motions and deformations involved in applications ranging from wearable sensors and artificial skins to artificial muscles and biologically inspired robots. One particular problem in the area of soft robotics and soft hands is actuation. While considerable progress is made on fabrication methods of the main body of these robots, and excellent advances are reported on integration of the ultra-thin soft sensors, actuation of these systems is still not soft. Pneumatic systems and electrical motors are still the available reliable options for soft robots and soft hands. Both of these systems are rigid, large and suffer from a low power to weight ratio. One option to address this problem are Dielectric Elastomer Actuators (DEAs). DEAs consist in a thin dielectric elastomer film, which is coated on both sides with compliant electrode material. When applying a high DC voltage (in the range of kV) to the electrodes an electric field is induced and, therefore, a mechanical compression of the elastomer film occurs. Recent on this type of actuator is receiving and increasing attention. This includes research on different materials, fabrication methods, and different geometries. Objectives are usually to increase the actuation range (stroke), and to show case possible applications. On the presented dissertation, the goal is to gain the know-how on fabrication methods of this class of actuators and compare some of the most accessible fabrication methods and materials that have been used in the last couple of years. By actual fabrication of different versions of these actuators, it is understood some details of fabrication process and their associated problems. The goal is also to use accessible equipment and fabrication methods that can be easily replicated. Within this dissertation, a commercial stretchable tape (VHB) and Poly-dimethylsiloxane (PDMS) based DEAs are prototyped and its production methods accessed. The stretchable conductive materials are also studied, namely carbon grease and eGaIn. The area strain and the bending angle of different actuators are also presented. Finally, different fabrication methods are compared and materials and obtain some conclusions. It is expected that this dissertation can serve as a practical guideline for easy and accessible production of DEAs.

Palavras-chave: EAP - Electro Active Polymer; DEA - Dielectric Elastomer Actuator

Resumo

As máquinas comummente usadas na engenharia são feitas de peças rígidas, enquanto que os sistemas biológicos são compostos por materiais macios (*soft materials*). Esta discordância conpíscua é a principal motivação para a nova área da eletrónica e robótica macia. As aplicações incluem robôs móveis macios, pinças macias, novas *interfaces* humano-máquina suaves e dispositivos multimédia, tal como um *smartphone* que se pode dobrar. A robótica macia e a computação *wearable* requerem novas classes de electrónica macia e elasticamente deformável. O material eletrónico macio deve ser flexível e/ou deformável de modo a permitir a execução de grandes movimentos e deformações envolvidas em aplicações que variam desde peles e músculos artificiais até sensores portáteis e robôs inspirados em sistemas biológicos. Um problema particular na área da robótica macia e das mãos macias é a atuação. Embora se verifique um progresso considerável nos métodos de fabricação do corpo principal destes robôs e sejam relatados excelentes avanços na integração dos sensores macios ultra-finos, a actuação destes sistemas ainda não é suave. Sistemas pneumáticos e motores elétricos ainda são as opções disponíveis e confiáveis para robôs macios e mãos macias. Ambos os sistemas são rígidos, grandes e sofrem de uma baixa relação potência / peso. Uma opção para resolver este problema são os Atuadores Elastómeros Dielétricos (*Dielectric Elastomer Actuators - DEAs*). Os DEAs consistem numa fina camada de elastómero dielétrico, que é revestida em ambos os lados com elétrodos. Quando se aplica uma tensão DC elevada (na gama dos kV) é induzido um campo eléctrico e, por conseguinte, ocorre uma compressão mecânica do dielétrico. Estudos recentes sobre este tipo de atuador estão a ter impacto em termos de investigação e o interesse à sua volta tem vindo a aumentar. Assim sendo, estes residem em pesquisas sobre diferentes materiais, métodos de fabricação e diversas geometrias. Com efeito, os objetivos são, geralmente, aumentar o alcance de atuação e para sugerir possíveis aplicações. Na presente dissertação, o objetivo é obter o conhecimento sobre os métodos de fabricação desta classe de atuadores e comparar alguns dos métodos e materiais de fabricação mais acessíveis que foram utilizados nos últimos anos. Através da fabricação de diferentes versões destes atuadores, são compreendidos detalhes do processo de manufaturação, assim como problemas associados. O objetivo é também usar equipamentos acessíveis e métodos de fabricação que possam ser facilmente reproduzidos. Consequentemente, são prototipados DEAs utilizando uma fita adesiva disponível comercialmente (VHB) e Poli-dimetilsiloxano (PDMS) e os seus métodos de produção são avaliados. Os materiais condutores flexíveis também são estudados, nomeadamente a cera de carbono e eGaIn. A tensão superficial e o ângulo de flexão de diferentes atuadores são apresentados. Finalmente, são comparados diferentes métodos e materiais de fabricação, obtendo-se conclusões. Espera-se que esta dissertação possa servir como uma diretriz prática para a produção fácil e acessível de DEAs.

Palavras-chave: EAP - Electro Active Polymer; DEA - Dielectric Elastomer Actuator

Acronyms

CAD	Computer Aided Design
DC	Direct Current
DEA	Dielectric Elastomer Actuator
EAP	Electro Active Polymer
EGaIn	GalliumIndium Eutectic
IPN	Interpenetrating Polymer Network
PDMS	Poly(dimethylsiloxane)
RT	Room temperature

Chemical Elements

Ar	Argon
Cu	Copper
Ga	Gallium
Hg	Mercury
In	Indium
K	Potassium
Na	Sodium
Ni	Niquel

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Chapter 1

Introduction

In this chapter, the general motivation behind the soft robots in general and Dielectric Elastomer Actuators (DEAs) in particular is discussed. After an introduction about DEAs, the working principle, the mechanical behavior and some application examples of these actuators are presented in this section. Subsequently, the objective is set. Finally, a brief description of the dissertation structure is provided.

1.1 Soft robotics

Traditional robotics are based on rigid materials and hard robots, while the biological systems are made of soft materials. Such conspicuous mismatch is the main motivation for the new area of soft robotics and soft electronics. In fact, soft robotics are hyper flexible and highly adaptive, and their functionality should be enabled and not blocked by large deformations of body parts. These are inspired on the morphology and locomotion of biological systems and some mobile soft robots examples are on Figure 1.1 [1, 2].

In what respects to soft grippers, advances are performed to enhance grasp and manipulation of a variety of objects as seen in Figures 1.2 [1] and 1.3 [3].

Moreover, last evolutions on mobile and soft electronics comprise a bendable OLED touchscreen smartphone prototype - Figure 1.4(a) [4] - and mobile phones which can bend onto users wrist - Figure 1.4(b) [5]

Thus, soft robotics may provide many advantages such as intrinsically safe physical human-robot interaction, efficient/stable locomotion, adaptive morphology which allows

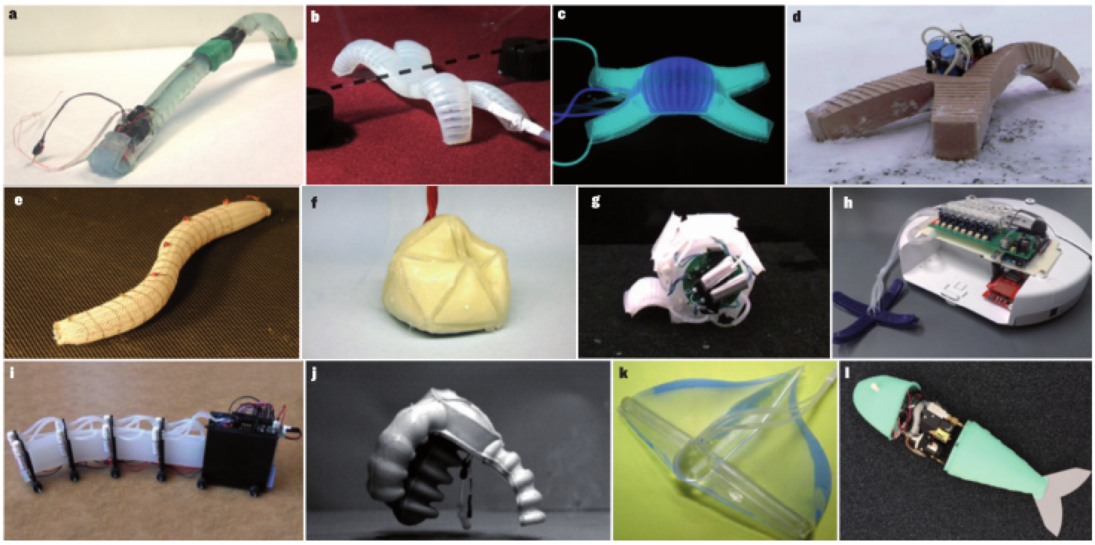


Figure 1.1: Soft robots inspired in biological systems. (a) A caterpillar; (b) a multi-gait quadruped with (c) active camouflage which (d) walks in hazardous environments; (e) a worm. (f) A particle-jamming; (g) a rolling powered by a pneumatic battery; (h) a hybrid hardsoft robot. (i) A snake; (j) a jumping powered by internal combustion. (k) A manta-ray and (l) an autonomous fish [1]

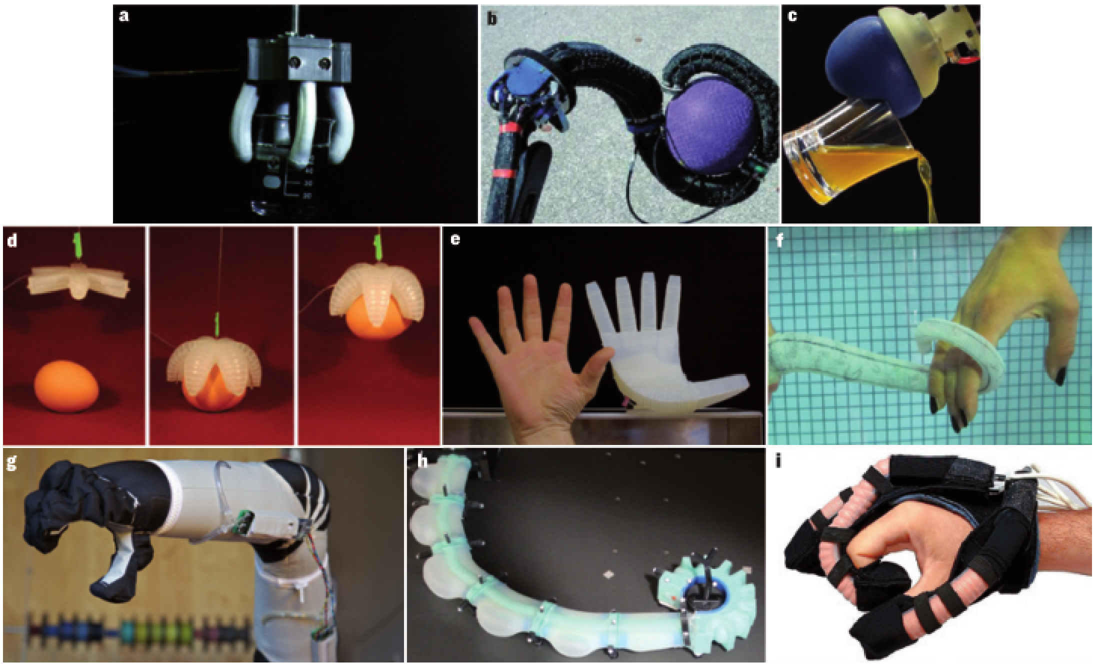


Figure 1.2: Soft grippers. (a) Microactuation, (b) soft-continuum manipulation, (c) grasping with particle jamming, (d) simple gripper fabrication by soft lithography, (e) underactuated dextrous grasping, (f) octopus-inspired manipulation, (g) inflatable robotic manipulators, (h) feedback control of a multisegmented arm and (i) a soft glove for rehabilitation [1]

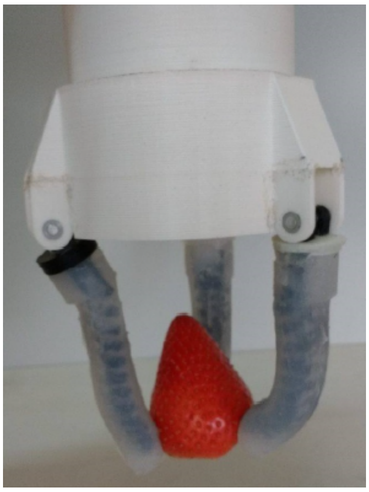
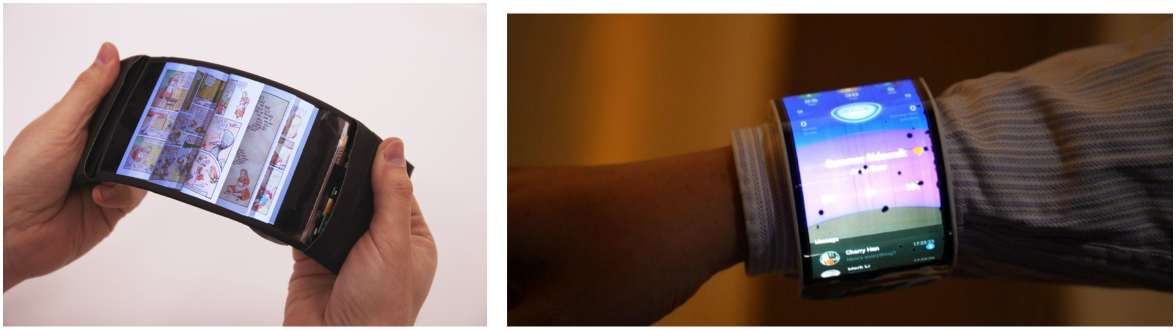


Figure 1.3: Gripper with hydrogel-silicone soft skin and 3D printed endoskeleton [3]



(a) Bendable smartphone prototype

(b) Bendable mobile phone [5]

them to adapt to unpredictable environment. Therefore, they are expected to solve a variety of tasks in a mechanically simpler and computationally more efficient way. The soft-matter electronics must be flexible and/or stretchable in order to accommodate the large motions and deformations involved in applications ranging from wearable sensors and artificial skins to artificial muscles and biologically inspired robots. Progress also depends on the reliable integration of soft electronics with external circuitry [2, 6, 7].

In fact, actuation is a challenge on soft robotics and soft hands field of study. While considerable progress is made on fabrication methods of the main body of these robots, and excellent advances are reported on integration of the ultra-thin soft sensors, actuation of these systems is still not soft. Pneumatic systems and electrical motors are still the available reliable options for soft robots and soft hands. Both of these systems are rigid, large and suffer from a low power to weight ratio.

One option to address this problem are Dielectric Elastomer Actuators (DEAs).

1.2 DEAs

In the last decade, the interest in smart materials - namely soft dielectric EAPs (Electro Active Polymers) - has essentially increased due to its outstanding active deformation potential [8]. Dielectric Elastomer Actuators (DEAs), are a subgroup of EAPs [9]. They were first announced by *Kofod, et al.* [10] back in 2006.

1.2.1 Properties

DEAs are light weight [7,8,10–13], flexible/stretchable [6,7,11,12] show high strain, having high force/weight ratio [9] and short response time [6,7,9].

Therefore, they are adaptable to different applications, which makes them good as soft actuators for conforming and wearable devices [11,12].

1.2.2 Working principle

By applying electrical power to the EAP, it produces mechanical work due to the change in the capacitance. Inversely, application of mechanical work on the DEA causes capacitance variation, which can be detected, that is directly proportional to electric charge [14].

DEA consists in a thin dielectric elastomer film, which is coated on both sides with compliant electrode material [9, 14]. DEA work on the simple principle that opposite charges attract and alike charges repel each other [14] .

When applying a DC high voltage (in the range of several kV) to the electrodes an electric field is induced and, therefore, a mechanical compression of the elastomer film occurs (Figure 1.4) [8, 9, 12, 15].

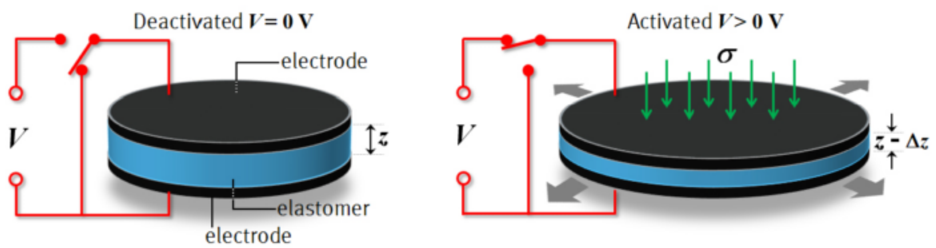


Figure 1.4: Working principle of a DEA [9].

An electric field is applied through the thickness by a pair of electrodes attached to both surfaces of the film. Stretchable electrodes are commonly used to accommodate the large in-plane deformation of the elastomer [16].

Just as in a Parallel Plate Capacitor [14], charge accumulates on both electrodes upon application of the voltage. The electrostatic attraction between the two oppositely charged electrodes, together with the polarization-induced intrinsic deformation of the material (often referred to as the electrostriction), causes a dielectric elastomer to change in thickness and lateral dimensions [16]. This contraction effect can be exploited directly in order to prototype linear contractile actuators. This occurs because the actuation direction is parallel to the electrostatic field lines the electrostatic force can be turned directly into mechanical force [9]. The charges interaction are represented in Figure 1.5. That transmission requires that the electrodes need to have high stiffness and tensile strength in the thickness direction [8].

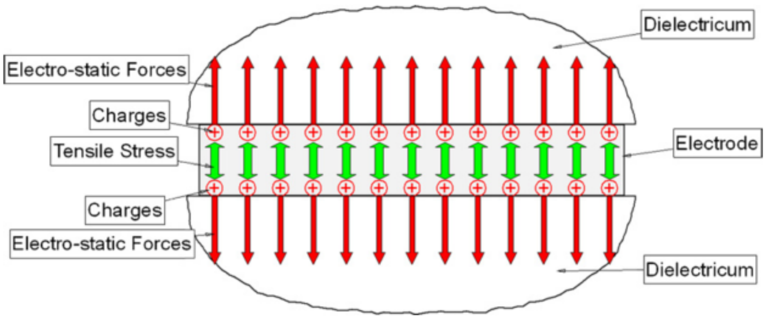


Figure 1.5: Mechanical tensile stress transmission and electro-static forces within the electrode. Interlayer attraction forces create mechanical tensile stress within the electrode material allowing external force to be transmitted from one side to the opposite side of the electrode by the resulting tension stress state of the electrode material [8].

The compressive pressure produced, the Maxwell stress p, is given by,

$$p = e_0 e_r (\frac{V}{t})^2 \tag{1.1}$$

where e_0 is the free space permittivity, e_r is the relative permittivity of the dielectric elastomer and t is the elastomer thickness and the distance between the complaint electrode active areas. The $\frac{V}{t}$ term is the electric field [12]. As soon as the voltage is switched off and the electrodes are short-circuited the film deforms back to its initial state [8].

The compressive Maxwell stress also gives rise to in-plane prestress relaxation (through material incompressibility), causing a change in equilibrium state and thus actuation as described [12].

To prevent buckling or wrinkles, it is preferred that a free- standing dielectric-elastomer film is under tension throughout the entire actuation process, and thus a lateral pre-stretch is usually applied in actuator designs. Pre-stretch is also believed to have a tremendous enhancement to the actuation performance of a dielectric elastomer [16]

1.2.3 Applications

This novel material has several ranges of applications. It can be used for programmable haptic surfaces and interfaces [17–20] like braille displays [15, 18, 19, 21]. Other usability is energy harvesting like shoe generators [21–23], for remote sensors [21, 23] as well as wave and [18–24] and wind energy [21, 22]. Additionally, it can behave as an electrically controlled valve [9, 19, 25]. Moreover, there are applications regarding adaptive optical components [19, 26]. Furthermore, it has a high potential respecting artificial muscles [6, 14, 15, 26–28] mimicking biology and nature [14, 18, 27–29] and even on deformable devices for cell-culture [28]. These actuators are utilized on prosthetic devices [14,21,25,28] and on biomedical applications [16, 19].

1.3 Objective

On the presented dissertation, our goal is to gain the know-how on fabrication methods of this class of actuators and compare some of the most accessible fabrication methods and materials that have been used in the last couple of years. By actual fabrication of different versions of these actuators, we understand some details of fabrication process and their associated problems. The goal is also to use accessible equipment and fabrication methods that can be easily replicated. Within this dissertation, a commercial stretchable tape (VHB) and Poly-dimethylsiloxane (PDMS) based DEAs are prototyped and its production methods accessed. The stretchable conductive materials are also studied, namely carbon grease and eGaIn. The area strain and the bending angle of different actuators are also presented. Finally, different fabrication methods and materials are compared and some conclusions are obtained. It is expected that this dissertation can serve as a practical guideline for easy and accessible production of DEAs.

1.4 Thesis Overview

This dissertation is divided into six chapters.

The first chapter, Introduction, presents the overview on soft robotics and how DEAs can play an important role facing challenges on this area. Therefore, DEAs are described and some general applications are listed. Finally, there it explained how the thesis is organized.

The second chapter, State of the Art, describes techniques for fabrication of DEAs and materials used in the literature. So, stretchable insulators, stretchable electrodes and how they can be patterned is presented.

The third chapter, Materials and Equipment, describes the more important materials in a broden way and lists the others as well as the equipment used. In the end, there are two tables which summarize the material and the equipments used, its models and application.

In the fourth chapter, Fabrication Methods, it is explained the process of manufacturing different types of DEAs. Furthermore, steps and errors upon its fabrication are shown.

In the fifth chapter, Results and Discussion, the outcomes of the previous chapter are presented and discussed.

The last chapter, Conclusions, the most important issues are pointed. There are also tables which summarize and compare the materials regarding its fabrication. Finally, opportunities and future applications are suggested.

In the end, there is also the *Appendix A - Designs*, which include some designs used for frames and stencil patterning.

Chapter 2

State of the Art

Considering the objective of this dissertation, which is to evaluate different fabrication methods and materials, the stare of the art is organized based on the fabrication methods and materials, namely VHB based actuators and PDMS based actuators. VHB and PDMS are both stretchable polymers, the first one a commercially available tape used for bonding surfaces and the second can be obtained as a two liquidpart polymer which can be casted. Each of these materials present different advantages and disadvantages.

2.1 VHB based DEAs

The method for circular VHB-based DEAs fabrication is minutely described by *Soft Robotics toolkit* on its website [30] and it can be seen on the following videos [31].
It is used a VHB 4910 tape which is stretched onto a circular frame. After, the red cover foil of the acrylic tape is patterned and it is a stencil for electrode painting. The conductive electrode used is MG 846 carbon grease. The sample is flipped and the opposite side is painted. Meanwhile, copper tapes are attached on opposite positions and a strip of grease is drawn from each one of these tapes to the center where it was previously painted.

Conn & Rossiter 2012 [32] suggest the construction of a Hoberman pre-strainer. It is also used by *Knoop et al. 2015* [24] and allows a radious pre-stretching of the VHB. *Rosset et al. 2016* [20] use a machine for pre-stretching the DEA (Figure 2.1). In this case, the VHB sticks to metallic pads which retract making the VHB to expand.

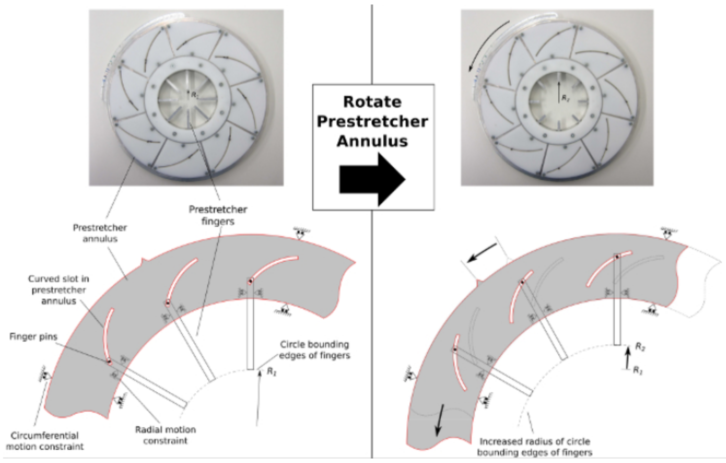


Figure 2.1: Advanced prestretcher for radial strain [20]

Stacked DEAs can be designed with VHB. Its construction is illustrated on Figure 2.2, where an alternate connection to the common line supplies can be observed.

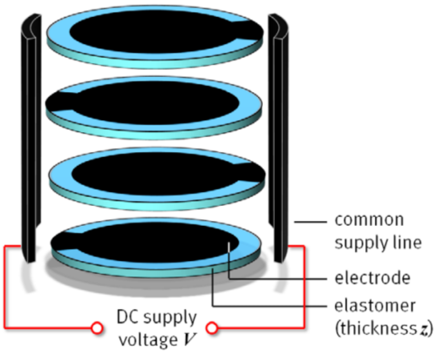
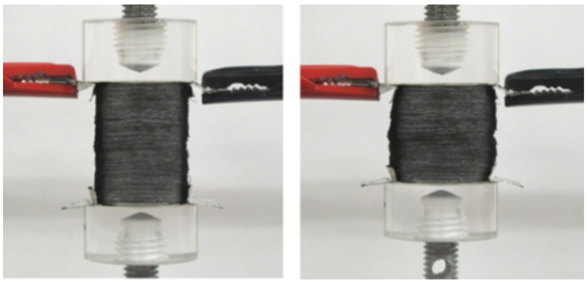


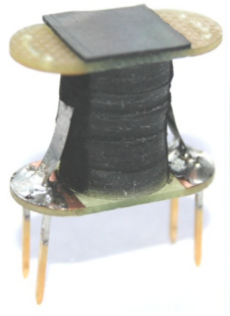
Figure 2.2: Illustration of stacked DEAs disposition [9]

By stacking layers of DEAs, a device for tensile force transmission [8], a contractile actuator ([28]), a pneumatic valve [9] and a power generator ([23]) can be produced - Figure 2.3.

Other conformation is to fabricate a ring with VHB - Figure 2.4. It is obtained by placing a 76.2 μm thick sheet of ABS plastic with the desired pattern on the stretched VHB tape. The carbon electrodes are applied and DEA is cut off from the outer frame. [29]

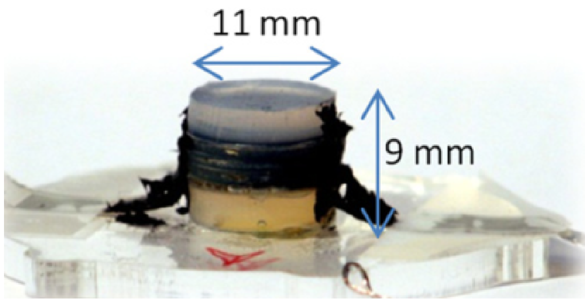
A novel approach is to interprenetrate polymer networks (IPN) to preserve the pre stretched VHB film. In this case, a (1, 6-hexanediol diacrylate) additive is thermo-mechanical cured, preserving a percentage of the strain. The addictive and the VHB do not form chemical bonds; in fact, the individually crosslinked networks simply coexist and interact through physical mechanisms as illustrated in Figure 2.5. [33]





(a) Tensile force transmission. Left: actuator at rest position; right: actuation effect [8]

(b) Pneumatic valve [9]



(c) Power generator [23]

Figure 2.3: Stacked DEAs made with VHB

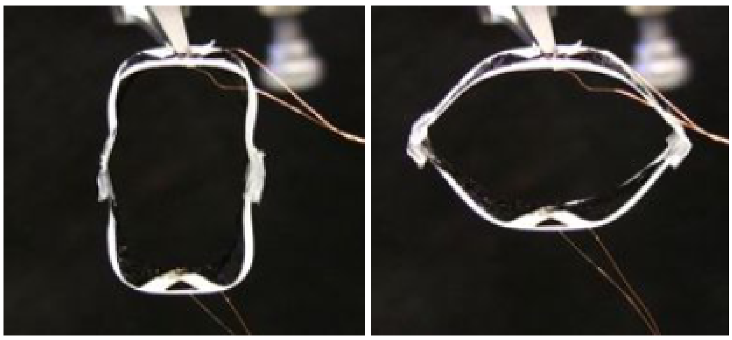


Figure 2.4: VHB ring. Left: rest postion; right: actuation conformation [29]

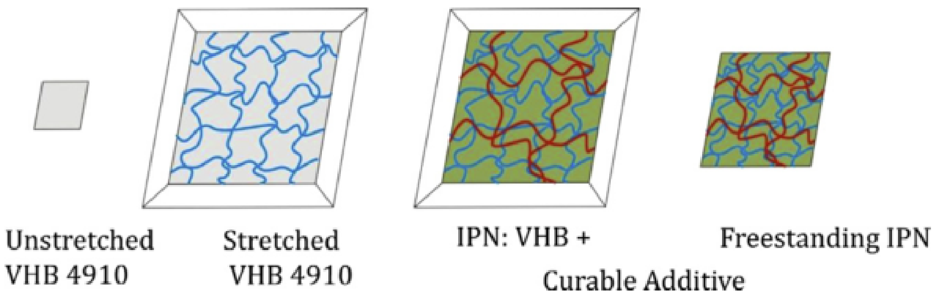


Figure 2.5: Principle of interpenetrating polymer network (IPN) formation [33]

Niu et al. 2013 manipulate the composition to create a rapid stiffening behavior above a certain stretch value, suppressing the onset of electromechanical instability. The films are casted by ultraviolet curing of precursors comprising a mixture of acrylate comonomers. The addition of plasticizing agents increases the sensivity to strain. [34]

2.2 PDMS based DEAs

The PDMS used in the literature are *Sylgard 184* or *186* from *Dow Corning*. Their difference is the curing time at room temperature - 186 has a faster cure time at RT.

PDMS is done by mixing two parts. Thus, to ensure proper linking, a planetary mix is used [20] (*Thinky ARE-310*. This elastomer mixture can be thinned using a silicone solvent (*OS-20, Dow corning*) at 20 wt% solvent fraction relative to the PDMS mixture [11, 12]

DEAs based on PDMS are composed by layers with thicknesses of μm. To cast a thin membrane a *Zehntner ZAA2300 [35]* automatic film coater [11, 12] or a *Zehntner ZUA2000 [36]* variable gap applicator [6, 37] are used - [7, 13] use both. While the film coater allows to set the speed, length, change the base namely for a heating or vacuum plate; the gap applicator lets the user set the film thickness. And so, they can be combined for an efficient membrane production.

The low thickness of film production result in a high surface tension between them and the substrate. Thus, it is hard to peel off. To do so, a *ease release 200* from *Mann* is used [6, 37]. Another possible surface coating for anti-adhesion is in CHF3 plasma treatment [38]. An alternative is to use a 5% poly acrylic acid in isopropanol by weight as a sacrificial layer on a PET substrate is a vacuum table. To separate the membrane from the PET substrate, it is dipped in hot water to dissolve the sacrificial layer [20]. The application of these methods reduce the mechanical deformation of the membrane upon its release.

The stacking of DEAs enables the production of a tactile display - Figure 2.6

More complex DEAs are fabricated.

Araromi et. al 2014 designed a multi-segmented DEME for a microsattelite gripper. It is formed by carbon grease on PDMS and the bending position is obtained by applying a PET frame on the stretched structure. It has a nylon wire to deploy the actuator.

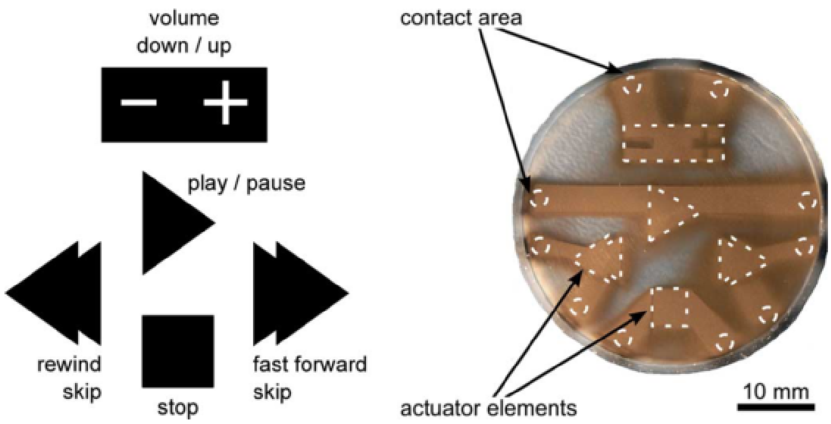


Figure 2.6: Tactile display. Left: buttoms schematic; right: actuator view

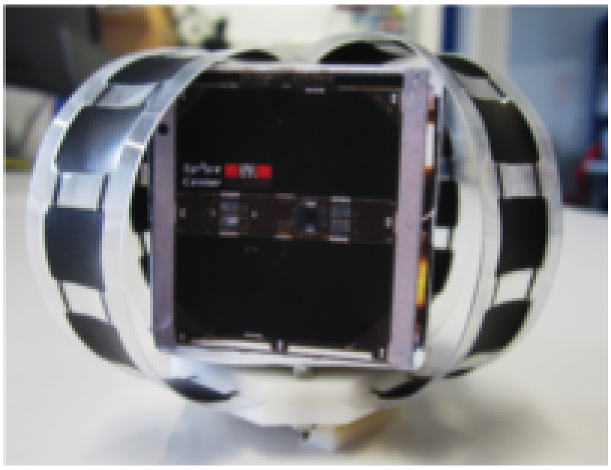


Figure 2.7: Multisegment gripper holding the Swiss Cube sattelite [12]

2.3 Stretchable conductive materials

The stretchable conductive materials used on DEAs are carbon grease, graphite powder, liquid metal, gold ions and carbon nano-tubes. The authors who use carbon grease are [22, 24, 29]; carbon powder is used by [8, 39, 40]. As an alternative, liquid metals are used such as galinstan [37, 41] and eGaIn [6, 41–44]. On its hand, *Duduta et al. 2016* construct a multilayer dielectric elastomers incorporating single wall carbon nano-tube electrodes. These are obtained by spin coating, patterning, UV curing and transferring by stamping the electrodes to a polyethylene terephthalate glycol-modified layer. The result is a DEA with fast and programmable actuation without pre stretch [45].

2.4 Electrode patterning techniques

Regarding the electrode application, it can be applied using a shadow mask which protects selectively the material. The electrode on top of the mask is removed leaving the patterned electrode on the surface. For example, a graphite powder can be mixed with isopropanol (volatile solvent) and, this suspension can be sprayed to the material [40].

An alternative is to use a patterned stamp with the electrode material made of an elastomer and apply it on the membrane.

Another technique is drop-on-demand inject printing. [46]

These techniques are illustrated in Figure 2.8

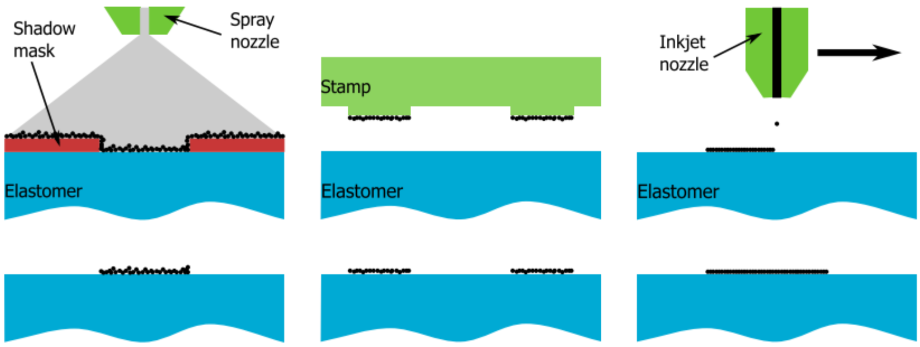


Figure 2.8: Electrodes application techniques. Left: shadow mask; center: stamp; right: inject printing

In fact, *Shintake et. al 2013*, *Araromi et. al 2014* , *Mckay et al. 2015*, and *Rosset et al. 2016* use a *Teca Print TPM101* pad-printing machine which can print a desired area with a controllable thickness for electrodes reproducibility and repeatability.

Chapter 3

Materials and Equipment

The materials and the equipment used will be summarized in this section. The stretchable insulators - VHB^{TM} and PDMS - and stretchable electrodes - carbon grease and eGaIn - are characterized in this section. There is also a brief description for other materials and equipment used. It ends with a summary tables of both materials and equipment.

3.1 Stretchable insulators

3.1.1 PDMS

Polydimethysiloxane (PDMS) is made with the *SYLGARD 184 SILICONE ELASTOMER KIT* from *Dow Corning*. It is is a two-part, clear, 10:1, room temperature and heat cure, good strength, UL and Mil Spec. polymer [47]. PDMS has a repeating unit of $(CH_3)_2SiO$ as shown in Figure 3.1 [48]

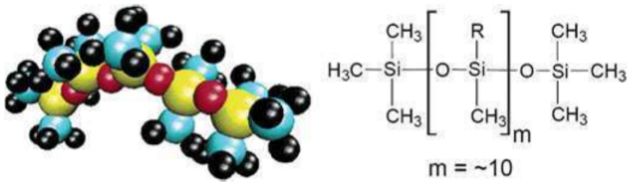


Figure 3.1: Molecular structure of PDMS [48]

The curing/solidification of PDMS is rationalized by an organometallic cross-linking reaction (Figure 3.2). The platinum-based curing agent catalyzes the addition of the Si-H bond across the vinyl groups of the siloxane base oligomers, forming $Si-CH_2-CH_2-Si$ linkages. Therefore, the three-dimensional cross-linking is allowed by multiple reaction sites on both the base and cross-linking oligomers. If the ratio of curing agent to base is increased, a harder, more cross-linked elastomer results [48].

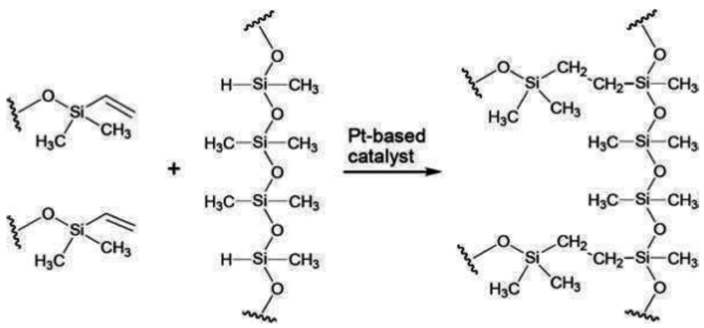


Figure 3.2: Cross-linking of PDMS [48]

The DEAs made with this polymer are water proof, non flammable, non toxic, light weight, and have thickness in the range of 100μm or less [14]. Compared with other materials like polycarbonate, polyimides, polyurethane, polymethyl methacrylate or polystyrene, PDMS has advantageous properties. It typically has low surface interfacial free energy, which enables it to conform to the surface of a master; good elastic characteristic (conformability), which allows it to be easily removed [49]. These two properties and the very low glass transition temperature are associated to the polymer chains packing and the amount of *free volume* [48]. Plus, it has optical transparency, which improves transmission of UV and visible light and chemical inertness; it is non-toxic, biocompatible and durable [49]. Along with these properties, it is low cost and it is gas permeable [50] . Adding to the high difusivity of gases, it has low density which is a repercussion of the larger Si-O and Si-C bond lengths compared to the C-C bond length [48]. Furthermore, PDMS is an inert polymer, lacking conductive and magnetic properties [49], being a good insulator or a dielectric for a capacitor. Added to that, it has a weak metal adhesion making it difficult to pattern metallic structures on its surface or into the bulk [49].

As the material comes in a two part viscous liquid, it has to be made in thin membranes to be used in DEAs. Nonetheless, this gives the user a potential degree of freedom to choose the film thickness and also its shape, concerning the final application.

Generally, authors main advantages points to used PDMS is that silicones remain its

Table 3.1: Properties of PDMS [48]

Property	Value
Glass transition temperature (Tg)	≈ -125° C
Mass density	0.97 kg/m3
Youngs modulus	360-3000 kPa
Poisson ratio	0.5
Tensile or fracture strength	2.24 MPa
Specific heat	1.46 kJ/kg K
Thermal conductivity	0.15 W/m K
Dielectric constant	2.3-2.8
Index of refraction	1.4
Electrical conductivity	$4 \times 10^{13} m$
Magnetic permeability	$0.6 \times 10^{5} cm^3/g$
Wet etching method	Tetrabutylammonium fluoride ($C_{16}H_{36}FN$) + n-methyl-2-pyrrolidinone (C_5H_9NO) 3:1
Plasma etching method	$CF_4 + O_2$
Adhesion to silicon dioxide	Excellent
Biocompatibility	Nonirritating to skin, no adverse effect on rabbits and mice, only mild inflammatory reaction when implanted

elasticity and stiffness constant over a wide temperature range and have lower viscosity resulting in higher response speed. The lower viscosity is the argument used by *Knoop et al. 2015* to conclude that silicones-based actuators outperform VHB ones (described next); by its turn, the lower response speed and higher range of temperature tolerance of PDMS are the properties defended by *Shintake et al. 2013* that enhance robotic systems in terms of controllability of the motion and survivability in the external environment.

The mechanical and other properties of PDMS are listed on Table 3.1 [48]. Consequently, PDMS is a good polymer for soft sensors production.

All the specifications can be consulted on [51].

3.1.2 VHB^{TM}

The VHB^{TM} tape used is 3M^{TM} 4910 adhesive tape. It is a double side and double coated tape made by acrylic and which the red backing cover tape is a polyethylene film with a total thickness of 1.016mm and with a width of 5cm [52]. It is a pressure sensitive adhesive elastomeric film made of a mixture of aliphatic acrylate, photocured during film processing. The combination of soft, branched aliphatic groups and the light cross-linking of the acrylic polymer chains result on the polymers elasticity [15]. These branched or side chains form a network ilustrated on Figure 3.3, filling the space around the networked chains.

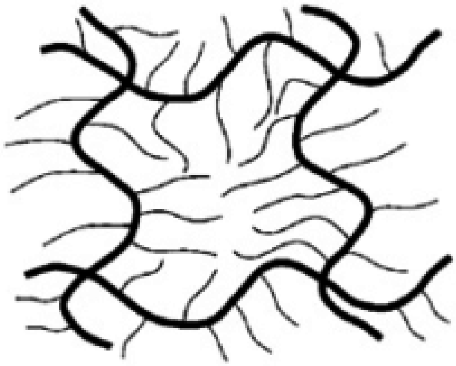


Figure 3.3: Molecular structure of a network of polymers with side chains [18]

The motion of the networked chains is lubricated, lowering the glass transition temperature. In fact, it also reduces the density of the networked chains, lowering the stiffness of the elastomer when the stretch is small. While the side chains do not change the contour length of the networked chains, the side chains pull the networked chains towards their full contour length even when the elastomer is not loaded. Once loaded, the elastomer may stiffen sharply, averting electromechanical instability [18].

This material is good as dielectric layer because it is intrinsically sticky, the conductive particles bound to its surface, assuring the transfer of the electrodes to the membrane, fixing them on the elastomer surface [46]. VHB tape is widely and commercially available [15, 20, 24, 27] and easy to use [15, 24]. 3M VHB 4910 acrylic tapes show an impressive performance due to the high dielectric constant (4.7) [27], showing high dielectric properties when prestrained [24]. Moreover, it shows high actuation/active strain potential [20, 27–29]. *Lai et al. 2011* report that they are able to bare over 6 times of axial stretch on both planar directions; while *Brochu et al. 2010* announce strains in excess of 380% for highly prestrained films; on its turn, *Goulbourne et al. 201* set a range of biaxial prestrain between 200% and 400%. Furthermore, when pre-strained, VHB shows high breakdown fields of up to 200V/μm. Along that, the theoretical energy density of this elastomer is 3.4MJ$\cdot$m^{-3}, with possible efficiencies up to 90% and excellent coupling efficiency, if the film is pre-strained [28].

The pre-strech that is being emphasized requires bulky support frames, significantly increasing the mass of VHB acrylic based devices and, consequently, reducing their effective energy densities [28]. Thus, VHB has very large viscoelastic losses, limiting its maximum response frequency to the 10-100Hz range [24, 28]. The viscoelastic nature of these films also limits their overall efficiency and results in time dependent strain that can make their performance erratic [28], having a nonlinear stress-strain curve [24]. *Brochu et al. 2010* suggest low molecular weight additives to increase the frequency response of VHB. Finally, it suffers from stress relaxation which degrades the actuation of the DEA, ending, eventually, to fail from dielectric breakdown. A possible explanation is the relaxation of the polymer chains which eliminate the stretch-induced enhancement in dielectric breakdown strength.

Regarding the materials properties, *Bozlar et al. 2012* prefer acrylic dielectric elastomer film due to its low shear modulus of 73kPa and over 800% linear strain before failure (see Table 3.2). The PDMS-based DEAs exhibit a comparably large shear modulus of 300kPa, imposing significant mechanical impedance on the mechanical response during actuation tests if they have a thickness comparable to that of the dielectric elastomer.

Table 3.2: Mechanical properties of DEAs of VHB 4910 and CB/PDMS [26]

Specimen	**Youngs modulus (kPa)**	**Shear modulus (kPa)**	**Strain at failure (%)**
VHB 4910	220	73	860
CB/PDMS	910	300	148

Overall, 3M VHB 4910 tape is widely used due to its ease of manipulation and ability to achieve high active strains as referred. Adding to that, it accepts large stretches during manufacturing and reliably produces actuation without failure. So, they are desirable for prototyping new concept of flexible actuators [15, 27, 29].

3.2 Stretchable conductive materials

3.2.1 Carbon Grease

MG Chemicals 846 carbon conductive grease is an economical electrically conductive silicone grease. It improves electrical connections between sliding, irregular or pitted surfaces and loose or vibrating parts. It provides excellent lubrication; though, it may migrate and cause shorts when used incorrectly. Moreover, it inhibits corrosion, and repels humidity. It also prevents arching, pitting, hotspots, and welds. It has a service temperature range of -68°C to 200°C, a volume resistivity of 117 Ω·cm and a density 2.7 g / ml. [53]

The main advantage of the MG Chemicals 846 carbon grease is the ease of appliance. Nonetheless, it remains wet and viscous after application. Subsequently, it spreads away and it is prone to smears and short circuits, creatinng a host of practical issues for manufacturing and testing all but the simplest DEMES prototypes. Attempts at encapsulation were successful, but proved cumbersome and unreliable. In addiction, short application times are important because it is needed to minimize the time the film is exposed to the air in order to prevent dust and debris from settling on the film surface and remaining between the dielectric film and the electrode. When fabricating more complex designs (e.g with multiple DEMES linked together), more complex techniques for the application and encapsulation of the stretchable electrodes are required. [27, 29]

The common applications are switches lubrication and insulation, surface gap bridging, irregular or potted surface electrical conduction. [53]

3.2.2 eGaIn

Gallium-based liquid metal alloys are passive, electrically conductive components to realize stretchable interconnects, compliant electrical probes, stretchable antennas, aligned electrodes in microfluidic systems and pressure sensors [38] These alloys are eutectic Gallium-Indium (75.5% Ga by weight), which melts at 15.6 ^{o}C, and Galinstan 68.5% Ga, 21.5% In, 10% Sn, with a melting temperature of 219 ^{o}C and also Ga 62.5%, In 25%, Sn 12.5%, which has a melting temperature of 10 ^{o}C [37, 38, 41, 42]. These alloys are an alternative to mercury or reactive sodiumpotassium alloy, NaK, due to to their low toxicity and low reactivity [37, 41, 42]. For instance, In has been used in dental fillings and Ga is a trace nutrient [42].

According with Table 3.3, both Galinstan and eGaIn alloys show similar physical properties. As eGaIn only requires Ga and In, both readily available, this alloy is chosen. Therefore, its production is done by mixing Ga 75.5% on weight and 24.5% of In on a hot plate at 195^{o}C for 24 hours, which causes the melting and alloying of Indium and

Gallium.

Table 3.3: Properties of galinstan, eGaIn, and mercury [41]

	Galinstan	**eGaIn**	**Hg**
Melting point (^{o}C)	-19	15.5	-38.8
Boiling point (^{o}C)	>1300	2000	357
Density (kg m^{-}3)	6440	6280	1353
Electrical conductivity (S m^{-}1)	3.46×10^{6}	3.4×10^{6}	1.0×10^{6}
Viscosity (Pa·s)	2.4×10^{-3}	2.0×10^{-3}	1.5×10^{-3}
Surface tension (N m^{-1})	0.718	0.624	0.487

The liquid metal alloy eutectic Gallium-Indium (eGaIn) has high conductivity and complete soft-matter functionality. It has similar electrical conductivity as conventional metal wiring (consult Table 3.4), being a five order of magnitude improvement over the commonly used carbon blacks [6]; in fact, eGaIn has a resistivity of $\sim 29.4 \times 10^{-6} \Omega \cdot$cm, which allows it to be utilized as an electrode in contact with organic thin-films and semiconductor devices [42].

Moreover, it provides no mechanical resistance to bending or stretching of the DEA because it is liquid at room temperature (consult Table 3.3). The electrode should be as thin as possible, also to minimize that resistance.

Gallium-Indium alloys have already been used to make soft and stretchable resistive strain sensors; though, using it as an electrode is still a challenge. Knowing that DEAs require a thin film of liquid eGaIn to be sealed over a large area, eGaIn selectively wets only to the surface of the PDMS dielectric layer and not to the mask as it is brushed

Table 3.4: Comparison of PDMS, carbon black and eGaIn conductivity to other metals; *first number was determined along the length of cPDMS sample, while number in brackets is through the thickness) [6]

MATERIAL	**CONDUCTIVITY ($\times 10^{4}$ S-cm^{-1})**
cPDMS	1.4×10^{-6} [3.8×10^{-10}]*
Carbon black	3.8×10^{-5}
eGaIn	3.4
Aluminum	35.0
Gold	41.0
Copper	59.6
Silver	63.0

or sprayed onto the stencil electrode [6]. In contact with air, an oxide skin is formed by eGaIn. This is another property which makes it advantageous as DEA electrodes. In fact, this layer coats the inside of the encapsulating elastomer membrane and ensures uniform conductivity. The unique wetting properties of eGaIn, again due to its oxide skin, allow for deposition via stencil lithography onto elastomer substrates for use as flexible circuitry [6]. In fact, when the substrate is tilted, gravitational forces make the eGaIn to flow and redistribute underneath the confines of the skin. This occurs due to its low viscosity (consult Table 3.4), allowing it to flow readily and to be applied as electrically conductive, thermally stable lubricant [42].

This behavior can be explained because the surface tension of eGaIn at ambient conditions is 624 mN/m (consult Table 3.4); on its turn, the surface tension of eGaIn during exposure to aqueous HCl (which presumably causes acid-promoted dissolution of the oxide) is 435 mN/m. The high surface tension of eGaIn measured under ambient conditions may therefore be explained by the presence of a surface oxide which "stiffens" it, being capable of supporting more weight from a pendant drop [42]. All these characteristics make eGaIn as an alternative *soft* conductor for DEA. [6]

3.3 Conductive connectors

3.3.1 Copper tape

3M^{TM} copper foil tape 1181 used comes is a conductive adhesive-backed tape.

3.3.2 Fabric copper/nickel tape

A 3M^{TM} Shielding fabric tape CN-3490. It is a nickel copper-coated non-woven fabric backing with a conductive pressure-sensitive acrylic adhesive and a liner, which makes it easy to handle and cut. Nickel on copper-plated polyester fabric backing provides corrosion resistance and good shielding effectiveness. Polyester non-woven makes a very thin and mechanically strong backing with excellent flexibility, conformability and light weight. The conductive particles in the adhesive provide low contact resistance between the substrate and the backing to drain static charge. Acrylic pressure-sensitive adhesive has good resistance to heat, oxidation, solvents and oils. [54]

3.3.3 Fabric textile

The fabric textile used is the Conductive Fabric MedTex130. It is a high ionic silver release plated (99.9%pure silver) nylon elastic knit. Is is composed by 78%nylon and 22%elastomer that is stretchy in both directions with a thickness of 0.45mm. It is highly conductive with an average surface resistance $< 5\ \Omega$ /A. This knit fabric can be used in e-textiles once it can be sewed. Other applications are wound care, antimicrobial products and garments. [55]

3.4 Kapton

Kapton its a polyimide film which maintains its excellent physical, electrical and mechanical properties over a wide temperature range and can be used in a variety of electrical and electronic insulation applications. [56]

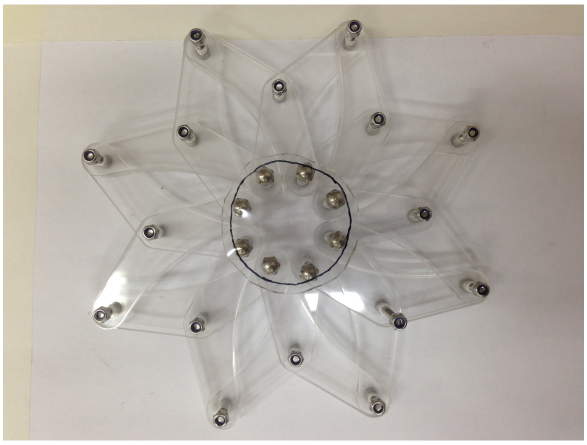
3.5 Ease Release Spray

Ease Release 200 from *Mann* is an aerosol release agent, being Dichloromonofluoroethane Dimethylmethane Butane the solvent carrier. It releases polyurethane elastomers, polyurethane foam, epoxy resin, polyester resins, platinum silicones, rubber and thermoplastic polymers. It is effective on aluminum, chrome, platinum silicone, epoxy, rubber and steel molds. Furthermore, it is non-flammable, easy to apply, dries fast, works from 21.1 to 260 °C and it has excellent wettability. Therefore, it is an excellent release agent for making molds and casting parts [57]. In this case, it is used to help the peel off of PDMS from the glass or katpon substrate.

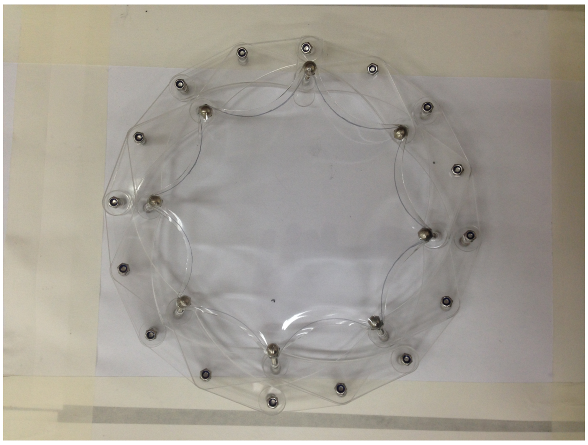
3.6 Stretchers

3.6.1 Circular

A structure obtained by laser cut a 3mm acrylic-like material. The design is suggested by [32]. It allows a radious pre-stretch of the VHB tape. It has a locking clip to keep the material pre-stretched. A circular crown of 8.2 of inner radius and 10.8 of outer radious is used as a frame to maintain the VHB stretched.



(a) VHB circumference alligned with Hobermans domes



(b) Hoberman open and locked up

3.6.2 Rectangular

A stretcher for an one-axis stretch based on [11,12]. It is obtained by laser cut. The VHB sticks to the pads, enabling the expansion of the film. It is locked by two bars as seen in the Figure 4.7(a). A rectangular frame is obtained to keep the VHB stretched.

3.7 Isopropanol alcohol

Isopropanol plays an important role on erase out imperfections on the electrodes pattern. It evaporates quickly, leaves nearly zero traces and it is relatively non-toxic.

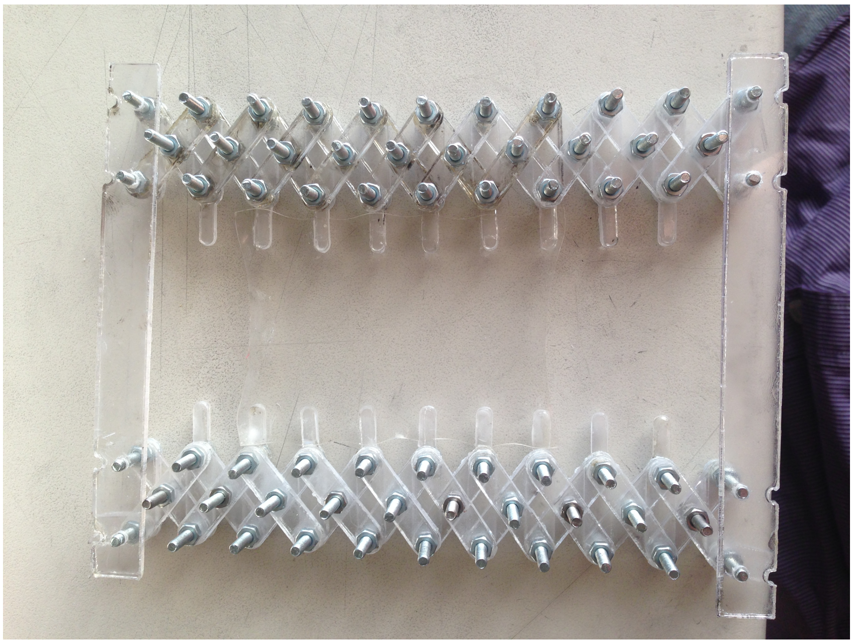


Figure 3.4: Rectangular stretcher

3.8 Equipment

3.9 Laser cut

The laser cut utilized is *VLS3.50 Desktop* from *Universal Systems*. It has a working volume of 610 x 305 x 102 mm. The VLS3.50 can be equipped with one of five 10.6μ CO_2 laser sources ranging in power from 10 to 50 watts or one 9.3μ CO_2 30 watt or 50 watt laser source. It is equipped with an air-cooled laser source and it has a laser fan control. It comes with a laser pointer enabling material alignment. It has an excellent power stability, which originate reliable and predictable results. [58]

3.10 Thin Film Applicator

ZUA 2000 Universal Applicator from *Zehntner GmbH* used to produce uniform films with several thicknesses. Its gap height is adjustable from 0μm to 3000μm with a 5μm resolution. [36]

Figure 3.5: ZUA 2000 Universal Applicator

3.11 Spray Gun

The spray gun has a recipient to store the liquid metal. It is connected to an argon bottle which has a pressure manometer. The spray gun is handled manually, allowing the user to control the amount of quantity sprayed. It is used to spread the eGaIn on the PDMS.

3.12 High voltage power source

The instrument to drive high voltage is the *EW Series Extended Current* 500 Watt Regulated High Voltage DC Power Supplies*. It has an output voltage ranging from 0 to 10 kV and an output current from 0 to 10 mA [59].

3.13 Others

- Oven
- Hotplate and stirrer
- LCR meter
- Multimeter
- SOGO weightning machine with a resolution of 0.01g
- Ruler with a reolution of 1mm
- Acetate pen
- Caliper with a resolution of 0.01mm

- *Perfect Screen Ruler 3.0*
- Vaccum pump
- Gloves
- Lab coat

3.14 Summary tables

The materials are summarized on Table 3.5 and equipment/tools are listed on Table 3.6.

Table 3.5: Model and application of each material

Material	Model	Application
PDMS	SYLGARD 184	Insulator
VHB	3M 4910	Insulator
Carbon grease	MG Chemicals 846	Electrode
Liquid metal	eGaIn	Electrode
Cu tape	3M 1181	Electrical connector
Fabric Cu/Ni tape	3M CN-3490	Electrical connector
Fabric textile	MedTex130	Electrical connector
Kapton	Dupont	Heat resist
Ease release	Mann 200	Thin film release agent
Hoberman stretcher	Hoberman	Radial pre stretching
Rectangular stretcher	-	Bi-axial pre stretching
Circular frame	-	Hold stretched VHB
Rectangular frame	-	Hold stretched VHB
Isopropanol alcohol	-	Erase imperfections

Table 3.6: Model and application of each equipment/tool

Equipment	Model	Application
Laser cutter	Universal Systems VLS3.50	Cut: stencils; stretchers; frames
Thin film applicator	Zehntner GmbH ZUA 2000	Thin film casting
Spray Gun	-	eGaIn appliance
Power source	EW Series Extended Current 500 Watt	Drive high voltage
Oven	Euro Circuits	Cure PDMS
Hotplate and stirrer	JENWAY 1103	Alloy eGaIn
LCR meter	ISSOTECH LCR819	C and R measurement
Multimeter	Fluke 45 Dual Display	C and R measurement
Weightning machine	SOGO (resolution =0.01g)	Weight measurement
Ruler	Resolution of 1mm	Distance measurement
Caliper	Resolution of 0.01mm	Distance measurement
Perfect Screen Ruler	3.0	Angle measurement
Vaccum pump	SCHOTT	Air trapped release
Acetate pen	Acetate	Write on PDMS, VHB and glass
Glass	Flat	PDMS film casting substrate
Gloves	-	Protection
Lab coat	-	Protection

Chapter 4

Fabrication methods

The fabrication methods are here described. It is explicated the method for manufacturing VHB and PDMS based DEAs.

4.1 VHB

4.1.1 Circular

The first approaches for DEA fabrication are based on the process detailed by *Knoop & Rossiter 2015* [24]. In this subsection, the DEAs manufactured are based on a radial pre stretching of VHB. Carbon grease, as reported on literature, and eGaIn are used as electrodes, all using the red backing foil of the VHB tape as a stencil. While carbon grease is applied by painting it, eGaIn is either spread by rolling and by spraying. The representative schematic for these DEAs are in Figure 4.1.

In order to keep the DEA stretched, a circular crown with a diameter of 10.8cm acrylic frame is cut by laser. To have a radius stretching of the DEA, a Hoberman stretcher ([32]) is obtained by laser cut. Concerning the same stretching strain on all directions, a circumference with a 2cm radius is drawn on the 3M 4910 VHB tape with an acetate (or similarly soft writing end) pen. Afterwards, it is peeled of from the red backing. After, it is placed on the top of the Hoberman stretcher by aligning the bolts and domes with the circumference (Figure 4.2(a)). The VHB is sticky, so it is just needed to apply pressure towards the domes and also to the excess of tape around the domes. Then, the Hoberman

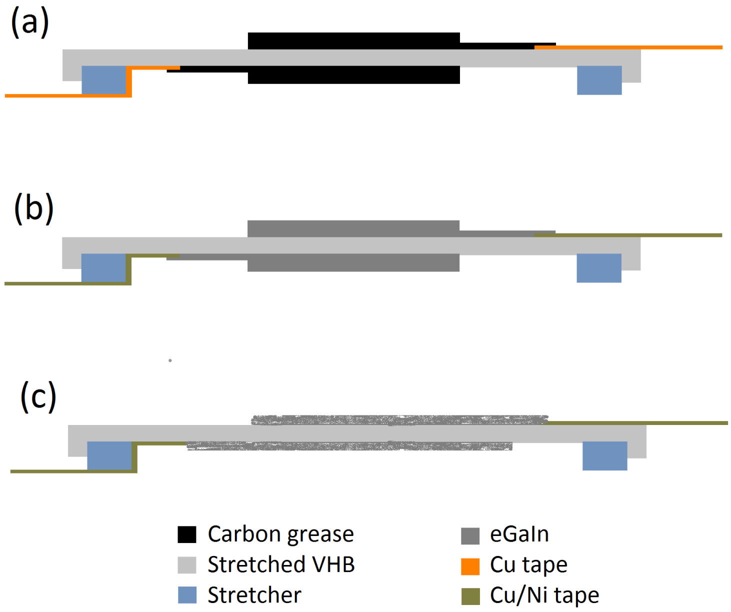


Figure 4.1: Schematic of circular DEAs with (a) carbon grease, (b) eGain by rolling and (c) by spraynig

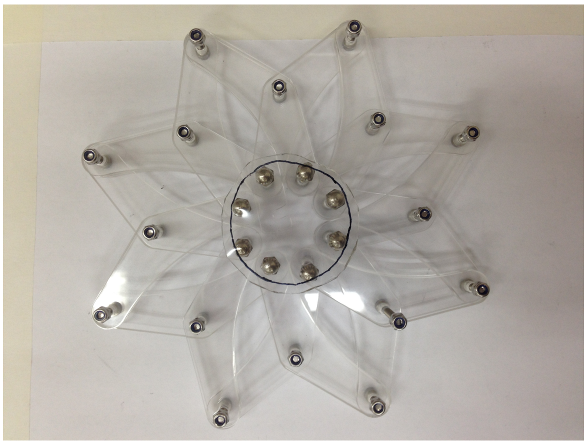
is opened and it is locked up with the built-in clip (Figure 4.2(b)). Subsequently, the circular frame is placed on its bottom (Figure 4.2(c)). Later, the VHB is taken off the dome and is attatched to the frame according to the circumference. It is done alternating between opposite sides (Figure 4.2(d)) till de tape is completely stretched on the acrylic frame (Figure 4.2(e)). At this stage, the VHB is stretched 270 % from its initial state.

4.1.2 Carbon grease

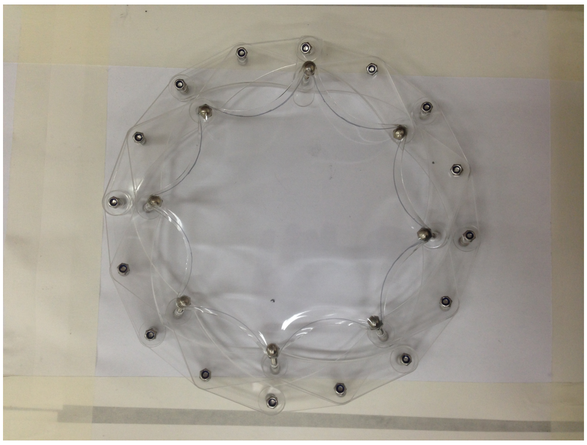
On the phase presented in Figure 4.2, gloves and the lab coat are worn to paint a circular carbon grease electrode with a radius of 2cm on the center of the VHB (Figure 4.3(a)). This figure also demonstrates that is possible to ensure that all the area is covered with grease by observing the actuator against a light source (if light passes, it is not properly painted on that zone).

Meanwhile, copper electrodes are placed on opposite sides, one on the top and the other on the bottom of the DEA. Finally, a line of carbon grease is used to connect the electrode to the copper tape (Figure 4.3(b)).

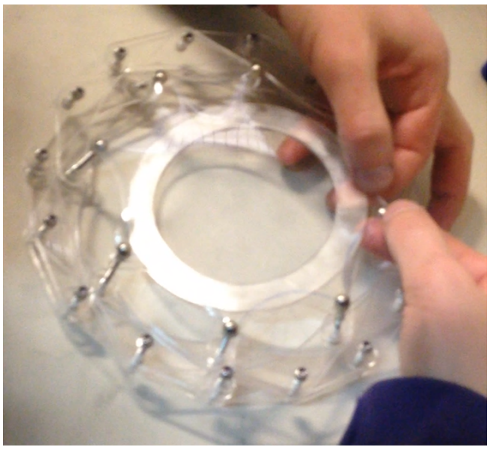
The design can be freely made or with a stencil. In this last case, it is used the red



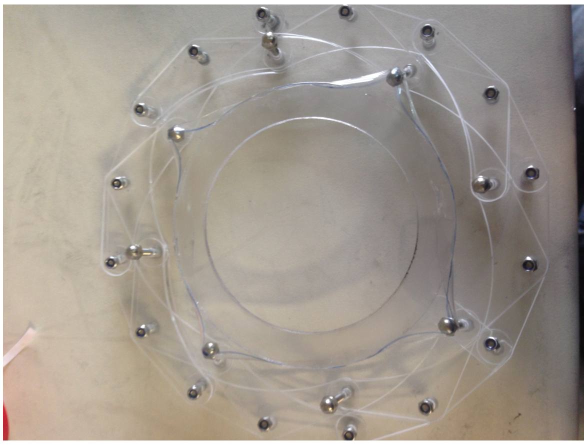
(a) VHB circumference alligned with Hobermans domes



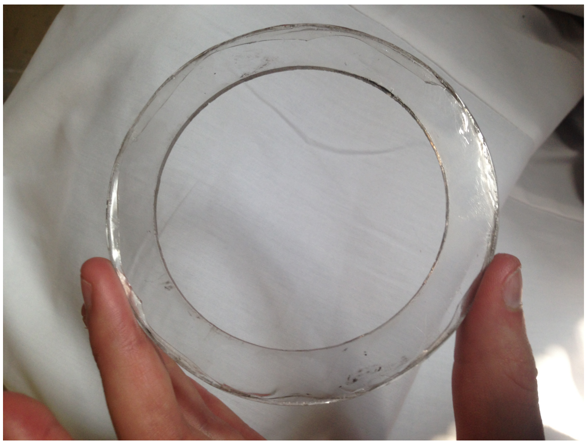
(b) Hoberman opened and locked up



(c) Allign by hand the circumference with the outer radius of the frame



(d) Alternate the sides sticked to the frame



(e) VHB stretched

Figure 4.2: VHB radial stretching steps

backing of VHB once it can be detached from this material and designed stencils are obtained with the laser cutter.

(a) Stencil for carbon grease painting the electrode of the opposite side; first layer full painted (no gaps)

(b) Circular DEA of carbon grease

Figure 4.3: VHB based DEA with carbon grease

An example of a free-form hand design is presented in Figure 4.4.

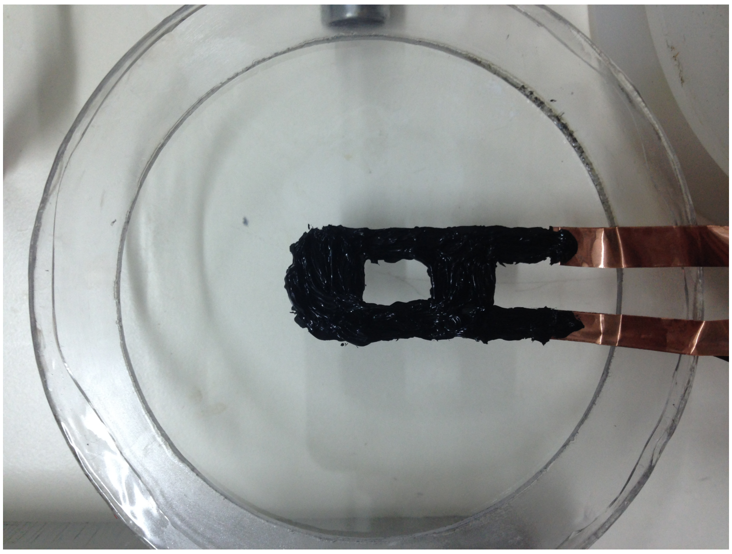


Figure 4.4: Free-form hand painted carbon grease DEA

Additionally, more complex designs can be used to pattern stencils which result in more complex DEAs prototypes. Thus, a fingertip design is painted on a stretched VHB. Its backing tape is both stencil and frame by letting it on the elastomer in order to maintain the stretch upon its releasing from the outer frame. However, it is not effective once the DEA splits on its layers - Figure 4.5(b).

(a) Fingetip carbon grease electrodes with a VHB backing foil as a frame.

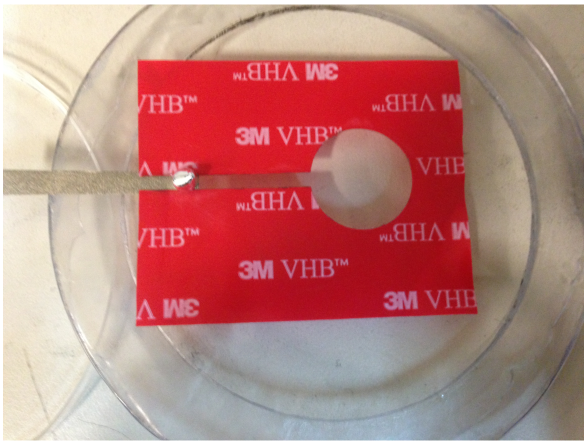
(b)

Figure 4.5: VHB radial stretching steps

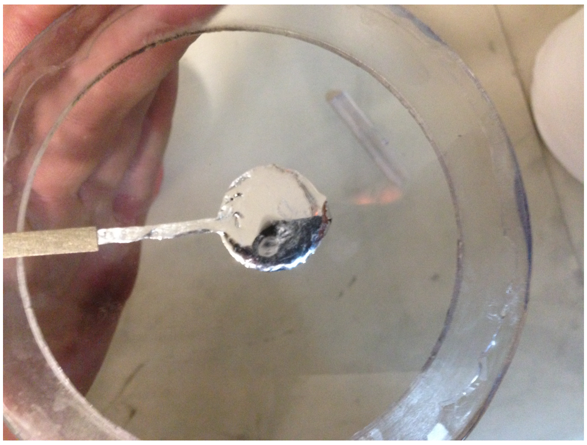
4.1.3 eGaIn

The same procedure is performed to strecth the VHB tape as showed in Figure 4.2. However, the electrode applied now is liquid metal. The red backing of the VHB is used as a stencil and a drop of eGaIn is dropped on the Cu/Ni tape - Figure 4.6(a). Afterwards it is **rolled** with an Ecoflex casted cylinder till covering all the area - Figure 4.6(b). In the same way, the liquid metal is applied on the opposite side. When the DEA is flipped to apply the second electrode, the liquid metal painted moves along itself and keeps inside of its skin. Howerver, this causes the liquid to move along itself and provokes either bad connection with the connectors and the loss of the uniformity of the layers.

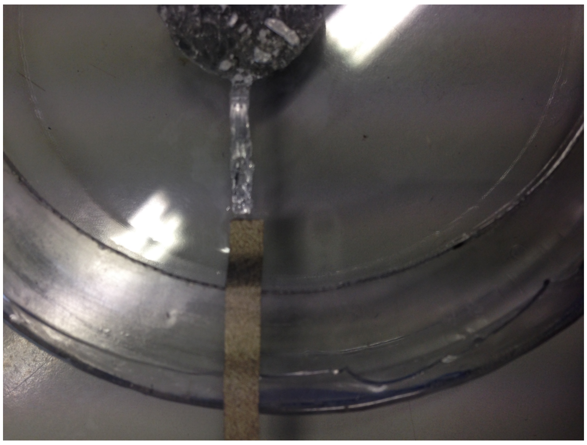
Another electrode appliance liquid metal strategy is performed, being the eGaIn **sprayed**. The sprayed eGaIn particles oxidize in contact with air adhering to the VHB surface. The red backing of the VHB is also used on this case for the pattern and the Cu/Ni tape.



(a) Liquid metal droplet on the connector

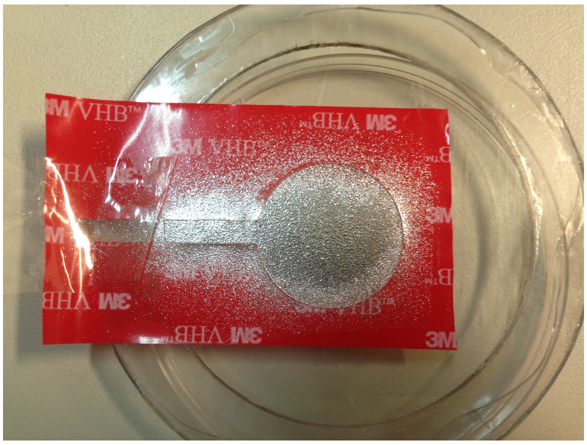


(b) Top electrode of eGaIn by rolling

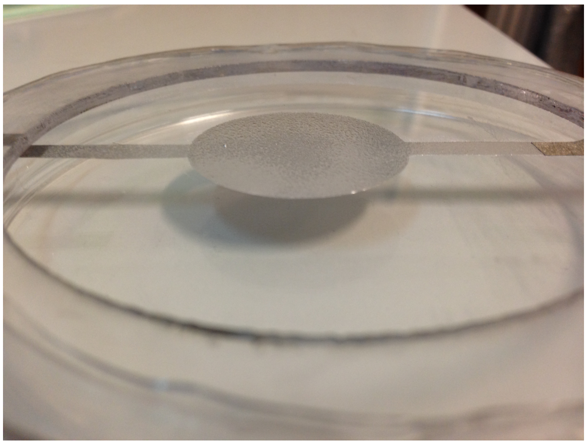


(c) Bad connection between the liquid metal and the connector

(d) Non uniformous layer of eGaIn after flipping the DEA



(e) Stencil for eGaIn spraying



(f) Circular DEA of srayed liquid metal

Figure 4.6: eGaIn DEAs by rolling and spraying

4.1.4 Rectangular

To produce a finger-like DEA, a rectangular stretching structure is designed and built. As VHB sticks, pressure is applied onto the supports which are inside the structure. After, the VHB is stretched till de desired length and locked up with two bars (with marks pre-made of the referred length). At this time, a rectangular acrylic frame is put in contact with the VHB and it is taken out the structure. Afterwards, a layer of kapton is stripped onto the outer frame position. Then, the VHB backing tape is used as a stencil (Appendix, electrode pattern) and the pattern is painted with carbon grease on both sides. Its thickness can be controlled by defining it on the film applicator on the top side while on the bottom one it is not possible due to the outer frame's thickness constraint. This piece goes to the oven. Additionally, copper connectors are added to provide electrical connexion. Finally, a plastic frame with the electrodes pattern is added on each side. This PET frame has an outset of 1mm to the exterior to avoid premature breakdown, so that the stretchable electrodes have space to actuate. Finally, the DEA is released from the frame. Rast mode on laser cutter does not cut the sample. Therefore, a scalpel is used. These manufacturation steps are depicted on Figures 4.7 and 4.8.

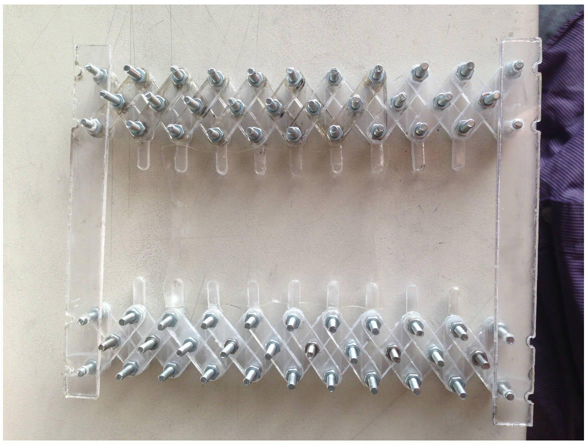
During fabrication, as the VHB is sticky, dust and debris can easily attach to it. On Figure 4.7(b) is shown paper sticked to the acrylic tape.

A smaller prototype is performed - see Figure 4.9. This time, it is not used a rigid frame but a softer one from the beginning. This way, the VHB is stretched onto it as supra described. Cuts are done in order to require less force to move the actuator.

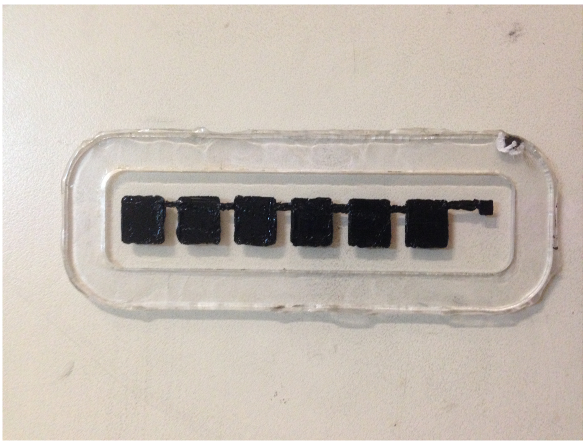
4.2 PDMS

4.2.1 Carbon grease

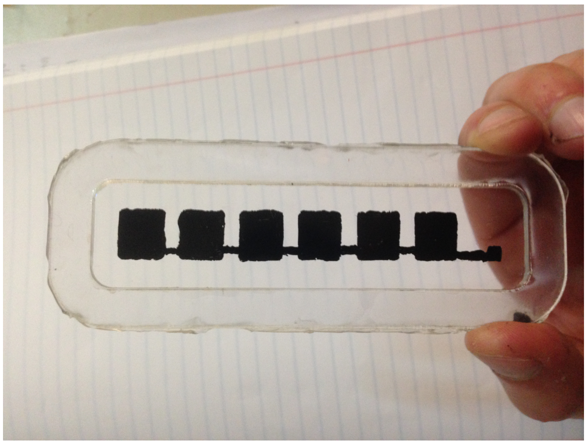
To manufacture a DEA of carbon grease, a 100μm PDMS layer is casted on a glass substrate and it is cured. After, the desired pattern is painted with carbon grease and it is cured. Even that it does not cure, is is tried to peel it off from the glass, but without success. As so, after this process, a 300 μm layer is casted on top of it, is cured and these are peeled off. Both failure attempts are on Figure 4.10. On successful cases, the electrode is painted on the opposite side and encapsulated with a carbon grease membrane. The DEA is strained by adding an extra PDMS layer to it while stretched. The Figure 4.10(f) suggests that the connectors should be out of the stretched zone.



(a) Rectangular stretcher with VHB locked up in the open position

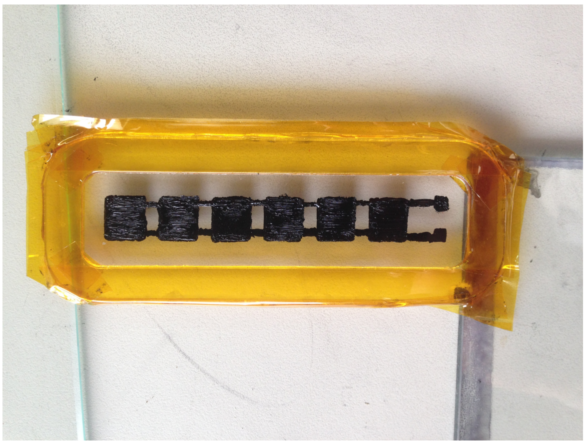


(b) Top electrode; paper sticked to the VHB

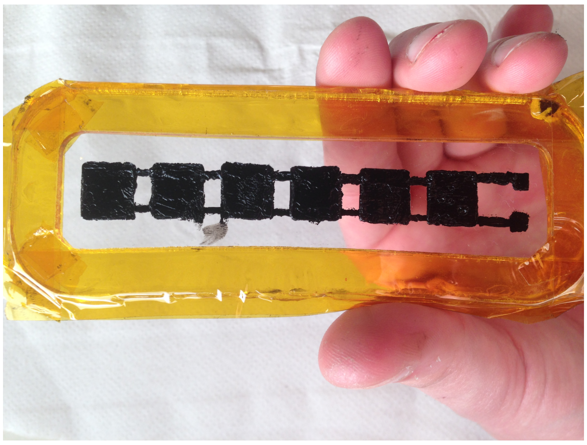


(c) Bottom view

(d) Stencil for opposite electrode painting; kapton along the frame



(e) Two complaint electrodes

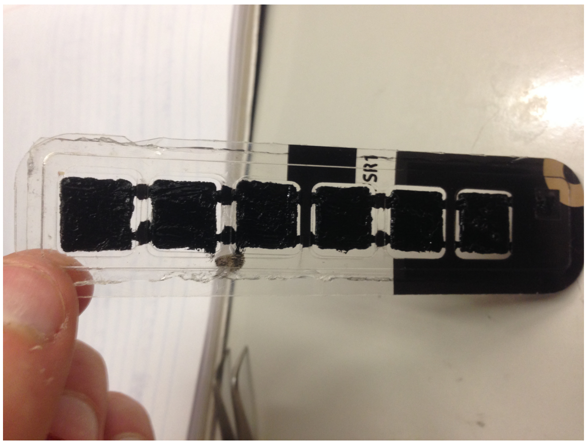


(f) Frame shrunk after going to the oven; carbon grease does not cure and it blurs easily

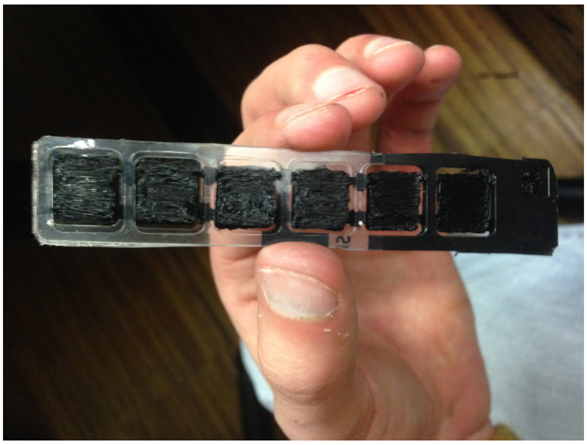
Figure 4.7: Rectangular DEA with carbon grease stretching and electrode patterning

4.2.2 eGaIn

A simple DEA is manufactured. Firstly, the PDMS is casted by mixing the two parts in a 10:1 ratio. The film applicator is regulated for 100μm and a thin PDMS layer is casted on



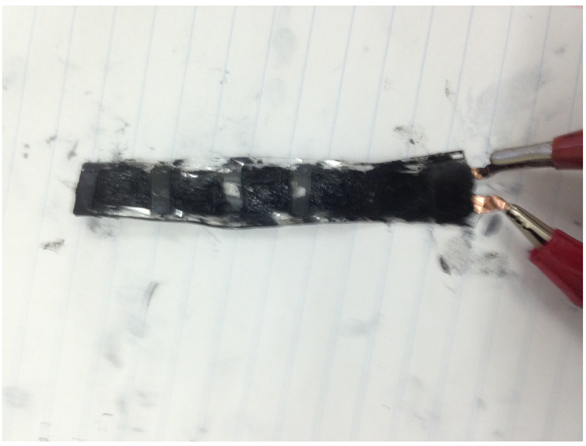
(a) DEA cut off the outer frame; with a plastic frame with an outset of 0.1mm



(b) Both inner plastic frames cut

(c) Frame shrunk after going to the oven; carbon grease does not cure and it blurs easily

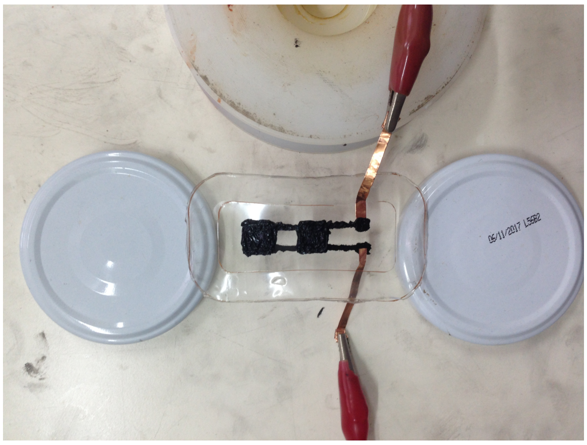
(d) Both inner plastic frames cut



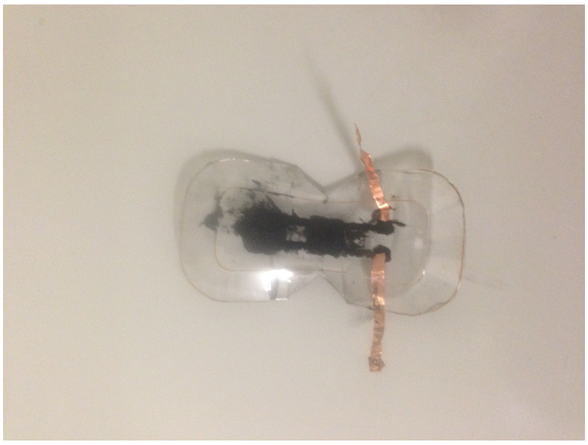
(e) Effect of VHB release from the outer frame

Figure 4.8: Rectangular DEA with carbon grease released from outer frame

(a) Rapid prototyping of a segmented DEA



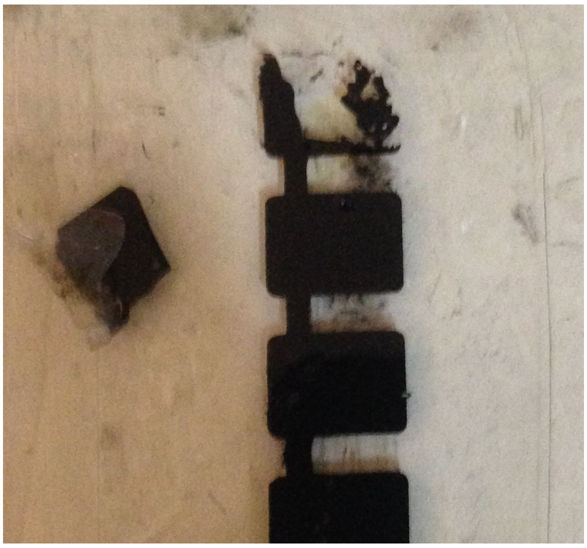
(b) Stretched directly onto a plastic frame



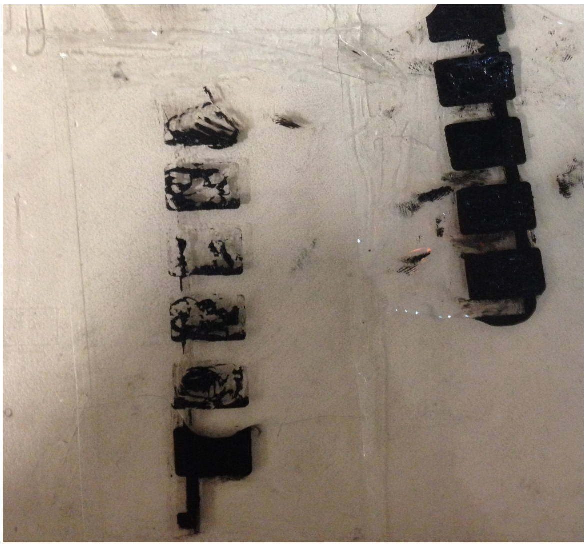
(c) Cuts are done to require less force to move the actuator

Figure 4.9

(a) The membrane is too glued to the surface on the electrodes places

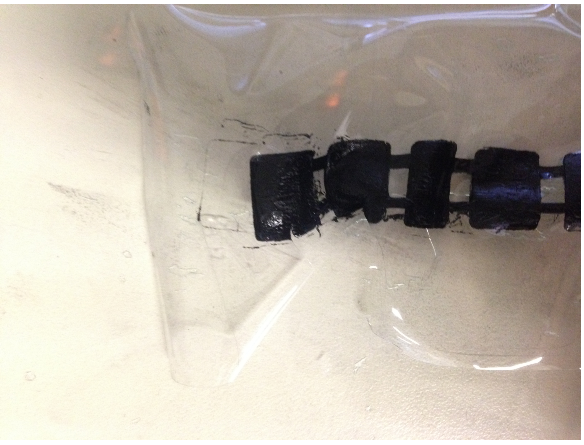


(b) Which makes the DEA to rupture



(c) It can be peeled off and but it eventually brakes

(d) Electrodes are encapsulated by PDMS; rupture near the connection



(e) A breach from the side to the electrodes

(f) Fissure near the connection upon stretching

Figure 4.10: Examples of defects on DEAs fabrication

a glass substrate. After curing the PDMS, a layer of eGaIn is applied on its surface and a CU/Ni connector is applied on the pad. After that, the applicator is set at 400μm in order to produce a 300μm PDMS layer which insulates the PDMS-eGaIn sample. The PDMS is cured, the piece is released from the glass and flipped. This way, another liquid metal electrode matching the first one is added, also with the Cu/Ni connector. Subsequently, a 300μm PDMS layer is spread on top and it is cured. At this stage, the DEA is released from the substrate. It is stuck with duct tape to the glass at the bottom, where the pads are placed. Afterwards, marks are drawn to indicate the desired strain - 10% strain is performed. Thus, the piece is strected to the mark and is held with duct tape. At this moment, a PDMS with the desired thickness is spread on top of it. When cured, the DEA is released - first a cut is done on top and then the cuts on its length are performed alternatively till the duct tape. So, the DEA is released and curls to the bottom.

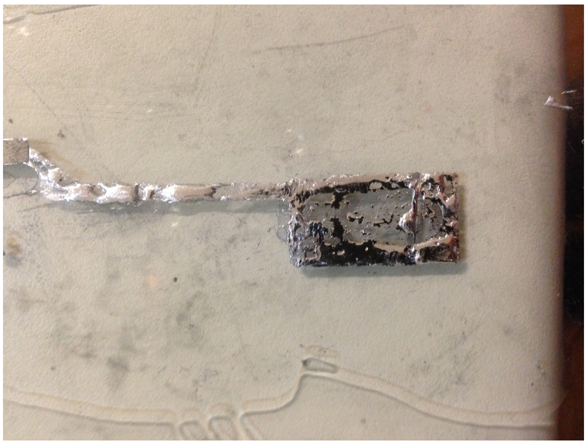
To avoid air trapped in the DEA, after the PDMS mixing it is vacuum pumped.

The liquid metal application is done either with a roller made of EcoFlex or passing the film applicator along it. By passing the Ecoflex roller, the eGaIn thickness is not controlled and the sample is more prone to get dragged when passing the new PDMS layer 4.11(a). By passing the film applicator to spread a liquid metal drop, the eGaIn layer can be made thinner than the next layer casted - Figure 4.11(b). Finally, the liquid metal is sprayed at a low pressure (approximately 10 psi) and, afterwards, the film applicator is passed so that it is ensured that the amount of eGaIn sprayed thickness is thinner than the next PDMS layer which will be casted on top of it - Figure 4.11(c)

Due to the high surface tension between the substrate and the thin films, a mold ease release is sprayed prior to film casting and when it is flipped. Considering that with its use the membrane is released easier, the images 4.11(d) and 4.11(d) also show that the membrane with the ease release comes out with a satin an brighter aspect and without the wrinkles (to underline that the images seen are from the dielectric membrane/the one which was on the substrate side view).

A note to take is that the paths to the connectors are split away so that the tension does not ionize the air and goes directly from one connector to the other.

In order to evaluate the effect of pre stretching strain on the bending angle, a 30% in strain actuator is done. To access the outcomes of the extra PDMS layer, DEAs with 200,



(a) Liquid metal dragged

(b) eGain surface after roll

(c) eGain surface after spray and pass the film applicator

(d) No use of ease release: wrinkles

(e) Use of ease release: satin aspect

Figure 4.11: PDMS with eGaIn fabrication

300, 400 and 600μm are manufactured. These are discussed on the next chapter *Results and Discussion*.

It is also fabricated a longer actuator - Figure 4.12.

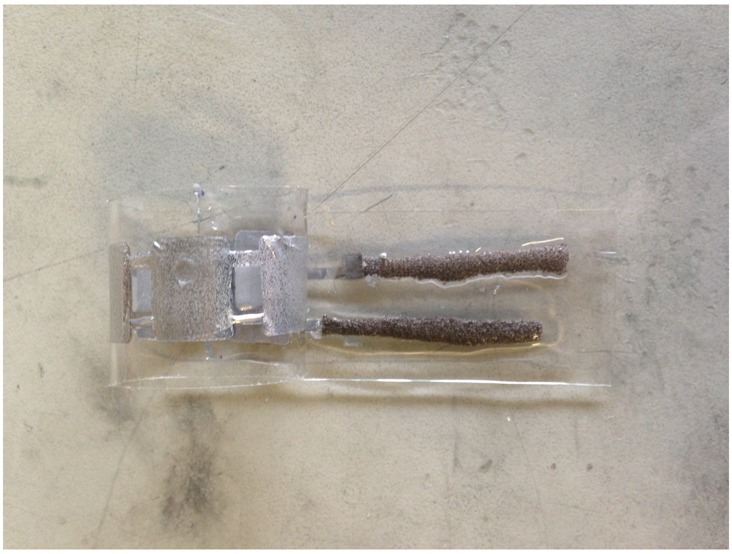


Figure 4.12: Segmented eGaIn DEA

Connectors

The resistance for the three connectors is measured and is presented on the results.

Its influence on the fabrication is also discussed.

Chapter 5

Results and Discussion

The results obtained, following the methods described above, are presented in this chapter.

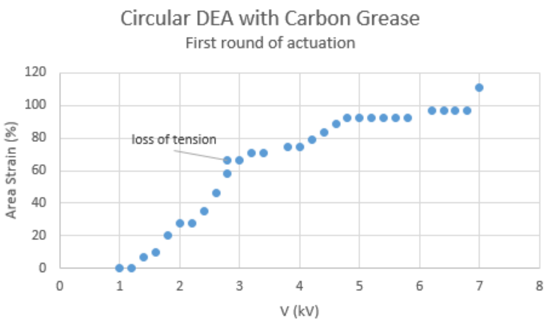
5.1 VHB

5.1.1 Circular

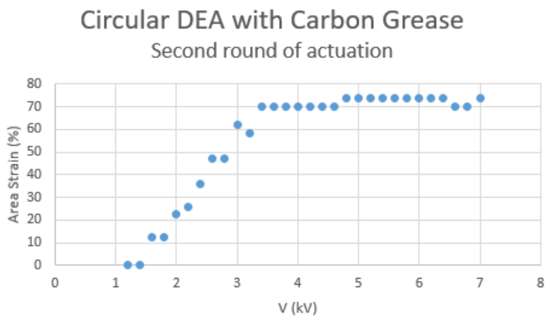
5.1.2 Carbon grease

The circular DEA with carbon grease is connected to the high voltage machine. A ruler is placed above the DEA. Tests are performed to evaluate the actuator. The current is kept constant and the voltage is changed. Two repetitions are performed for each voltage, for approximately one second and allowing the high voltage to reach the set peak. This way, the measures can be compared and confirm each other or eliminate outliers as result of different actuation time. The voltage is increased in increments of 200 V till 7 kV. Three rounds are taken to access the actuation over its cycles. In the third round, the voltage provided till 10 kV, the maximum voltage of the machine. The process detailed is recorded and analyzed afterwards. The images are stopped on the maximum lateral displacements for each voltage, enabling its measurement. Therefore, the area strain (%) is calculated. The area strain (%) is given by the difference between its area when it is active and at rest, divided by the area when it is at rest and multiplied by 100.

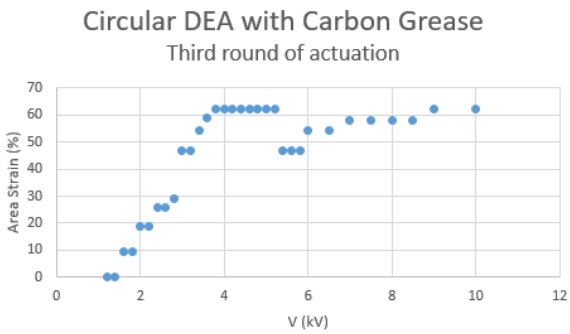
The supra procedure enables a graphic characterization of V in function of the area strain for the the first 5.1(a), second 5.1(b) and third 5.1(c) rounds of actuation.



(a) First actuation round



(b) Second actuation round



(c) Third actuation round

Figure 5.1: Circular DEA with carbon grease actuation

These are superimposed on Figure 5.2.

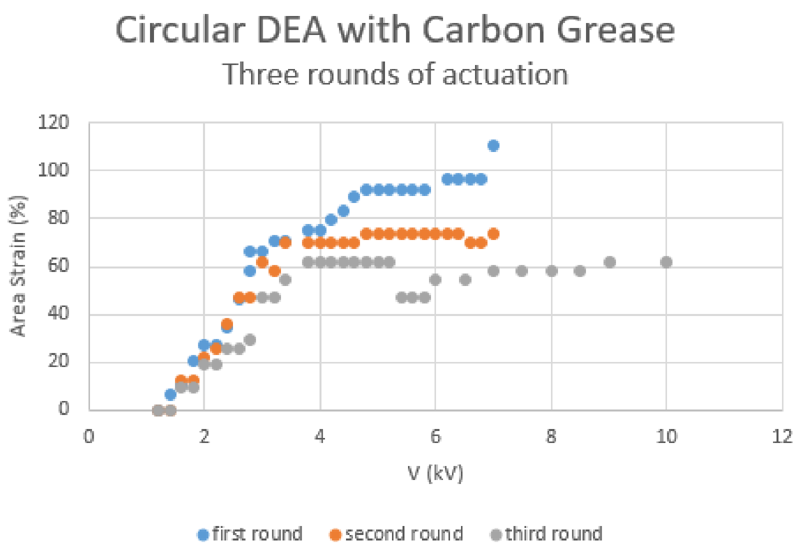


Figure 5.2: Superimposition of the three rounds of actuation

On the three, for some voltage increments, the area strain keeps the same. This occurs as the consequence of the simple experimental setup. The ruler resolution is 1mm, being seen differences down to 0.05mm. Another possible error is the frequency provided to the system. The voltage is given manually and one second of active driving was taken. However, it is a possible error source. Therefore, at least two measures are done, either to confirm the measurement and also to eliminate over or lower actuation (as consequence of time and not voltage). Additionally, the moment which the video is stopped may also be susceptible to mistakes - this one can be more monitored.

Generally, the actuation increases as the voltage increases.

On the first round of actuation, it is noticed that the actuation starts at 1.4kV and on the second and third, it starts at 1.6 kV.

On Figure 5.1(a) it can be seen that at 2.8 kV there is a second point on which the DEA loses tension. At this stage, it is observed a region on its surface which becomes softer and undulates - interior of the green trace on Figure 5.3. As a consequence, that area offers less resistance and spreads away more easily - the lateral displacement is higher and, therefore, the area strain is also higher.

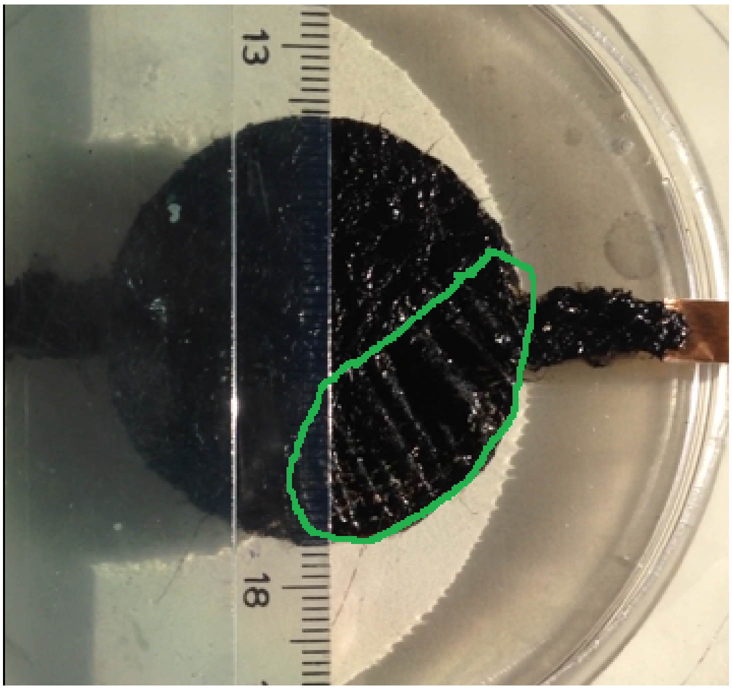


Figure 5.3: Loss of tension (inside the green line) at 2.8 kV

In the same way, a boost on area strain is also noticed on the second and third rounds at 3 kV. At this voltage, the loss of tension is also present. By superimposing the graphics it is clear that the strain decreases for the same voltage. This is more evident for the voltages superior to 3 kV. Therefore, the voltages reached on previous times affect negatively the mechanical properties of the actuator - it suffers stress relaxation. For voltages superior to 4kV, one can observe that there is not a significant increase of the area strain. The actuation behavior of the material can be explained due to atomic dislocations. For low voltages - presumably lower than 3kV -, it presents an elastic deformation; for higher voltages, it shows a plastic behavior, resulting in permanent dimensional changes. The permanent deformation during one cycle of loading is normally just a fraction of the total deformation produced by each load repetition. In fact, the gradual accumulation of a large number of these small plastic deformation increments could lead to an eventual failure of the material due to excessive rutting. However, for 10 kV the actuator did not it did not fail neither rupture and kept actuating. This can be explained due to the low frequency applied.

For voltages superior to 4kV, one can observe that there is not a significant increase of the area strain. Another interesting aspect is that for 10 kV the actuator did not reach its electric breakdown - it did not fail and keeps actuating.

On the second and third rounds, there are voltage increments on which the area strain decreases. This happens because at those times the elapsed time was bigger between the actuations. This is important once, even when the DEA returns to the rest position at naked eye, in fact it is still shrinking. Furthermore, when the actuation is performed with shorter interval times, possibly the initial position does not coincide with the resting position and the dielectric is eventually slightly squeezed. Consequently, there is a bigger actuation.

Other relevant aspect is that the recovery time - time that the actuator takes to go from the actuated to the rest position - increases along the experiment.

The tables 5.1 and 5.2 ha the capacitance on **nF** and the resistance on **k**Ω measured before test and after each round of tests. The multimeter used is the Fluke 45 Dual Display and the LCR meter is from Iso-Tech with a frequency of 100 kHz. The resistance is measured from the center circle and the strip of carbon grease and the 'center' is on the the circle. R_t stands for top resistance and R_t for bottom resistance.

The resistance on each layer does not have significant changes. Thus, the layer keeps it integrity. The capacitance measured through the dielectric on the LCR is similar on

Table 5.1: Capacitance and resistance priot and after the first round of testing

		prior to tests	I
multimeter	center - connection	-	-
	center	-	-
LCR	Capacitance	0,18440 +- 0,0001	0,15560 +- 0,0005
	Resistance	11,14 +- 0,1	48,80 +- 0,5

Table 5.2: Capacitance and resistance after second and third rounds of testing

		II	III
multimeter	center - connection	(Rt =5,5; Rb = 4,5) +- 0,5	(Rt=10; Rb = 4,5) +- 1
	center	(Rt =2,8; Rb = 4,5) +- 0,5	(Rt =2,0; Rb =1.5) +-1
LCR	Capacitance	0,17830+-0,0005	0,00567 +-0,00001
	Resistance	34,80 +-0,1	319,4 +-0,1

the first three cases but has a decrease of two orders of magnitude after the third test. The resistance also increased in one order of magnitude. Knowing that the second trial went up to 7 kV, it can be concluded that the voltages of 7 to 10 kV driven damaged significantly the DEA.

Regarding the hand designed DEA, there is actuation. This experiment and also the previous ones with carbon grease reflect that its wettability implies that it spreads and loses its integrity along the actuation cycles.

In respect to the fingertip prototype, one can infer that the frame thickness is too small once it does not keep the DEA intact when it is released from the outer rigid frame. Hence, a PDMS already casted is sticked on both sides of a similar DEA and it gets loose in the same way.

eGaIn by rolling

The effect of voltage on actuation is also accessed for the DEA of VHB and liquid metal.

On these, the eGaIn layer is non-uniform due to flipping the DEA during construction.

It starts to actuate at 2.5kV and as the voltage is increased, the area strain increases.

The liquid metal actuates in a discrete way, either on actuation and also on relaxation. This can be explained because, even with the VHB sticky layer, the liquid metal's high surface tension and, therefore, the skin on its surface result in a poor linking with VHB. As a consequence, it offers more resistance to the signal transition on the dielectric, causing

Table 5.3: Capacitance and resistance for the eGaIn sprayed DEA

C (nF)	0,14600(10)
R (kΩ)	19,55

the effect observed.

In addiction, even with stencils path overlapping on top of the connector and dropping the liquid metal drop on top of it, the eGaIn flows to the center, disconnecting with the tape. This may also lead to the effect prior described.

Another note to register is that at 4 kV, the skin of the eGaIn is blasted and the dielectric membrane is over squeezed. As a consequence, the liquid metal rearranges itself - Figure 5.5

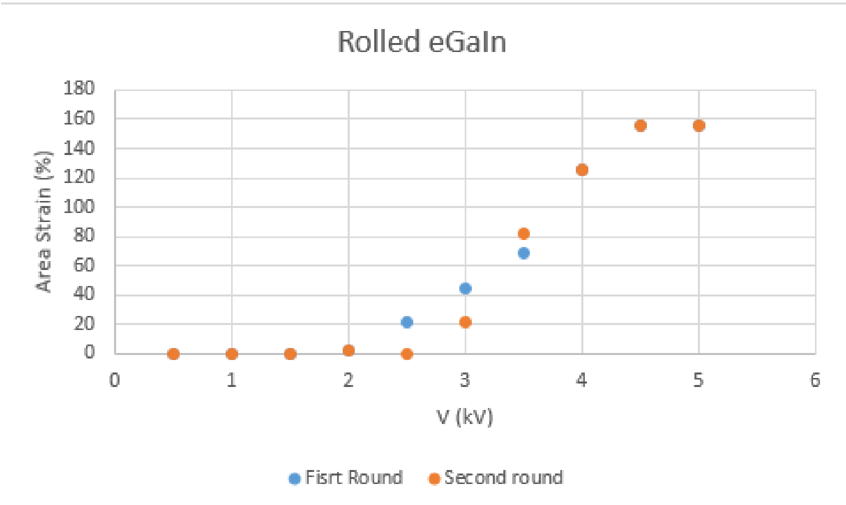
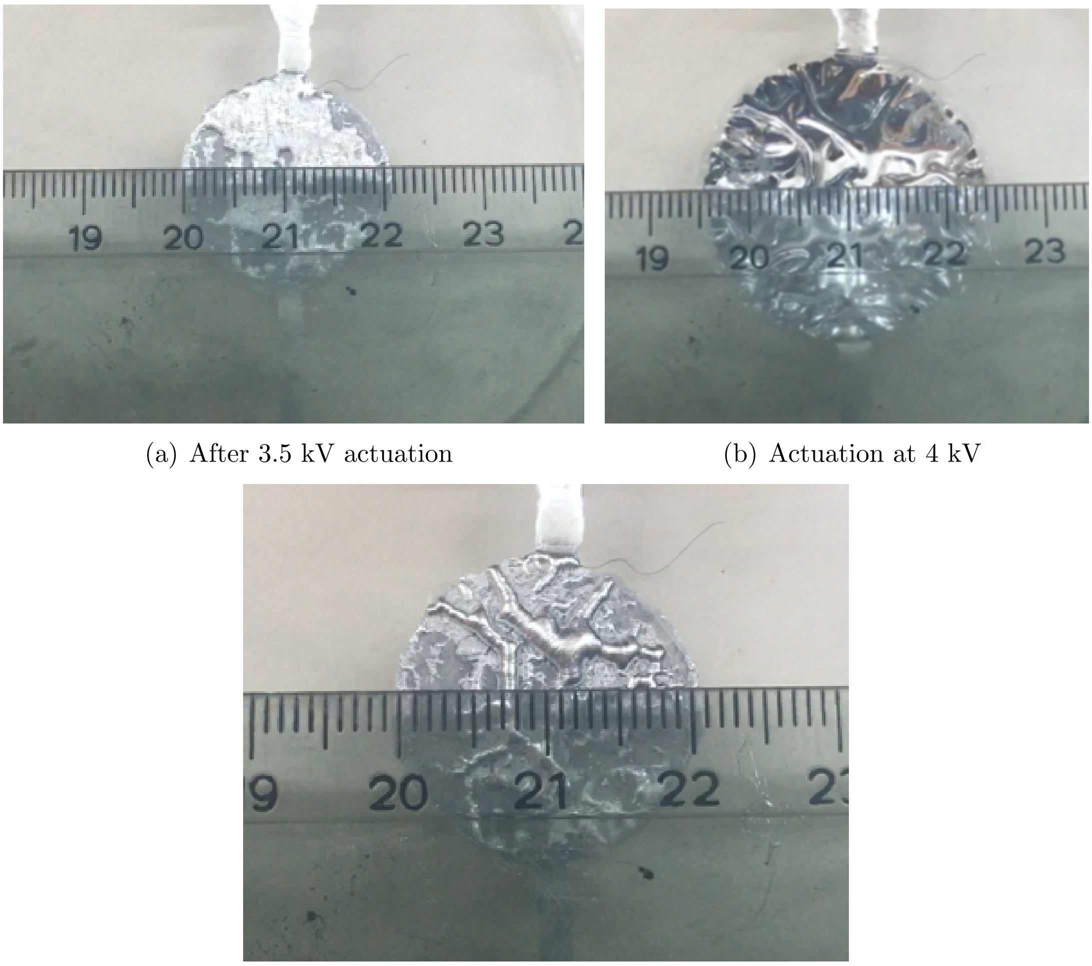


Figure 5.4: Actuation for a rolled eGaIn DEA

eGaIn by spraying

The same behavior is observed for eGaIn by spraying when compared with the rolling method. This time, the connection with Cu/Ni connectors is ensured. However, the liquid metal is sprayed onto the PDMS, forming a layer of small dots. As the voltage is provided, the DEA actuates and the dots spread away from each another and recover to the rest position. This phenomenon increases the resistance to the current flow and reduces either the time response and the recovery time.

An interesting phenomenon to highlight is, when there is a spark on the actuation in the DEA, the spark appears again when it relaxes - Figure 5.7. So, the movement



(a) After 3.5 kV actuation

(b) Actuation at 4 kV

(c) After 4 kV actuation

Figure 5.5

provokes a discharge of the accumulated energy on the DEA. Thus, there are evidences that mechanical stresses can induce the energy harvesting.

5.2 PDMS

The DEAs described are performed with 10% strain.

Two methods are considered to apply the electrode: spraying and rolling. The roll is achieved recurring to a Ecoflex roll. To underline that the excess of sprayed eGaIn is taken off by passing the film applicator on it. This enables the casting of the top layer of elastomer. It is possible to check that the capacitance is one order of magnitude bigger for the spray method - Table 5.4. The roll made of Ecoflex is not a perfect cylinder. This

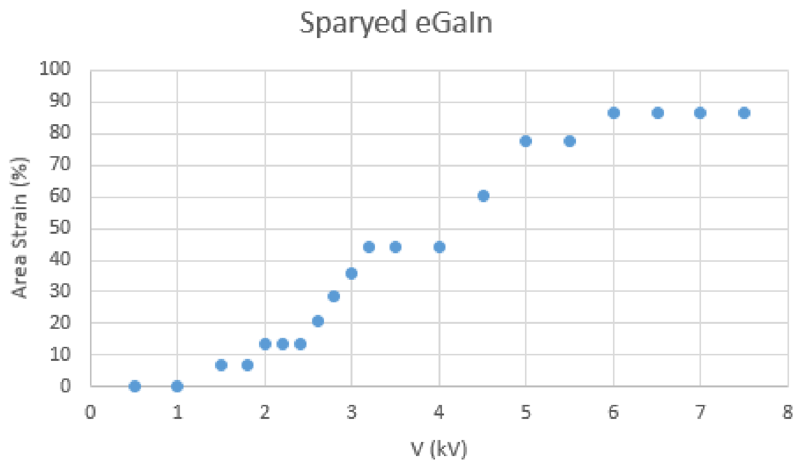


Figure 5.6: Actuation for a sprayed eGaIn DEA

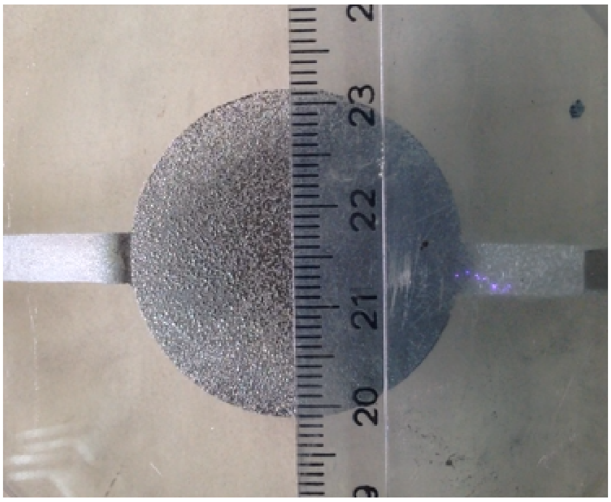


Figure 5.7: Electrical discharge upon DEA relaxation from 2.6kV

does not blast its skin and does not allow a proper spread of the eGaIn. Therefore, some space can be left not filled with liquid. Another aspect to highlight is that one of the DEAs manufacturing failed. This happened because the electrodes height depends on the amount of liquid metal dropped. So, on casting a new layer, it tear apart liquid metal.

Consequently, spraying is performed so that the eGaIn particles fill all the area desired and allow a proper spread-ability of the liquid metal when rolled.

Table 5.4: Comparision of roll and spray on DEA final properties

	Roll with Ecoflex roller	**Spray**	
C (nF)	0,03098(5)	0,15551(5)	0,162000(5)
R (kΩ)	38,40(1)	1,456(10)	0,0216(10)

Table 5.5: Sensing sensibility

	I	I by touch	II	II by touch
C (nF)	0,19240(5)	0,1894(100)	0,16000(50)	0,1565(50)
R (kΩ)	0,0065(5)	0,0060(50)	0,0095(5)	0,100(20)

The properties of two actuators made by rolling are on Table 5.5. It shows the capacitance and the resistance at rest and the affect of a (slight) touch on the properties referred. The capacitances are high and they vary at the order of the dozens of pF when touched. Therefore, these are good sensors. The capacitance and the resistance of the two actuators are similar, meaning that the production technique is reproducible. Also, when comparing with Table 5.4, the capacitances are similar.

Trials are performed to access the consequence of changes of strain and extra PDMS layer thickness on bending angle and further actuation. The angle measurement is done recurring to a user friendly software: Perfect Screen Ruler 3.0. It allows distance and angle measurement of captured image of the screen. For this reason, the recorded video is stopped at the DEA maximum displacement. Hence, a line is done at the center of the DEA which is at on the ground till the point on which it lifts. From this point, the tip is marked in its center and the program does a triangle. Thence, the lifting angle corresponds to the supplementary angle of the angle on which the DEA lifts.

To access the functionality of the DEA, the bending angle is measured in function of the voltage - see Figure 5.8

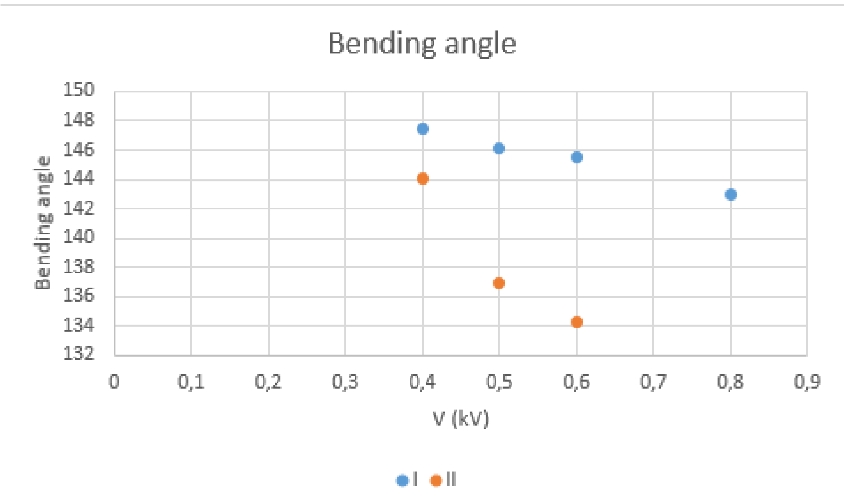


Figure 5.8: Bending angle change with voltage for two DEAs

Both actuators failed at 0.8kV. While actuator *I* performed the full movement at 0.8kV and failed, the DEA *II* started the movement and failed before reaching the maximum bending angle for this voltage.

Thereupon, the factors which affect the bending angle of an actuator are depicted: the pre stretching strain and the extra PDMS layer thickness.

The result of pre stretching the DEA in 30 % is on Figure 5.9.

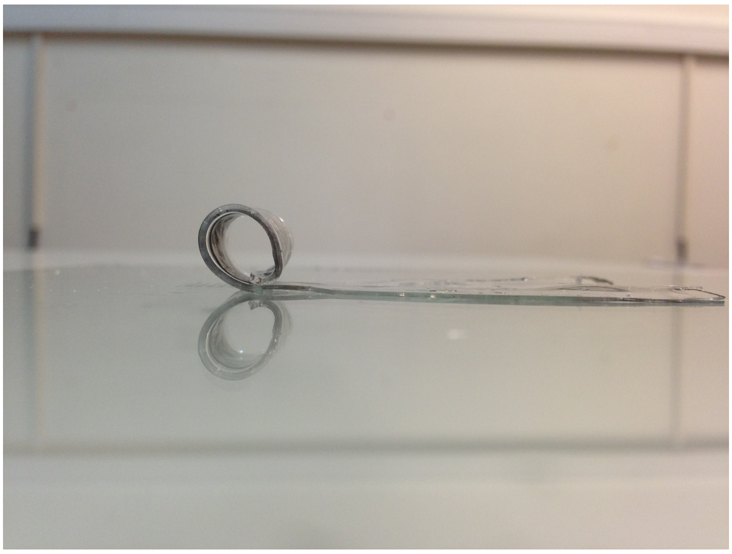


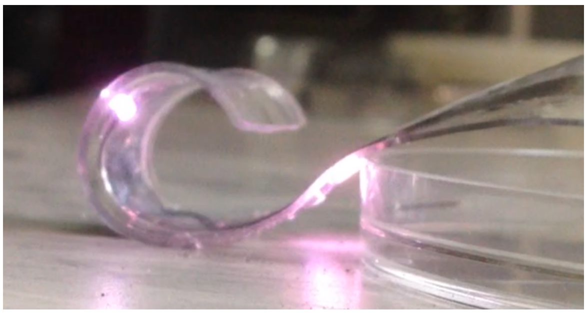
Figure 5.9: DEA with 30% strain

Thus, this strain makes the DEA to curl over itself, flipping approximately 180 degrees. Furthermore, in comparison with the 10 % strain performed on actuators previously described, it can be concluded that the more strain is applied to the DEA, the more bended it remains. The bonding of the extra PDMS layer on top of the flat PDMS-eGaIn-PDMS-eGaIn-PDMS structure while strained provokes the DEA to bend to the its bottom when released from the substrate. That occurs as a consequence of the longitudinal stresses induced by the stretching and the top layer makes it to bend downwards. In this case, as the strain is bigger, the forces which force the DEA to bend are bigger. So, the equilibrium position is manifested at a bigger angle. This bending angle at rest physically inhibits its actuation.

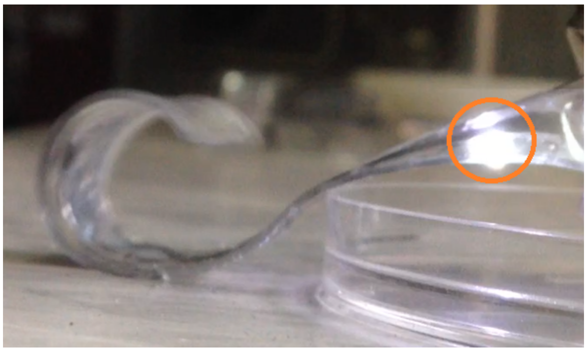
On a previous version, the extra layer was casted not from the beginning of the electrode but from a distance in between the it and the connectors. Consequently, it was not ensured that the layer had the same length. Moreover, as the layer was bigger, the DEA bends more for the same thickness of extra PDMS. It resulted on a curled DEA - Figure 5.10. When the DEA is released, it bends; however, when the sparks show up, it stops actuating and re-actuates again til the next spark cyclic till the high voltage machine is suspended. It can be concluded that the electrical breakdown observed in steady spots inhibits the actuation by short circuiting the system.

Figure 5.10: Physical inhibition to the DEA actuation

On the DEA of Figure 5.11, an actuation of 3.5kV is provided and the electrical breakdown occurs (Figure 5.11(a)). After, the same voltage is driven and the short circuit occurs at the connections 5.11(b). The DEA keeps the actuation as referred for the DEA described in the previous paragraph.



(a) Electrical breakdown



(b) short circuit spark inside the orage circle

Figure 5.11: Circular DEA with carbon grease actuation

Another element which influences the bending angle is the thickness of the extra PDMS layer.

As so, DEAs with extra PDMS layers of 200,300,400 and 600 μm are manufactured. The angles at 0V are presented in the Figure 5.12

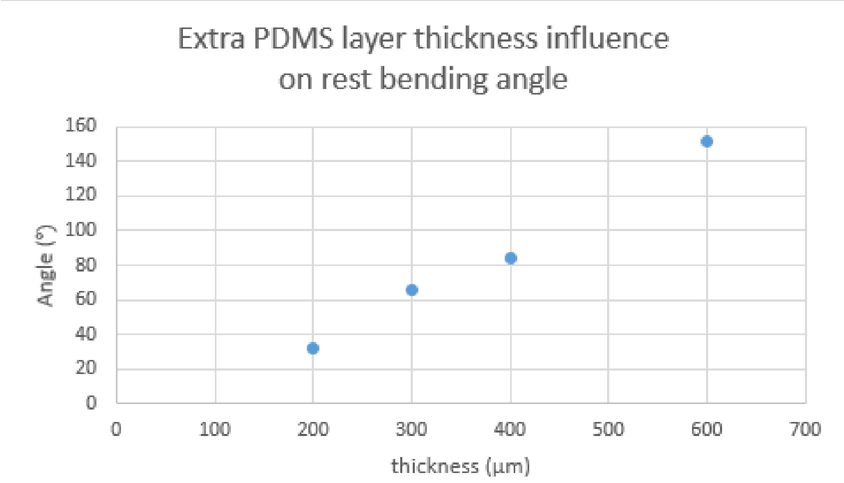


Figure 5.12: Extra PDMS layer thickness influence on bending angle at 0V

According to the graphic, the thicker the layer is, the more the DEA curls. This is the expected result once the more thick it is, the more force it does and, consequently, it bends more to the opposite side.

An aspect to consider is the influence of gravity on the bending angle. The actuators behavior concerning its bending is such that the gravity has more effect when the tip of the actuator passes the 90° angle and starts to point to the ground. On this case, the own weight of the DEA forces it to bend more as seen for 600μm. On other hand, when the DEA is before and near the 90°, the more curled tip compared to less thick samples also imposes a bigger gravity force. This demands more force to bend and to overcome the 90°. The DEA of 400μm illustrates this situation when compared to the 200 and 300μm ones on his left.

To highlight that these conclusions regarding gravity force cannot be drawn as a certain associated with the low amount of samples and also with errors related with the angle measurements.

A segmented and longer actuator is fabricated with 10% in strain and with an extra layer of 600μm. Here, the equilibrium position is achieved remaining flat on the surface and just lifting its end - Figure 5.13. It can curl more as one can lift it and leave it with a different area adhered and, as a consequence, a different curling.

(a) Equilibrium position with the DEA adhered to the surface (b) Equilibrium position with the DEA curled

Figure 5.13: Adhesion to surface and gravity influence on a longer DEA

Regarding manufacturing, doing first the 100μm dielectric layer in spite of doing the 300μm, spread the liquid metal electrode and then the 100μm dielectric layer is preferably. In one hand, on the first case it is ensured that the layer has an uniform 100μm layer - on the second case, the dielectric layer is smaller on the electrode direction because of its length. On the other hand, the electrode thickness is not completely controlled; being the middle layer thinner than the exterior ones, it is more likely to drag out the electrode while applying the thinner one.

Upon actuation, a spark can be seen in some cases. On those, the applied voltage exceeds the breakdown voltage. Thus, the dielectric becomes conductive and it leads to an arc (the spark observed) because the high voltage machine does not suspend the current. The figure 5.14 presents the spot where a fail occurs. It is observed that the arc is on a air trapped location.

To avoid this problem, PDMS goes to the vacuum pump before casting the PDMS thin films. With this process, the air trapped on and beneath the polymer is released, resulting in a more uniform liquid.

5.3 Connectors

The resistance of the connectors is of the same order of magnitude (Ω) - Table 5.6. Thus, this factor does not implicate a prior choice.

Figure 5.14: Spot where arc occurs - inside the red circumference

Table 5.6: Resistance measured for the three types of connectors used

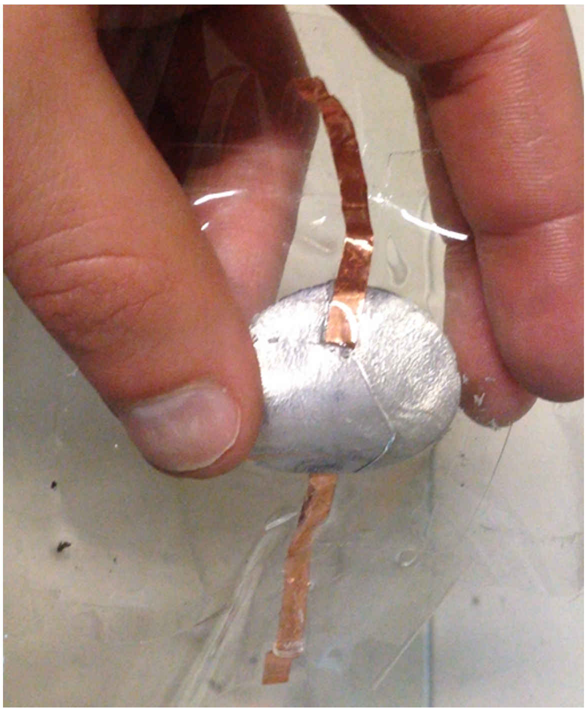
	Fabric textile	**Cu/Ni**	**Cu**
R(Ω)	1.5 (0.5)	0.20 (0.05)	0.10 (0.01)

Regarding the DEA construction, Cu connectors bend and wrinkle being hard to place down flat on the desired spots, like connection pads. Consequently, the applicator drags it out while placing the encapsulating PDMS layer. Even though, it can be implanted after the PDMS appliance. However, it does not ensure a connection with electrode and it can detach and lift off from it while the PDMS is curing (having no connection).

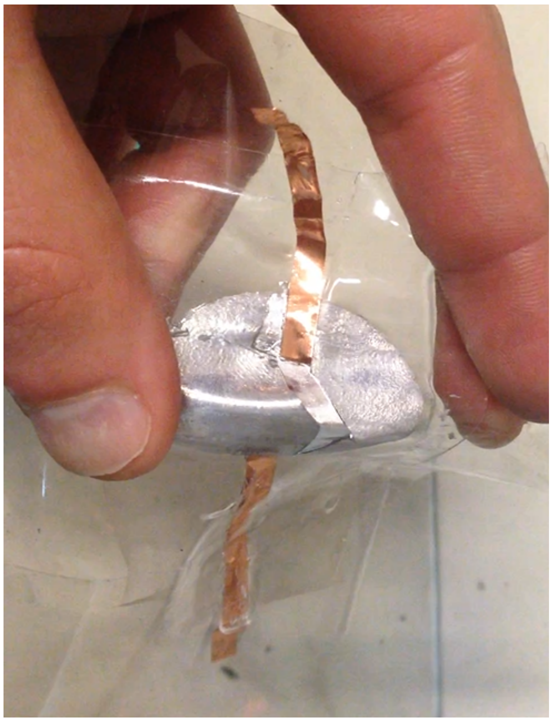
In addition, they brake the electrodes even when encapsulated - Figure 5.15. Image 5.15(b) shows that the movement makes the dielectric and electrode layers to spread apart while the copper tape keeps on his place. So, the connectors should be placed out of the actuation region.

Fabric textile connector is also dragged by the applicator for a 300μm height. In regards with the tests, fabric textile sparks all over itself at 3kV. During fabrication, connectors can be encapsulated by PDMS and it is taken off. On this process, the fabric is stretched and also on the crocodiles placing, making the fabric to release silver which conducts preferably along it - being those the sparks observed.

By its side, Cu/Ni tape remains flat when peeled off of its backing and when placed on DEA pads. Moreover, when the applicator is passed along it remains at its place. For these reasons, it is the connector chosen on the last DEAs versions.



(a) Electrode fracture on top side



(b) Connector moves along and the electrode brakes away

Figure 5.15: Electrode fracture

To highlight the distance between the connectors is important. The shorter the distance, the less voltage is required to ionize the air and make the current to flow directly from one to another.

Chapter 6

Conclusions

- The main challenges of DEAs made with VHB are pre-stratching and a solid frame to keep it stretched. This results in a constraint for possible applications. That is why recent studies which do not need these seem promising;
- As the MG chemicals 846 carbon grease does not cure and is always wet, it loses its integrity as the paste is taken out when in contact with other objects;
- The VHB of eGaIn shows an inadequate performance for a DEA due tu its discrete behavior, long response and recovery time;
- The lack of encapsulation of eGaIn results in undesired flows of the DEAs normal actuation but also other tiltings with addiction to gravitational force;
- The Cu/Ni connectors are the ones which best fit for low thickness layer cast on top of it;
- The more strain, the more the DEA bends;
- The thicker the extra layer is, the more the actuator bends.

The Table 6.1 summarizes the properties of PDMS and VHB. The PDMS takes more time to cast and produce a DEA while the VHB is just needed to stretch and apply the electrodes; however, PDMS allows an higher degree of freedom to design actuators once it does not require bulky frames. The actuation displacement and area strain obtained for VHB are higher; nonetheless, the response and recovery speed are lower.

Table 6.1: Comparison between VHB and PDMS

	VHB	PDMS
Manufacturing time	+	-
Manufacturing freedom design	-	+
Actuation displacement	+	-
Response speed	-	+
Recovery speed	-	+

Table 6.2: Comparison between carbon grease and eGaIn properties

	Carbon grease	eGaIn
Conductivity	-	+
Cost	+	-
Appliance	+-	+-
Fabrication speed	+	+-

Regarding the stretchable electrodes, the Table 6.2 summarizes its properties. The eGaIn has higher conductivity but is more expensive. In what converns appliance, carbon grease is easily applied on VHB but there are difficulties on ensuring a uniform layer; in fact, one can set the top layer thickness with the applicator (even with an acrylic frame with a thickness of 3mm, a support can be placed on applicators pads), although the bottom one no due to the frames thickness constraint. the manipulation of liquid metal is a challenge according to the literature but in the presented work it is suggested a practical way of fabricating DEAs with it. The fabrication speed is fast carbon grease while eGaIn requires more care on handling the samples making it less fast.

6.1 Opportunities

- As the carbon grease does not cure, it can be mixed with PDMS in 20% in weight. This way, it can be cured and the bonding with the PDMS insulating layers would be higher.

- The eGaIn blasts through voltage drive can be interesting to extrapolate for substances release upon an electric stimulation. Therefore, it can be used on self-healing structures on which an active compound is encapsulated. Hence, these structures can be linked and the fracture of one these by impact can also crack others and enhance the healing effectiveness.

- Once the capacitance depends on electric field, the DEA can work induced by a magnetic field. With this, one can have actuation triggered without connectors on the actuator which can enhance new fabrication methodologies. This fact that the actuator does not have to be in contact with its stimulator also broadens applications. However, it would also be sensitive to interferences from the medium.

- The energy harvesting enabled by this material can be exploited. Application on shoe wave and wind generators are being discussed. Additionally, it can be applied to daily activities to charge electrical devices. Therefore, it can be introduced on textiles and clothes to generate energy from movement.

- As the capacitance changes are significant, the fabrication technique can be used to fabricate pressure capacitive sensors with multiple electrode layers.

- A fabrication technique which can be explored is cure an exterior PDMS layer with a cantilever with the desired thickness of the electrodes. After, the electrode is applied and these are covered with the PDMS dielectric layer. Afterwards, a mold can be placed with the thickness of the electrode layer. On top of it, the PDMS layer is casted. Finally, the electrode can be injected with a serynge. For that, a secondary path is created with the referred mold so that air can be pumped out, so that the electrode can go in and fill the space. Finally, it can be stretched and an extra PDMS layer added to bend the actuator.

6.2 Future Applications

The mechanical properties achieved may be suitable to integrate the finger in a glove (and not on a prosthetic finger/hand, even on its palm surface). On this case, the prosthetic stiffness may interfere with the designed DEA. However, on a glove, the bottom surface can be fabricated with DEME technology allowing its user to better grasp and handle objects. It can be coupled to a smart device - like a watch or a smartphone - to recognize the object and adapt the right voltage to be provided and the grasping technique according to the object and situation. Additionally, it can track its user, collect metrics, record data and have an algorithm to predict future grasps with similar objects with pattern recognition and machine learning. This solution fits elderly and other people with hand disabilities, professionals with heavy manual work and sports athletes/fitness lovers. These would have the possibility to share it with its family, health professionals, bosses and personal trainers.

Other possibility is to use the bended DEAs to form a gripper - Figure 6.2. An advance would be to use a segmented DEA (Figure 6.1) in which its tip would have the design of *"fingertip 1", Appendix A - Designs*. This way, one would have in-plane actuation and, as a consequence, an intrinsic electroadhesion which enables a better grasping. Thus, a variety of objects can be grasped with this gripper.

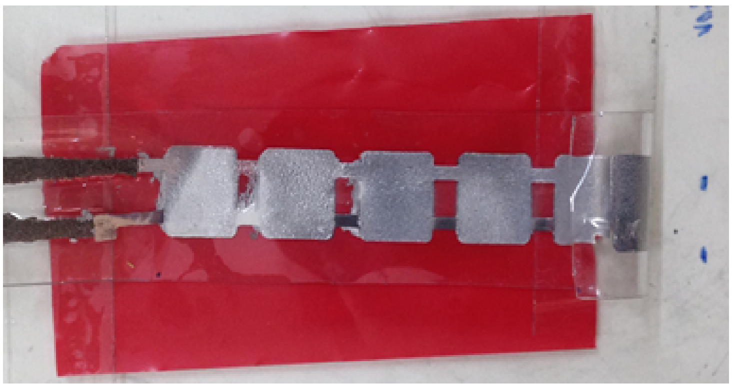


Figure 6.1: Segmented eGaIn DEA

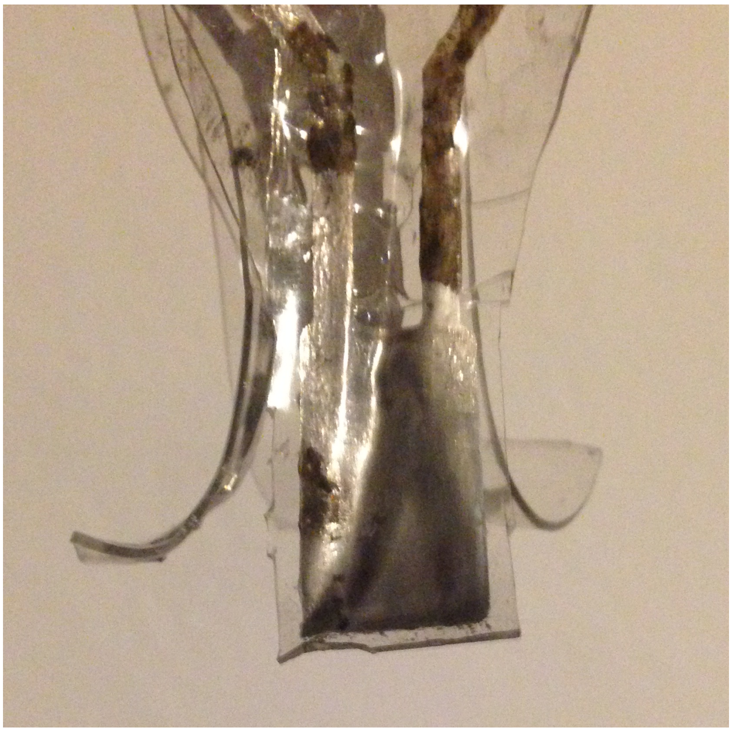
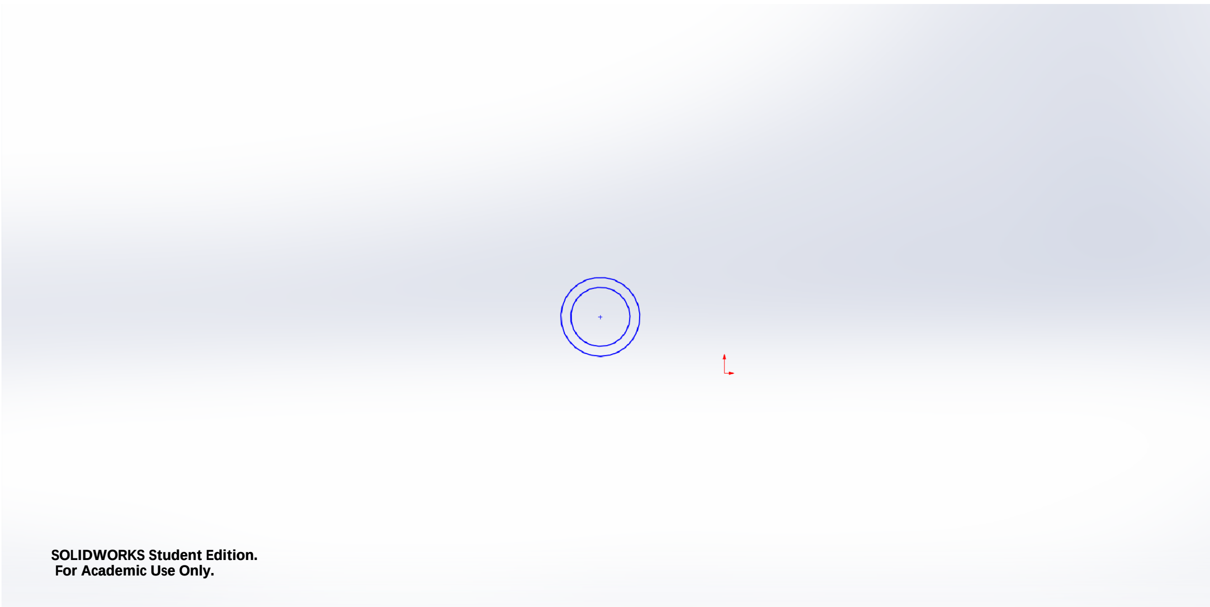
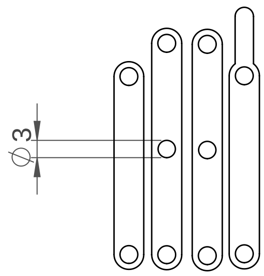


Figure 6.2: Gripper prototype made with three DEAs

Appendix A - Designs

On this appendix, the designs draw either for laser cut and also for electrode patterning are presented.





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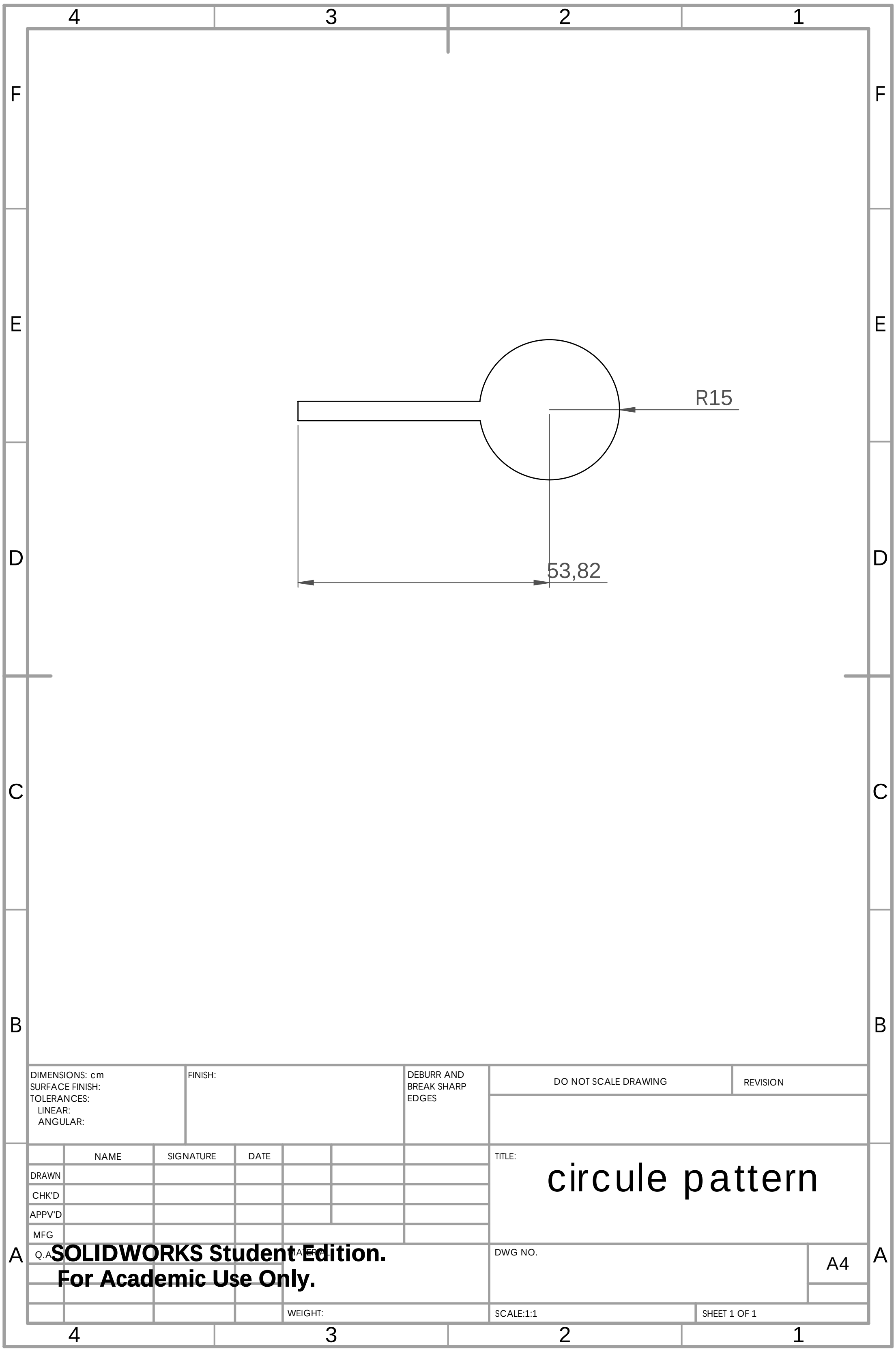
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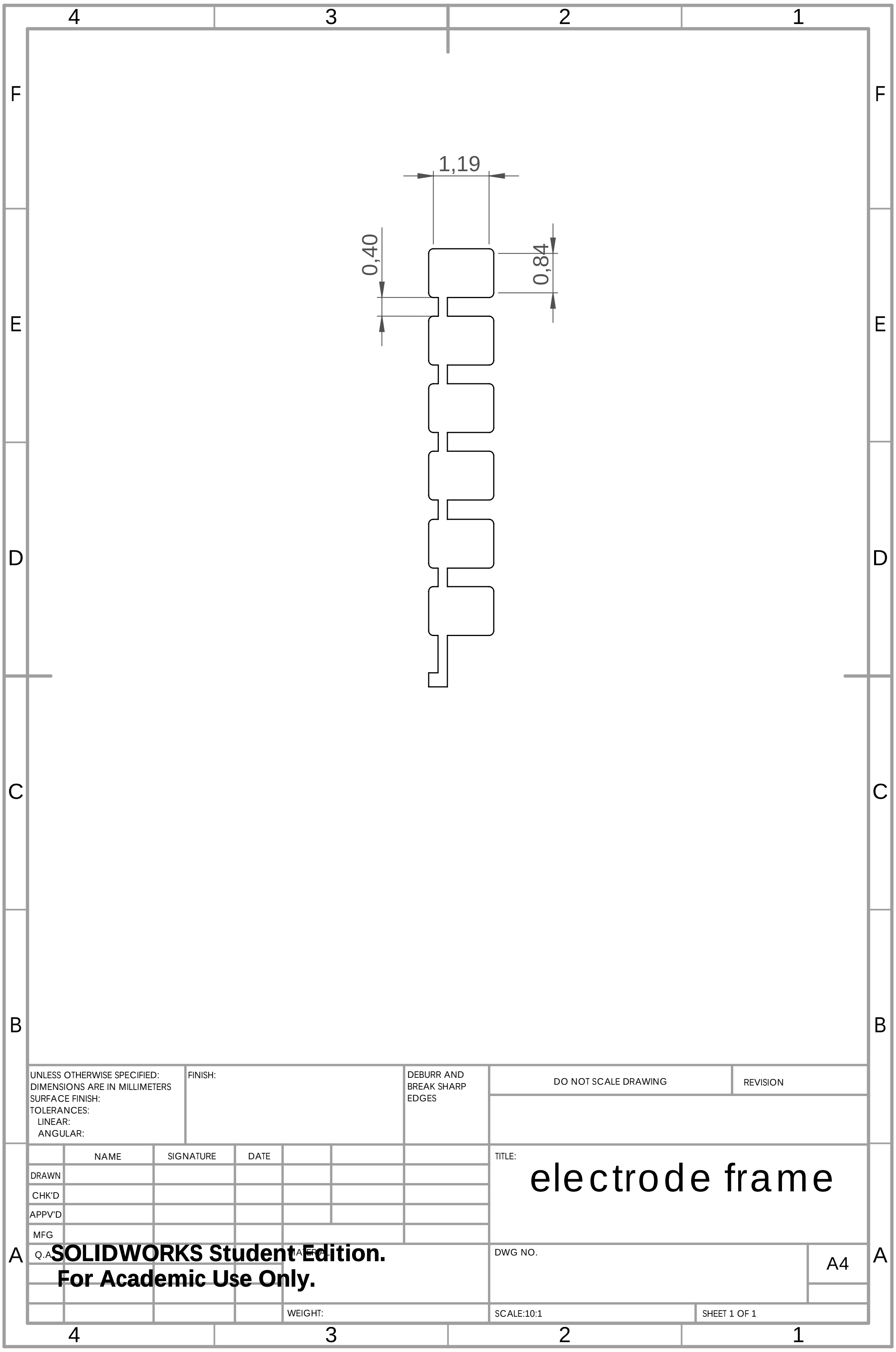

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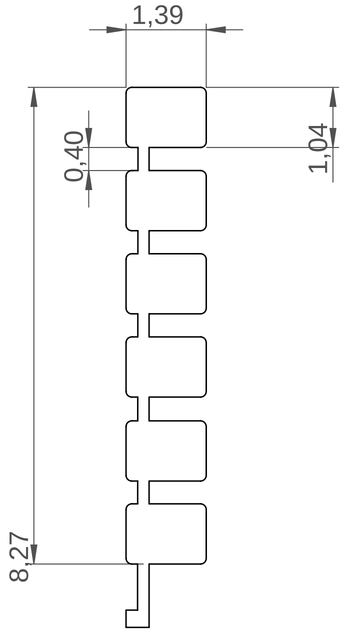

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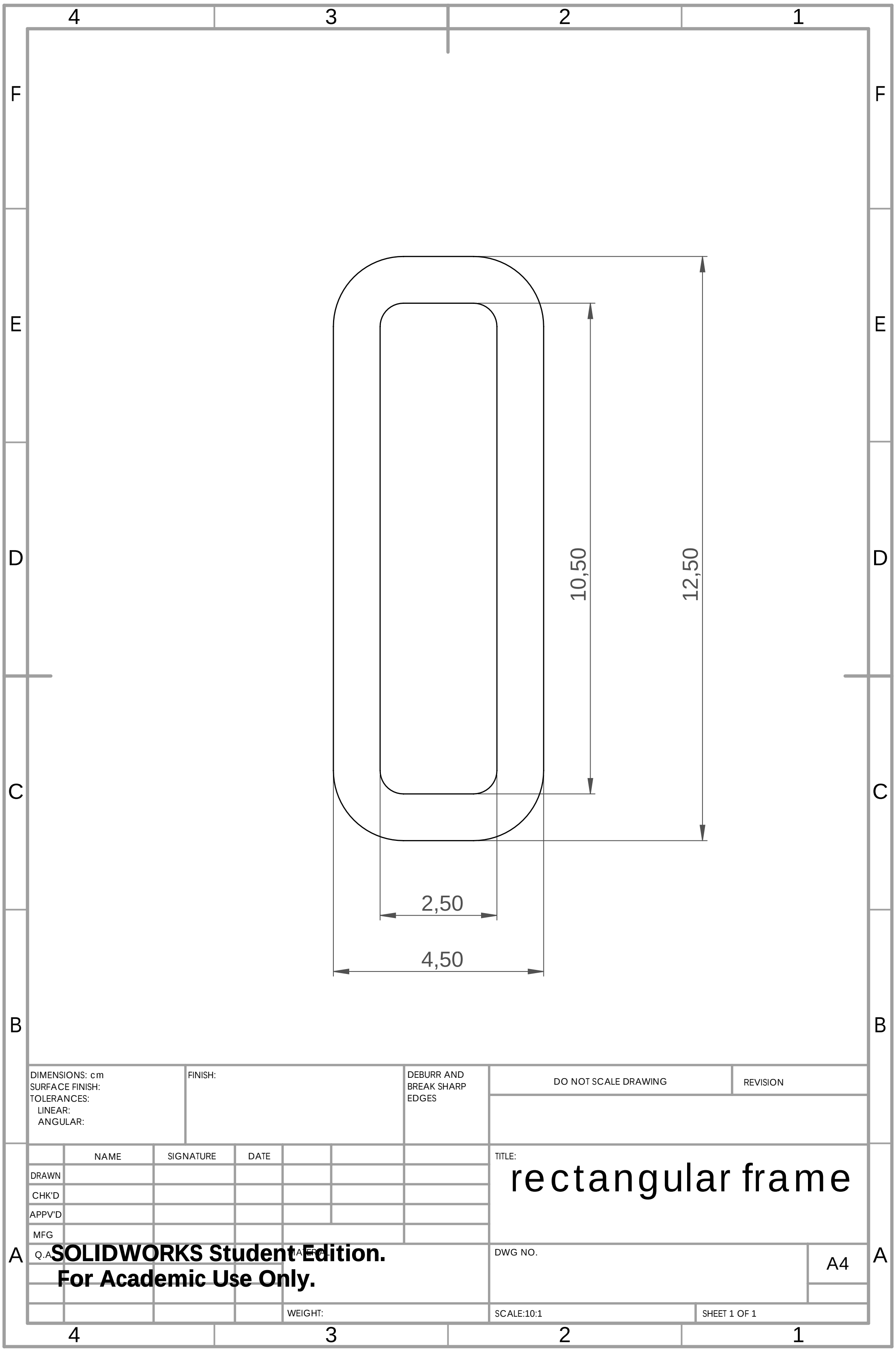
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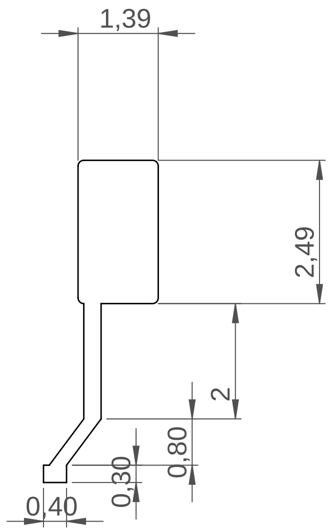

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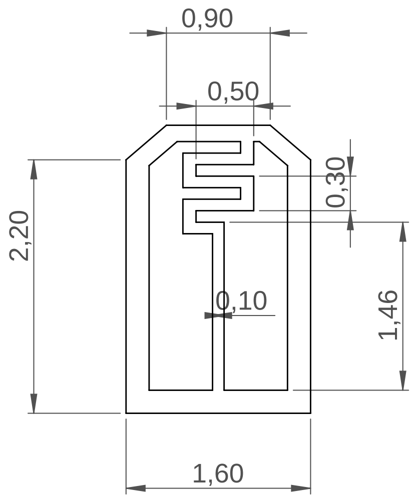

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