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High-voltage Photonic Switching of Dielectric Elastomers with Amorphous Silicon Thin-Films.

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ABSTRACT

Optically-switched composite materials based on semiconducting materials have the potential to simplify the circuitry required to control artificial muscles. This contactless control method has the potential to improve visual technologies by enabling controllable haptic and morphing interfaces. Optically-switched active displays could provide enhanced user interaction, especially for those with visual impairments. Research into morphing interfaces with dielectric elastomer actuators (DEAs) centralizes on segmented electrode architectures that can achieve large active strains in multiple degrees of freedom. However, controlling the activation of multiple electrodes typically requires an array of discrete rigid components (e.g. MOSFETs) as well as the separation of high-voltage power lines and low-voltage control signals. In this work, we develop a photo-switched DEA system that removes the need for wired control signals, reducing complexity. Photonic switching of DEA electrodes is achieved by exploiting the light-dependent resistance of a thin film of deposited amorphous silicon (a-Si). Samples with layer thicknesses of 0.84 μm have been fabricated using plasma enhanced chemical vapor deposition. Breakdown voltages of above 6kV were obtained when using a non-conducting substrate (glass). Preliminary testing of the system shows that voltage swings of up to 865V can be achieved between ambient and direct illumination, producing an out of plane actuation of 2 μm in a weight-biased DEA disc actuator. Further tuning of the electric circuit should lead to larger actuation strains. Future work will focus on the control of multiple DEA electrodes using localized light patterns as well as testing and characterizing other materials to improve the voltage swing across the DEA.

Keywords: Photonic switching, amorphous silicon, dielectric elastomer actuators, high voltage.

1. INTRODUCTION

Dielectric elastomer actuators (DEAs) are an emerging class of actuators that produce high strains and can be designed to create both in-plane and out-of-plane actuation [1]. DEAs consist of a dielectric elastomer that separates two compliant electrodes. Applying a potential across these electrodes generates an electric field dependent Maxwell pressure, which leads to a through thickness compression of the pre-strained dielectric elastomer membrane [1]. Maxwell pressure equation for a DEA where e_r is the relative permittivity and e is the permittivity of free space, V is the applied voltage and T is the thickness of the membrane.

$$P = e_r e \left(\frac{V}{T}\right)^2 \quad (1)$$

Typical applied electric fields are of the order of 100Vμm^{-1}[2], which for DEAs typically corresponds to an operational voltage of 2-3kV [2]. These voltages are limited by the dielectric breakdown strength of the elastomer. However, some designs have been shown to operate with as low as 300V by reducing the membrane thickness to 3μm through a pad-printing fabrication technique [3].

DEAs can be designed with multiple segmented electrodes on a single membrane, to achieve advanced functionality such as multiple degree-of-freedom actuation [4] or peristaltic pumping [5]. To actuate individual

DEA elements in controlled sequences, numerous MOSFETs or relay switches are required. These may be bulky, an obvious downside in the field of robotics [6], and difficult to integrate into a compliant actuator without using external circuitry. DEA technologies have the potential to create small controlled deformations of a thin membrane, by the implementation of optically-switched functional materials into the actuator design. These materials are required to withstand high voltage without risk of electrical breakdown and provide enough change in resistance between the light and dark states to allow enough voltage 'swing' for actuation. The potential scope of this technology has several application [7] including the generalized benefit of a wireless control of a DEA system. As well as morphing visual membranes [8] or aerodynamic surface tailoring.

Light dependent Resistors (LDRs) are commonly used in electronics to provide variable resistances with light intensity. They largely consist of two electrodes connecting a photo-resistive ceramic material. Photo-resistive ceramics such as cadmium selenide/telluride and zinc oxide [9] have been widely used in LDRs. It is possible for these ceramic powders to be deposited as thin ceramic films[9], however ceramics are typically brittle without significant additions, such as plasticizers. This is an important consideration when implementing these materials in actuator devices. Semiconducting materials such as silicon provide an alternative as they can be doped to provide a varying range of electrical properties. Commercially available silicon photovoltaic cells fall into three categories; single crystal, arranged polycrystalline and amorphous. These have an increasing number of randomized grains respectively. With amorphous silicon being the most commercially available and often found in small electronic devices such as calculators. Amorphous silicon has no long-range orientation of the crystal grain structure rather than being a truly amorphous material[10]. Amorphous silicon is a semiconductor with a number of dangling bonds in its electron structure, this creates a lower energy path for free moving electrons to pass from the valence band to the conduction band [11]. The dangling bonds caused by the amorphous structure creates several electron recombination centers. These provide a lower energy pathway into the extended states where electron transport can occur. We can deduce that amorphous silicon should have a sensitive response to stimulus that would allow for conduction but potentially localized to where the stimulus occurs due to the 'amorphous' nature. As mentioned in the literature the availability of free moving electrons in the a-Si structure leads to a "short ambipolar electron diffusion length of less than 115nm"[12]. This therefore opens the potential to utilize this resolution to create multiple electrodes on a single sample of amorphous silicon as a control switch for multiple actuators that are independent of one another. For this investigation the following samples where tested; amorphous silicon, a 15kΩ LDR and p-type Silicon wafer.

2. METHODOLOGY

2.1 Amorphous silicon deposited onto Glass substrate

Amorphous silicon (a-Si) was deposited onto a chosen substrate using a plasma enhanced chemical vapor deposition process (PECVD). A glass substrate was used for optical transparency. The deposition process of thin films has a high risk of contamination from surface dirt and dust, therefore the manufacture process was carried out in a clean room facility (Class 10000 cleanroom; 21C +/- 1C; 50% +/- 5% humidity). The glass substrate was thoroughly cleaned using a two-stage cleaning process of acetone followed by Isopropanol ultrasonic baths for 5 minutes respectively. Once the substrate had been dried using a nitrogen air supply, the substrates were transferred to a silicon carrier wafer which was placed into the PECVD system (Oxford Instruments Plasmapro System 100 PECVD). The PECVD deposits amorphous silicon at a rate of 28 nm per minute. A 30-minute deposition time created a 0.84μm layer of amorphous silicon. Once the sample had been removed from the PECVD it was masked to allow for gold electrodes to be spluttered onto the sample. The electrodes consisted of a 400nm titanium layer followed by a 200nm gold layer. The sample was then mounted onto a specially designed printed circuit board and attached using epoxy adhesive. The gold electrodes were connected to the PCB using bond wires of 5μm diameter gold wires to header pins which allows the samples to be connected using readily available high voltage wires.

2.2 Manufacture of DEA

A single membrane disc DEA was fabricated using 3M 4905 VHB tape, stretched over an acrylic frame with 4x4 biaxial pre-strain. Carbon grease electrodes (MG Chemicals) were applied using a mask onto the surface of the tape. The process for this is shown in Figure 2. The actuator was weight-biased by a small 9.1g metal component placed in the center of the electrode to generate an out of plane displacement during actuation. Displacement was measured using a laser displacement sensor (LK-G152 and LKGD500, Keyence).

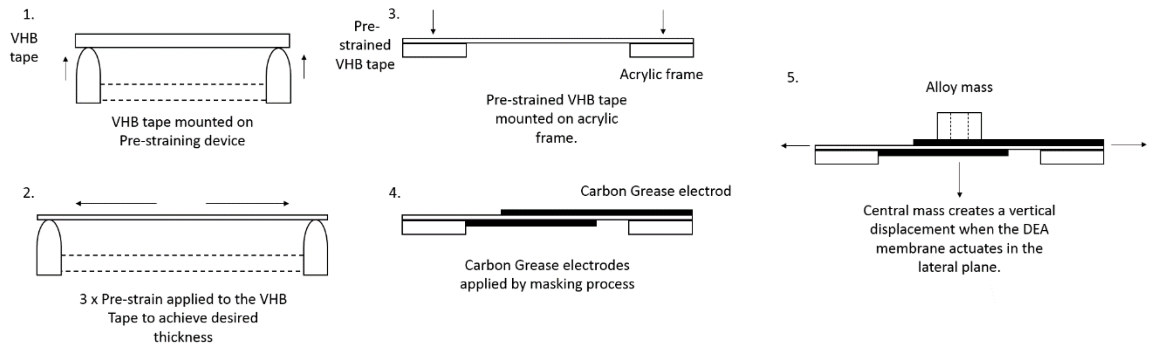

Figure 2: Schematic showing the process used to manufacture a dielectric elastomer actuator from 4905 VHB tape.

2.3 Breakdown voltage and light/dark resistance of the a-Si thin-film.

The samples were tested using a voltage ramp test to check for electrical breakdown. The test consisted of a voltage ramp from 250V to 2kV increasing at a rate of $5Vs^{-1}$ using a high voltage amplifier (Ultravolt 5HVA23-BP1). The ramp test was conducted in various lighting conditions, dark (~ 0 Lux), ambient light (307.5Lux) and various light intensities to a maximum of 51 kLux this was measured using a Urceri MT-912 light meter. The current was measure using a DAQ device (National Instruments BNC-2111) and the results of which are shown in Figure 4.

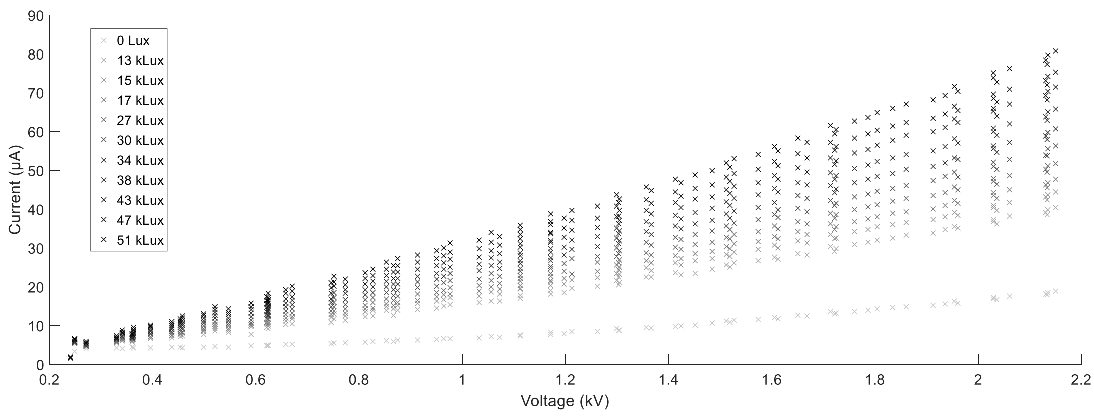

Figure 2: Current passing through the a-Si film as a function of voltage at different light intensities.

No electrical breakdown occurred in the a-Si sample during the test, however P-Type silicon showed breakdown at 1.3 kV and a 15 kΩ LDR did not provided enough resistance to limit current reaching the DEA even at the lowest light intensity. Therefore, it was deemed that a-Si would be the most appropriate material to be used for a high voltage photoactive switch. To determine how much voltage swing can be generated at high voltage (~2.18 kV) the maximum current at this voltage was taken and plotted with different light intensity. For this initial study the relationship between current and light intensity was assumed to be linear and a linear regression was fitted to the data set with a norm of residuals of 8.68. The equation for this linear fit is as follows;

$$I = 1.1076L + 24.2 \tag{2}$$

Where I is the current and L the light intensity. From this equation the resistance change of the a-Si film can be calculated using Ohm's law. The achievable voltage changes can be calculated from the dark and illuminated resistances with a fixed 50MΩ bleed resistor. In future work this relationship can be used to help optimize the voltage divider set up and improve the achieved change in voltage.

2.4 Temperature effects

An initial concern was that there would be an increase in temperature of the a-Si due to the proximity to the light source. The hypothesis was that this would increase electron mobility and therefore a reduction in the resistance of the a-Si leading to increased displacement creep of a DEA actuation over time. To test this, the a-Si sample was placed at the closest proximity to the light source (51klux) and a ramp test was conducted with the thermal response measured by a camera (FLIR E4). The sample was illuminated for 10 mins, reaching a maximum temperature of 34.5°C. The results of this ramp test are shown in Figure 3. As can be seen there is no significant difference in the current with heating of the a-Si switch.

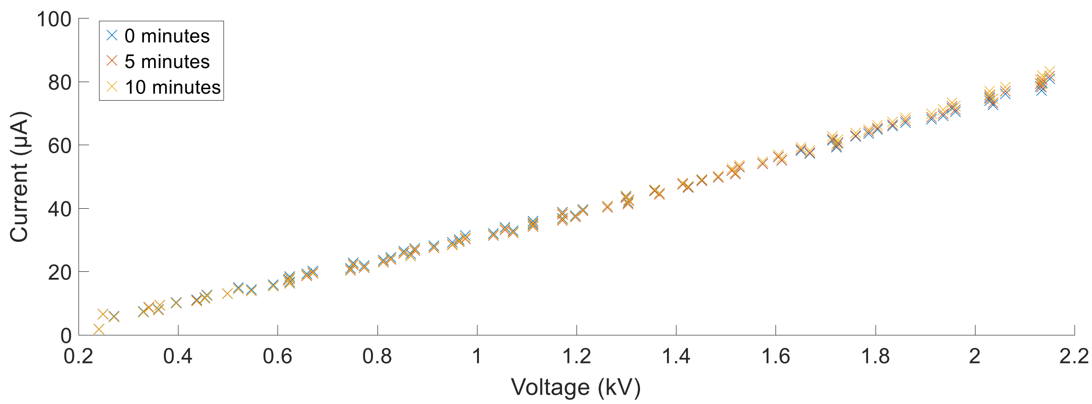

Figure 3: Current as a function of voltage for a-Si with increasing exposure time to the light source.

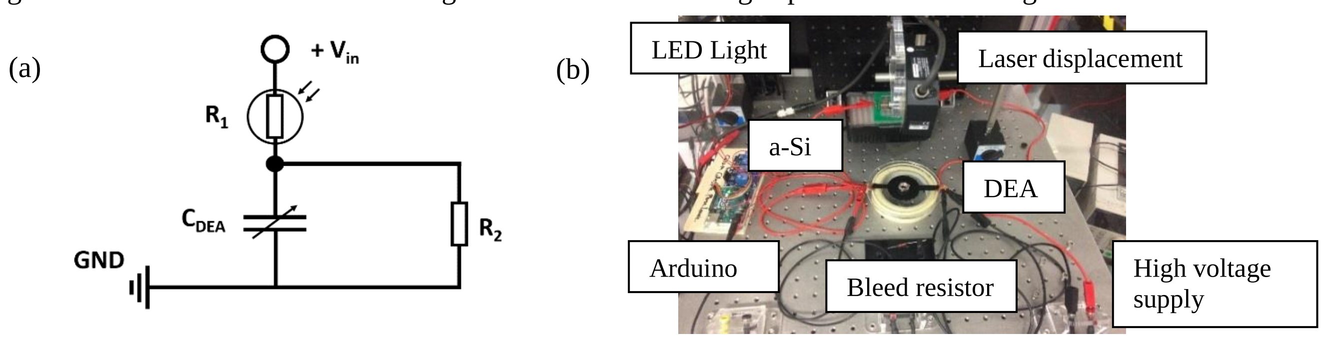

Figure 4: (a) a schematic of the Voltage divider circuit for the optically controlled DEA. (b) The Experimental set up for the optically controlled DEA.

To discharge the DEA after actuation, a bleed resistor of 50 MΩ was placed in parallel with the DEA. The light source was controlled via a relay with an Arduino circuit with a loop function turning the light on for 5 seconds and turning it off for 10 seconds.

3. RESULTS

Actuation tests were conducted at 3kV input for 30 seconds. The light source was turned on at 9 seconds and held for a 5 second period, after which it was turned off for 10 seconds and then on again for a final 5 seconds at 24 seconds as highlighted in Figure 5 A displacement of 2.2 μm was recorded by the laser displacement meter. As shown in Figure 5, small latency can be seen between the application of light and the increase in current seen in the circuit. The DEA has a slightly delayed response and takes some time to reach full actuation, but this is likely due to the capacitive nature of the actuator. This low latency can be extremely beneficial in electronics where high frequency switching of input signals is required. The results show a measurable displacement of the DEA; however, it is difficult to observe with the naked-eye. This is largely due to the relatively small change in resistance that of the a-Si between the ambient and illuminated states.

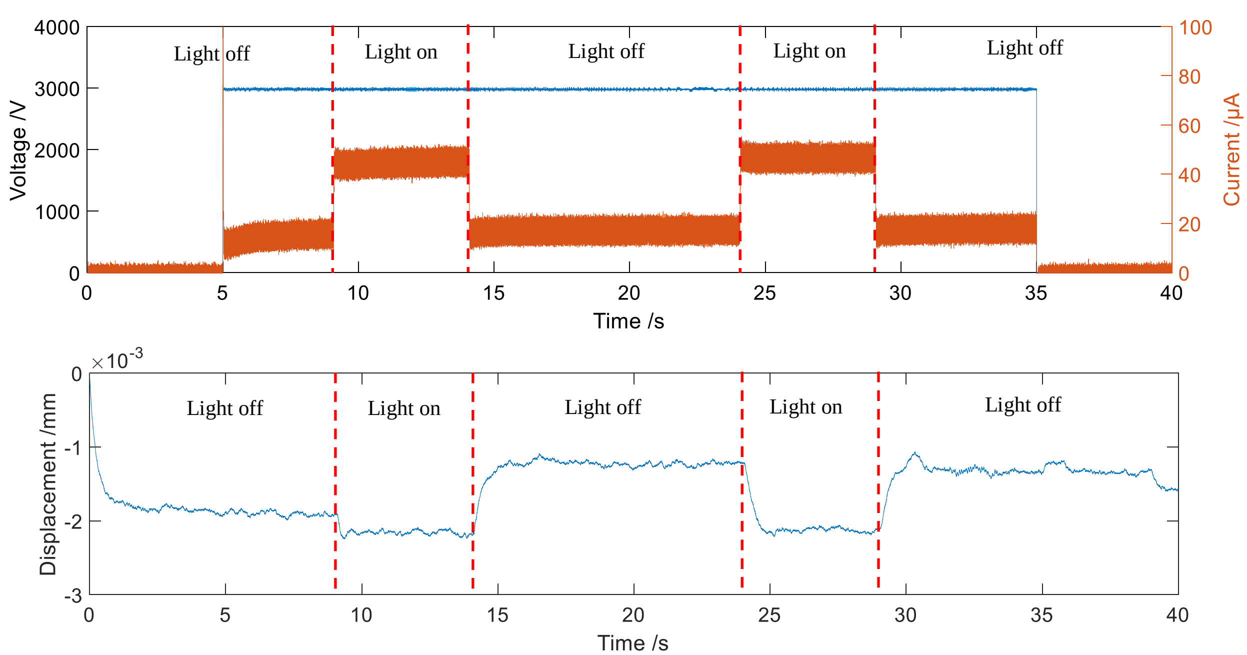

Figure 5: DAQ results from the experimental tests showing the voltage, current and displacement of the actuator as a function of time. The illumination periods have been overlaid in the charts.

This led to a relatively small voltage change across the DEA. This could be improved by improving the material properties as well as refining the resistance of the bleed resistor to better tune the voltage change. Other materials could be investigated as well as doping techniques to help improve this resistance change. One difficulty is that for this to be beneficial the maximum resistance would need to remain close to the value of ambient a-Si as any lower would allow more current to flow to the actuator when the voltage is initially applied.

4. CONCLUSIONS

This work proposed a potential method for the wireless control of DEAs using an optical switching of amorphous silicon thin films. It was shown that an optical switch can be placed in series with a high voltage supply to simplify the electronic circuitry required for controlling a DEA actuator. A simple linear regression was proposed for the resistance of amorphous silicon with light intensity at 2.18kV which can be used to inform the design of an optically-controlled DEA device. Clear actuations of 2.2 μm were achieved, providing the basis for wireless optical control of dielectric actuator muscles. Future work will focus on controlling multiple DEA electrodes using localized light patterns a well as testing and characterizing other materials to improve the voltage swing across the DEA.

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