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On the fabrication of durable dielectric-barrier discharge plasma actuators

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Abstract
This work revolves around the experimental investigation of different materials for electrode and dielectric as well as different fabrications of dielectric barrier discharge actuators, followed by a recommendation and characterization of a possible actuator configuration. The tested materials for the dielectric were: polyimide (Kapton), polymethylmethacrylate (PMMA), quartz glass and ceramic (Al_2O_3). As electrode materials copper, an electrically conductive paint, silver-platin (AgPt) and silver-palladium (AgPd) was tested. The ceramic-dielectric actuators, in compliance with quartz glass, showed a very constant power consumption over time. As electrode material copper was the best in terms of endurance of the tested materials. A new set of actuators made by screen-printing electrodes on a ceramic plate were tested as a reproduceable manufacturing process.

1. Introduction

Plasma actuators (PA) generate an ionic wind with discharges on aerodynamic surfaces. The design of the actuators is very simple and does not feature any moving parts. Therefore, they are unique in their controllability and can influence flows for active flow control (AFC) close to surfaces with fast response time and under absence of any moving parts [1]. Since flow control using plasma actuators is rather young compared to other AFC approaches, the demand for knowledge regarding the characteristics and performance of the actuators is still high. To achieve a better understanding of the flow induced by the plasma actuators measurements capturing the velocity and force field is necessary. Due to the high-frequency operation of the actuators, particularly high temporal resolution is likewise required for the measurements. Since these measurements at the same time might take a lot of time to ensure e.g. statistical significance, the requirements for the actuators are a constant performance with as little degradation as possible. However, most commonly applied materials such as e.g. Kapton or PMMA are known to degrade during operation [2]. Therefore, this study revolves around the topic or durable materials for dielectric as well as electrodes.
Dielectric-barrier discharge (DBD) plasma actuators are built of a dielectric with two electrodes on each side. While one electrode is exposed to the fluid, the second electrode is encapsulated by dielectric material. The plasma develops between the edge of the exposed electrode and the surface of the dielectric.

The region in proximity to the forming plasma is attacked by various stresses. In the plasma region radicals, ozone in particular for operation in air, are formed [3]. Furthermore, the temperature, the electron bombardment and UV-light emission is to be mentioned [4]. Often used actuators made of Kapton a polyimide-based adhesive tape as dielectric and electrodes made of copper [5], [6] show strong degradation due to oxidation [2]. PMMA degrades under electron bombardment. However, there are only a few studies on durability of materials for plasma actuators. To reach constant forcing and actuation, the body force induced by the actuator must be constant, which is directly linked to the electrical properties [7]. Therefore, observing the actuators' electrical properties is a good way to monitor the degradation progress.

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2 Methods and Experimental set up

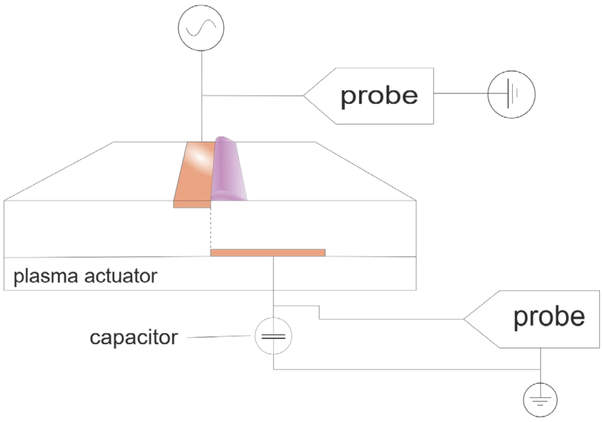

Figure 2: Experimental set up and DBD actuator

As a high voltage and alternating current source, a Minipuls 6 from GBS Elektronik GmbH in combination with a VOLTCRAFT VLP-1405 PRO was used. The oscilloscope A DSO-X 2004A from Agilent Technologies was used as the wave generator specifying the frequency of the voltage. The set up can be seen in Figure 2. The so-called capacitor (see Ashpis et al. [8]) was used to measure the actuators' power consumption and capacitance. The Lissajous curve obtained by plotting charge versus voltage, is a good way to determine the electrical properties of a DBD plasma actuator.

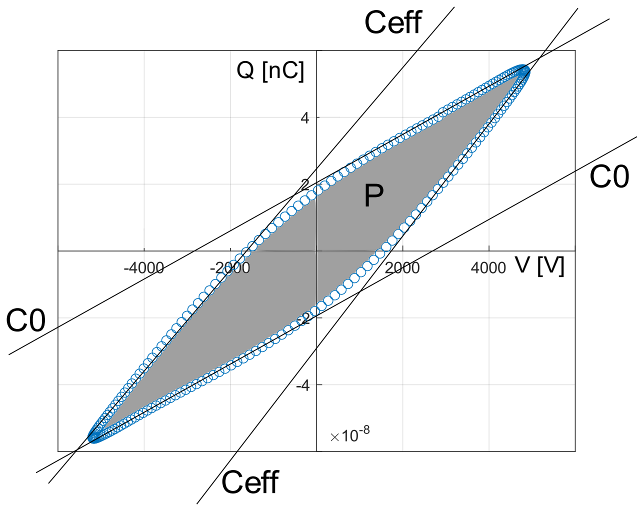

Figure 3: Lissajous figure of a DBD plasma actuator

The Lissajous curve of a DBD plasma actuator has a typical almond shape, which can be seen in Figure 3. The surrounded area of the figure equals the power consumption of the actuator, while the capacitance of the actuator equals the gradient. There are two capacitances that can be determined by the Lissajous figure. One is the effective capacity (Ceff) during discharge and the passive capacity (C0) during charging [9]. Following P=UI the power consumption is only dependent on current and voltage. Therefore, a change in power consumption can either be a variation in the voltage signal or a change in the drawn current. The width of the encapsulated electrodes used was 10 mm, while the exposed electrode had a width of 2.5 mm. The thickness of the dielectric varied between the different materials. A summarisation can be found in Table 1.

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Table 1: Tested dielectric and electrode material configurations.

Manufacturing technique	Exposed electrode	**Encapsulated electrode**	**Dielectric**	**Diel. width[a]**	**Actuator length[a]**
Tape, hand made	Cu	Cu	Kapton	0.44	150
Milled groove in dielectric	Paint	Paint	PMMA	8.00	150
Taped groove, hand made	Paint	Cu	Quartz-glass	1.00	80
Tape, hand made	Cu	Cu	Quartz-glass	1.00	80
Tape, hand made	Cu	Cu	Al_20_3	0.68	90
Screen-printing	AgPd	AgPd	Al_20_3	0.68	75
Screen-printing	AgPt	AgPt	Al_20_3	0.68	75
Screen-printing	Cu	Cu	Al_20_3	0.68	75

[a] all measures in [mm]

2.1 Manufacturing process

A highly important criterion for the actuator is a reproducible manufacturing process. Since the actuators degrade during operation, several actuators are commonly needed per experimental campaign. To continue the work efficiently it must be possible to produce several actuators of identical properties. During preliminary material tests the actuators were hand made. Later on, a screen-printing technique was used to print electrodes on a ceramic (Al_2O_3) plate. This procedure uses masks that can be reused and ensure a repeatable actuator shape upon fabrication.

In Figure 3 the geometry of the printed plasma actuators is sketched in top view. The exposed electrode is shown in green, the encapsulated electrode in blue. In addition to the electrodes, a layer of dielectric overglaze over the encapsulated electrode was printed. This leads to a well isolated lower electrode. For comparison purposes, the following electrode materials were printed on to the ceramic plate: Cu, AgPd and AgPt.

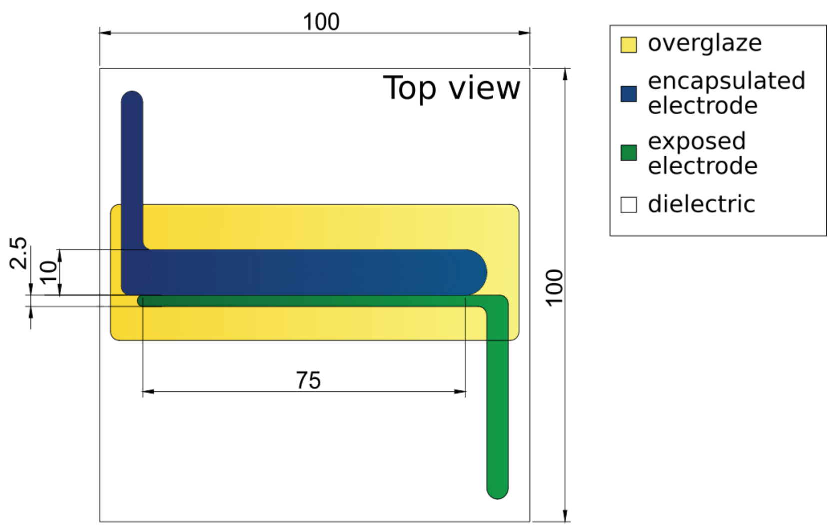

Figure 3: Screen-printed actuator geometry.

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2.2 Materials

The widely-used Kapton-copper actuators do not match the expectations for durability in quiescent air [2]. However, to provide a common reference for the present comparative study, first tests with this material combination were included to the considered parameter space of the study.

The tested configurations were Cu-Kapton, Paint-PMMA, Paint-glass, Cu-glass and Cu-AlO3. To achieve a reproducible manufacturing process a groove was milled into a block of PMMA. The groove was then filled with an electrically conductive paint. At last, the screen-printing production was used to build three configurations with electrodes made of AgPt, AgPd and Cu. The commonly used Aluminium oxide was chosen as dielectric due to the high melting temperature suitable for screen-printing with melted metal [10].

3. Results and Discussion

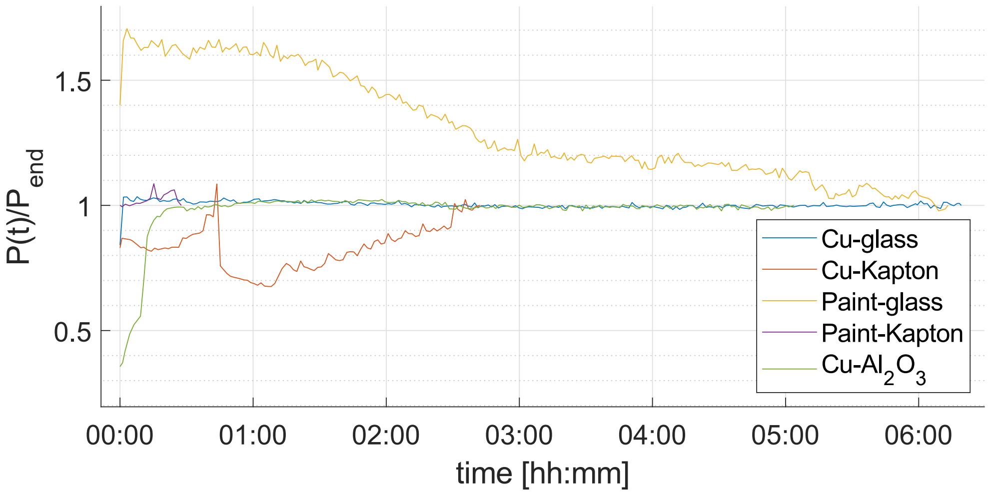

Figure 4: Power consumption of handmade actuators.

In Figure 4 the power curves of the handmade actuators are shown. Note that the paint-PMMA parameter combination is excluded from the diagram due to parasitic plasma occurrence at the upstream edge of the exposed electrode, which resulted from an excessively thick dielectric. The run of Cu-Kapton as well as paint-Kapton actuators have been aborted after half an hour and two and a half hours, respectively. This was due to defects that caused the breakdown of the plasma.

The paint-glass actuator was running throughout the planned six-hour measurement duration. Nevertheless, over that time the power consumption dropped by 60%, thus not behaving consistently. However, the combinations Cu-glass and Cu-Al2O3 showed a convergence towards a smooth and constant behaviour after initial transient periods of a few minutes and 30 minutes, respectively. Cu for electrodes and glass as well as Al2O3 are therefore considered well suitable for further durability tests.

In Figure 5 the most important parameters voltage and power consumption of a 10h-lasting experimental run of the printed plasma actuators are shown. All the three actuators exhibit a similar progression of power consumption. Nevertheless, the AgPt and AgPd actuators show an inconstant behaviour of up to 13% in power consumption. While the Cu actuator is constant in power consumption after a run-in period of two hours with deviations varying between +/-3%. As obvious from the ordinate increments of either diagram, the relative changes of the power consumption is an order of magnitude more pronounced than the voltage changes.

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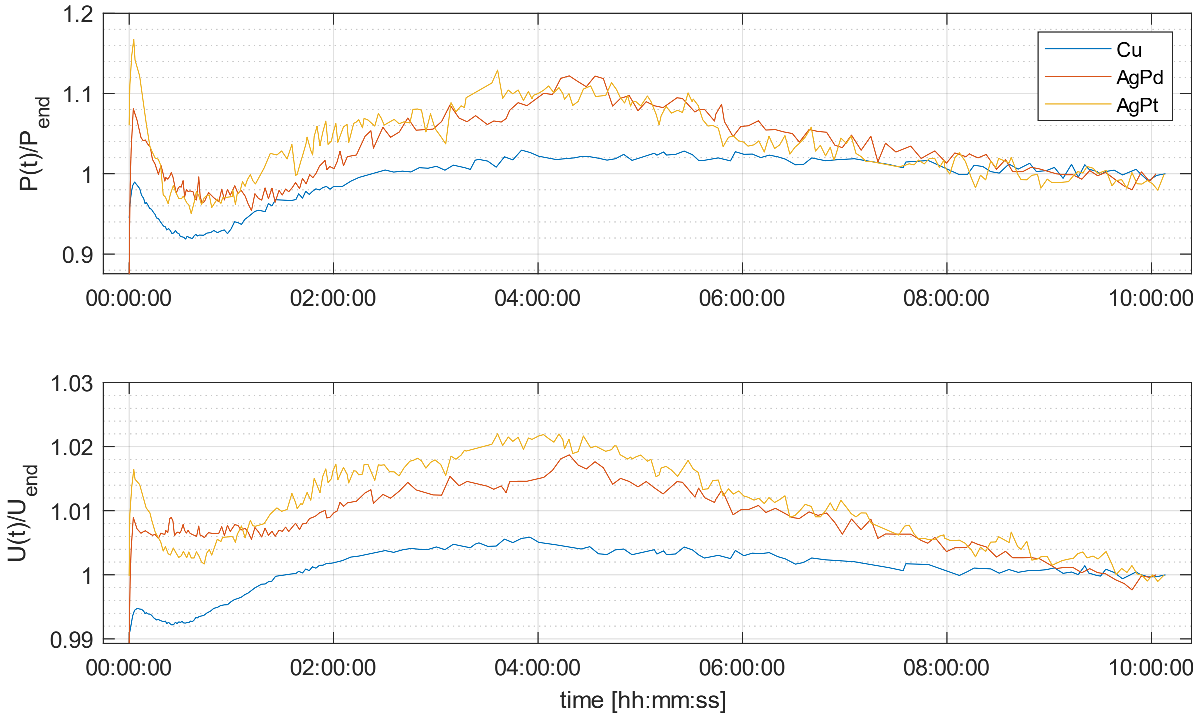

Figure 5: Power consumption and voltage in progress of a 10h run

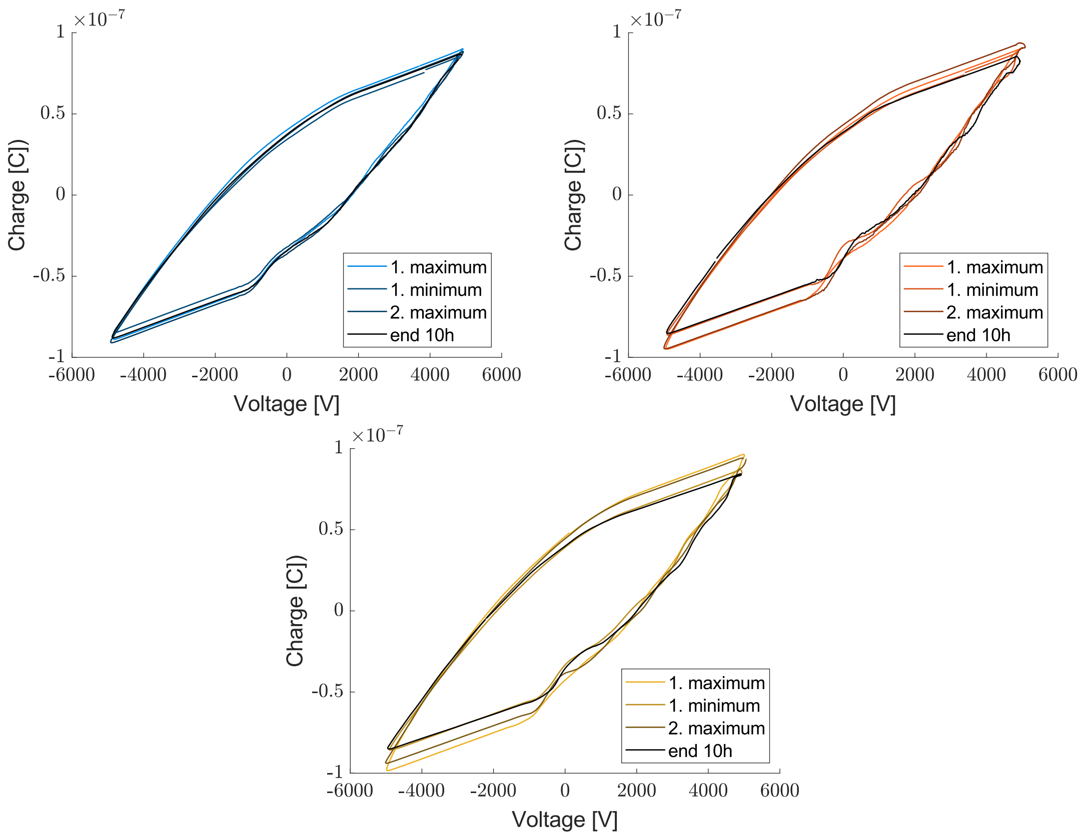

Figure 6: Lissajous figures of the considered material at selected times along the curves in Figure 5; top-left: Cu, top right: AgPd, bottom: AgPt (color groups also correspond to Figure 5)

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Figure 6 provides various Lissajous figures at different times for the different experiments, superimposed per experimental run to determine the qualitative changes in power consumption a capacitance. The four times are determined by the following characteristic points of the power consumption: the first maximum shortly after the start, the following minimum at around 30 minutes, the second maximum and the finally last point measured. The Lissajous figures support the analysis made before. The Cu actuators' results show a comparatively smooth and constant behaviour. Neither the capacitance, which equals the slope of the cyclogram nor the power consumption in terms of surrounded area of the Lissajous figure change significantly.

In contrast, a larger difference in charge can be seen in the curve of the AgPd actuator while the peak of the voltage remains constant. The passive capacitance shows little change, while the effective capacitance shows a higher value at the two maxima times. The AgPt actuators' Lissajous figure shows similar results – only the modulus of the maxima is even higher. The deformation of the curve again affects the effective capacitance. In summary, AgPd and AgPt show a non-constant behaviour while the Cu actuator remains comparatively constant throughout the 10 hours of continuous operation.

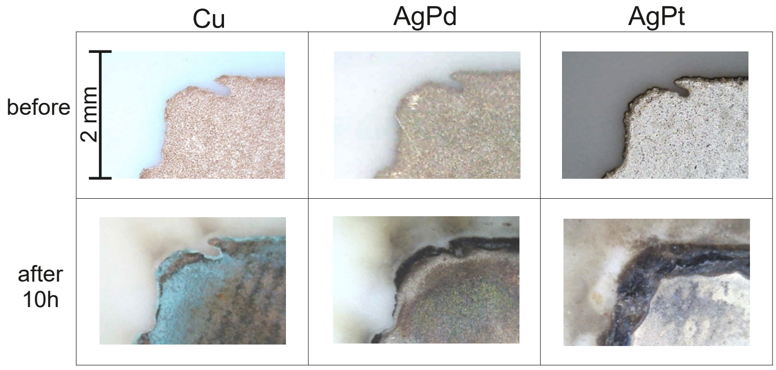

Figure 7: Blackening of electrode edges

An immediate comparison of the electrode edges before and after the 10h operation is provided in Figure 7 to emphasize the varying degrees of degradation and wear. The Cu electrode changes to a darker colour as well as to the typical blue copper oxide. The overall shape of the edge, however, remains undamaged. The AgPd actuators' edge shows a significantly larger blackening and the geometry of the electrode indicates mild changes. The most drastic blackening occurs with the AgPt actuator, which reveals thick black areas at the electrode edges. The initial electrode geometry is significantly manipulated and several spots of considerable erosion of the electrode material are obvious.

4 Summary

Degradation and wear of both dielectric and electrodes has a large impact on the lifetime and accordingly long-term control authority of DBD plasma actuators. In accordance with literature, the dielectric materials Kapton and PMMA showed weak resistance to the high stresses of the plasma discharge area. In contrast, glass and the ceramic Al2O3 showed constant behaviour throughout the tests. For electrode material copper was found to experience the least wear, thus revealing the most durable properties. The electrically conductive paint had strong deviations in power consumption. AgPt and AgPd showed strong blackening on the electrode edge and were heavier attacked by the plasma than Cu. For the exact determination of the durability of a plasma actuator controlled environmental conditions are necessary since plasma actuators are very sensible to any changes for example in temperature or air composition [11], [3]. Nevertheless, the screen-printed Cu-Al2O3 actuator has shown to be a robust and durable plasma actuator.

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