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Fabrication of high adhesion cm-scale compliant electrodes for dielectric elastomer transducers using O_2 plasma activation

O. A. Araromi, S. Rosset, H. R. Shea

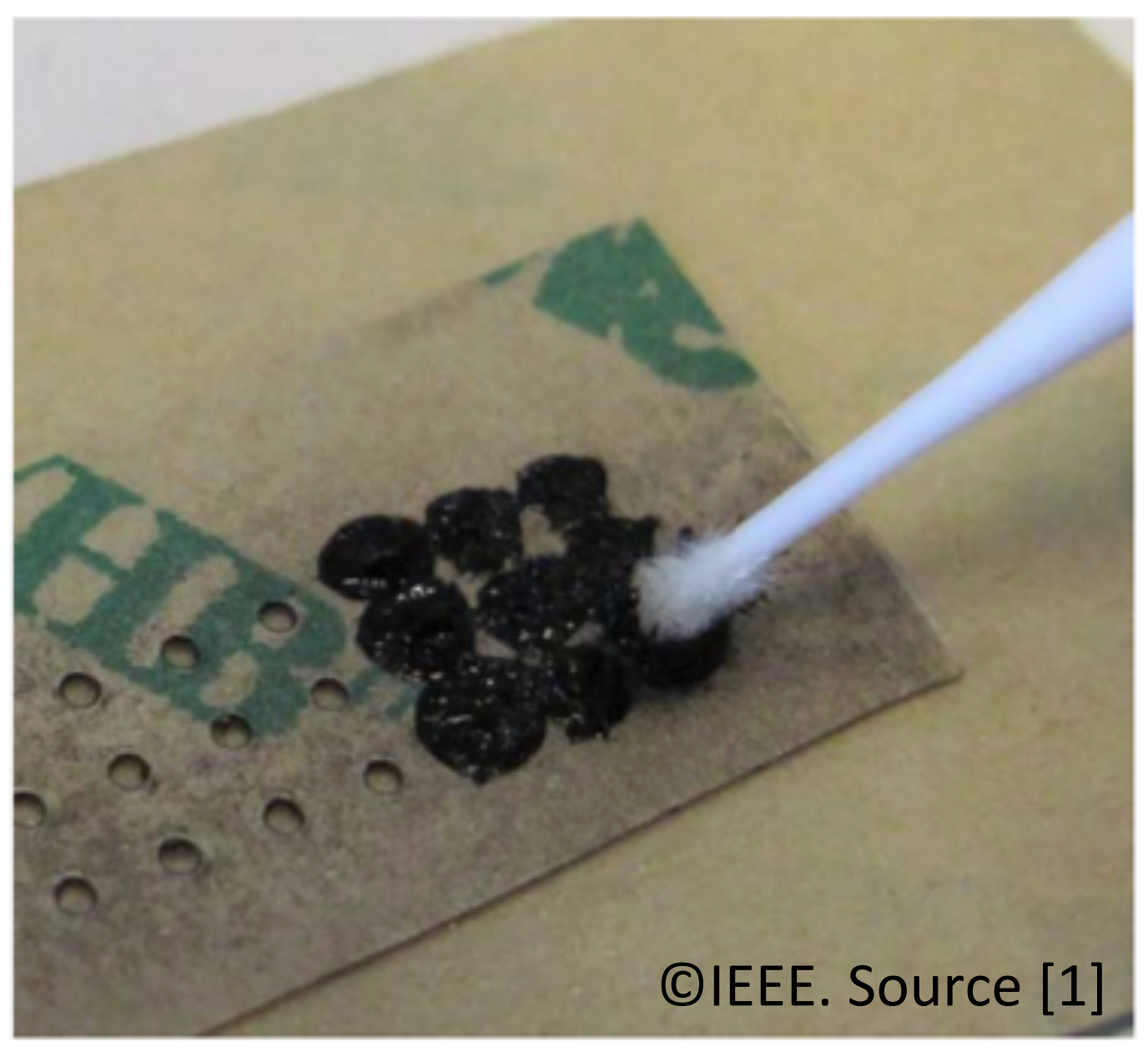
Mircosystems for Space Technologies Laboratory, École Polytechnique Fédérale de Lausanne, Neuchâtel, Switzerland

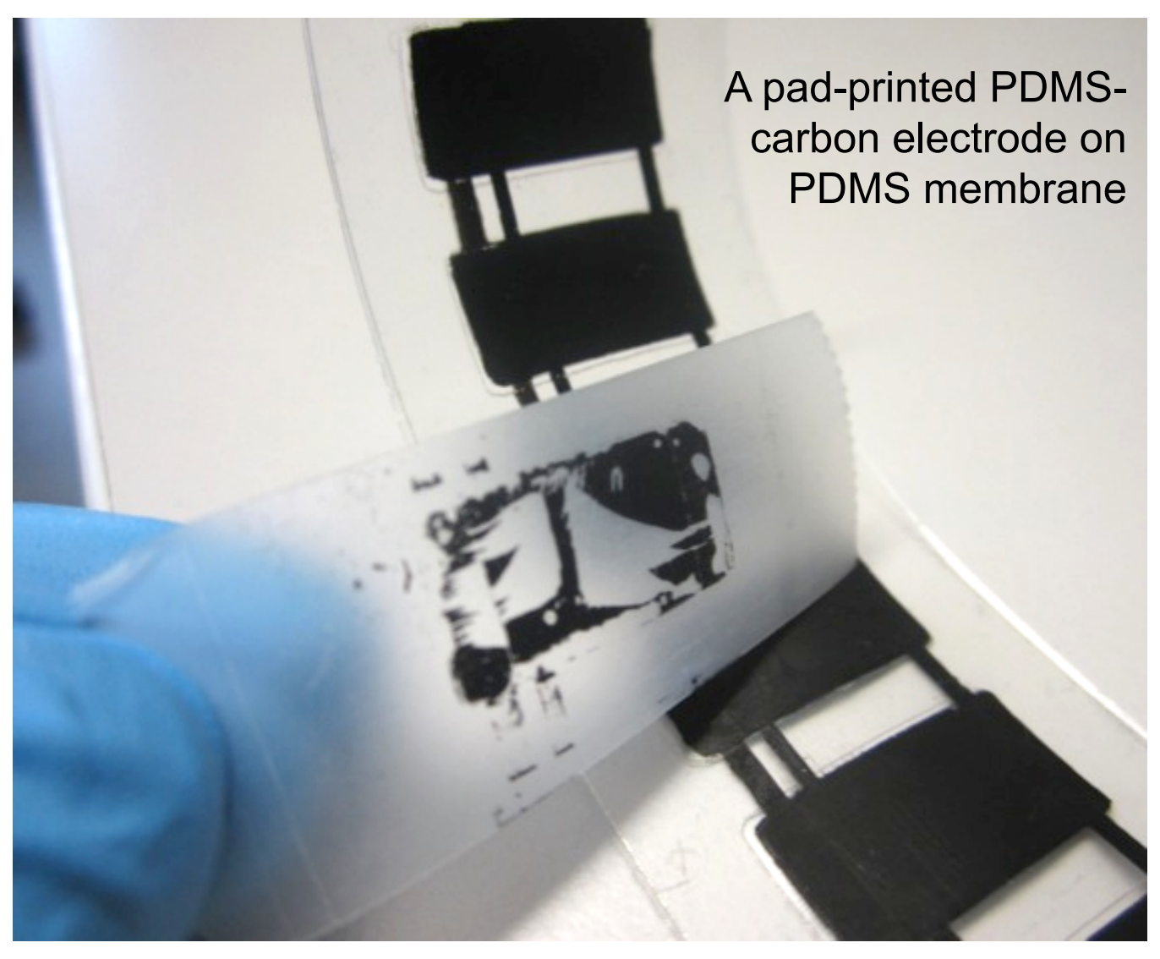
Contact e-mail:
seun.araromi@epfl.ch
Website: lmts.epfl.ch/DEA

Abstract

We present a novel methodology for the production of PDMS-carbon powder electrodes with high adhesion for dielectric elastomer (DE) transducers. DE transducers have received significant interest in recent years due to their potential as stretchable-flexible actuators, sensors and energy harvesters. As the field matures, the need for mechanically resilient devices able to perform in "real-world" conditions, not just laboratory environments, increases. Our methodology produces electrodes of various thicknesses using a blade casting technique. The electrodes are subsequently laser cut with the desired pattern, activated together with the dielectric membrane in oxygen plasma and finally placed in contact to achieve bonding. In this way we are able to produce large area (up to several cm in length) compliant electrodes with impressive adhesion qualities. Electrode adhesion is qualitatively evaluated using the "scotch-tape" method with a 4 µm thick electrode. We also produce electrodes for multi-segment dielectric elastomer minimum energy structure actuators approximately 10 cm in length using this fabrication procedure, validating its ability to produce functioning DE devices.

Electrode Realisation for DE Transducers


©IEEE. Source [1]

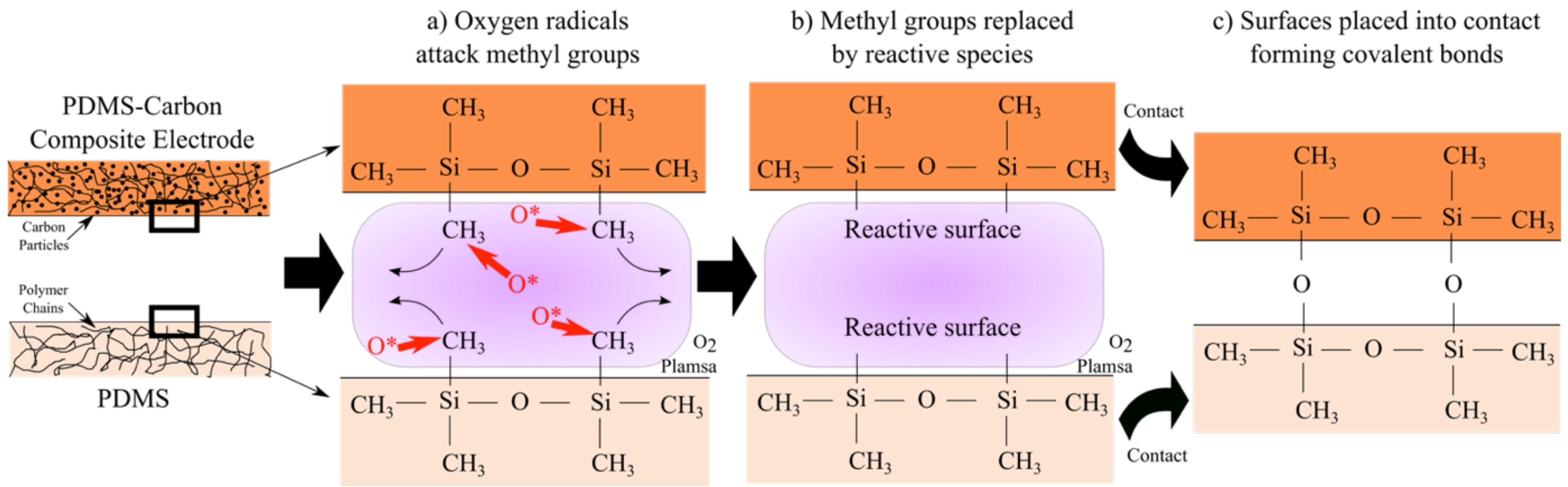

A pad-printed PDMS-carbon electrode on PDMS membrane

Dielectric elastomer (DE) transducers have proved themselves to be versatile stretchable-flexible actuators, sensors and energy harvesters [2]. However, anyone who has ever conducted any experimental work in the field of DE transducers will be familiar with the scene shown in the photo to the top left. The sometimes arduous process of realising a compliant electrode on the elastomer membrane using a material such as carbon grease. Methods like these have provailed in the past due to their convenience and low-cost [3], but they lack the mechanical robustness required for many "real-world" applications.

Other carbon based materials, such as elastomer-carbon composites, are more mechanically robust and can be applied onto dielectric elastomer membranes with good pattern resolution using various stamping/printing techniques [3][4]. However, good adhesion between the dielectric and the electrode is not always guaranteed with these techniques (see photo bottom left).

Bonding of silcone by O_2 Plasma

So is there another way? Our solutions is to use **blade-cast polydimethlysiloxane (PDMS)-carbon composite electrodes bonded to PDMS dielectric elastomer membranes using low pressure oxygen plasma**. Oxygen radicals produced in the plasma create and highly reactive layer on the surfaces of the PDMS based materials (as depicted in the idealized schematic below). When these activated surfaces are placed in contact with each other they form a strong covalent bond. Bonding of PDMS materials to various polymer substrates in this way is a well known technique in the field of microfluidics [5].



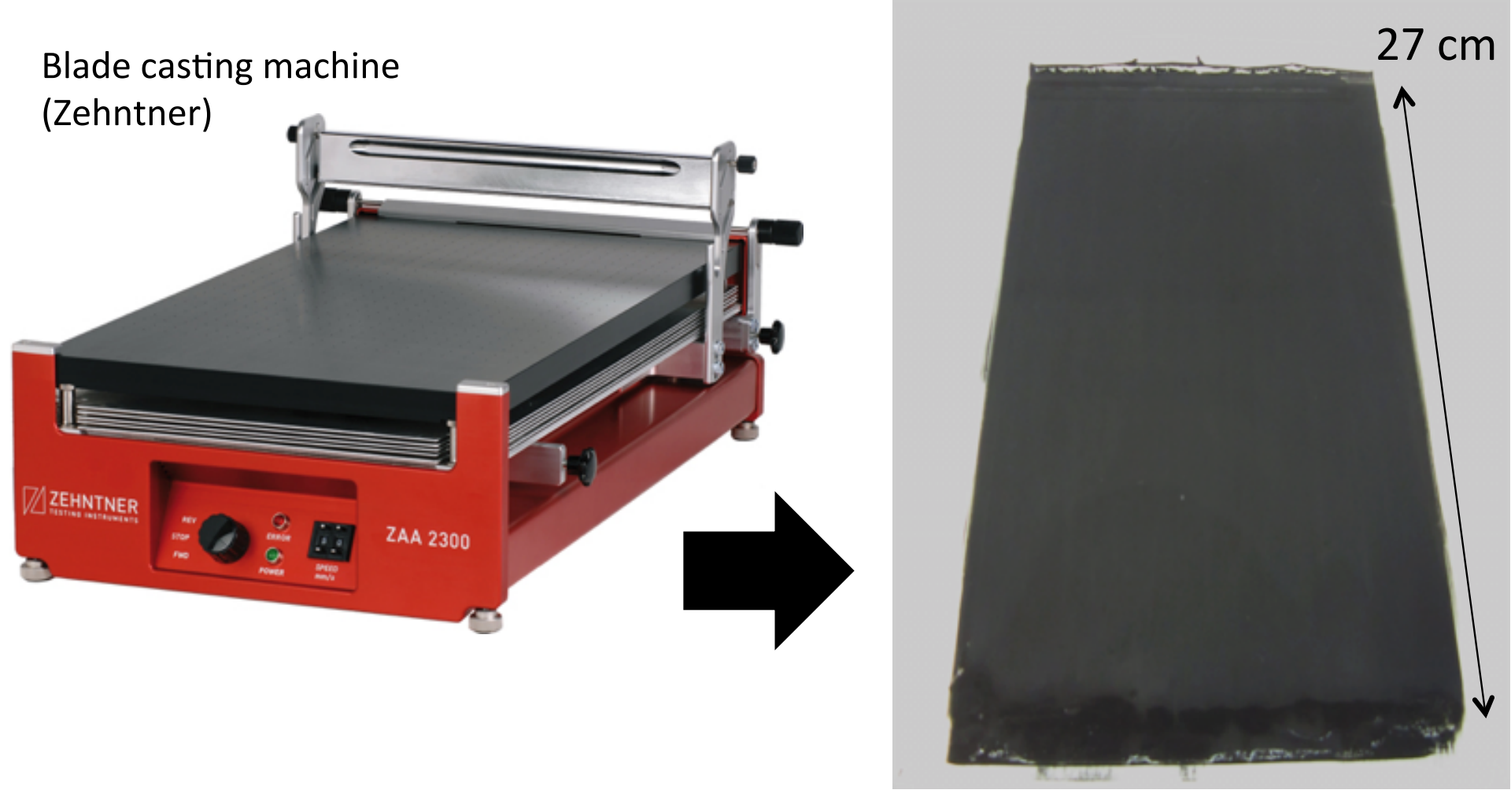
Fabrication Procedure

1) Electrode Material Preparation

The first step, mix some carbon black particles into PDMS. We use a very soft PDMS (MED 4901, NuSil) with a **Young's modulus an order of magnitude less** than that of the dielectric (≈ 0.1 Mpa), hence **minimizing the stiffening impact**. This PDMS is also highly stretchable **enabling large strains without rupturing**. We mix the carbon black in the PDMS at a ratio of 10:1 and further thin the mixture with solvents to enable casting.

2) Blade Casing of Electrode

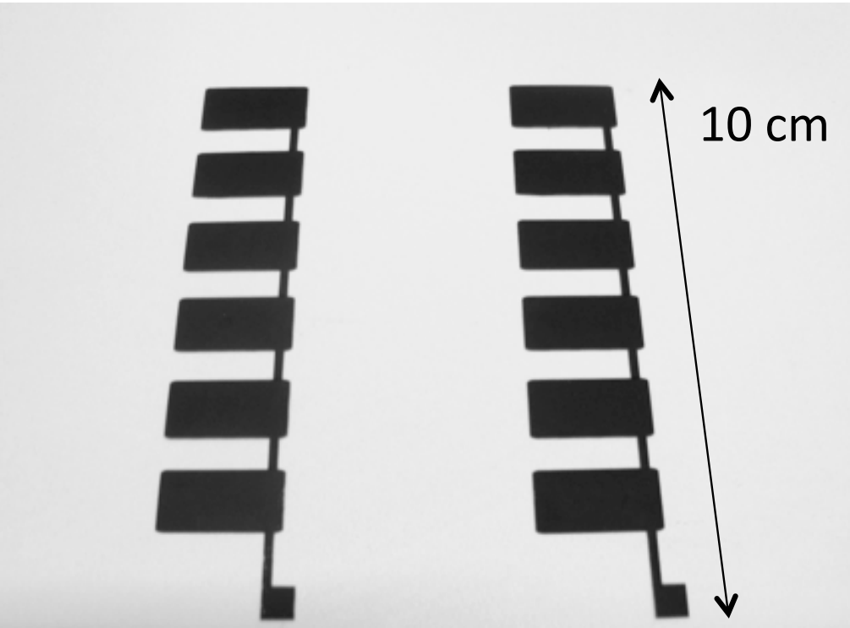
We use a blade casting machine electrode films a few microns thick with reasonable homogeneity. We cast our electrodes onto 50 µm PTFE substrates (Angst-Pfister) which allows us to easily remove our electrodes once they are bonded due to substrate's non-stick properties. Once casted the electrode film is cured in an oven at 80° for approximately 2 hours.



Cast PDMS-carbon composite electrode

3) Laser Cut Electrode Pattern

Now its time to pattern the electrodes. We do this using a laser cutter to produce **highly repeatable electrode patterns** resolution of ≈ 100 µm can currently be achieved.



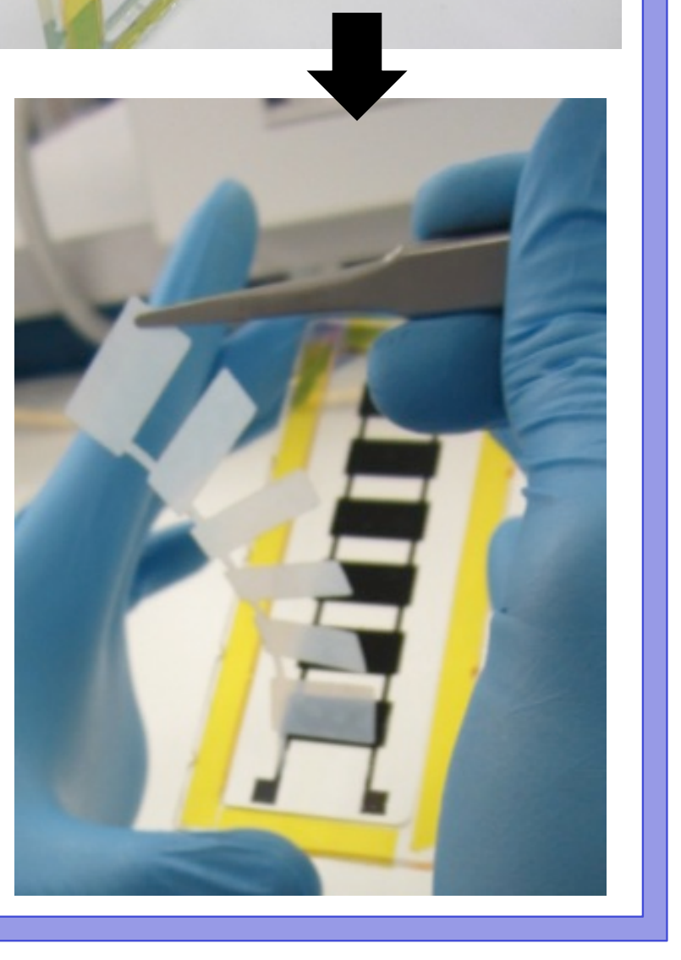
4) Oxygen Plasma Activation

The key step. The laser cut electrodes and dielectric elastomer membrane are placed in a plasma chamber (Zepto, Diener Electronic) and activated at approximately 0.2 mbar, 25 W for 20 seconds. It should be noted that **"more is less" with this process as over exposure of the surfaces can lead to them becoming brittle**.

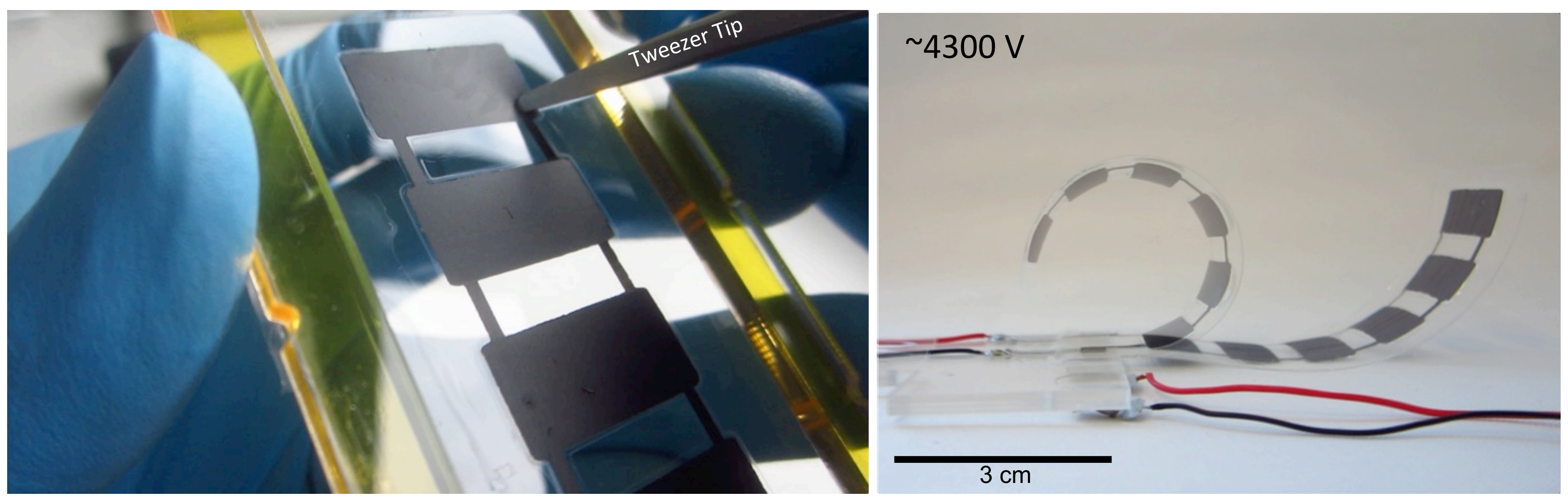
Once activated we bring the surfaces close to each other an place a thin film of methanol in between. This wets the two surfaces minimising bubble formation and brings them slowly in contact with each other when the solvent evaporates. The surface are left in contact with each other for at least 30 minutes.

5) Release

The easy part. Simply peel off the Teflon substrate to reveal the electrode. The process can be repeated on the reverse side if required.

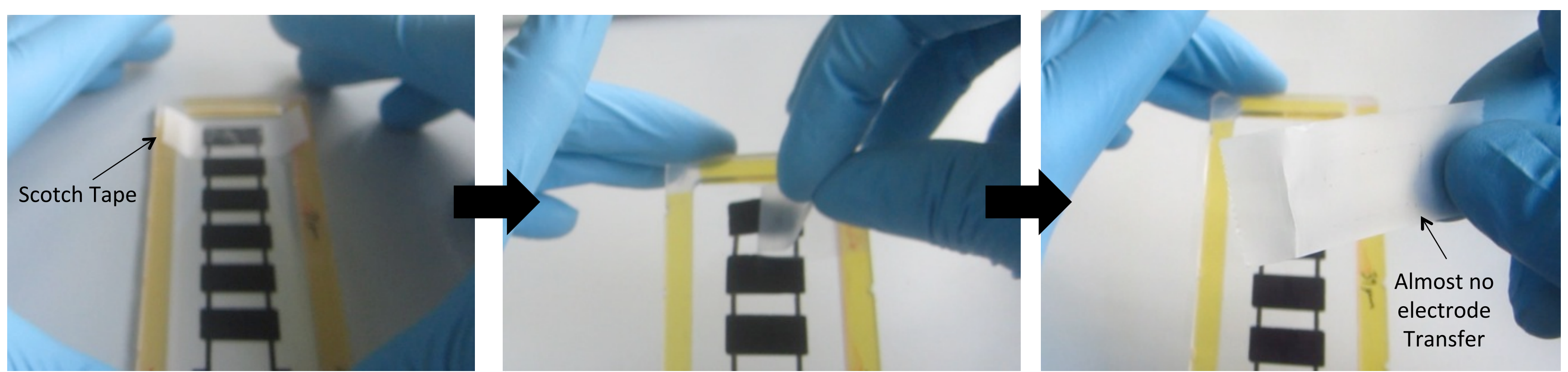


Results



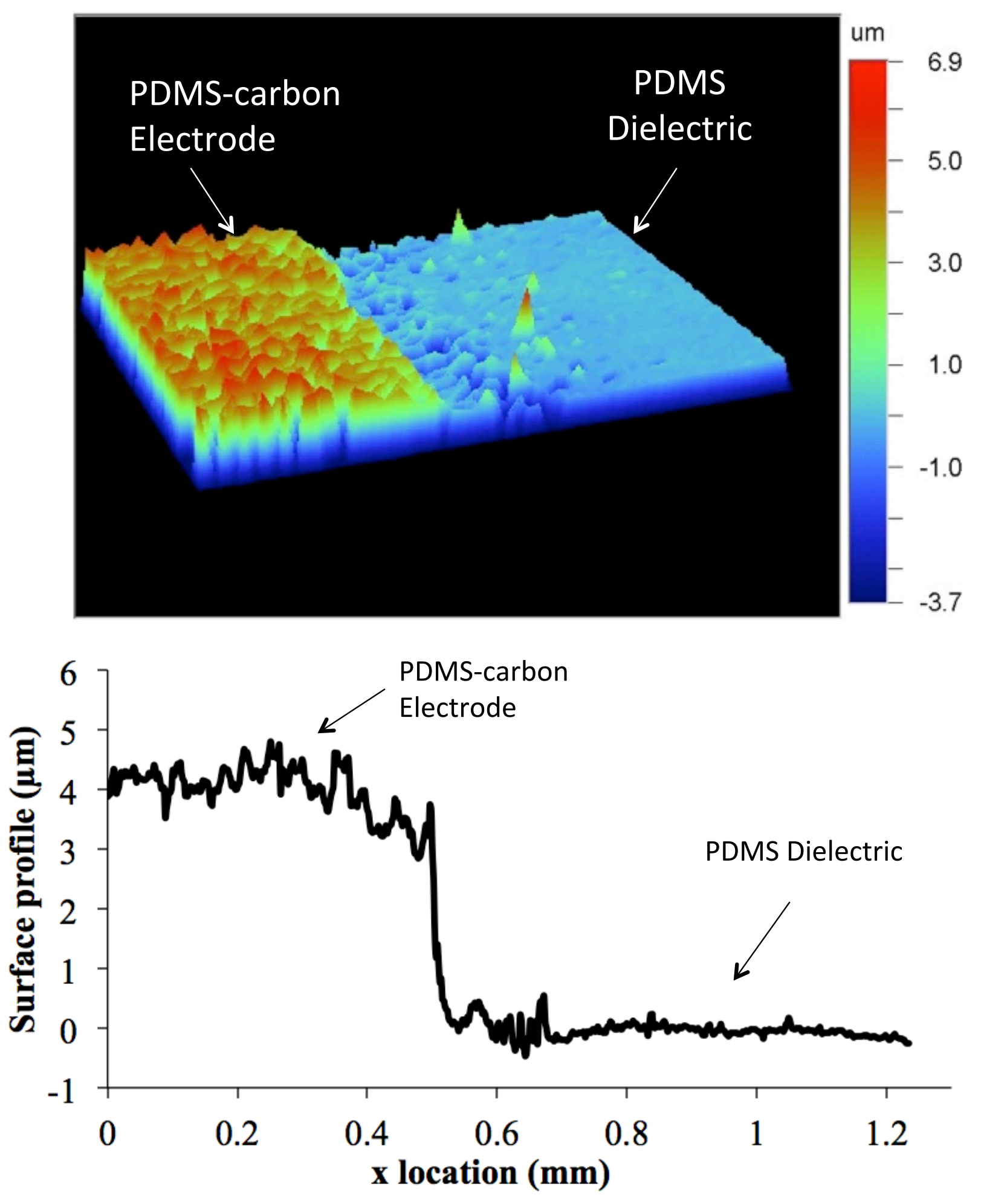
a) High mechanical robustness b) Able to make functioning DE actuators

(4µm thick electrodes on a 50 µm thick PDMS membrane, Sylgard 186 (Dow Corning). Electrode sheet resistance ≈ 250 kOhm/☐)



c) Impressive adhesion properties

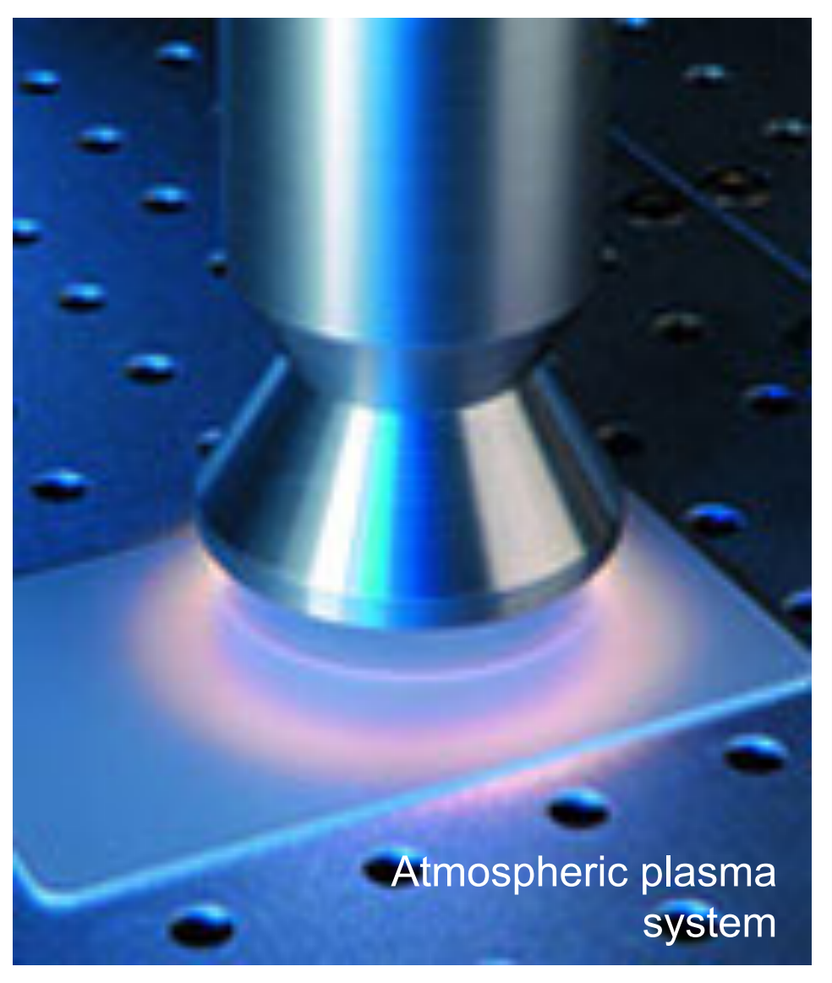
d) Good thickness homogeneity (3D and 2D profiles)



Discussion and Conclusion

The process of bonding blade-casted PDMS-carbon composites to silicone dielectric elastomer membranes produces DE transducers with impressive adhesion properties and robustness to external mechanical disturbances. The process is versatile and well adapted to the production of cm-scale devices, producing electrodes with reasonable thickness homogeneity. The sheet resistance of a 4 µm thick electrode was ≈ 250 kOhm/☐, the electrical properties can be easily modified by adjusting the carbon content and electrode film thickness. Other advantages include:

- Process can also be parallelised for batch fabrication.
- Uses equipment and sub-processes readily used in many laboratories.
- Process can be adapted to commercial scale high-volume production of devices with the use of in-line (atmospheric) plasma systems (see example in photo on the right).
- Process compatibility – works with various silicone elastomers


Atmospheric plasma system

Acknowledgments

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