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Driving forces, surface morphology and mechanical properties of single-layer dielectric elastomer actuators

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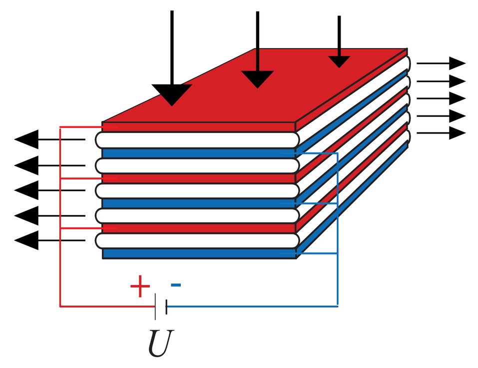
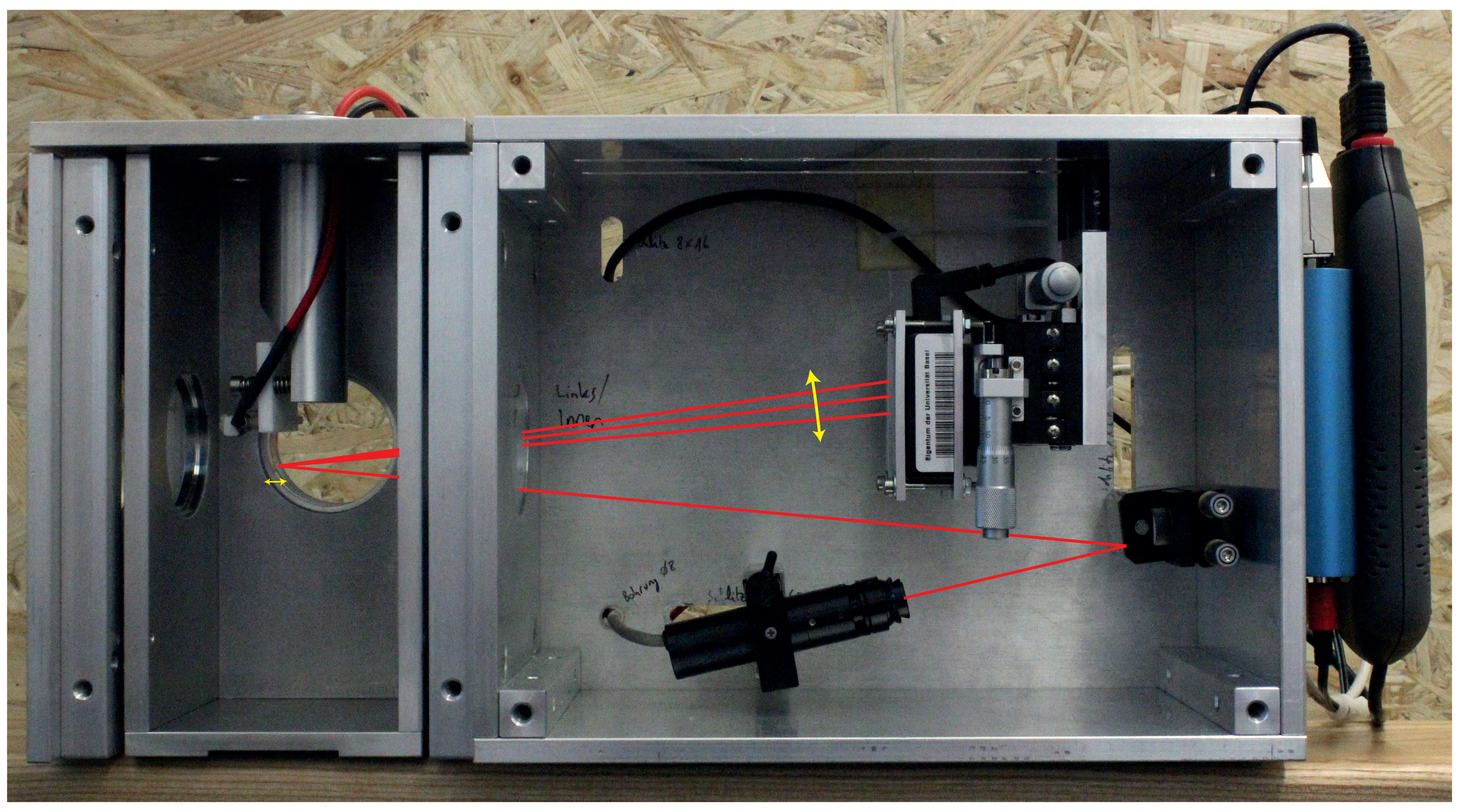
Introduction



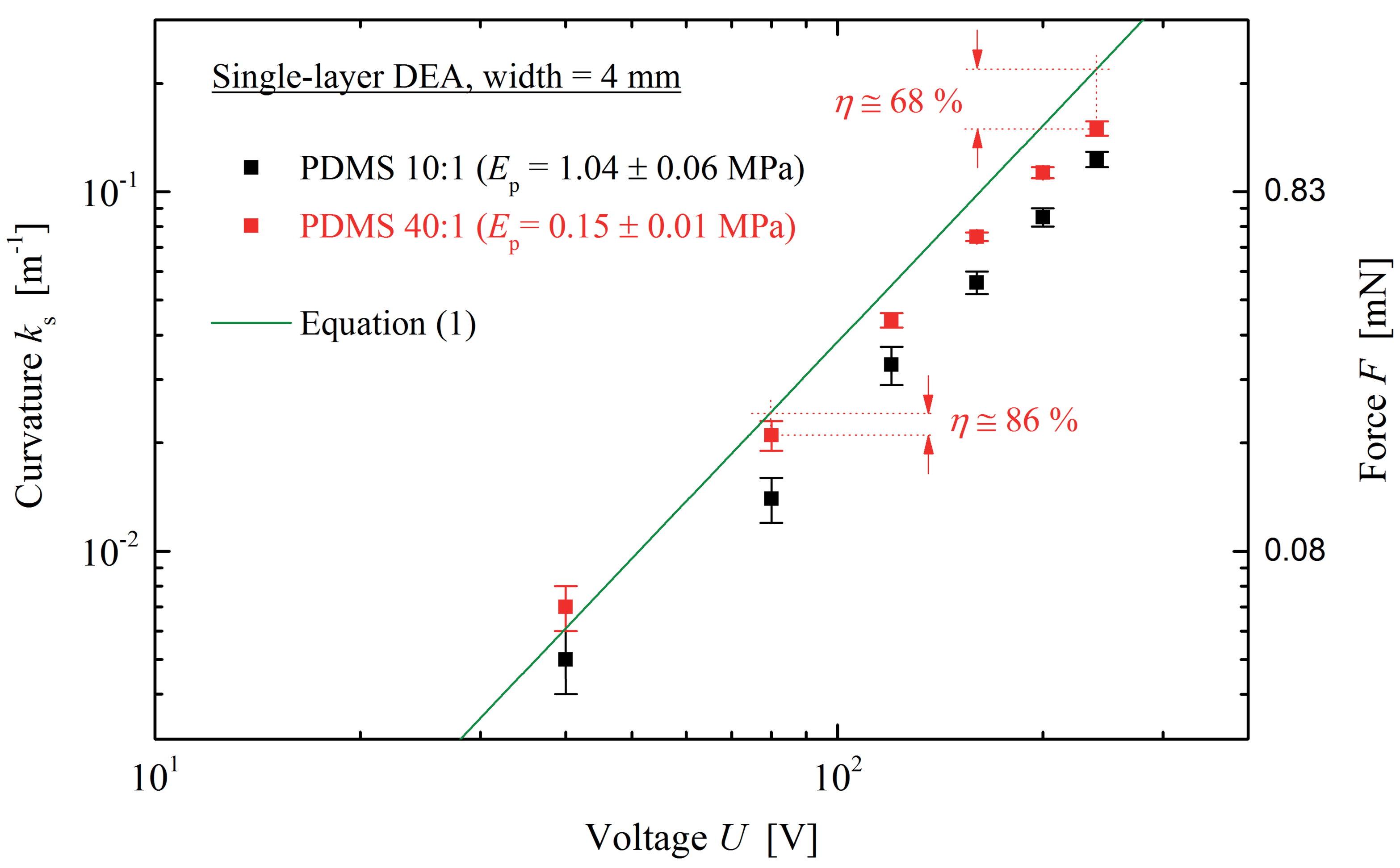
Fecal incontinence treatments are currently based on mechanical systems which are slow and difficult to operate [1]. Our goal, within the nano-tera.ch initiative SmartSphincter, is to develop an actuator based on electrically activated polymers acting as artificial muscles by analogy to natural muscles. Dielectric elastomer actuators (DEA) show outstanding performances including millisecond response times with a specific continuous power up to 10 times higher than human skeletal muscles [2]. Polydimethylsiloxane (PDMS) is widely used in medical applications and is often referred as the dielectric layer of choice for DEA. A proper nanoscale characterization is crucial for the design and functionality of DEA implants.

Actuation forces of DEA



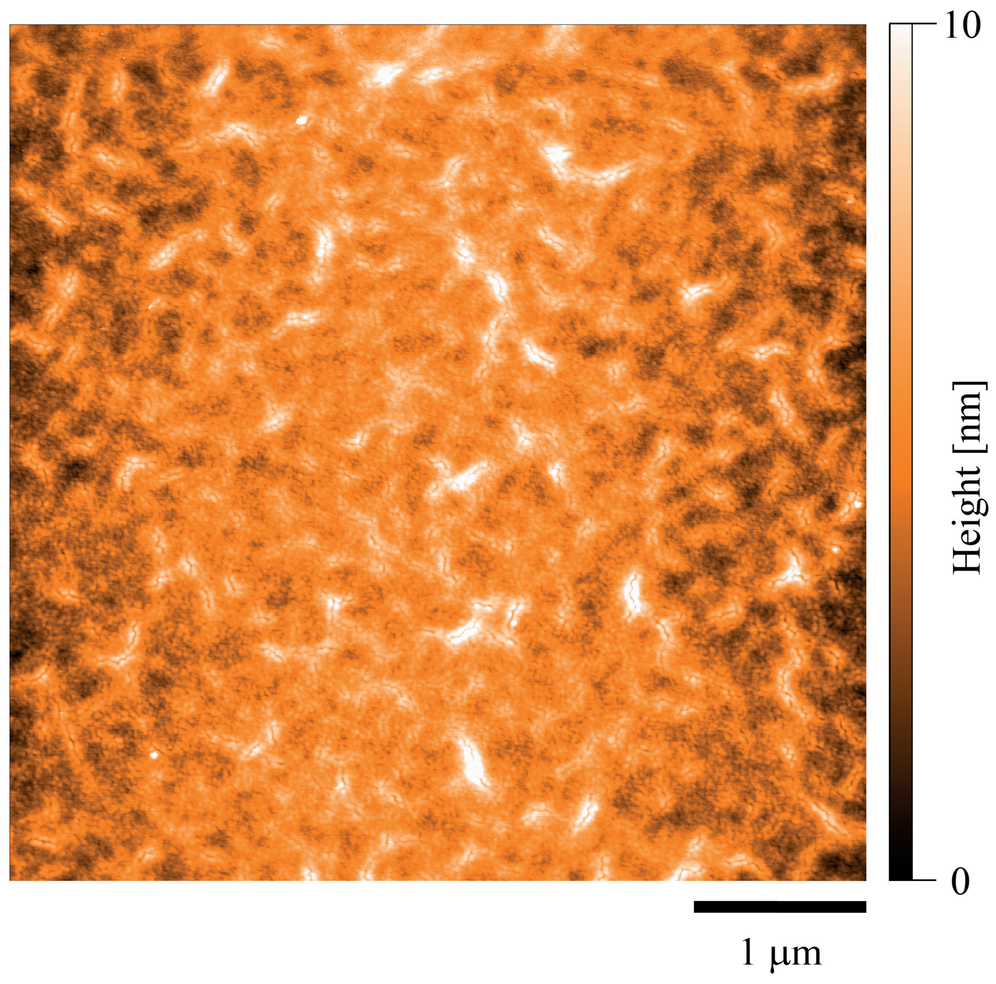
A custom-built device is used to measure the actuation forces of single-layer DEA (Au 20 nm/ PDMS 4 µm/ Au 20 nm) which were fabricated on top of biaxially oriented polyethylene naphthalate (PEN 38 µm) cantilevers. The bending curvature k_s of the substrate and therefore the actuation forces can be described with the following equation:

$$k_s \cong \frac{\partial^2 z}{\partial x^2} \cong \frac{M}{E^* \cdot I} \cong \frac{F \cdot (h_p + h_s) \cdot (1-\nu_s)}{E_s \cdot I_s} \cong U^2 \cdot const \qquad (1)$$

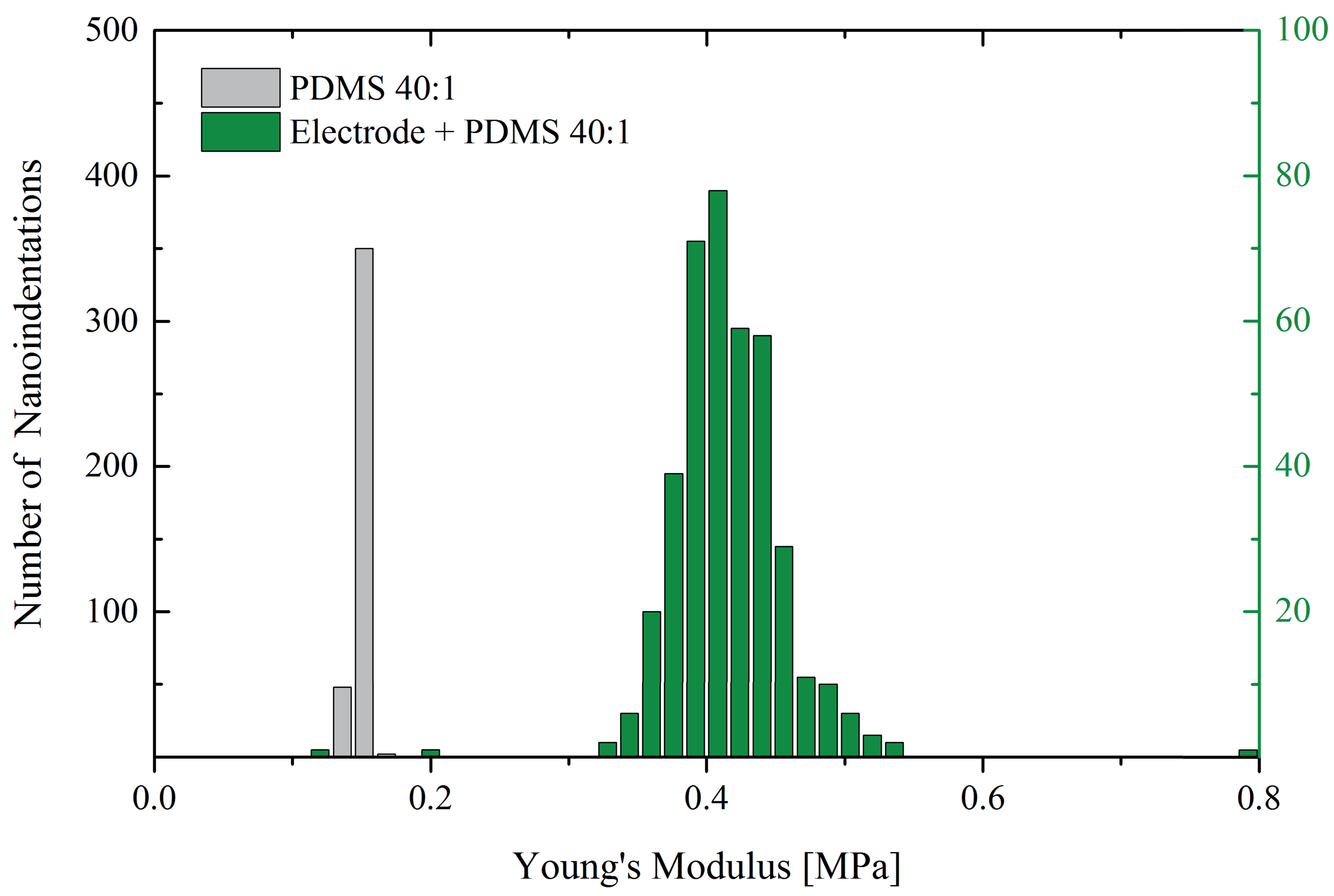


The measured data are represented as a double logarithmic plot showing the quadratic relationship between the driving voltage U and the curvature k_s. The generated force F is independent of the polymer stiffness.

Surface morphology and mechanical properties of DEA



The AFM image (5 x 5 µm^2, tapping mode, PPP- NCSTR probe, tip radius < 7.0 nm) of the 20 nm Au-electrode on top of a PDMS 40:1 polymer layer reveals the presence of Au-nanoclusters and cracks in the submicrometer range. The size of the nanoclusters is 40 ± 20 nm and can be explained by the low surface energy of PDMS leading to a Volmer-Weber growth mode [3].



AFM was used to perform 400 nanoindentations on 60 µm x 60 µm arrays at a load of 100 nN using a spherical tip with a radius of 500 nm. PDMS films (Dow Corning® 184 Silicone Elastomer Kit) were prepared by mixing the siloxane base with the cross linking agent at a ratio of 10:1 and 40:1 resulting in Young's moduli of 1.04 MPa and 0.15 MPa.

The overall stiffness for single-layer DEA (Electrode + PDMS 10:1 and Electrode + PDMS 40:1) was reduced from 5.80 MPa to 0.41 MPa. Substrate effects can be neglected since all nanoindentation depths were below 500 nm. The calculations were based on the Hertzian contact theory.

Conclusions and acknowledgement

We have measured the actuation forces of single-layer DEA with a reliable reproducibility. We have also demonstrated that nanoindentation tests using the Nano-surf ARTIDIS System are an accurate method to reveal the mechanical properties of the electrode and the dielectric polymer layer. The authors thank Monica Schönenberger from the Nanotech Service Lab (SNI, University of Basel) for the polymer thickness measurements with the 3D-Laser Microscope and SYNFLEX GERMANY for providing us with PEN (Teonex Q51) substrates.

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