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A small-gap electrostatic micro-actuator for large deflections

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Common quasi-static electrostatic micro actuators have significant limitations in deflection due to electrode separation and unstable drive regions. State-of-the-art electrostatic actuators achieve maximum deflections of approximately one third of the electrode separation. Large electrode separation and high driving voltages are normally required to achieve large actuator movements. Here we report on an electrostatic actuator class, fabricated in a CMOS-compatible process, which allows high deflections with small electrode separation. The concept presented makes the huge electrostatic forces within nanometre small electrode separation accessible for large deflections. Electrostatic actuations that are larger than the electrode separation were measured. An analytical theory is compared with measurement and simulation results and enables closer understanding of these actuators. The scaling behaviour discussed indicates significant future improvement on actuator deflection. The presented driving concept enables the investigation and development of novel micro systems with a high potential for improved device and system performance.

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Electrostatic actuation provides efficient, low-power and fast-response driving and control of movable micro and nano structures, for example, in high frequency switches, oscillators, mirrors, motors and sensors. Owing to a prominent scaling behaviour, electrostatic forces have gained a dominant position in micro and nano device actuation. Every downscaling in electrode gap further expands its superiority over other physical driving principles, such as electromagnetic or piezoelectric actuation. In addition, it is at least as important that electrostatic actuators are easy to fabricate with standard micro and nanotechnologies, and that they offer the advantage of integration with complementary metal-oxide-semiconductor (CMOS).

However, most electrostatic actuators suffer from an operational instability – the so-called pull-in effect – which was first discovered on resonant gate transistors in 1967 (ref. 1). The highly non-linear dependence of the electrostatic force on the separation of a mechanically suspended electrode to a fixed electrode results in a prevailing electrostatic force once a critical deflection is reached. From this point on, the mechanical restoring force is always smaller than the electrostatic attraction, which leads to snapping and subsequently sticking of the electrodes. Theory suggests a characteristic travel range of typically 1/3 of the electrode gap for the static[1,2], 1/2 for the dynamic[2] and $1/\sqrt{3}$ for the resonant case[3]. In practice, the pull-in effect causes significantly higher constraints as fabrication tolerances and safety margins need to be considered. Pull-in related effects, such as stiction, adhesion, electrical discharge and dielectric charging, are considered to be the primary causes of device failure for a large variety of electrostatically actuated micro devices[4]. The main challenges to the future development of electrostatic micro and nano actuators and sensors are to control the pull-in instability and to extend the travel range beyond the pull-in limit.

A minority of electrostatic actuator classes, such as in-plane actuated comb drives[5] and resonant out-of-plane moving comb drives[6], enable travel magnitudes that are significantly larger than the electrode separation. Pull-in instabilities do not affect the fundamental operation principle but needs to be considered as parasitic effects on these concepts. Typical electrode separations are in the lower micrometre range, but further significant downscaling is rather challenging due to the fabrication process. Recent publications have reported various attempts to enhance the controllable travelling range of static or quasi-static out-of-plane operating electrostatic actuators[4]. Among these are electrical control strategies[7], leverage methods[8], active or passive suspension spring stiffening methods[9,10], mechanical non-linearities within the actuated micro component[11,12], a non-constant electrode separation[13,14] and the usage of electrostatic fringing fields[15]. Thus far, travel ranges up to 94 % of initial electrode separation have been reported[13].

We believe that an extension of the travel range beyond the pull-in limit can be efficiently provided by a specific leverage approach. In the approach we present here, the high electrostatic forces generated by small electrode gaps are transformed into high deflection magnitudes. Some of the best-known mechanical levers are bimorph actuators[16], where small lateral thermomechanical, piezoelectric or other electroactive material strain results in high deflection magnitudes. Combining electrostatic forces with the bimorph leverage principle, lead to the development of a novel class of efficient, CMOS integrable electrostatic actuators. In the concept presented, electrostatic forces are transformed into lateral forces via non-planar electrode geometries. This induces a lateral strain at the surface of a cantilever and forces the cantilever to bend. In other words, electrostatic forces stretch or compress the surface of a cantilever and cause the cantilever deflection. With this novel electrostatic actuator concept, the cantilever tip deflection depends on electrostatic forces instead of the electrostatically generated electrode deflection. This enables reasonable actuator deflection to be achieved with very small electrode separation, and enables travel ranges widely beyond the pull-in limit. The small electrode separation can keep the control voltage at moderate levels, and downscaling the electrode separation can further reduce the control voltage. The concept proposed of a novel electrostatic actuator class operates with electrode gaps far below micrometre, hence will now be referred to as nano electrostatic drive (NED).

In this work, we present the theoretical description, a fabrication process and first characterization results of NED actuators. The measured deflection curves are fitting well with the prediction done by analytical and simulation models. We demonstrate a travel range of 136 % on characterized samples of these cantilevered electrostatic actuators. The scaling of NED principle discussed provides the information on how to improve the presented actuation concept and achieve significant higher travel ranges.

Results

Theory of the novel electrostatic actuators. The NED actuator is composed of periodically repeated electrostatic-force-based elementary actuator cells processed at the surface of a cantilever. Figure 1 illustrates schematic cross-sections of the whole actuator (Fig. 1a), the elementary actuator cell (Fig. 1b) and a half elementary actuator cell labelled with the fundamental parameters (Fig. 1c). The role of the elementary actuator cells is to transform the electrostatic forces into lateral mechanical forces, which consequently leads to a bending of the cantilever. Each elementary actuator cell is a section part of the cantilever (Fig. 1a). A single actuator cell is composed of a base on which two electrodes are placed, separated by two spacers on the left and right-hand side of an air gap. The difference of electrostatic potential applied between the top and the bottom electrode generates an electrostatic force that creates a bending of the top electrode, in addition to its downward displacement. The spacers constrain the top electrode from large deflection by connecting it with other parts of the structure, but it produces significant strain in the upper electrode. The top electrode transforms this surface

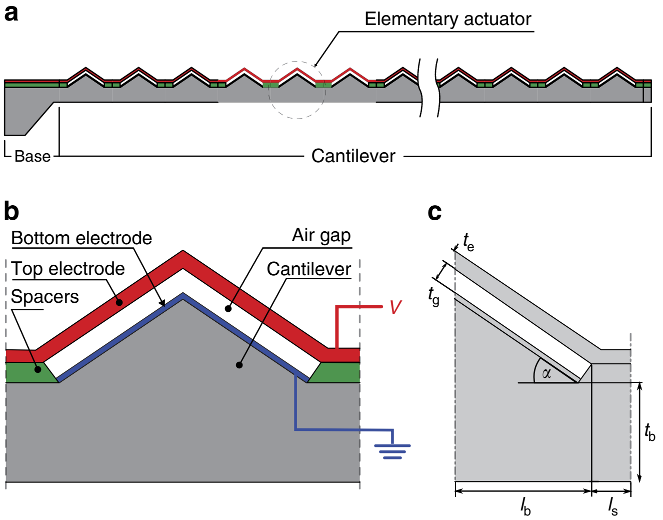

Figure 1 | Schematic cross-section of a Λ-shaped NED. (**a**) Schematic design of a whole electrostatically actuated cantilever. (**b**) Schematic image of a single elementary actuator cell with the indication of ground (blue) and control potential (red). (**c**) Illustration of a half elementary actuator cell and the fundamental geometric parameters.