Electrical actuation on Digital Microfluidics with a Ta2O5 insulating layer: a comparison study

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Introduction

The introduction of electronic automation in the digital microfluidic (DMF) system has been highlighted it as a prospective platform for managing the intricacy of large-scale micro-reactors and underpinned a wide variety of on-chip biochemical applications such as immunoassays , DNA sample processing and cell-based assays. Yet, to further position DMF in high throughput applications such as cell sorting and drug screening, the velocity of the droplet transportation (v_{droplet}) must be improved, without compromising its reliability and controllability. The velocity of the droplet transportation depends on the actuation voltage and the size of the droplet. Empirically it barely reaches 2.5 mm/s at an droplet actuation voltage below 20 V .

A few attempts have been made to address the problems based on either hardware or software improvements. Banerjee *et al.* have proposed a top-plate-less DMF system using co-planar electrodes to reduce the viscous dragging force between the liquid-solid interface. Brassard *et al* have engineered the droplets with a water-oil core-shell structure to achieve a high v_{droplet}. Regrettably, both of them are vulnerable to sample contamination and evaporation that are intolerable for essential biochemical applications like polymerase chain reaction (PCR). Naturally, elevating the electrode-driving voltage could increase the electric field to accelerate the v_{droplet}. But it would compromise the chip lifetime due to dielectric breakdown, and the cost of the electronics for high-voltage-tolerant design. To our knowledge, there is no electrode-driving technique that concurrently improves the v_{droplet} and elongates the electrode lifetime of a DMF chip.

By incorporating NDAP in our DMF system, we experimentally achieved 24.9% lower RMS voltage but 26.8% and 49.5% higher v_{droplet} than the commonly used DC and AC actuation practices, respectively. The electrode lifetime of a chip actuated by NDAP was also improved almost threefold over that actuated by DC under critical dielectric coating conditions, while AC was superior to both NDAP and DC. Under the daily used coating conditions all the three actuation signals have shown excellent performance in terms of the electrode lifetime. This work, together with our previous publications, should be valuable for scientists and engineers working on enhancing the throughput and the reliability of control-engaged DMF systems for automated applications.

Methods

1 Device fabrication

The DMF devices were fabricated and assembled following the protocols described previously. A drop of aqueous solution (~0.5 uL) immersed in silicon oil (1 cSt) (Sigma-Aldrich, MO) or hexadecane (3.34 cSt) (Sigma-Aldrich, MO) was sandwiched by a bottom glass and a top Indium Tin Oxide (ITO, Kaivo Optoelectronic) glass with a 0.25 mm spacer. Electrodes (1 mm × 1 mm) patterned on the bottom glass were separated from each other with a 0.01 mm gap. A dielectric layer of Ta_2O_5 (250/50 nm) was coated on the electrodes followed by a layer of Parylene C (480nm) (Galxyl) and then a layer of Teflon AF 1600 (100 nm) (DuPont). Silane A-174 (Momentive Performance Materials) was utilized to improve the bonding between the Ta_2O_5 and Parylene C layers. The top ITO glass (Kaivo, ITO-P001) was coated with a layer of 100 nm Teflon AF 1600.

2 Experimental setup

A red LED was placed on chip next to the electrode matrix and controlled by the FPGA. It lighted up when any of the electrodes was connected to the power source. The chip was put under a microscope and monitored with a high speed camera (Nikon V2), which have a maximum frame rate up to 1200 frames/second. The movement of the droplet was captured in every 0.83ms. The top glass was grounded to provide an electric field over the droplet.

3 Data analysis

Individual frames extracted from videos were analyzed using an image processing software, *Image J*. The centroid of the droplet was obtained as the center of mass of an irregular shape and was used as the droplet position for calculating the transportation velocity.

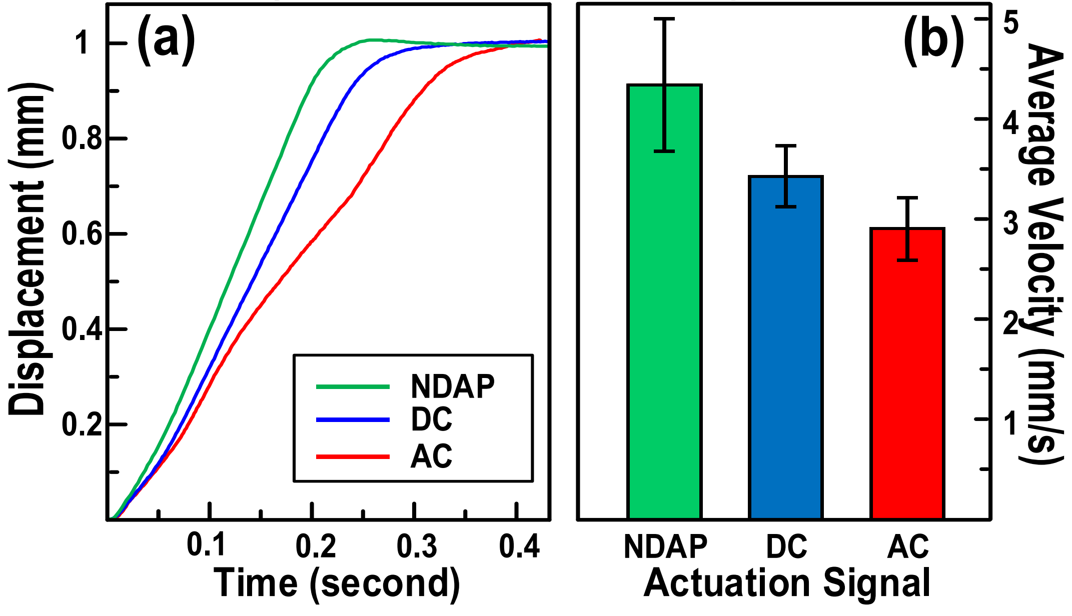

Figure #1

Results

In the experiments of velocity determination, a droplet of DI water (0.5 uL) was transported from one electrode to the next under different actuation signals. The same electrodes were used for running DC, AC and NDAP. AC signal used in experiments was symmetric square wave. The peak-values of all the three signals were fixed at 15 V. In NDAP signal, 15 ms t'_{α} was used for the best driving performance. The charging of AC or DC was sustained till the movement had been completed. Therefore, the RMS voltages of AC, DC and NDAP were 15 V, 15 V and 11.27 V, respectively. The frequency of the AC signal was set at 1 kHz which was a widely used frequency in literatures.

A droplet running across an 8-electrode straight array was monitored to obtain the average velocities driven by DC, AC and NDAP. The charging duration of DC and AC was empirically optimized at 300 ms and 400 ms, respectively, to complete the movement from one electrode to the next. The average velocities were calculated over the droplet movement period disregarding whether the actuation signal stopped or not.

In order to touch the limit of the electrode lifetime, we coated a batch of chips with a critical thickness of 50 nm of dielectric layer which were prone to breakdown. As shown in Fig. 6b, NDAP had an electrode lifetime about 3 times longer than that of DC with a value of 200 and 63 shuttles, respectively. This could be attributed to the lower RMS value of NDAP. But unexpectedly, DMF chips actuated by AC were still robust even under those critical coating conditions. This may be attributed to the defects or impurities in the thin layer of the dielectric material. For a dielectric layer as thin as 50 nm, the occurrence of defects and impurities dramatically increase.

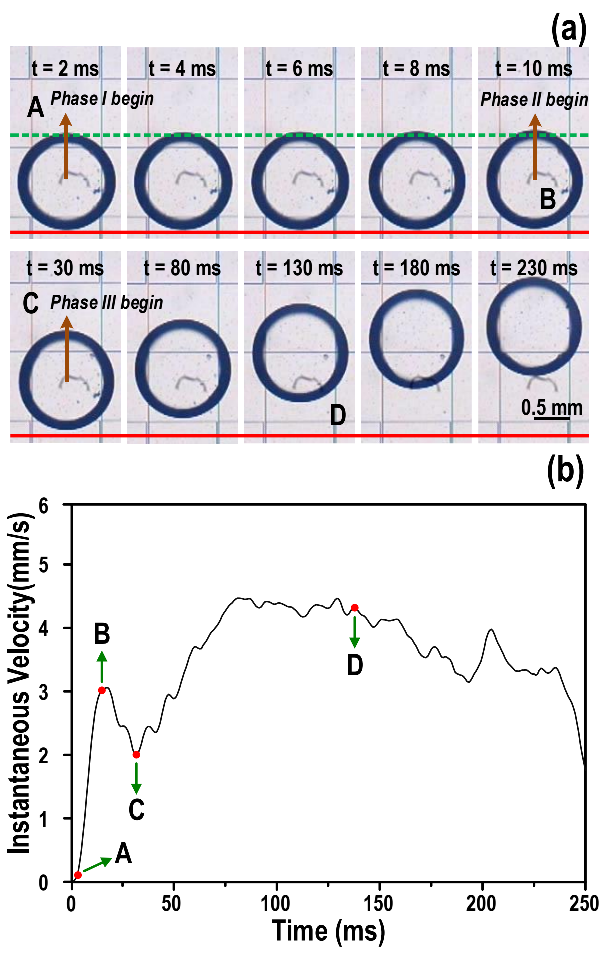

Figure #2

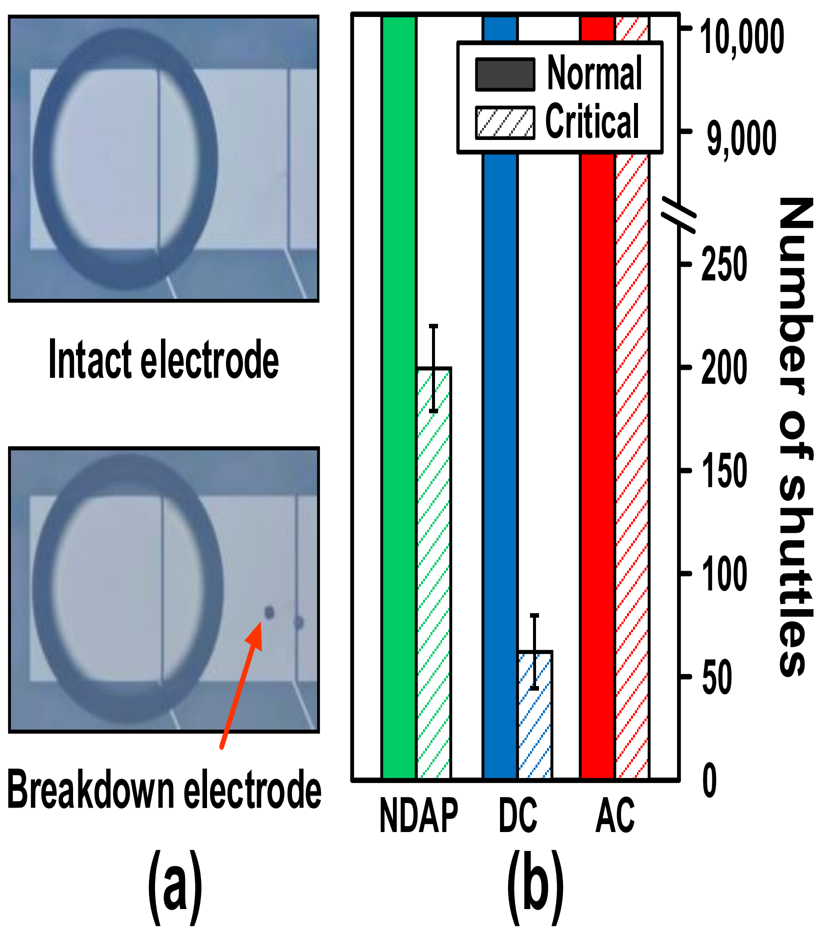

Figure #3

Conclusions

By matching the droplet dynamics with the strength and duration of the applied electric field we have speeded up the droplet movement to a higher value than DC and AC actuation signals by incorporating *feedback control* with *Natural Discharge after Pulse* (NDAP) as the electrode-driving techniques. The electrode lifetime comparison under DC, AC and NDAP has revealed that AC is the safest actuation signal, and NDAP is superior to DC. The entire NDAP scheme involves only regular electronics and software programming, being highly upgradable for the following-up research, customizable to other applications, and easily repeatable by other research groups. The thorough comparisons on the performance of NDAP with currently widely used DC and AC signals has established a clear guideline and provided another option for choosing the right actuation signal in different applications, such as DNA analysis and protein manipulations, etc.

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