Fabrication and characterization of liquid metal-based micro-electromechanical DC-contact switch for RF applications

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ABSTRACT

We demonstrate that room-temperature liquid metal alloy droplets of Eutectic Gallium Indium (EGaIn) and Gallium Indium Tin alloy (Galinstan) can be actuated using electro-wetting-on-dielectric (EWOD) effect. With the application of 80-100V across the actuation electrode and ground electrode, the metallic liquid droplets were observed to be actuated. We have studied the actuation characteristics using different electrode architectures in open-air configuration as well as in encapsulated microfluidic channel test-beds. The resulting microfluidic DC actuation might potentially be used for RF switching applications.

Keywords: Liquid-metal, EWOD, droplet microfluidics, switch, micro-fabrication

1 INTRODUCTION

Electrowetting-on-dielectric (EWOD) is the phenomenon in which the wetting properties of a liquid are modified by the influence of an applied electric field [1]. This is achieved by applying voltage between a metal surface and the droplet on it. Devices used for this purpose consist of a metal electrode, the droplet to be actuated and a dielectric layer in between them (Fig. 1(a)). Using EWOD, both conducting and non-conducting liquids can be actuated [2]. When voltage is applied between the droplet and the metal electrode, their charge distributions are changed. As a result, the droplet spreads over the dielectric. If there is more than one electrode under the dielectric, the droplet moves towards the electrode on which the voltage is applied (Fig. 1(b)). This is the principle we make use of in this work. Electrowetting phenomenon finds use in several different fields and disciplines, such as lab-on-a-chip systems and electrical switches [3, 4]. Here, in our work we demonstrate structures which might have potential applications as alternative RF-switches.

Mainly two basic types of EWOD devices have been studied in the literature: open setup and closed setup devices, which are shown schematically in Figure 2(a) and Figure 2(b), respectively. The main difference between the two is that the closed setup has a continuous ground electrode on the top plate, whereas in the open setup, the ground electrode is on the same wafer as the actuation electrodes. A summary of the previous efforts carried out in this field is presented in Table 1. Potassium chloride solution (KCl), DI-water and mercury (Hg) droplets have been used and different electrode materials have been utilized including chromium (Cr), titanium (Ti) and gold (Au).

The main motivation behind our efforts in using liquid metal droplet actuation for electrical switching lies in the inherent advantages compared to solid-state and MEMS switches. When compared to solid-state switches, micro-electromechanical liquid metal-droplet based switches provide higher isolation and lower insertion loss. In addition, since they do not have fragile moving parts, EWOD systems overcome the fatigue problems seen in RF-MEMS switches. They potentially are reliable and show no performance degradation during the lifetime of the switch.

Group	Setup	Droplet	V_{act}	Electrodes	Dielectric
Rajabi	Closed	KCl Sol'n	55V DC	Cr	Parylene C
Chang et al.	Open	DI –Water	<15V	Au	Al_2O_3 (ALD)
Chang et al.	Open	DI – Water	90V	Cr	Polyimide
Chen & Peroulis	Open	Mercury	110V	Ti/Au/Ti	SiO_2 (PECVD)

Table 1: Summary of previous work on EWOD-based droplet actuation

In this work, we have fabricated microfluidic platforms (Fig. 4) and examined the actuation of metallic liquid droplets, namely EGaIn and Galinstan, using EWOD. EGaIn and Galinstan are used instead of Hg because they are non-toxic and liquid at room temperature [5]. We have investigated the effect of different actuation electrode geometries like rectangular, inter-digitated fingers and crescent-shaped electrodes on the droplet actuation.

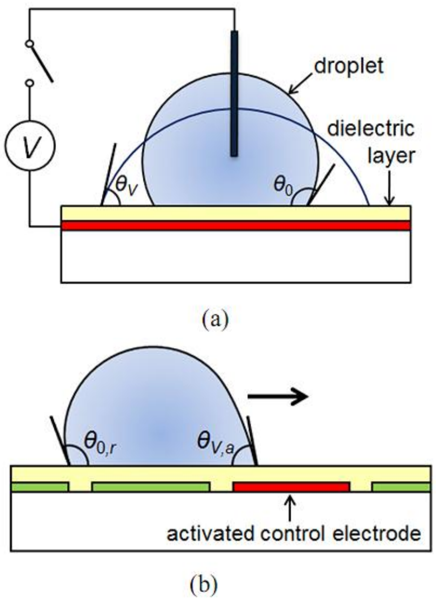

Figure 1: (a) EWOD device consisting of a metal electrode, the droplet to be actuated and a dielectric layer in between. (b) Actuation of a droplet on a device with more than one electrode [6]

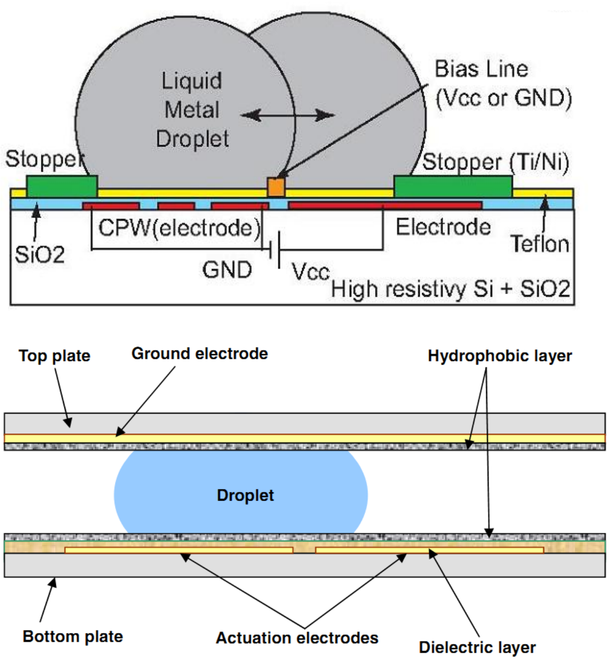

Figure 2: (a) An open setup EWOD device consisting of a metal electrode, the droplet to be actuated and a dielectric layer in between. (b) A closed setup EWOD device [7, 8]

2 MICRO-FABRICATION

The fabrication of the devices used in this work consisted of a five-mask micro-fabrication process. Quartz wafers are used as substrates on which the test devices are built. As the first step of fabrication, 100nm-thick Cr layer is deposited using sputter. Then, a photolithography step is carried out with the electrode mask to define the actuation and ground electrodes and the Cr layer is etched. Next, a 300nm-thick SiO_2 layer is deposited using plasma-enhanced chemical vapor deposition (PECVD) to form the dielectric layer. Next, another photolithography process is carried out with the oxide etch mask. Afterwards, a dry etch process is performed in the inductively coupled plasma (ICP) system to open the ground electrodes and contact pads. Then, an image reversal photolithography process is carried out to define the signal lines. 100nm/100nm-thick Cr/Ni layer is deposited using sputter. After lift-off, 100nm-thick Teflon AF 2400 layer is spin-coated as the hydrophobic layer and patterned using mask four. As the final step, a 400µm-thick SU8 layer is spin-coated and patterned using mask five. The schematic cross-sections of the micro-fabrication steps and an optical microscope image of the fabricated device can be seen in Figure 3 and Figure 4, respectively.

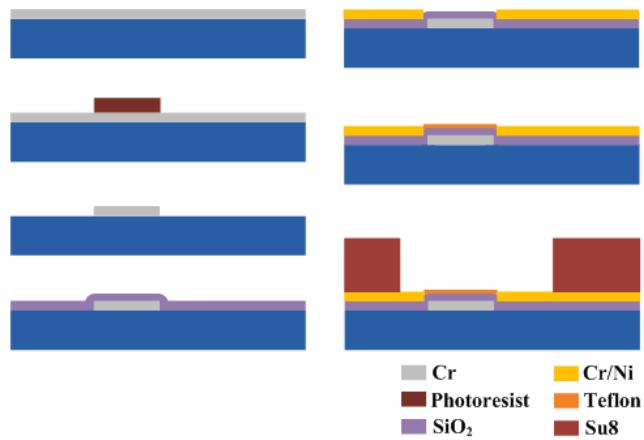

Figure 3: Micro-fabrication steps of test devices.

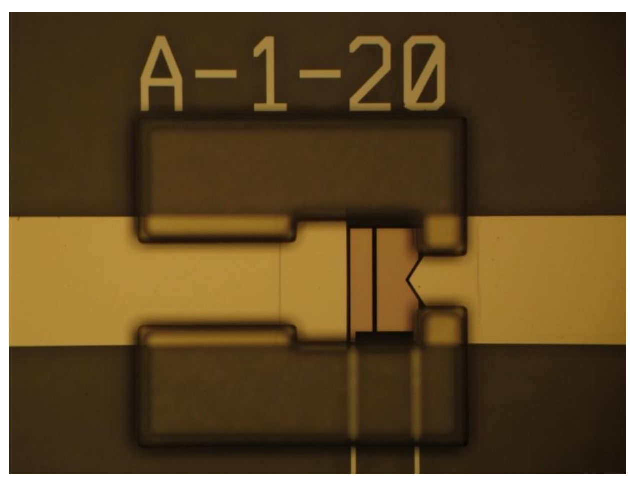

Figure 4: Optical microscope image of a test device

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3 RESULTS AND DISCUSSION

Characterization of the test devices involved visual inspection with optical microscope and FEI-brand Nano-SEM, contact angle measurements of DI-water on hydrophobic surfaces using Dataphysis OCA 30 and voltage actuation experiments under a Cascade-Microtech electrical probe station connected to a Keithley 4200-SCS parameter analyzer (Fig. 5).

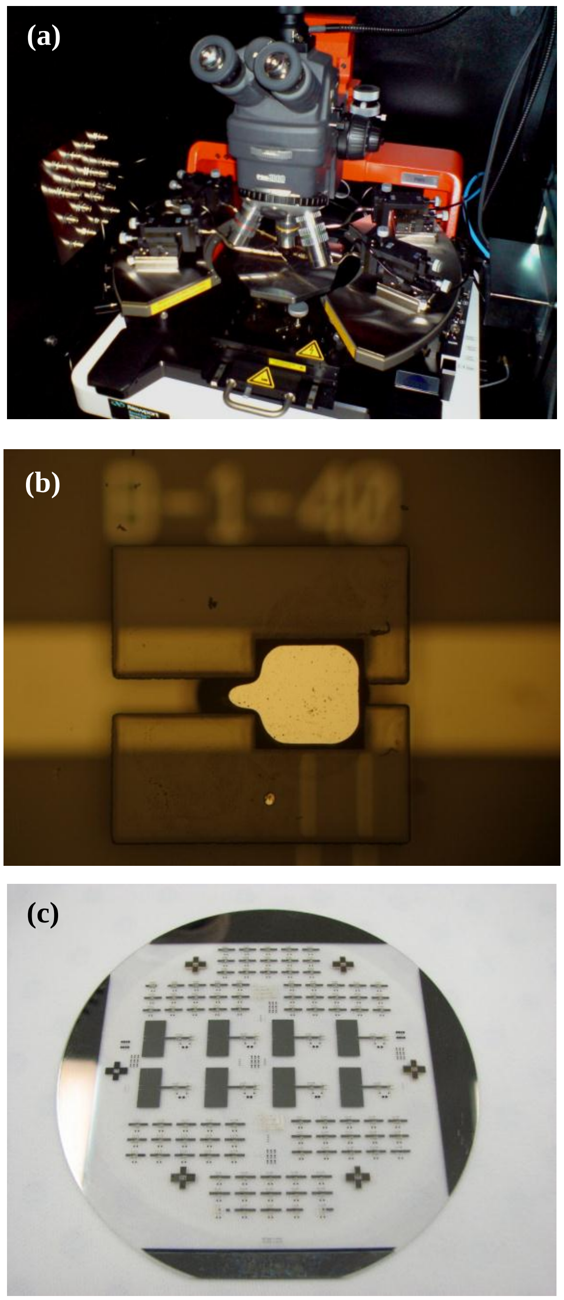

Figure 5: (a) The experimental setup used in this work: a probe station connected to a parameter analyzer; (b) A test device with a positioned metallic droplet; (c) a fabricated 4-inch quartz wafer with many test devices.

Figure 6 shows the contact angle measurements of the hydrophobic layer with DI-water: the contact angle on Teflon AF 2400 is 130.1°. The aim of Teflon coating is to get the optimum initial contact angle during droplet actuation.

During actuation experiments, two different metallic liquids have been used: Eutectic Gallium Indium (EGaIn) and Gallium Indium Tin alloy (Galinstan). With the application of 80-100V across the actuation electrode and the ground electrode, the metallic liquid droplets were observed to be actuated (Fig. 7).

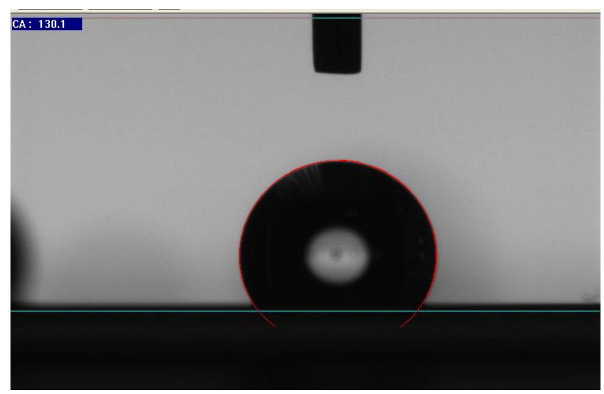

Figure 6: Contact-angle measurement of Teflon-coated surface

We have observed significant differences in the actuation behavior of the metal droplets with the application of AC and DC voltages. Actuation experiments in closed-pack microfluidic channels were also successful with slightly higher actuation voltages. We attribute this result to the partial adhesion of liquid-metal droplets to the SU-8 walls, especially at the corners. The effect of dielectric layer thickness on the actuation voltage was also studied. Thinner dielectric layers resulted in lower actuation voltages as low as 30 V. Results of this study may be potentially used in non-toxic alternative RF-switching applications. RF-measurements of the microfluidic switches are currently in progress.

Figure 7: Top: Test device before actuation; Bottom: Actuation of the droplet with an actuation voltage of 100V.

4 CONCLUSIONS

In this work, we demonstrate that room-temperature liquid metal alloy droplets of Eutectic Gallium Indium (EGaIn) and Gallium Indium Tin alloy (Galinstan) can be actuated using electro-wetting-on-dielectric (EWOD) effect. With the application of 80-100V across the actuation electrode and the ground electrode, the metallic liquid droplets were observed to be actuated. Actuation experiments with and without thick SU-8 wall structures, different dielectric thicknesses, different droplet materials (EGaIn and Galinstan) and different droplet sizes, different dielectric materials including SiO_2, Al_2O_3, and HfO_2 were carried out, as well as DC and AC actuation experiments. The initial results are promising and with a systematic experimental optimization the micro-electromechanical droplet-based switches might provide an alternative technology for RF-switching applications.

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