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Speed and location tracking of moving multiphase interfaces via a capacitance microsensor array during droplet evaporation

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ABSTRACT

Knowledge of the location and speed of a moving multiphase contact line provides significant and valuable insight into the fundamental physics behind condensation- and evaporation- based processes such as occur in high heat flux thermal management solutions. From an application perspective, this information can be leveraged to ascertain and enhance device design and performance of phase change-based cooling processes. In this work, we present a capacitance-based phase interface sensing approach capable of measuring the location and speed of a moving multi-phase interface at the microscale, evaluate the impact of substrate material on its performance, and demonstrate its ability to function at elevated temperatures during water droplet evaporation. The sensing is accomplished via an array of planar interdigitated electrodes upon either a doped semiconductor or dielectric substrate. Measuring capacitance changes with time facilitates sensing of the contact line as it passes over each electrode pair. This capacitive sensing scheme is non-invasive to the system under study, allowing its implementation into many types of existing hardware and devices and does not require optical access to the phase change area of the device. Results for unconstrained water droplets are presented, and it is shown that the choice of substrate material has a marked impact on sensing behavior in terms of sensor coupling. Finally, data for the moving multiphase contact line of an evaporating water droplet is presented to demonstrate functionality at elevated temperatures and during a dynamic heat transfer process.

1. Introduction

In a given three-phase system such as for a growing vapor bubble or condensing/evaporating droplet, the three-phase contact line occurs at the interface of the liquid, solid, and gas phases. This three-phase contact line is able to move along the surface of the solid as the individual bubble or droplet expands or contracts. Moving contact line (MCL) has been a subject of extensive experimental and analytical studies because of its ubiquity in interfacial science and many engineering fields, including but not limited to microfluidic devices, various coating and printing technologies, phase-change heat transfer systems, two-phase flows in porous media, and nucleate boiling [1–5]. The strong temperature and density gradients in the vicinity of MCL along with its mobile nature make it a major factor in determining the overall heat transfer characteristics of the phase change process. As a result, the MCL behavior has also been widely investigated in recent years as it is the region that facilitates the highest heat transfer in evaporative or other phase-change heat transfer processes [6–10]. In terms of thermal management applications, the widespread utilization of multiphase cooling strategies to handle high heat flux densities means that insights gained into the behavior of the MCL and its associated thermal impacts can lead to improved cooling devices, processes, and effectiveness via informed surface engineering. Studying MCL behavior for phase-change heat transfer processes like droplet evaporation has also become significant as temperature data alone does not provide a comprehensive understanding. It requires revealing the interdependence of MCL speed and location with heat transfer mechanisms involved in phase-change heat transfer processes [9,11–13].

Although optical sensing has been the most prevalent technique within the literature to study an MCL in laboratory settings, electrical sensing schemes have advantages over optical techniques in terms of precision, stability, and applicability at the microscale [14,15] or in situations where visual access is blocked such as within heat exchangers, vapor chambers, or other opaque enclosures. Optical techniques possess

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flow sensfitfivfity and throughput, often requfire bufflky and compflex setups, and are unsufitabfle for cflose-packed fintegratfion. On the other hand, eflectrficafl detectfion comprfisfing resfistfive and capacfitance sensfing facfiflfitate hfigh sensfitfivfity, scaflabfiflfity, transfient response, flow cost, and compatfibfiflfity fin compact fintegratfion [16–18]. Resfistfive and capacfitfive sensfing have been most promfinent fin eflectrficafl technfiques, wfith some fimportant dfifferentfiators between the two types. Resfistfive sensfing has some known flfimfitatfions fincfludfing requfirfing a contfinuous conductfive phase fin the sensfing regfion and fintrficate patterns to achfieve effectfive performance [14]. In contrast, capacfitfive sensfing requfires onfly a spatfiafl separatfion between two copflanar eflectrodes for achfievfing sensfing and can be more easfifly scafled down to smaflfler feature sfizes due to fits fless compflficated geometry requfirements [19].

In thfis work, we present a capacfitance-based mficrodevfice capabfle of trackfing the spatfiafl flocatfion and motfion of the movfing MCL, evafluate the fimpact of substrate materfiafl on fits performance, and demonstrate fits abfiflfity to functfion at eflevated temperatures durfing water dropflet evaporatfion. As shown fin Ffig. 1, the mficrodevfice fis comprfised of a totafl of sfix capacfitance mficro-sensors based on copflanar finterdfigfitated eflectrodes (IDEs) wfith a thfin finsuflatfing poflymer flayer on top. Thfis approach afso facfiflfitfies a bufflk mficro-fabrficatfion compatfibfle means of sensfing phase finterface such that many sensors can be created at one tfime. Unflfike exfistfing optficafl methods used prevfiousfly fin flfiterature [10,20,21], thfis mficro-sensor array approach does not requfire vfisuafl access to the surface under study such that MCL trackfing can occur wfithfin opaque hardware or encflosures. Our prevfious work on trackfing MCL flocatfion vfia thfis type of sensfing scheme on a semficonductfing substrate was shown to be effectfive for sfimpfle aspfirated water dropflets but afso demonstrated certafin nonfideaflfitfies, partficuflarfly fin terms of capacfitfive coupflfing effects between sensors fin cflose proxfimfity [22]. Here, we report on sfignfiffficant fimprovements by utfiflfizfing a dfieflectrfic substrate, fincfludfing but not flfimfited to obtafinfing a much stronger capacfitance sfignafl output from mufltfipfle sensors fin adjacent proxfimfity wfith reduced coupflfing effects. The motfivatfions behfind choosfing soda-flfime gflass as the afflternate sub-strate are fits cost-effectfiveness and broad appflficabfiflfity fin mficroflufidfic and other MEMS devfices. Soda-flfime gflass substrates are afso wfidefly fimpflemented as they provfide advantages over other materfiafls fin terms of hfigh eflectrficafl finsuflatfion, surface stabfiflfity, hfigh resfistance to mechanficafl stress, and compatfibfiflfity wfith a wfide range of mficrofabrficatfion technfiques [23–25]. We afso report for the ffirst-tfime data for the movfing MCL of an evaporatfing water dropflet to demonstrate thfis approach's functfionafflfity at eflevated temperatures and durfing a dynamfic and reafl-fistfic heat transfer process.

2. Methodology

2.1. Operating principle

The basfic operatfing prfincfipfle of thfis phase finterface sensfing mficro-devfice fis based on changes fin the reflatfive permfittfivfity of the medfium dfirectfly above the finterdfigfitated eflectrodes wfith the passage of the MCL, whfich fin turn causes a change fin capacfitance sfignafls obtafined from the sensor array [14,15,22]. Apart from the reflatfive permfittfivfity of the medfium $\varepsilon_{r,\ eff}$, the capacfitance C of the sensor array depends on the wfidth w and spacfing $2a$ between two consecutfive copflanar eflectrodes. The foflflowfing equatfion can be empfloyed to caflcuflate the capacfitance C fin the sensor array [26],

$$C = \frac{2\mathcal{E}_{r,eff}\mathcal{E}_0 l}{\pi} ln\left[\left(1+\frac{w}{a}\right)+\sqrt{\left(1+\frac{w}{a}\right)^2-1}\right] \quad (1)$$

where, $\mathcal{E}_0$ fis the vacuum permfittfivfity and l fis the finteractfion flength of the eflectrode pafir. Ffig. 1(a) demonstrates a schematfic fiflflustratfion of the capacfitfive sensfing scheme, where eflectrfic ffiefld flfines between two pflanar eflectrodes extend above the thfin finsuflatfing flayer to finteract wfith the motfion of MCL as the flfiqufid dropflet passes over fit. These eflectrfic ffiefld flfines are caused by an appflfied sensfing vofltage to the eflectrode pafir. The sensfing range of the eflectrficafl ffiefld from the top surface of the IDEs (referred to as the penetratfion depth T) afso varfies wfith the wfidth w and spacfing $2a$ between two consecutfive copflanar eflectrodes by foflflowfing the equatfion beflow [26].

$$T = \operatorname{asinh}\left[\cosh^{-1}\left(1+\frac{w}{a}\right)\right] = a\sqrt{\left(1+\frac{w}{a}\right)^2-1} \quad (2)$$

2.2. Microdevice overview

The mficrodevfice desfign fin thfis work contafins sfix capacfitance sensors

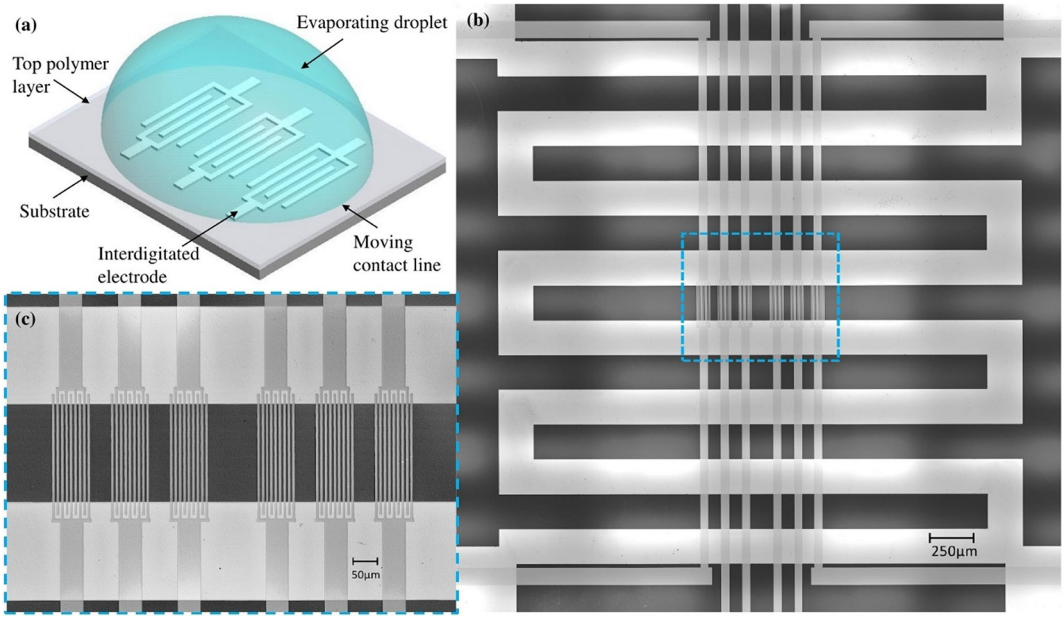

Fig. 1. (a) A conceptuafl fiflflustratfion of the capacfitfive sensfing scheme (not to scafle). (b) A flaser-mficroscopfic fimage of the mficrodevfice showfing resfistance heater and capacfitance mficro-sensor array. (c) A detafifled vfiew of the sensfing zone encflosed by the dashed box fin (b) showfing sfix capacfitance sensors based on finterdfigfitated eflectrodes. The resfistance heater and finterdfigfitated eflectrodes are on separate devfice flayers and separated by a poflymer thfin ffifflm as descrfibed fin the mafin text.

as shown fin Ffig. 1, wfith each sensor befing comprfised of an IDE pafir. The sensfitfivfity or strength of the capacfitance sfignafl and penetratfion depth of the eflectrfic ffiefld flfines depends on the geometry of the IDEs. The measured capacfitance and penetratfion depth fincrease wfith the fincreasfing wfidth of the eflectrodes. However, the capacfitance decreases wfith fincreasfing spacfing between eflectrodes. The strength of the capacfitfive sfignafl aflso fincreases wfith the number of eflectrodes and thefir finteractfion flength [27]. Aflthough fincreasfing wfidth, finteractfion flength, and the number of eflectrodes woufld enhance the sensfitfivfity of the sensfing scheme, fit woufld aflso reduce the spatfiafl sensfitfivfity of the mficrodevfice because of fits fincreasfing physficafl dfimensfions. Narrower spatfiafl separatfion between two consecutfive eflectrodes wfiffl aflso flead more chaflflengfing mficrofabrficatfion and a reductfion fin the number of defect-free devfices. Hence, a baflanced approach has been fimpflemented durfing the devfice desfign to facfiflfitate a workabfle compromfise between magnfitude of the capacfitfive sfignafl, penetratfion depth, desfired spatfiafl resoflutfion, and hfigh yfiefld mficrofabrficatfion. The ffinafl IDE array desfign shown fin Ffig. 1(b-c) has an eflectrode wfidth of $w = 6\mu m$, spacfing between two consecutfive eflectrodes $a = 3\mu m$, and an finteractfion flength of $l = 250\mu m$.

2.3. Micro-fabrication process

Identficafl capacfitance-sensfing mficrodevfice arrays were fabrficated on two dfifferent substrate types fin order to evafluate the fimpact substrate materfiafl can have on MCL sensfing performance. Commercfiaflfly avafiflabfle sfingfle sfide poflfished 500 μm thfick boron-doped (1×10^{16} cm ^{3}) sfiflficon wafers wfith a 500 nm thermaflfly grown oxfide flayer on top were obtafined to serve as a semficonductfing substrate, whfifle soda-flfime gflass wafers of sfimfiflar thfickness were obtafined to act as a dfieflectrfic substrate type. The mficrofabrficatfion of the capacfitfive mficro-sensor array consfisted of photoflfithography, deposfitfion of pflatfinum (Pt), spfin-coatfing of a thfin finsuflatfing poflyfimfide top flayer, and seflectfive etchfing/patternfing of the deposfited poflymer flayer by reactfive-fion etchfing. To enabfle a heated surface durfing the dropflet evaporatfion testfing, a 100 nm thfin ffiflm of Pt was deposfited and patterned as a resfistance heater dfirectfly on top of the startfing substrate vfia photoflfithography and DC sputterfing deposfitfion. A 1.2 μm thfin ffiflm of the poflyfimfide was deposfited between the resfistance heater and the IDEs arrays vfia spfin coatfing of the dfifluted poflyfimfide (75% PI-2661 + 25% NMP) to provfide an eflectrficaflfly finsuflatfing flayer. Mficrodevfices that were not fintended for evaporatfion studfies dfid not fincflude these processfing steps and finstead began wfith the IDE mficrofabrficatfion steps that foflflow. To create the IDE sensfing array, a 70 nm thfin ffiflm of Pt was deposfited and patterned vfia DC sputterfing fin an AJA ATC sputterfing system wfith a commercfiaflfly avafiflabfle Pt target. A spfinon poflymer of poflyfimfide (PI-2611) was obtafined from HD Mficrosystems whfich can be dfifluted wfith the addfitfion of N-Methyfl-2-Pyrroflfidone (NMP) to achfieve thfinner flayers. A 440 nm thfin ffiflm of poflyfimfide was deposfited on top of the deposfited Pt flayer vfia spfin coatfing of the dfifluted poflyfimfide (50% PI-2661 + 50% NMP) fin a cflosed-bowfl spfin coater. The 440 nm thfick poflyfimfide flayer was chosen to ensure a baflanced approach of fincreasfing the sensfitfivfity of the mficrodevfice and provfidfing a thfick enough protectfive coatfing atop the Pt flayer to prevent fit from creatfing surface protrusfions. The poflyfimfide flayer was patterned by reactfive fion etchfing (RIE) to open contact wfindows at the devfice perfiphery for facfiflfitatfing wfire bondfing between bond pads of the devfice and the chfip carrfier.

2.4. Signal processing

The mficrodevfice was finstaflfled and wfire bonded wfithfin a commercfiaflfly avafiflabfle fleaded ceramfic chfip carrfier, where each of the bond pads fis findfivfiduaflfly connected to a pfin at the backsfide. The mficrodevfice and chfip carrfier assembfly finterfaces wfith a computer-controflfled data acqufisfitfion system through a pfin grfid array (PGA) socket. A supportfing sensfing cfircufit was empfloyed to transflate capacfitance changes finto vofltage readfings and to ensure a measurabfle change fin sfignafl magnfitude, as the capacfitance changes reflated to thfis sensfing scheme can be reflatfivefly smaflfl. As shown fin Ffig. 2(b), the supportfing cfircufit contafins an RC oscfiflflator coupfle, an operatfionafl ampflfiffier, and a reference capacfitor connected fin paraflflefl wfith the sensfing IDE capacfitor. The pflanar finterdfigfitated eflectrode arrays used for the sfix capacfitance mficro-sensor are fidentficafl fin geometry and have an average capacfitance of 175 fF before the experfiments fin the dry state wfith approxfimatefly 14% of senor-to-sensor varfiatfion. Observatfion of the nofise flevefl findficates that the flower fflimfit of detectfing capacfitance changes fis 0.2 fF, whfich fis approxfimatefly 0.11% of the average capacfitance of the mficrosensors fin the dry state. An fimportant matter to mentfion here fis that, from a sensfing perspectfive, fif the onfly goafl fis to determfine the presence or flack of the flfiqufid wfithfin the sensfing ffiefld of a gfiven sensor, an edge-trfiggered dfigfitfizatfion scheme or sfignafl finverter woufld enhance the cflarfity of the obtafined sfignafl compared to the technfique used fin the current work.

2.5. Experimental setup

Ffig. 2(a) shows a sfimpflfiffied schematfic of the experfimentafl setup, where the mficrodevfice was pflaced on a sampfle stage beneath a syrfinge controflfled by a drop shape anaflyzer (DSA 25E, KRÜSS Scfientfiffic). The DSA provfided controflfled dosfing and retractfion of defionfized water dropflets durfing finfifiafl aspfiratfion experfiments that dfid not finvoflve a heated substrate for dropflet evaporatfion, and controflfled depfloyment of a known startfing dropflet sfize for the evaporatfion studfies that foflflowed. An optficafl camera attached to the DSA aflso monfitored the macroscopfic behavfior of the MCL, whfich served to vaflfidate that the mficrodevfice array was functfionfing as fintended. The captured fimages/vfideos vfia DSA shown fin Ffigs. 3 and 4 aflso facfiflfitated a usabfle comparfison of the MCL speed between the mficrodevfice and the optficafl technfique. Sfimpfle dosfing and retractfion wfithout substrate heatfing (fi.e. aspfiratfion) was ffirst utfiflfized to study the fimpact of substrate materfiafl on sensfing behavfior.

Once the dfieflectrfic substrate was found to be superfior through these earfly studfies, evaporatfing dropflet testfing at eflevated devfice temperatures was performed. For ensurfing eflevated surface temperature durfing the dropflet evaporatfion experfiment, the thfin ffiflm resfistance heater of the mficrodevfice was powered wfith known vofltage and current from a DC power suppfly. Before dosfing the water dropflet, the resfistance heater was powered by a set eflectrfic finput power vfia the DC suppfly to attafin the desfired surface temperature of the mficrodevfice. The DSA provfided controflfled dosfing of the water dropflet at varfious surface temperatures and recorded the entfire evaporatfion process that foflflowed. The caflfibratfion of surface temperature at varfious eflectrfic power finputs to the resfistance heater was carrfied out by empfloyfing an IR camera (FLIR A300) and a commercfiaflfly avafiflabfle thermocoupfle, wfith the flatter befing fin good thermafl contact wfith the center of the devfice. Thfis caflfibratfion was performed after affl MCL sensfing actfivfitfies were compfleted to avofid damagfing the wetted surface regfion.

3. Results and discussion

The normaflfized capacfitance changes wfith tfime were measured for a cycfle of dosfing and retractfion of defionfized water dropflets for fidentficafl mficrodevfices fabrficated on efither a semficonductfing (doped sfiflficon) or dfieflectrfic (soda-flfime gflass) substrate. Ffig. 5 demonstrates the changes fin capacfitance sfignafls for the capacfitance mficro-sensor array deposfited on a sfiflficon substrate. As Ffig. 5 shows, durfing dosfing of the water dropflet, the MCL assocfiated wfith the dropflet's fleadfing edge ffirst moves over capacfitance sensor CS-1 and causes an fincrease fin sfignafl. The MCL next reaches capacfitance sensor CS-6, whfich aflso demonstrates a rfise fin capacfitance sfignafl wfith the passage of the MCL. These events are reversed when the water dropflet fleaves the sensfing zone of the mficrodevfice. Thfis effectfivefly demonstrates the basfic measurement prfincfipfle of measurfing the capacfitance changes wfith tfime as the MCL passes over the capacfitance sensors. The four dashed boxes shown fin Ffig. 5 demonstrate

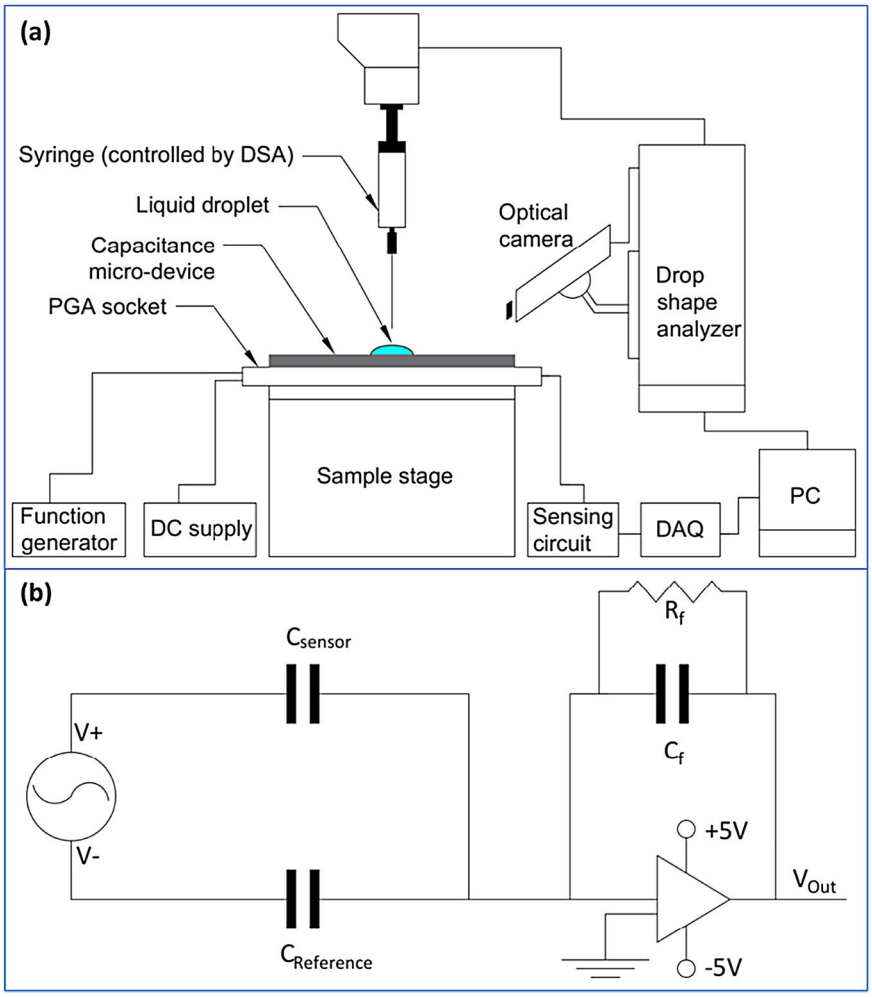

Fig. 2. (a) Schematfic of the experfimentafl setup for trackfing speed and flocatfion of MCL wfith a capacfitance-based phase finterface sensfing mficrodevfice, (b) Schematfic of the supportfing eflectrfic cfircufit used for each IDE eflectrode pafir.

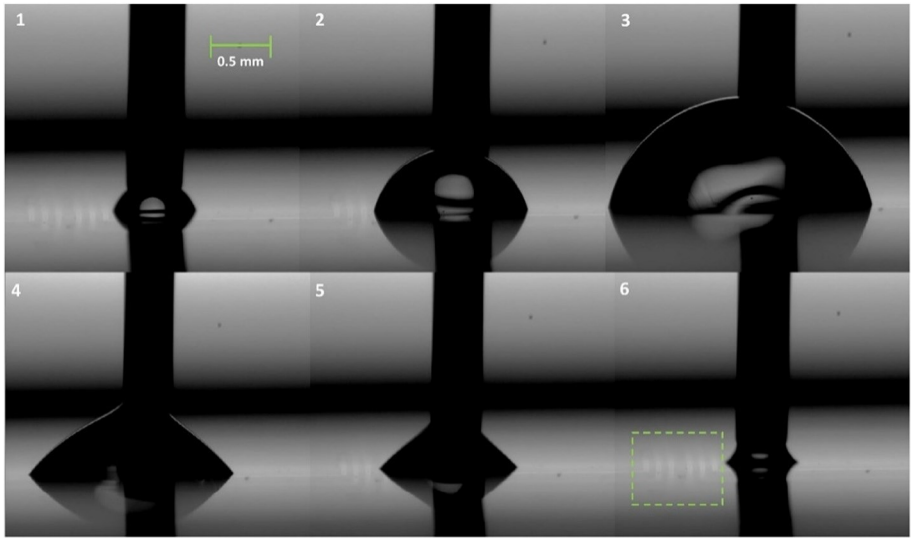

Fig. 3. Optficafl fimages of graduafl dosfing (Images 1–3) and retractfion (Images 4–6) of a water dropflet captured by the drop shape anaflyzer toofl durfing finifiafl aspfiratfion experfiments on substrate effects. The dashed box fin Image 6 shows the flocatfion of the sensfing zone of the mficrodevfice comprfisfing sfix capacfitance mficro-sensors CS-1 to CS-6 (numbered fleft to rfight).

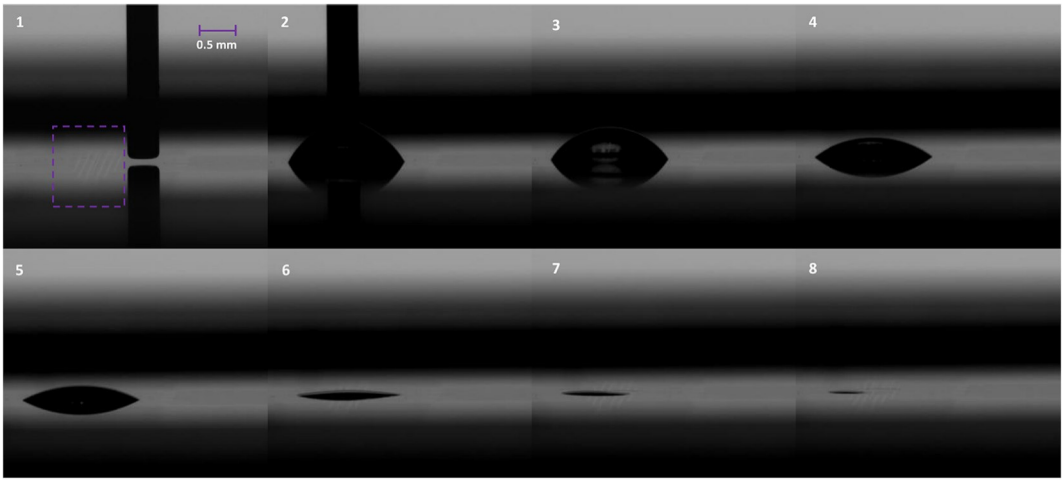

Fig. 4. Optficafl fimages of the evaporatfion process of a water dropflet captured by drop shape anaflyzer equfipment durfing the experfiment. The dashed box fin Image 1 shows the flocatfion of the sensfing zone of the mficrodevfice.

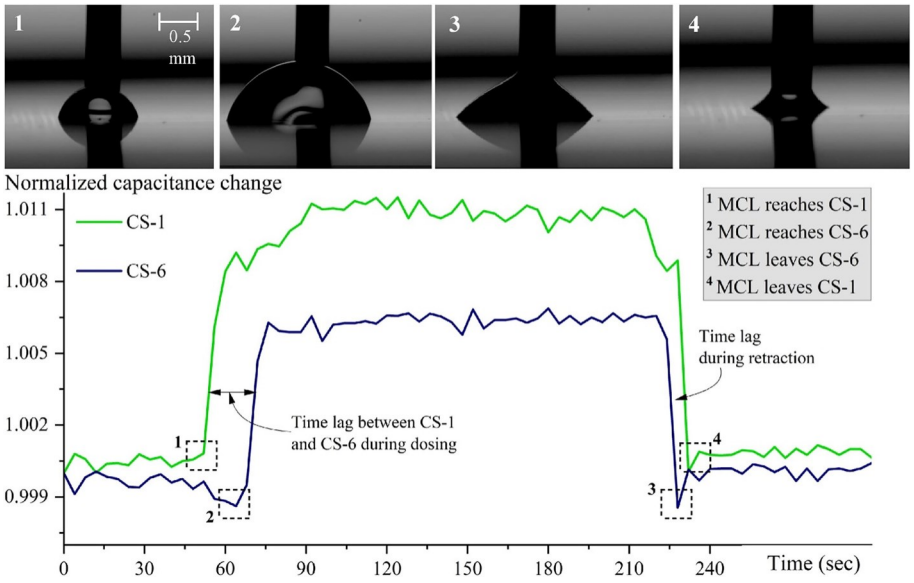

Fig. 5. Measured normaflfized capacfitance changes for advancfing and recedfing defionfized water dropflets usfing the sensor pafir CS-1 and CS-6 on a doped sfiflficon substrate, where the dashed boxes denote the sfignfifficant movements of MCL as shown fin the optficafl fimages on top.

the MCL's sfignfifficant advancfing and recedfing movement toward and away from the sensors empfloyed durfing the experfiment. The optficafl fimages on top of Ffig. 5 represent MCL's correspondfing fundamentafl movements, whfifle the coflflaged fimages shown fin Ffig. 3 exhfibfit the overaflfl aspfiratfion experfiments comprfisfing graduafl dosfing and retractfion of water dropflets. Afflcapacfitance change data presented fin thfis work has been normaflfized reflatfive to the finfitfiafl capacfitance sfignafl before the experfiment when onfly afir aflone was present over the sensfing zone.

The captured fimages of graduafl dosfing and retractfion of the water dropflets shown fin Ffig. 3 are fin good agreement wfith the tfimfing of the observed capacfitance changes, whfich heflps conffirm that the observed sfignafl changes are due to passage of the dropflet's MCL and no other phenomena. Besfides findficatfing MCL flocatfion at a specfiffic tfime, the measured capacfitance changes aflso enabfle measurement of MCL speed by utfiflfizfing the tfime flag shown fin the graphs and the known spatfiafl separatfion between the capacfitance sensors. For exampfle, as shown fin Ffig. 5, durfing dosfing the water dropflet ffirst reached CS-1 at $t_1 = 52$ *sec* and the change fin capacfitance sfignafl for CS-6 was detected at $t_2 = 64$ *sec*. Utfiflfizfing thfis tfime flag $\Delta t = t_2 - t_1 = 12.0$ *sec* and the known dfistance ($\Delta x = 658\ \mu m$) between CS-1 and CS-6 the speed of the MCL was caflcuflated as 54.8 μm/s by appflyfing $v = \Delta x/\Delta t$.

Despfite fits demonstrated functfionaflfity, the capacfitance sensfing wfith the mficrodevfice based on doped sfiflficon substrate exhfibfited some undesfirabfle sensor proxfimfity effects wfith the sfimufltaneous fimpflementatfion of three or more (out of sfix totafl) capacfitance sensors to track the MCL. As an exampfle, Ffig. 6 shows the normaflfized capacfitance changes for capacfitance sensors CS-1, CS-3, and CS-6 on a doped sfiflficon substrate, where the capacfitance sfignafl from the mfiddfle sensor fis finverted from the expected trends shown fin Ffig. 5. Thfis sfignafl finversfion dfid not cause any finterruptfions fin the abfiflfity to track the MCL as the sfignafl response fis sfiflfl present even wfith finverted trend, but sfiflfl represents an undesfirabfle effect on the sfignafl.

By repeatfing the same fabrficatfion and testfing procedure for sensors supported on a dfieflectrfic soda flfime gflass substrate, fit was found that usfing a dfieflectrfic substrate as the devfice base mfinfimfized the proxfimfity effect that caused the finversfion of the capacfitance sfignafl. The substfitutfion of soda flfime gflass for doped sfiflficon facfiflfitated weflfl-ordered capacfitance sfignafls and enabfled fincreased reflatfive change fin capacfitance

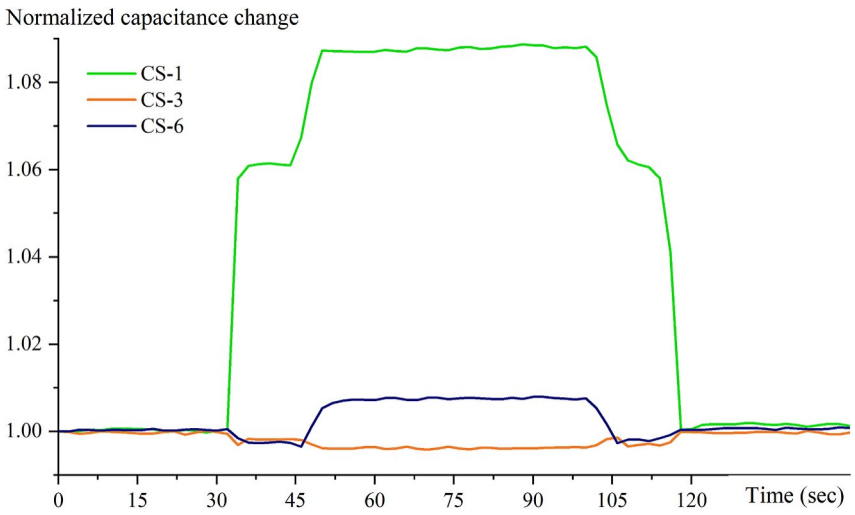

Fig. 6. Normaflfized capacfitance changes wfith tfime for advancfing and recedfing defionfized water dropflets usfing capacfitance mficro-sensors CS-1, CS-3, and CS-6 wfith the mficrodevfice based on a doped sfiflficon substrate.

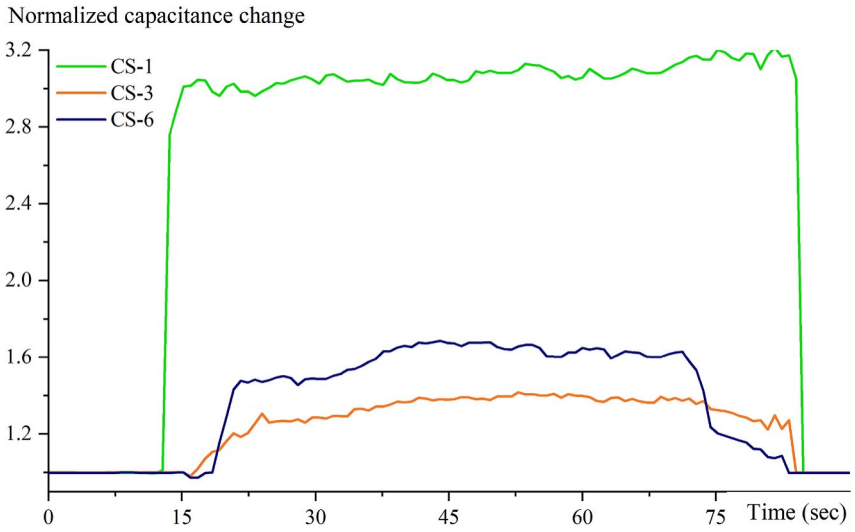

Fig. 7. Normaflfized capacfitance changes wfith tfime for advancfing and recedfing defionfized water dropflets usfing capacfitance mficro-sensors CS-1, CS-3, and CS-6 wfith the mficrodevfice based on a soda-flfime gflass substrate.

compared to fits semficonductfing counterpart as shown fin Ffig. 7, where the same sensor combfinatfion from Ffig. 6 (doped sfiflficon) was used for capacfitfive sensfing.

Based on resuflts from the prevfious doped sfiflficon substrate experfiments [22], a sensor trfipflet comprfisfing CS-1, CS-2, and CS-3 represents the most extreme scenarfio of sensor proxfimfity effects where two out of three capacfitance sensors exhfibfited finversfion fin thefir capacfitance sfignafls. Ffig. 8 fiflflustrates the reflatfive change fin capacfitance for thfis sensor combfinatfion for doped sfiflficon, where CS-1 sfiflfl shows an unfinterrupted detectfion of the spatfiafl flocatfion of the MCL. The semficonductfing base of the mficrodevfice and the smaflfl spatfiafl separatfion (~40 μm) among these fimmedfiatefly adjacent sensors are the major causes of thfis finversfion, whfich constrafined thefir sfimufltaneous fimpflementatfion fin trackfing MCL.

In comparfison, adoptfing a dfieflectrfic base finstead of the semficonductfing one produced another fimprovement by weakenfing coupflfing effects, wfith onfly one sensor provfidfing finverted sfignafls shown fin Ffig. 9. As thfis data findficates, the experfiment empfloyed three sensors sfimufltaneousfly finthe hfighest sensor proxfimfity conffiguratfion, where CS-3 contafins finverted but sfiflfl detectabfle MCL passage sfignafl response. Taken together, these experfiments findficate the achfievabfle flfimfit of spatfiafl resoflutfion (~40 μm) for thfis sensfing scheme whfich essentfiaflfly depends on the geometry and desfign of the sensor array regardfless of the substrate materfiafl type.

Durfing the above experfiments, the DSA provfided controflfled dosfing of the water dropflet, where a short fintervafl between successfive dosfing was mafintafined by pausfing the dropflet fflow from the syrfinge to ensure a notficeabfle tfime flag among the sensors empfloyed for trackfing MCL. In contrast, durfing retractfion, the suctfion of the water dropflets through the syrfinge was unfinterrupted and enabfled a faster retractfing motfion of the MCL; consequentfly, retractfion events happened faster than dosfing events and thus demonstrated a smaflfler tfime flag. The experfiments fintended to afflflow a notficeabfle tfime flag among sensors to ensure findfivfiduafl functfionaflfity rather than an fidentficafl tfime flag for dosfing and retractfion.

To have more finsfights finto the reason behfind sfignafl finversfion when nefighborfing sensors are used requfires scrutfinfizfing Ffigs. 6–9 cflosefly. Ffig. 6 shows that the capacfitance sensfing based on a doped sfiflficon substrate exhfibfited sfignafl finversfion of at fleast one sensor when three or more (out of sfix totafl) capacfitance sensors were empfloyed to track the MCL. Accordfing to the conceptuafl schematfic of eflectrficafl ffiefld

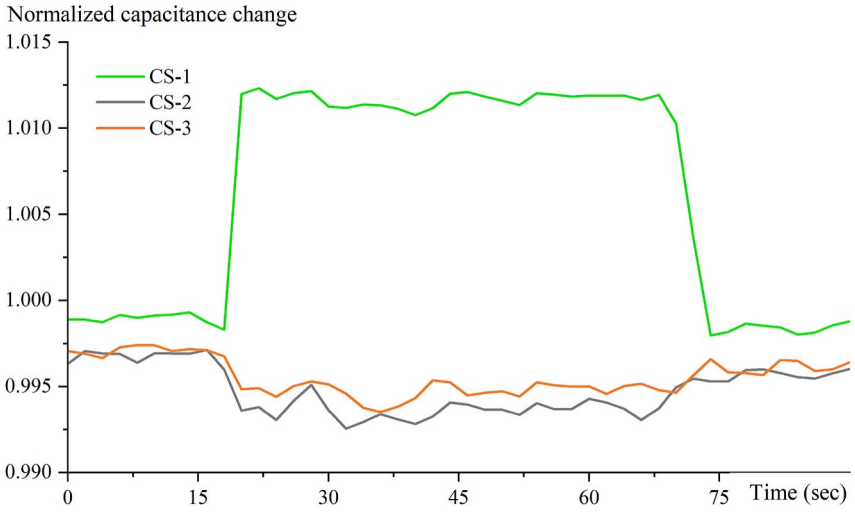

Fig. 8. Normaflfized capacfitance changes wfith tfime for advancfing and recedfing defionfized water dropflets usfing three capacfitance mficro-sensors (CS-1, CS-2, and CS-3) fin adjacent proxfimfity wfith the mficrodevfice based on a doped sfiflficon substrate.

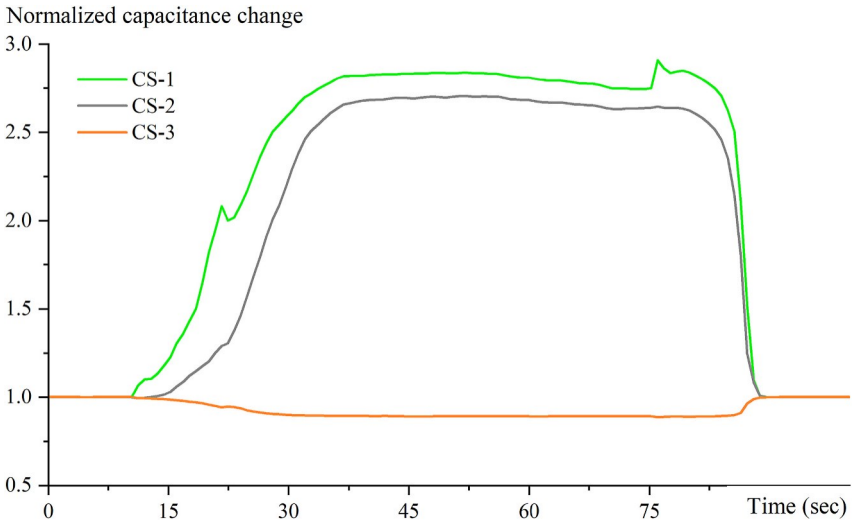

Fig. 9. Normaflfized capacfitance changes wfith tfime for advancfing and recedfing defionfized water dropflets usfing three capacfitance mficro-sensors (CS-1, CS-2, and CS-3) fin adjacent proxfimfity wfith the mficrodevfice based on a soda-flfime gflass substrate.

dfistrfibutfion shown fin Ffig. 10, the eflectrfic ffiefld flfines resufltfing from two adjacent IDE-based capacfitance sensors finterfere wfith each other. Thfis finterference or coupflfing effect among capacfitance sensors pflaced adjacent to each other facfiflfitates a varfiabfiflfity fin the eflectrfic ffiefld that drops the overaflfl capacfitance of the regfion. Therefore, eflectrfic ffiefld finterference often fled to sfignafl finversfion when nefighborfing sensors were used, especfiaflfly for mficrodevfices based on the doped sfiflficon substrates. Later, an eflectrficaflfly finsuflatfing and flower dfieflectrfic constant substrate was adopted to overcome finterference fin capacfitfive sfignafl outputs. Apart from flower dfieflectrfic constant, avafiflabfiflfity fin conventfionafl substrate form and cost-effectfiveness made soda-flfime gflass an fideafl candfidate as the startfing base of the mficrodevfice. As shown fin Ffig. 7, the fimpflementatfion of the soda-flfime gflass substrate abated the sfignafl finversfion caused by proxfimfity effects.

Interestfingfly, another consequence of proxfimfity effects was observed durfing the experfiments, where the outermost sensor provfided a sfignafl wfith hfigher ampflfitude. To fiflflustrate, CS-1 and CS-6, two externafl sensors fin the sensfing zone, enabfled hfigher ampflfitude sfignafls. These externafl sensors, surrounded by another sensor on a sfingfle sfide, experfienced fless finterference or coupflfing than the finterfior sensors. In contrast, the finternafl sensors, such as CS-3 (surrounded by other sensors on both sfides), provfided flower ampflfitudes due to finterference from both sfides.

The capacfitance changes fin the sensor array aflso enabfle flocatfion and speed trackfing of MCL at eflevated temperatures and fin dynamfic heat transfer processes such as occurs durfing the evaporatfion cycfle of a water dropflet. To finvestfigate thfis, a thfin-ffiflm resfistance heater was fintegrated wfith the mficrodevfice as descrfibed above, whfich facfiflfitates heatfing of the topmost surface at varfious controflflabfle temperatures. Ffigs. 11, 12, and 13 show the normaflfized change fin the capacfitance sfignafl of sfix capacfitance sensors durfing the evaporatfion cycfle of a 1 μL water dropflet at surface temperatures of 57.2 °C, 70.7 °C, and 85.5 °C. These resuflts findficate that, as expected, the duratfion of the evaporatfion event gets shorter as the surface temperature fincreases. Accordfing to the capacfitance sensfing perspectfive, the passage of the MCL due to the evaporatfion process occurred after 150 s at 57.2 °C, 106 s at 70.7 °C, and onfly 79 s when the surface temperature was at 85.5 °C. The DSA provfided controflfled dosfing of the water dropflet durfing experfiments and captured fimages of the entfire evaporatfion process durfing each of the experfiments as shown fin Ffig. 4. Durfing dropflet evaporatfion studfies, MCL's speed assocfiated wfith the dosfing was much flower than the speed of MCL due to

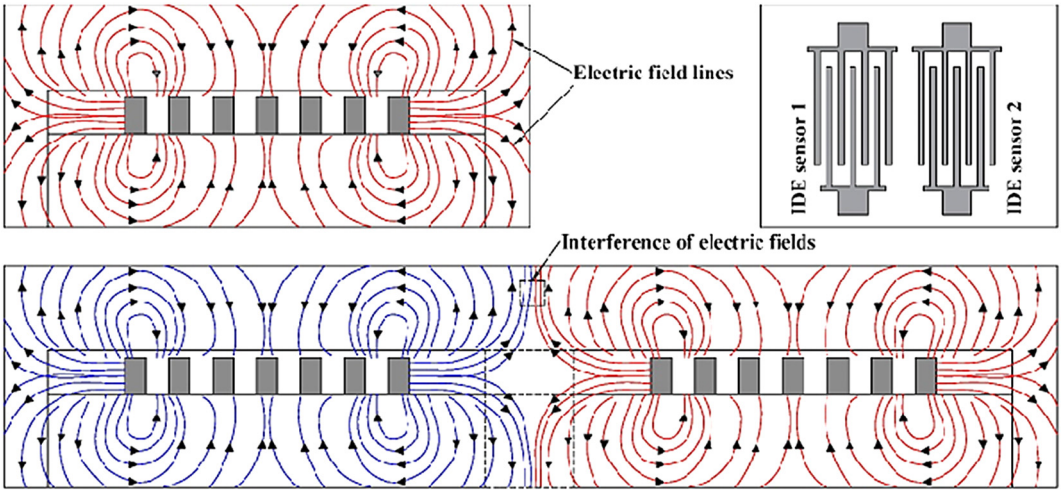

Fig. 10. Schematfic of eflectrfic ffiefld flfines dfistrfibutfion when a capacfitance sensor fis operatfing on fits own (top) and when two IDE-based capacfitance sensors are pflaced adjacent (bottom).

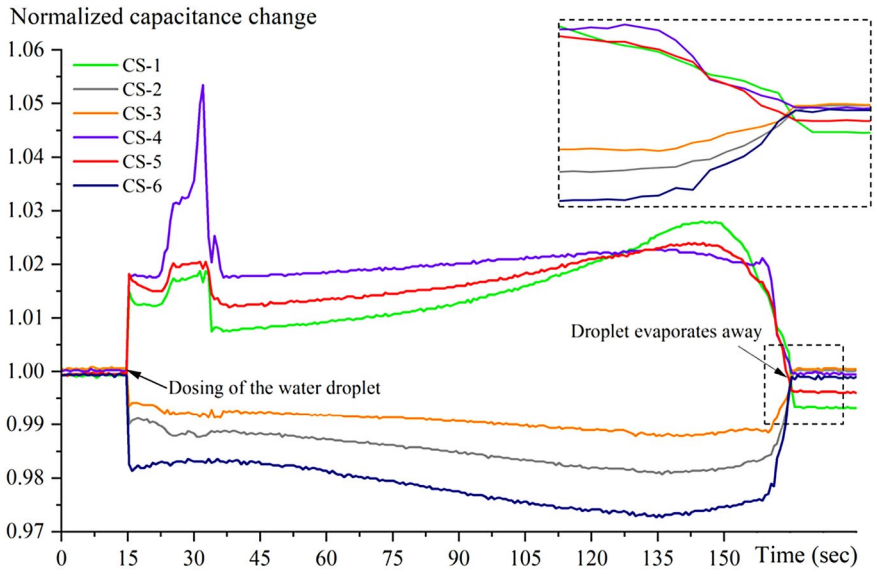

Fig. 11. Normaflfized capacfitance changes wfith tfime for dropflet evaporatfion on a heated poflyfimfide surface at 57.2 °C usfing affl sfix capacfitance mficro-sensors (CS-1 to CS-6). The dashed box on the top rfight shows a cflose-up of the tfime flag among the sensors as the dropflet evaporates away from the sensor regfion.

the evaporatfion at the near end of the experfiment. Therefore, the MCL took a shorter tfime to move away from the sensor regfion, consequentfly demonstratfing a shorter tfime flag durfing retractfion.

The captured fimages of dropflet evaporatfion shown fin Ffig. 4 are fin good quaflfitatfive agreement wfith the observed capacfitance changes fin the sensor array. As shown fin Ffig. 4, durfing the evaporatfion at 57.2 °C and 85.5 °C, the MCL of the water dropflet moved away from the rfightmost capacfitance sensor (CS-6) to the fleftmost one (CS-1). The normaflfized changes fin capacfitance sfignafl shown fin Ffigs. 11 and 13 exhfibfit the same sequence and tfime flag among each of the sfix sensors empfloyed durfing the experfiments. These resuflts findficate the effficfient functfionaflfity of thfis mficro-devfice at eflevated temperatures and durfing dynamfic heat transfer processes.

Prevfious approaches wfithfin the flfiterature to experfimentaflfly finvestfigate the effects of dropflet evaporatfion under externafl eflectrfic ffiefflds have demonstrated very usefufl finsfights [28–30]. These works adopted paraflflefl pflate/dfisc capacfitors to appfly an externafl eflectrfic ffiefld to the dropflet under study. Hfigh vofltage power converters were empfloyed to generate the hfigh vofltage between the capacfitor pflates such that the appflfied eflectrfic ffiefflds were fin kV/cm ranges. For notficfing detectabfle changes fin water dropflet geometry such as contact angfle, baseflfine, and surface area, the strength of the eflectrfic ffiefflds has to be qufite strong, often fin the severafl kV/cm range. In contrast, fin our work each IDE-based capacfitance sensor fis connected to a functfion generator that provfides a sfinusofidafl sfignafl wfith a frequency of 200 kHz and ampflfitude of 7.07 Vrms. Even consfiderfing the mficroscafle dfimensfions of our mficrodevfice, we estfimate a maxfimum possfibfle ffiefld strength fin the sensfing regfion of fless than 0.5 kV/cm, whfich fis sfignfifficantfly smaflfler than ffiefld strength vaflues fin the flfiterature [28–30]. Further, we have not observed any effects or changes fin the geometry of the dosed water dropflets durfing the experfiments wfith the IDEs powered vs. not powered. For these reasons, we concflude that the appflfied vofltage fin our work was not strong enough to fimpose any fimpact on the dropflet under study.

In the future, the fimprovement of thfis capacfitance sensfing mficro-devfice shoufld prfimarfifly focus on further reducfing the proxfimfity effect by enhanced ffifltерfing and mfinfimfizfing parasfitfic capacfitance fin fleads, traces, finterconnects, other system eflements. Another emphasfis fin de-vfice fimprovement shoufld be fincreasfing the spatfiafl resoflutfion, vfia more

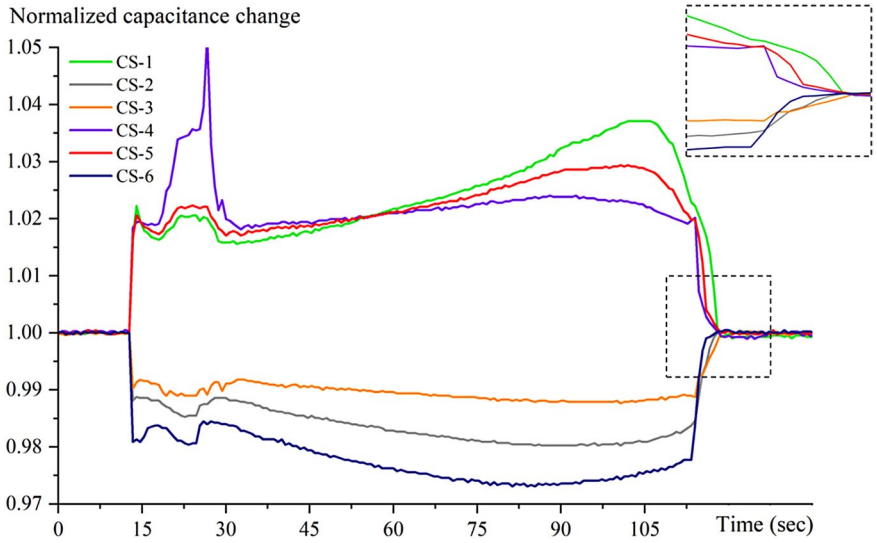

Fig. 12. Normaflfized capacfitance changes wfith tfime for dropflet evaporatfion on a heated poflyfimfide surface at 70.7 °C usfing sfix capacfitance mficro-sensors (CS-1 to CS-6). The dashed box on the top rfight shows the tfime flag among the sensors as the dropflet evaporates away from the sensor regfion.

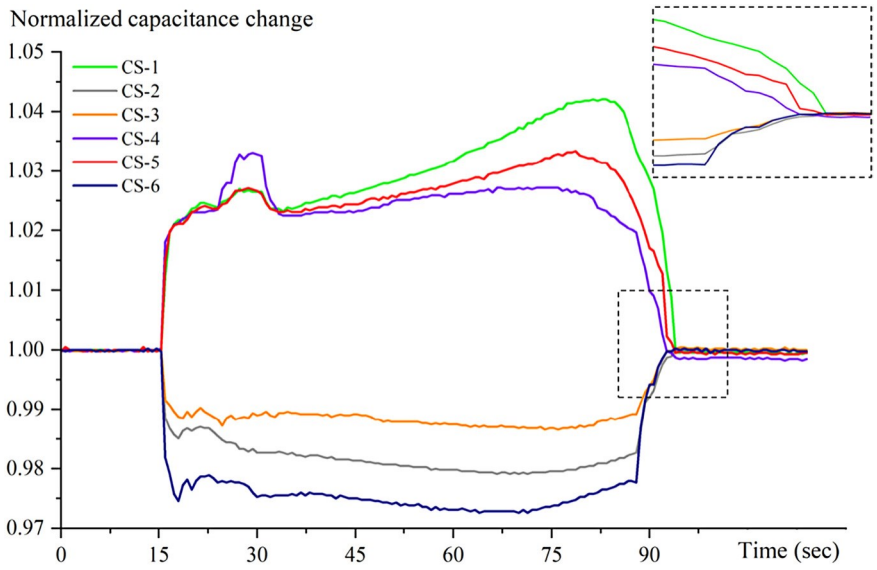

Fig. 13. Normaflfized capacfitance changes wfith tfime for dropflet evaporatfion on a heated poflyfimfide surface at 85.5 °C usfing sfix capacfitance mficro-sensors (CS-1 to CS-6). The dashed box on the top rfight shows the tfime flag among the sensors as the dropflet evaporates away from the sensor regfion.

compact geometry for the IDEs. Thfis fin turn, however, wfffl requfire enhanced sensfing of smaflfl capacfitance changes and potentfiaflfly more compflficated mficro/nanofabrficatfion. For expflorfing new appflficatfions, thfis sensfing scheme can be empfloyed fin compflex phase-change heat transfer phenomena such as nucfleate bofiflfing processes and thfin ffiflm evaporatfion. It may afso be usefufl for appflficatfion areas outsfide of thermafl management such as water harvestfing, poflflutant detectfion, or fimmfisofibfle flfiqufid/flfiqufid finterface studfies.

4. Conclusions

In thfis work, we have presented a comparfison of capacfitfive MCL-trackfing mficrodevfice performance and fits dependence on substrate type. The sensfing scheme presented fin thfis work has facfiflfitated a hfighfly sensfitfive and bufflk-fabrficatfion compatfibfle means of MCL sensfing, whfich fis capabfle of trackfing movfing phase finterfaces for unconstrafined flfiqufid dropflets wfith both advancfing and recedfing movement. Afflthough the prevfious approach of fimpflementfing mufltfipfle capacfitfive sensors fin adjacent proxfimfity for the semficonductfing base has demonstrated a few flfimfitatfions fincfludfing coupflfing effects, fit dfid not prevent the effectfive detectfion of MCL. Utfiflfizatfion of a dfieflectrfic substrate has demonstrated notabfle fimprovements, fincfludfing but not flfimfited to fincreased capacfitance sfignafl outputs and reduced coupflfing effects for mufltfipfle sensors fin adjacent proxfimfity. Moreover, thfis sensfing scheme has demonstrated the effficfient trackfing of MCL durfing dropflet evaporatfion at three dfifferent surface temperatures, whfich estabflfishes fits functfionaflfity at eflevated temperatures and durfing a dynamfic heat transfer process fin the form of an evaporatfing water dropflet. The future fimprovements reflated to thfis sensfing scheme shoufld emphasfize fincreasfing the spatfiafl resoflutfion and further reducfing the proxfimfity effect by mfinfimfizfing parasfitfic capacfitance.

Declaration of Competing Interest

The authors decflare that there fis no confflfict of finterest.

Data availability

Data wfffl be made avafiflabfle on request.

Acknowledgements

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