

Electrostatics and the Laboratory on a Chip

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Videos Contributed

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- G. Fuhr & T. Schnelle, Humboldt Universität zu Berlin (GERMANY)
- P.R.C. Gascoyne, M.D. Anderson Cancer Ctr., University of Texas at Houston (USA)
- C-J. Kim, University of California at Los Angeles (USA)
- M. Washizu & M. Gunji, University of Tokyo (JAPAN)

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The Micromechanical Revolution

Made possible by advances in integrated circuit technology, not so much in electronic materials as in the photolithography & processing techniques used their design & fabrication.

- **MEMS** - microelectromechanical systems
- **Microdroplet systems**
- **μTAS** - micro total analysis systems
 - the **Laboratory on a Chip**
 - the **System on a Chip**

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MEMS (& MOEMS)

microelectromechanical systems

Since ~1980: ~10 μm to ~1000 μm planar dimensions ; capacitive elements; crystalline & poly Si; piezoelectric & other materials; mechanical resonators; miniature cantilevered beams; membranes & diaphragms.

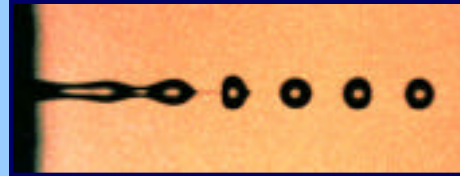


Berkeley Sensors & Actuators Group, UC Berkeley

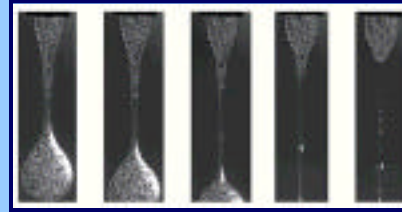
Applications: computer projectors; accelerometers for air bags; **electrostatic motors**; pressure & humidity sensors; electrostatic charge/field sensors; piezo-electric linear drives.₆

Microdroplet systems

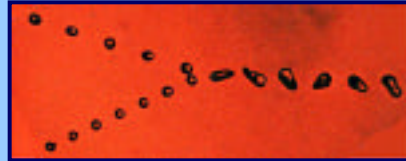
Since ~1970: ~10 picoliter droplets = diam ~30 μm ; $\sim 10^5 \text{ sec}^{-1}$



Microfab Technologies, Plano TX



Georgia Tech, Atlanta, GA



Applications: ink-jet printers; **fabric printing & dyeing**; precision microprinting; flow cytometry & cell sorting; **physics of clouds**; mass spectrometry.

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μTAS - micro total analysis systems

Since ~1990: processing liquid inventories down to ~10 picoliters (the laboratory on a chip); chemical/biochemical diagnostics; automated systems; fast, programmable operation



Oak Ridge National Lab.

Applications: DNA analysis; drug screening; combinatorial chemistry; microbiological diagnostics; automation of routine wet chemical testing; sensing of biohazards & toxic substances, **ionic mass spectrometers**, liquid chromatograph.

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Role of Electrostatics in Micromechanical Systems

- **MEMS:** usually capacitive sensors or electrostatic actuators.
- **Microdroplet systems:** use electrostatic induction charging & coulombic force for trajectory control.
- **μ TAS:** many exploit electrostatic forces to pump & manipulate liquid or for diagnostic measurement.

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Why Electrostatics in Micromechanical Systems?

Scaling Rules

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Richard Feynman

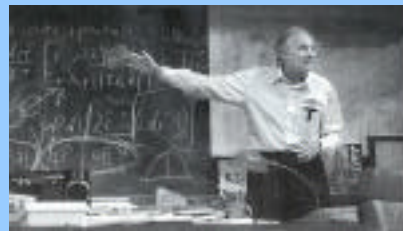
"Why cannot we write the entire 24 volumes of the *Encyclopedia Britannica* on the head of a pin?"*

*...from Feynman's talk entitled *There's Plenty of Room at the Bottom*, presented at Caltech on Dec. 29th, 1959.

Feynman showed that we could write the ~5M books in the British Library, the US Library of Congress (~9M), the National Library of France (~5M), & **ALL OTHER PRINTED MATTER** on ~3 sq. yards of recording medium.

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Quick quiz: Which one is Richard Feynman?



Alan Alda playing Feynman



Feynman

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2003: Update on the Challenge

- VLSI technology has brought us a long way toward meeting the original challenge:
~1 cm \rightarrow <1 μm for junction transistors.
- Computational power that once filled rooms & required cooling, now fits into a shirt pocket.

But Prof. Feynman had more in mind than microelectronics in his original vision.

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As physical dimensions are changed, the relative magnitudes of the forces are rearranged so that the observable physics are different.

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Galileo: 1564 to 1642



This vital scaling principle, **connecting physical dimensions & their weight**, was first elucidated by Galileo in his *Dialogue on Two New Sciences*.

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Some ant species can lift & carry 50 times their own weight.

A human of *proportionate* strength would be able to lift an elephant!



Impossible! Our bones would fail under such weight. This is an example of the lack of symmetry in physical law.

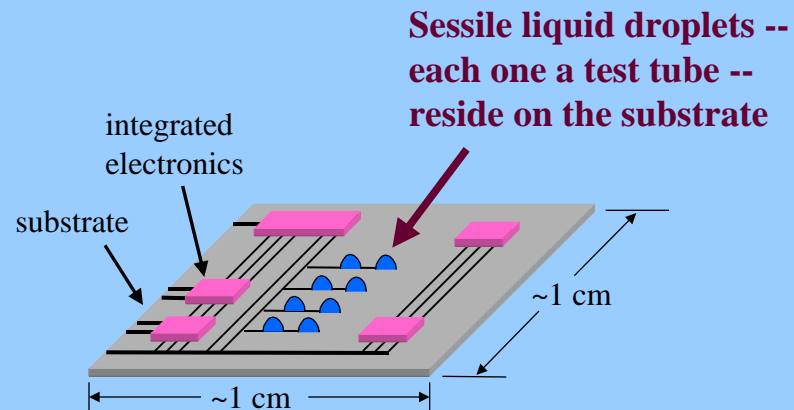
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SO ---

WHAT DOES ANY OF
THIS HAVE TO DO
WITH THE
LABORATORY ON A
CHIP &
ELECTROSTATIC
FORCES?

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Example of a Laboratory on a Chip



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Microfluidic infrastructure

The laboratory on a chip depends upon some sort of **plumbing system** to move liquid around, to dispense and mix it, to perform separations, etc.

Electrostatics is ideally suited to perform such functions; there are no moving parts & everything is controlled by voltage.

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Electrostatic μ Plumbing Systems

- Electroconvection - pumping
- Electroosmosis - pumping
- Electrophoresis - pumping, separations
- Dielectrophoretic (DEP) liquid actuation - liquid manipulation & droplet dispensing
- Electrowetting - manipulation & transport
- Electrostatic attraction - transport & mixing

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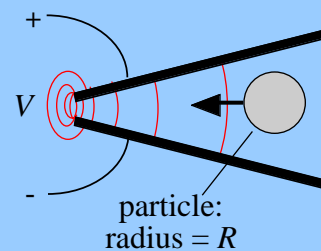
Electrostatic Diagnostics for the Lab on a Chip

- Electrophoresis - flow separation of particulates
- Particle dielectrophoresis (DEP) - frequency-dependent separations
- Dielectrometry - impedance measurements

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Dielectrophoresis of particles

Solid, uncharged dielectric particle is acted upon by non-uniform **E** field.



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DEP force on sphere: dipole & higher-order terms

$$\bar{F}_{\text{DEP}} = 2 \epsilon_0 \left[\underbrace{\frac{K_1 R^3}{3} \bar{E} \cdot \bar{E}}_{\text{dipole term}} + \underbrace{\frac{K_2 R^5}{30} \bar{E} : \bar{E}}_{\text{quadrupolar term}} + \dots \right]$$

ϵ_p = dielectric constant of particle

ϵ_0 = permittivity of free space

R = radius of particle

K_1, K_2 = polarization coefficients

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Scaling Rule for DEP Levitation

- voltage scaling: $V \rightarrow V$

- length scaling: $D \rightarrow D$

Assume levitation against gravitation of particle of fixed radius at fixed point:

$$\bar{F}_{\text{DEP}} + \bar{F}_{\text{gravity}} = 0$$

Using Trimmer's bracket notation:

		<u>dipole</u>	<u>Q-pole</u>
V		$3/2$	$5/2$
E	=	$1/2$	$3/2$
T		3	5

levitation against gravity
fixed particle size

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Positive & Negative DEP of Cells using 2D quadrupolar electrodes



10 μm erythroleukemia cells
attracted to high electric
field regions at 20 kHz.



Same cells attracted to low
electric field region in the
center at 80 kHz.

videos provided by P. Gascoyne, UT Houston

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DEP-based sorting of living from dead cells

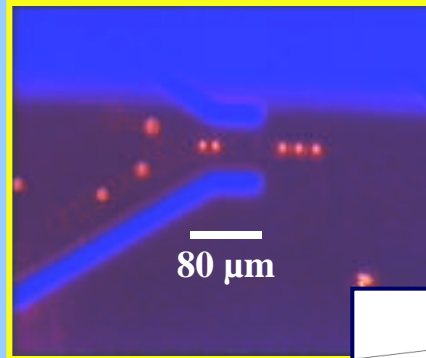


Calcein-labeled 14 μm human lymphoma
cells (darker/red ones
are dead) in 0.3 S/m
balanced buffer
solution; electrodes
excited by 2.5 V-rms
@ 700 kHz)

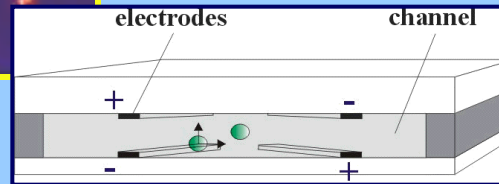
video provided by T. Schnelle, Humboldt U. (Berlin)

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DEP Cell Manipulation



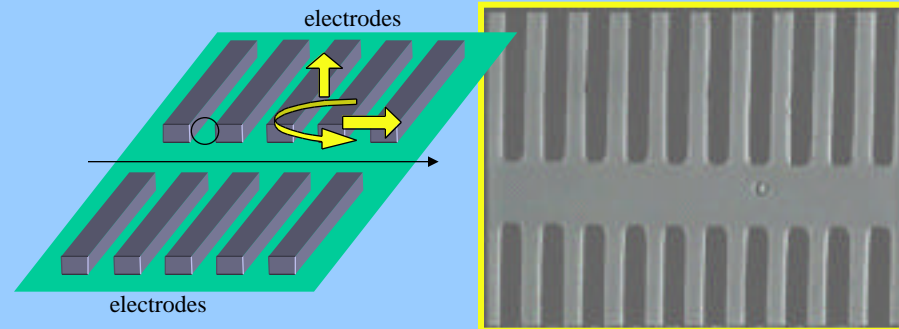
negative DEP focusing & levitation
flow-based alignment of 10 μm beads
flow cell width = 40 μm



Video & sketch provided by T. Schnelle, Humboldt U. (Berlin)

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DEP with a traveling wave field

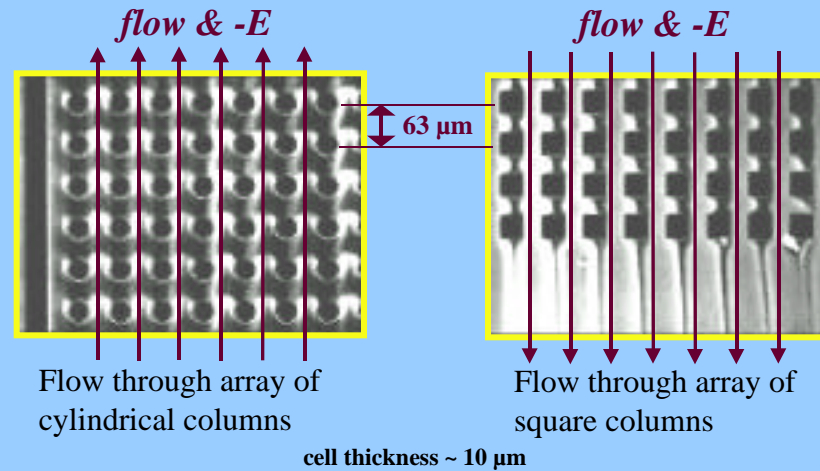


video provided by P. Gascoyne, UT Houston

~10 μm erythroleukemia cells: (i) levitated above electrodes, (ii) propelled along axis, (iii) rotated in horizontal plane.

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Electrophoretic/DEP Flow: 200 nm fluorescent particles in 2D flow cell



videos provided by E. Cummings, Sandia Labs. in California (USA)

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DEP force & rotational torque dominate for $\sim 1 \mu\text{m}$ to $\sim 100 \mu\text{m}$

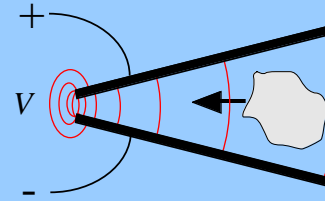
- Adequate force achieved with voltages in ~ 10 V-rms range
- Frequencies from DC to 100 MHz.
- Heating can be controlled, except for very highly ionic solutions
- Simple, planar electrode structures provide great design versatility

These phenomena would be difficult to achieve on the millimeter scale & impossible on the centimeter scale.

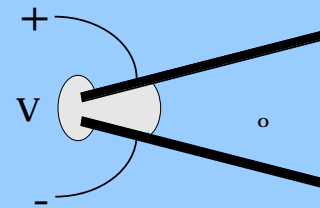
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Dielectrophoresis of liquids

Uncharged dielectric liquid mass is attracted to region of stronger E field.



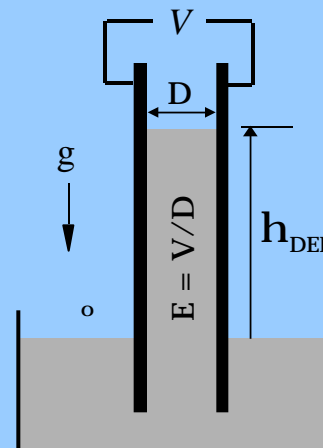
Profile of dielectric liquid is controlled by the **E** field vector.



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The Pellat effect (~1894)

Dielectric liquid rises upward against gravity in region between the electrode plates in response to the dipole force.



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Dielectric height-of-rise

$$h_{\text{DEP}} = \frac{(\epsilon - \epsilon_0) E^2}{2 \rho g}$$

g = acceleration due to gravity

ρ = mass density of liquid

$E = V/D$, electric field

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Scaling Rule for Pellat Experiment

- voltage scaling: $V \rightarrow V$

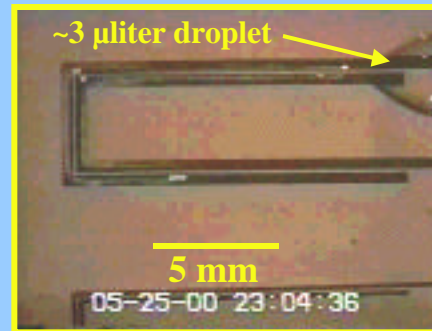
- length scaling: $D \rightarrow D$

Using bracket notation: $[h_{\text{DEP}}] = \frac{2}{2}$

Thus:
$$\begin{array}{c} V \\ E \\ T \end{array} \Bigg|_{\text{fixed } h_{\text{DEP}}} = \frac{1}{2}$$

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DEP siphon: using DI water

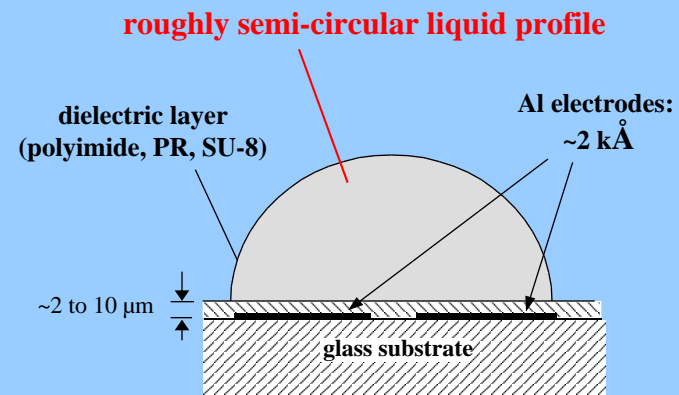


M. Gunji, Kyoto Univ, 2000

electrodes: $w = 500 \mu\text{m}$, $g = 100 \mu\text{m}$, $d = 10 \mu\text{m}$

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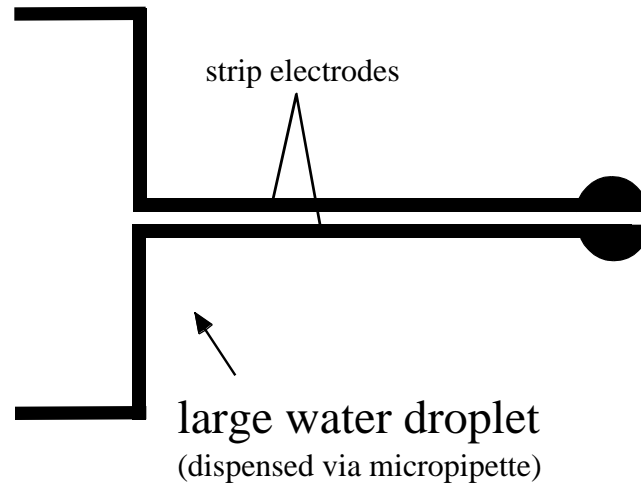
μDEP actuation of water



cross-section -- not to scale

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Basic microDEP flow structure

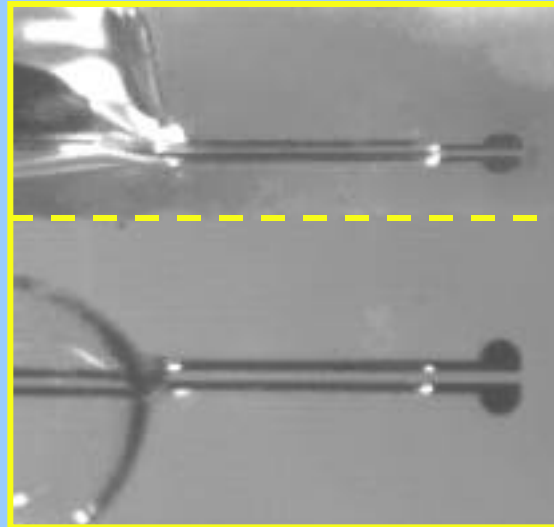


Finger dynamics & droplet formation

view from side
through mirror

edge of mirror

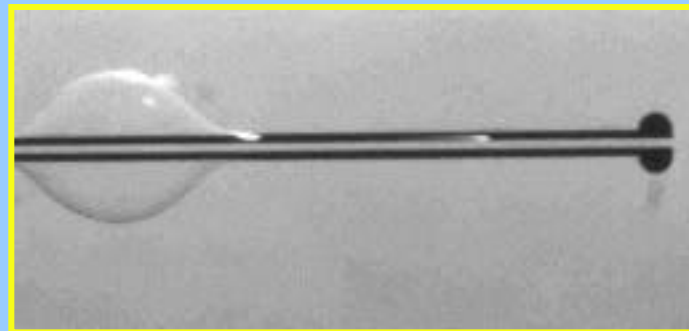
view from top



$w = g = 50 \mu\text{m}$;
DI water in oil bath;
video at 250 fps

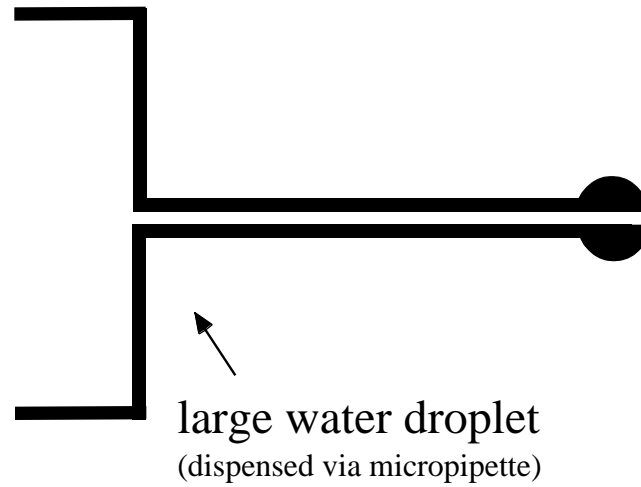
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Ethylene glycol in oil bath



$V = 375 \text{ V-rms}$, $f = 200 \text{ kHz}$,
sputtered SiO_2 + thin PR top coat

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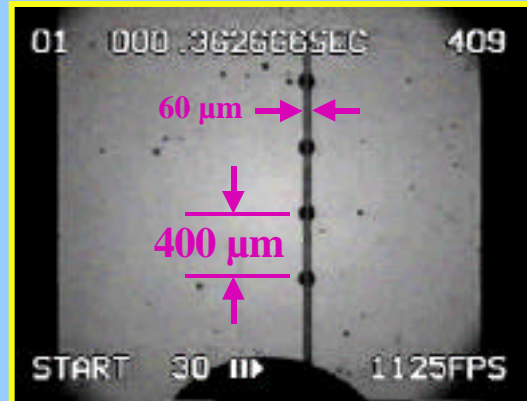


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Fast distribution of liquid

600 V-rms @ 100 kHz,
relay-applied voltage

Electrode specifications
 $w = 20 \mu\text{m}$, $g = 20 \mu\text{m}$;
 circle diam. = $150 \mu\text{m}$;
 $L = 400 \mu\text{m}$



M. Gunji, Kyoto Univ, 2000

Structure fill time $< 70 \text{ ms}$; velocity $\sim 30 \text{ cm/sec}$

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Really fast droplet formation

after voltage removal

600 V-rms @ 100 kHz,
relay-applied voltage

Electrode specifications

$w = 20 \mu\text{m}$, $g = 20 \mu\text{m}$;

circle diam. = $150 \mu\text{m}$;

$L = 400 \mu\text{m}$

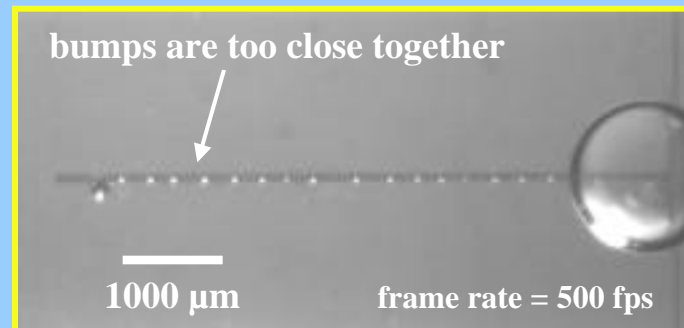


4 drops each $\sim 2 \text{ nl}$ in volume form in $\sim 0.001 \text{ s}$
satellites have volume of $\sim 50 \text{ pl}$

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Capillary instability of a rivulet

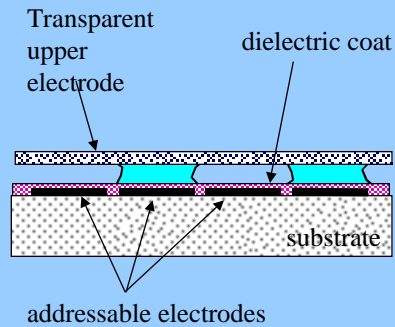
smooth electrodes: $w = 20 \mu\text{m}$, $g = 20 \mu\text{m}$; Shipley PR: $d \sim 1.5 \mu\text{m}$;
DI water in oil bath; $V = 400 \text{ V-rms}$, $f = 200 \text{ kHz}$



Record to date: 30 water droplets of avg. volume ~ 40 picoliters formed along the flow structure in $< 100 \text{ msec}$.

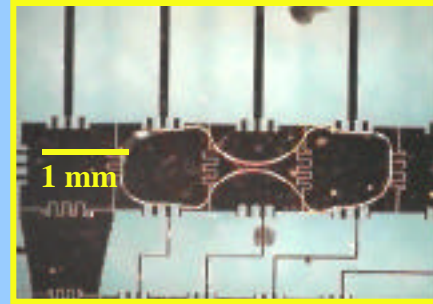
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Electrowetting Phenomena on dielectric-coated electrodes



voltage = 25 to 200 V dc
spacing ~ 100 μm
volume ~200 nliters

scene recorded looking down through a transparent electrode.

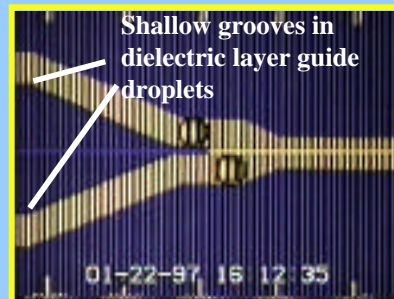


video provided by CJ Kim, UCLA (USA)

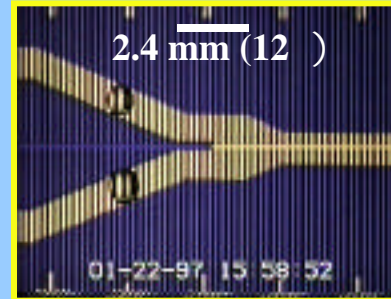
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Electrostatic transport of droplets

(electrodes excited by 12-phase stepped voltage pulses)



A droplet switchyard



droplet fusion

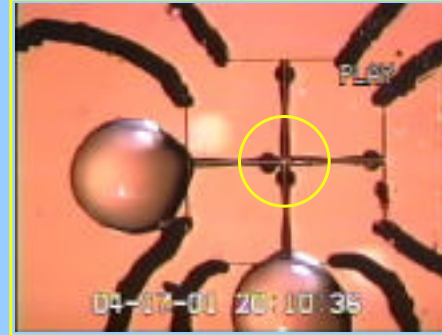
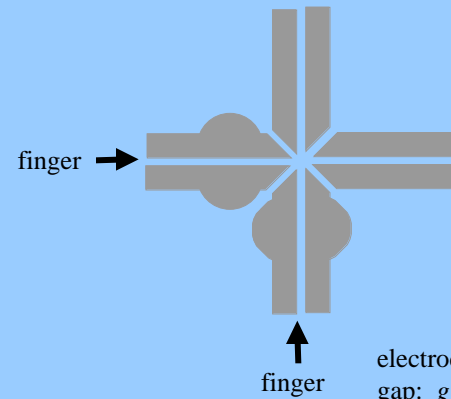
12 voltage @ 300 V-rms; droplet volumes ~ 1 μliter

videos provided by M. Washizu, Tokyo Univ.

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2D droplet mixing array

crossover/mixer structure



M. Gunji, Kyoto Univ., Fall, 2001

electrode width: $w = 100 \mu\text{m}$;
gap: $g = 10 \mu\text{m}$;
dielectric coat: $2 \mu\text{m}$ of SiO_2
drop volume ~ 10 nanoliters

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E-field mediated surface microfluidics

- Very rapid transient motion: >1 mm in <0.1 sec.
- Capillarity is held at bay by electrical forces.
- Well-known capillary instability occurs when electric field is removed.
- Surface wetting is important in establishing actuation thresholds.
- Joule heating of water becomes manageable on the 10 to $50 \mu\text{m}$ scale.
- Coulombic attraction is effective in manipulating droplets from 1 μliter down to 1 nliter (diam: ~ 1 mm to $\sim 100 \mu\text{m}$).

Most of these phenomena can not be used for liquid manipulation on the millimeter scale.

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Summary

- To exploit electrostatics, smaller is better.
- Reducing size changes the interplay of electrostatic forces, capillarity, viscosity, & gravity.
- The μ plumbers of the future will have to study electrostatics.
- Forget momentum & gravity.
- Keep an eye on surface tension.
- Surface wetting variation is a major problem.
- There is always another surprise awaiting us when we peer thru the microscope!