Additive Manufacturing – Module 11

Spring 2015

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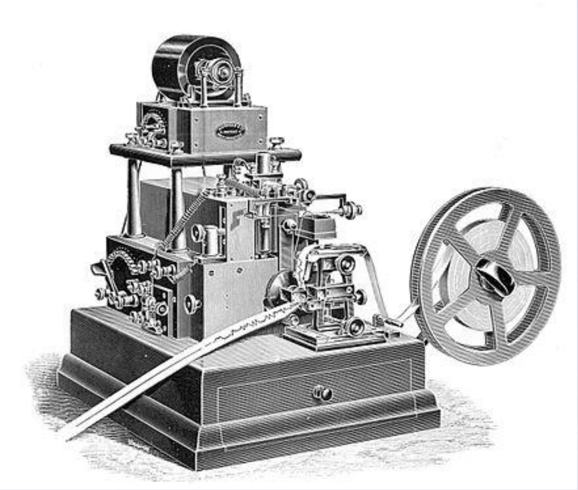
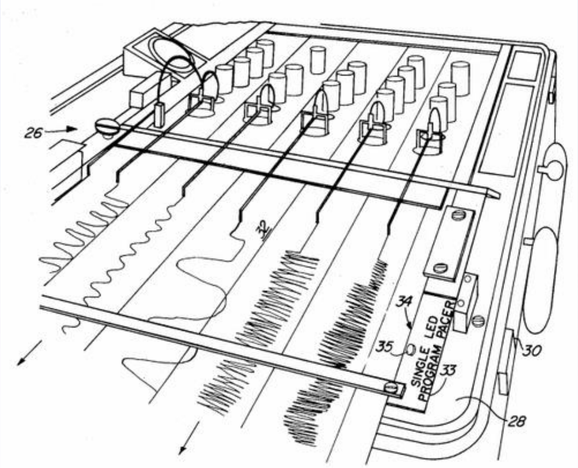
Inkjet Deposition

History

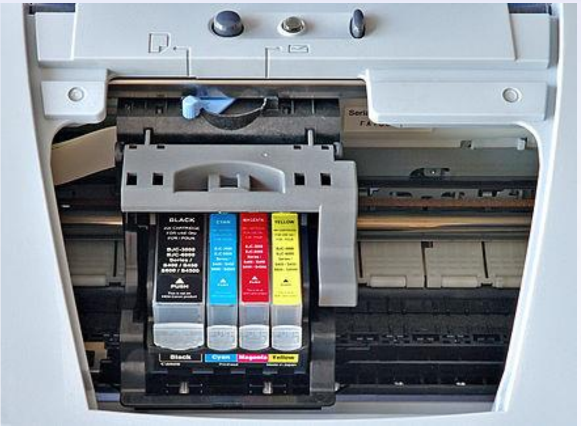
Syringe



1867 Lord Kelvin: Syphon recorder
Continuous inkjet



1951: Chart recorder -- Siemens
Continuous inkjet



1970s: Desktop printer
DOD inkjet

1990s: 3D printer
DOD inkjet

Inkjet
- Overview
- Complexity
- Printhead
- Falling
- Deposition
- Drying

Inkjet Deposition

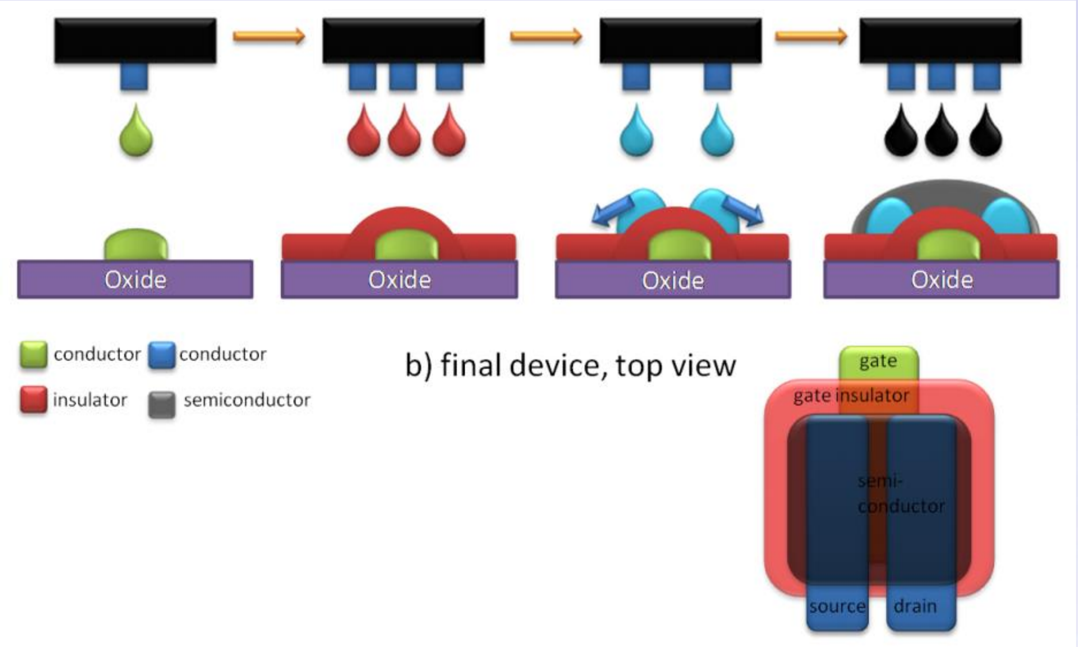
Commercial Engagement

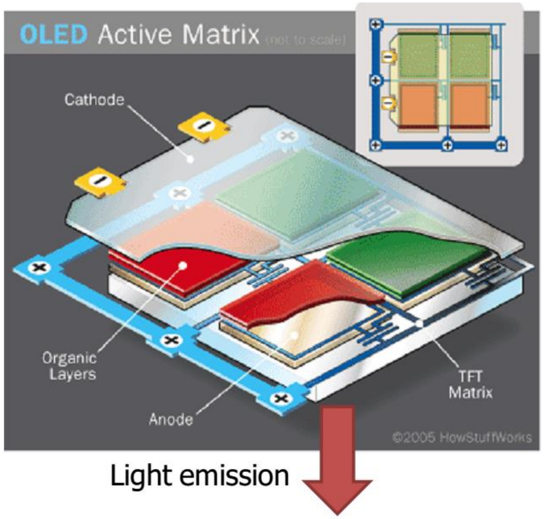
Canon
IBM
SHARP
hp
brother
EPSON
LEXMARK
Passion for printing ideas.
HSG IMIT
Kodak
3M
HITACHI
Hitachi Koki Imaging Solutions, Inc.
XAAR
DUPONT
Tektronix
SIM
AstraZeneca
International
Packard
A Packard BioScience Company
olivetti
Agilent
THE DOCUMENT COMPANY
XEROX
ExxonMobil

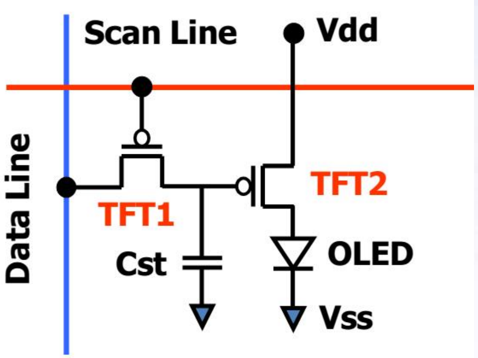
Credit: Microfluidics - Jens Ducrée

Inkjet Deposition

Applications

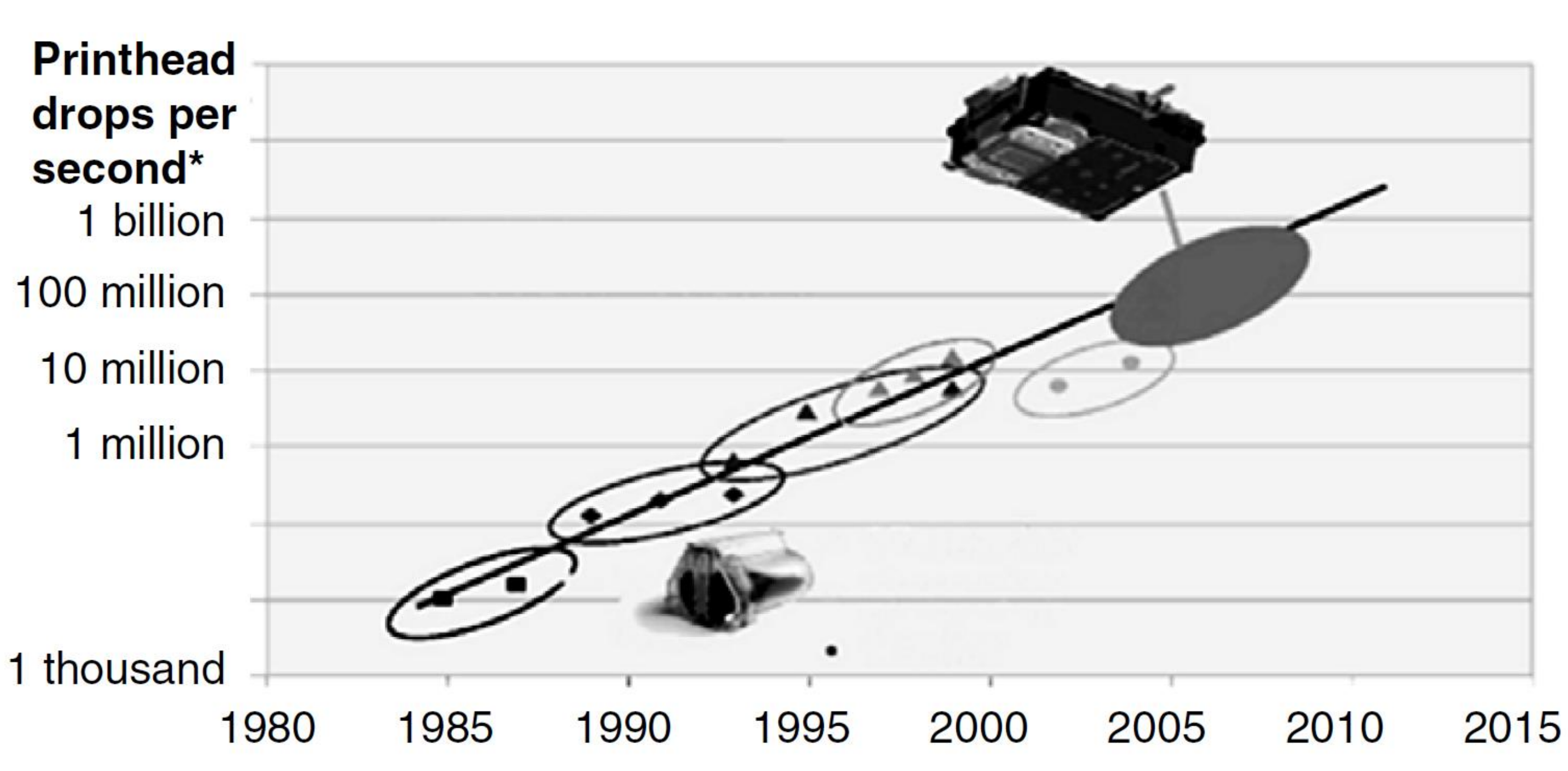






Tseng, Huai-Yuan. "Scaling of Inkjet-Printed Transistors using Novel Printing Techniques." (2011).

HP Moore’s Law



HP Moore's law: inkjet printhead performance as printhead drops per second (the number of nozzles times the maximum drop-on-demand frequency) doubles every 18 months for the past 20 years.

Wijshoff, Herman. "The dynamics of the piezo inkjet printhead operation."*Physics reports* 491.4 (2010): 77-177.

Inkjet Deposition

- Inkjet
  - Overview
  - Complexity
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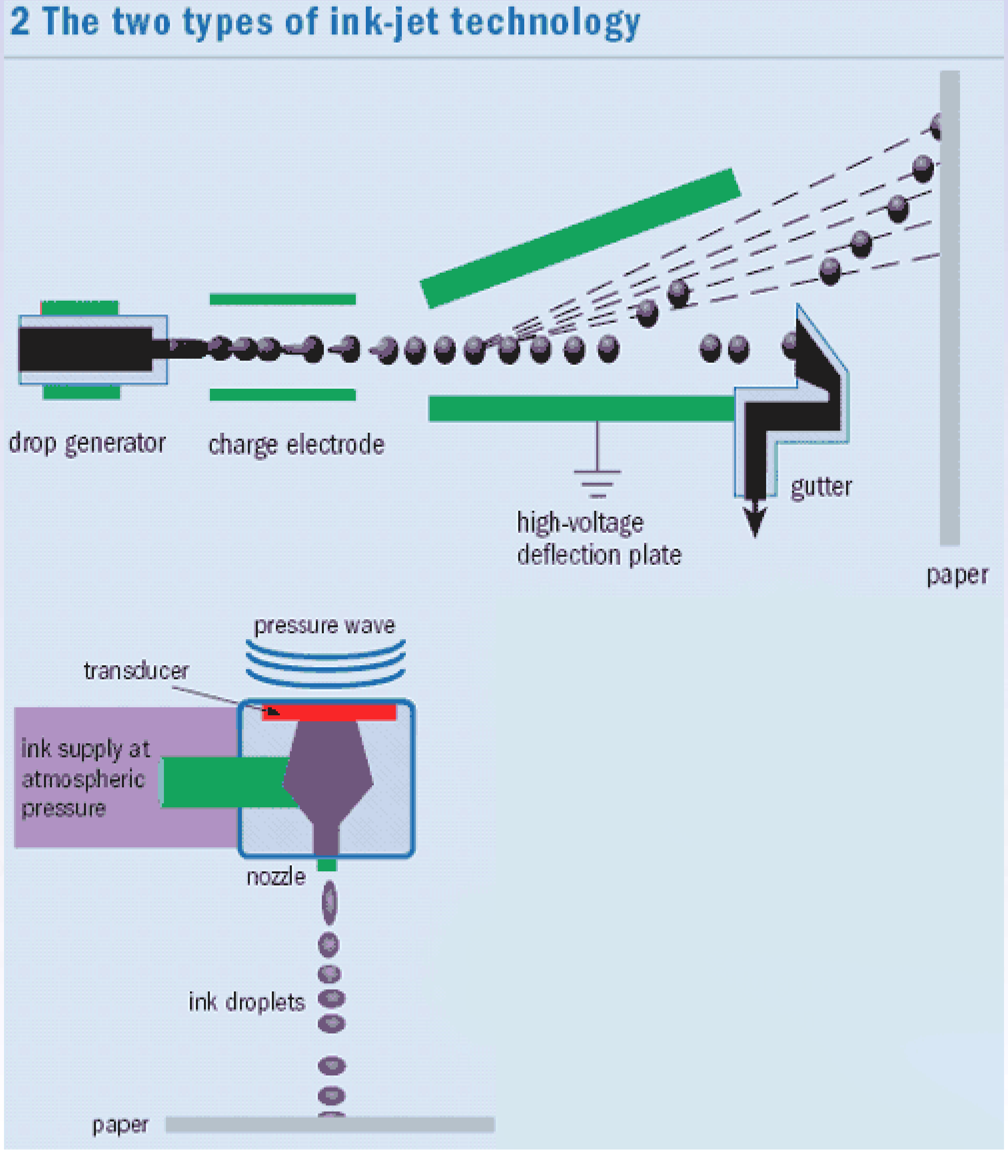
  - Drying

Types of inkjet



Inkjet Deposition

Complexities – Jetting

Inkjet
Overview
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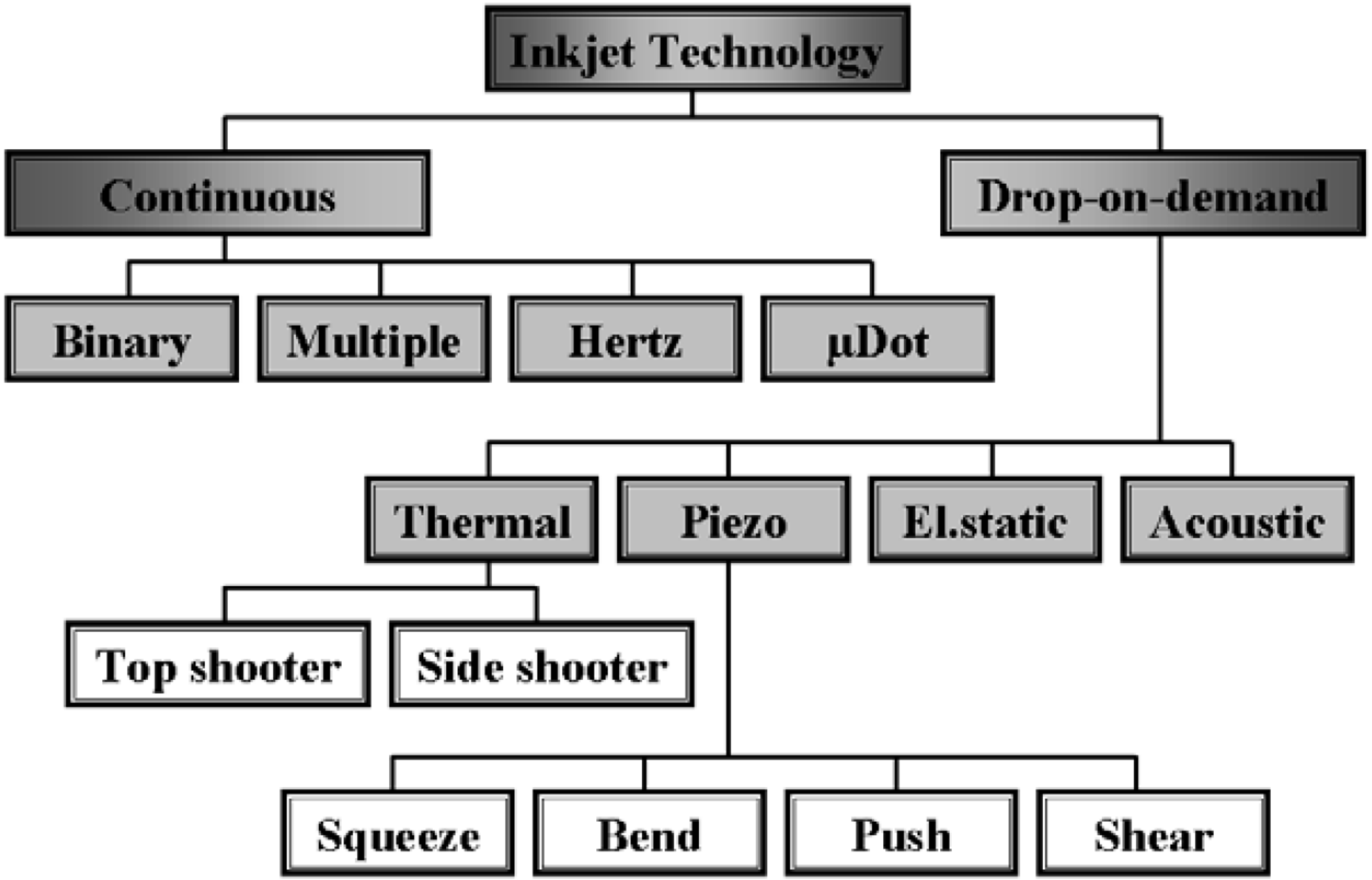
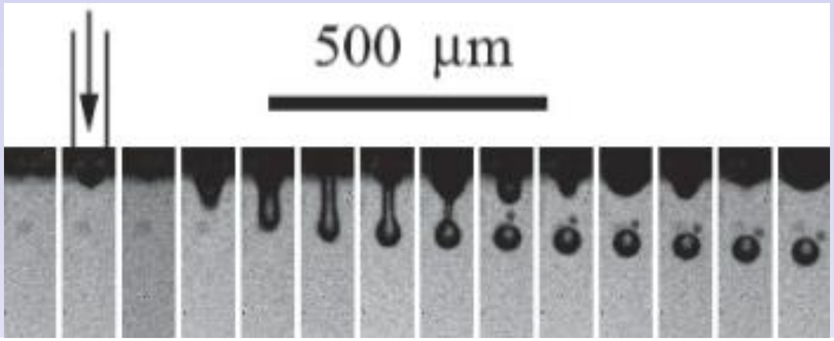
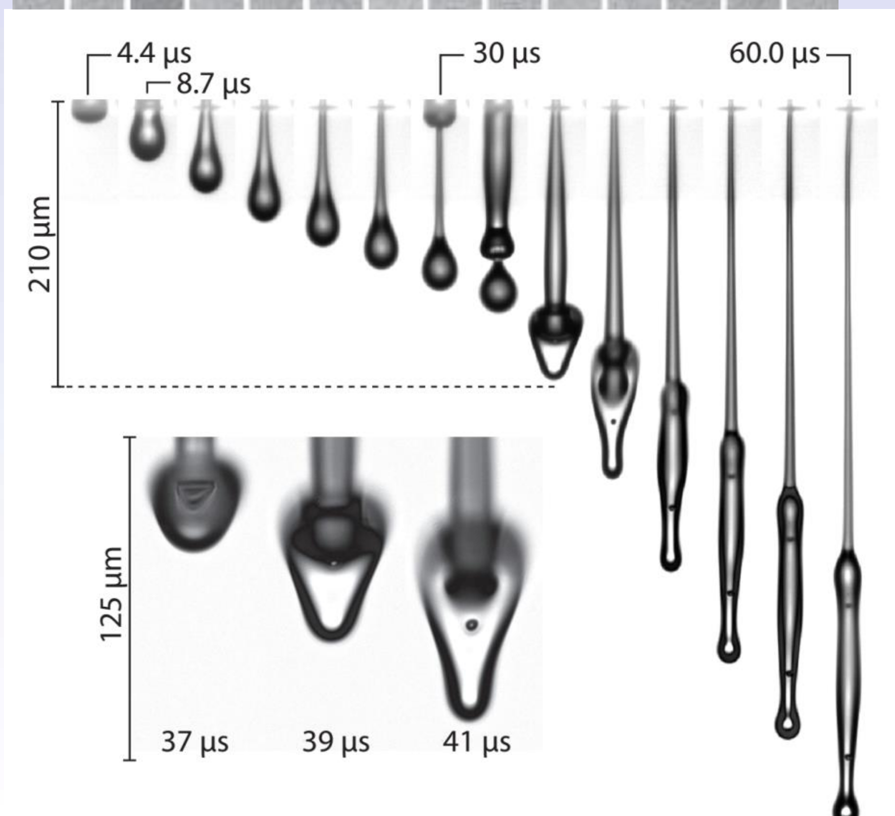


Wijshoff, Herman. "The dynamics of the piezo inkjet printhead operation." *Physics reports* 491.4 (2010): 77-177.

Inkjet Deposition

Complexities – Drop Formation



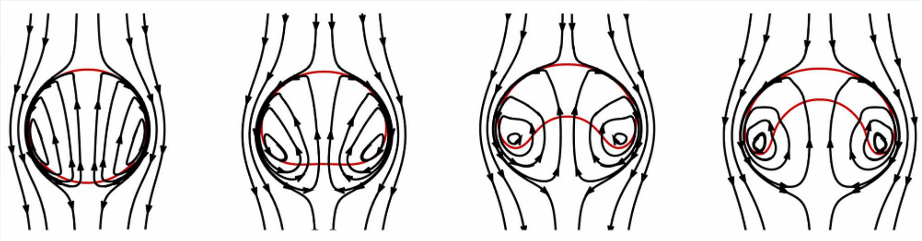


Wij…)10): 77-177.

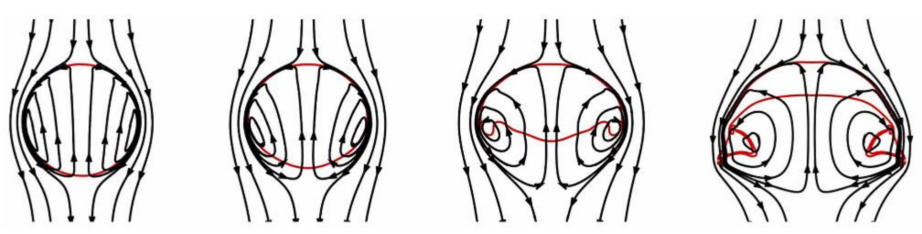
Inkjet Deposition

Complexities – Falling

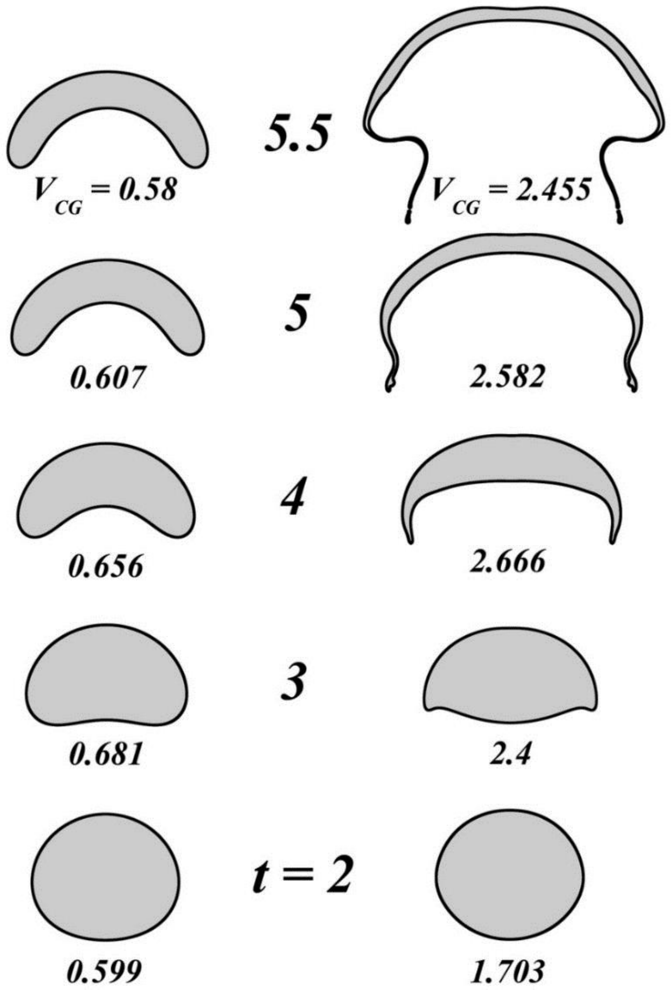
Falling droplets



Streamlines in the vicinity of a bubble. The shape of the bubble is plotted in red.



Streamlines in the vicinity of a drop The shape of the drop is plotted in red.

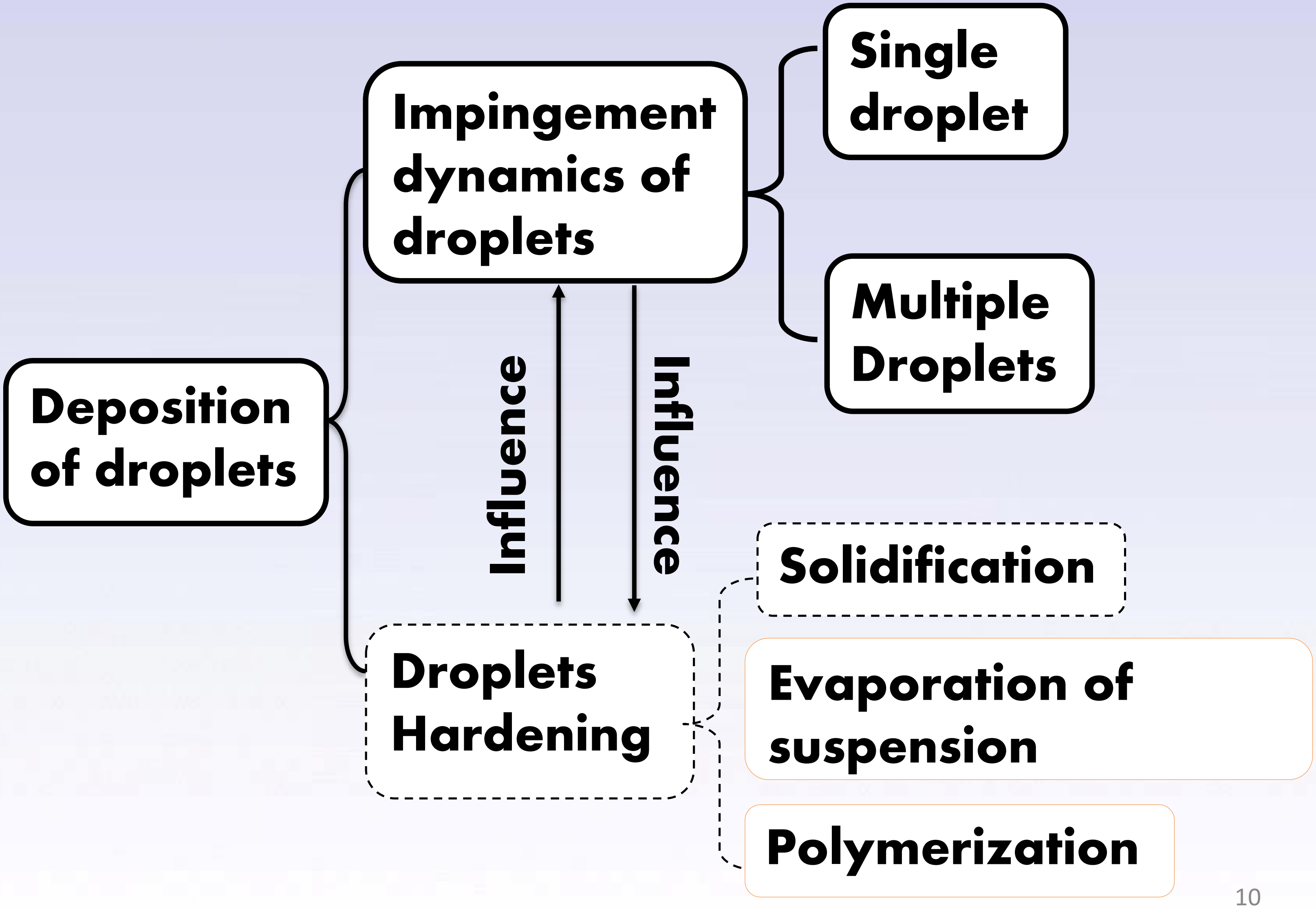


Evolution of (a) bubble and (b) drop (gravity reversed) shapes with time.

Tripathi, Manoj Kumar, Kirti Chandra Sahu, and Rama Govindarajan. "Why a falling drop does not in general behave like a rising bubble." *Scientific reports* 4 (2014).

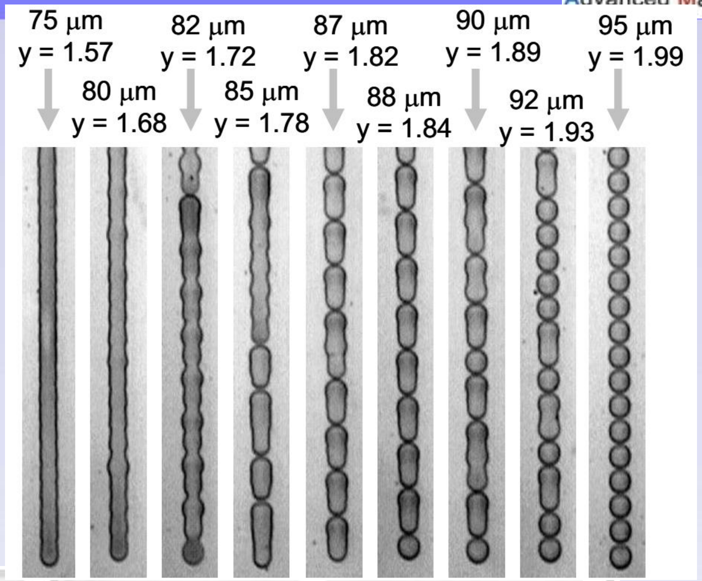
Inkjet Deposition

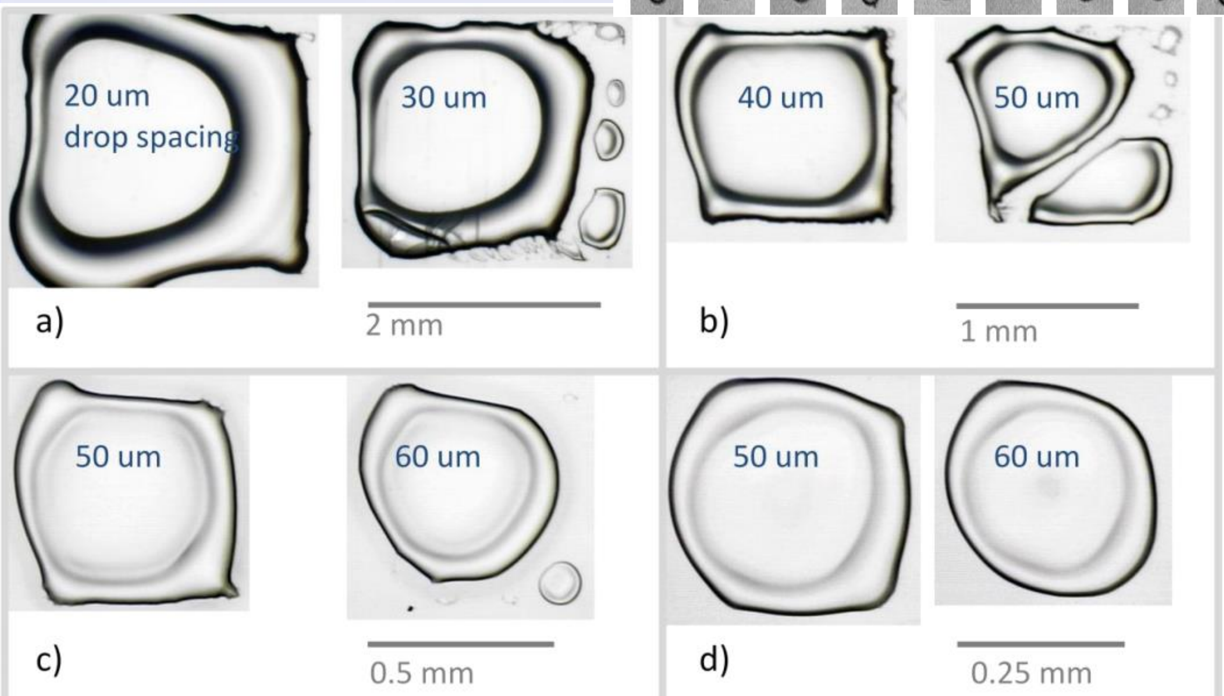
Complexities – Droplet deposition



Inkjet Deposition

Complexities





Soltman, Daniel Benjamin. "Understanding inkjet printed pattern generation." (2011).

Inkjet Deposition

Inkjet

- Overview
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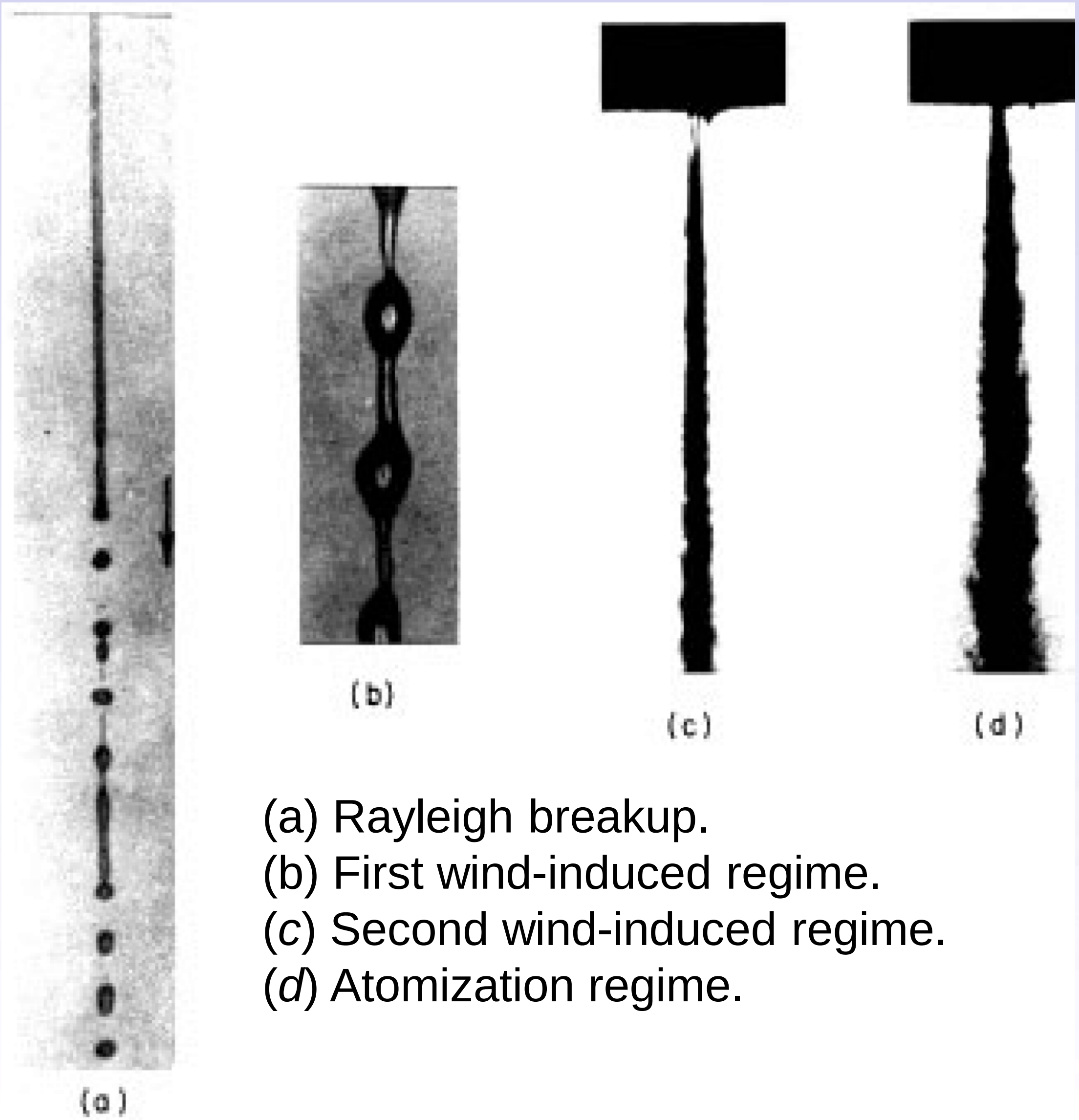
Droplet formation

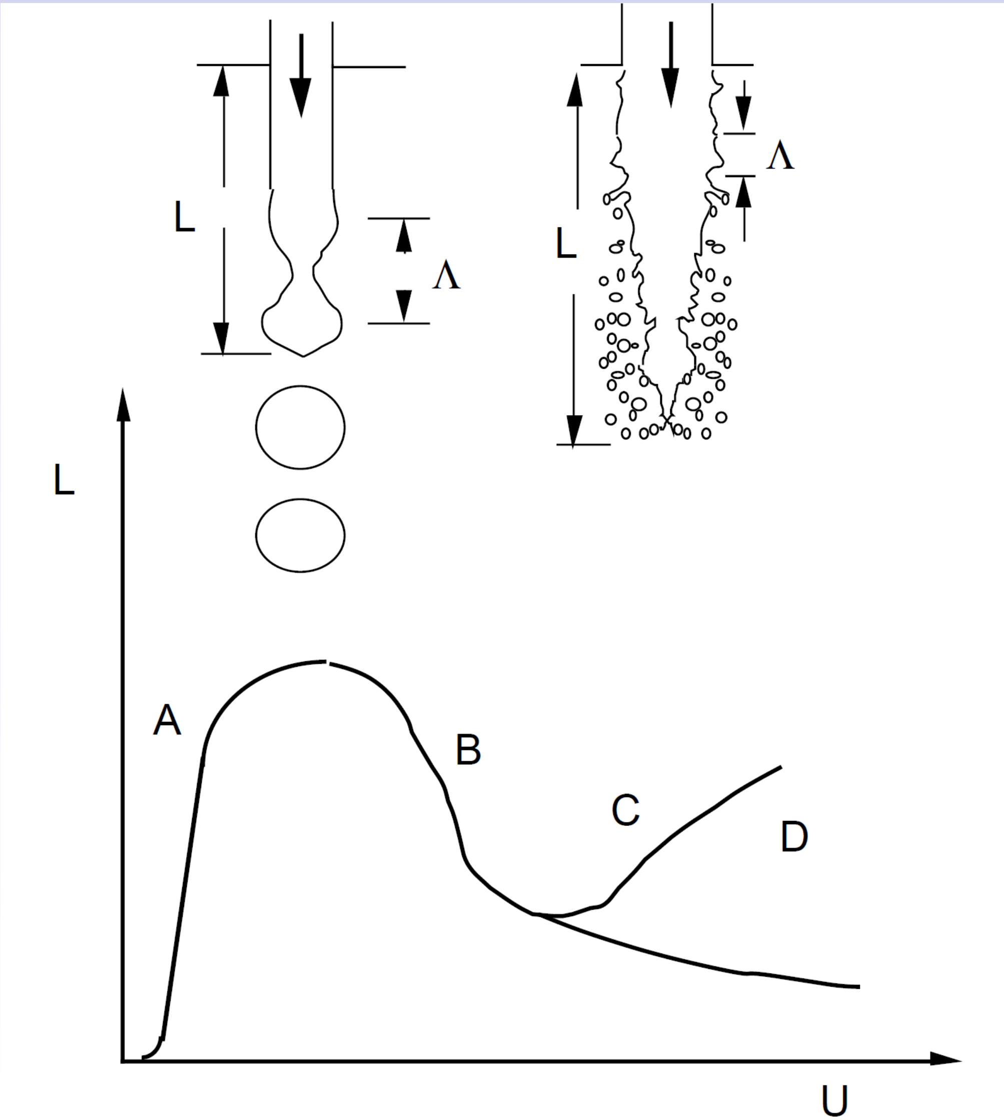


(a) Rayleigh breakup.
(b) First wind-induced regime.
(*c*) Second wind-induced regime.
(*d*) Atomization regime.

Lin, S. P., and R. D. Reitz. "Drop and spray formation from a liquid jet." *Annual Review of Fluid Mechanics* 30.1 (1998): 85-105.

Inkjet Deposition

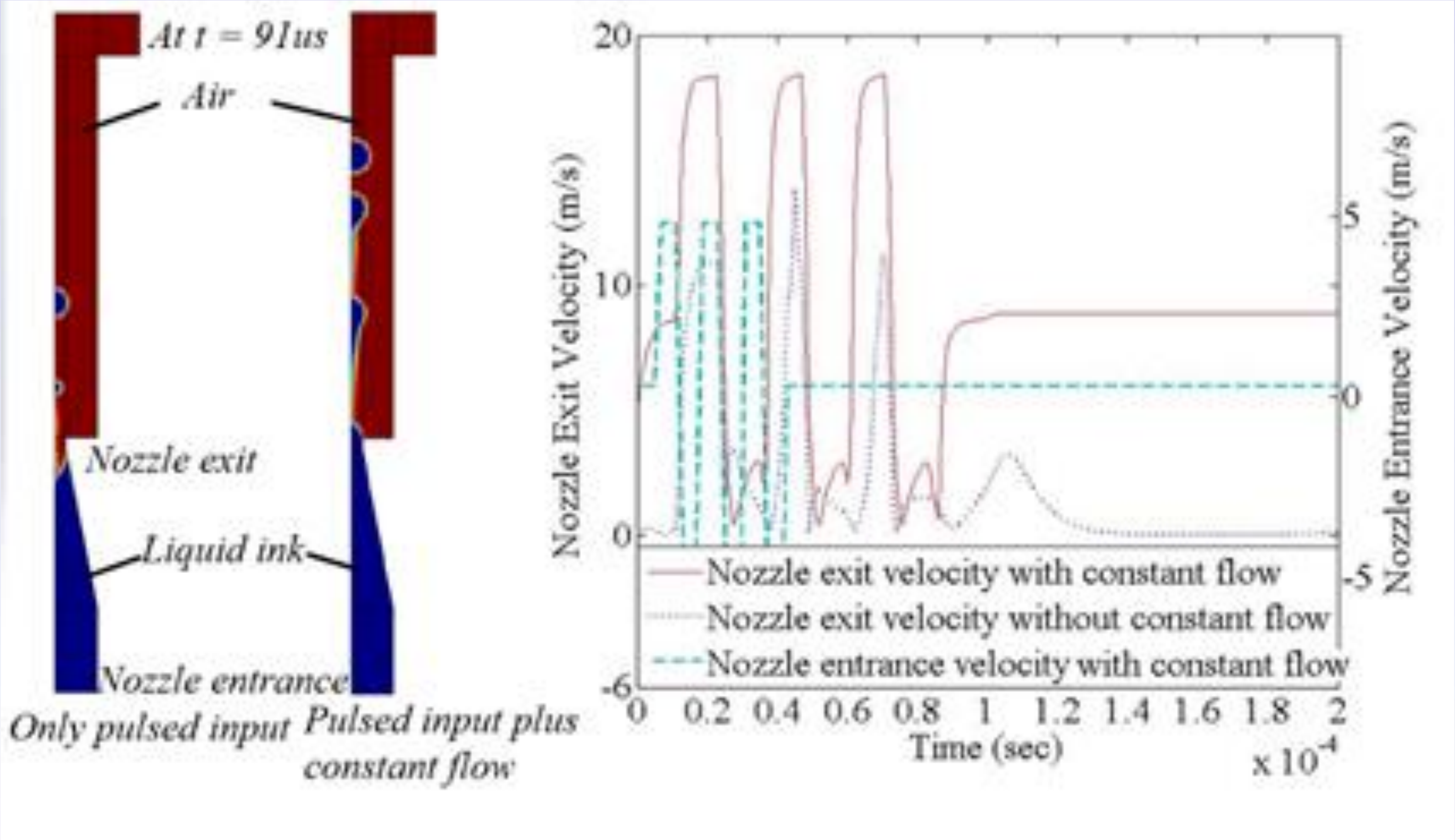
Droplet formation



Lin, S. P., and R. D. Reitz. "Drop and spray formation from a liquid jet." *Annual Review of Fluid Mechanics* 30.1 (1998): 85-105.

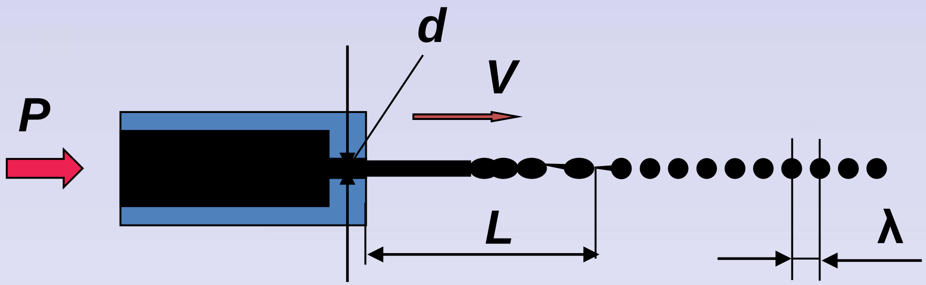
Inkjet Deposition

Droplet formation



Inkjet Deposition

Continuous inkjet



Emerging from an orifice liquid jet breaks-up into droplets. Because of the surface tension:

- **Droplets have random size**
- **Droplets have random spacing**

$$L = K*\ln(d/2\alpha_0)V(\rho d^3/\sigma)^{0.5}$$

$$\lambda = 4.51d;\ f_s = V/4.51d$$

α_0 – the initial disturbance

ρ - the density of the fluid

σ – the surface tension of the fluid

L – break-up length

f_s – the frequency of spontaneous drop formation

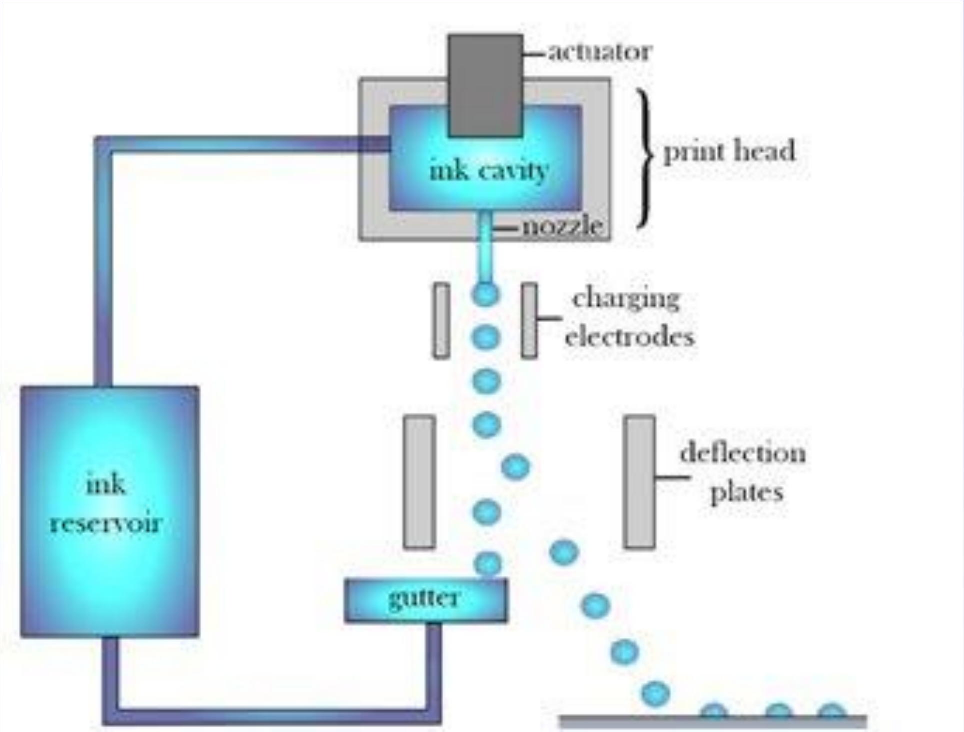
λ – wave length

Credit: Rafi Bronstein @ HP

Inkjet Deposition

Continuous inkjet

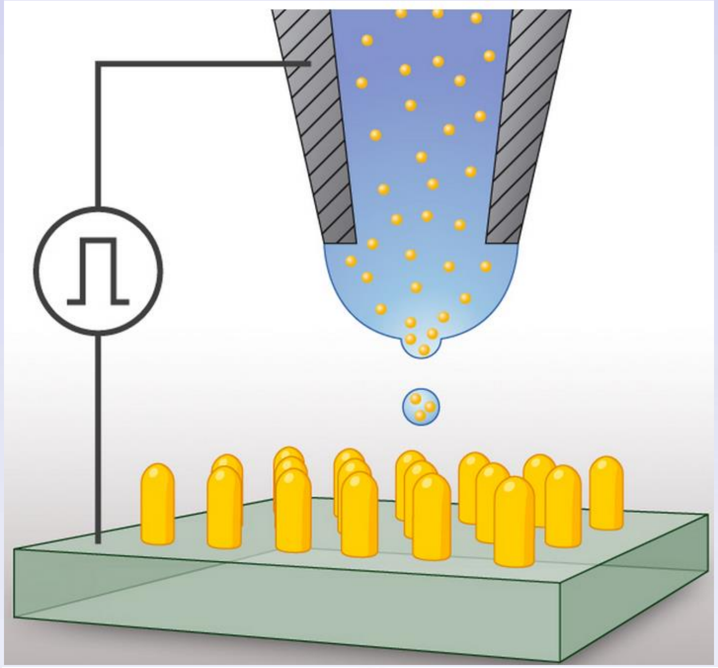
- Can the drop size be controlled?
- Can the spatial spacing of the drops be controlled?
- Can the break-up length be controlled?
- What would be the drop selection method?

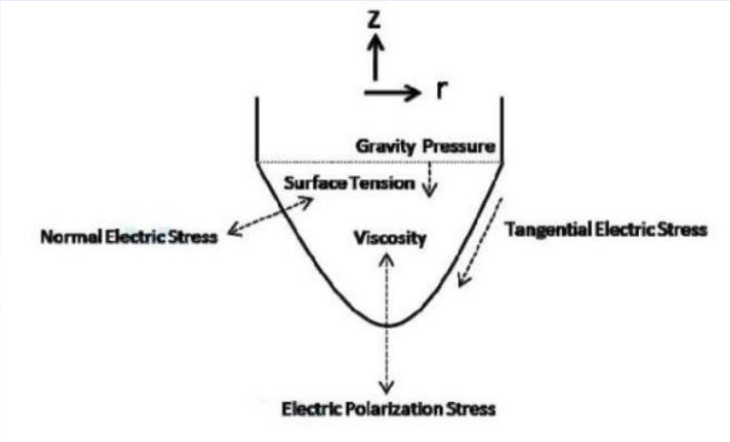


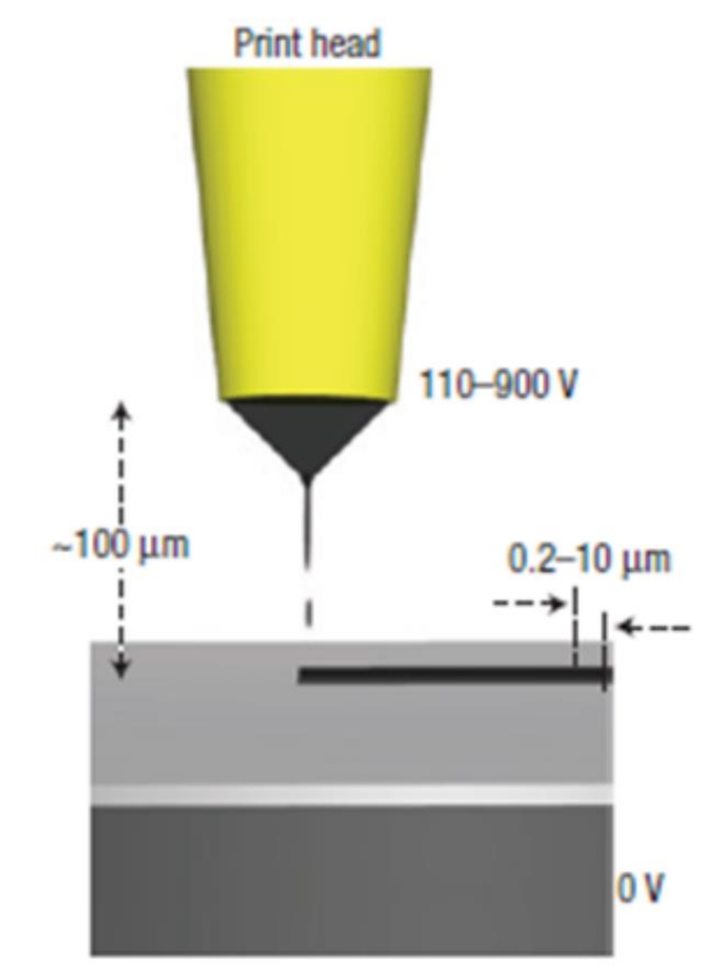
Credit: Rafi Bronstein @ HP

Inkjet Deposition

Electrostatic Inkjet



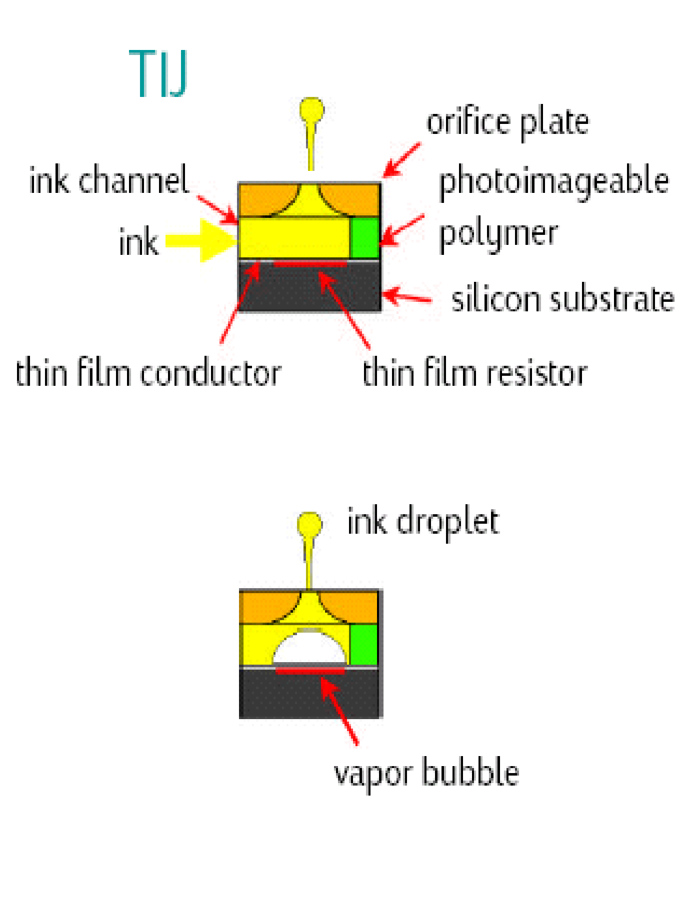




Soltman, Daniel Benjamin. "Understanding inkjet printed pattern generation." (2011).

Inkjet Deposition

Thermal inkjet

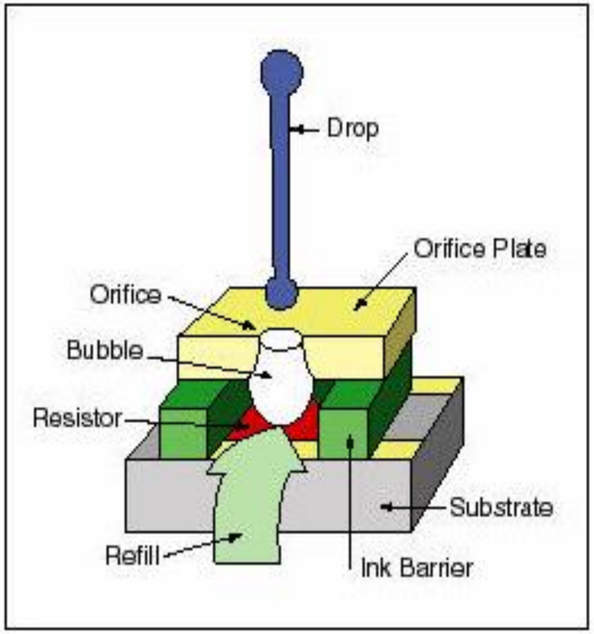


- Uses tiny resistor to rapidly heat a thin layer of liquid ink
- Vaporize a tiny fraction of the ink to form an expanding bubble that ejects a droplet (and any trapped air)
- Nothing moves but the ink – very high frequency attainable
- Use fabrication technology similar to semiconductor manufacturing; nozzles can be integrated at very high densities – provides high throughput and spare nozzles for reliability

Credit: Rafi Bronstein @ HP

Inkjet Deposition

Thermal inkjet

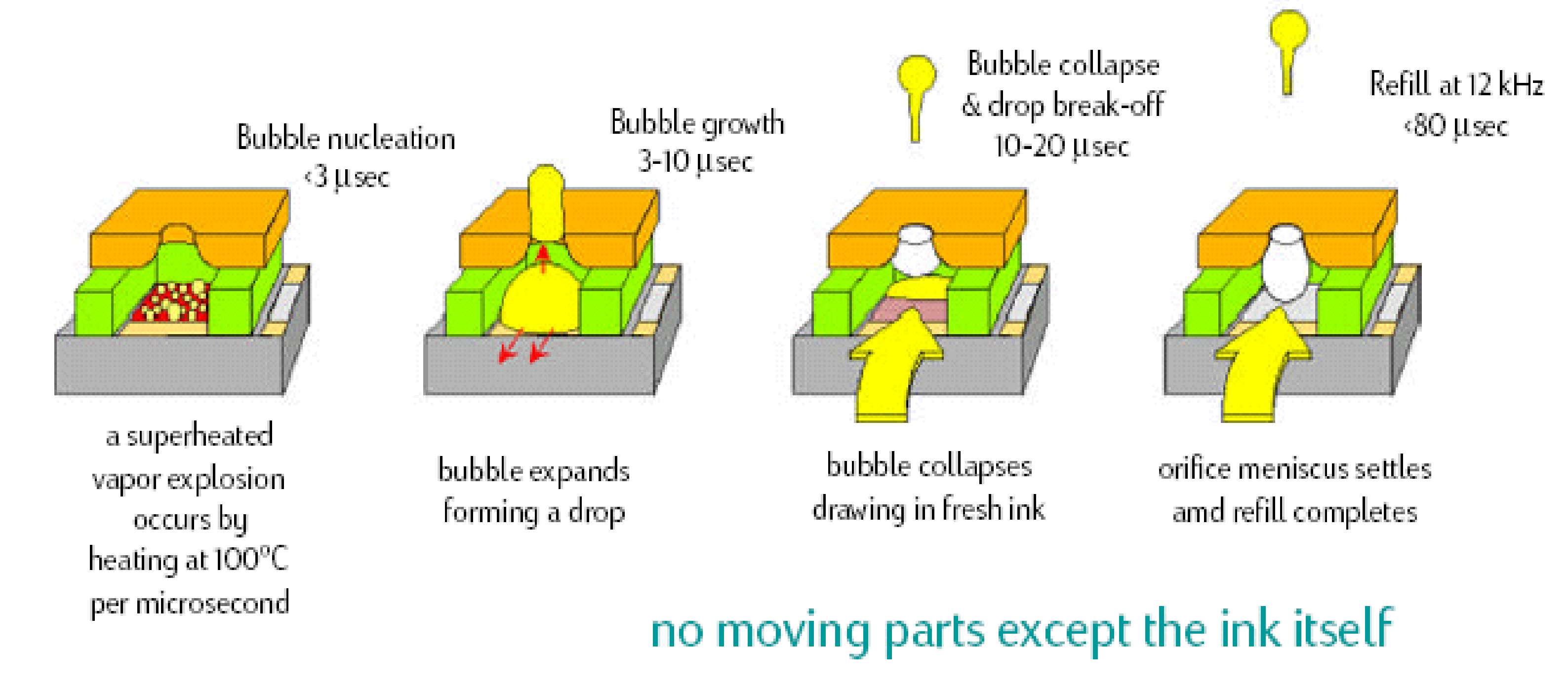


- **Stack of extremely thin films form the floor of each firing chamber, some are electrically conductive, others are insulators.**
- **Thin film resistor is located in the center of each firing chamber floor and gets extremely hot when electricity passes through**
- **Each resistor is 60um or smaller on each side, but power density on its surface is 1.28 billion watts per square meter – more than on the surface of the Sun!**

Credit: Rafi Bronstein @ HP

Inkjet Deposition

Thermal inkjet



- A film of ink about 100nm thick is heated to ~340C
- A vapor bubble forms to expel the ink, but it doesn't "boil"

Credit: Rafi Bronstein @ HP

Inkjet
Overview
Complexity
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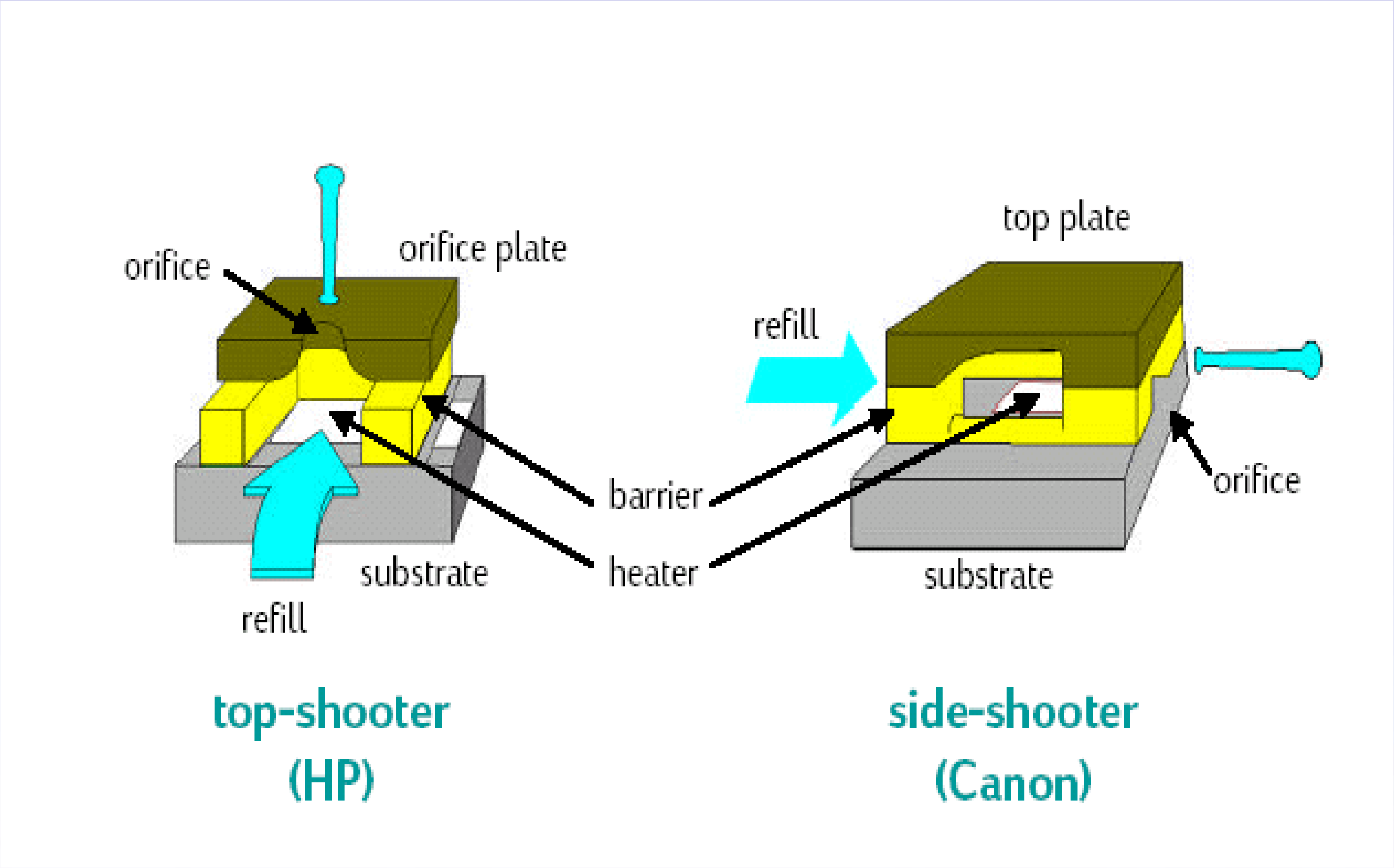
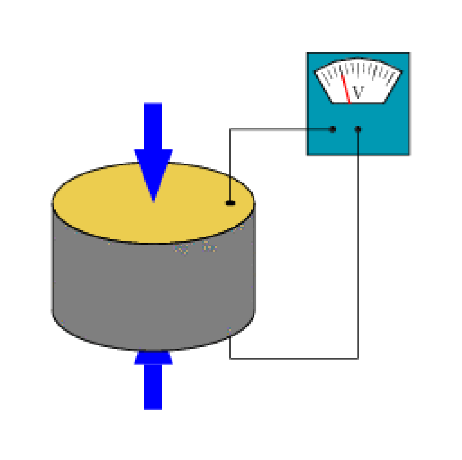
- Thermal inkjet

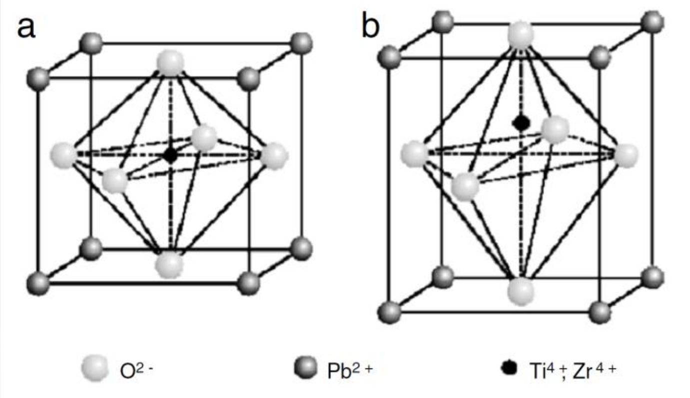


Credit: Rafi Bronstein @ HP

Inkjet Deposition

Piezoelectric Inkjet





Piezoelectricity

$$\underline{S} = \underline{\underline{d}}\,\underline{E}$$

$$\underline{D} = \underline{\underline{d}}^T\,\underline{T}$$

- The elementary cell of PZT: (a) above the Curie temperature; (b) below the Curie temperature. At a high temperature, the electric charges coincide in a cubic structure and there is no piezoelectricity. Below the Curie temperature the electric charges do not coincide anymore. This results in piezoelectric effect.
- D is the electric displacement field (or the charge density), S is strain, E is the applied electrical field, T is stress, d and d^T are matrices for the piezoelectric effects
- Caused by lack of symmetry, and therefore inherently anisotropic

Wijshoff, Herman. "The dynamics of the piezo inkjet printhead operation."*Physics reports* 491.4 (2010): 77-177.

Inkjet Deposition

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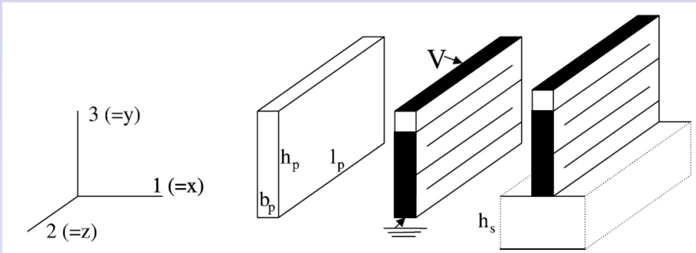
Piezoelectric Inkjet



$$\{S\} = \left[s^E\right]\{T\} + [d^t]\{E\}$$

$$\{D\} = [d]\{T\} + \left[\varepsilon^T\right]\{E\},$$

- s is compliance matrix, characterize mechanical behavior;
- ε is permittivity matrix, characterize electrical behavior;
- d is the piezoelectric matrix, characterize the coupling effects
- $\Delta y = d_{33}V$, $d_{33} \approx 0.4\mathrm{nm/V}$ for most piezo materials;
- For 25 pl droplet with a channel of 10 mm length and a width of 250 mm, the displacement of the piezo element should be 20 nm. This requires a driving voltage of 80 V.

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{21}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 \\ s_{31}^E & s_{32}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E = 2\left(s_{11}^E - s_{12}^E\right) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

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Inkjet Deposition

Inkjet

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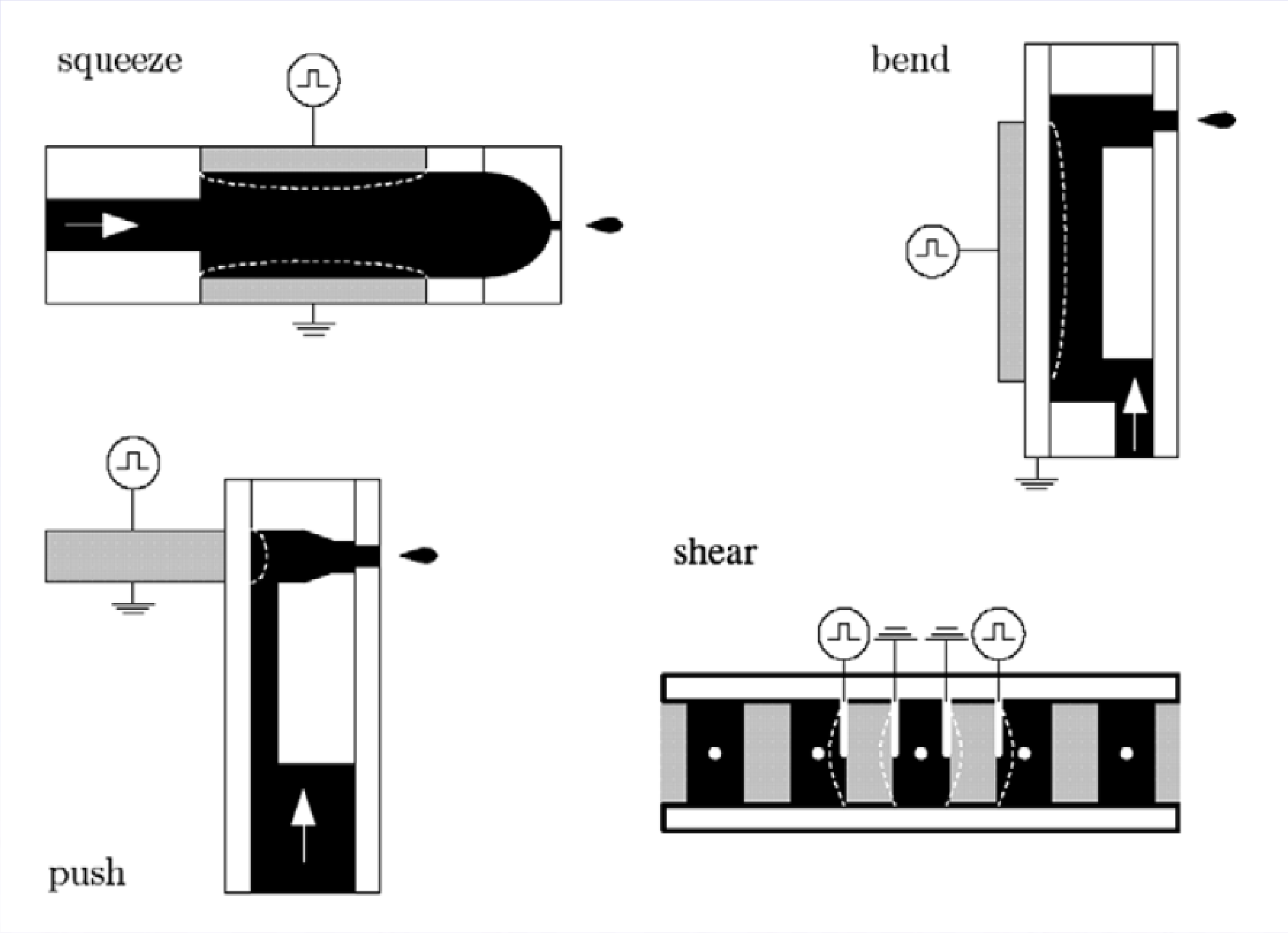
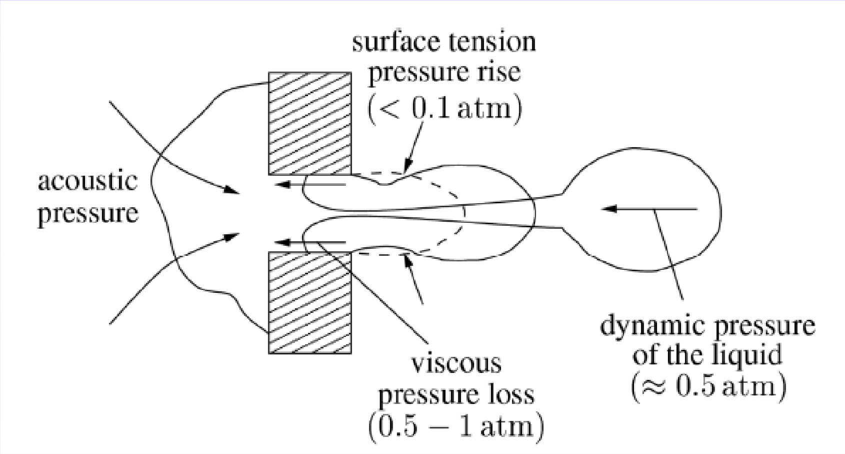
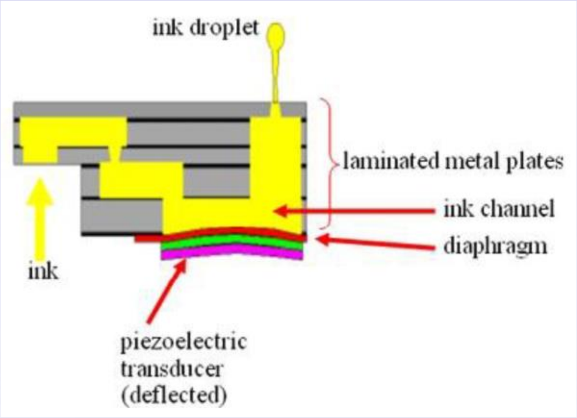
Piezoelectric Inkjet



Inkjet Deposition

Piezoelectric Inkjet





- **Actuation efficiency**
  - **Piezo (electrical to mechanical): ~15% to 25%**
  - **Piezo deformation to channel deformation: ~13%**
  - **Channel deformation to acoustic pressure wave: ~20%**
  - **Acoustic pressure to droplet (for low viscosity): ~10%**
  - **Total efficiency: ~0.07%**
  - **For a 32pL droplet with a ejection velocity of 7m/s, the surface energy and kinetic energy of the droplet is ~0.85 nJ. As a result, the required input of electric energy is 1200 nJ.**
  - **For an operation frequency of 100 kHz (10us), the required power is then 0.12W. For a voltage of 40V, current 3mA.**

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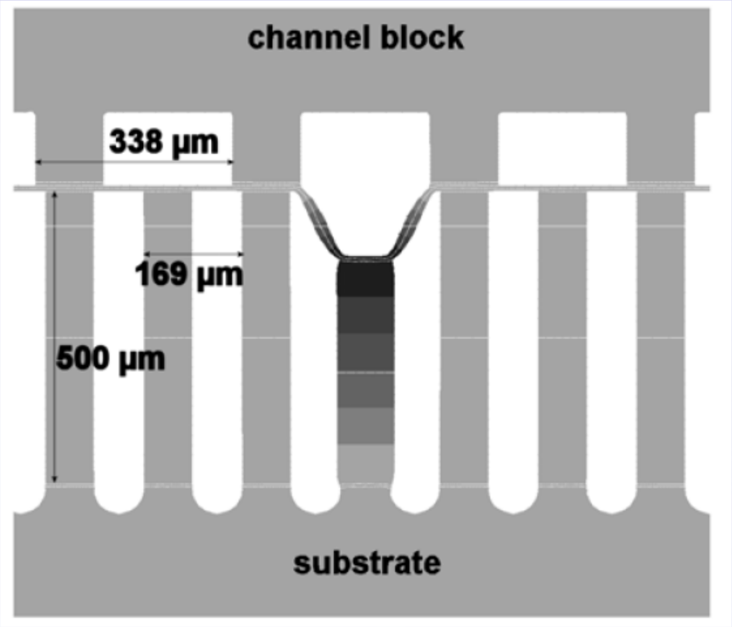
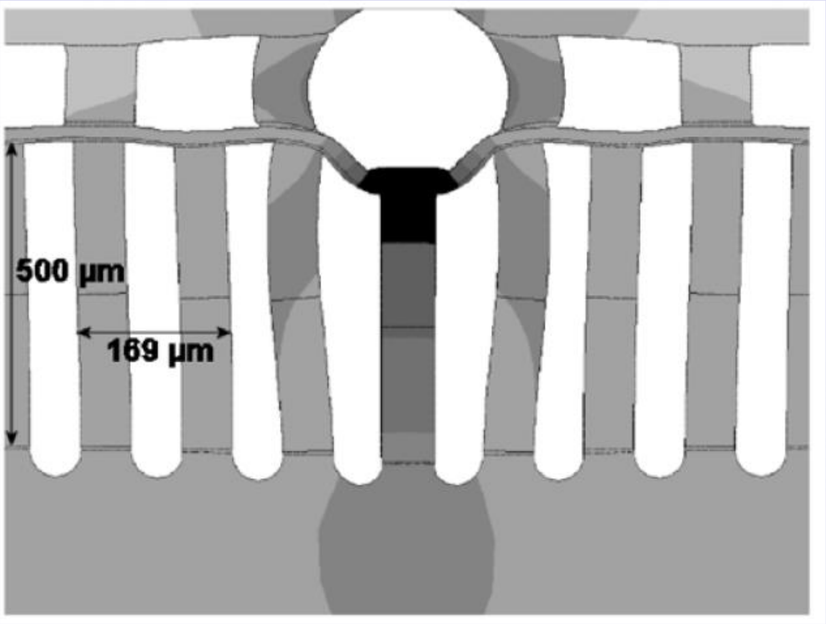
Inkjet Deposition

Piezoelectric Inkjet



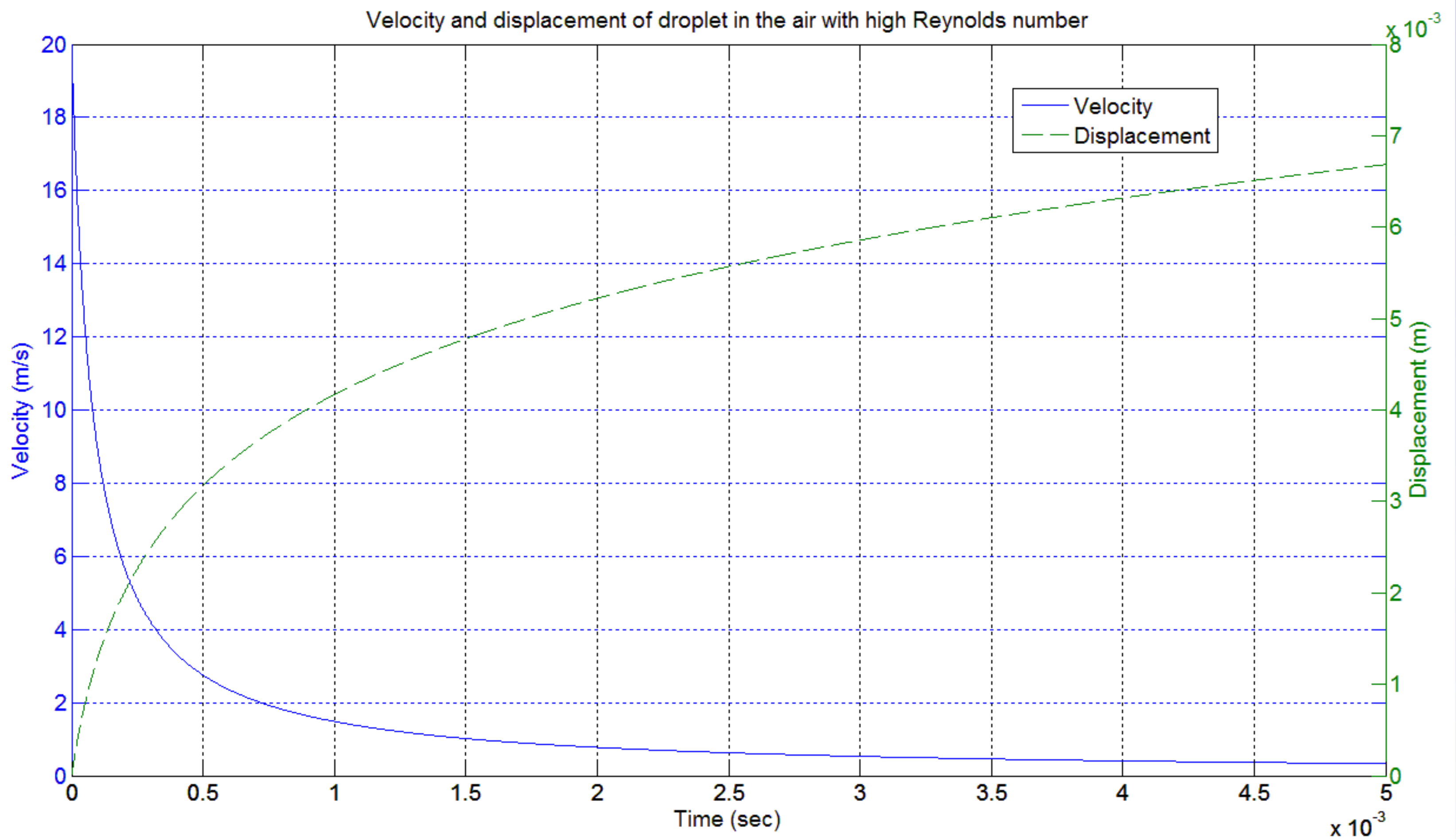


Cross talk

Wijshoff, Herman. "The dynamics of the piezo inkjet printhead operation."*Physics reports* 491.4 (2010): 77-177.

Inkjet Deposition

Droplet falling in the air



$$\vec{F}_g - \vec{F}_v - \vec{F}_d = 0$$

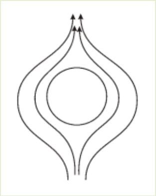
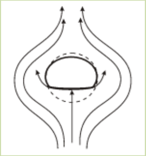
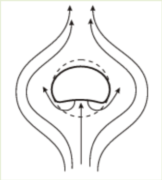
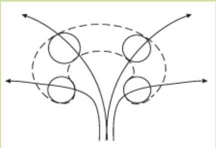
$$\vec{F}_d = -b\,\vec{v}$$ or $$\vec{F}_d = -\frac{1}{2}\rho\,\vec{v}^{\,2} A C_d$$

Low speed

High speed

Inkjet Deposition

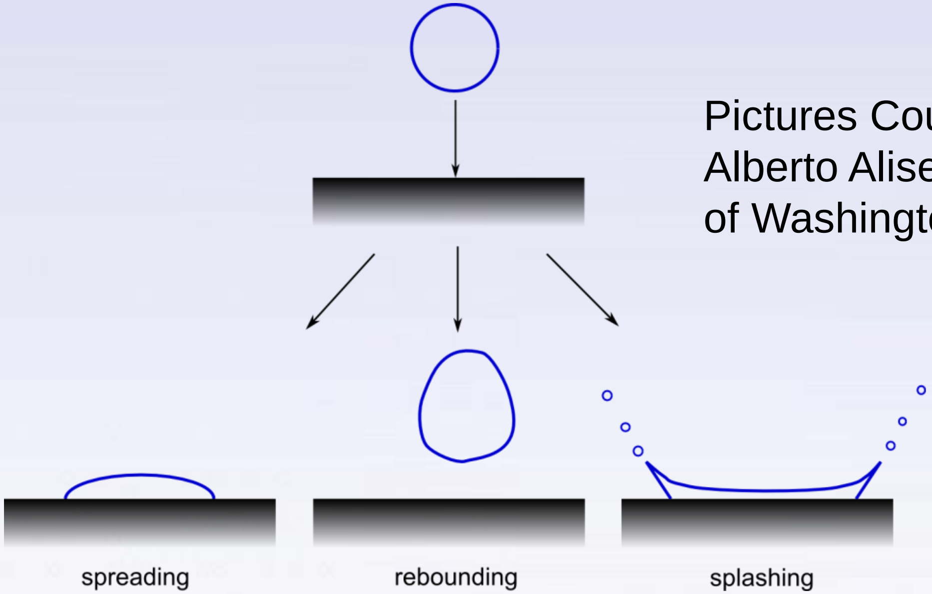
Droplet falling in the air

	Drop size	Characteristic shape
Surface-tension forces are able to maintain the spherical shape against external forces.	0.14 mm	
A very slight shortening of the vertical axis and the drop is an "oblate spheroid". The vertical axis is about 98%of the horizontal axis.	0.50 mm	
Flattening of bases begins.	1.4 mm	
Concavity of the flattened base begins.	2 mm	
At 5 mm the force of the air through which the drop is falling causes the drop to break up.	5mm	

Raindrop falling in the air

Inkjet Deposition

- Droplet deposition



Pictures Courtesy Dr. Alberto Aliseda at University of Washington

Inkjet

Overview

Complexity

Printhead

Falling

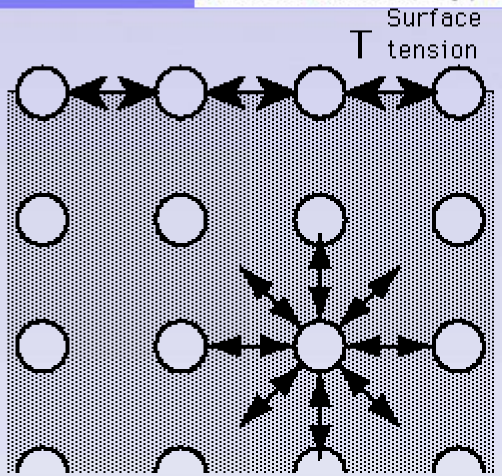
Deposition

Drying

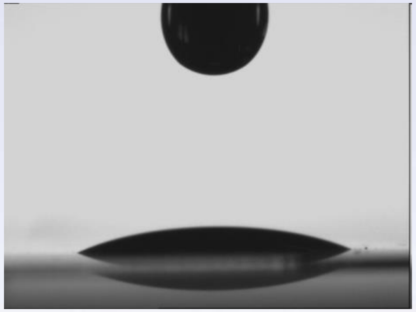
Inkjet Deposition

Droplet deposition

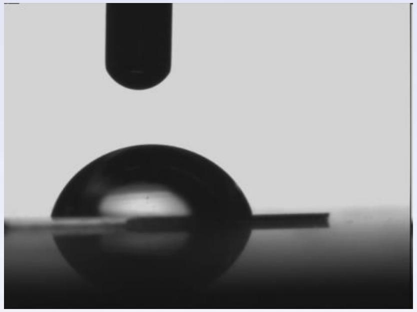
- **Wetting on a solid surface**



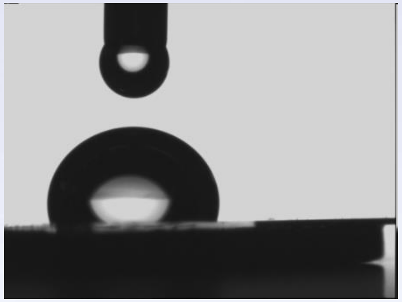
Reason for Surface tension



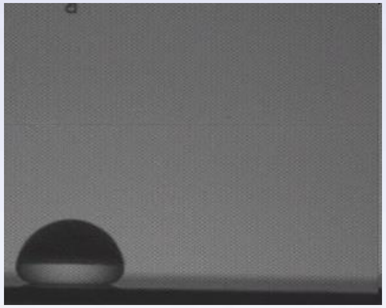
Total wetting



Partial wetting



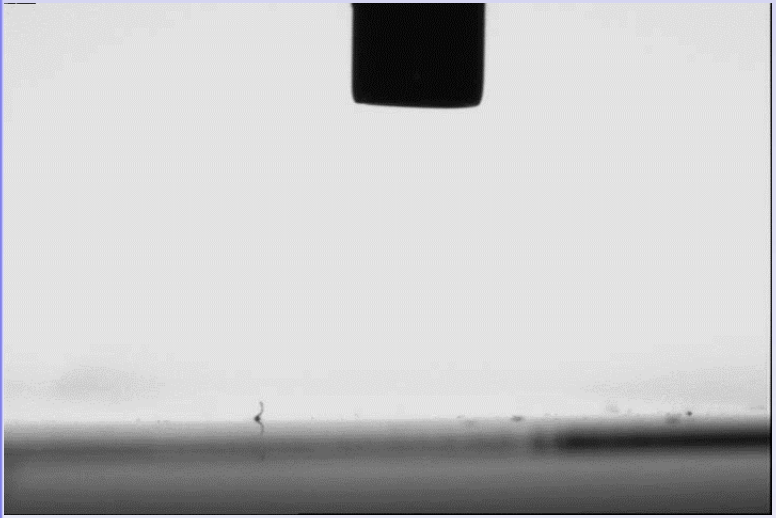
Partial non-wetting



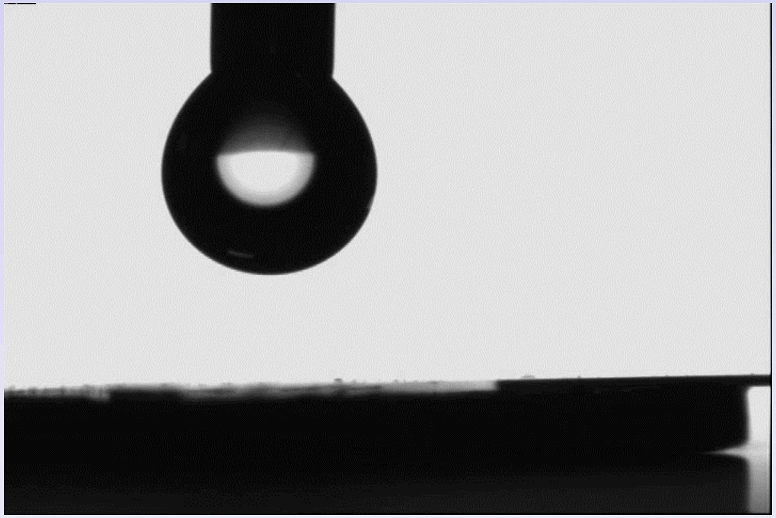
Non-wetting

Inkjet Deposition

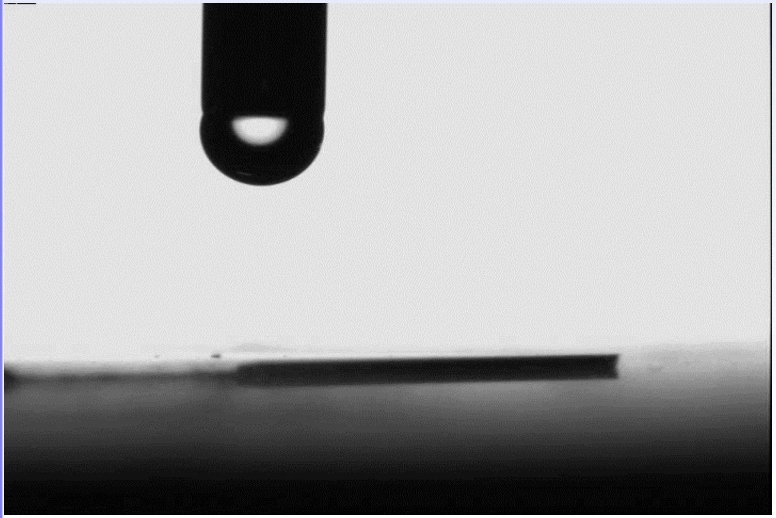
- Droplet deposition – different wetting



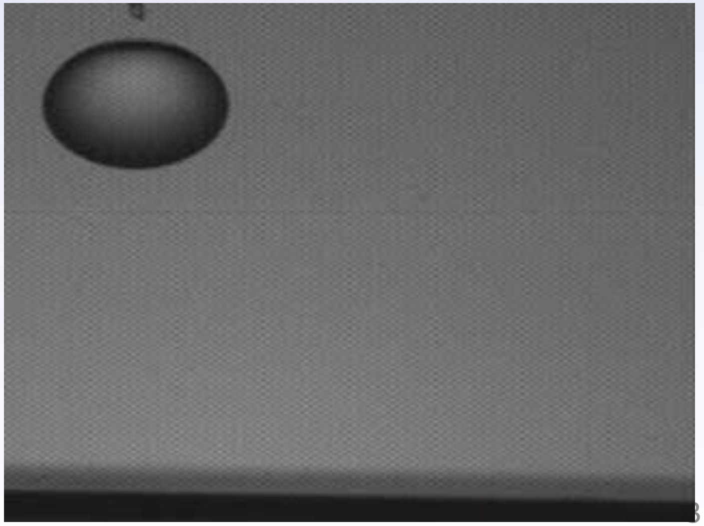
Hydrophilic



Hydrophobic



Partial Wetting

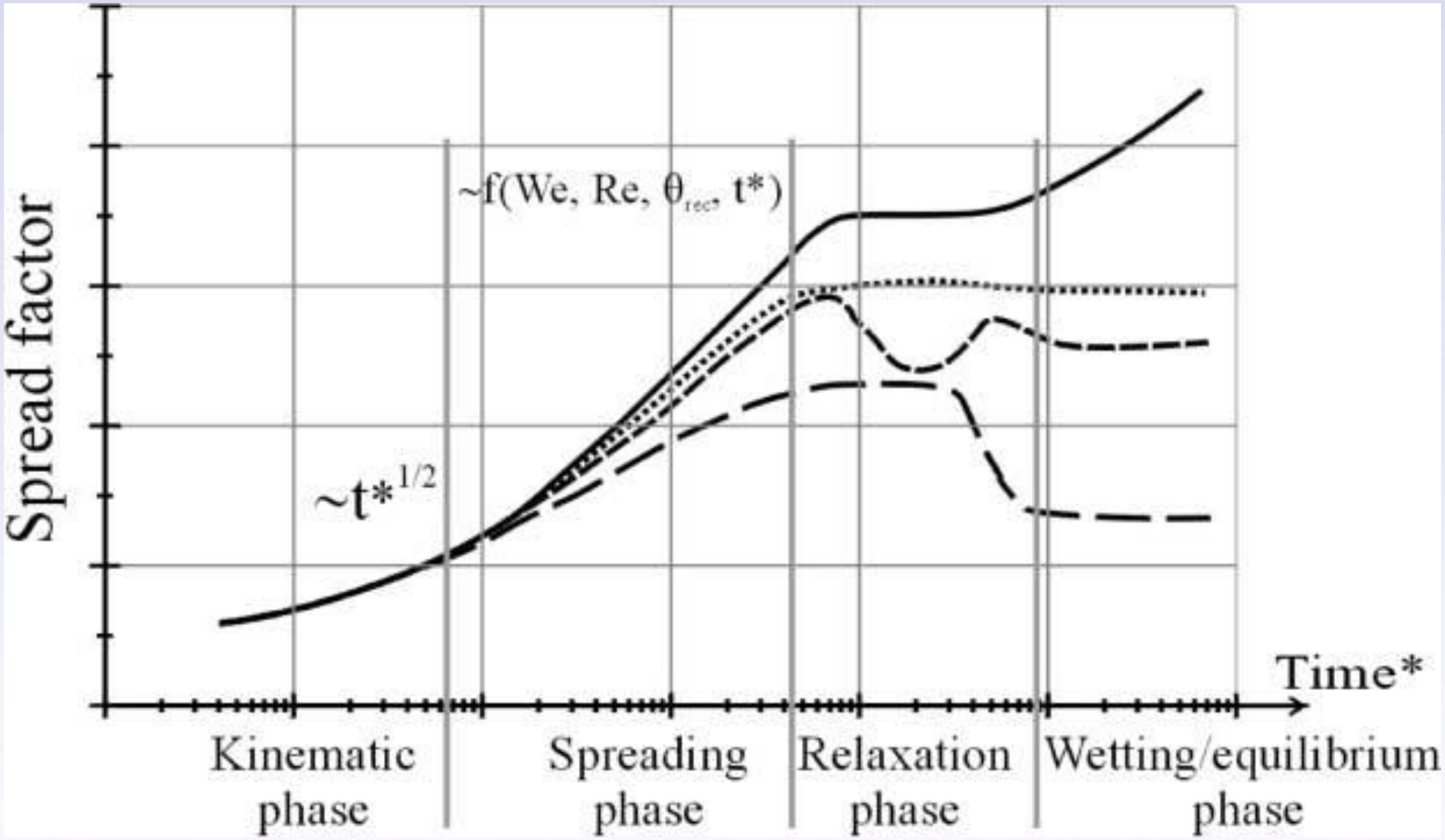


Ultra-hydrophobic

Inkjet Deposition

Droplet deposition

Droplet spreading dynamics



Schematic representation of the spread factor with time

Inkjet
Overview
Complexity
Printhead
Falling
Deposition
Drying

Inkjet Deposition

Droplet deposition

Physics of droplet spreading dynamics

Inkjet
- Overview
- Complexity
- Printhead
- Falling
- Deposition
- Drying

Kinetic Energy

Viscous Dissipation →

← Viscous Dissipation

Interface Energy

$F_p = \rho U^2 D^2$

$F_{vis} = \eta U D$

$F_\sigma = \sigma D$

Inertial Force

− Viscous force >

< − Viscous force +

Surface Tension

Favor uniform film

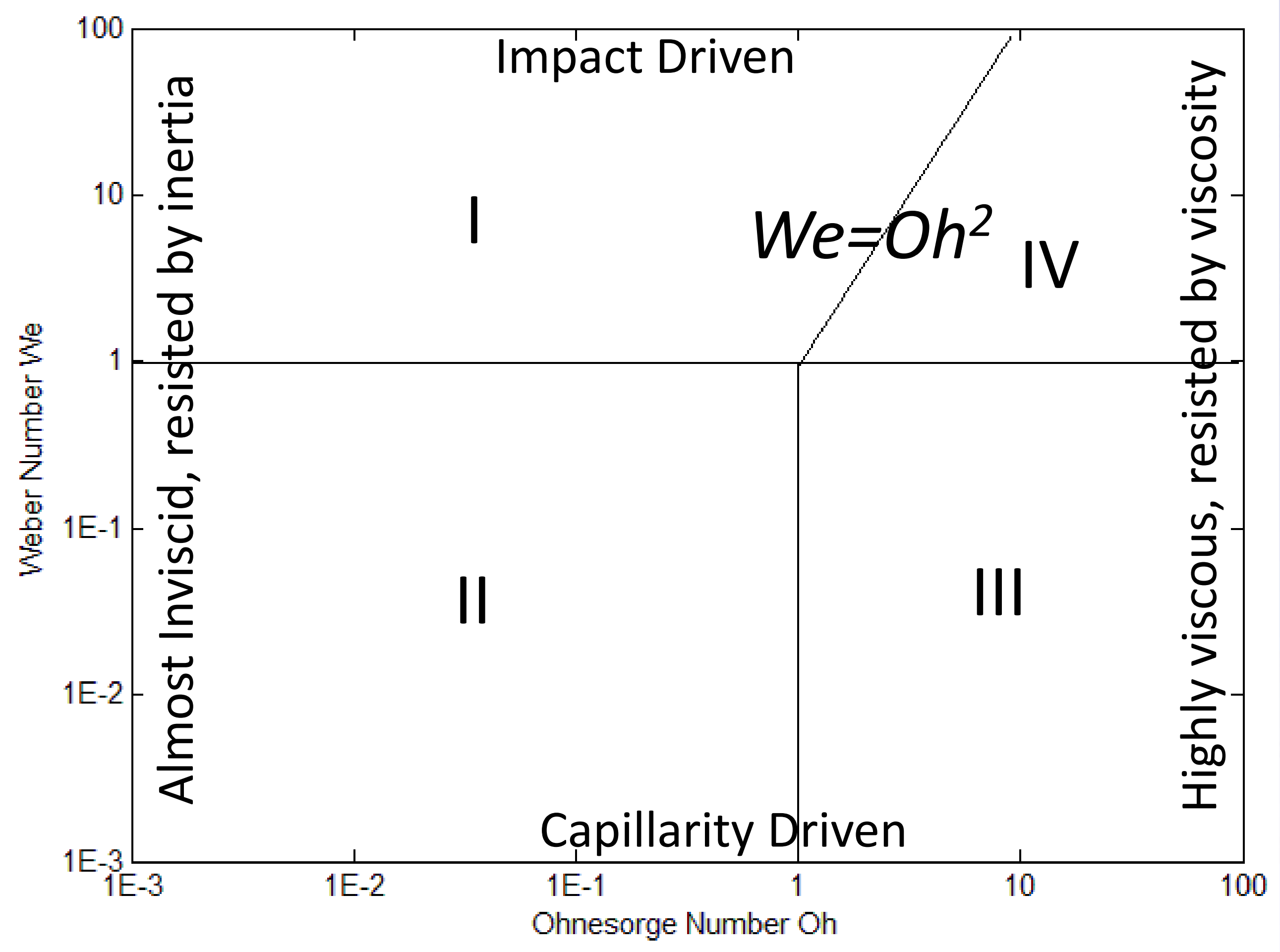
Favor sphere cap

Inkjet Deposition

Inkjet
Overview
Complexity
Printhead
Falling
Deposition
Drying

Droplet deposition

Regimes of droplet spreading dynamics

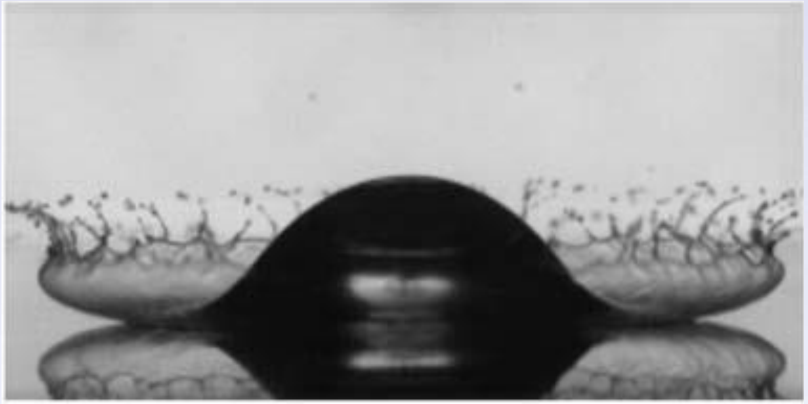


Impact Regime

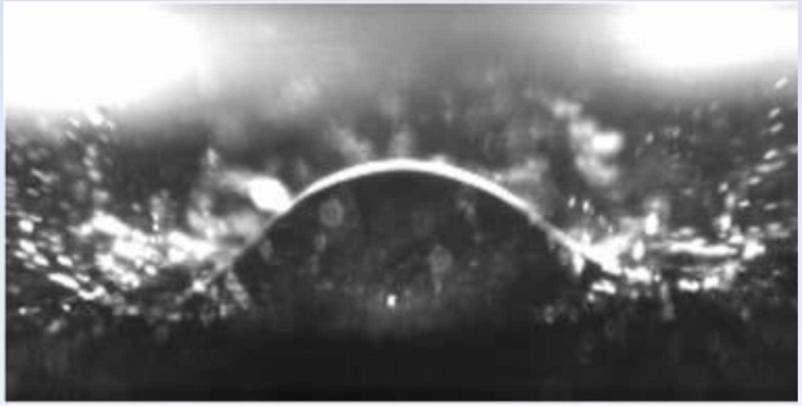
Inkjet Deposition

Droplet deposition

- **Splash**
  - **Corona splash**
  - **Prompt splash**



Caused by surrounding gas



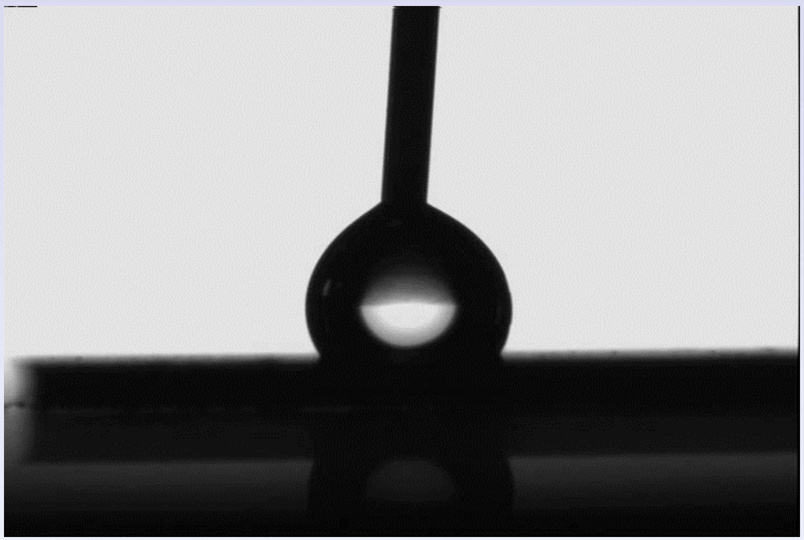
Caused by rough surface

Inkjet Deposition

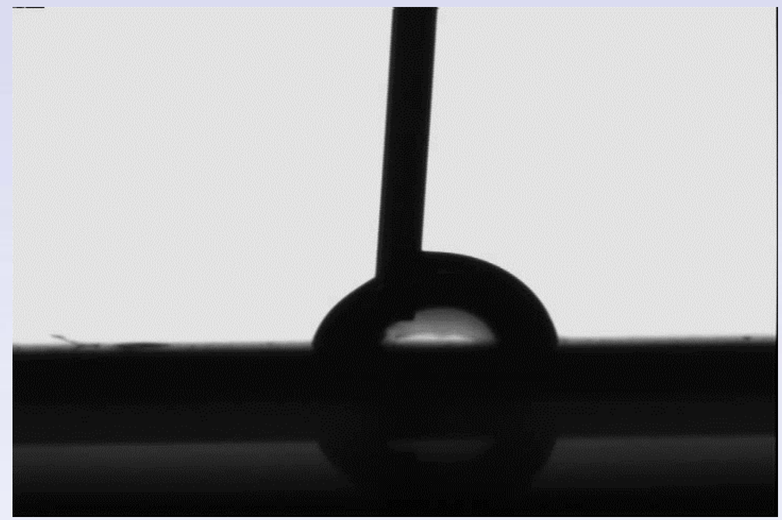
Inkjet
Overview
Complexity
Printhead
Falling
Deposition
Drying

Droplet deposition

Contact angle hysteresis



Advancing contact angle



Receding contact angle

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Inkjet Deposition

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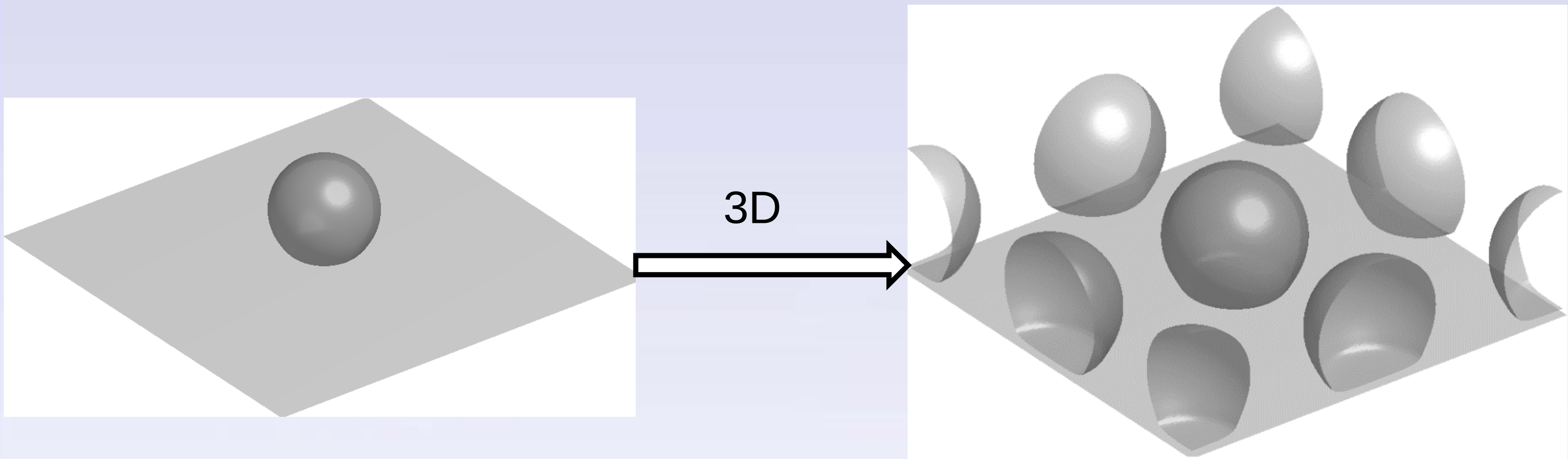
Droplet deposition

- **Simulations of droplet impingement dynamics**



Most previous research: single droplet impact due to prohibitive computational complexity and cost

Make it more relevant to manufacturing, we need to study multiple droplet interaction

Inkjet Deposition

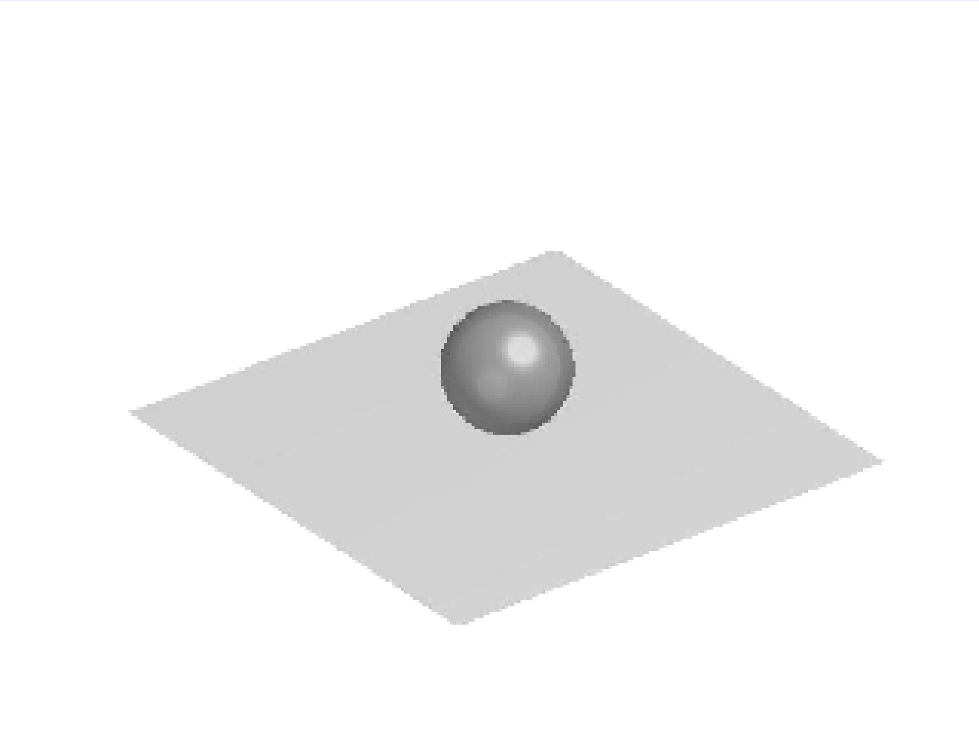
- Inkjet
  - Overview
  - Complexity
  - Printhead
  - Falling
  - Deposition
  - Drying

Droplet deposition

- **Simulations of droplet impingement dynamics – Lattice Boltzmann method**

Re: 238.26
We: 12.88

Fluid: Water
Droplet size: 48.8um
Density: 1e3 kg/m^3
Impact velocity: 4.36m/s
Viscosity: 8.93e-4Pa*s
Surface tension: 0.072N/m



COMSOL on a cluster
CPU: 16-core
Memory: Over 100GB
Time: Over a month

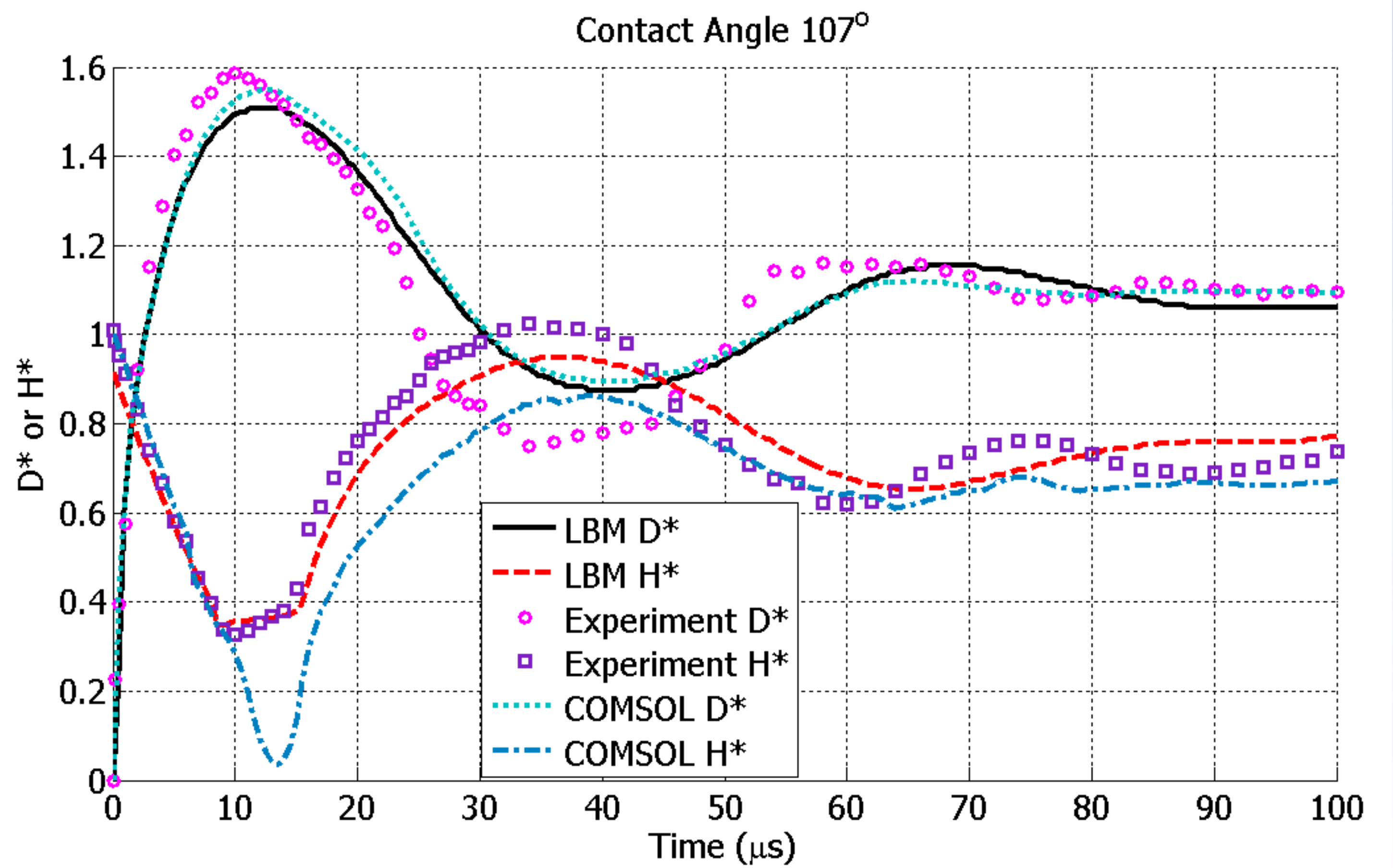
VS

Our LBM on a Laptop
CPU: single thread
Memory: ~ 1GB
Time: Less than 20 hrs

Inkjet Deposition

Droplet deposition

- **Simulations of droplet impingement dynamics – Lattice Boltzmann method – validation**

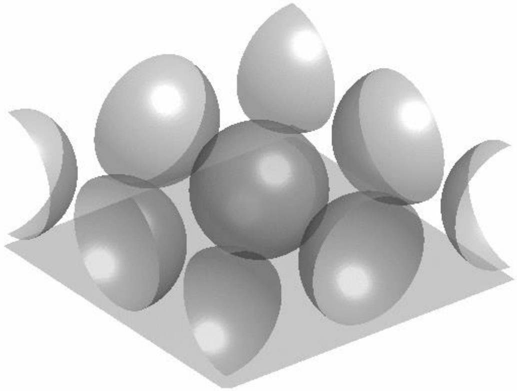


Inkjet
- Overview
- Complexity
- Printhead
- Falling
- Deposition
- Drying

Inkjet Deposition

Droplet deposition

Multiple droplet interaction



Droplet spacing = 0.3*Droplet Diameter

Regime I: We = 100; Oh = 0.04; High impact velocity and low viscosity

Inkjet Deposition

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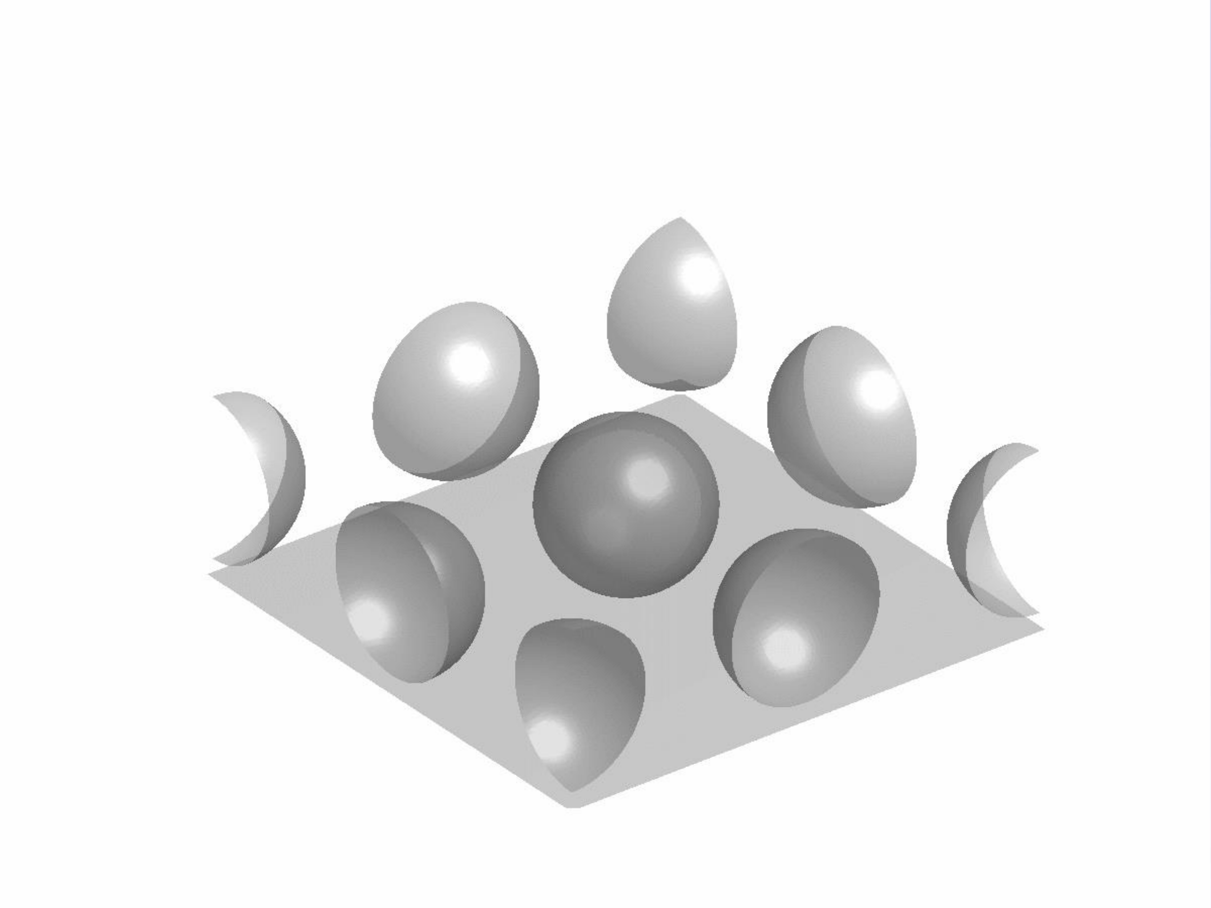
Inkjet

- Overview
- Complexity
- Printhead
- Falling
- Deposition
- Drying

Droplet deposition

Multiple droplet interaction



Droplet spacing = 0.6*Droplet Diameter

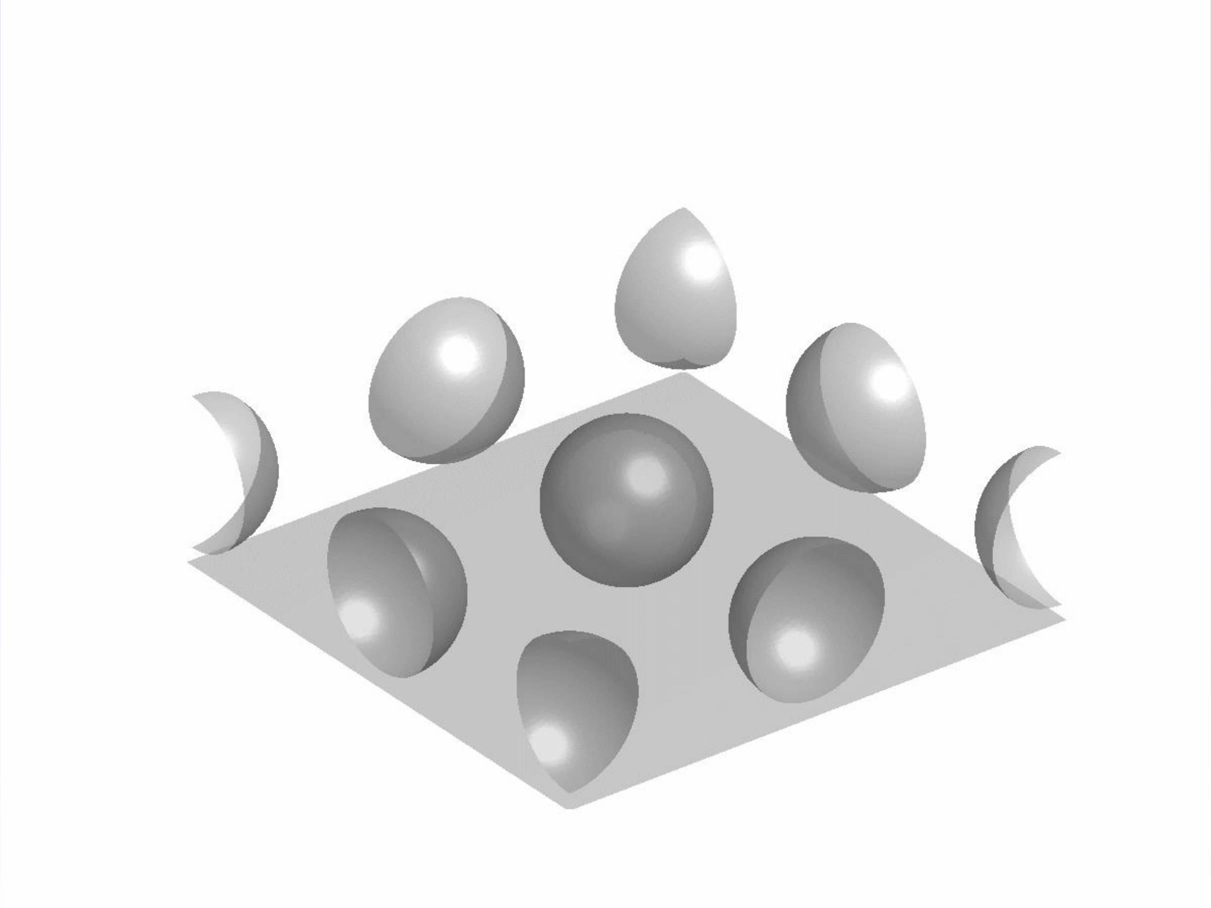
Regime I: We = 100; Oh = 0.04; High impact velocity and low viscosity

Inkjet Deposition

Inkjet
Overview
Complexity
Printhead
Falling
Deposition
Drying

Droplet deposition

Multiple droplet interaction



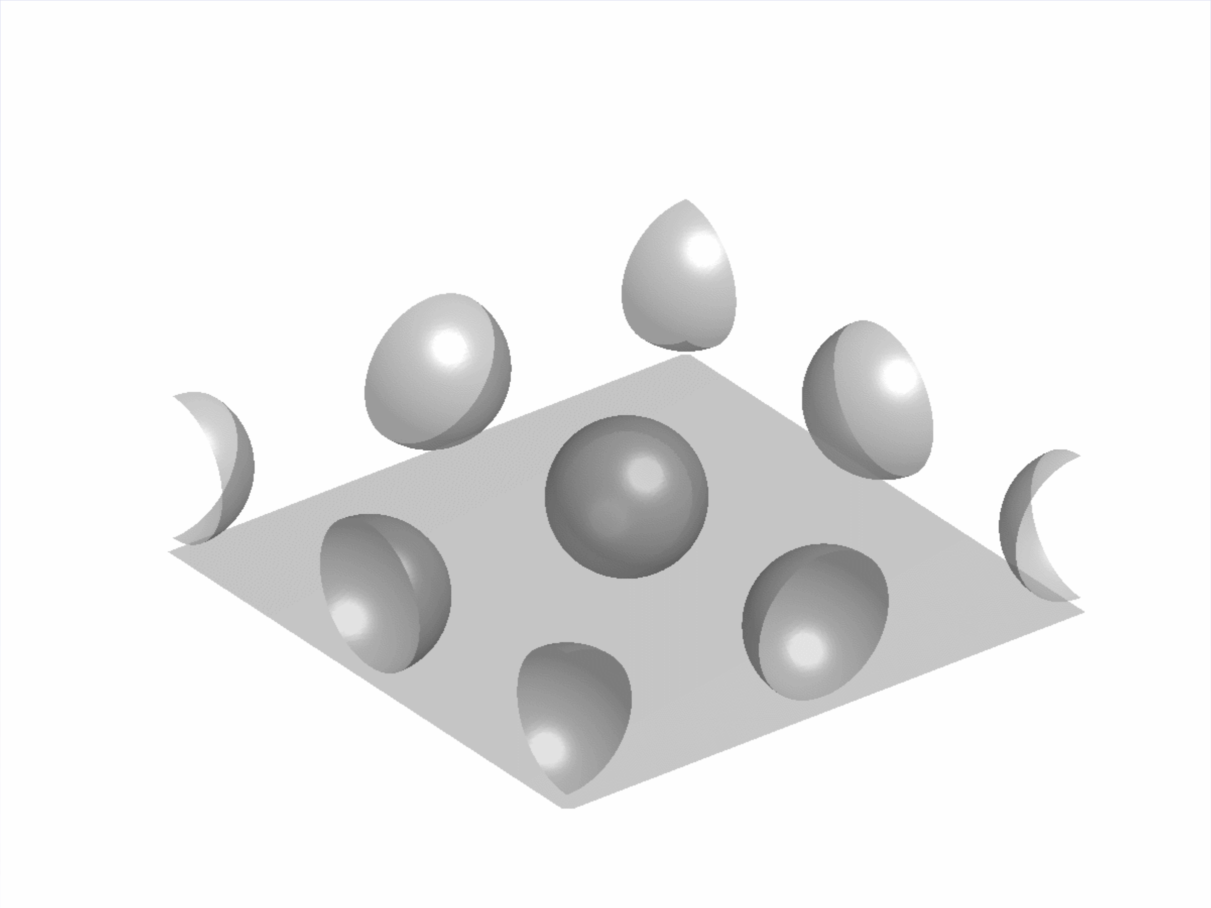
Droplet spacing = 0.8*Droplet Diameter

Regime I: We = 100; Oh = 0.04; High impact velocity and low viscosity

Inkjet Deposition

Droplet deposition

Multiple droplet interaction



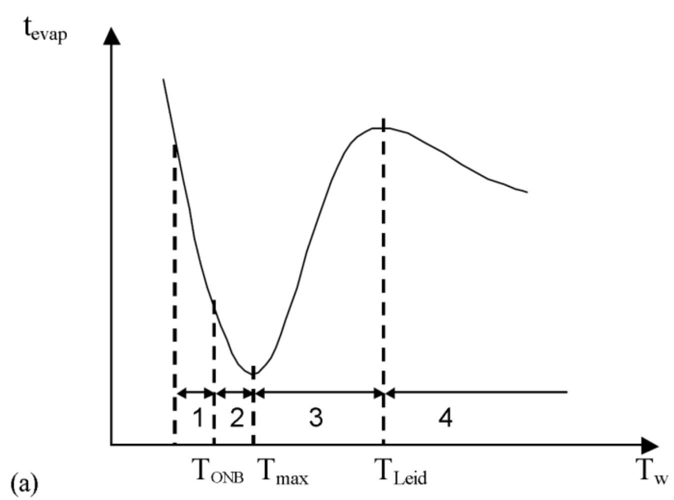
Droplet spacing = 1.0*Droplet Diameter

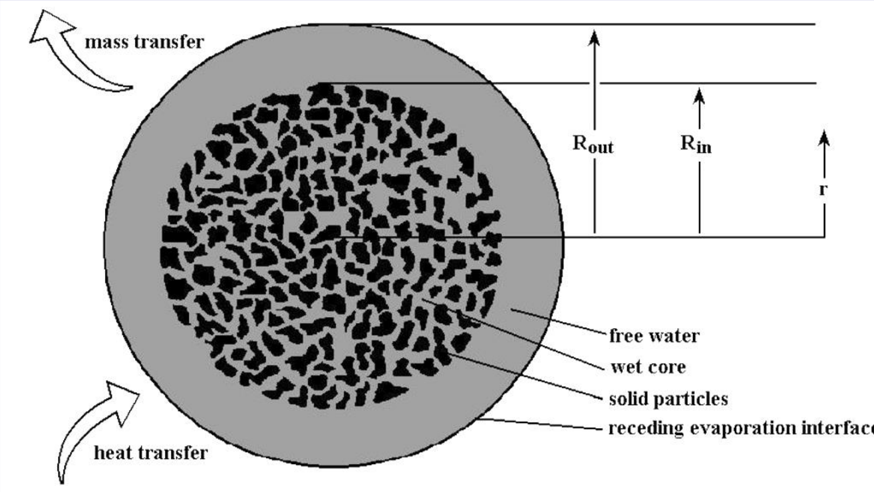
Regime I: We = 100; Oh = 0.04; High impact velocity and low viscosity

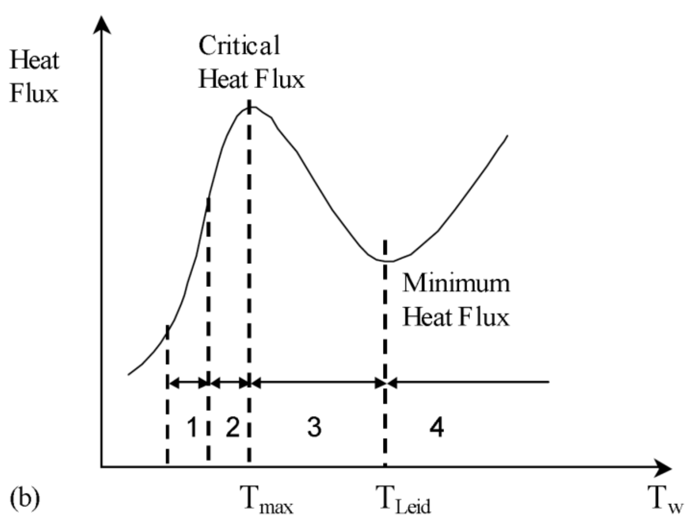
Inkjet Deposition

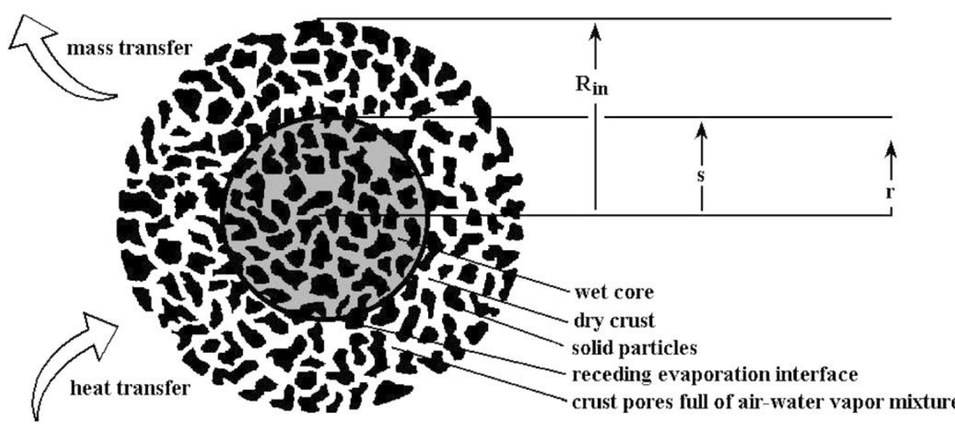
Droplet deposition

Suspension droplet drying









Inkjet Deposition

Droplet deposition

Suspension droplet drying

Zone	Regime	Superheat	Description
1	Film evaporation	Low	- When $T_w < T_{ONB}$, the droplet spreads and evaporates slowly - Total contact of the droplet with the surface - Conduction is the dominant mechanism inside the droplet
2	Nucleate boiling	Intermediate	- When $T_{ONB} \leq T_w \leq T_{max}$, vapor bubbles arise in the droplet - Increase in momentum transport around the droplet causes increase of heat transfer - Partial and intermittent contact of the droplets and solid surface
3	Transition boiling	Intermediate	- When $T_{max} < T_w \leq T_{Leid}$, the frequency of contact of the droplet and solid surface decreases, causing a decrease in heat transfer - Formation of an unstable vapor film between droplet and solid surface
4	Film boiling	High	- When $T_w > T_{Leid}$, a thin and stable vapor film is present - No contact between the liquid and solid surface

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Inkjet Deposition

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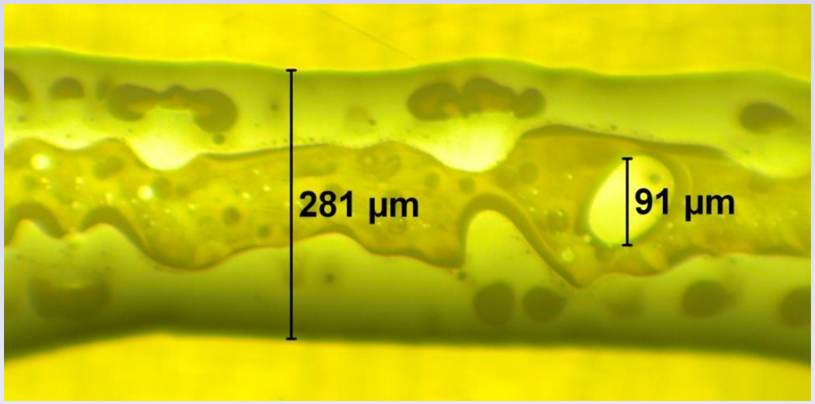
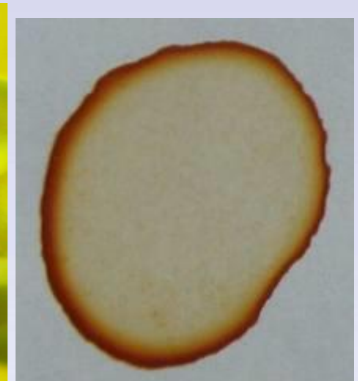
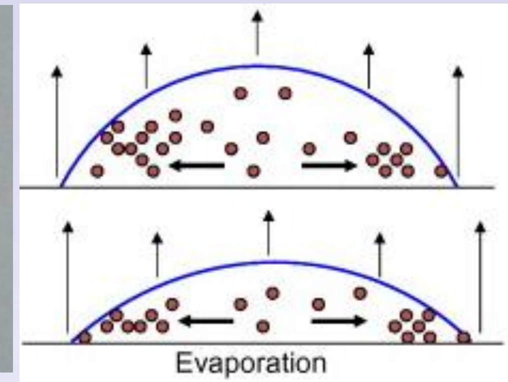
Droplet deposition

- **Suspension droplet drying – coffee ring effect**

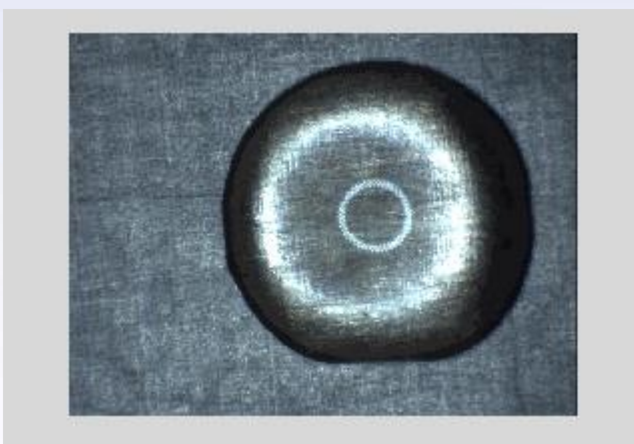


Cracks in the printed line – not conductive





Coffee ring effect: evaporation flow



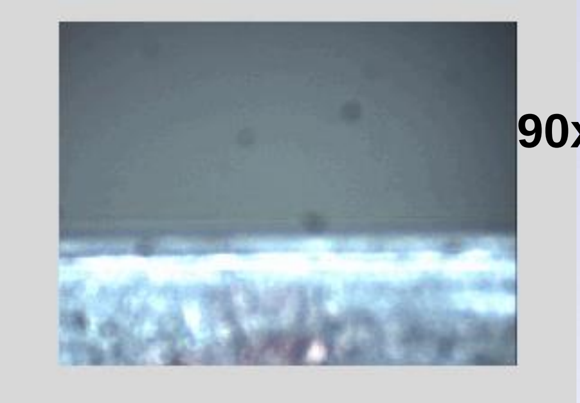
8x faster

Contact line pinned – form a ring

Contact line moving – no ring

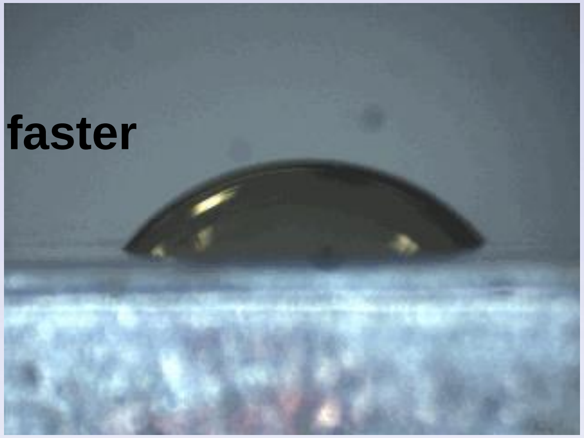
Inkjet Deposition

- Droplet deposition
  - Suspension droplet drying – skinning effect



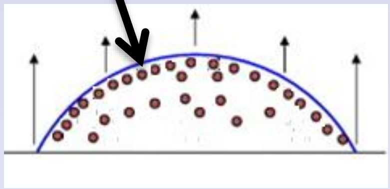
Water on substrate

90x faster



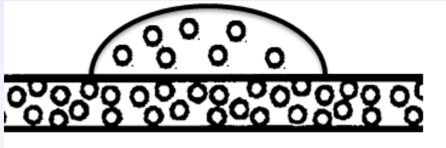
NovaCentrix ink on substrate

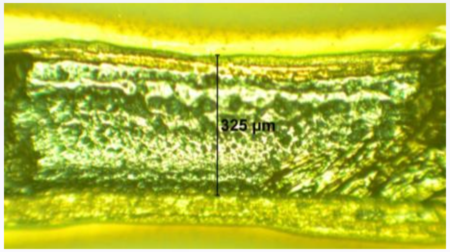
Nanoparticle skin



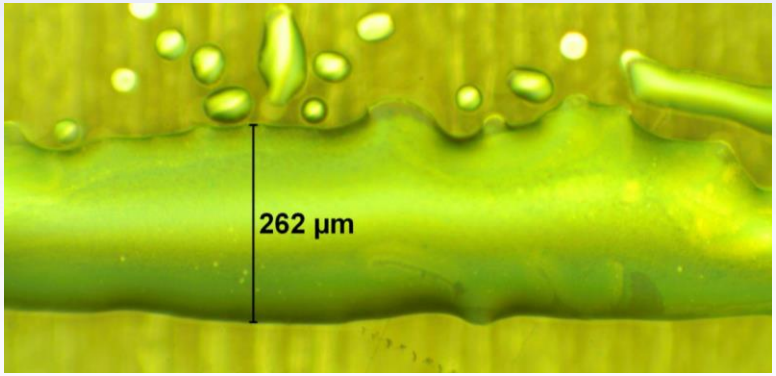
Form a skin on top of the surface, prevent further drying

  - Possible solutions





Porous substrate: change evaporation flow



Larger particle size and high viscosity: reduce particle motion


THANK
YOU!