MAE285 DESIGN OF MICRO/NANO ACOUSTOFLUIDICS DEVICES

1 INTRODUCTION

Ute Compahgre Indian Quartz Rattle: ***Earliest known use of piezoelectric materials — Whitley et al. (1999).***

INTRODUCTION

- The discipline of micro/nano acoustofluidics spans materials, acoustics, structural/solid mechanics, fluid mechanics, micro/nanofabrication, and metrology at small scales.
- We'll briefly introduce the topic with an overview today spanning all the material.
- Keep in mind we only have 24 hours together to cover this topic: a brief period indeed to accomplish anything useful.

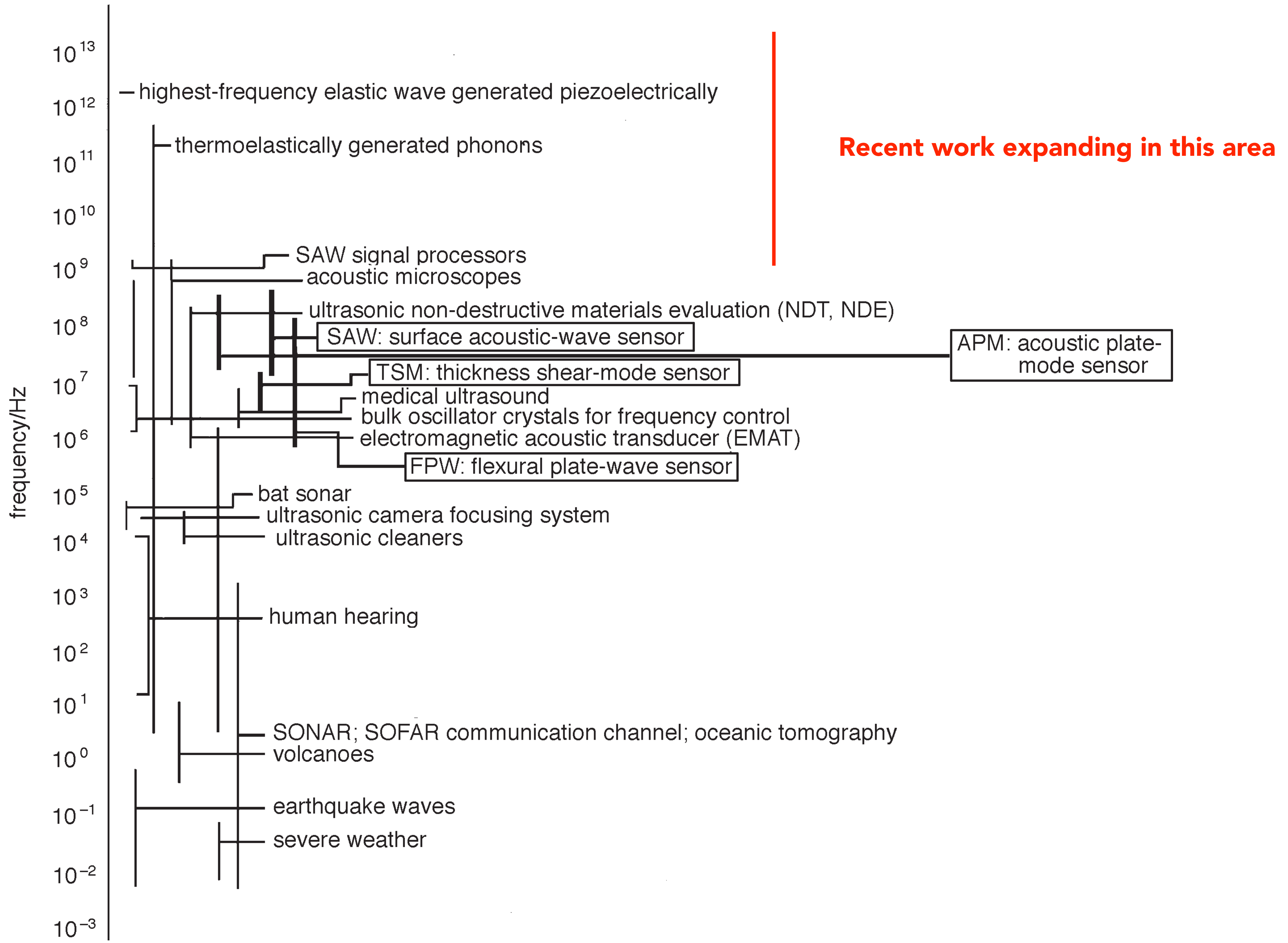
Singing Bowl (from around 100BC)
YouTube: Chinese Singing Bowl 3 — *demiurgeau*

Race/Person	Year	Development
Ute Compahgre Indians	Ancient	Quartz ceremonial rattles: mechanoluminescence
Babylonians	1800BC	Hurrian Melodic Texts
Greece?	~500BC	Music
Han Dynasty China	~100BC	Chinese "singing bowl"
Theophrastus	314BC	Discovery of pyroelectricity
EFF Chladni	1787	Chladni figures
Michael Faraday	1831	Acoustic streaming, Faraday heaping, Faraday waves
	~1850	Seismology (SAW)
August A. E. E. Kundt	1866	Particle collection in tubes from acoustics
Joseph Plateau	1873	Fluid surface instability (dripping faucet)
John William Strutt (Lord Rayleigh)	1878/1879	Instability in and capillary waves of jets
Marie and Pierre Curie	~1880	Discovery of piezoelectricity
Chilowsky and Langevin	1916	SONAR
Schlichting	1932	Acoustic streaming in the boundary layer
King	1934	Acoustic forces on particles
A. E. H. Love	1944	Treatise on acoustics
Clevite Corp	1950	PZT piezoelectric ceramics
White & Voltmer	1965	SAW interdigital electrodes
	1970s	Lithium niobate and tantalate, SAW resonator, ion milling, acousto-optic modulator
Quate & Lemons	1980s	Focusing bulk acoustic wave (microscope)
	1990s	SPUDT, resonators, 3GHz, laser generation of acoustic waves
	2000s	SAW motors, SAW microfluidic *physics*

A very brief history

...of acoustics, ultrasonics, and piezoelectrics

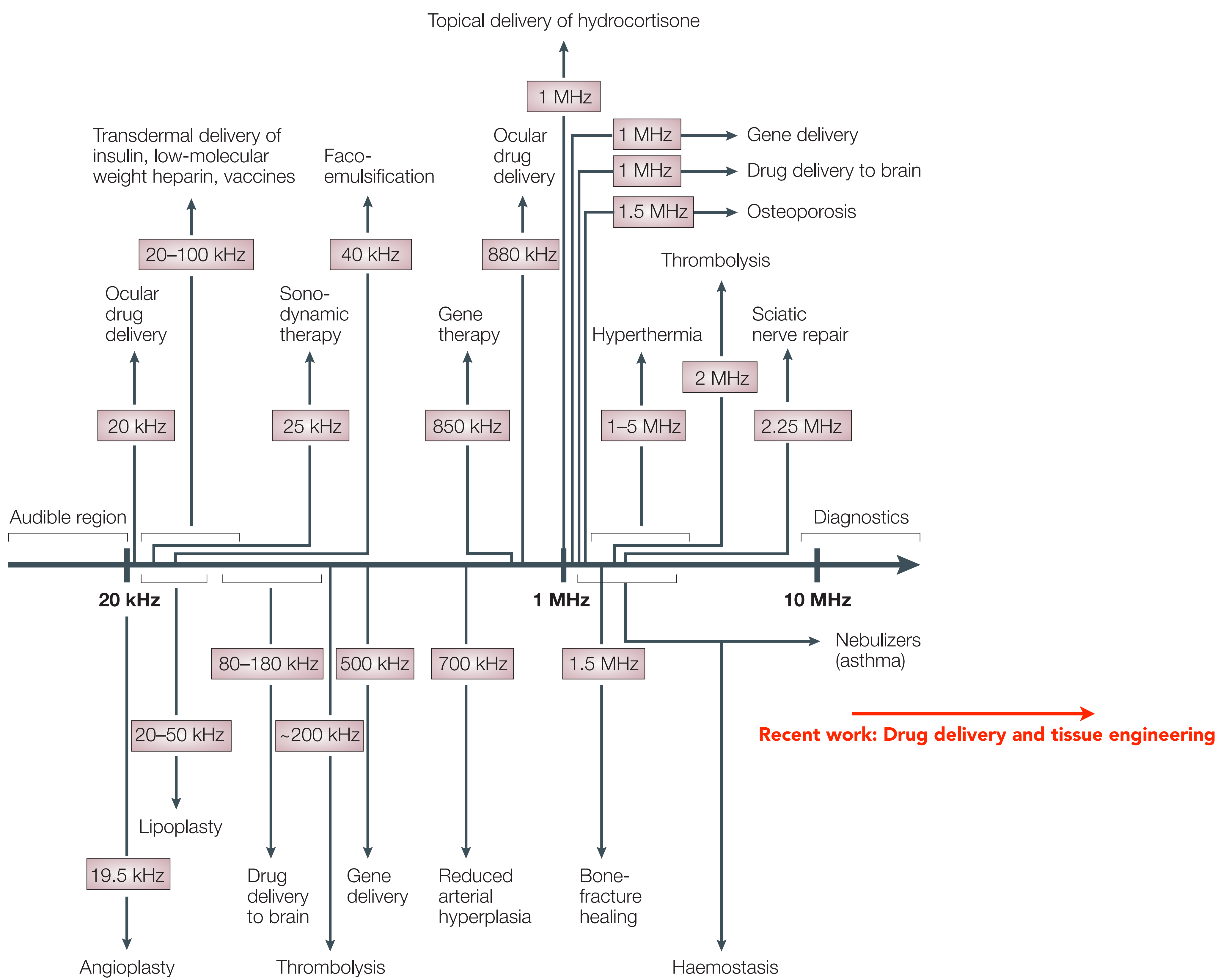
(microfluidics is very recent)



Frequency Range of Acoustics

Spans 15 orders of magnitude

White 1997



Range of medical acoustics and ultrasonics

Mitragotri S. (2005), Nature Reviews Drug Discovery

An average young human can perceive sound at 1 kHz with an amplitude of only 7.8 nm.

The most intense acoustic waves in air have amplitudes of 1.5 mm at 50 kHz.

Amplitude range of acoustics

...spans 10 orders of magnitude

The nonlinearity in hearing and sound generation in man-made and natural systems is *remarkable*

Eguíluz et al., 2000; Hughes, et al., 2009

Acoustics in microsensors

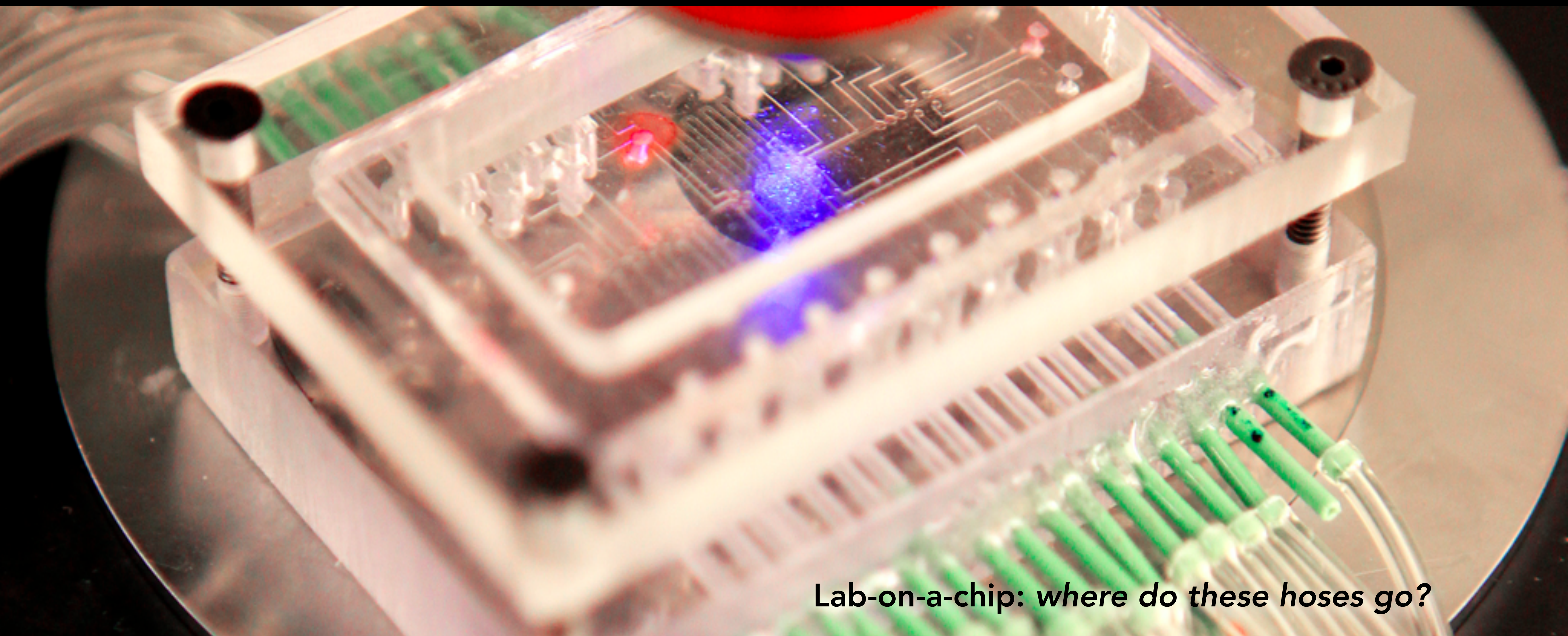
- Topic in itself
- Good general review papers
  - Lucklum and Hauptmann (2006)
  - Grate et al. (1993)
  - Marx (2003)
- Love-wave devices: McHale et al., 2003
- Biosensors: Länge et al., 2008
- Molecular binding: Čavić et al., 1999
- We will focus principally on actuation in this as
  - the developments in sensing have already been reported on
  - much of the work in that area has progressed well in advance of actuation

Quartz Crystal Microbalance Chips

WHY ACOUSTIC MICRO/NANOFLUIDICS?

LAB ON A CHIP?
MORE LIKE CHIP IN A LAB...

WHY ACOUSTIC MICRO/ NANOFLUIDICS?



FLUID ACTUATION IS THE KEY PROBLEM IN MICROFLUIDICS, MADE WORSE IN NANOFLUIDICS

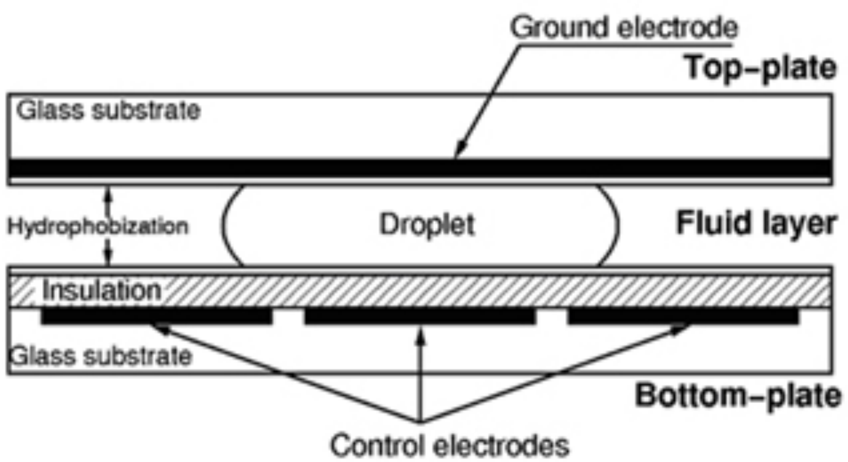
Driving force	Subcategorization	Remarks; representative references
Pressure gradient ∇p		Familiar case as in pipe flow
Capillary effects	Surface tension, γ	Capillary pressure difference
	Thermal	(e.g., Sammarco & Burns 1999)
	Electrical (electrocapillarity)	(e.g., Pollack et al. 2000; Prins et al. 2001)
	Surface tension gradients, $\nabla\gamma$	Typically involve thin films
	Chemical	(e.g., Gallardo et al. 1999)
	Thermal	(e.g., Kataoka & Troian 1999)
	Electrical	
	Optical	Photoresponsive materials
Electric fields **E**	DC electro-osmosis	Uniform velocity field
	AC electro-osmosis	Rectified flows
	Dielectrophoresis	Response $\propto \nabla \mathbf{E}^2$
Magnetic field/ Lorentz forces	Magnetohydrodynamic stirring	(e.g., Bau et al. 2001)
Rotation	Centrifugal forces	(e.g., R.D. Johnson et al. 2001)
Sound	Acoustic streaming	***Last 5–10 years!***

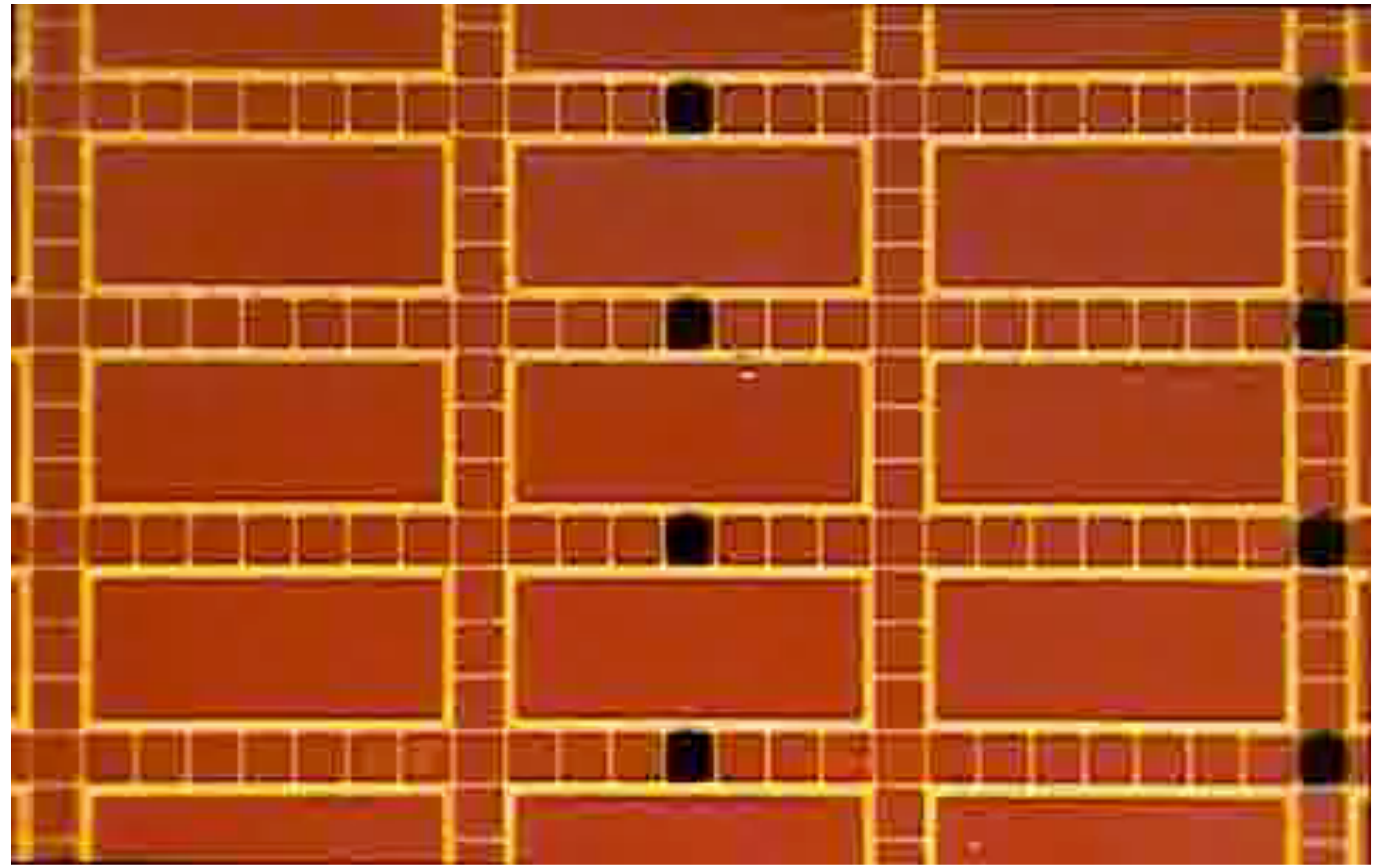
Stone and Stroock 2004

Methods for actuation in microfluidics

Absence of acoustic forces?

***Nano*fluidics?**





Prof Fair, Duke Uni 2013

Liquid Logic 2012

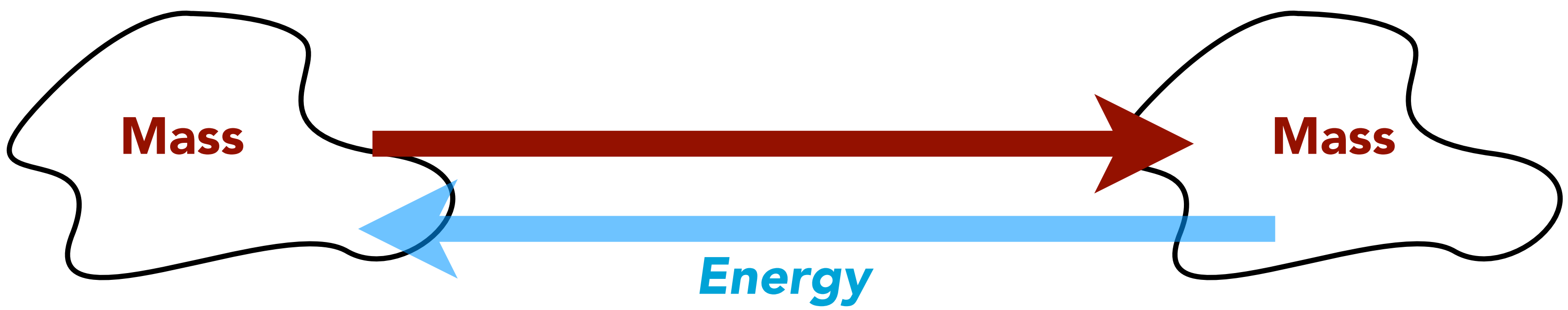
Digital Microfluidics

Via electrowetting…spot the problem?

Transport equation $E = mc^2$

$m = E/c^2$ ***Mass transport equation***

For a system in equilibrium...



...the amount of *mass transfer* depends upon the energy transfer divided by the speed squared...

$m_{\mathrm{El}} = E/c^2_{\mathrm{light}}$	10^6	$m_{\mathrm{Ac}} = E/c^2_{\mathrm{sound}}$
Electricity driven	**<<**	**Acoustics driven**

Lighthill 1978
See Friend & Yeo RMP 2011 and Dentry, et al PRE 2014 for corrections

Something to think about...

...mass transport from acoustics is far more effective

Acoustic Waves Show a Maximum (Practical) Amplitude

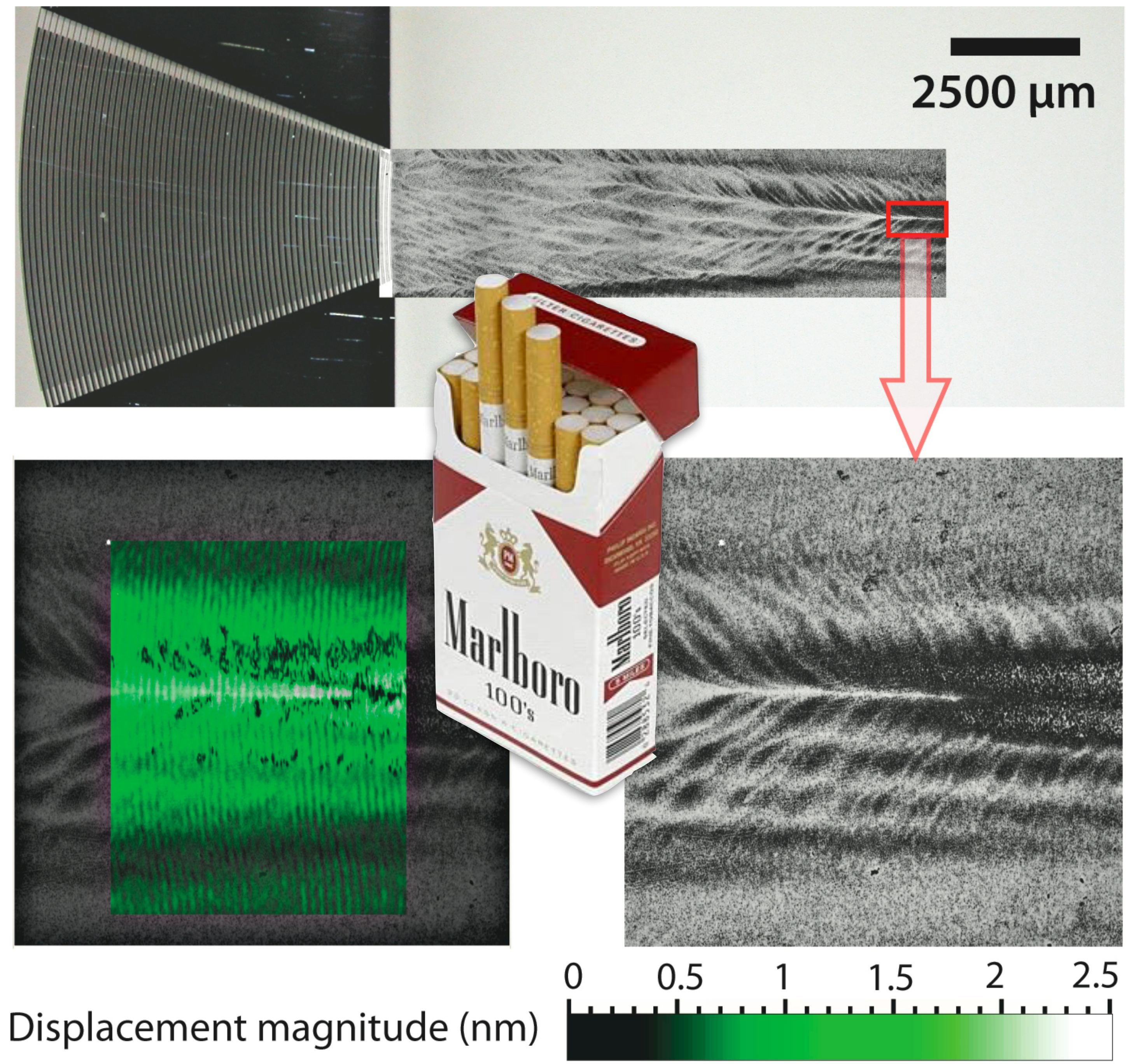
- **Maximum vibration velocity *v* ~ 1 m/s:** a key observation of vibration-driven phenomena

UC San Diego Jacobs School of Engineering

MADLab Medically Advanced Devices Laboratory

Surface Acoustic Wave *(SAW)* Fluidics

- **Maximum vibration velocity v ~ 1 m/s:** a key observation of vibration-driven phenomena
- Frequency f ~ 10 MHz to 10 GHz
- Amplitude $v/(2\pi f)$~ 10 nm to 10 pm
- Acceleration a ~ $2\pi f\, v$ ~ 100 Mm/s^2 to 100 Gm/s^2 = **millions to billions of g's**



10~100 nm smoke particle patterning at 30 MHz

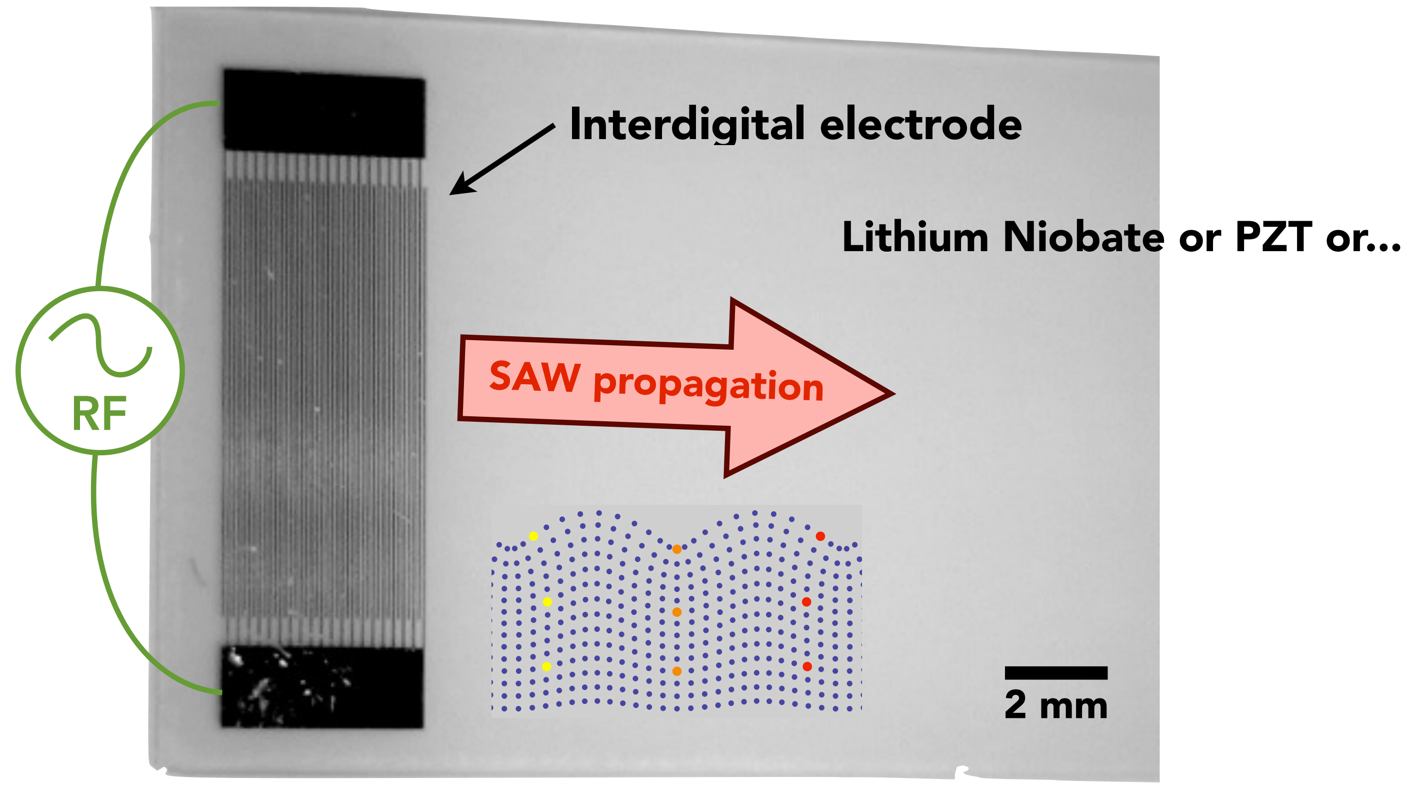
M. Tan, J. Friend and L. Yeo, Applied Physics Letters **91**, 224101 (2007).

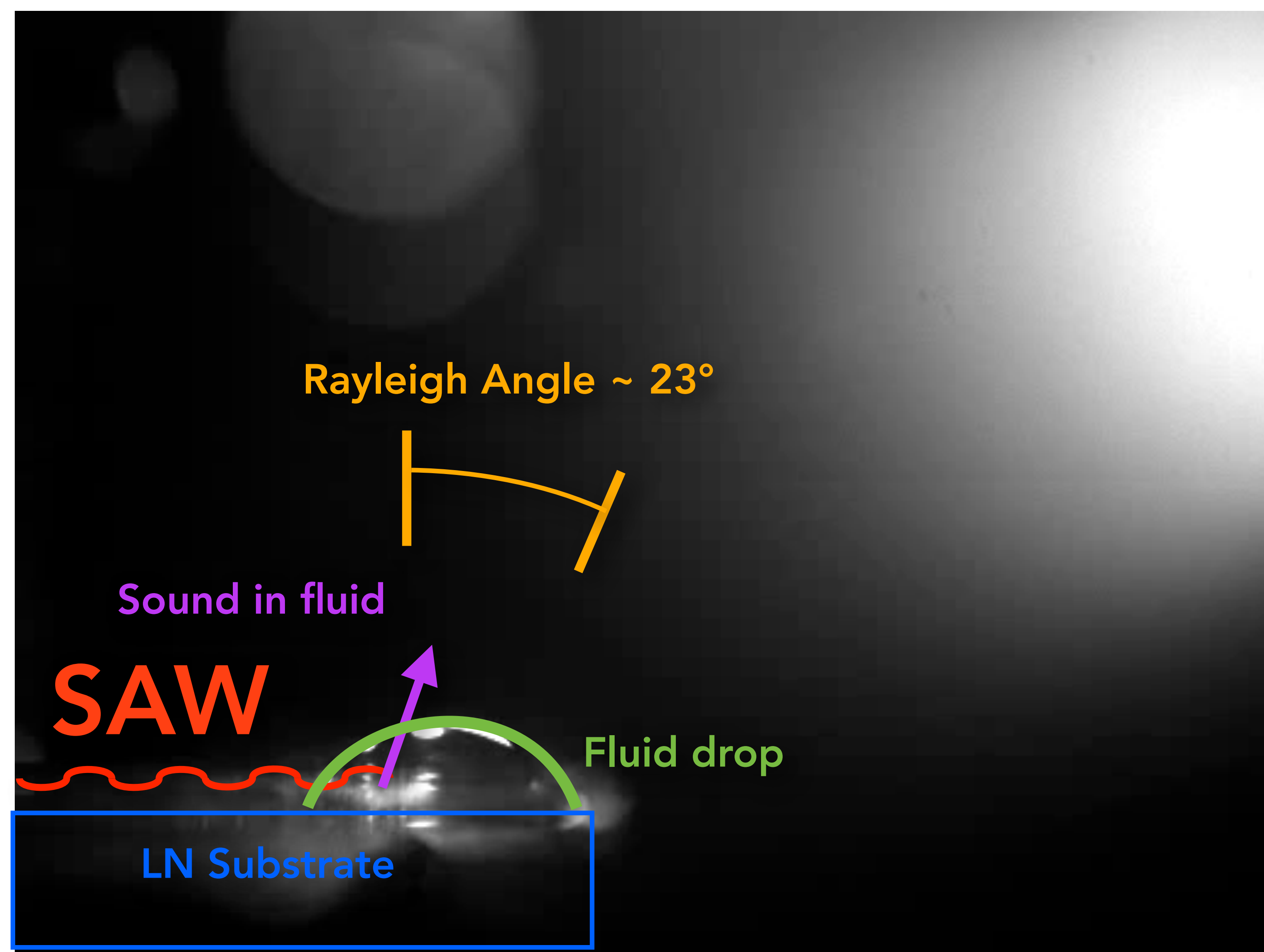
UC San Diego
Jacobs School of Engineering

MADLab
Medically Advanced Devices Laboratory

Surface Acoustic Wave (SAW) Fluidics

- Frequency f ~ 10 MHz to 10 GHz
- Maximum vibration velocity v ~ 1 m/s
- Amplitude $v/(2\pi f)$~ 10 nm to 10 pm
- Acceleration a ~ $2\pi f$ ~
  100 Mm/s^2 to 100 Gm/s^2 =
  millions to billions of *g*'s
- **SAW fluidics = fluid in the path of this acceleration**
  - Axially-polarized compression wave—**sound at >160dB**—propagates into droplet at *Rayleigh angle*
  - Compression and viscous losses give rise to steady **acoustic streaming**
    (Nyborg, Schlicting, Eckart, Markham)
- Friend & Yeo, *Reviews of Modern Physics*, **83,** 647-704, 2011 and Connacher W. Lab Chip 18:1952-1996, 2018.



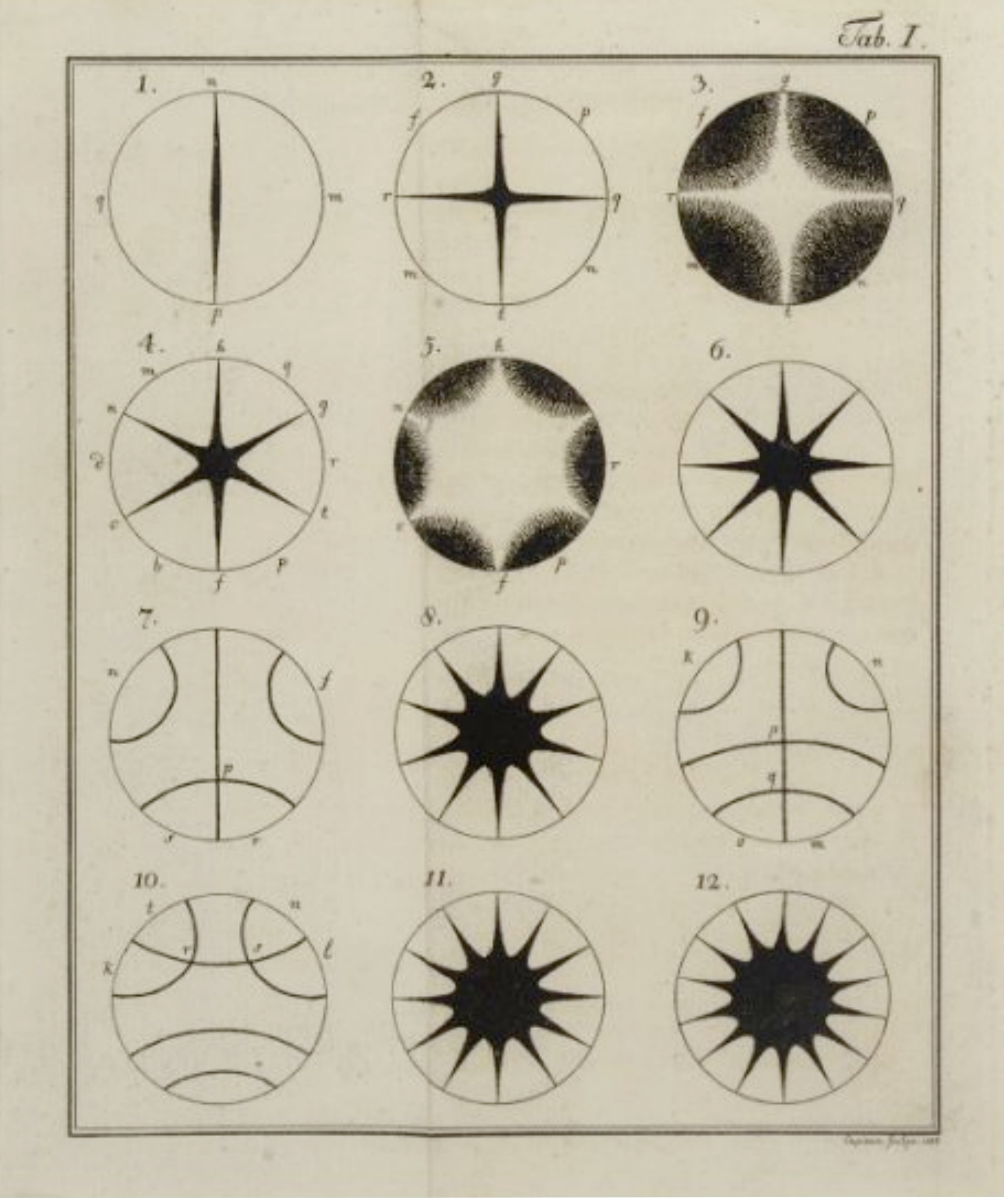


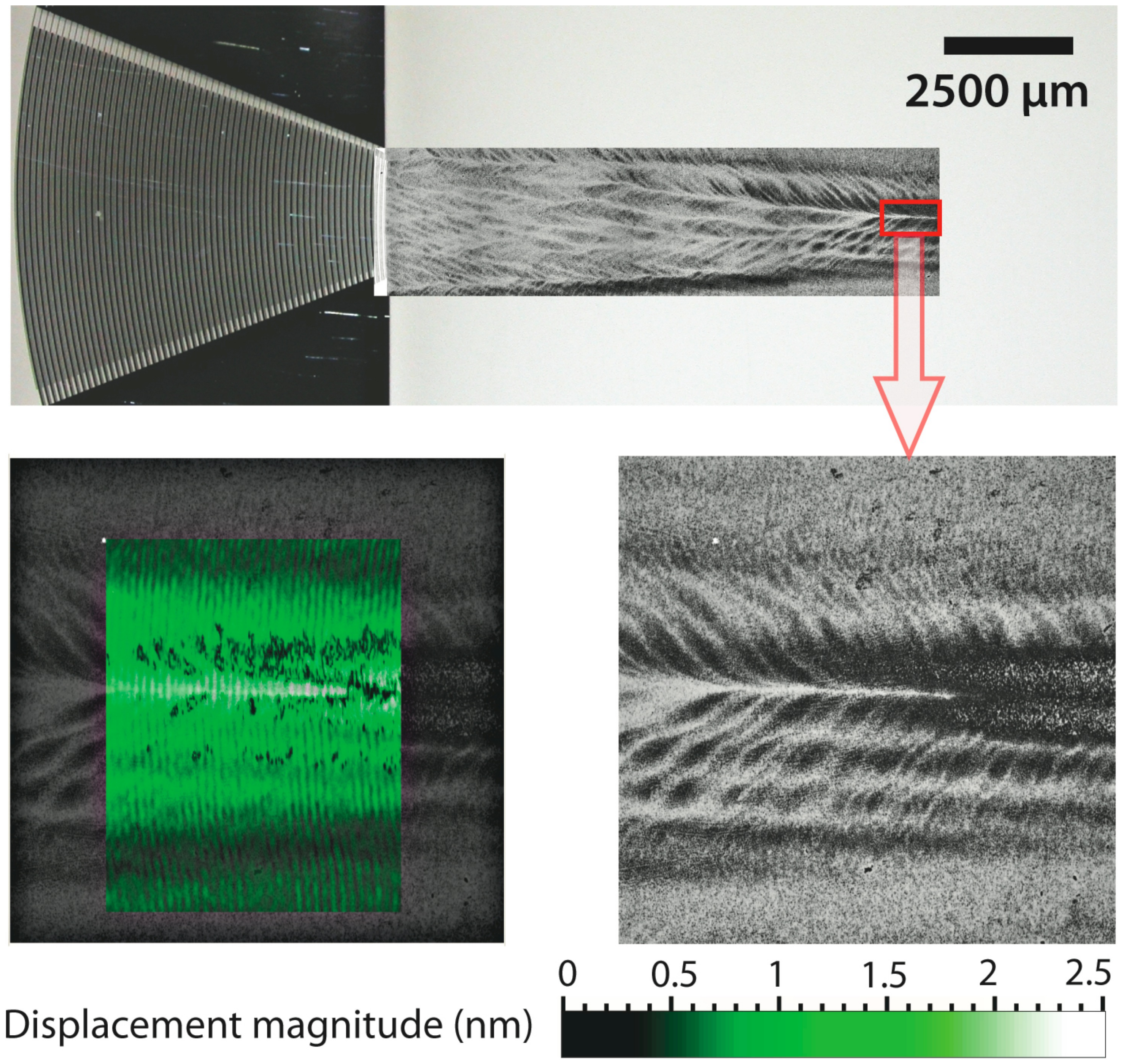
Illustrating the acceleration: *A smoking student found patterns on a SAW device*

Why was he smoking in the lab?

Which is cheaper: $500K laser Doppler vibrometer or a pack of cigarettes + increased risk of lung cancer?

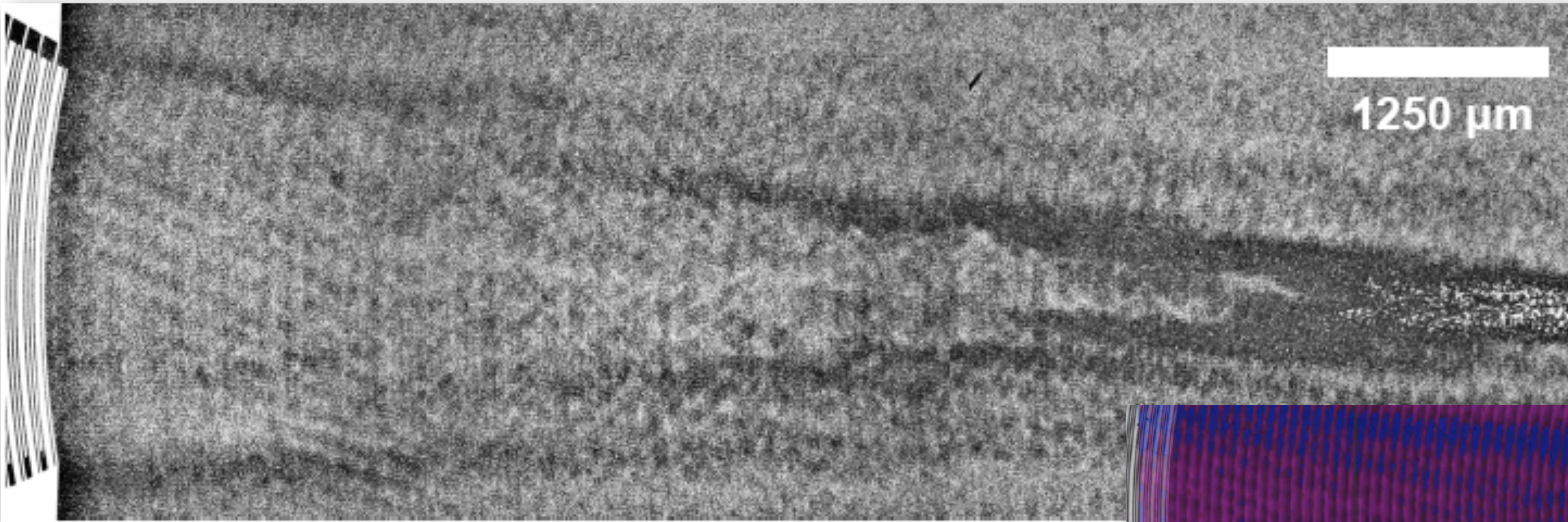
MK Tan, et al., *Appl Phys Lett* **91**, 224101 (2007).



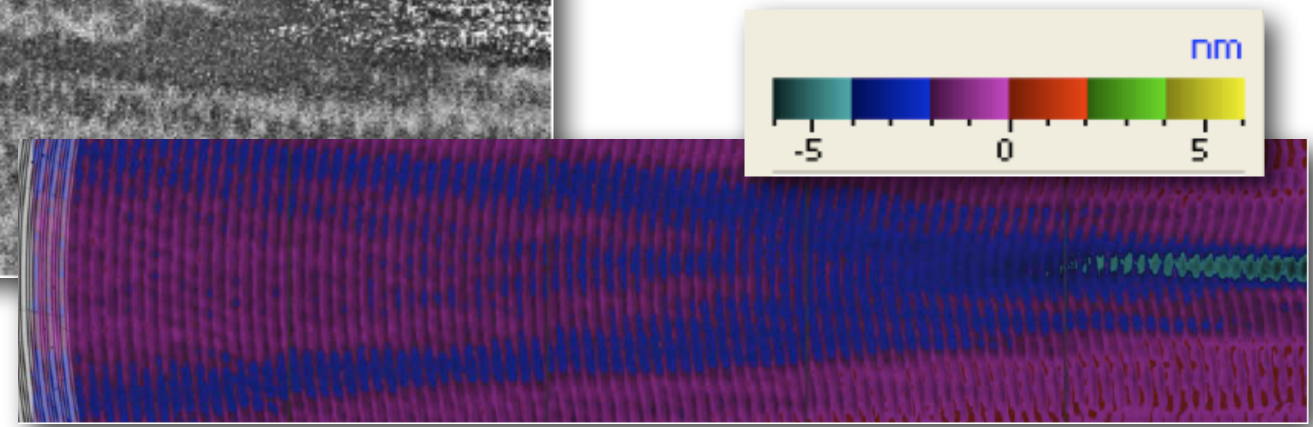


MK Tan, et al., *Appl Phys Lett* **91**, 224101 (2007).

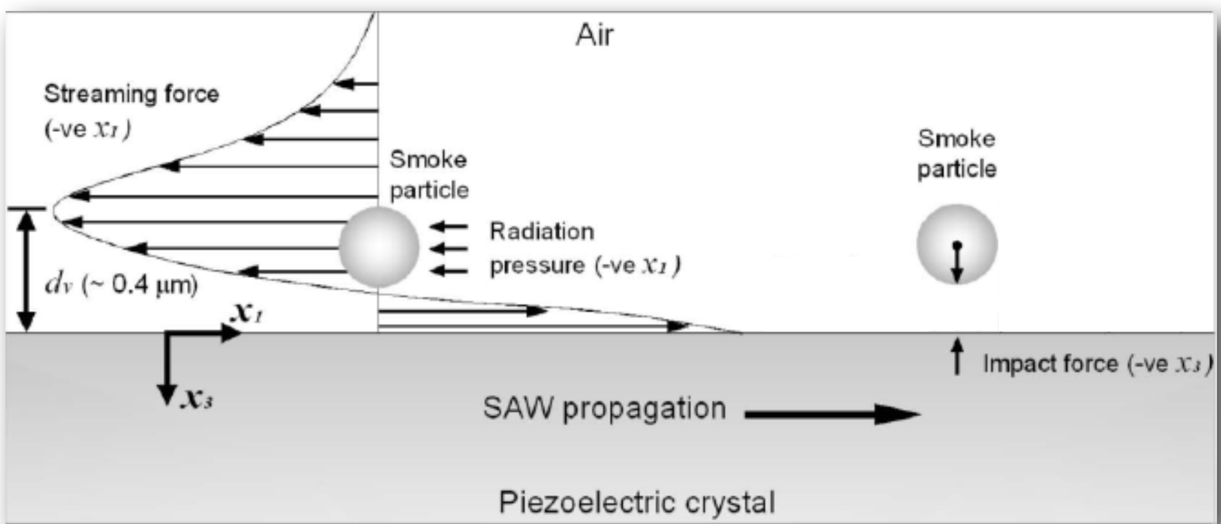
Smoke-based Chladni diagrams
for SAW identification

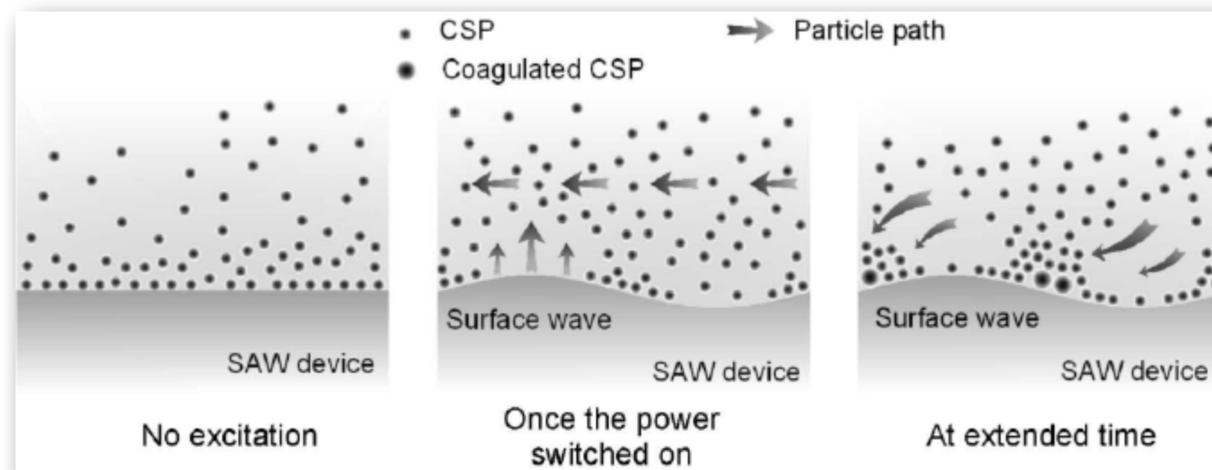


Smoke collection on SAW device



Measured with laser Doppler vibrometry





MK Tan, et al., *Appl Phys Lett* **91**, 224101 (2007).

Smoke Visualisation

Cigarette smoke particles ~ **10 nm** oily soot
Acceleration **inertially** ejects particles into
acoustic streaming layer to quiescent nodes

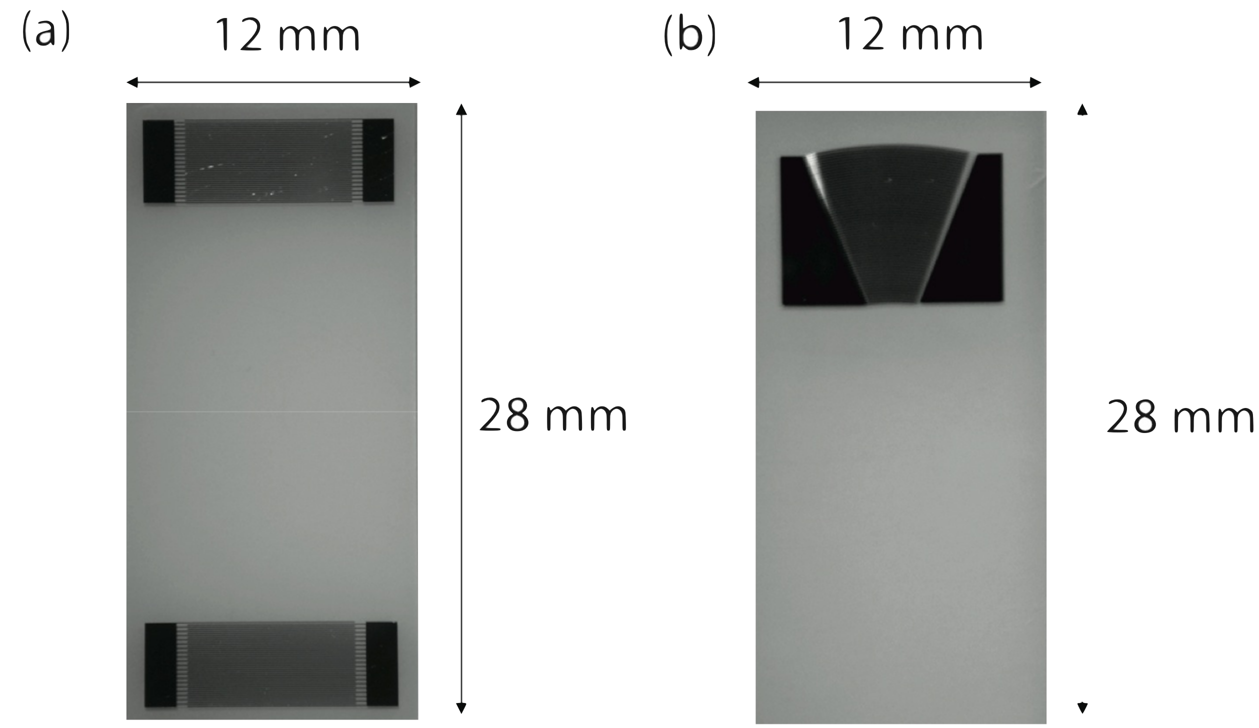
Experiment

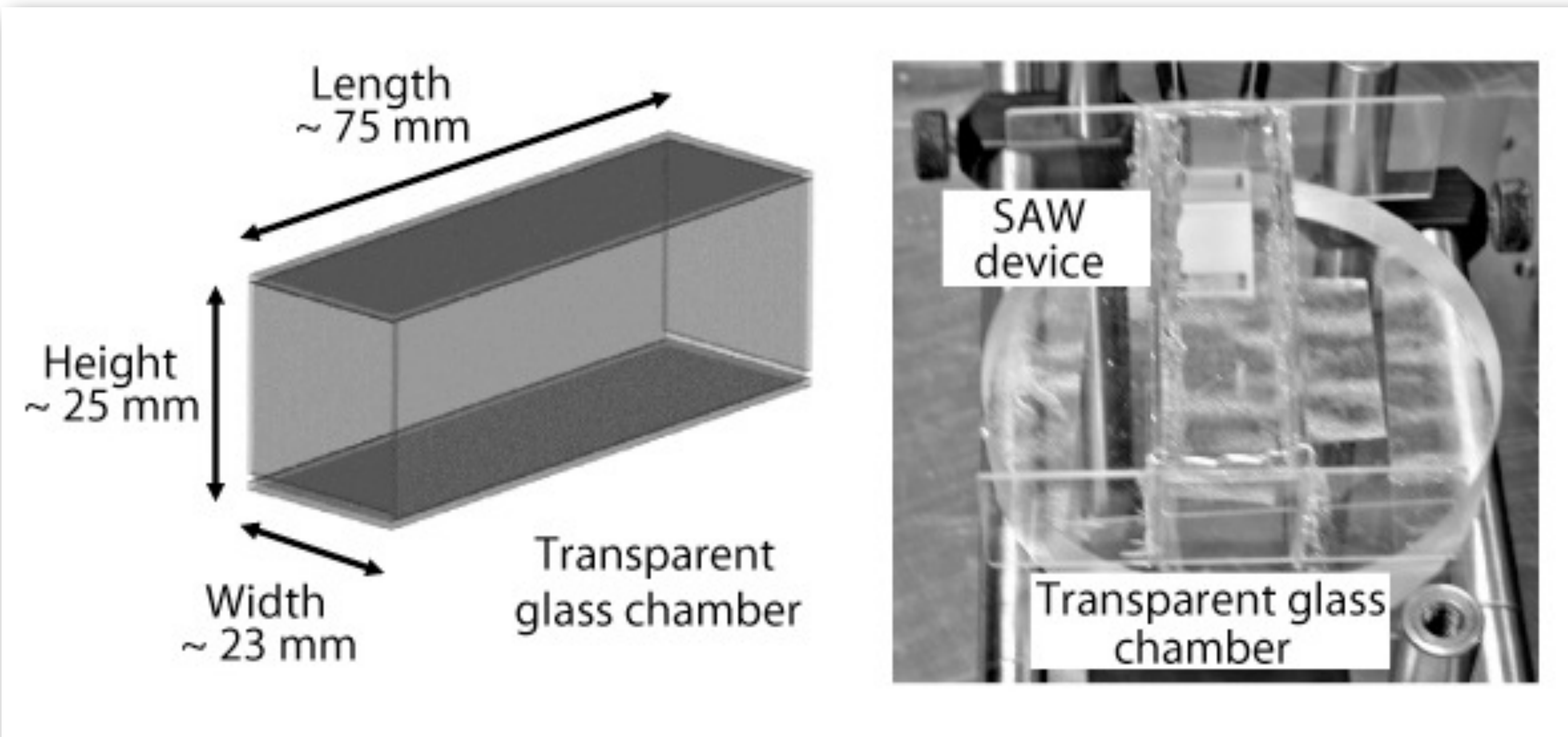
Frequency: 20, 30, 50, 135 MHz

2 different types of transducers:

- Straight IDT
- Curved (focusing) IDT (SPUDT)

Smoke particles* uniformly deposited
(mean diameter **250 nm)**





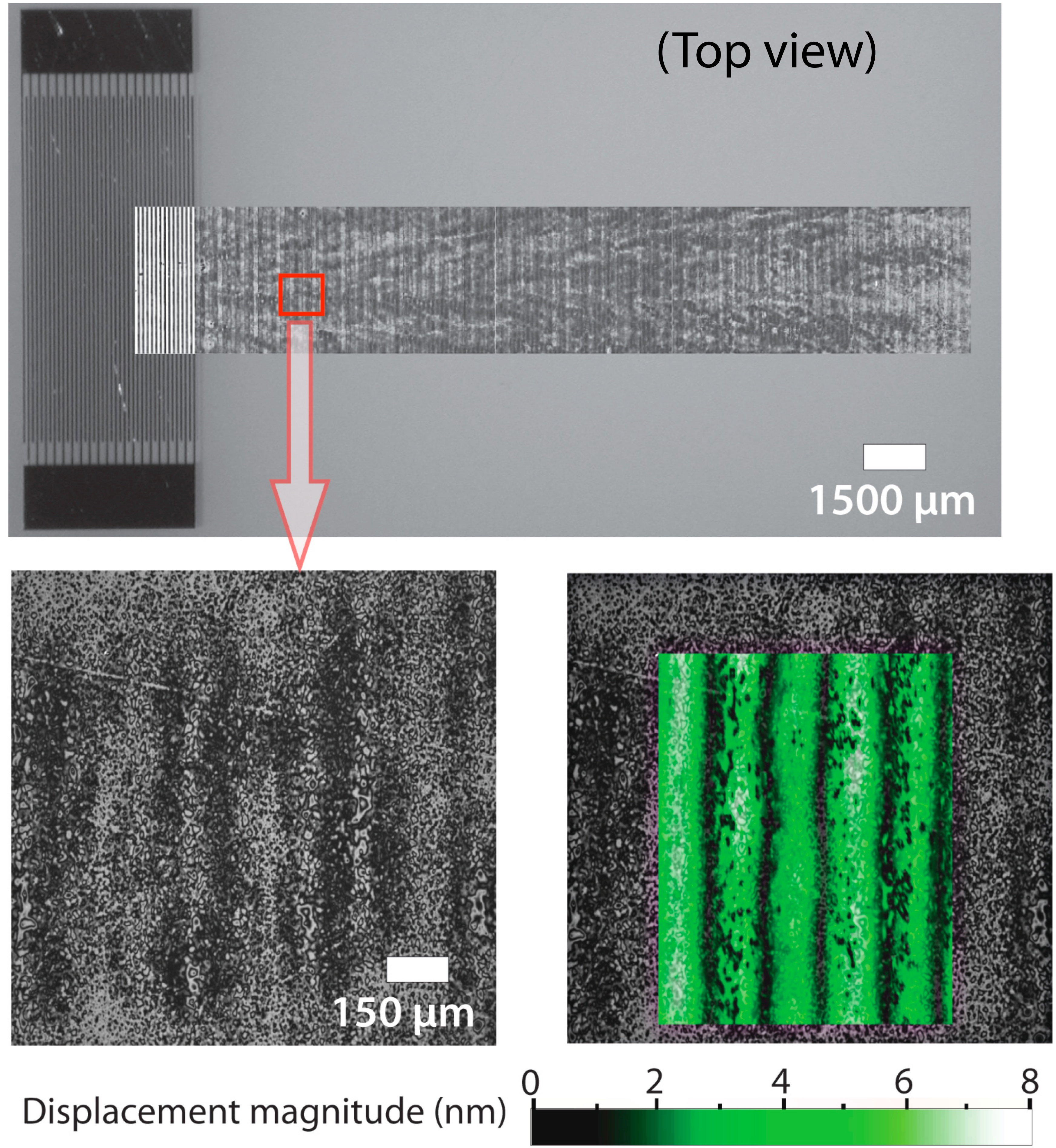
*From *cigarettes*: Marlboro Light 100s, Rayleigh-Durham NC USA

Experimental Results

- 20 MHz
- Straight IDT
- Standing wave SAW

(via reflections from free edges)

For standing wave SAW, particles are deposited on the displacement nodal lines



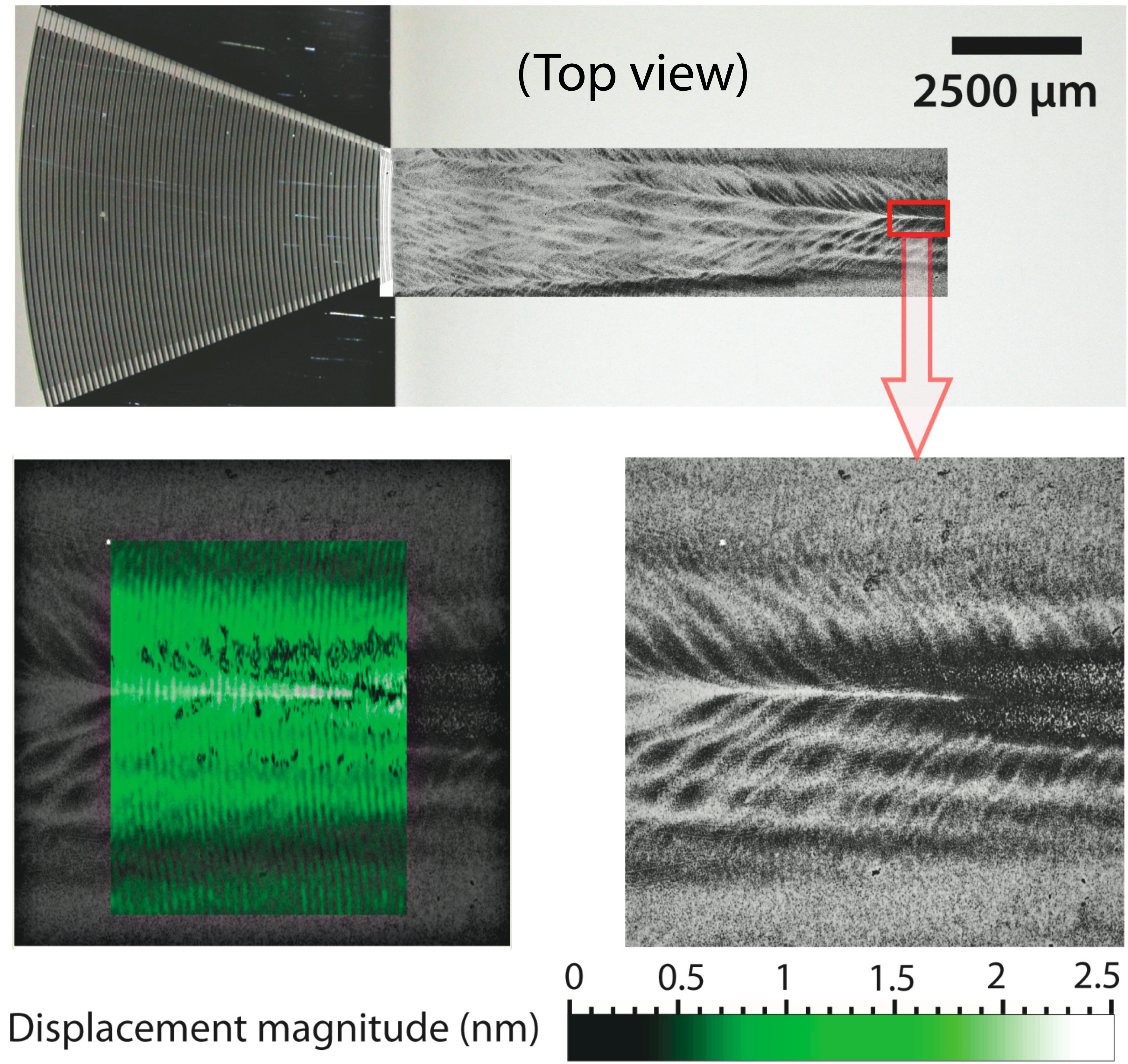
M. Tan, J. Friend and L. Yeo, Applied Physics Letters **91**, 224101 (2007).

Experimental Results

- 30 MHz
- Elliptical SPUDT IDT
- Reflections suppressed

For traveling wave SAW, particles are deposited at quiescent displacement regions...

What's the reason for this behavior?



M. Tan, J. Friend and L. Yeo, Applied Physics Letters **91**, 224101 (2007).

Particle patterning on a vibrating plate (*Chladni figures*) [1,2]

Particle size: 10 μm to 10 mm		Particle size: 100 nm to 1 μm	
Fluid medium: air		Fluid medium: water	
Low frequency ($< 10^6$ Hz)		High frequency ($> 10^6$ Hz)	
Large particles move to nodal regions [1,2]	Small particles move to antinodal regions [1,2]	**Large particles** move to antinodal regions [3]	Small particles move to nodal regions [3]
Mechanisms: Bouncing and Faraday heaping		Mechanism: Boundary layer streaming	

Competing mechanisms: which dominates?

[1] E. Chladni, Entdeckungen uber die Theorie des Klanges (Weidmanns, Erben und Reich, 1787).
[2] M. Faraday, Philosophical Transactions of the Royal Society of London **121**, 299 (1831).
[3] M. Dorrestijn, et al., Physical Review Letters **98**, 26102 (2007).

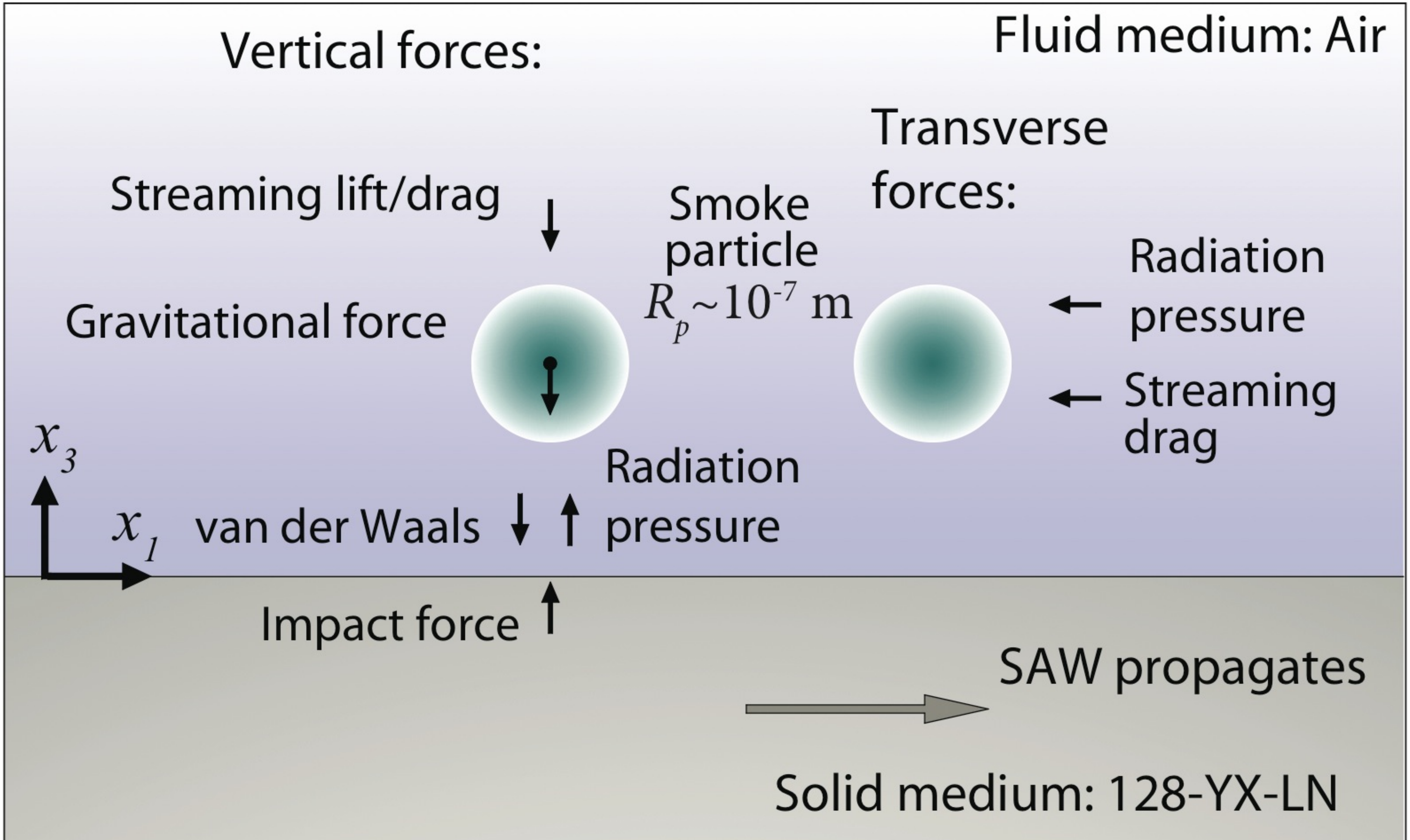
Particle patterning on a vibrating plate (*Chladni figures*) [1,2]

Solid microsphere powder [1]	**Airborne smoke nanoparticle** [2]
Fluid medium: Air	
Particle size: 1 to 10 μm	**Particle size: 10 to 100 nm**
Particles move *away* from high vibration amplitude regions	
Low resolution	**High resolution**
Mechanism: Bouncing	**Mechanism: Bouncing and boundary layer streaming**

[1] T. Reeder, E. Westbrook, and D. Winslow, Electronics Letters **6**, 30 (1970).
[2] M. Tan, J. Friend and L. Yeo, Applied Physics Letters **91**, 224101 (2007).

Analysis

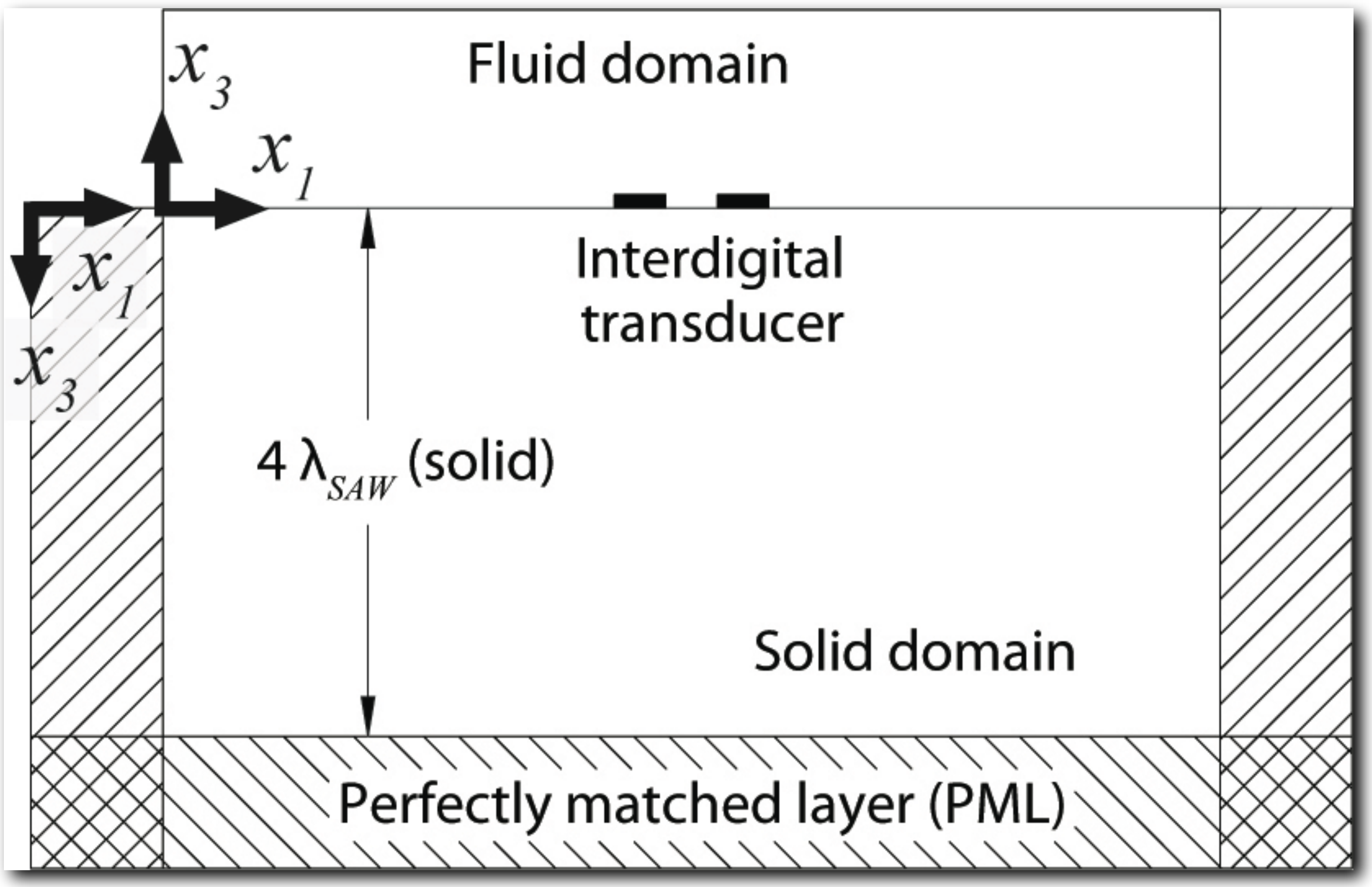
Forces exerted on a smoke particle



Numerics

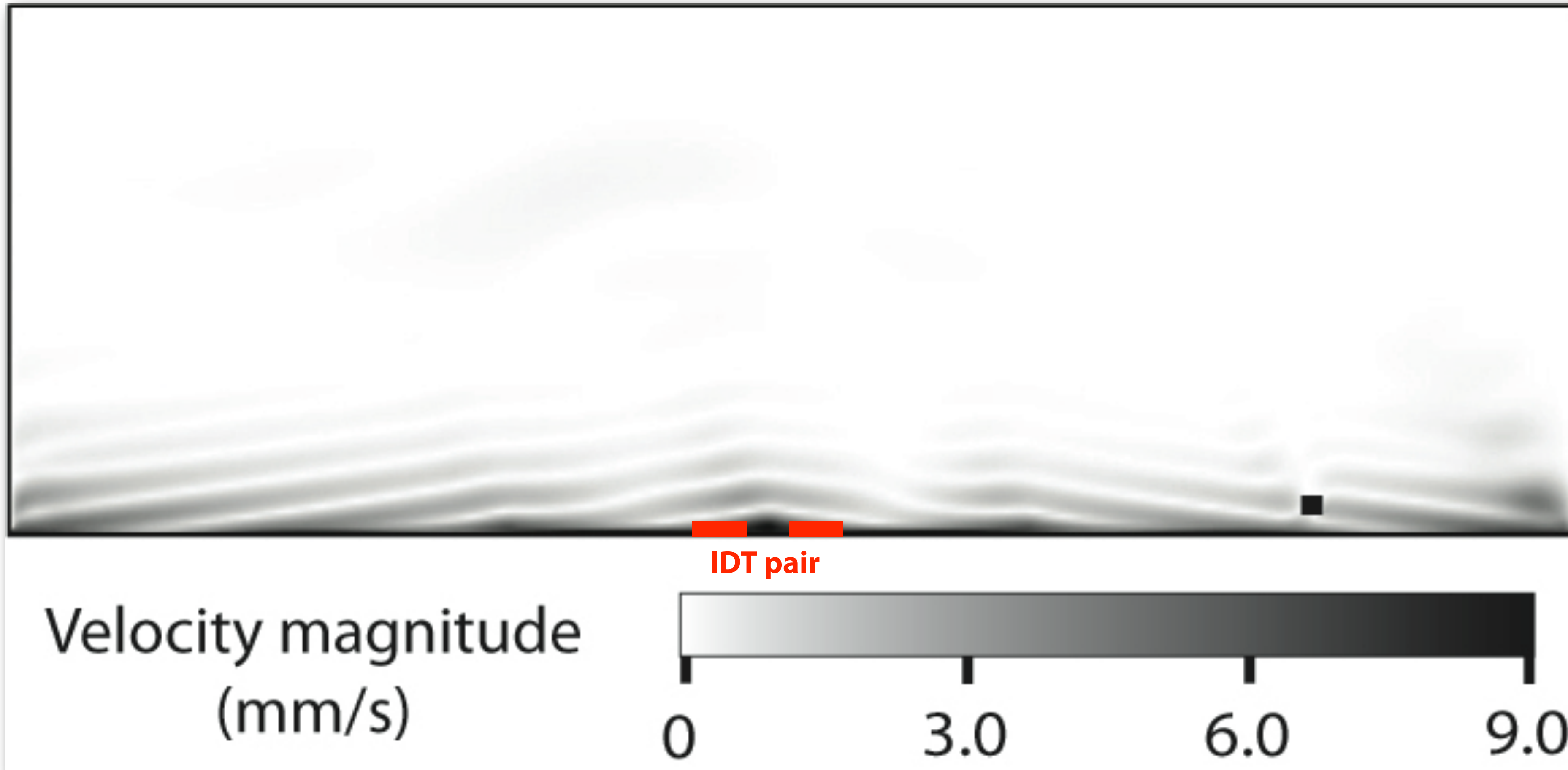
2-D numerical model (FDTD) constructed to

- Verify the flow is driven by boundary layer streaming
- Estimate the order of magnitude of the
  - Acoustic radiation pressure (p_1)
  - Acoustic streaming velocity (u_{dc})



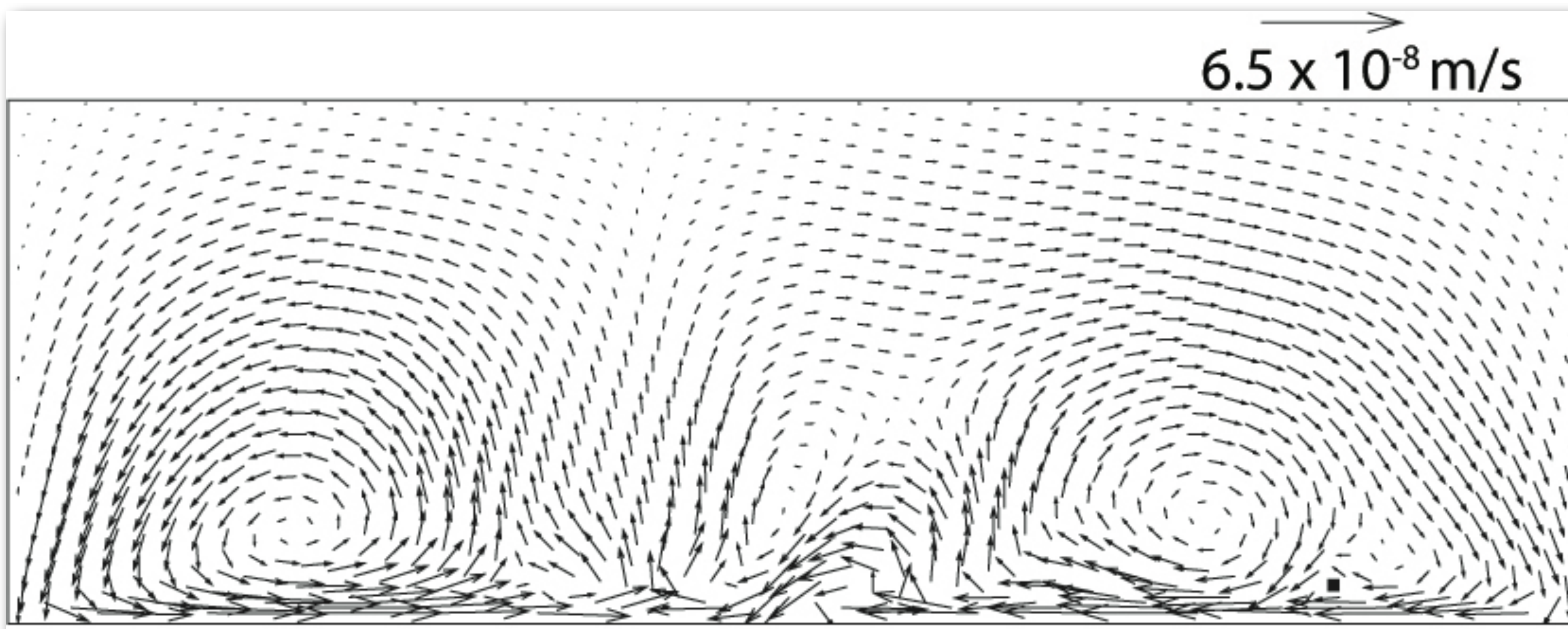
Numerical Results (fluid)

Sound velocity field



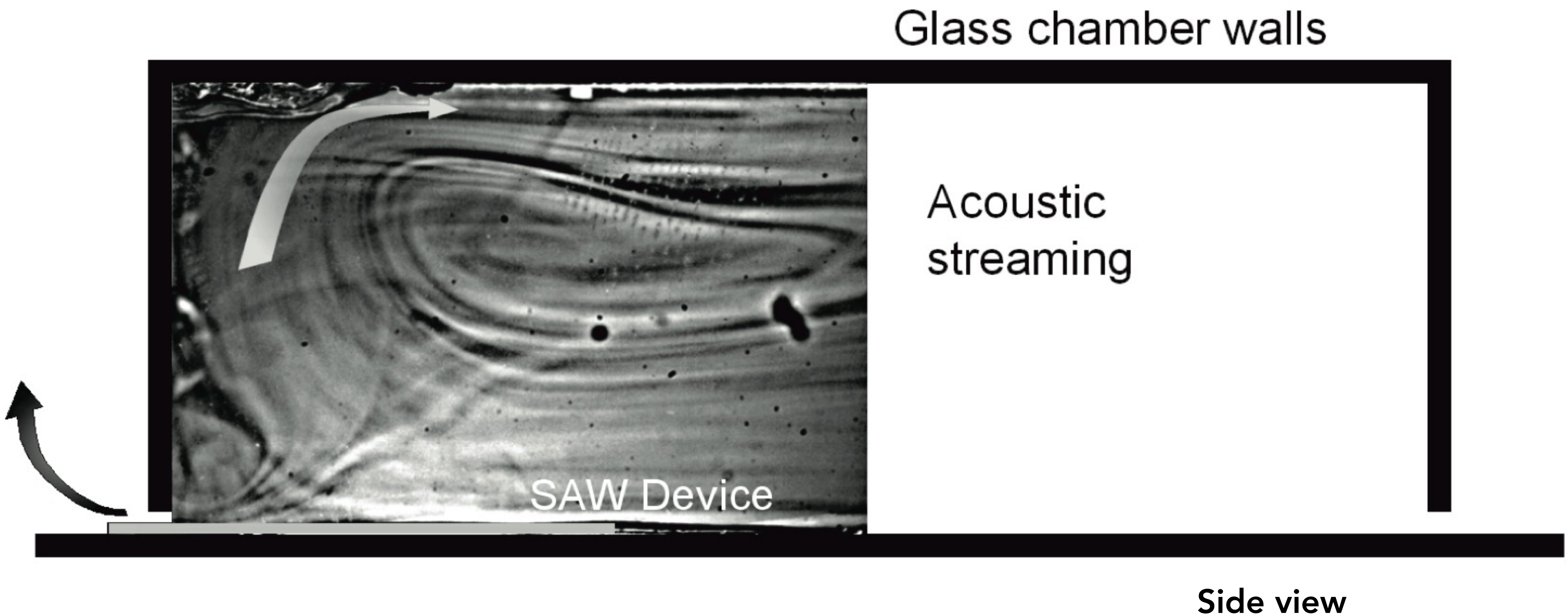
M. Tan, J. Friend and L. Yeo, Applied Physics Letters **91**, 224101 (2007).

Acoustic streaming velocity field



High streaming velocity close to substrate surface in a cellular configuration toward acoustic radiation source

Experimental Results (fluid)



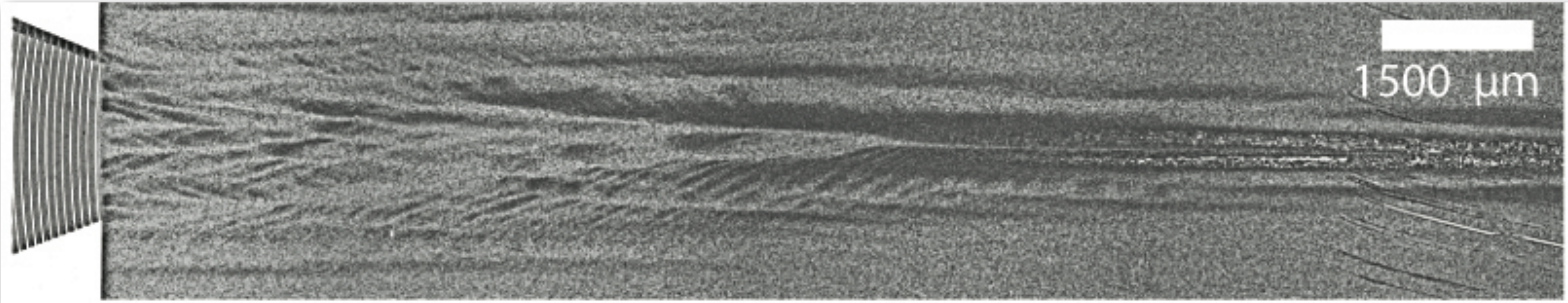
Close to the substrate surface, the airflow is in a direction opposite the propagating SAW.

Experimental Results

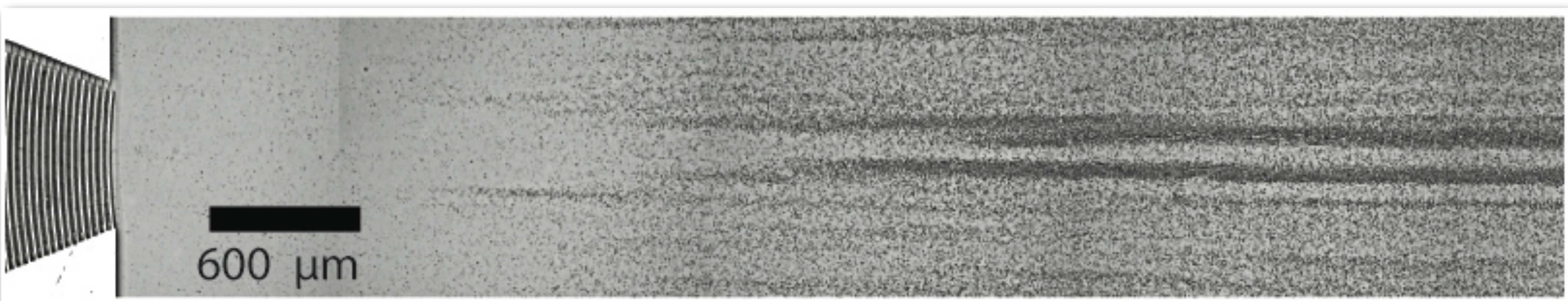
Images of particle patterning
(Top view)

SAW exposure time: **30 seconds**

50 MHz focusing transducer



135 MHz focusing transducer (exposure time ~ **30 seconds**)



M. Tan, J. Friend and L. Yeo, Applied Physics Letters **91**, 224101 (2007).

Focusing effect is visible for both cases.

As the frequency is increased, the effect weakens. ***Why?***

Effect of Particle Size

Viscous boundary layer thickness $\delta_v = \sqrt{2\mu/\rho\omega}$

≈ **490 nm** for 20 MHz SAW

≈ **73 nm** for 135 MHz SAW

Mean diameter of smoke particle **250 nm**

$\phi_p < \delta_v$ for 20 MHz SAW

$\phi_p > \delta_v$ for 135 MHz SAW

Deposition rate ↓ as frequency ↑

particles are less affected by viscous boundary layer as frequency ↑

Flow in boundary layer is significant: viscous dissipation of *shear*

Results

Calculating the order of magnitude for forces on a particle...

Force	$R_p \sim 10^{-7}$ m	$R_p \sim 10^{-8}$ m
$F_{\text{vdW}} \propto R_p$	10^{-8} N	10^{-9} N
$F_{\text{gv}} \propto R_p^3$	10^{-10} N	10^{-13} N
$F_{\text{Imp}} \propto R_p^3$	10^{-4} N	10^{-7} N
$F_{\text{Rad}} \propto R_p^2$	10^{-15} N	10^{-17} N
$F_{\text{lift}}^{dc} \propto R_p$	10^{-16} N	10^{-17} N
F_p^y	$+10^{-4}$ N	$+10^{-7}$ N
F_p^x	-10^{-15} N	-10^{-17} N

M. Tan, J. Friend and L. Yeo, Applied Physics Letters **91**, 224101 (2007).

Results

...Predicts the mechanism of particle patterning

Force	$R_p \sim 10^{-7}$ m	$R_p \sim 10^{-8}$ m
$F_{\mathrm{vdW}} \propto R_p$	10^{-8} N	10^{-9} N
$F_{\mathrm{gv}} \propto R_p^3$	10^{-10} N	10^{-13} N
$F_{\mathrm{Imp}} \propto R_p^3$	10^{-4} N	10^{-7} N
$F_{\mathrm{Rad}} \propto R_p^2$	10^{-15} N	10^{-17} N
$F_{\mathrm{lift}}^{dc} \propto R_p$	10^{-16} N	10^{-17} N
F_p^y	$+10^{-4}$ N	$+10^{-7}$ N
F_p^x	-10^{-15} N	-10^{-17} N

Vertical particle motion: large surface acceleration

Horizontal particle motion: streaming transport

Successive bouncing to quiescent region

M. Tan, J. Friend and L. Yeo, Applied Physics Letters **91**, 224101 (2007).

Acoustic Radiation is Powerful via Acceleration

- Nanoparticle patterning helps visualize SAW
  - Quick *(< 30 seconds)* and inexpensive *(pack of cigarettes)*
  - Easy to setup *(no sophisticated instruments)*
- Also provides scheme to study wall effects and particle motion
- Mechanism is acceleration ejection + streaming in viscous boundary layer
- For effective patterning ...

  ... particles need to be small enough to
  be *immersed* in boundary layer: $\phi_p < \delta_v$

  ... but not so small as to encourage *heaping:* $\phi_p \lesssim \delta_v/10$

Piezoelectric materials

- Material that develops an electric charge along an axis of polarization upon the application of strain (direct effect)
- All piezoelectric materials are anisotropic
- May be single crystal, polycrystalline ceramics, or polymers
- Figures of merit
  - electromechanical coupling factor
  - coercive field (polarizability)
  - dielectric constant
  - loss (tan delta)
  - maximum strain (<1% typ)
- All pyroelectric materials are piezoelectric

T *Mechanical Stress*	**S** *Mechanical Strain*	**E** *Electric Field Strength*	**D** *Electric Field Displacement or Flux Density*
g $= \frac{\text{field}}{\text{appl. stress}} = \frac{\text{strain}}{\text{applied charge / electrode area}}$ *Piezoelectric Field to Stress Coupling*	**h** $= \frac{\text{field}}{\text{appl. strain}} = \frac{\text{stress}}{\text{applied charge / electrode area}}$ *Piezoelectric Field to Strain Coupling*	**e** $= \frac{\text{stress}}{\text{applied field}} = \frac{\text{short circuit charge / electrode area}}{\text{applied strain}}$ *Piezoelectric Stress to Field Coupling*	**d** $= \frac{\text{strain}}{\text{applied field}} = \frac{\text{short circuit charge / electrode area}}{\text{applied stress}}$ *Piezoelectric Strain to Field Coupling*
Constant Electric Field (Short Circuit)		*Constant Stress (Free)*	
$\mathbf{s}^E$ *Compliance*	$\mathbf{c}^E$ *Stiffness*	β^T *Inverse Permittivity*	ε^T *Permittivity*
Constant Electric Displacement (Open Circuit)		*Constant Strain (Clamped)*	
$\mathbf{s}^D$ *Compliance*	$\mathbf{c}^D$ *Stiffness*	β^S *Inverse Permittivity*	ε^S *Permittivity*
$\mathbf{k}_i$ *Electromechanical Coupling Factor*	$i = \begin{cases} P & \text{— Planar} \\ 33 \text{ or } t & \text{— Thickness} \\ 15 & \text{— Shear} \\ 31 & \text{— Transverse} \end{cases}$	$\mathbf{K}^S$ *Relative Dielectric Constant*	$\mathbf{K}^T = \frac{\varepsilon^T}{\varepsilon^0} = \frac{\varepsilon^T}{8.85\times10^{-5}\,\mathrm{F/m}}$ *Relative Dielectric Constant*

Friend (PhD thesis 1998)

Piezoelectric materials

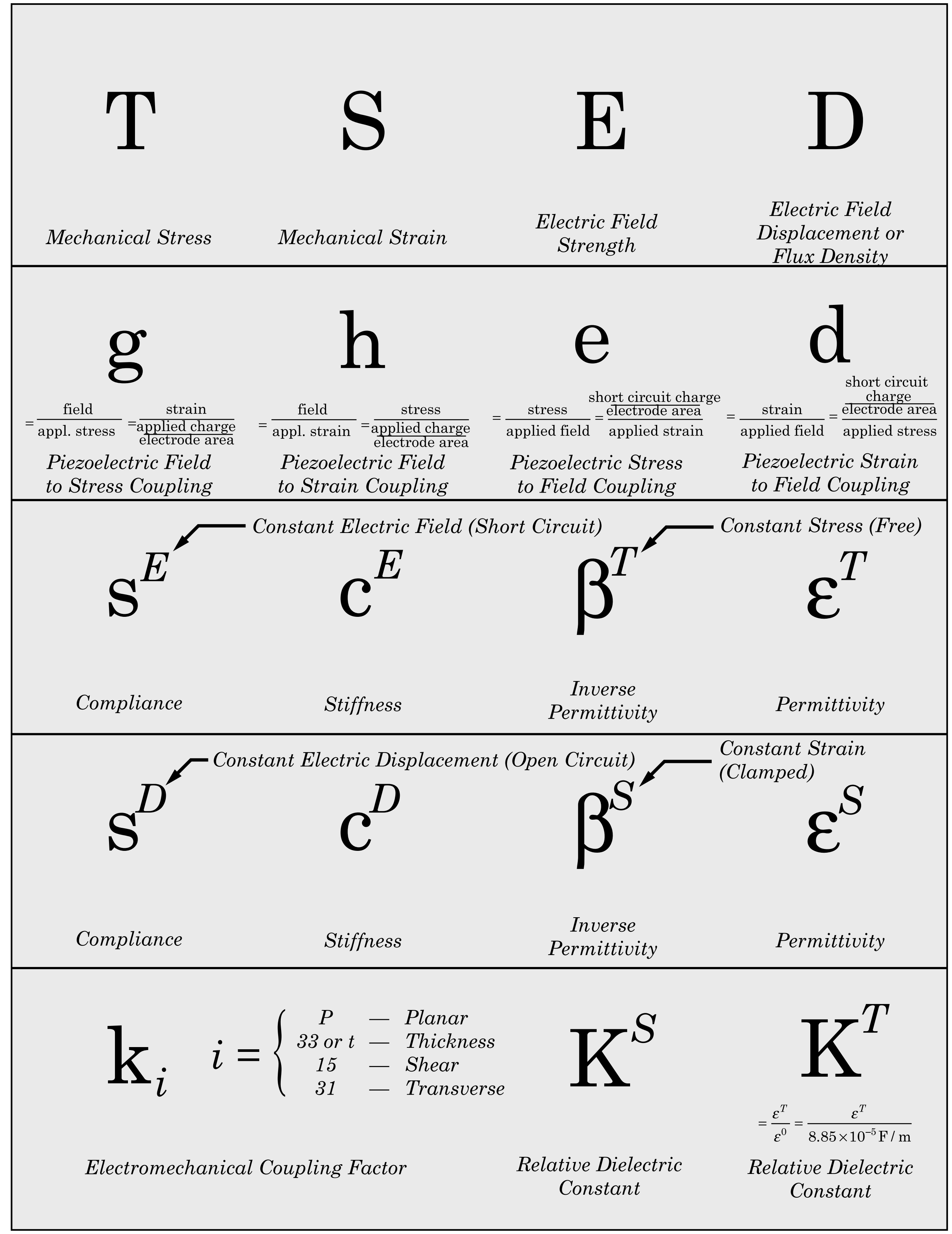
- Hermann–Mauguin notation: used to describe anistropy
- All HM *noncentrosymmetric* classes except [432] are *piezoelectric — 20 in all*
  1, 2, m, 222, mm2, 23, 3, 3m, 32, 4, –4, 422, 4mm, –42m, –43m, 6, –6, 622, 6mm, and –62m
- Ten of these lack symmetry along a particular axis and therefore permits *sponta- neous polarization* — these are *pyroelectric*
  1, 2, m, mm2, 3, 3m, 4, 4mm, 6, and 6mm
- Materials in this group that can have their polarization direction reversed are *ferroelectric*
  (hysteresis also necessary for strict definition of ferroelectric material)

T *Mechanical Stress*	S *Mechanical Strain*	E *Electric Field Strength*	D *Electric Field Displacement or Flux Density*
g $= \frac{\text{field}}{\text{appl. stress}} = \frac{\text{strain}}{\frac{\text{applied charge}}{\text{electrode area}}}$ *Piezoelectric Field to Stress Coupling*	h $= \frac{\text{field}}{\text{appl. strain}} = \frac{\text{stress}}{\frac{\text{applied charge}}{\text{electrode area}}}$ *Piezoelectric Field to Strain Coupling*	e $= \frac{\text{stress}}{\text{applied field}} = \frac{\frac{\text{short circuit charge}}{\text{electrode area}}}{\text{applied strain}}$ *Piezoelectric Stress to Field Coupling*	d $= \frac{\text{strain}}{\text{applied field}} = \frac{\frac{\text{short circuit charge}}{\text{electrode area}}}{\text{applied stress}}$ *Piezoelectric Strain to Field Coupling*
s^E *Compliance*	*Constant Electric Field (Short Circuit)* c^E *Stiffness*	β^T *Inverse Permittivity*	*Constant Stress (Free)* ε^T *Permittivity*
s^D *Compliance*	*Constant Electric Displacement (Open Circuit)* c^D *Stiffness*	β^S *Inverse Permittivity*	*Constant Strain (Clamped)* ε^S *Permittivity*
k_i	$i = \begin{cases} P & \text{— Planar} \\ 33 \text{ or } t & \text{— Thickness} \\ 15 & \text{— Shear} \\ 31 & \text{— Transverse} \end{cases}$ *Electromechanical Coupling Factor*	K^S *Relative Dielectric Constant*	K^T $= \frac{\varepsilon^T}{\varepsilon^0} = \frac{\varepsilon^T}{8.85\times10^{-5}\,\mathrm{F/m}}$ *Relative Dielectric Constant*

Friend (PhD thesis 1998)

Piezoelectric materials

- A piezoelectric material will lose its spontaneous polarization if its temperature is raised above the Curie temperature, near the temperature of maximum dielectric constant, the Curie–Weiss temperature
- Polycrystalline (PZT) and amorphous (PVDF) piezoelectric materials require *polarization* before use: they do not have an ordered spontaneous polarization
- Many such materials have an HM crystal class of ∞mm upon polarization



Friend (PhD thesis 1998)

$$\mathbf{T} = \mathbf{c}^{E} : \mathbf{S} - \tilde{\mathbf{e}} \cdot \mathbf{E}$$

Auld 1973

$$\mathbf{D} = \mathbf{e} : \mathbf{S} + \tilde{\boldsymbol{\varepsilon}}^{S} \cdot \mathbf{E}$$

Piezoelectricity is usually treated as a linear interaction between mechanical and electrical phenomena.

This is invalid for high-power applications or in materials either possessing large hysteresis losses or undergoing large deformations (Hall, 2001).

$\mathbf{T}$	$\mathbf{S}$	$\mathbf{E}$	$\mathbf{D}$
Mechanical Stress	*Mechanical Strain*	*Electric Field Strength*	*Electric Field Displacement or Flux Density*

$$\mathbf{T} = \mathbf{c}^E : \mathbf{S} - \tilde{\mathbf{e}} \cdot \mathbf{E}$$

Auld 1973

$$\mathbf{D} = \mathbf{e} : \mathbf{S} + \tilde{\boldsymbol{\varepsilon}}^S \cdot \mathbf{E}$$

g	h	e	d
$= \dfrac{\text{field}}{\text{appl. stress}} = \dfrac{\text{strain}}{\frac{\text{applied charge}}{\text{electrode area}}}$	$= \dfrac{\text{field}}{\text{appl. strain}} = \dfrac{\text{stress}}{\frac{\text{applied charge}}{\text{electrode area}}}$	$= \dfrac{\text{stress}}{\text{applied field}} = \dfrac{\frac{\text{short circuit charge}}{\text{electrode area}}}{\text{applied strain}}$	$= \dfrac{\text{strain}}{\text{applied field}} = \dfrac{\frac{\text{short circuit charge}}{\text{electrode area}}}{\text{applied stress}}$
Piezoelectric Field to Stress Coupling	*Piezoelectric Field to Strain Coupling*	*Piezoelectric Stress to Field Coupling*	*Piezoelectric Strain to Field Coupling*

$$\mathbf{T} = \mathbf{c}^{E} : \mathbf{S} - \tilde{\mathbf{e}} \cdot \mathbf{E}$$

Auld 1973

$$\mathbf{D} = \mathbf{e} : \mathbf{S} + \tilde{\boldsymbol{\varepsilon}}^{S} \cdot \mathbf{E}$$

Constant Electric Field (Short Circuit)

Constant Stress (Free)

$\mathbf{s}^E$	$\mathbf{c}^E$	β^T	ε^T
Compliance	*Stiffness*	*Inverse Permittivity*	*Permittivity*

$$\mathbf{T} = \mathbf{c}^E : \mathbf{S} - \tilde{\mathbf{e}} \cdot \mathbf{E}$$

Auld 1973

$$\mathbf{D} = \mathbf{e} : \mathbf{S} + \tilde{\boldsymbol{\varepsilon}}^S \cdot \mathbf{E}$$

Constant Electric Displacement (Open Circuit)

Constant Strain (Clamped)

$\mathbf{s}^{D}$	$\mathbf{c}^{D}$	β^{S}	ε^{S}
Compliance	*Stiffness*	*Inverse Permittivity*	*Permittivity*

$$\mathbf{T} = \mathbf{c}^{E} : \mathbf{S} - \tilde{\mathbf{e}} \cdot \mathbf{E}$$

Auld 1973

$$\mathbf{D} = \mathbf{e} : \mathbf{S} + \tilde{\boldsymbol{\varepsilon}}^{S} \cdot \mathbf{E}$$

$$\mathbf{k}_i \quad i = \begin{cases} P & \text{— Planar} \\ 33 \text{ or } t & \text{— Thickness} \\ 15 & \text{— Shear} \\ 31 & \text{— Transverse} \end{cases}$$

Electromechanical Coupling Factor

$$\mathrm{K}^S$$

Relative Dielectric Constant

$$\mathrm{K}^T = \frac{\varepsilon^T}{\varepsilon^0} = \frac{\varepsilon^T}{8.85\times10^{-5}\,\mathrm{F/m}}$$

Relative Dielectric Constant

$$\mathbf{T} = \mathbf{c}^E : \mathbf{S} - \tilde{\mathbf{e}} \cdot \mathbf{E}$$

$$\mathbf{D} = \mathbf{e} : \mathbf{S} + \tilde{\boldsymbol{\varepsilon}}^S \cdot \mathbf{E}$$

Auld 1989

Mechanical

s^{D}_{11}

- D — *Compliance measured with electrodes open circuited*
- first subscript 1 — *Related to* ***stress*** *in 1 dir. (****strain*** *for stiffness,* **c** *)*
- second subscript 1 — *Related to* ***strain*** *in 1 dir. (****stress*** *for stiffness,* **c** *)*

T_1 — *Indicates* ***stress*** *is in 1 dir.*

c^{E}_{36}

- E — *Stiffness measured with electrodes short circuited*
- subscript 3 — *Related to* ***strain*** *in 3 dir. (****stress*** *for compliance,* s *)*
- subscript 6 — *Related to shear* ***stress*** *around 3 dir. (****strain*** *for compliance,* s *)*

S_6 — *Indicates* ***strain*** *about 3 dir.*

Piezoelectric

d_{31}

- subscript 3 — *Electrodes to support this field are perpendicular to the 3 dir.*
- subscript 1 — *Piezoelectrically induced* ***strain*** *or the applied* ***stress*** *is in the 1 direction*

h_{15}

- subscript 1 — *Electrodes to detect this field are perpendicular to the 1 dir.*
- subscript 5 — *The applied* ***strain*** *or the piezoelectrically induced* ***stress*** *is in shear about the 2 direction*

g_{31}

- subscript 3 — *Electrodes to detect this field are perpendicular to the 3 dir.*
- subscript 1 — *The applied* ***stress*** *or the piezoelectrically induced* ***strain*** *is in the 1 direction*

e_{15}

- subscript 1 — *Electrodes to support this field are perpendicular to the 1 dir.*
- subscript 5 — *Piezoelectrically induced* ***stress*** *or the applied* ***strain*** *is in shear around the 2 dir.*

Electric

ε^{S}_{11}

- S — *Permittivity measured with material fixed (clamped)*
- first subscript 1 — ***Charge displacement*** *in 1 dir.*
- second subscript 1 — ***Electric field*** *in 1 dir.*

E_1 — *Indicates* ***field*** *is in 1 dir.*

β^{T}_{33}

- T — *Inverse permittivity measured with material free*
- first subscript 3 — ***Electric field*** *in 3 dir.*
- second subscript 3 — ***Charge displacement*** *in 3 dir.*

D_3 — *Indicates* ***charge displacement*** *is in 3 dir.*

Friend (PhD thesis 1998)

Units

Variable	Name	Derived Units (MKS)	Fundamental Units
c	*Stiffness*	Pa	$kg / m \cdot s^2$
s	*Compliance*	1 / Pa	$m \cdot s^2 / kg$
T	*Stress*	Pa	$kg / m \cdot s^2$
S	*Strain*	—	—
d	*Piezo. Strain Coefficient*	m / V *or* C / N	$C \cdot s^2 / kg \cdot m$
g	*Piezo. Voltage Coefficient*	$m \cdot V / N$ *or* $N \cdot m / C$	m^2 / C
e	*Piezo. Stress Coefficient*	C / m^2	C / m^2
h	*Piezo. Stiffness Coefficient*	V / m	$kg \cdot m / C \cdot s^2$
ε	*Permittivity*	F / m	$C^2 \cdot s^2 / kg \cdot m^3$
β	*Inverse Permittivity*	m / F	$kg \cdot m^3 / C^2 \cdot s^2$
D	*Electric Charge Displacement*	$F \cdot V / m$	C / m^2
E	*Electric Field Strength*	V / m	$kg \cdot m / C \cdot s^2$
K	*Relative Dielectric Constant* ($\varepsilon/\varepsilon_0$)	—	($\varepsilon_0 = 8.85 \times 10^{-5}$ F / m)
k	*Electromechanical Coupling Factor*	—	—

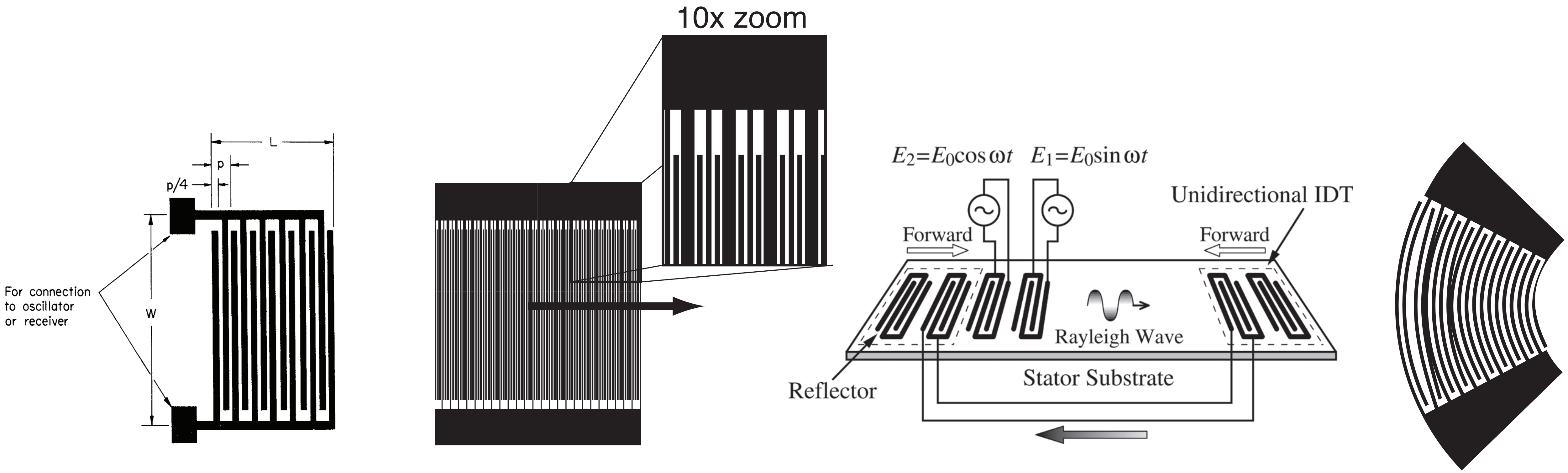
Friend (PhD thesis 1998)

Good references:
IEEE Ultrasonics Reference
Dieulesaint E, Royer D (2000)
Smits J (1976) IEEE T Son
Tiersten HF (1967)

Piezoelectric material fabrication: *five routes*

(Polla and Francis, 1998)

- **Traditional solid-state chemistry** in sintering powdered oxides to form a polycrystalline ceramic from a green state (PZT) (Randall et al., 1998).
- **Polymer-assisted techniques** (Jia et al., 2004) like screen printing (Yao et al., 2005), the hydrothermal technique (Deng et al., 2003; Kutty and Balachandran, 1984; Ohba et al., 1994), or tapecasting (Schwarzer and Roosen, 1999)
- **Czochralski process** to form single crystal materials, especially for lithium niobate and lithium tantalate (Nassau et al., 1966).
- **Physical vapor deposition** techniques including sputtering (Watanabe et al., 1995; Yoshino et al., 2000) and **pulsed-laser deposition** (Ryu et al., 2000)
- **Chemical vapor deposition** (CVD) techniques, particularly metalorganic CVD (Kim and Lee, 2007; Takeuchi et al., 2007)



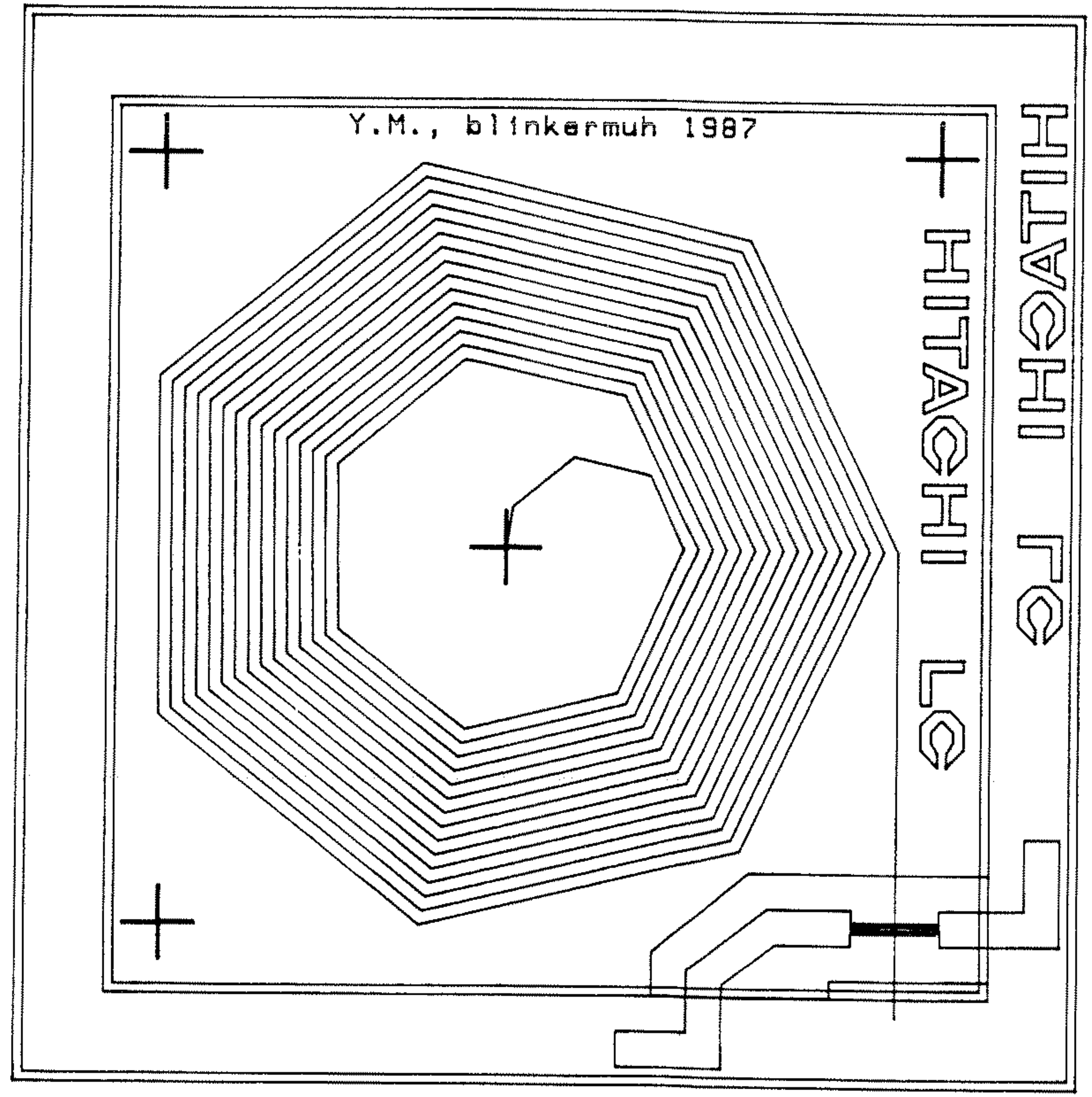
(a) **(b)** **(c)** **(d)**

Friend & Yeo RMP 2011

Ultrasonics

Best source of information on this topic is this conference...

IEEE Transactions on Ultrasonics

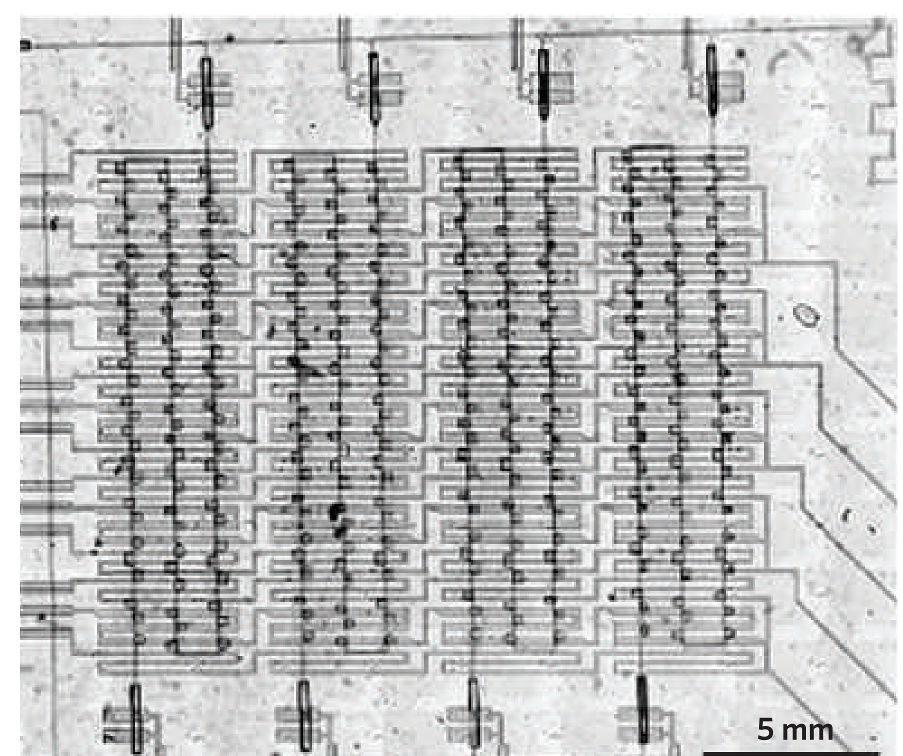


Microfluidics

Manz (1990): LC chip in Si at Hitachi

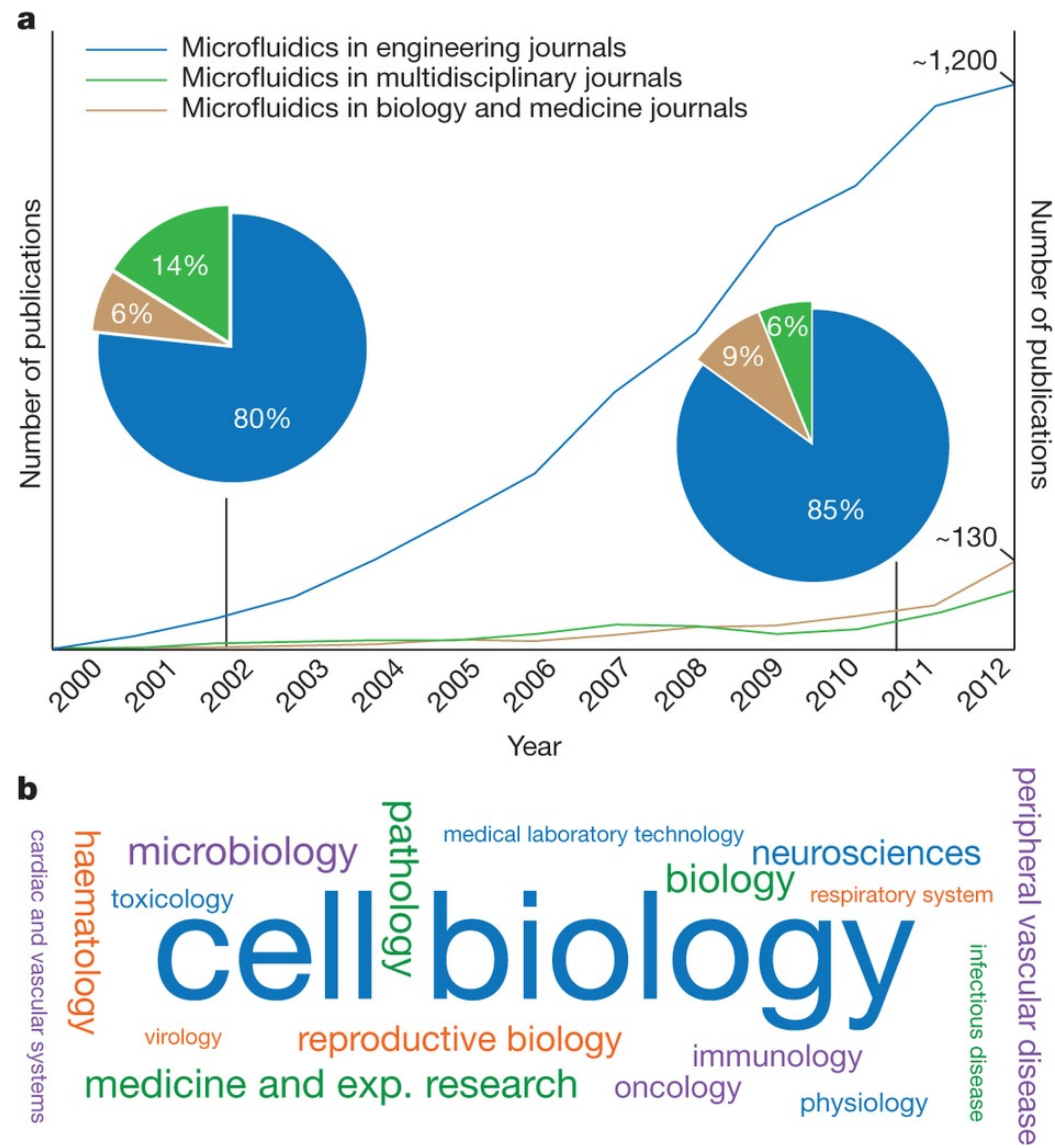
Origins of Microfluidics (Whitesides 2006)

- Molecular analysis
  - gas-phase chromatography (GPC)
  - high-pressure liquid chromatography (HPLC)
  - capillary electrophoresis (CE)
- Biodefence DARPA: field-deployable microfluidic systems for chemical and biological threats
- Molecular biology
  - genomics
  - high-throughput DNA sequencing
- Microelectronics
  - Silicon microelectronics from IC fabrication techniques
  - Microelectromechanical systems (MEMS)
  - *poly(dimethylsiloxane) PDMS — soft elastic elastomer*



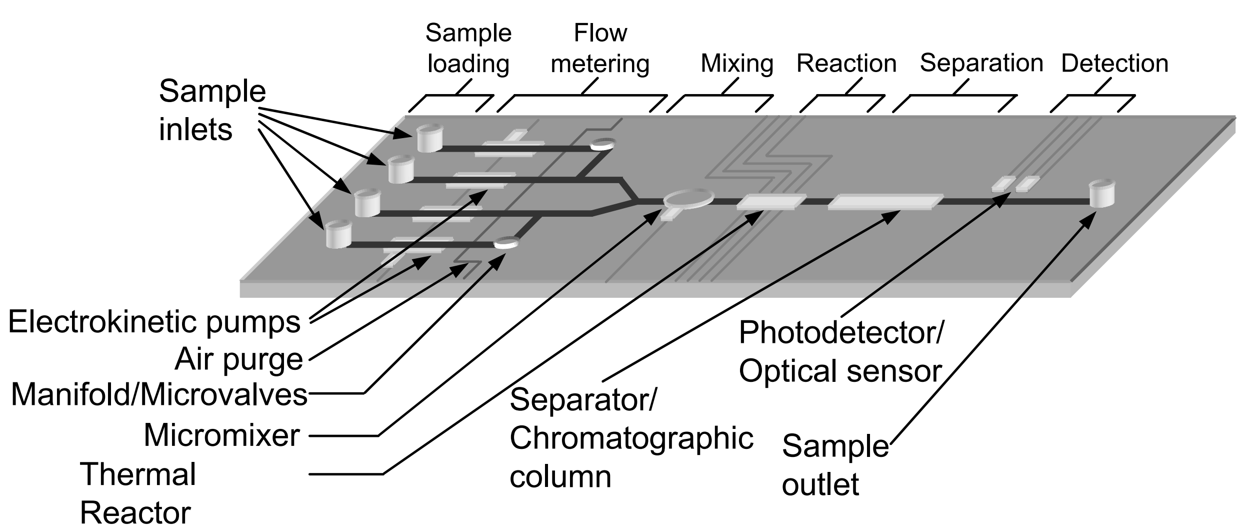
Progression of Microfluidics as Discipline

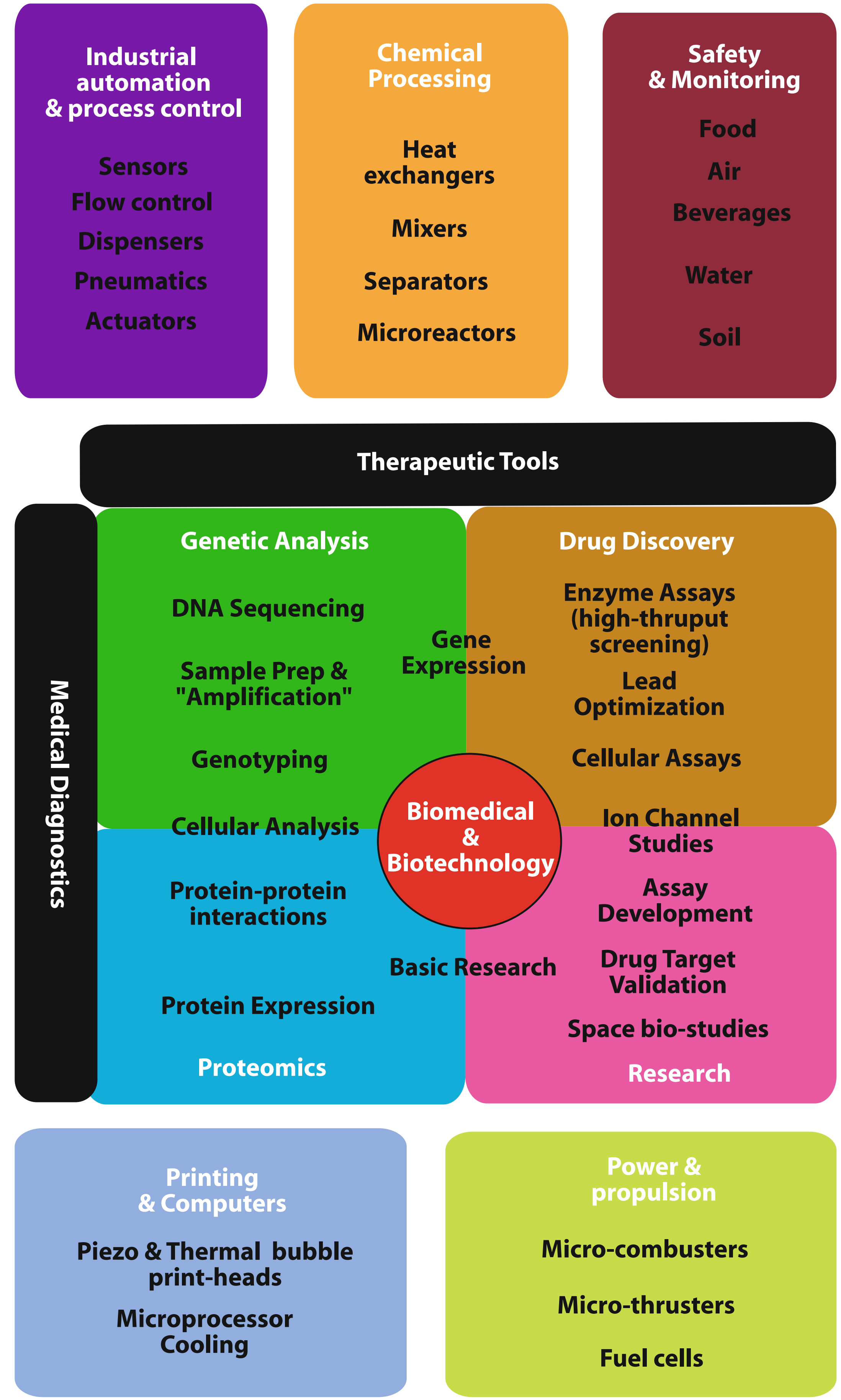
Microfluidics has rapidly matured from a science to an engineering discipline and beyond to applications



Sackman, Fulton & Beebe *Nature 2014*

Microfluidics: lab on a chip





Dongqing Li 2008

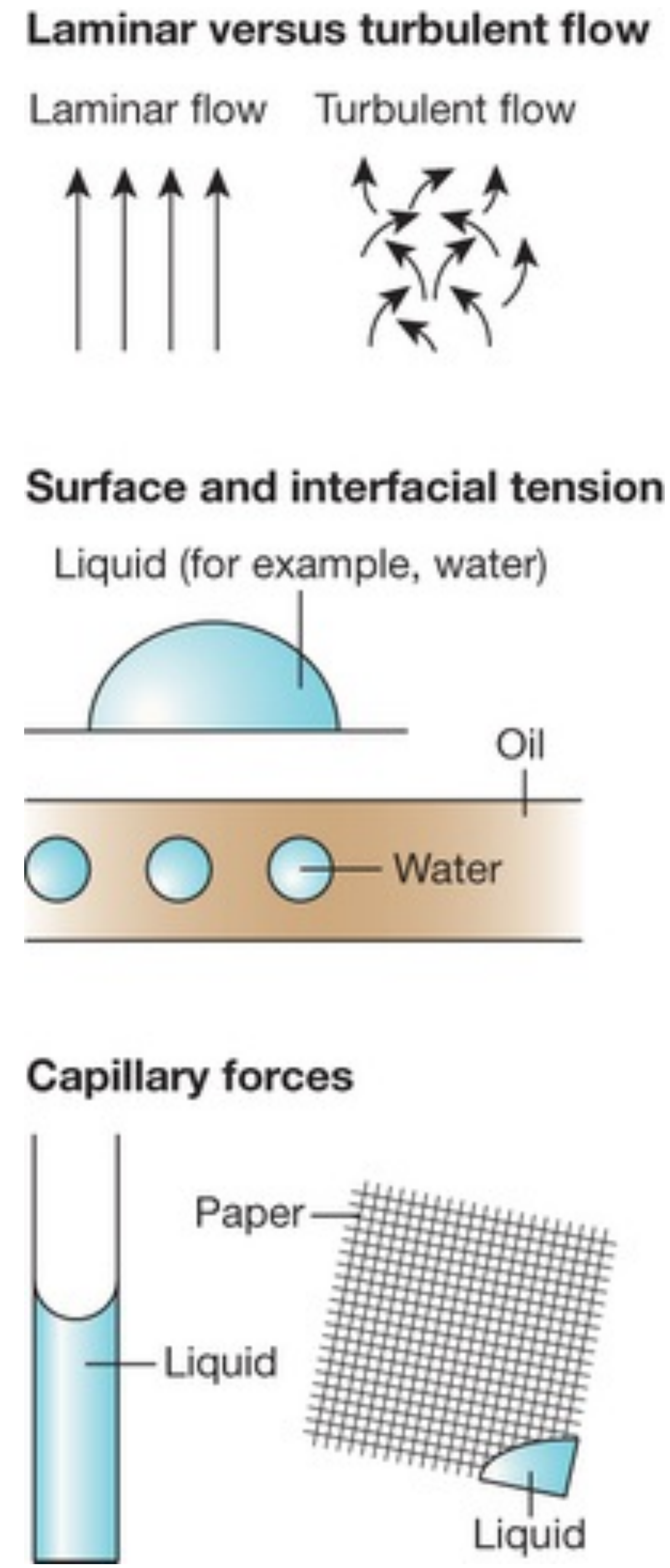
Key Concepts in Microfluidics

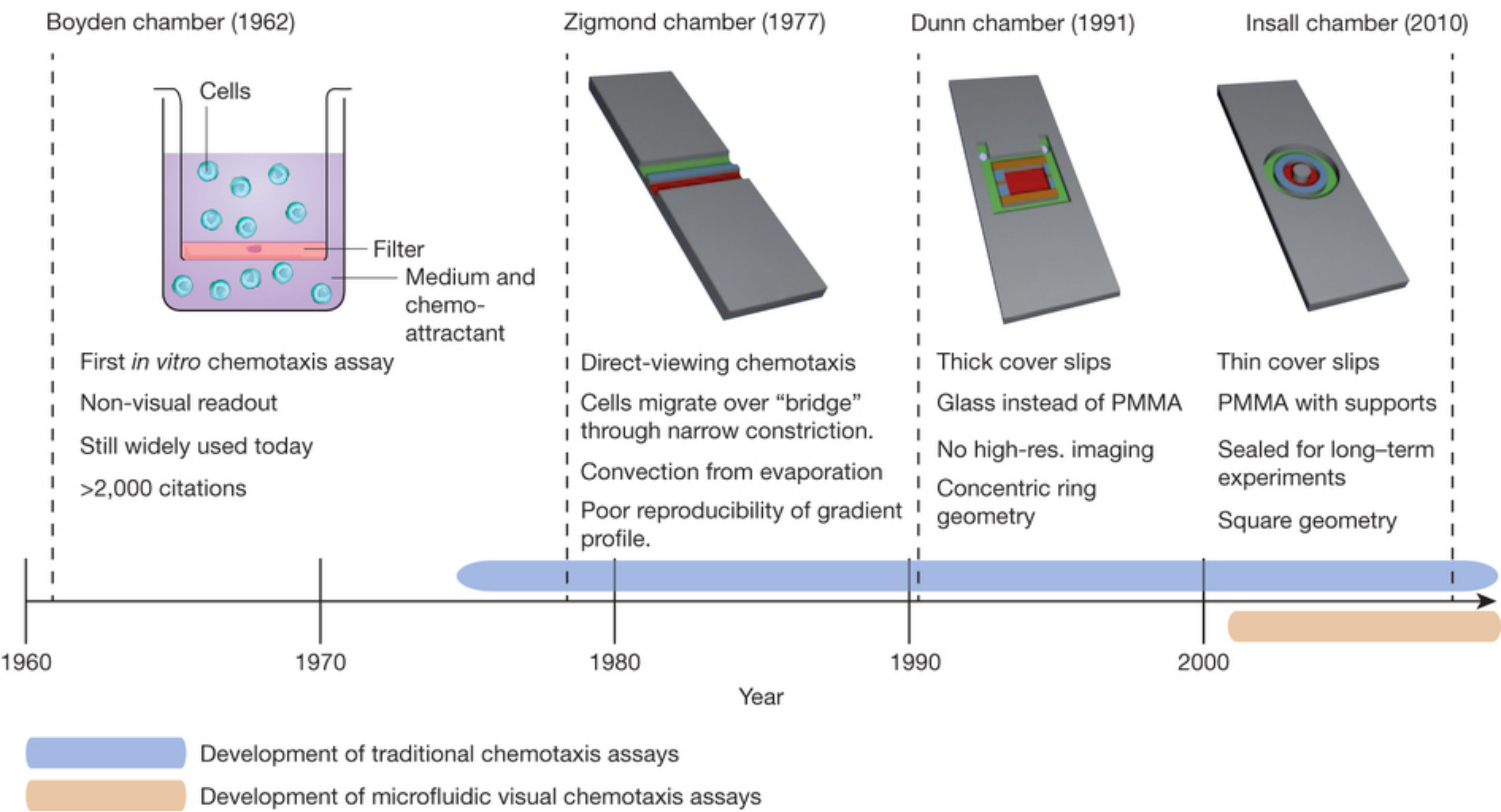
Sackman, Fulton & Beebe *Nature 2014*

- **Laminar versus turbulent flow.** The Reynolds number (Re) is a dimensionless quantity that describes the ratio of inertial to viscous forces in a fluid, proportional to the characteristic velocity of the fluid and the length scale of the system; it is inversely proportional to the fluid viscosity. High-Re (~2,000) fluids have flow profiles that increasingly mix stochastically (turbulent flow). For microfluidic systems, Re is almost always in the laminar flow regime, allowing for highly predictable fluid dynamics. Molecular transport also changes dramatically at this scale because convective mixing does not occur, enabling predictable diffusion kinetics.

- **Surface and interfacial tension.** Surface tension describes the tendency of a fluid in a surface to reduce its free energy by contracting at the surface–air interface. Interfacial tension is a similar phenomenon, but is generally applied to two immiscible fluids (for example, oil and water). These forces play more dominant roles on the microscale compared to gravity, which is much more dominant on the macroscale. Researchers have used these phenomena to conduct protein and cell sorting, perform nanoreactions for protein crystallization, and passively drive fluids through microchannels.

- **Capillary forces.** Capillary action describes the movement of a fluid through a narrow constriction, such as a narrow tube or porous material. At the microscale, capillary action is a more dominant force, allowing fluids to advance in opposition to gravity. Capillary forces have been used to manipulate fluids in many applications, the most famous examples perhaps being the at-home pregnancy test and portable glucometers to monitor blood glucose levels.





Sackman, Fulton & Beebe *Nature 2014*

Chemotaxis

Movement of an organism in response to a chemical stimulus: *a good example to indicate progress via microfluidics*

Tools to Achieve *Lab on a Chip*

Typical lab to determine cholesterol, WBC, ...

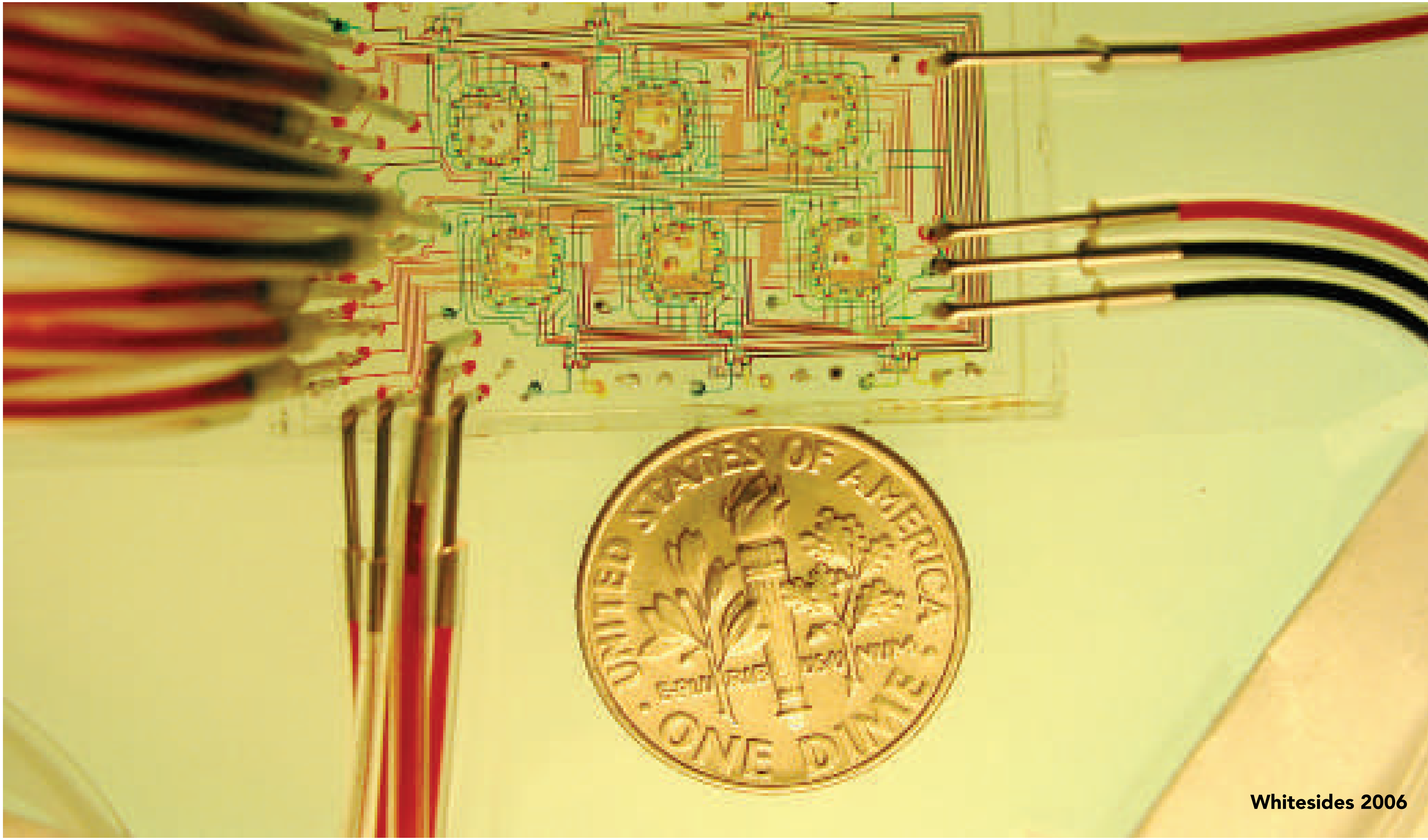
What about Parkinson's? Cancer? AIDS? Lupus?

Tools to Achieve *Lab on a Chip*

All replaced with point-of-care device for your GP

Sensors? *Done*

Actuators? Much work left to do



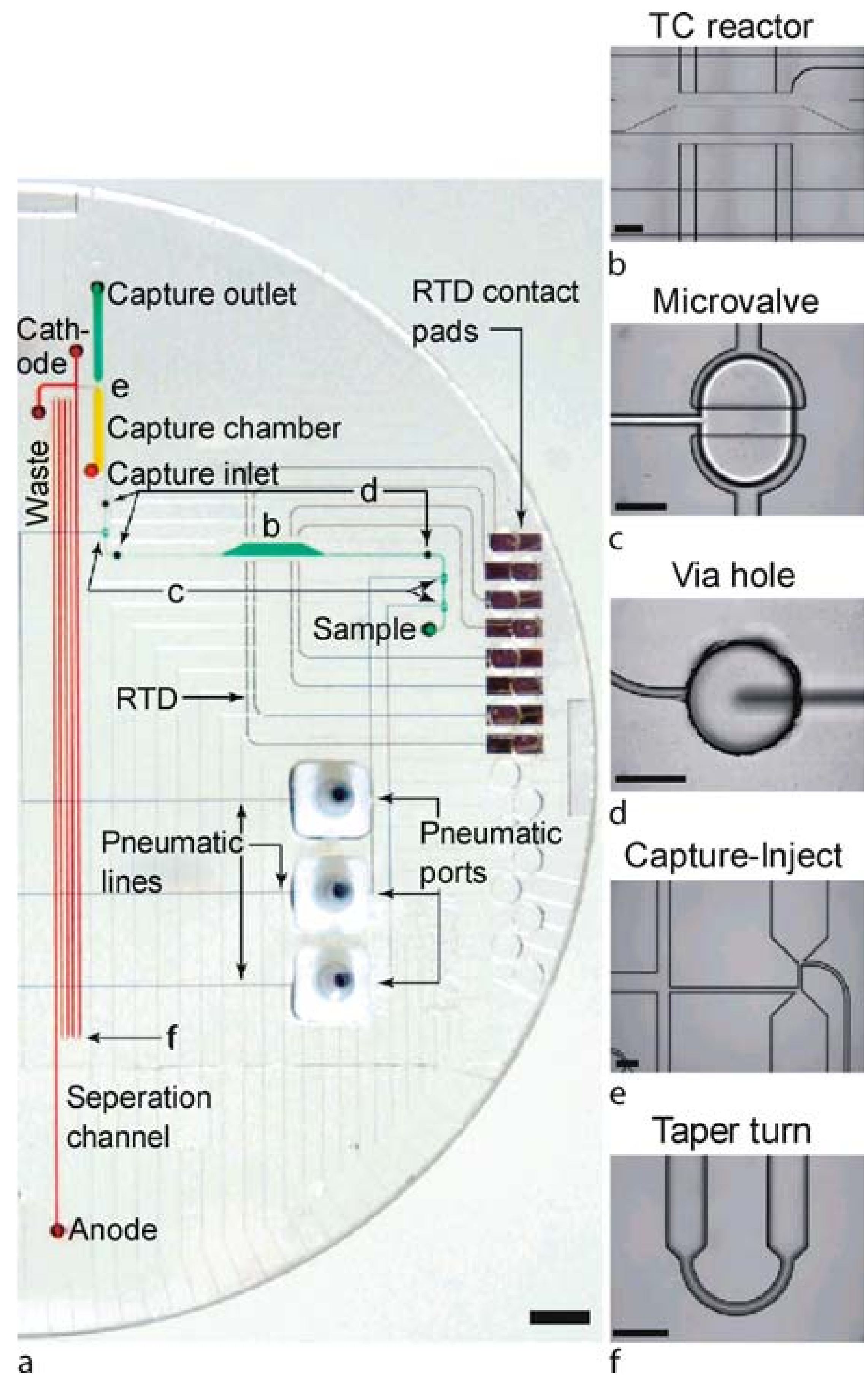
Current state of the art

IC microfabrication techniques
Complex geometries possible
Actuation, mixing, flow control remains a problem

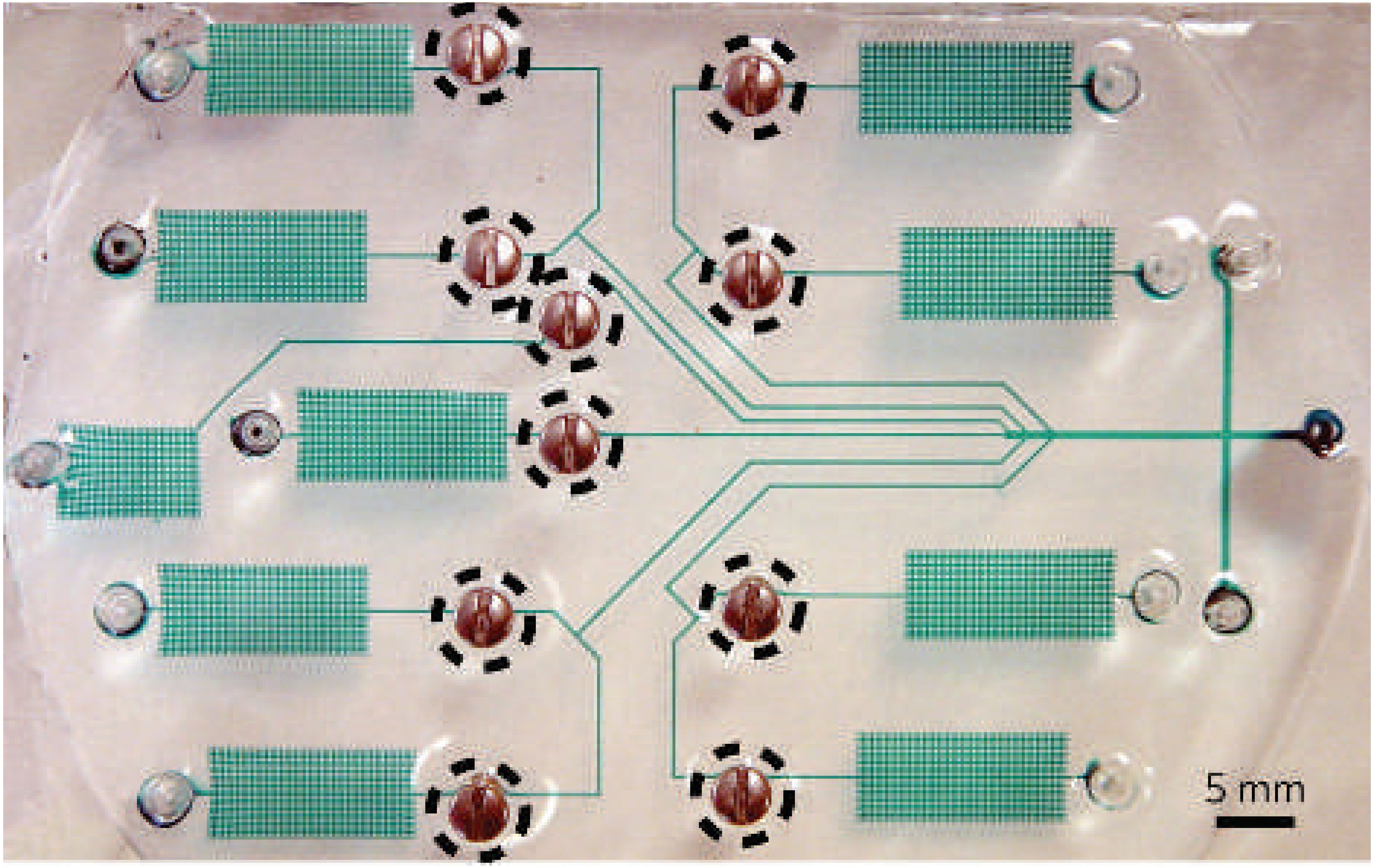
Integrated Sanger DNA sequencing

Note the variety of functional structures in the device made from PDMS.

Actuation performed via external syringe pumps and pneumatic pumps



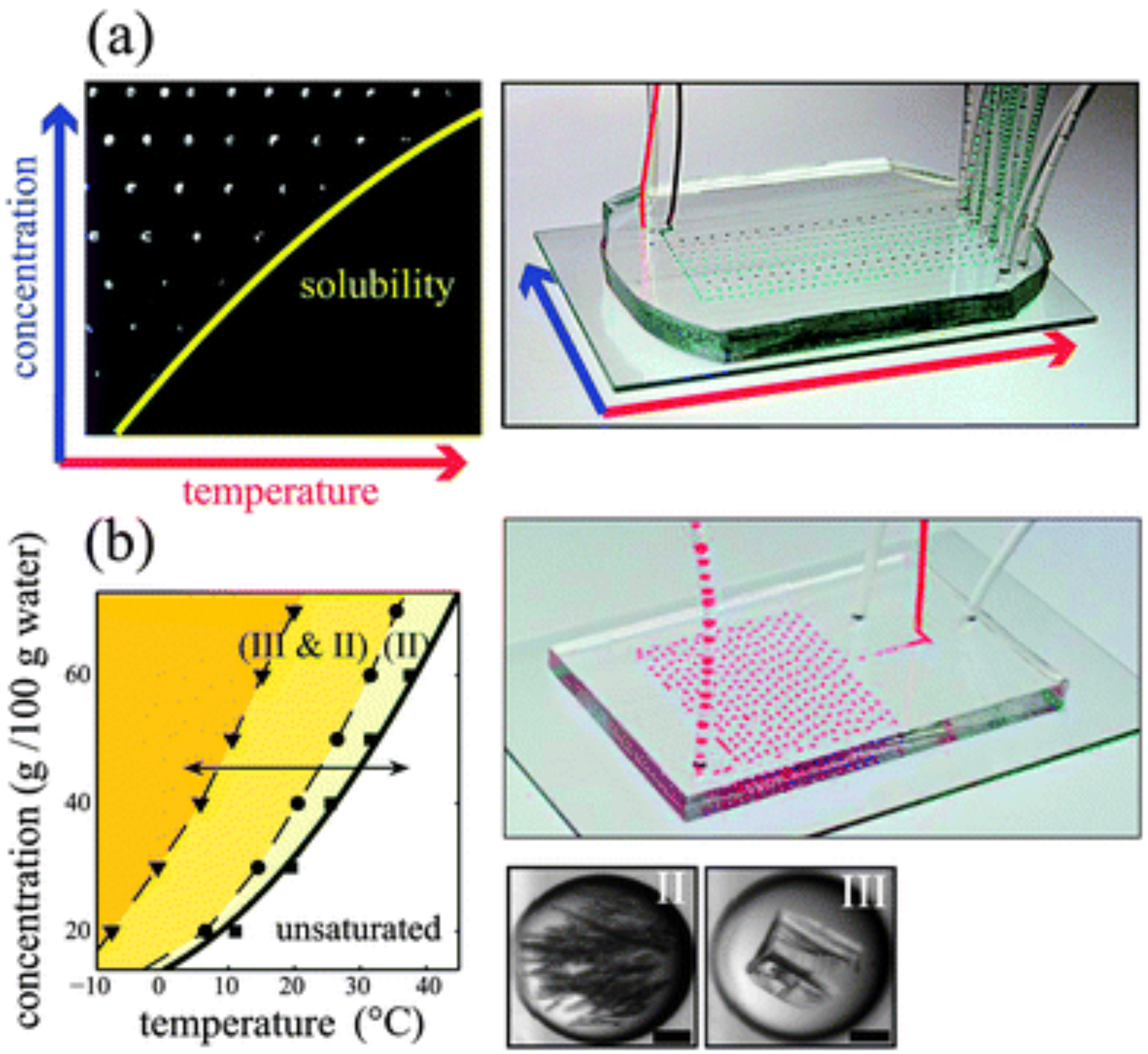
Blazej 2006

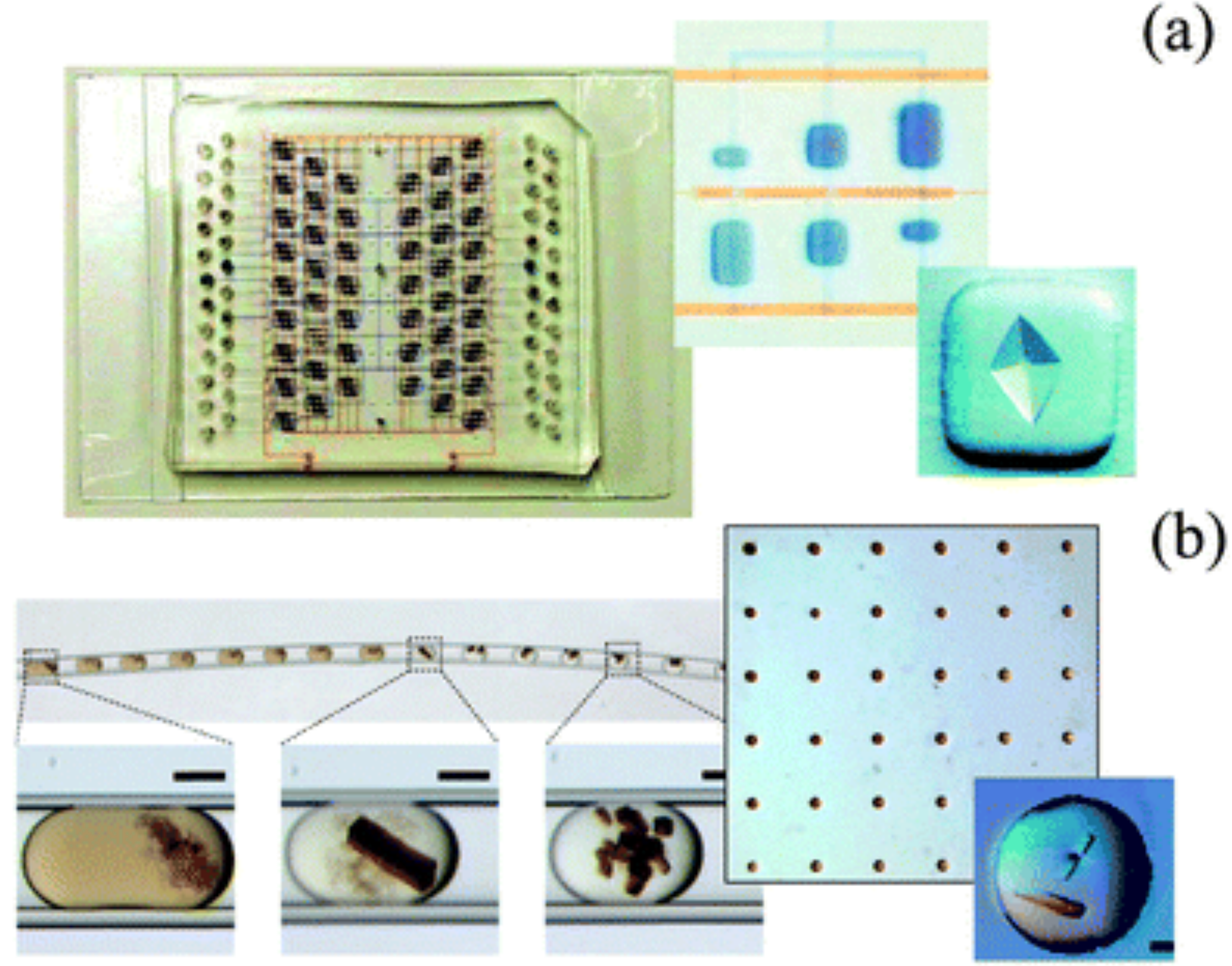


Whitesides 2006

Sandwich microassays

Disease detection
Chemical contaminants
Drug testing

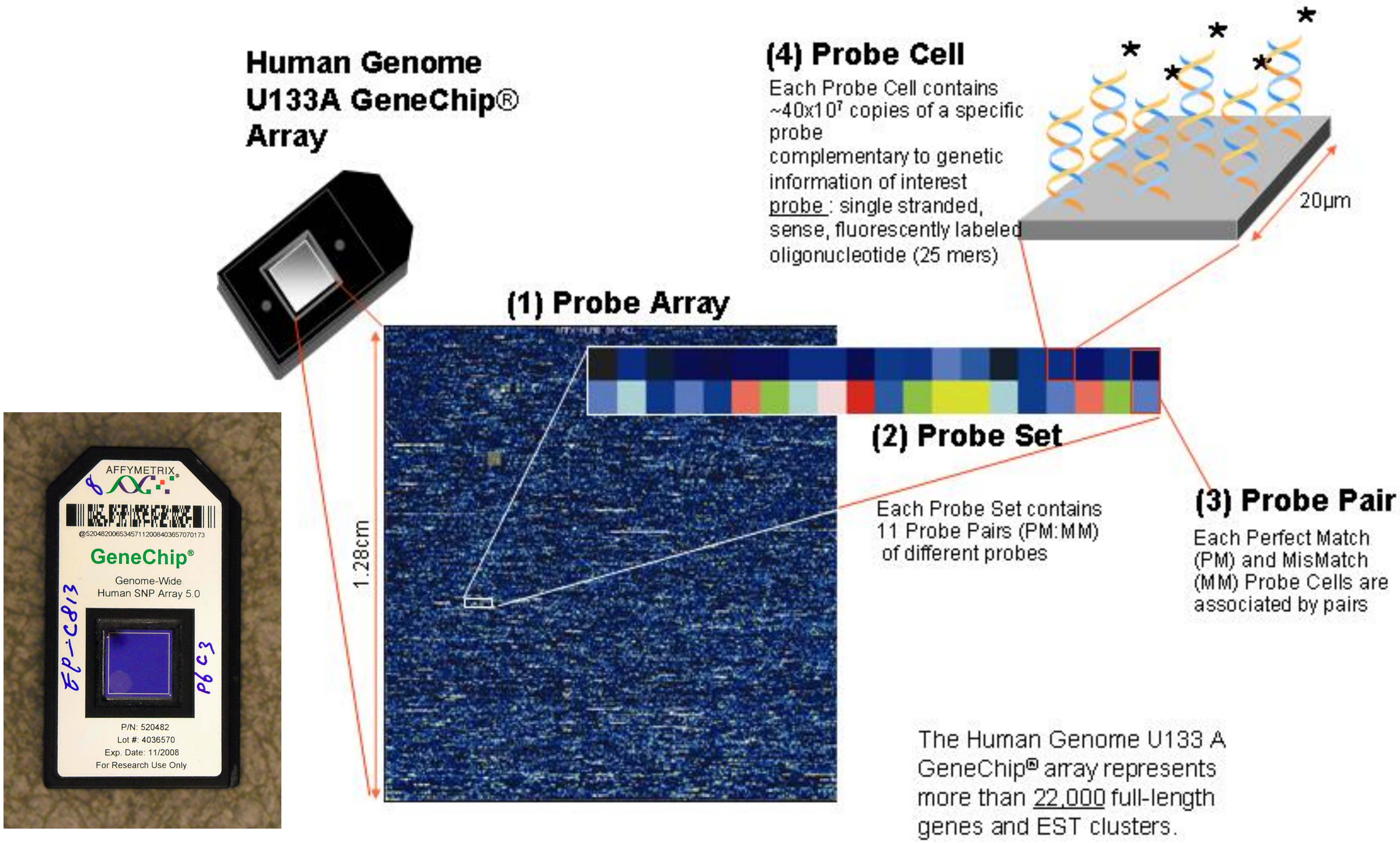




Leng & Salmon ***LOC*** **2009**

Protein crystallography

To understand the molecular composition of proteins, X-ray diffraction of crystals is needed. ***But making the crystals?***

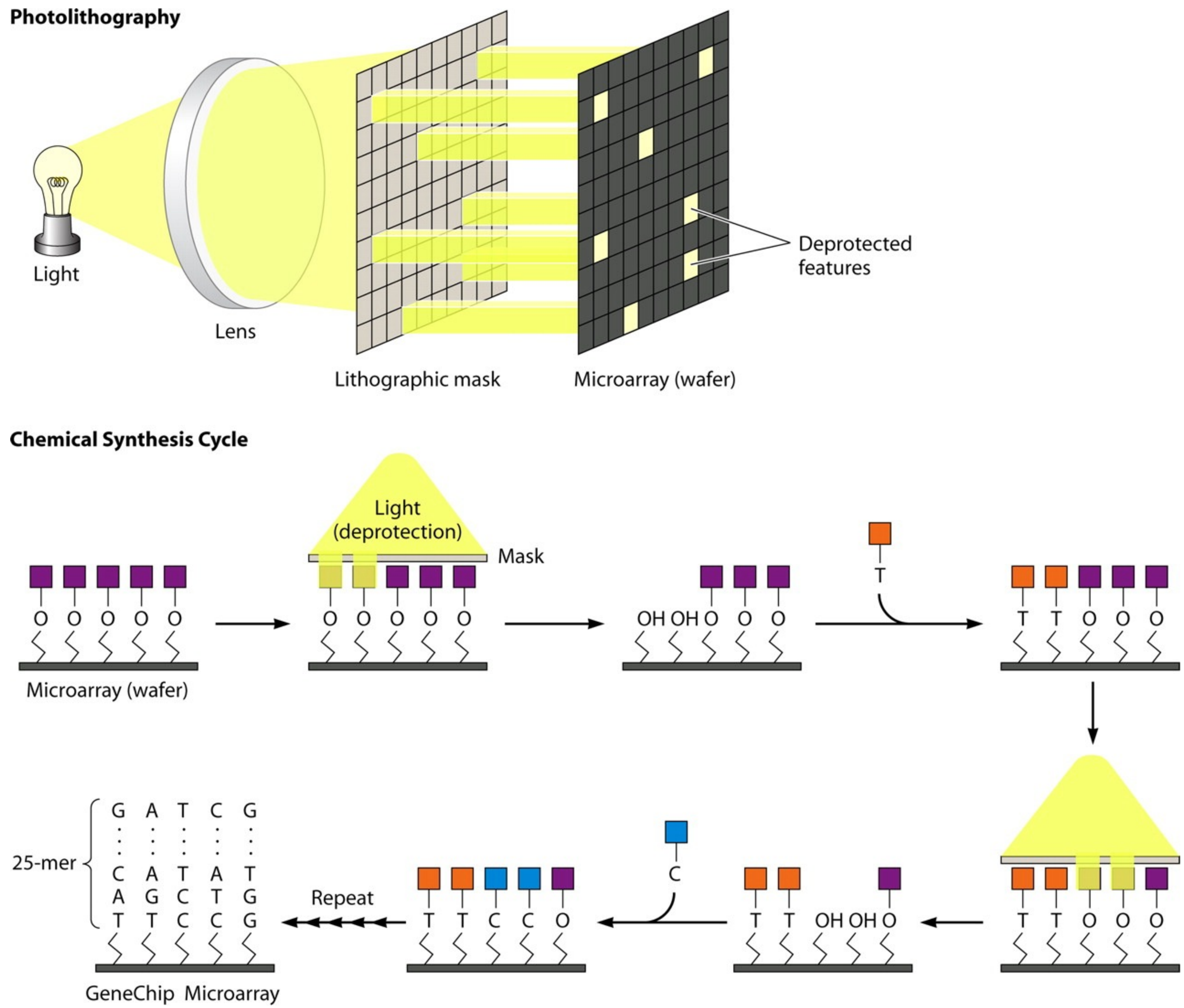


Affymetrix 2007

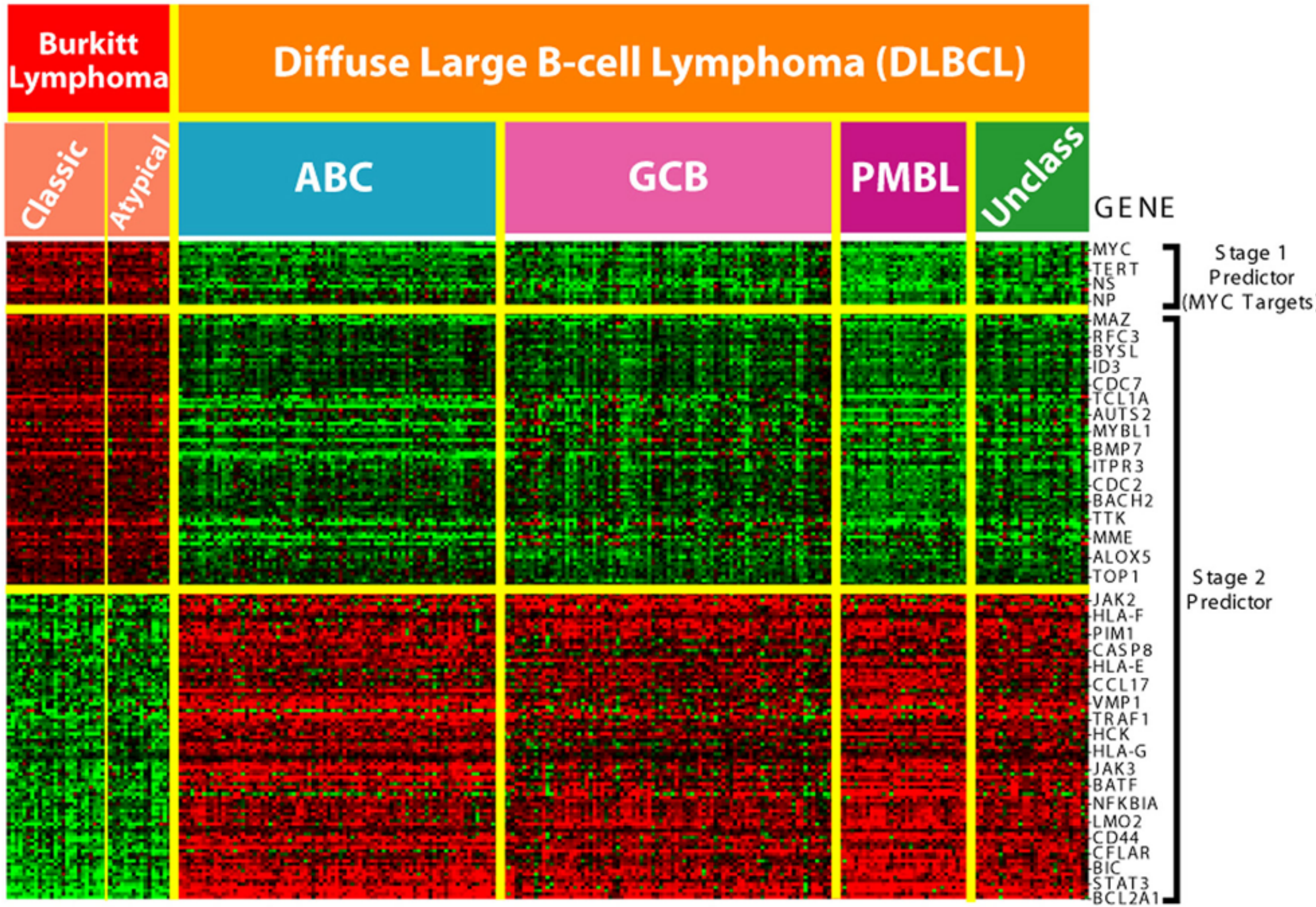
Affymetrix GeneChip

Human genome on a microfluidics chip: which genes are responsible for...cancer, heart disease, lupus..?

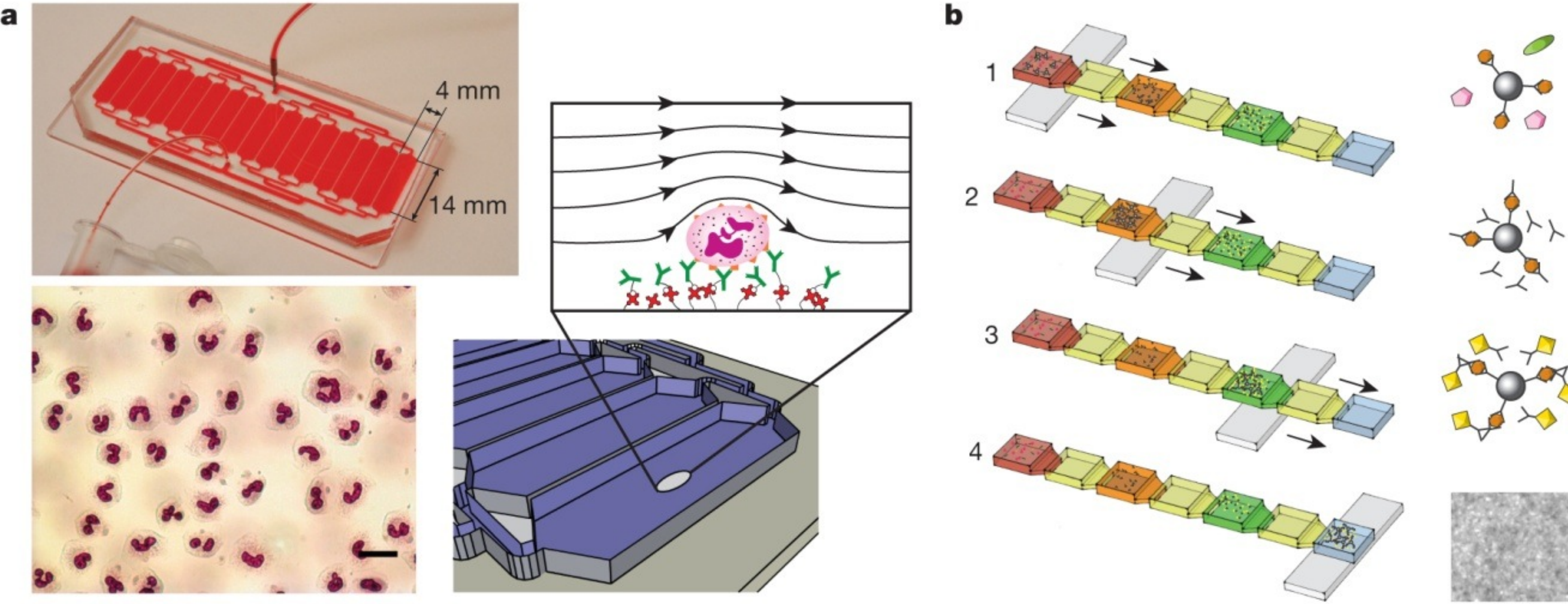
Affymetrix GeneChip oligonucleotide microarray.



Miller M B , and Tang Y Clin. Microbiol. Rev. 2009;22:611-633



DNA-microarray analysis of Burkitt's lymphoma and diffuse large B-cell lymphoma (NIH 2006)



Sackman, Fulton & Beebe *Nature 2014*

Rapid purification microfluidic systems

A microfluidic device to purify neutrophils (WBCs) within minutes using antibody-based capture for subsequent diagnostic or research analysis

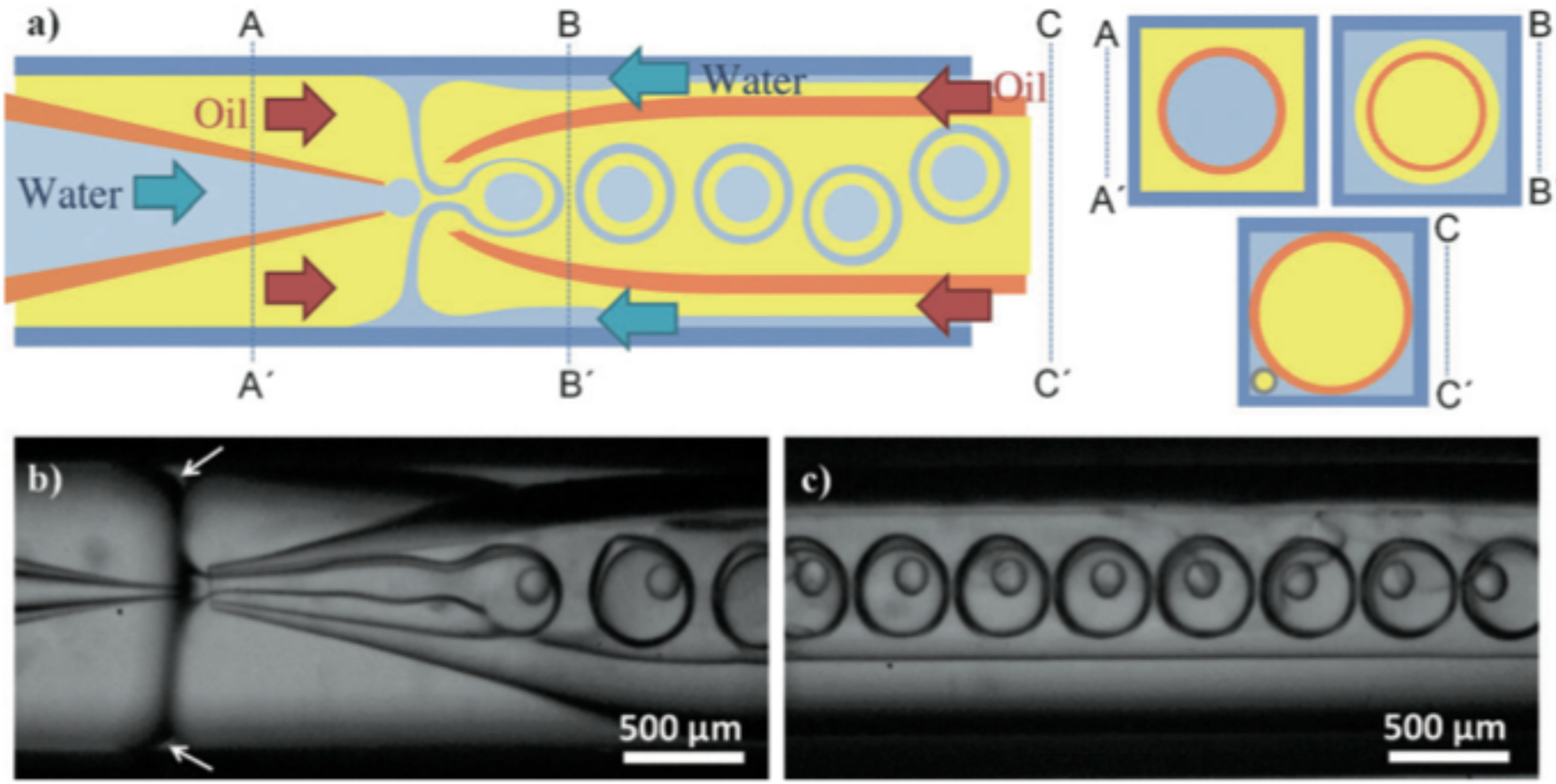


Figure 1. a) Microfluidic capillary device for preparation of W/O/W/O triple emulsion drops. The three cross-sectional schematics (A–A′, B–B′, and C–C′) are included for clarity. b,c) Optical microscope images showing triple emulsion generation and downstream motion. The white arrows in (b) denote the aqueous stream for the outer layers.

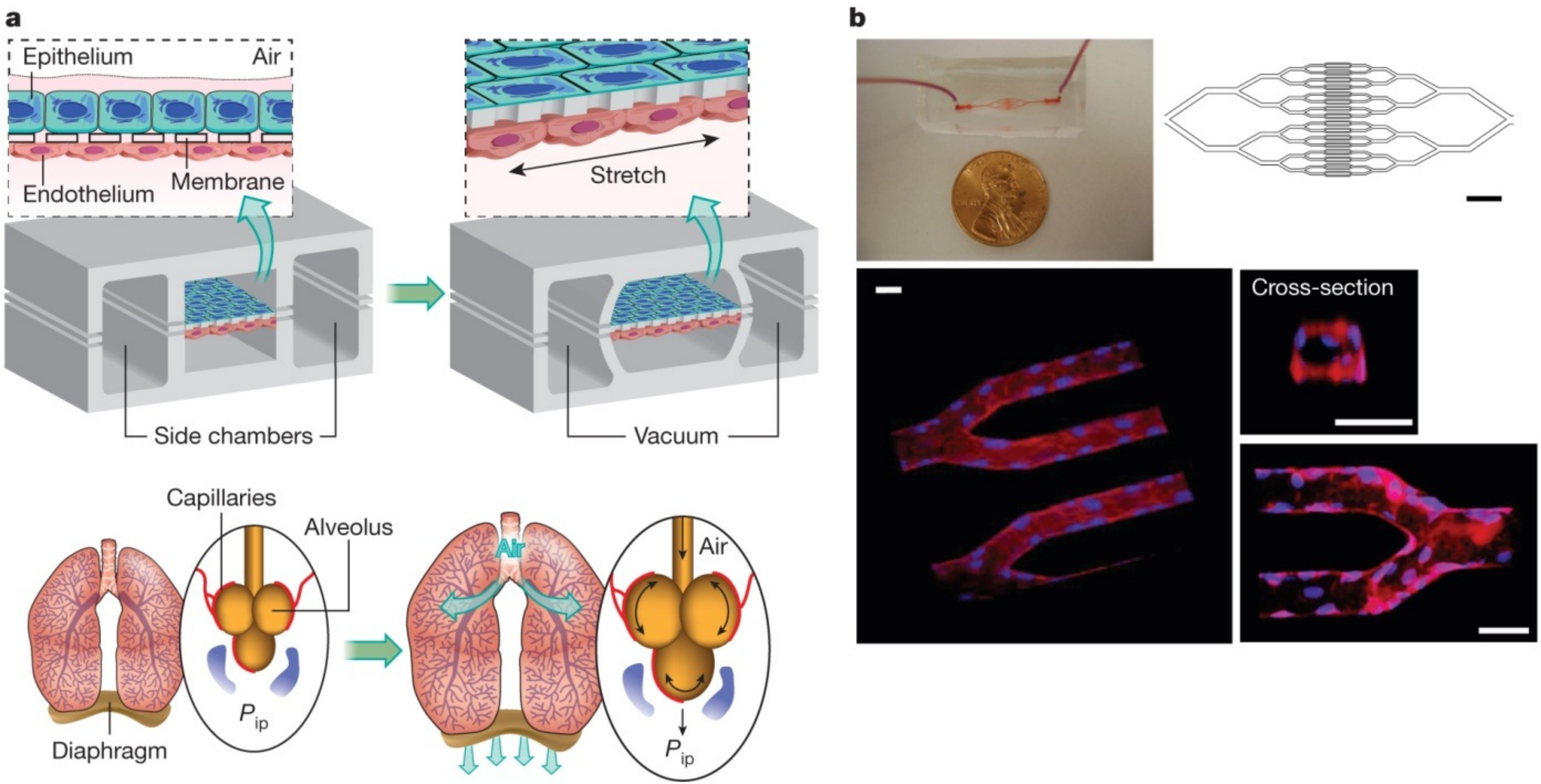
Weitz, et al: Angewandte Chemie International Edition, DOI: 10.1002/anie.201102946 (2011)

Droplet microfluidics

Dave Weitz (Harvard): Droplet is a laboratory — drop in a drop in a…

ABRATE AND WEITZ
APS MARCH MEETING 2010

QUINTUPLE EMULSIONS FORMED WITH MICROFLUIDICS



Sackman, Fulton & Beebe *Nature 2014*

Organ-on-a-chip assays for drug development and specialized diagnostic applications

Note the actuation necessary via vacuum

For next time

An assignment

Assignment

1. Why are you interested in acoustofluidics? (short answer)
2. What's the difference between hard and soft PZT (solid mechanics/applications)?
3. In the lecture it is stated that the maximum vibration velocity is ~1 m/s. Consult the paper (provided separately on TritonEd) by S Crandall and explain through his similarity arguments why this might be true.
4. What other nondimensional numbers are appropriate to consider for acoustofluidics than the Reynolds (streaming or standard) number? Why?

(due at beginning of next class)