Inkjet Printing

Materials Research Society

Liquid Crystal Institute

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November 30, 2005

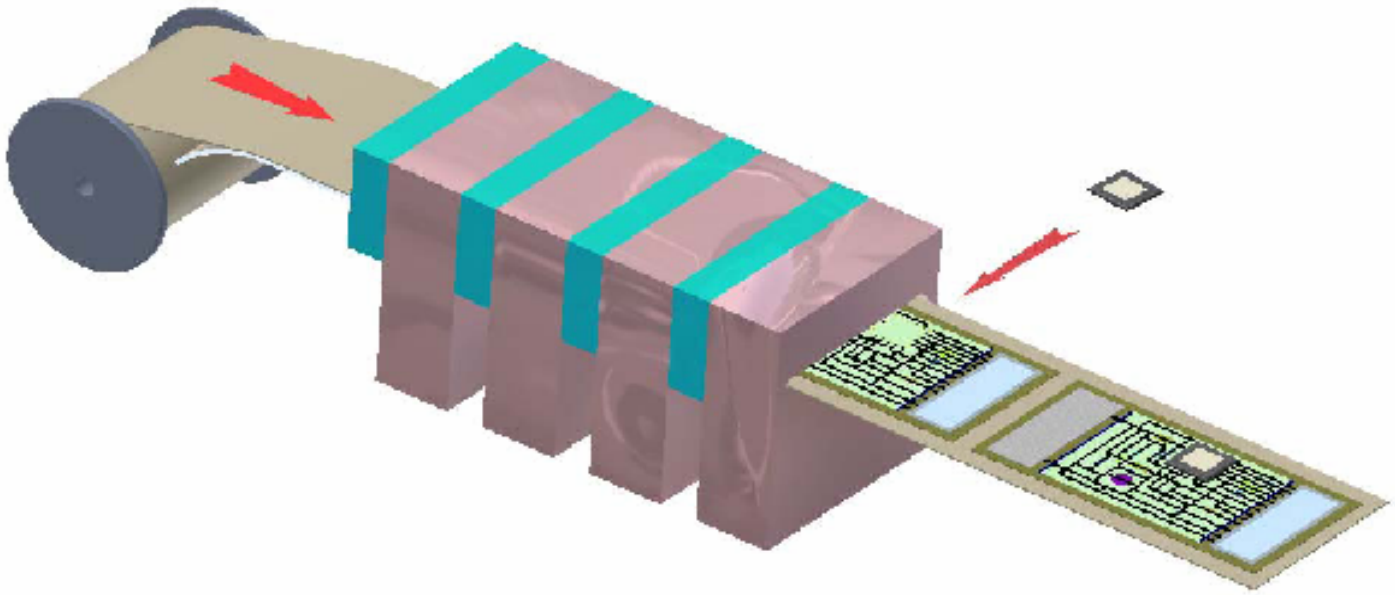
Overview

- Flexible Display Center
- Ink Jet Technology
- Ink Jet Concepts
- Conducting Polymer Deposition
- Survey

Wright FOEDMF

- Wright Capital Grant to develop flexible display manufacturing.
- Funding to buy equipment – what tools do we want?
- Ink jet early choice for many process steps.
- fdc.lci.kent.edu

Printed Electronics - The Dream



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Why Ink Jet?

- Data driven –
  - Flexibility, replace mask w/ tiff file
- Non contact-
  - Low impact to object being printed onto
- Additive
  - Eliminate process steps (e.g. photolithography)

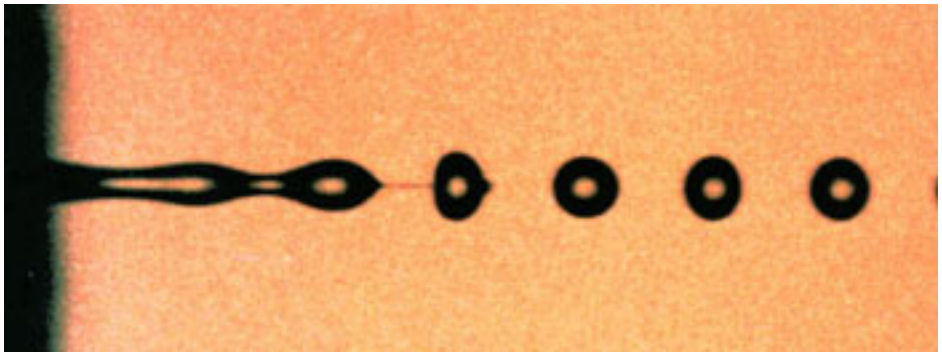
Why Ink Jet II

- Non Contact
- Potentially suitable for all deposition steps
  - Possible new solutions (e.g. spacers/adhesive)
- Efficient materials use
  - Spin coating wastes > 95% of material
  - Ink jet is direct write, effectively no waste

What's an ink jet printer?

Ink jet fundamentals

- Raleigh instability – cylindrical jets of fluid are unstable and will break apart into droplets.



Continuous Jet, Breakup Theory

- Weber's simplification of Raleigh theory, and extension to viscous fluids
  - exponential disturbance growth

$$r' = r_0' e^{at} \cos\left(\frac{x}{r_0}\xi\right) \qquad \xi \equiv \frac{2\pi r_0}{\lambda}$$

$$\alpha^2 = \frac{\xi^2(1-\xi^2)}{2} - 3\sqrt{2}\,\xi^2 Z \alpha$$

$$Z \equiv \frac{\sqrt{We_d}}{Re_d}$$

r_0 = *initial jet radius*
r' = *radius perturbation*
a = *disturbance growth rate*
t = *time*
x = *axial distance*
λ = *disturbance wavelength*

We_d = *Weber number*
Re_d = *Reynolds number*

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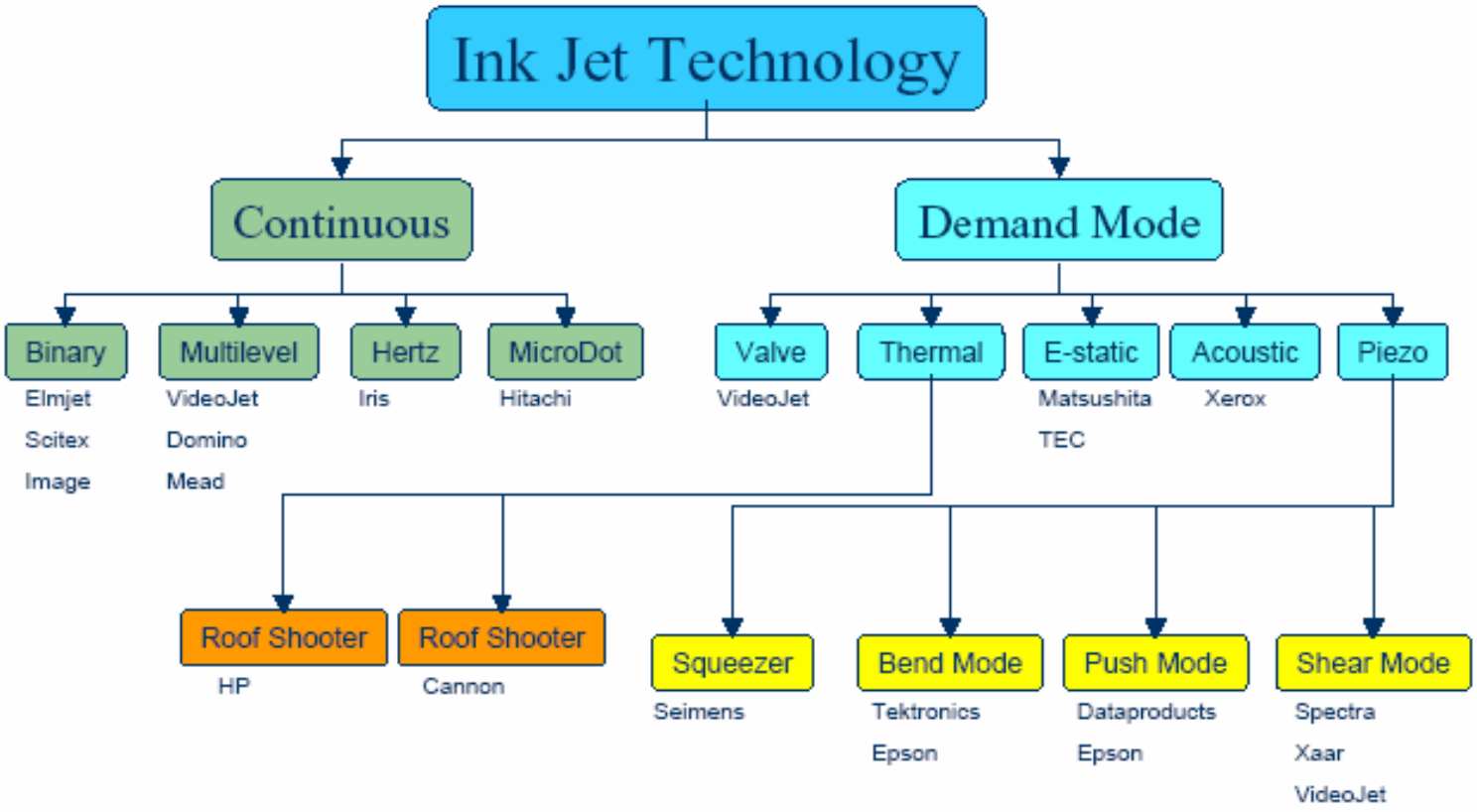
Multiple Technologies



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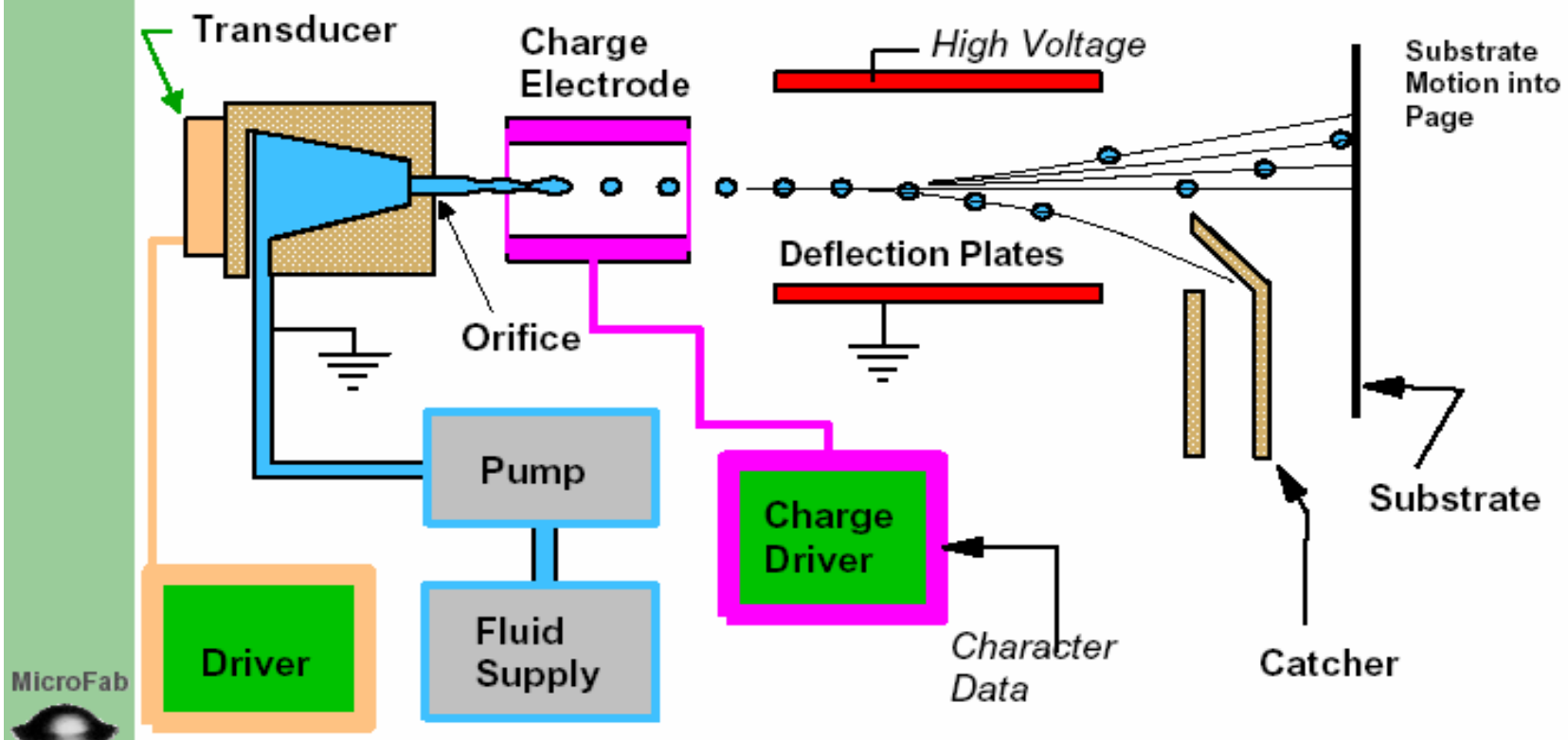
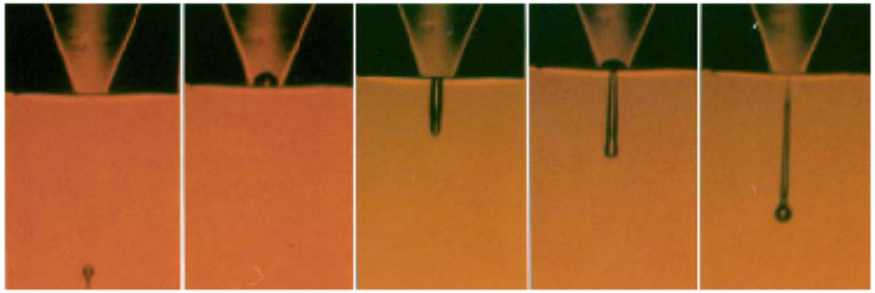
Continuous Ink-Jet



Drop-on-Demand Jet, Physics

- Transducer imparts energy to fluid volume
- Acoustic waves propagate to orifice or free surface
- Energy converted from pressure to velocity at orifice (atmospheric pressure)



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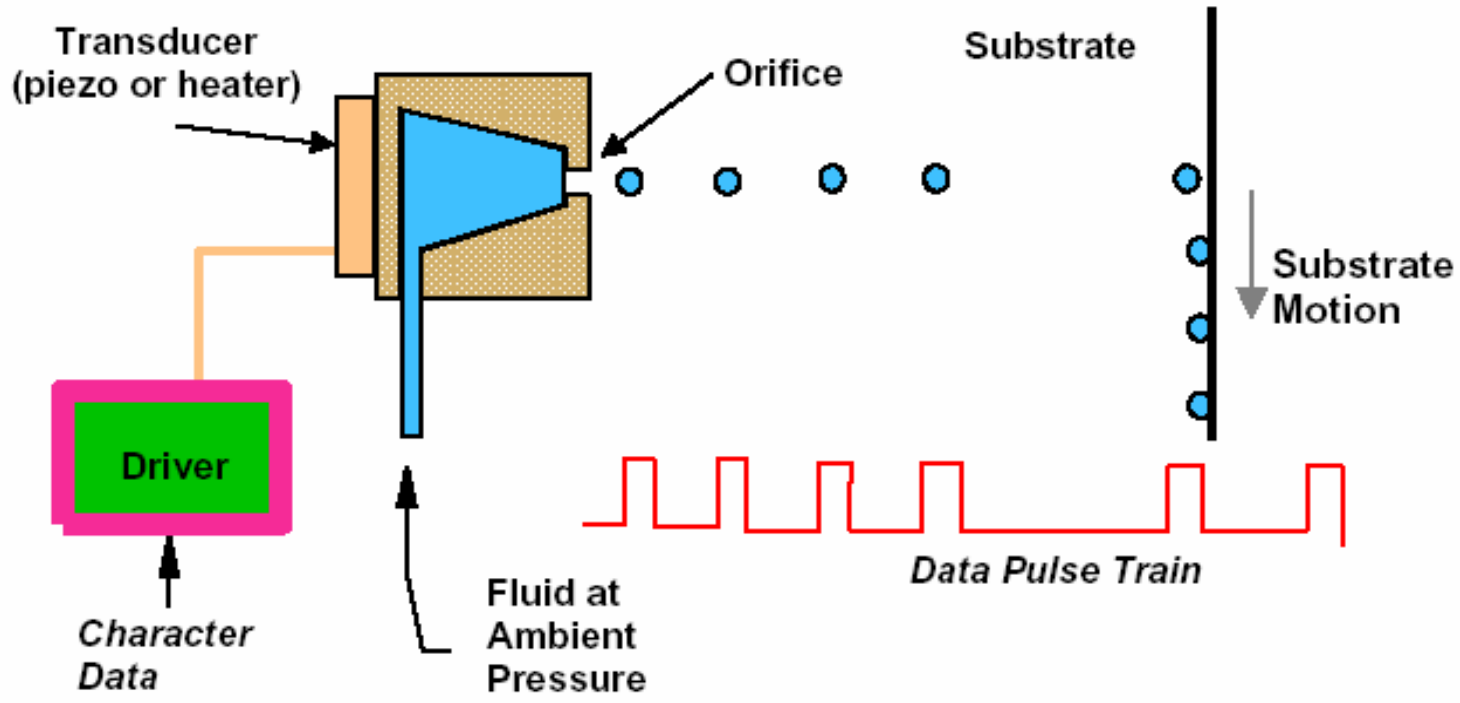
Drop-on-Demand Technology



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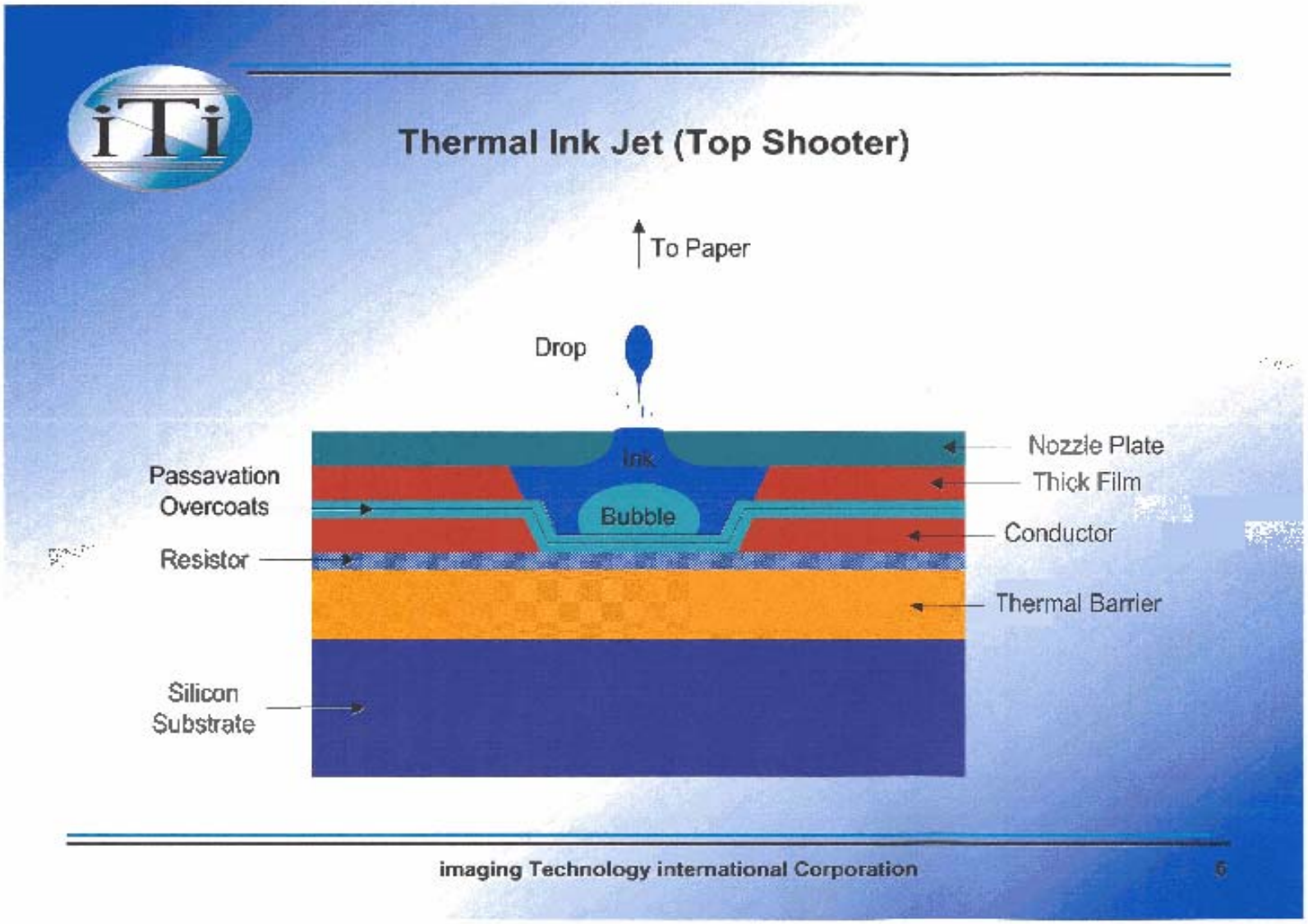
Thermal Jet

- Rapid heating induces a vapor bubble.
- Volume change causes pressure waves, fluid flow leads to drop ejection.
- Vapor bubble collapses after ejection, ink refills.

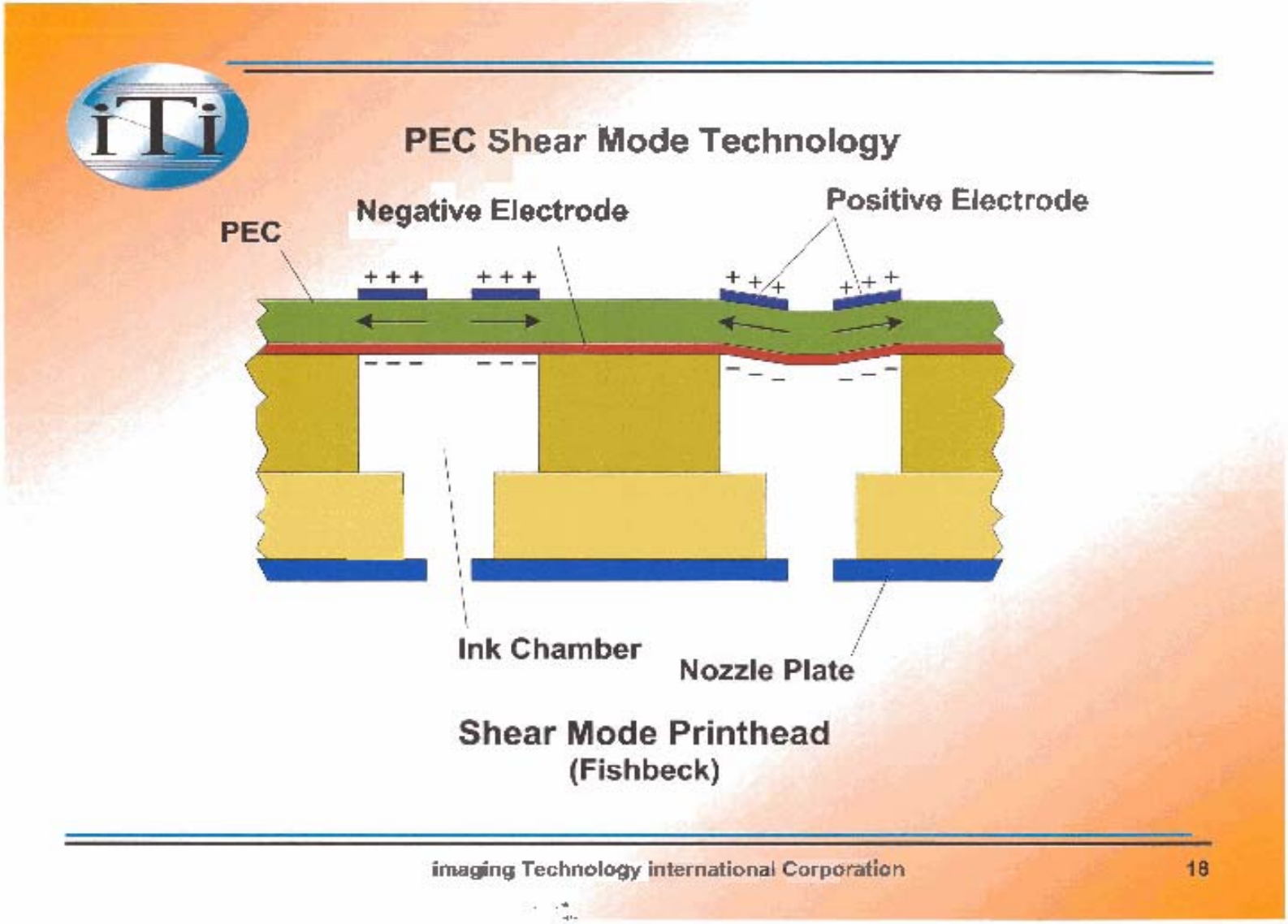

Thermal Ink Jet (Top Shooter)
To Paper
Drop
Ink
Bubble
Nozzle Plate
Thick Film
Conductor
Thermal Barrier
Passavation
Overcoats
Resistor
Silicon
Substrate
imaging Technology international Corporation
6

Thermal Jet Considerations

- Low vapor pressure, low flash point solution required
- Fluid must withstand thermal stress and not leave residue – kogation is the main failure mode.
- Large stresses on resistor leads to cavitation
  - Good design for throwaway print heads.

DOD Piezo Ink Jet

- Piezoelectric transducer imparts energy to fluid volume.
- Lead Zirconate Titanate (PZT)
- Acoustic waves propagate to surface.
- Energy converted from pressure to velocity at orifice.


PEC Shear Mode Technology
PEC
Negative Electrode
Positive Electrode
Ink Chamber
Nozzle Plate
Shear Mode Printhead
(Fishbeck)
imaging Technology international Corporation
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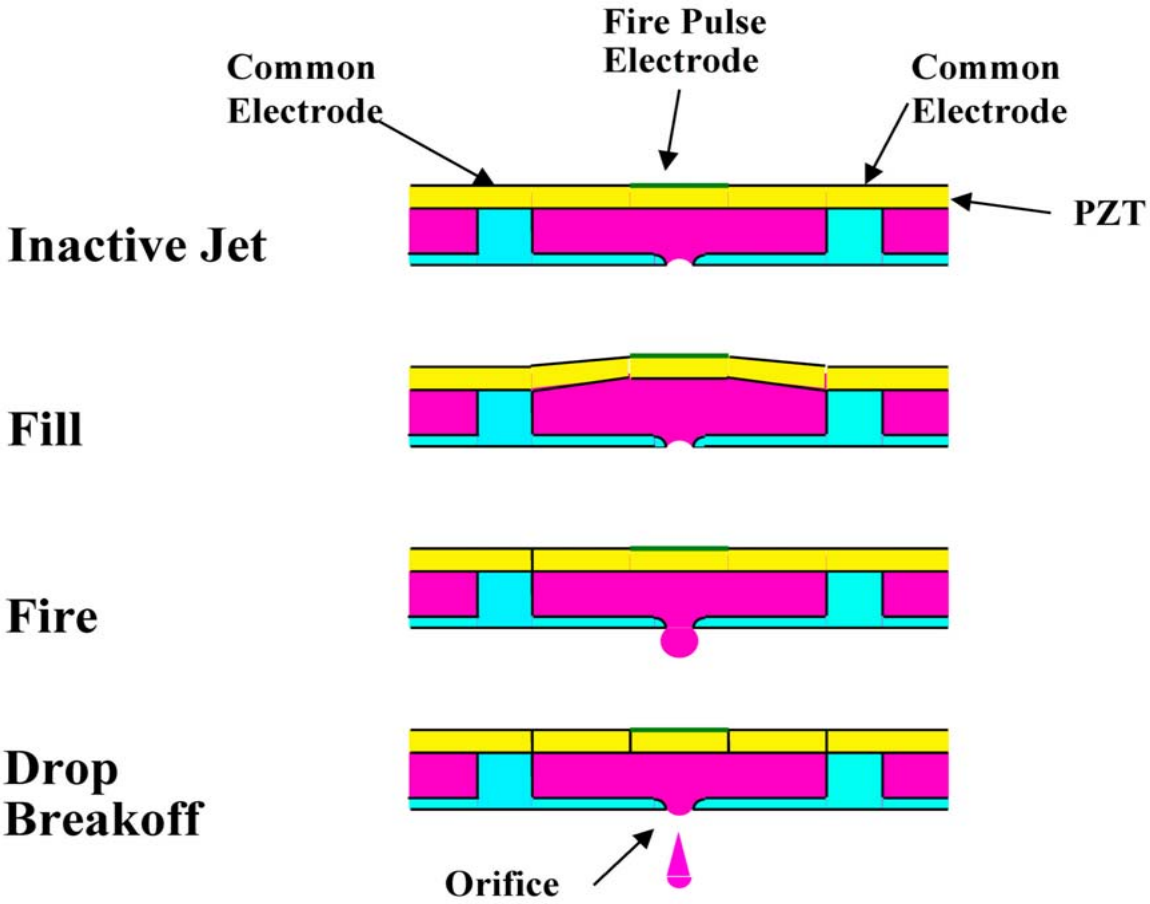
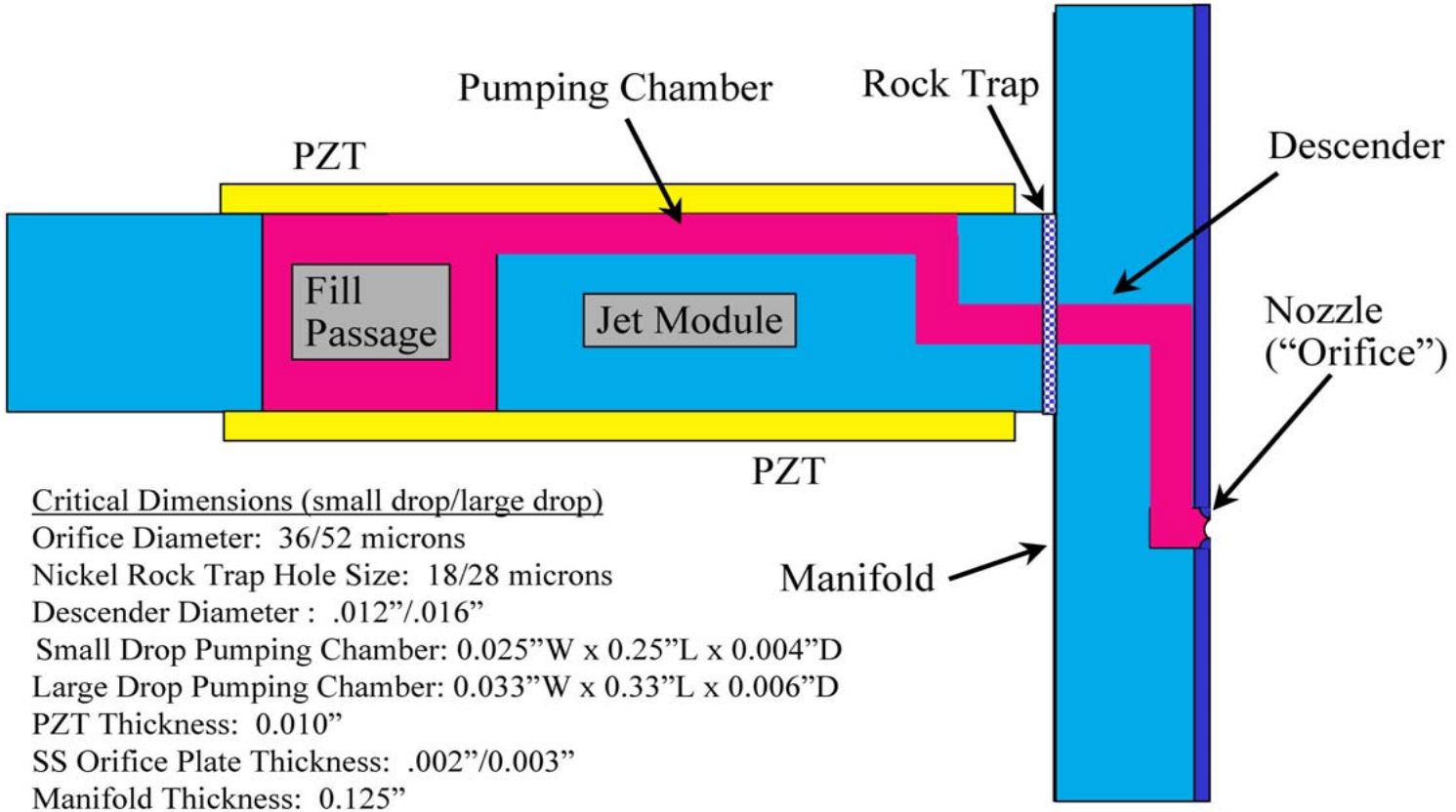
Shear Mode Piezo Action



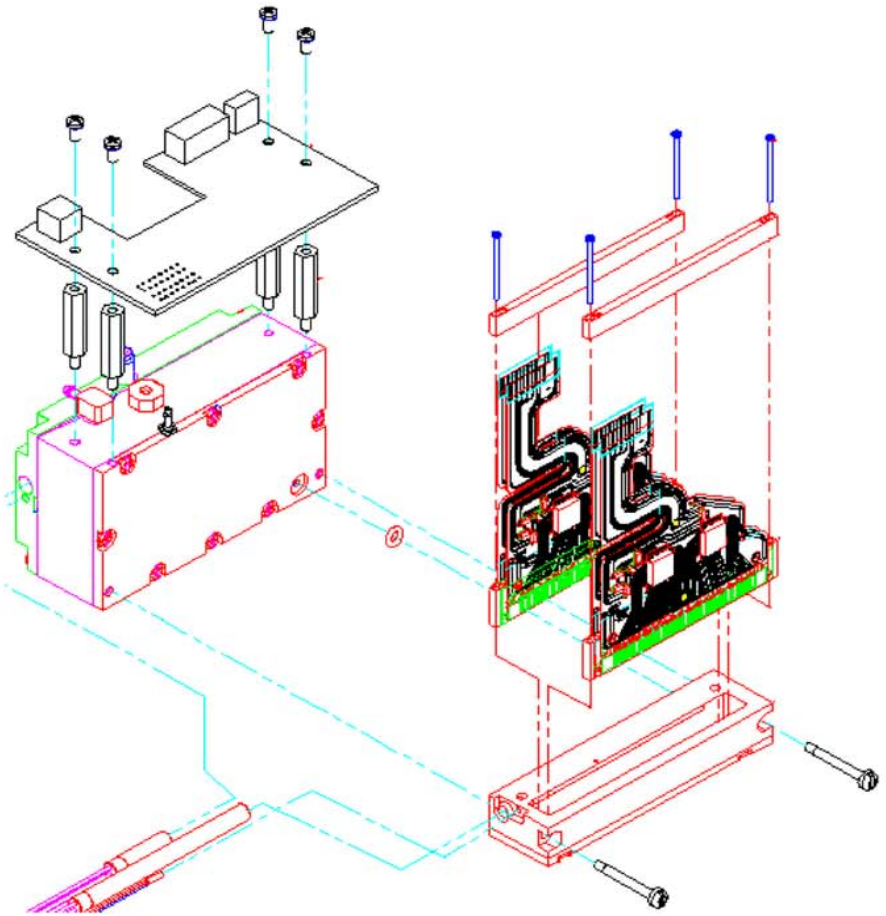
Jetting Assembly Fluid Path

256 Jet Structure and Elements



Critical Dimensions (small drop/large drop)
Orifice Diameter: 36/52 microns
Nickel Rock Trap Hole Size: 18/28 microns
Descender Diameter : .012"/.016"
Small Drop Pumping Chamber: 0.025"W x 0.25"L x 0.004"D
Large Drop Pumping Chamber: 0.033"W x 0.33"L x 0.006"D
PZT Thickness: 0.010"
SS Orifice Plate Thickness: .002"/0.003"
Manifold Thickness: 0.125"

Spectra Printhead

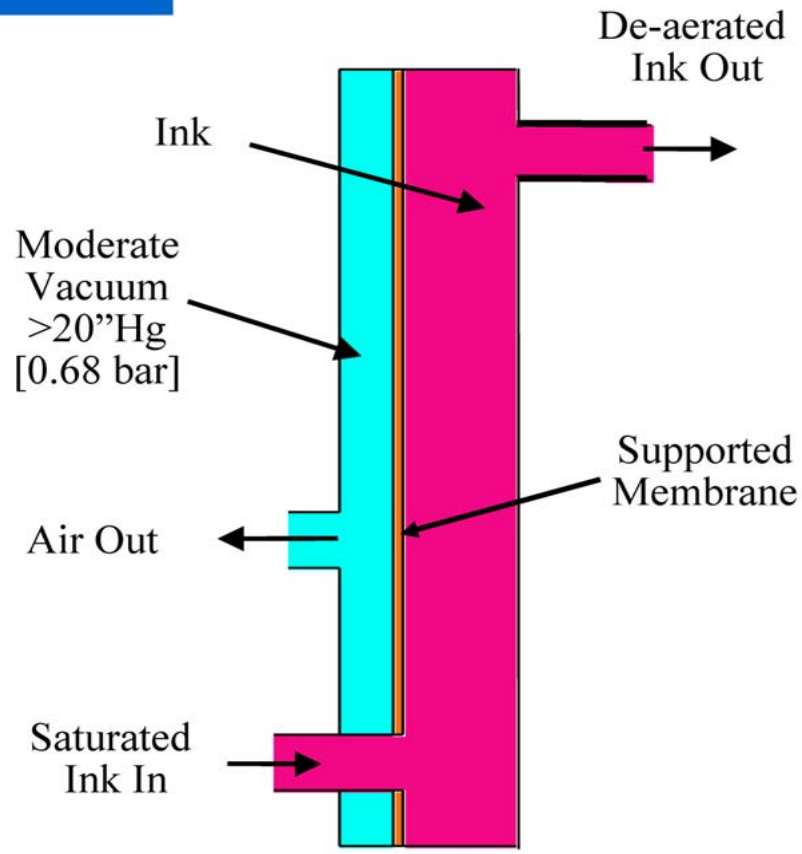


- Intended for a variety of applications
- 256 jets (2 128-jet modules)
- FLIP jet design
- Carbon jet bodies and manifold
- EDMed nozzles
- 300 - 600 dpi (30 - 80 ng)
- 1 color per head
- Driver chips soldered on flexprint
- Monochrome reservoir

Back-End Ink Reservoir Basics

Degassing

- Lung Design Parameters
- Lung Area: 30 cm^2
- Ink Thickness: 1 mm
- Lung Volume: 3 cc
- Time Constant: 2 min.
- Flow Resistance:
  - 1" H_2O / cc/sec.
  - [2.49 mbar/cc/sec]
- Max. Lung Flow: 1.5 cc/sec



Spectra Fluid Property Recommendations

Fluids should be formulated to meet the following criteria:

Viscosity	10-16 cPs
Surface tension	28-32 dynes/cm
Particle size	less than 1 micron
Rheology	Newtonian

Piezo DOD Considerations

- May use many types of fluids as heating is not involved.
- Piezo actuators (PZT's) less likely to fail so print head lifetime should be much greater.

Dimatix Apollo II PSK

System Components

- 1, 2 or 4 Printheads
- CPU -- Integrated PC Module with Windows 2000 Operating System
- C&DM -- Control and Data Module
  - Printhead Data Path, Temperature, Fluid Level Control Module
- HPM -- Head Pneumatics Module
- HDEM -- Head Drive Electronics Module
- Peristaltic Pump Ink Supply (1 per head).

iTi XY MDS

Figure 2: iTi XY MDS UV (Ultraviolet Cure and external Apollo PSK Options).

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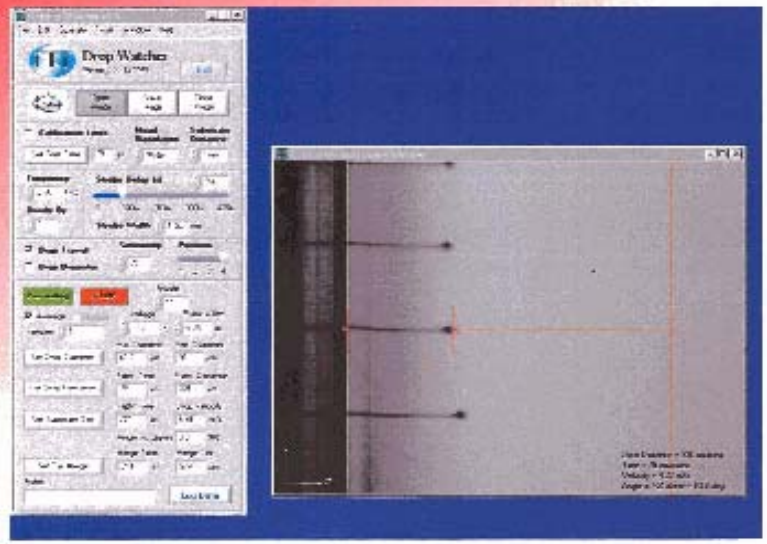
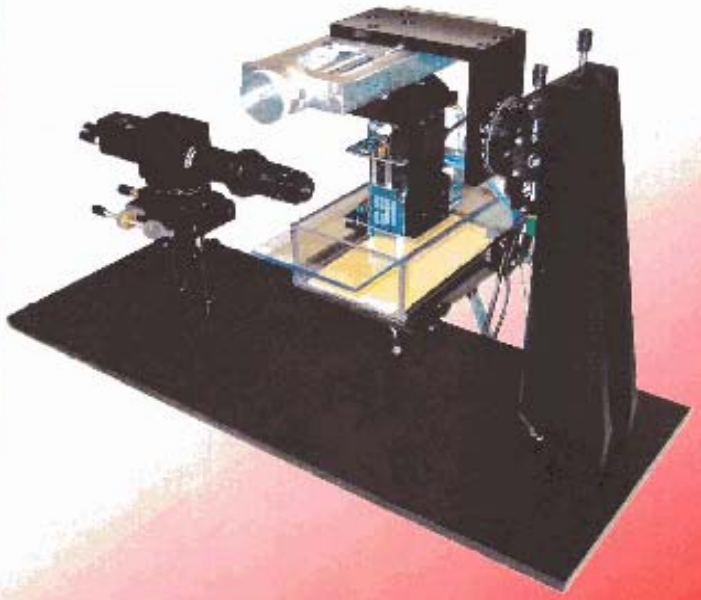
iTi Drop Watcher



Screen capture of iTi's Drop Watcher Measurement Software.



iTi's Drop Watcher with Spectra Print Head.

Drop Visualization

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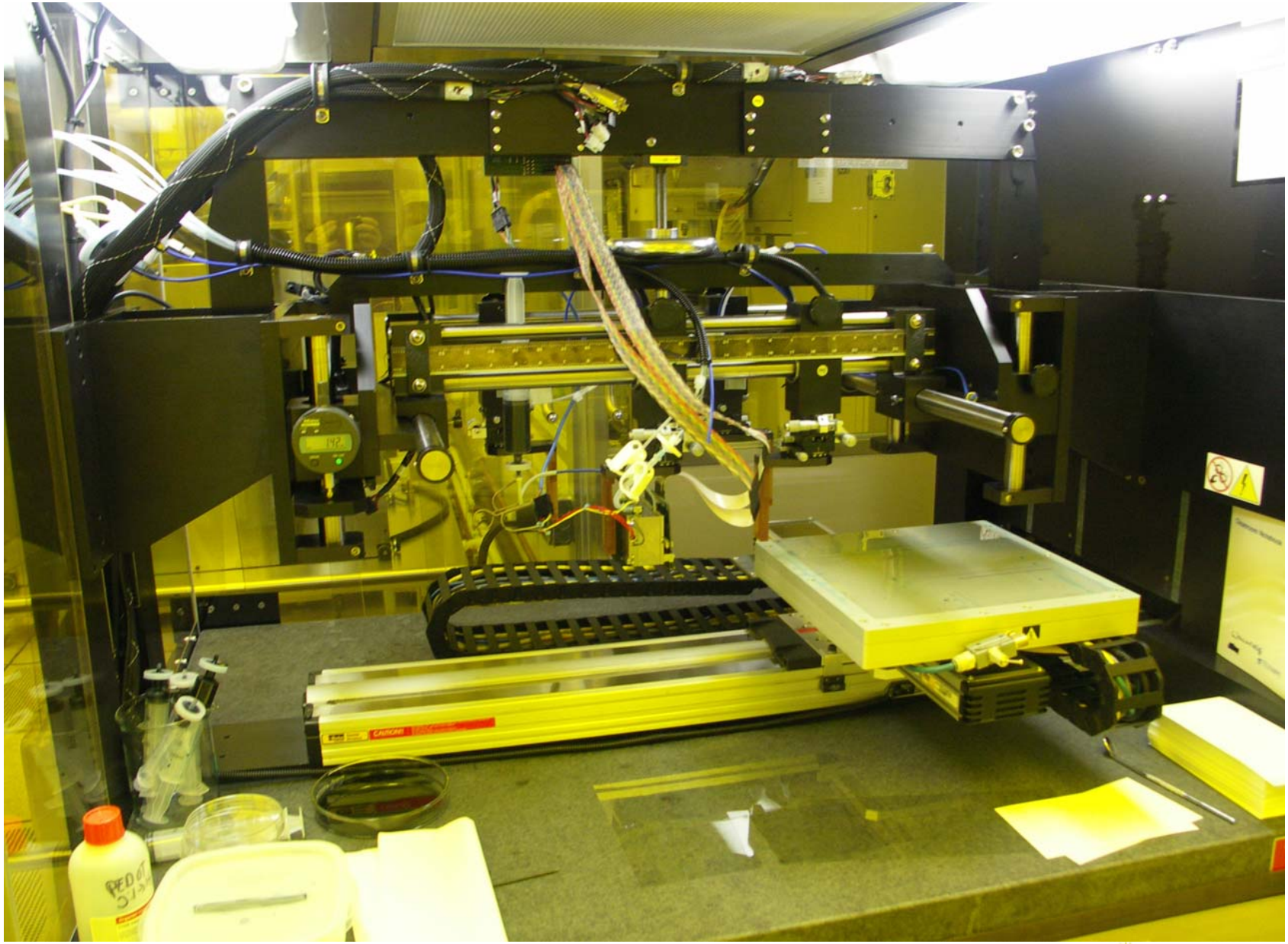
KENT STATE UNIVERSITY



What's the resolution?

- The ink jet printing triangle –print head, ink, and substrate.
- Ink – Print head
  - Materials compatibility
  - Wetting, internal and external
  - Dissolved gas
  - Jetability
  - Drying

Fluid Properties Effects

- In printhead
  - low viscosity for fast refill, low voltage
  - high viscosity for damping, satellite suppression, particle dispersion
  - low surface tension for ease of filling/purging, low voltage, uniform wetting
  - high surface tension for non-wetting, prevention of bubble ingestion
  - high solute (colorant) solubility to prevent contamination / drying

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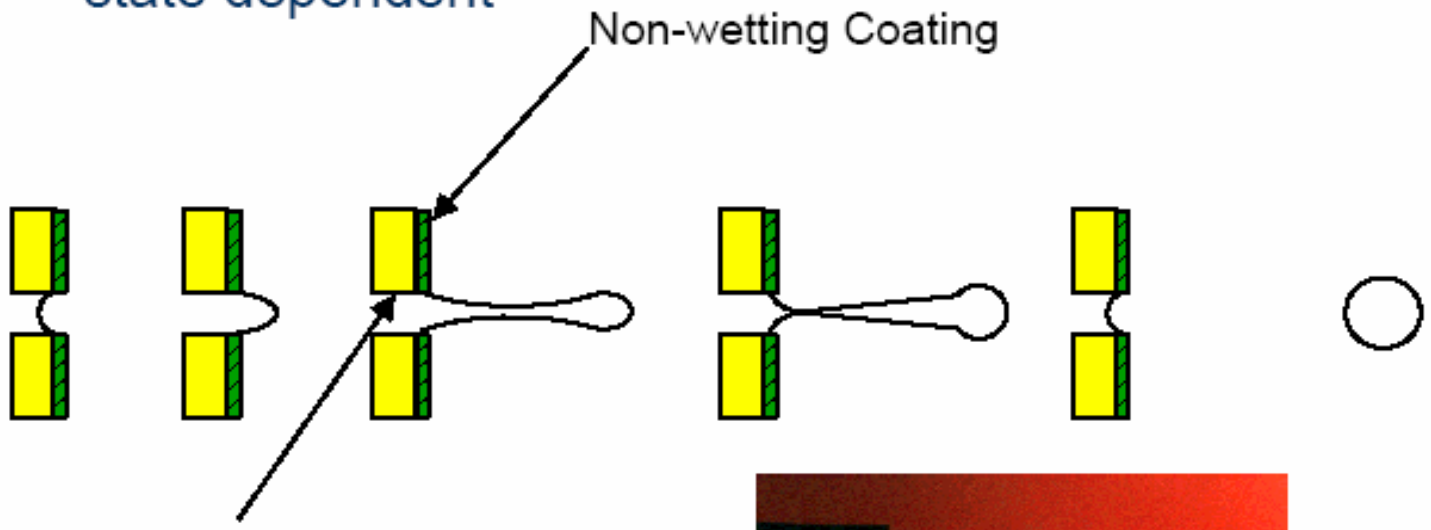
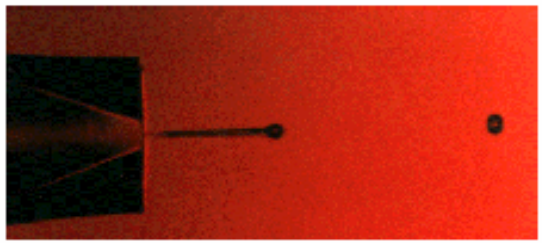
Orifice Plate: Ideal Wetting

- Actual wetting is materials, process, maintenance state dependent





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Fluid Properties

- Viscosity
  - viscoelastic behavior undesirable
  - Newtonian viscosity: 1-40cp
    - Lower = low voltage, less temperature effect
    - higher = damps acoustic & Raleigh oscillations
- Surface Tension: 20-70 dy/cm
  - lower = low voltage
  - higher = less wetting (outside of orifice plate)
- Functional
  - wetting, spreading, optical density, reactivity, etc.
- Operational
  - vapor pressure of solvents (drying); dissolved solids concentration (precipitation); materials compatibility; aging characteristics; ...

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Viscosity Effect

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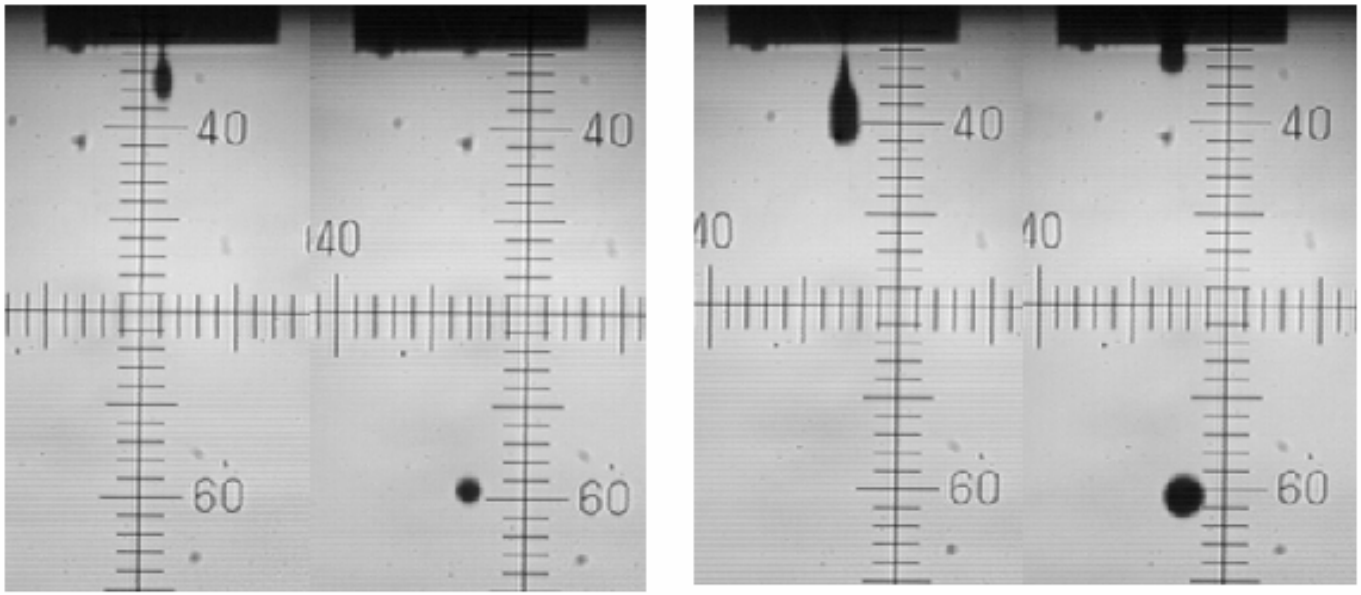
Surface Tension Effects

- Molten Solder at 240 Hz
  - σ = 400 dy/cm (DI water = 70)



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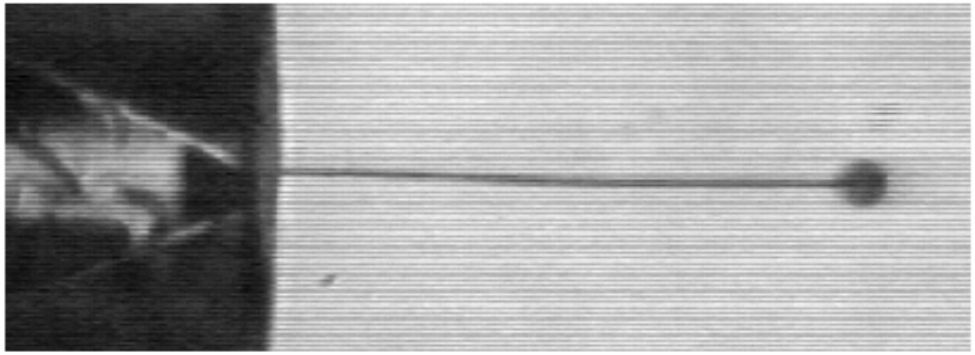
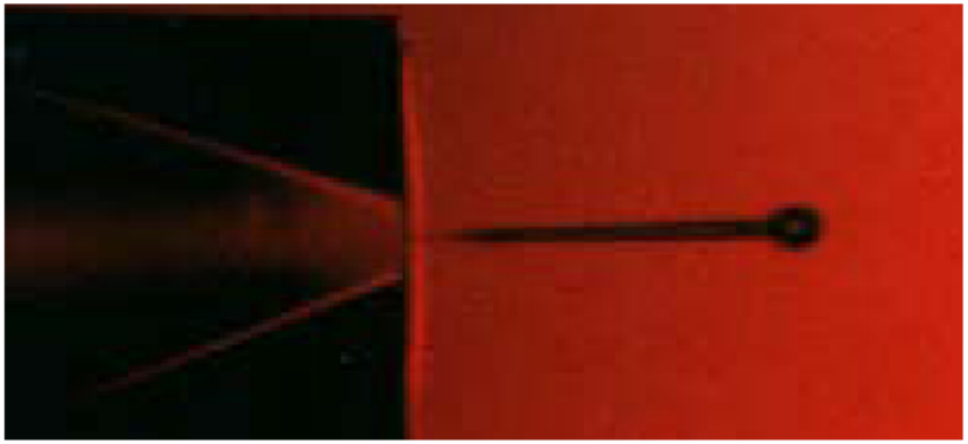
Non-Newtonian Effects



Lubricant



Glycerol

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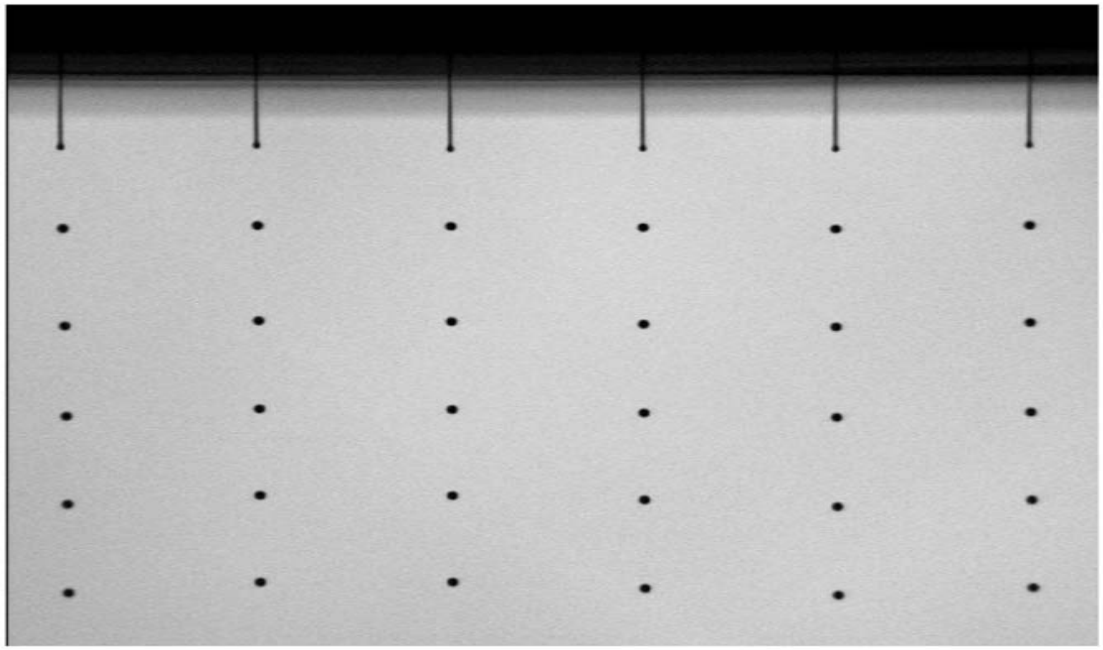
Jetting Well Formulated Fluids

Results from Jet Trimming

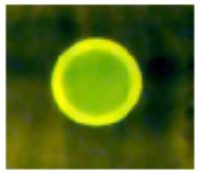
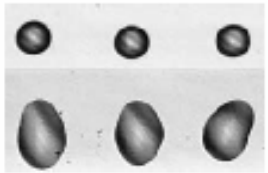
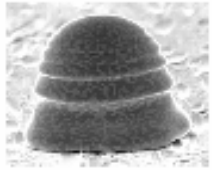


Resolution II

- Ink-Substrate
  - Absorption
  - Spread
  - Thickness
  - Splatter
  - Dry time
  - Substrate temperature

Fluid Properties Effects

- On substrate
  - high viscosity / surface tension for spot shape / size control, less non-uniform spreading (feathering)
  - low viscosity / surface tension for rapid penetration (minimum rub-off) or spreading, less spot "walking" on low wet surfaces
  - low solute (colorant) solubility for rapid fixing of image, dot gain control, minimize "coffee ring" effect.

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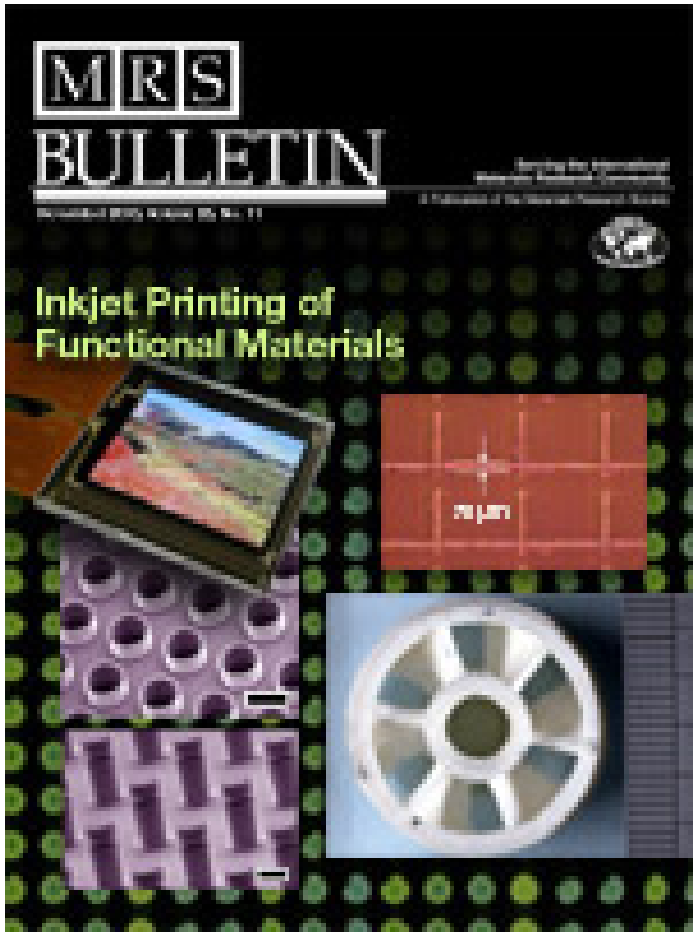
Substrates

- Typically ink jet has been used on porous media.
- Need to treat or coat plastic substrates to control drop spread.
- Treatment may affect properties of printed material (e.g. conductivity).
- Surface modification can induce drop confinement.

Printing polymers



First ink jet project - PEDOT

- Ink jetted conducting polymer PEDOT/PSS
  - Polyethyldioxythiophene-polystyrenesulfonic acid
  - Conjugated polymer
- Eliminates photolithography steps
  - Spin photoresist, expose, develop, etch, strip
  - Replace with one step direct write process
  - Conducting polymers in 300 ohm/square range
  - Flexible conductor avoids ITO cracking in flex displays

Conducting Polymer

- Want to print PEDOT on plastic substrates for conductors on displays.
- Using Agfa S300 PEDOT/PSS formulated for ink jet printing.
- What is maximum resolution?
- What conductivity can we achieve with acceptable transmission?

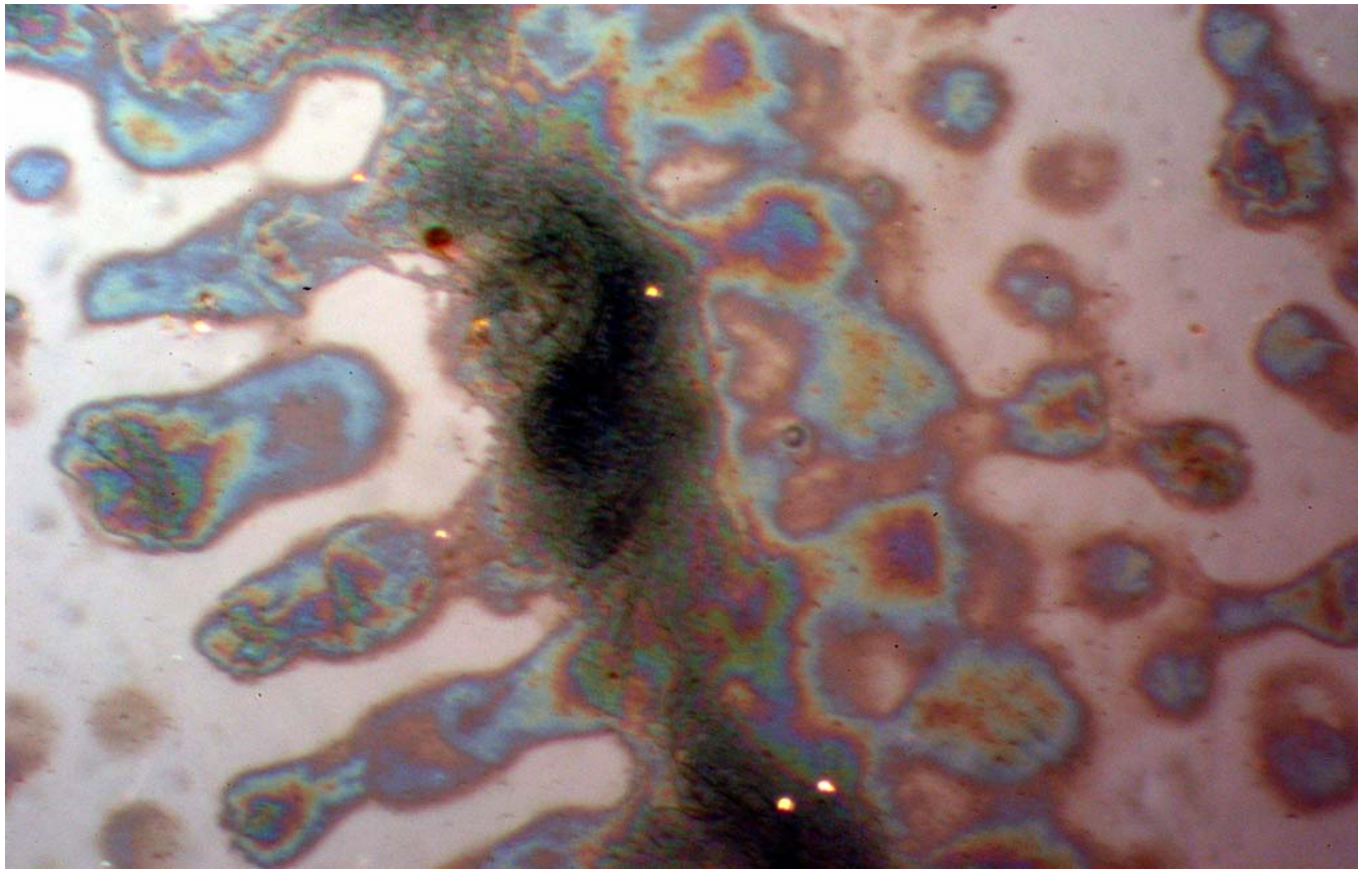
Art or Science?

"inkjet technology is still regarded by many experts in the field as black magic" H. Sirringhaus, 2003

- Ideal Inkjet Conditions
- Ink
  - Viscosity 8-12 cP
  - Surface Tension 28-32 dynes/cm
  - Low molecular weight Newtonian fluid
- Substrate
  - Porous, absorbent

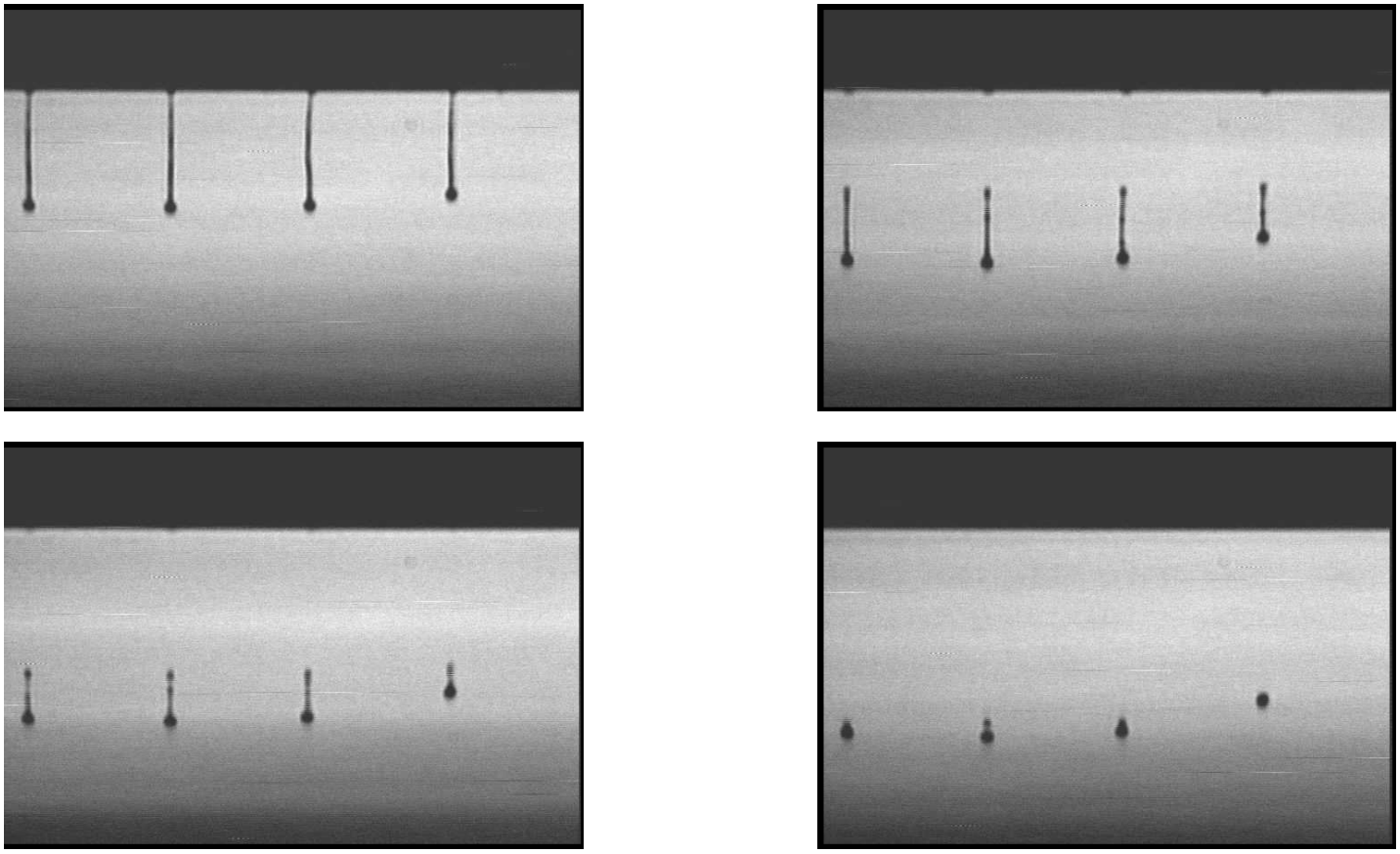
- Actual Conditions
- Ink
  - Viscosity 12-28 cP
  - Surface Tension 70 dynes/cm
  - High molecular weight non-Newtonian fluid
- Substrate
  - Plastic

PEDOT on PET

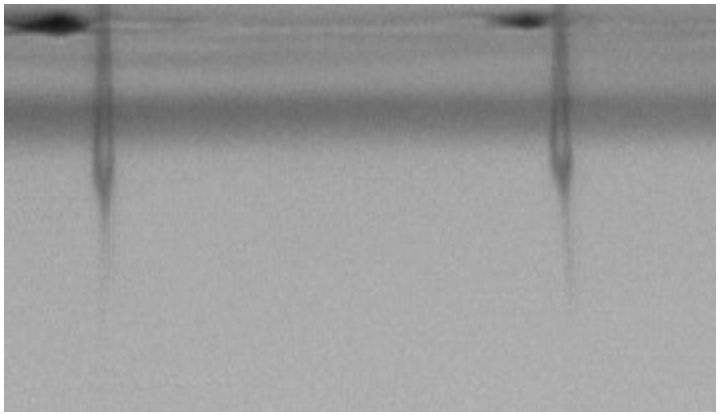


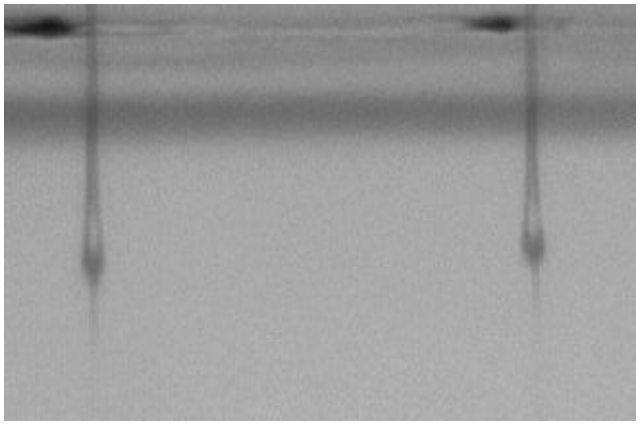
PEDOT on coated substrate.

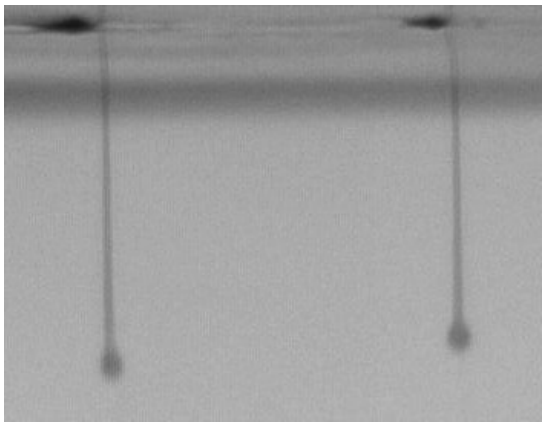
Well behaved drop formation

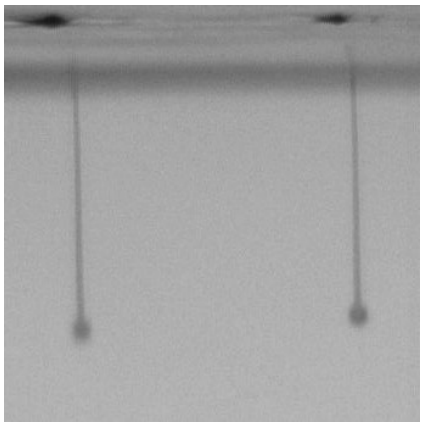


130 V 8 μS

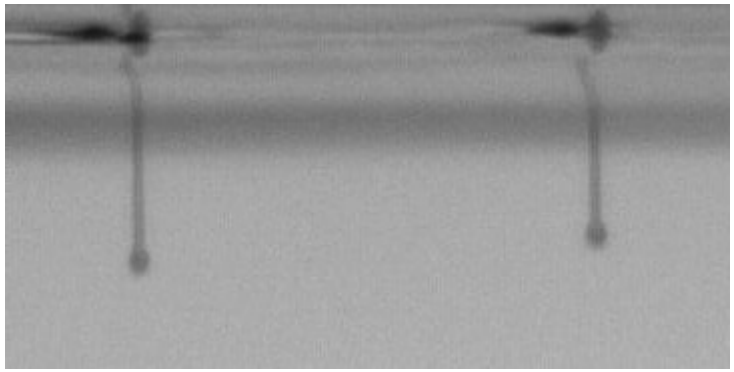


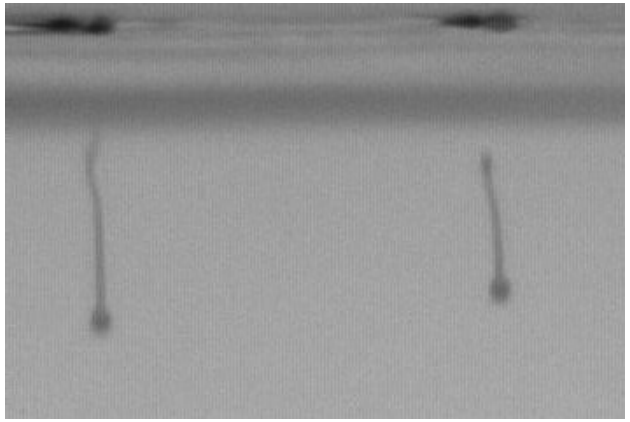


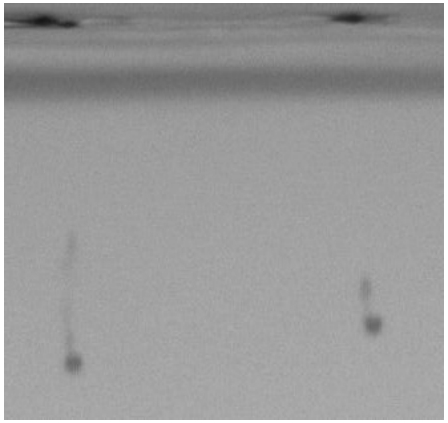


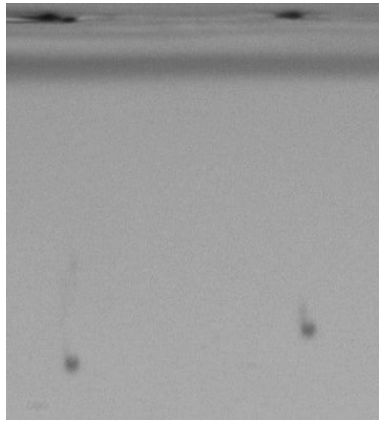


60V 6 μS

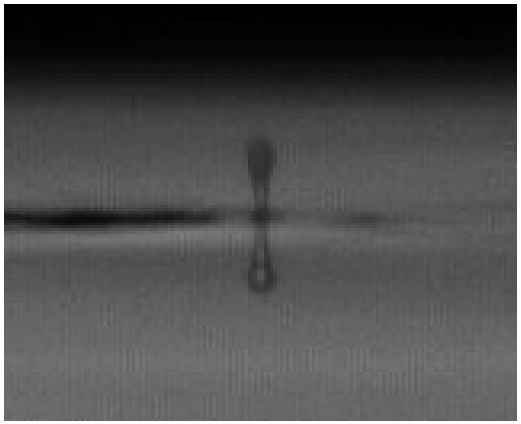
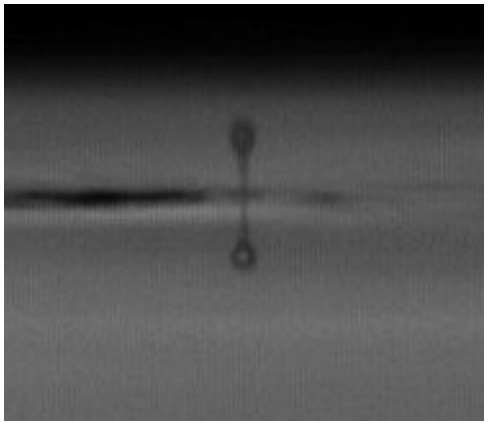
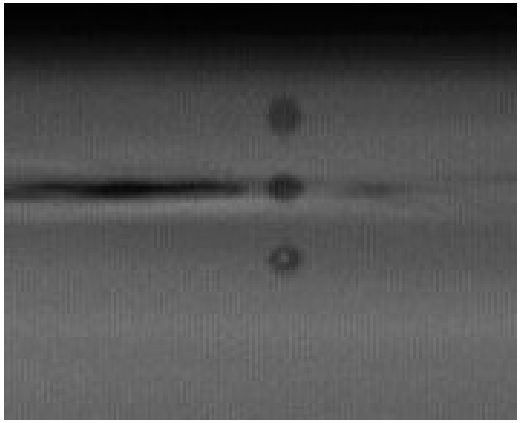
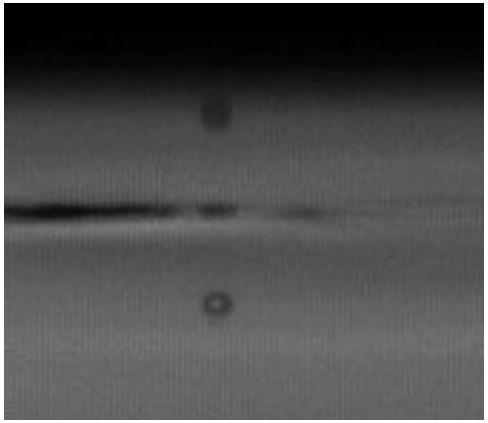




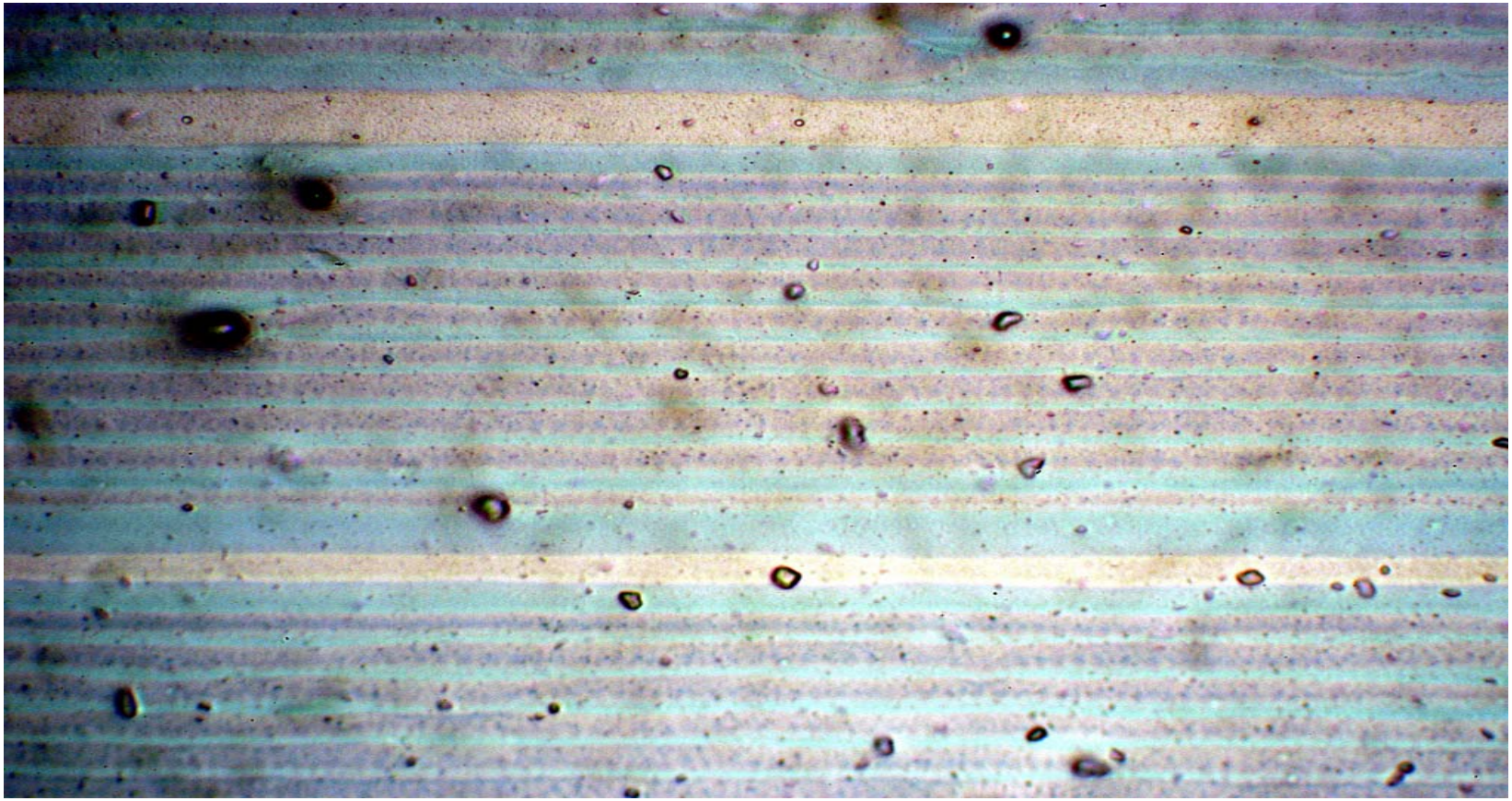




40 V 4 μS

850 DPI 60 V



Preliminary results

- Can successfully print PEDOT
- Current resolution is < 60 microns
- Conductivity function of film thickness achieved w/ multiple print passes -340 ohms/square on uncoated PET.
- Transmission > 90% in visible spectrum.
- Results are very preliminary!

Future work

- Hardcoat/Polyimide Printing
- Gasket Printing
- Spacer Posts or Spacers in IR cure fluid
- Liquid Crystal Deposition?
- LCD made using 2 plastic sheets and an ink jet printer.

PLED / PEDOT Printing

- Organic emitters and conductors printed by ink-jet technology
  - Materials: solvated (water and organic) polymers
  - Benefits: no process interaction, additive ($)
  - Competing technologies: photolithography for monochrome
  - Challenges: non-Newtonian effects (polymer), low surface tension / high wetting, volatile solvents

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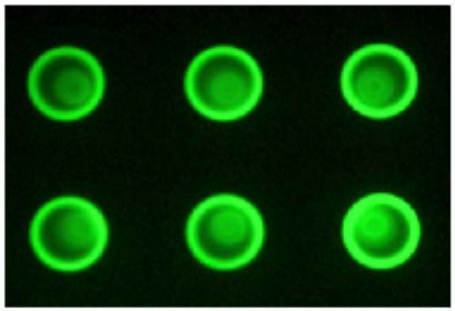
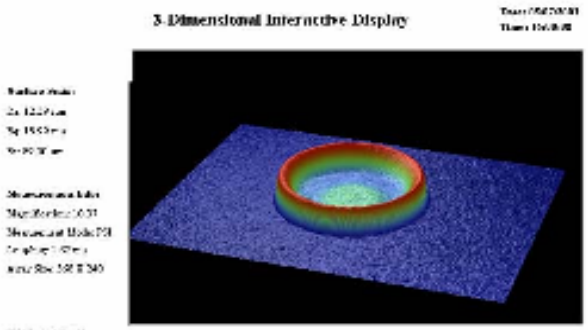
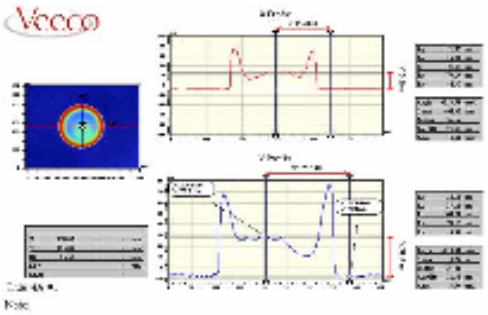
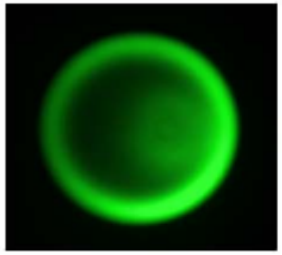
PLED Printing

- "Coffee" ring from solute mobility during drying



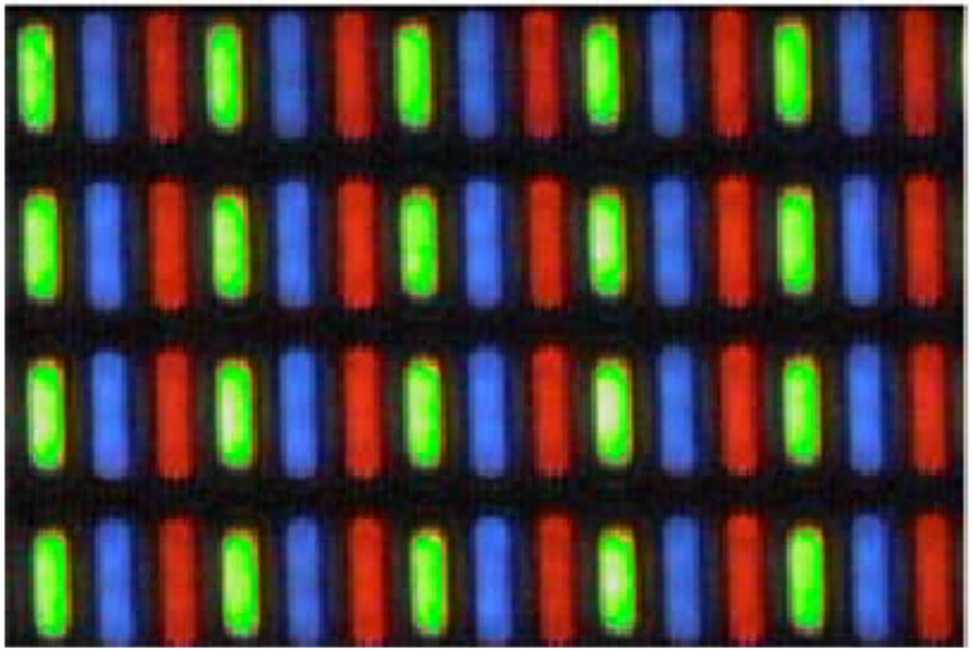






MicroFab

Color PLED Display



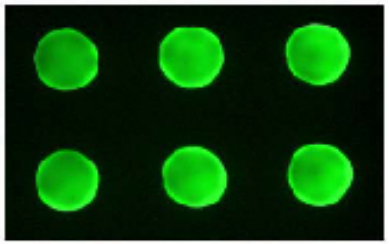
100µm and 300µm pixel pitch, ¼ VGA display

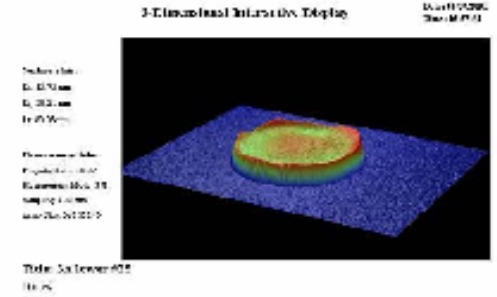
DuPont Displays

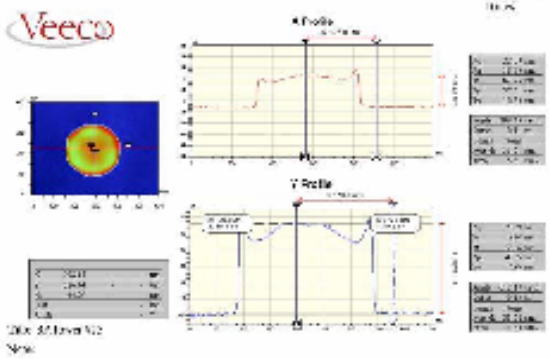
MicroFab

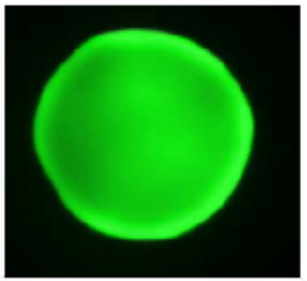
PLED Printing

- PLED: 0.5-1.5% polymer in organic solvent









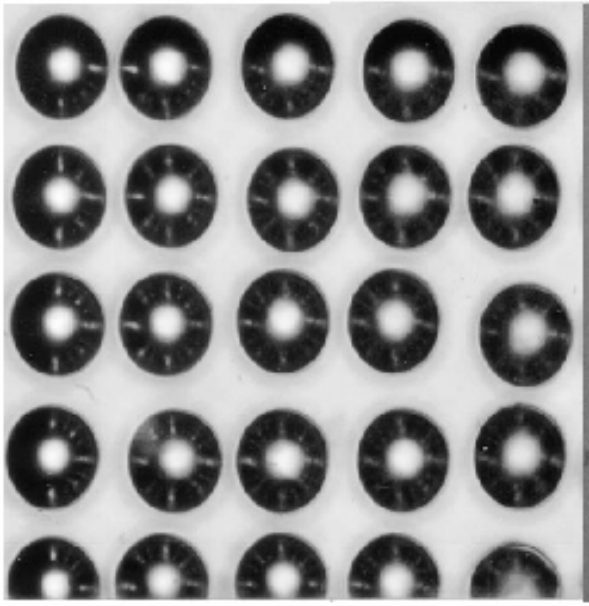
50nm thick, 200µm diameter features

MicroFab

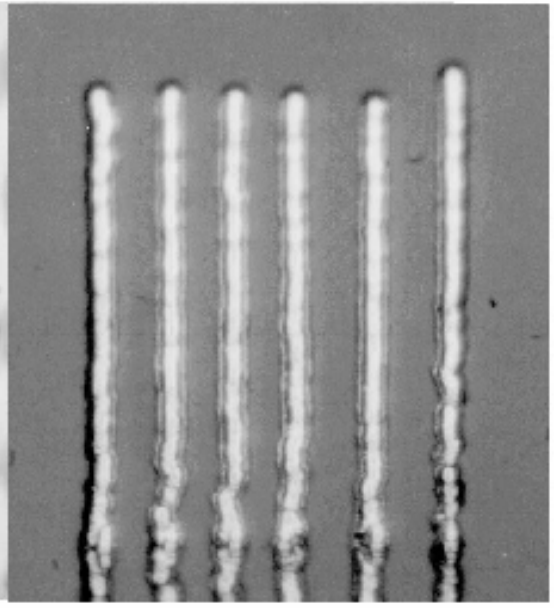
Solder Jet® Applications

- 3-D Assembly / High Resolution

24µm bumps on 35µm centers



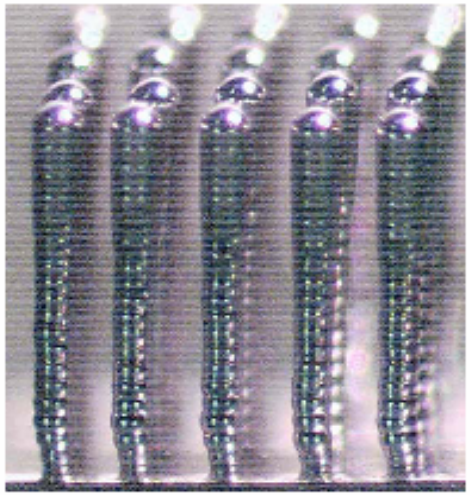
24µm towers

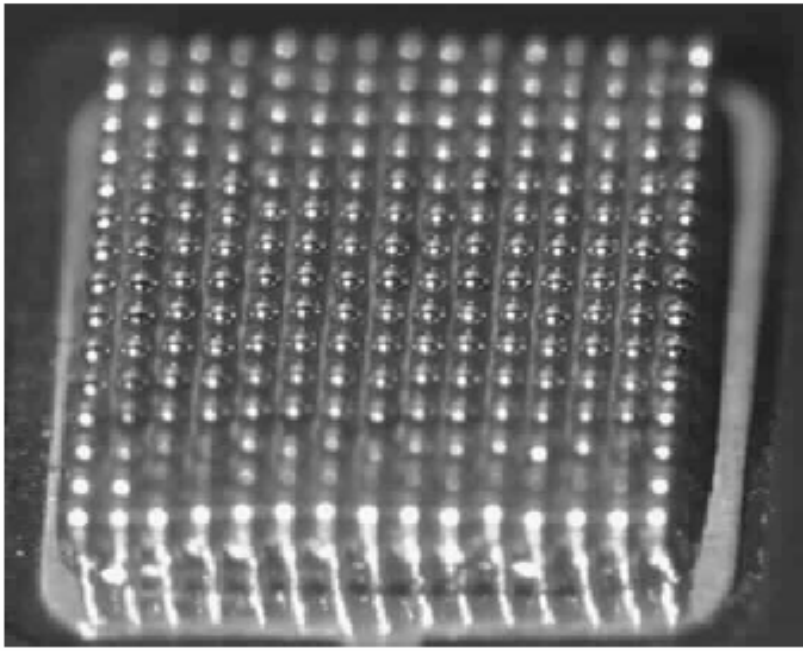


MicroFab

3-D Electronic Packaging

- Solder towers, 80µm wide at bottom,120µm wide at top, 800µm tall, 150 µm pitch

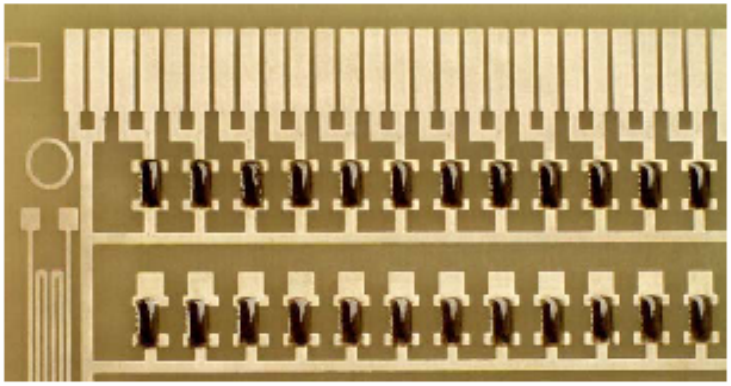




MicroFab

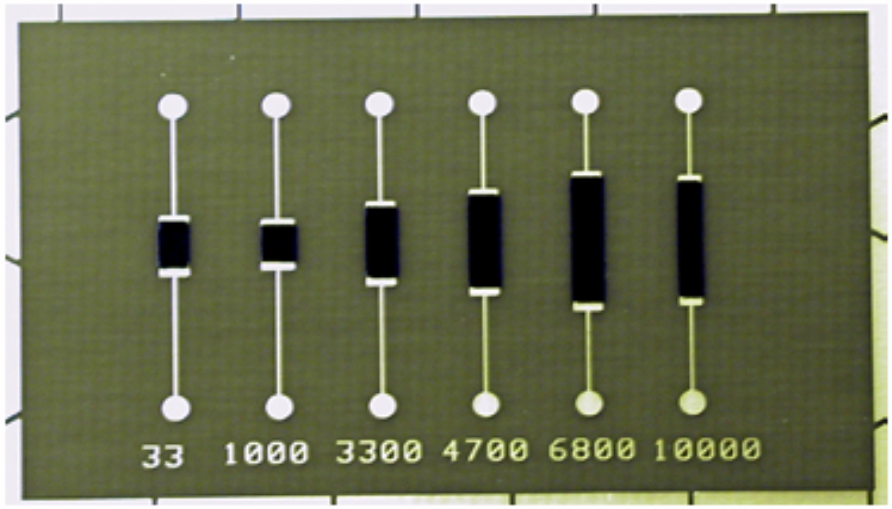
Resistor Printing

- Sizes: 2x4 mm
- Epoxy, carbon nanotube filled
- Tg = 165ºC
- Best to date 500 kΩ ±16%
- Key Issue: Better Dispersion @ Jetting Temperature



MicroFab

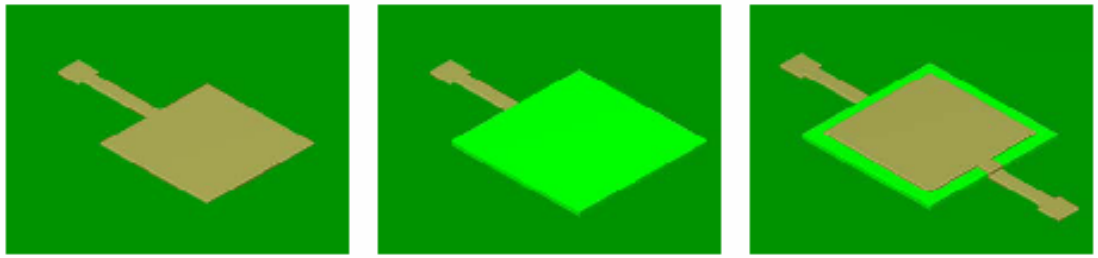
Resistor Printing



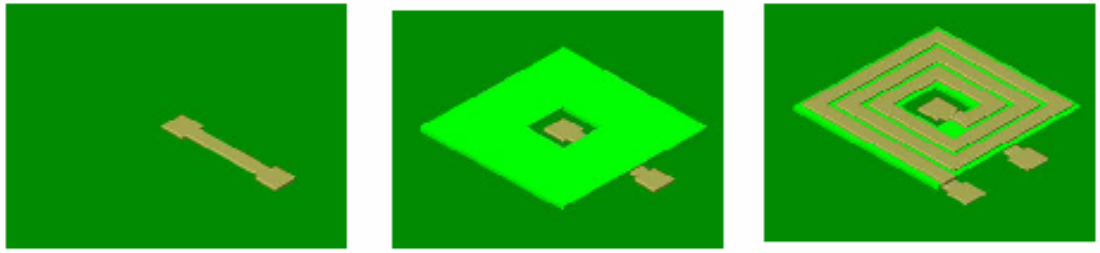
A Test Vehicle showing printed resistors of different aspect ratios

MicroFab

Passive Printing



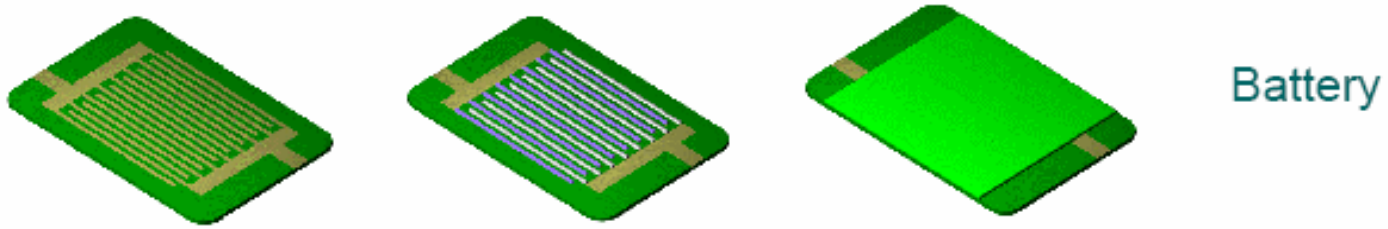
Capacitor



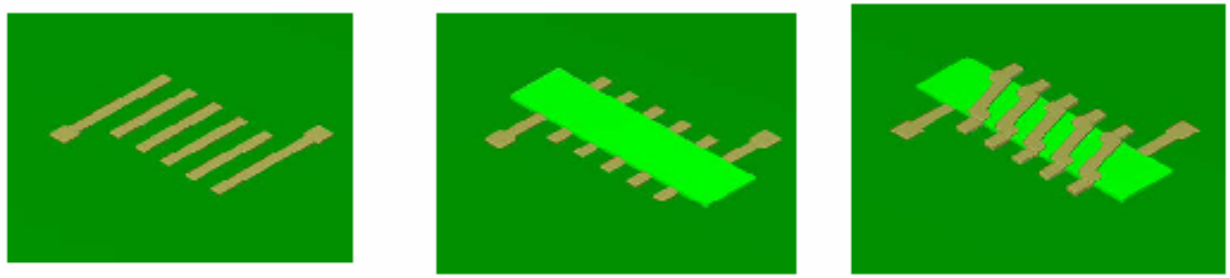
Inductor

MicroFab

Passive Printing



Battery

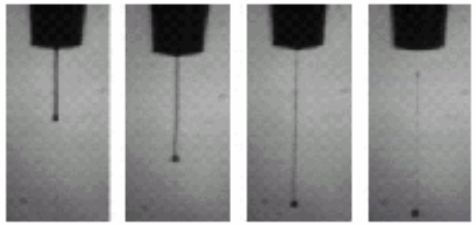


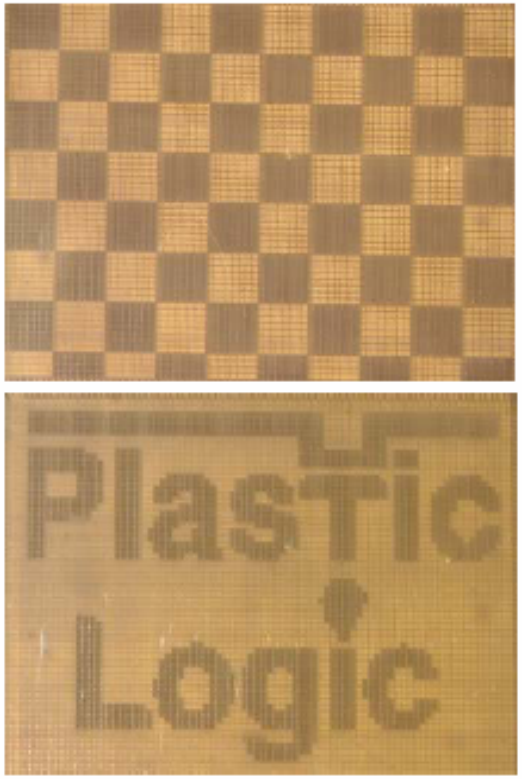
Coil

MicroFab

Organic Electronics Printing

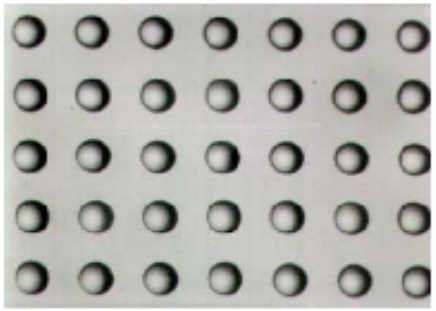
- Backplane for Active Matrix Display
  - Plastic Logic
  - 4800 Pixels, no defects
  - Running at 80 Hz, line address time of ~2ms
- Typical drop formation for polymer in solvent



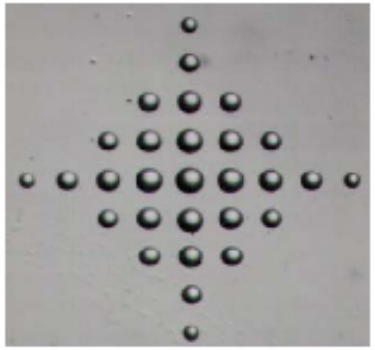


MicroFab

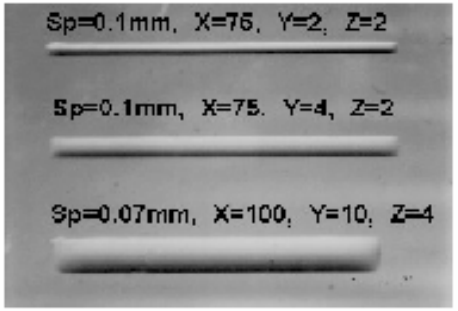
Adhesives Printing



80µm spots of optical adhesive



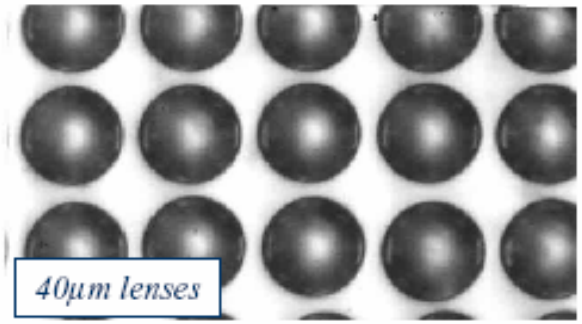
Varying volume adhesive spots, smallest is 80µm

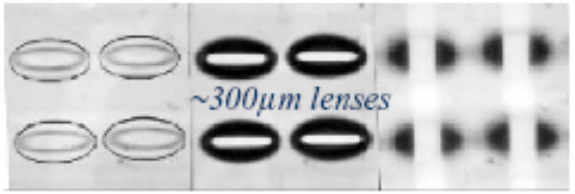


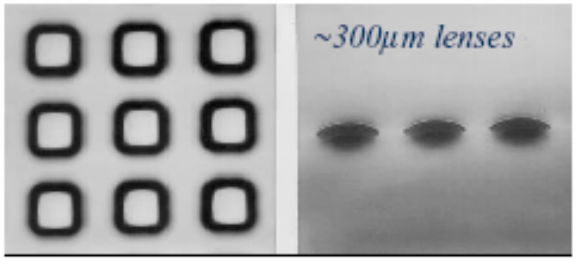
Adhesive lines

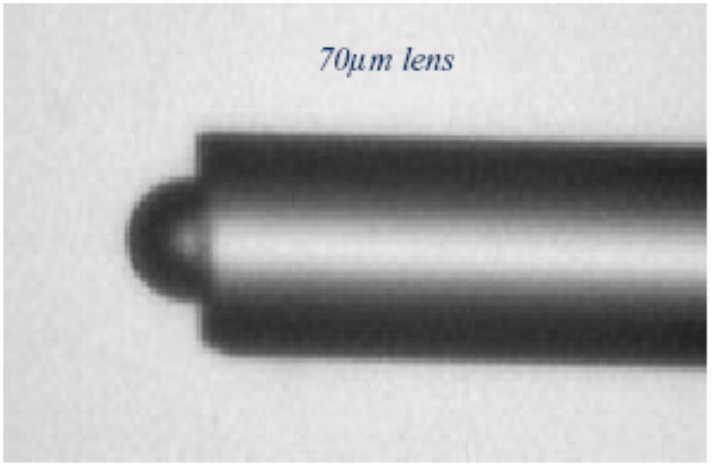
MicroFab

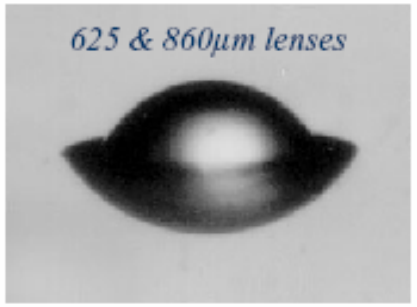
Microlens Printing







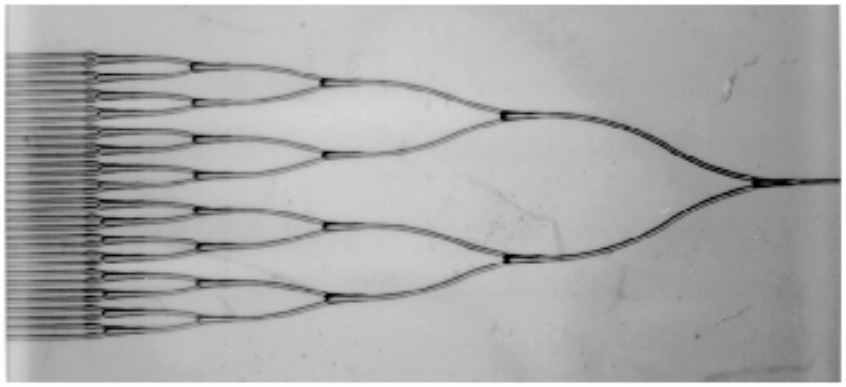




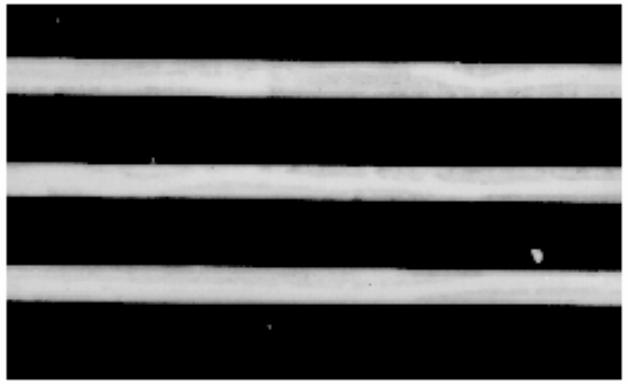
MicroFab

Multi-Mode Waveguides

1.74-index optical thermoplastic printed on glass as 1-32 splitter, 120µm wide branches



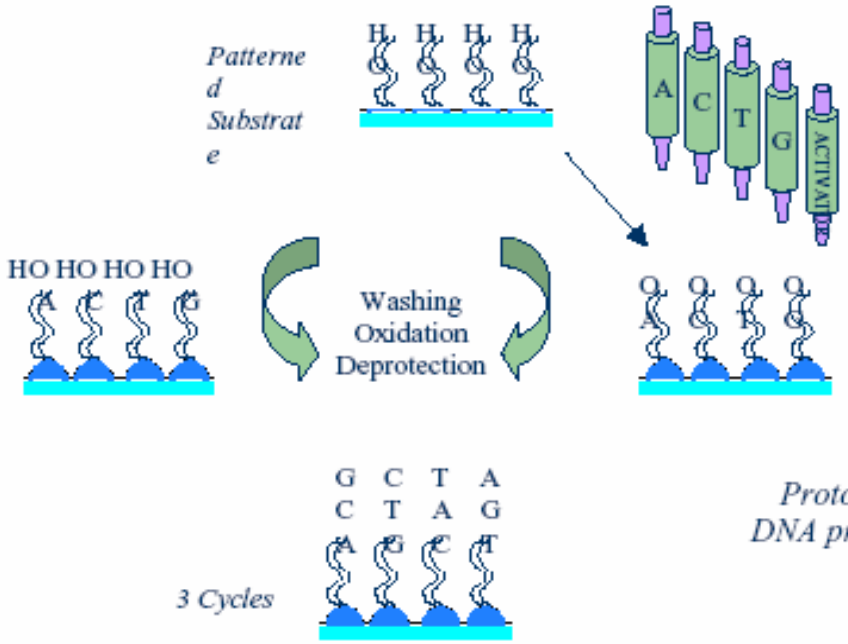
60x40µm waveguides, UV-cure optical epoxy into grooves micro-machined in silicon



MicroFab

DNA Array Synthesis

- 4 or 5 "colors" to create 10k+ oligos (10-20mers) in ~1cm2



Protogene DNA printer

MicroFab

And many more…

- Silver electrodes on plastic substrates
- Antibodies
- DNA and Peptide array assembly
- Chemical synthesis
- Chemical Analysis
- Laser surgery
- Sensors
- Tissue Engineering
- Nerve Growth Factor
- Nerve Guidance Conduits
- Bio Polymer spheres for drug delivery