Low-cost, Flexible Displays Using Nanoscale Droplets

Mateusz Bryning, Ph.D.

CTO

mbryning@zikon.com

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SF Bay Area Nanotechnology Council

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Zikon displays

"Electric Ink"

We are developing a new type of display based on nanodroplets that move in electric fields.

- Reflective paper-like displays
- Transmissive displays

Why it’s interesting

Big, beautiful, (relatively) inexpensive displays are everywhere…..

vs.

… But the time is ripe for the next big leap forward

Current LCD

- Poor readability in sunlight
- Rigid substrates
- Fixed form factors
- Expensive compared to static prints
- Poor energy efficiency
- Incremental improvements squeeze margins

The next big leap in displays

- Sunlight readable – paper-like appearance
- Flexible/bendable/ rollable
- Readily customizable form factors
- Paper-like price
- Very low power consumption
- New applications, new markets

Energy efficiency: The backlight

Backlight accounts for 2/3 of LCD TV power consumption

>90% of this light is wasted due to low LCD transmissivity

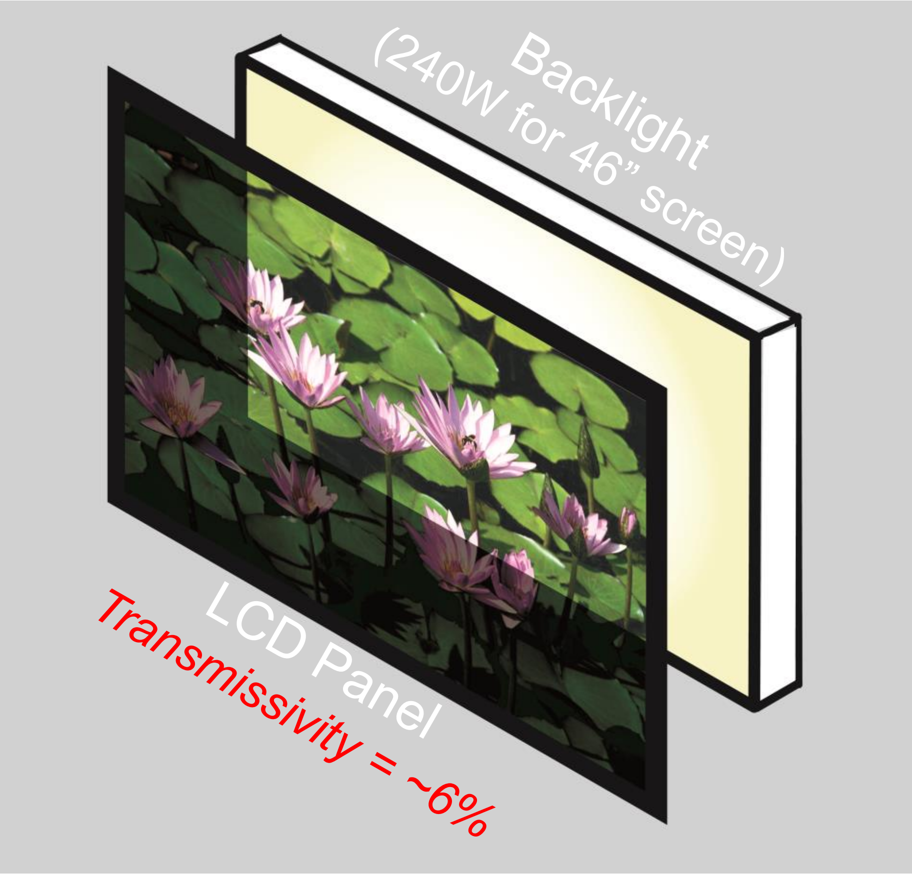
2008 PG&E study:

10% of power used by CA households is due to TV

Californians use…

9 Billion kWh per year or
5.2 Million barrels of oil equivalent (boe)

…for watching TV



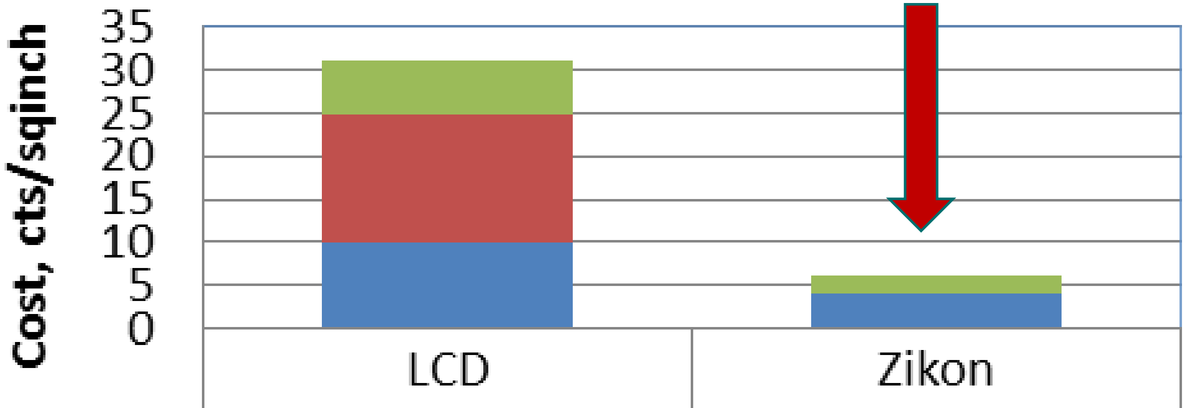
10x improvement in transmissivity = reduce backlight power by 90%.

Save 2-3M barrels of oil/yr in CA alone

*Sources: *Draft Efficiency Standards of Televisions*, California Energy Commission, 2008; bioenergy.ornl.gov

Can electronic displays be as cheap as paper?

80% Cost Reduction

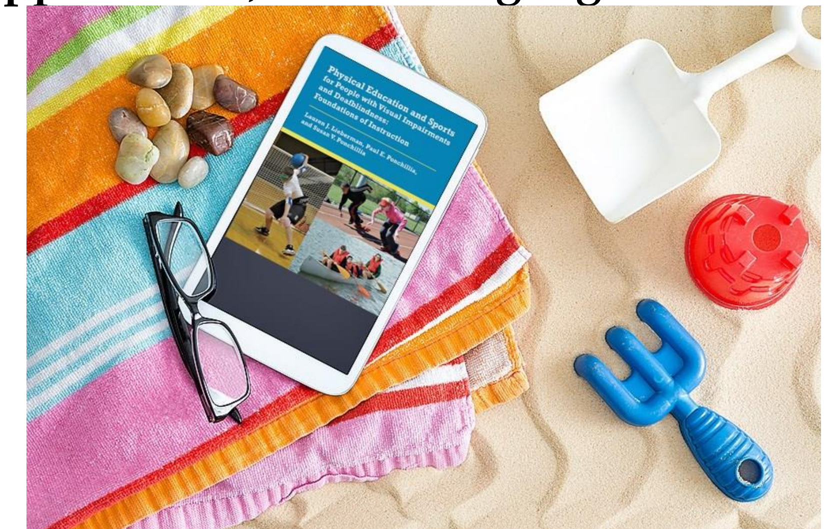


	LCD	Zikon
Ink	6	2
Polarizer	15	0
Substrate	10	4

Materials cost comparison between a basic monochrome LCD display and Zikon display

Sunlight Readability

Mobile devices, automotive applications, outdoor signage



Not just for advertising….

Display form factor

Wearable and mobile devices, new applications

Current LCD

- Active matrix
- Choose from 780p, 1080p, 2160p, etc….
- Choose 4:3 or 16:9 or 16:10 aspect ratio
- Choose diagonal size

- Custom shapes/sizes are $M investment

Moto 360: 1.56” round display, 320 x 290, 205ppi

Future displays

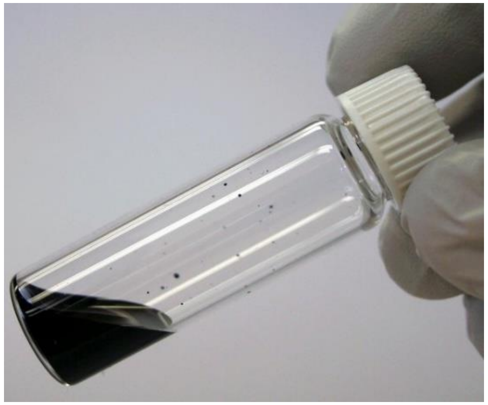
- Custom shape, size, resolution
- Small-batch customizability
- Flexible, bendable
- Round, irregular, conforming to shapes

Technology – Zikon "electric" ink and paper

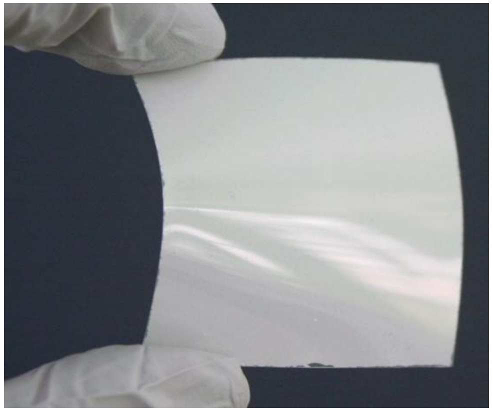
A modern analogue to a time-proven technology

Ink + *Paper*

- All liquid ink
- Provides color
- Responds to electric fields
- Printable



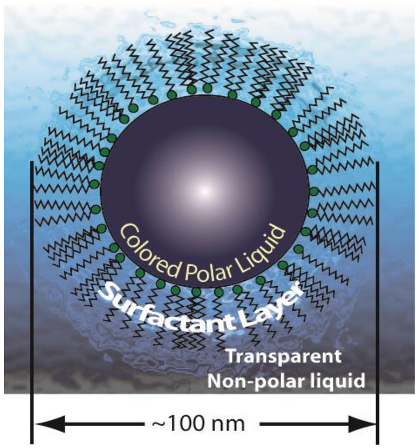
- White background
- Holds the ink
- Provides structural stability
- Flexible or rigid



Displays meet nanotechnology

Conceptually simple solution, cutting-edge science

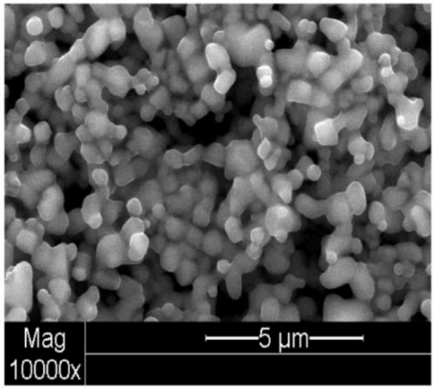
Ink



Color nano-droplets

- Stable - No sedimentation
- Light and responsive
- Self-assembled (mix and stir)
- Off-the-shelf components
- Low cost
- Tailored properties
- Printable

Paper



Porous matrix on flexible conductive substrate

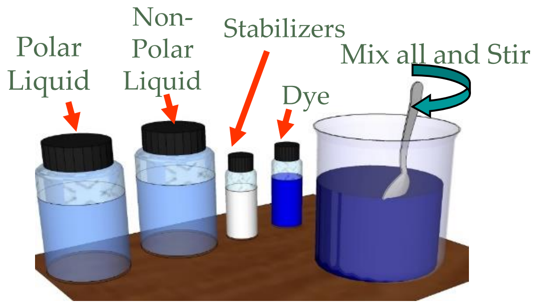
- Pores match ink droplets
- Off-the-shelf components
- 'Paint-on' deposition

<u>Nanotechnology enables:</u>

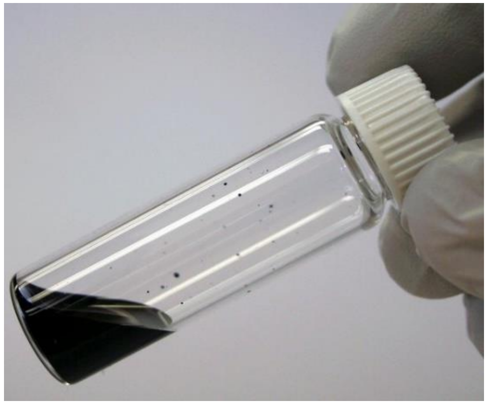
- ✓ Simple module design
- ✓ Low manufacturing cost
- ✓ Improved performance
- ✓ Energy efficiency
- ✓ Paper-like viewing angles
- ✓ Intrinsically a color technology
- ✓ Clean and "green" technology

The Ink

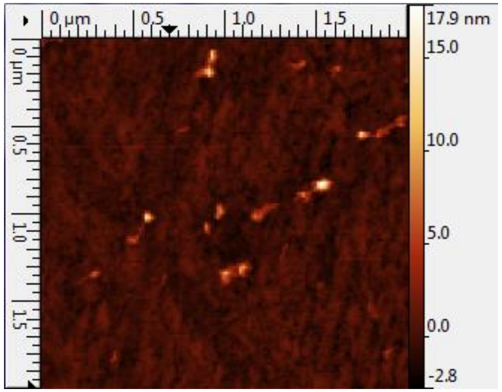
Mix-and-stir formulation



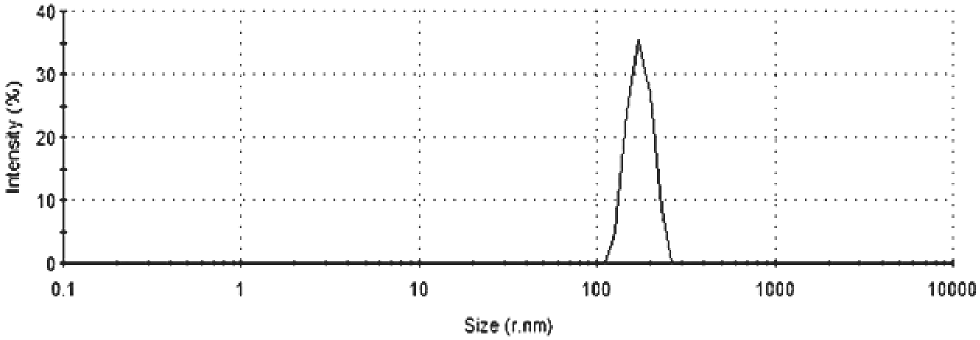
"mix and stir" ink production
Using off-the-shelf components.



Representative droplet size data:



AFM of dried out ink reveals features 160 nm to 220 nm diameter and up to 20 nm height

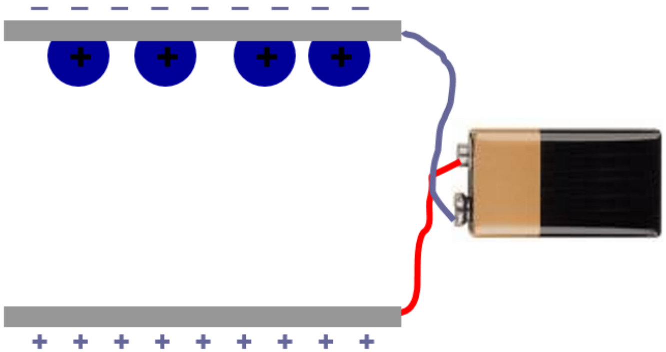


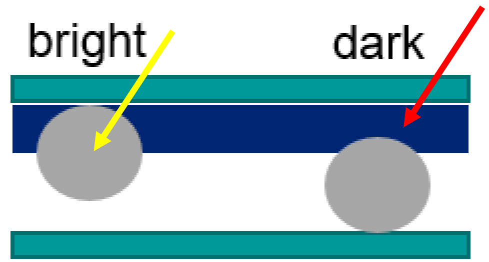
DLS of dilute ink sample reveals a single peak centered around **176nm**. Different ink formulations reveal droplet sizes as small as **40nm**

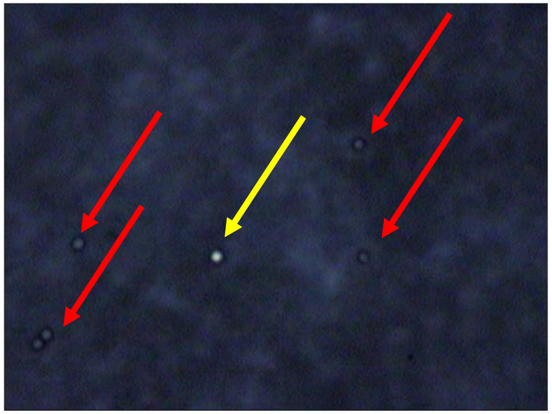
"Effect of nanodroplet ink concentration on switching response of reverse-emulsion electrophoretic displays", W. K. Wang, R. Cromer, M. Goedert, M. Mobed-Miremadi ; S. J. Lee Proc. SPIE 8643, 86430A, 2013

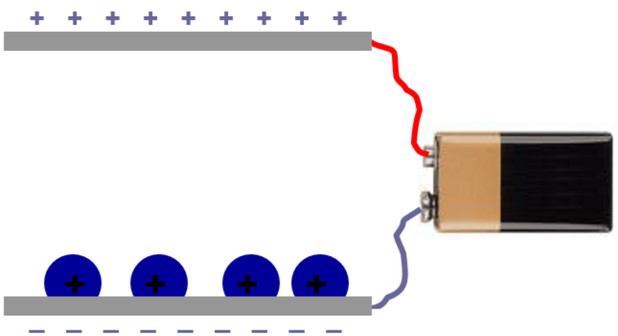
Reverse Emulsion Droplets in electric field

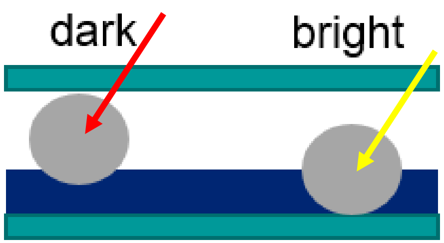
Charged droplets: *Electrophoretic motion*

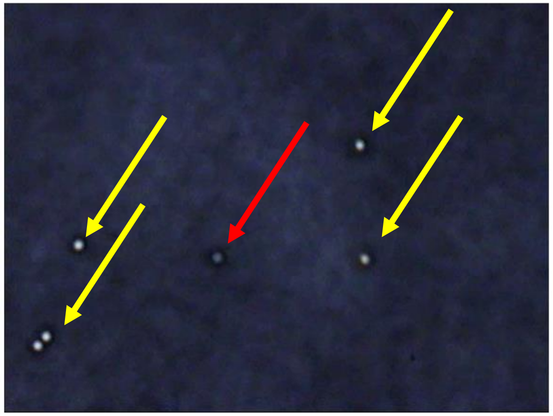










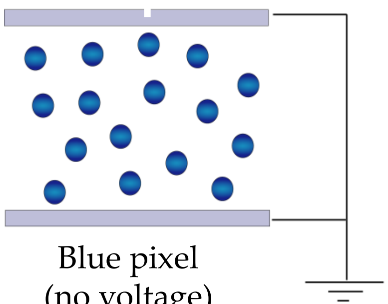


Transmissive Display

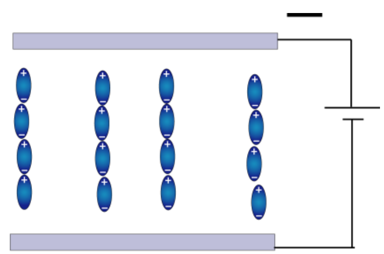
Principle of operation

Electrically polarized ink droplets

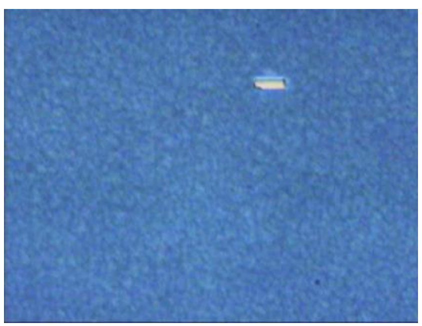
When in an electric field, ink droplets are polarized, becoming nano-scale electrical dipoles. They self-assemble into thin chains under electric fields through dipole-dipole interactions.

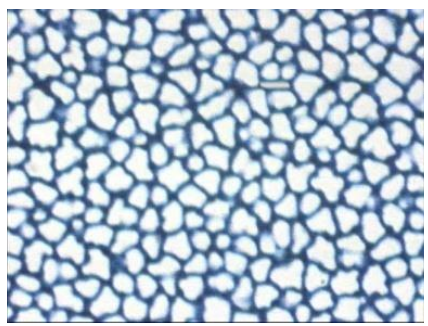


Blue pixel
(no voltage)



Transparent pixel
(voltage applied)

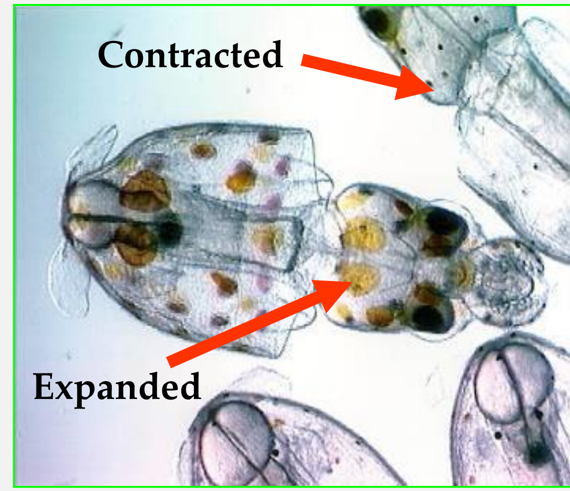




Microscopic images of blue (left) and clear (right) pixels

Video at www.zikon.com/demo

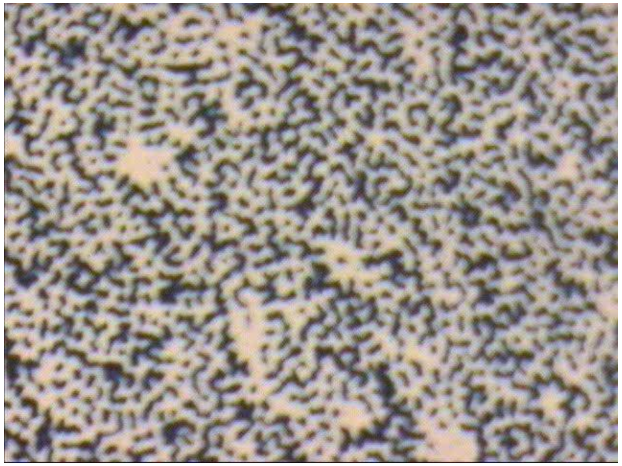
Analogy from Nature



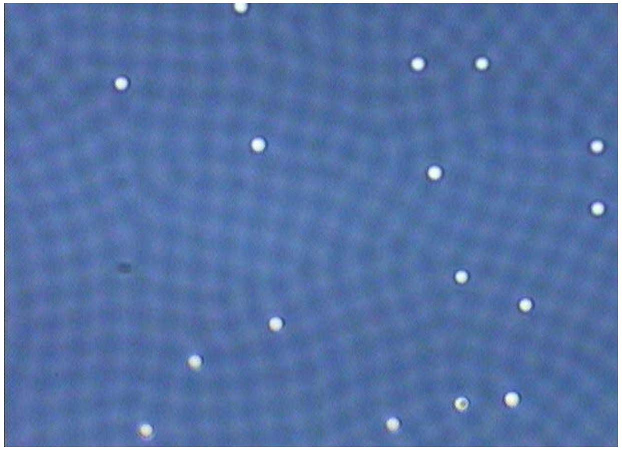
Some animals, like squid, change color by ***expanding*** and ***contracting*** chromatophores. A similar principle creates the color and transparency/light state in Zikon displays

Other ink behaviors

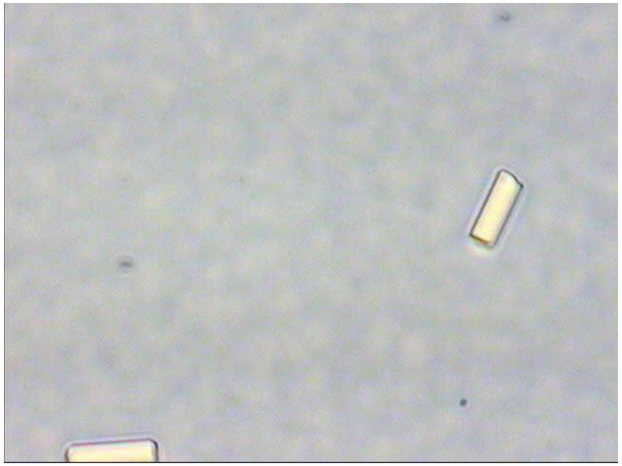
weak dipole moment, driven with DC +V, -V



strong dipole moment, driven with +V, 0

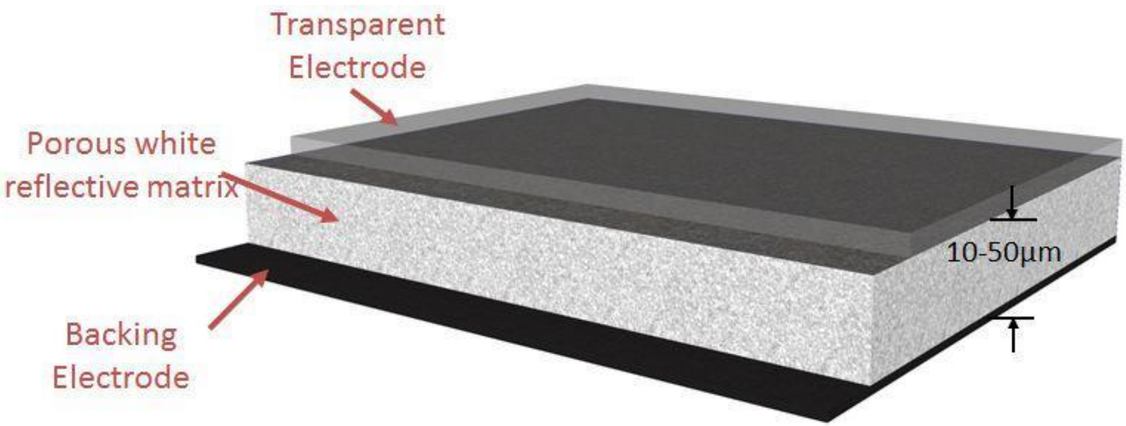


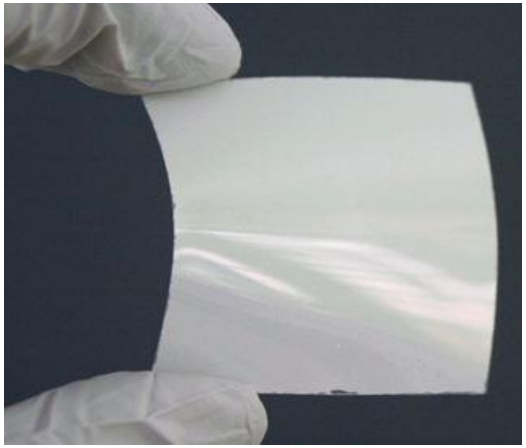
Weak charge, weak dipole moment, driven with frequency

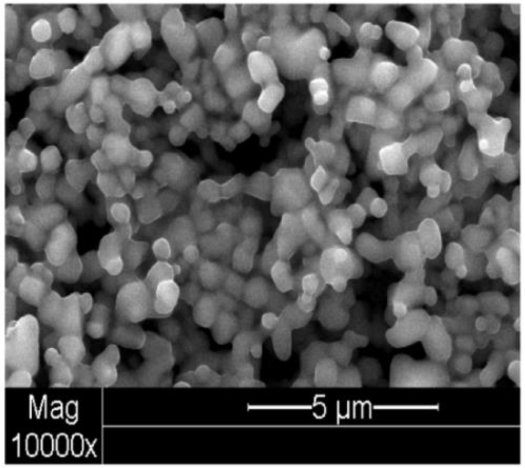


Weak charge, strong dipole moment, driven with frequency

The paper component

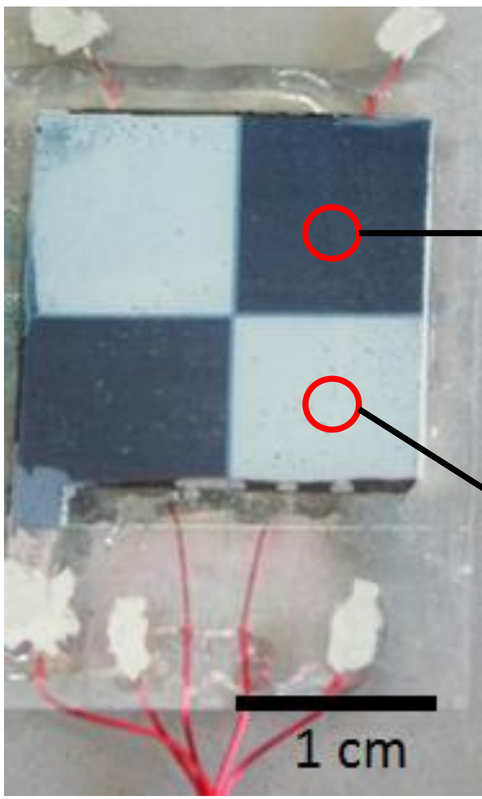


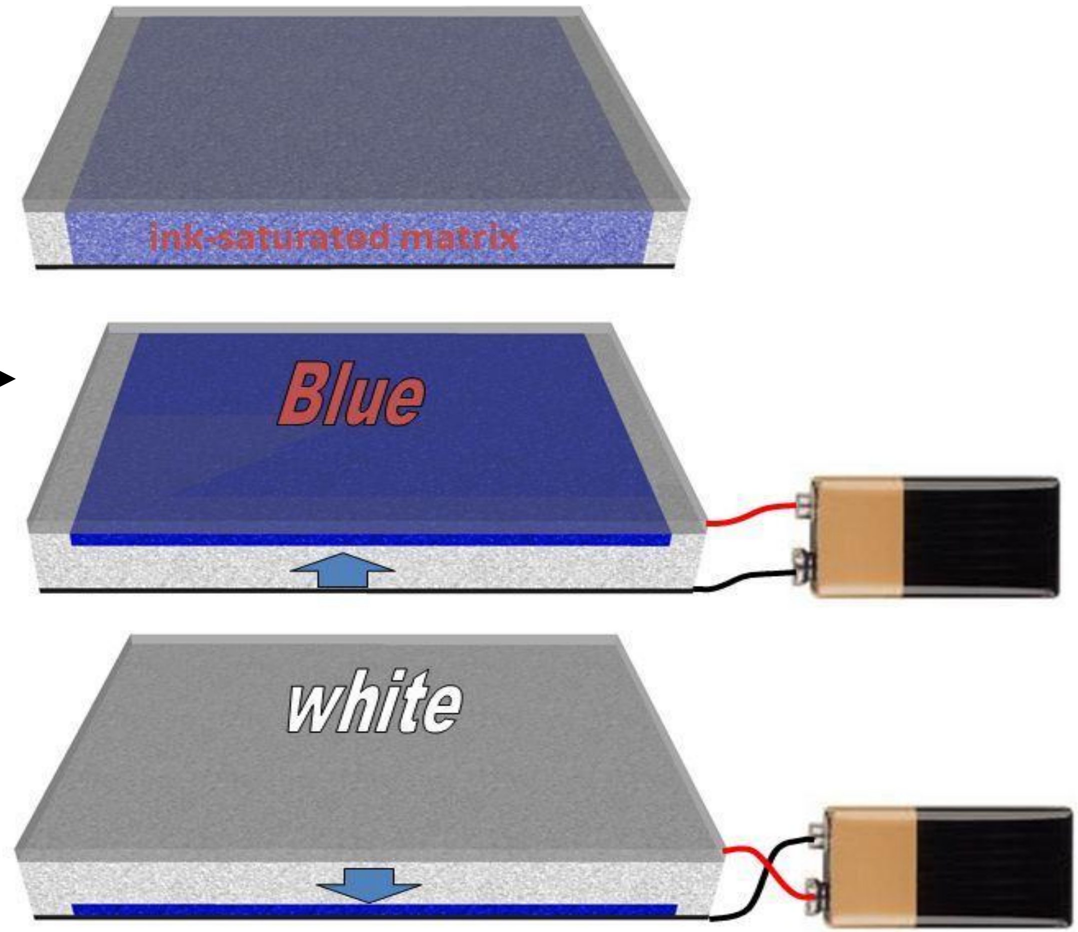




SEM shows packed, bonded TiO2 particles

Reflective display: Principle of operation





A simple “matrix”: Paste

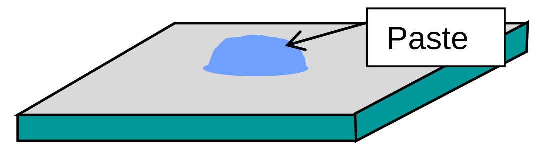
Mix ***ink*** and white ***TiO_2*** particles together into a ***Paste***

Use enough TiO_2 to achieve
Dense packing, up to ~40%
TiO_2 by volume

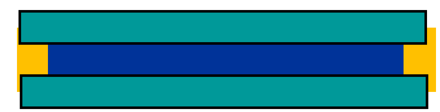
Mix in spacers to control gap

Assembly

1. Dispense a bead of paste



2. Cover, squeeze, and seal

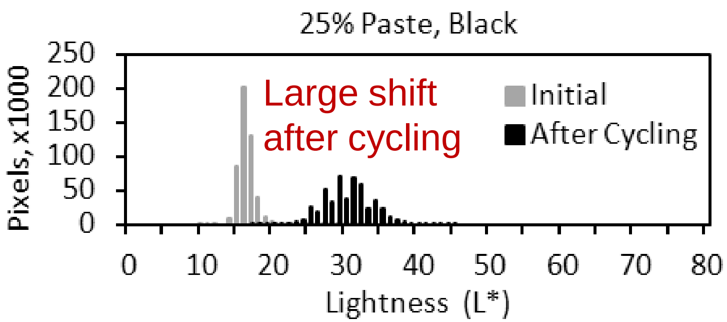


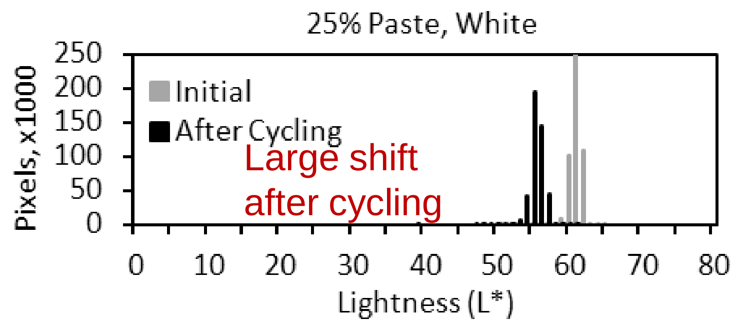
Stability under cycling

10 minutes cycling. Histograms of pixel lightness measurement

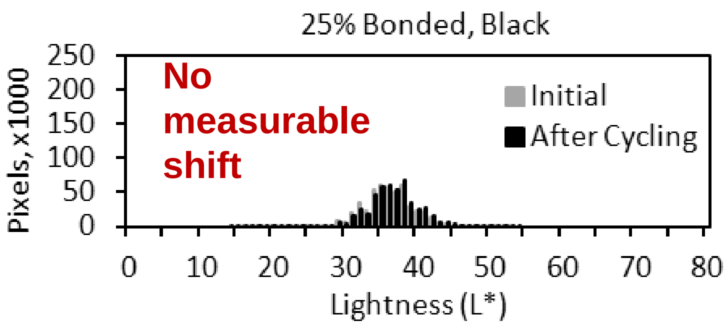
Black State | White State

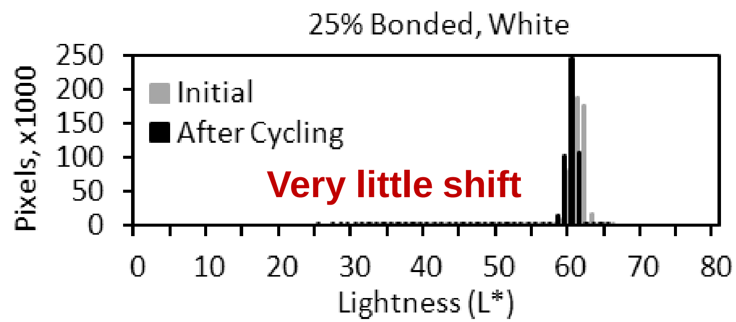
25% Paste



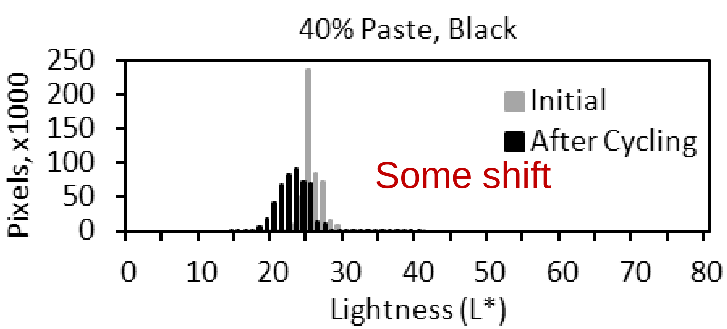


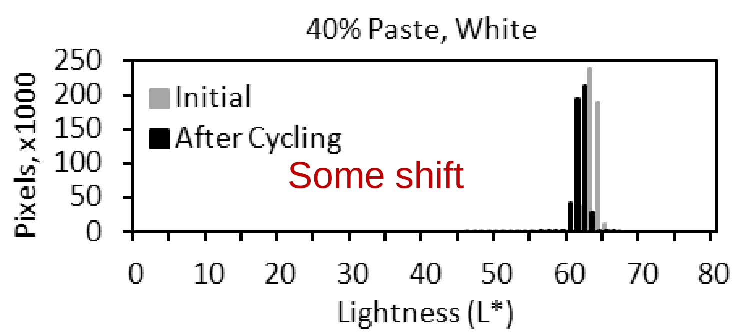
25% Bonded





40% Paste





"A thin porous substrate using bonded particles for reverse-emulsion electrophoretic displays", M. Ahumada, M. Bryning, R. Cromer, M. Hartono, S. J. Lee, Paper 8280-26, Proc. SPIE, Volume 8280, 2012

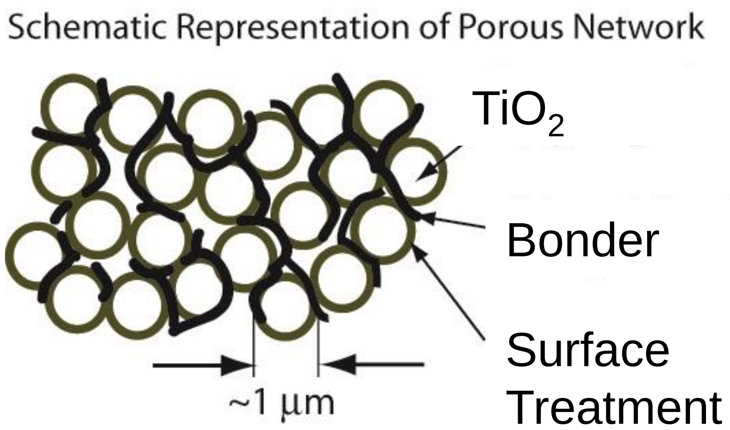
Bonded vs. Unbonded Matrix

Challenges of unbonded matrix – TiO_2 particles shift and repack

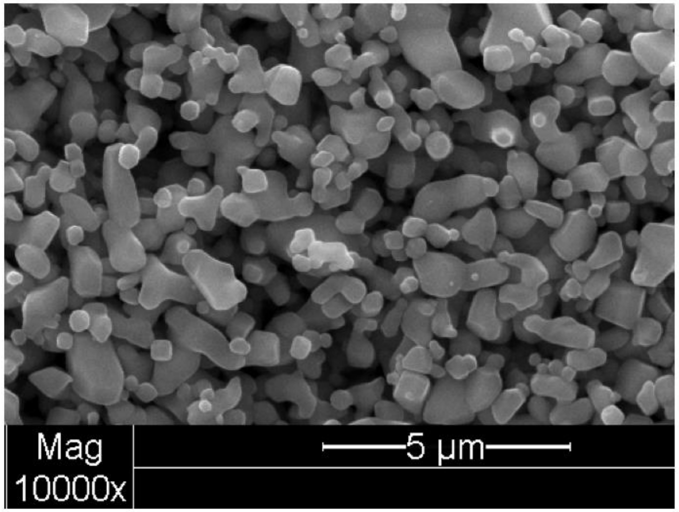
- Image uniformity worsens over time
- Not fully bistable

The Bonded Matrix

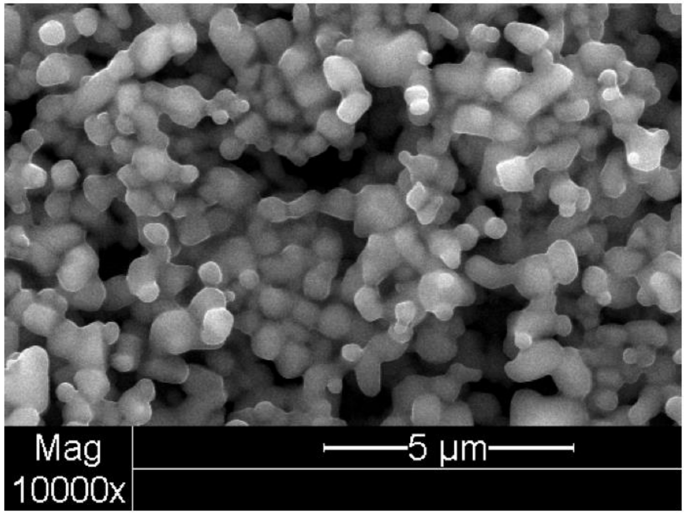
- Improve image uniformity
- Improve matrix stability over time by immobilizing the matrix



Bonded vs. Unbonded



Unbonded TiO_2



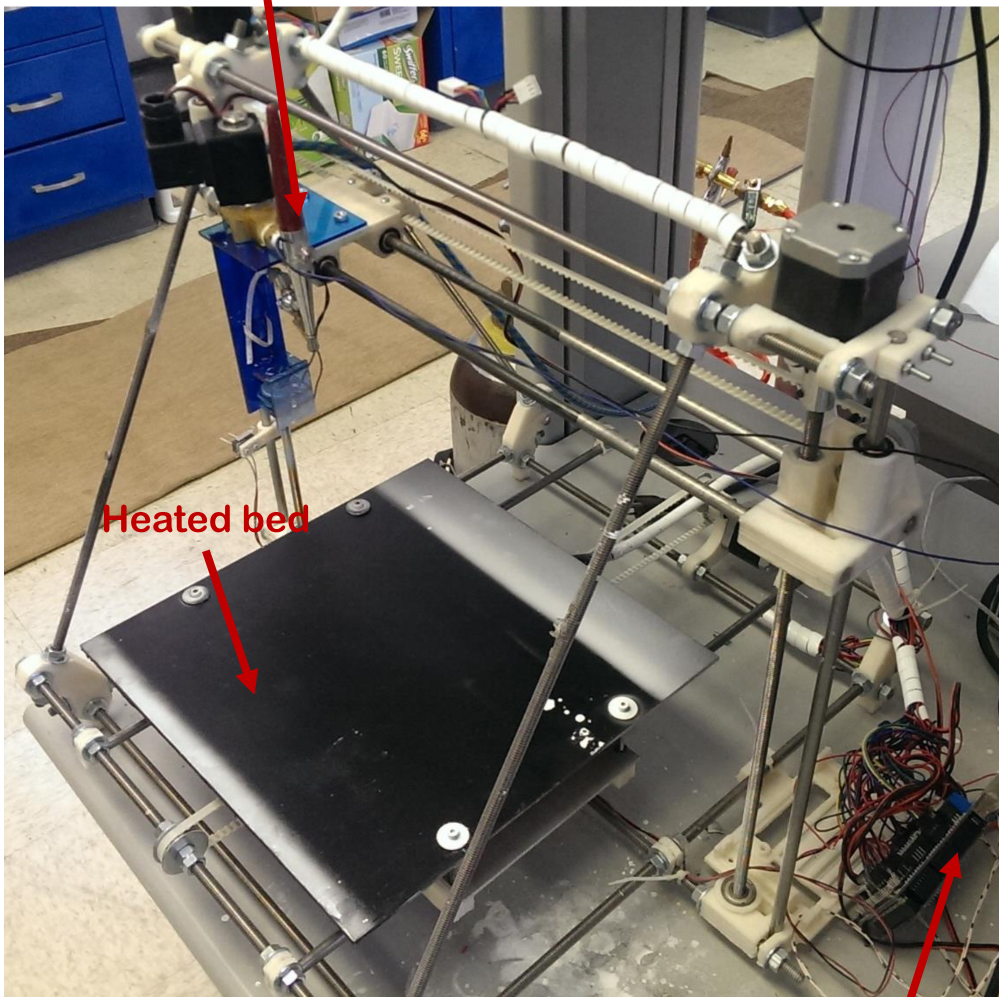
Bonded TiO_2

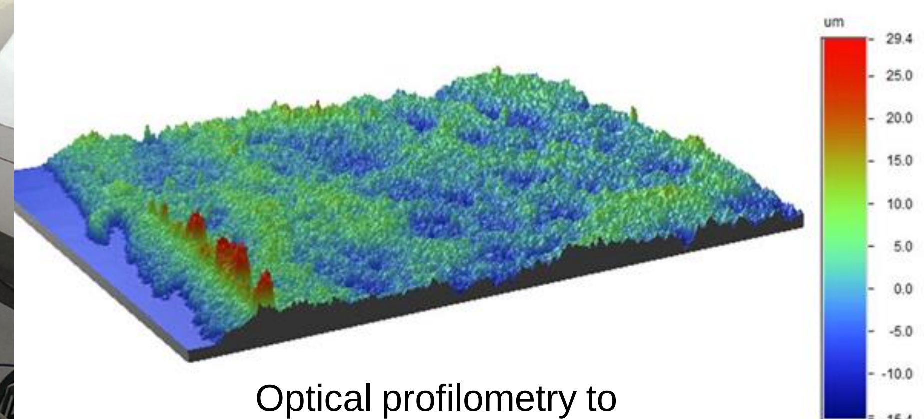
10% adhesive, 25% TiO_2 (by volume)

- Loose particles susceptible to repacking

- Immobilized particles cluster together due to adhesive
- Particle edges not as sharp as unbonded
- Good adhesive coverage
- Small pores are blocked
- Remaining pores give nano-droplets ability to move

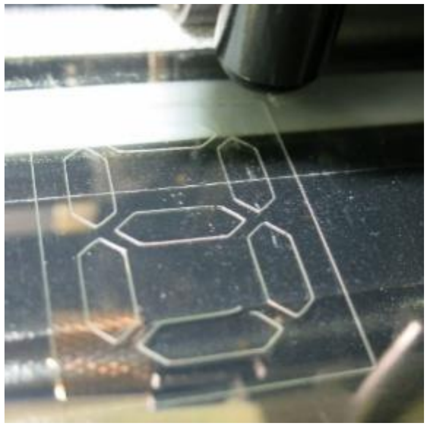
Matrix spray deposition



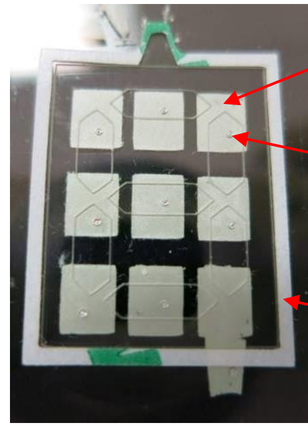


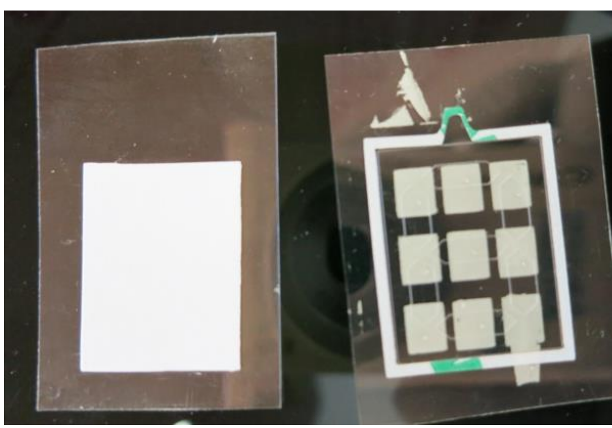
Optical profilometry to measure height and roughness

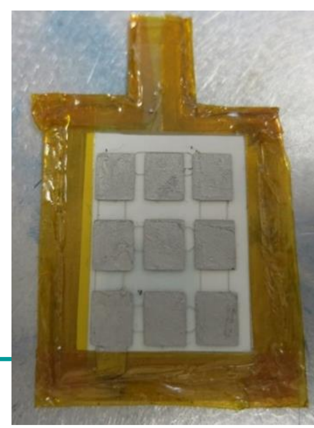
Demonstration module assembly

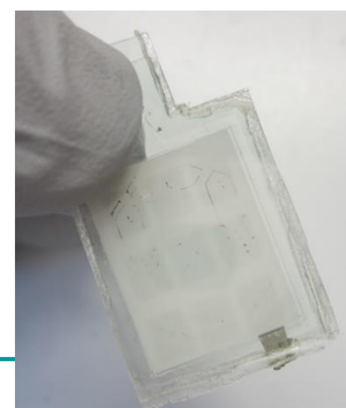


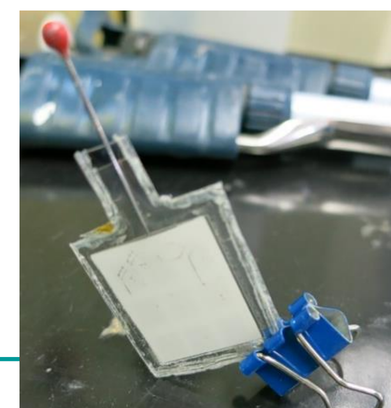
Direct-write ITO patterning using plotter



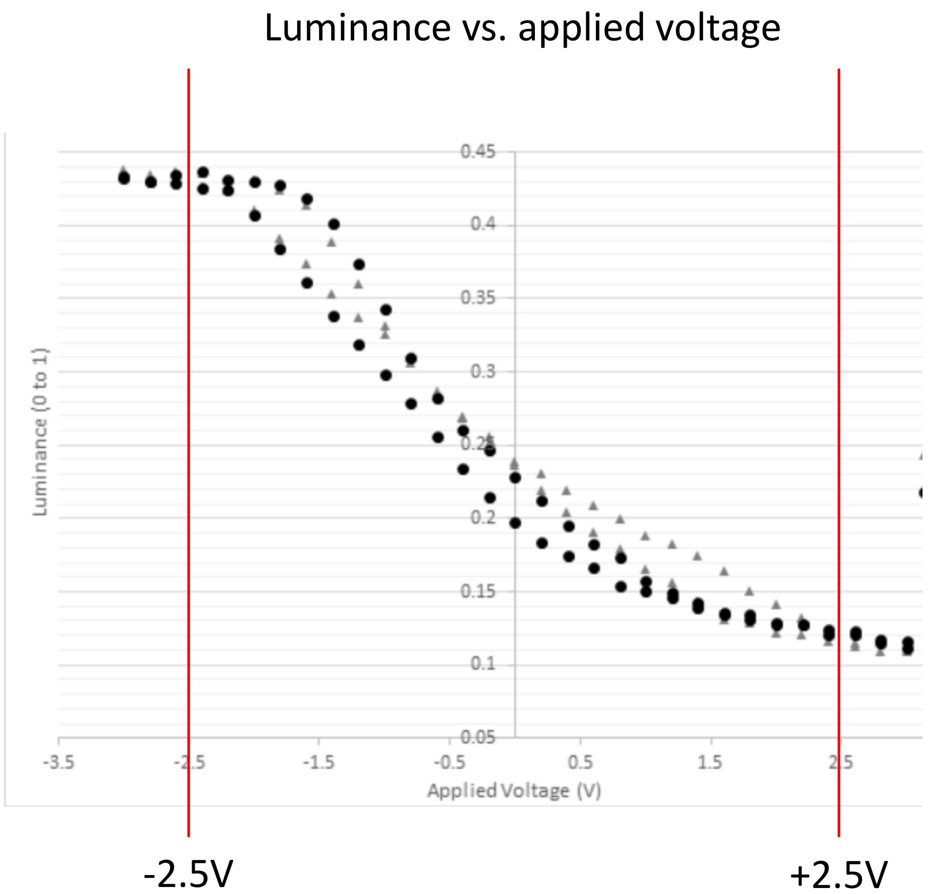


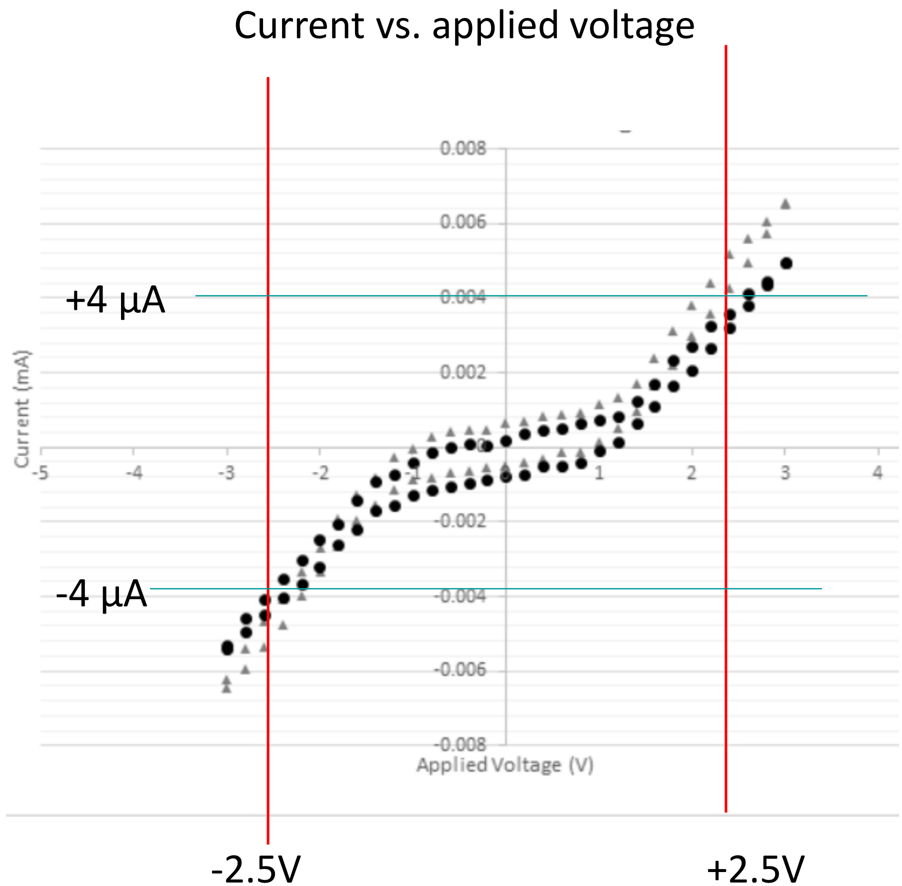






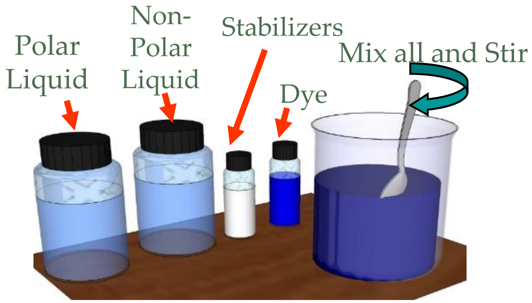
Typical optical performance and I-V curve





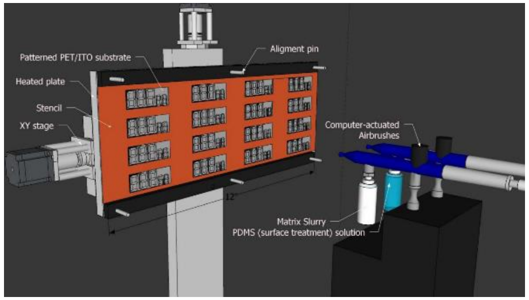
The "electric print shop"

Low cost, environmentally friendly manufacturing using simple tools

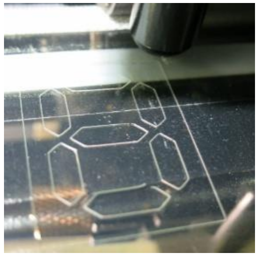


"mix and stir" ink production
Using off-the-shelf components.

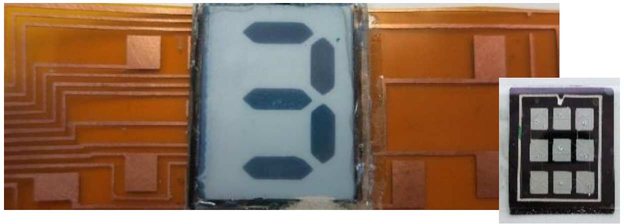
Low-cost, flexible (mylar, polypropylene, etc) substrate material.



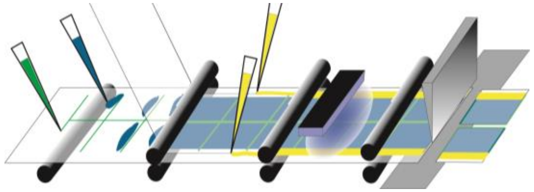
Spray-on porous matrix deposition
From non-toxic, water-based, suspensions.



Simple, direct-write electrode patterning using cutting plotter requires no lithography or toxic chemicals, and enables small-batch production and **distributed manufacturing.**



Modular design for easy customizability.



Roll-to-roll or sheet-by-sheet manufacturing.

Logic-level (5v) digital addressing eliminates need for analog driving electronics, reducing cost and improving power efficiency.

First product: Electronic Shelf Label (ESL)

- ✓ Price control and integrity.
- ✓ Enhanced productivity and efficiency.
- ✓ Strategic, dynamic, and flexible pricing.
- ✓ Enhanced customer interaction.
- ✓ Environmentally friendly.

Example of an LCD shelf label

Our current ESL development effort is funded in part by National Science Foundation through an SBIR Phase II grant

NSF

ZIKON

First product - electronic shelf labels (ESL)

Why do stores still use paper price tags?

Electronic labels that can be updated from a central location will save substantial labor costs, increase accuracy, and even enable dynamic pricing adjustments.

Why do we rarely see them? One reason.

Current display technologies don’t meet market needs.

ESLs require:

- Very low cost
- Very low power consumption
- Paper-like viewability

No current technology can fill all these needs

ESL market

Estimated market size
(@ $2 per tag)

$8B US
$20B Worldwide

Only 2% penetration (10,000 stores worldwide)

Some facts about paper tags

- ~1.5 Billion paper tags in US Supermarkets
- > 10 Billion paper tags Worldwide
- A typical grocery store has 20,000 products, with prices manually updated at least weekly

Competition in ESL displays

- **Liquid Crystal**
  - Poor viewability
    - narrow viewing angles
    - low contrast
  - High cost to install and maintain
  - High energy consumption
- **Electrophoretic (EPD)**
  - Prohibitively expensive for large-scale deployme
- **Emerging technologies**
  - Electrowetting
  - MEMS
  - PDLC and Ch-LC
- **Emissive** (OLED, backlit LCD)
  - Unsuitable due to high power consumption and high cost

Competition in ESL

Existing and emerging display technologies

Almost all existing ESLs use passive LCD displays, which suffer from poor readability. The remainder use very expensive E-ink technology

Typical ESL tag with a liquid crystal display (LCD)

Typical ESL tag with E-ink display

Competitor	Market share	Markets served	Differentiator
LCD	99	All	Relative low cost, poor visual appeal
EPD	1	High-end, low-volume installations.	Low power, paperlike, too expensive

Competitor	Strengths	Weaknesses	Our Response
LCD	Low cost	Not bistable Low contrast Low viewing angle	Pseudo-bistable = lower power Good contrast, paperlike viewability. No viewing angle problem Lower manufacturing costs.
EPD	Good contrast and viewing angle, low power	Prohibitively high cost. High driving voltages.	Low cost. Low driving voltages.

Indirect competition: emerging technologies (no significant market share)

- **Electrochromic**, aka. electrochemical displays (ECDs) (Acreo, Ntera).
- **Electrowetting** displays (EWDs) (Advanced Display Technology, Liquavista)
- **Micro-Electro-Mechanical System** (MEMS) displays, aka. IMOD (Qualcomm). *Qualcomm has stopped all development in July 2012
- **Ch (cholesteric) LCDs** (Kent Displays Inc., Fujitsu Frontech, Varitronix International.)
- **TN (twisted nematic) liquid-crystal** displays (LCDs) (Nemoptic, ZBD Displays, Seiko Epson)

Zikon competitive advantages - ESL

Cost, appearance, power efficiency

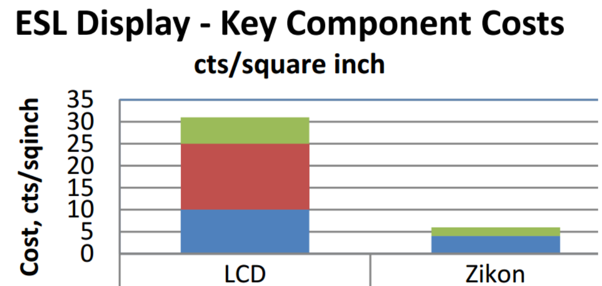
Zikon's technology addresses three key factors that are holding back ESL systems:

Display cost

Appearance/readability.

Power efficiency

Additional benefits include **low voltage operation**, **no complex tooling requirements**, and **low environmental impact** of production.



	LCD	Zikon
Ink	6	2
Polarizer	15	0
Substrate	10	4

Comparison of key component costs for monochrome LCD and Zikon displays

Comparison of performance characteristics for ESL display technologies

Specifications	ZIKON	LCD	EPD
Driving Voltage, V	±2.5V to ±3.5V	3V to 10V	±15V to ±20V
Peak Brightness (Luminance)	50	<20	~40
Typical contrast ratio	4-6	2	6
Unit cost, 3 inch display, $	~0.3	1	3-4
Operating lifetime , Years	5	3-5	n/a

Zikon's displays match or outperform the competition in key performance metrics desired in ESL applications

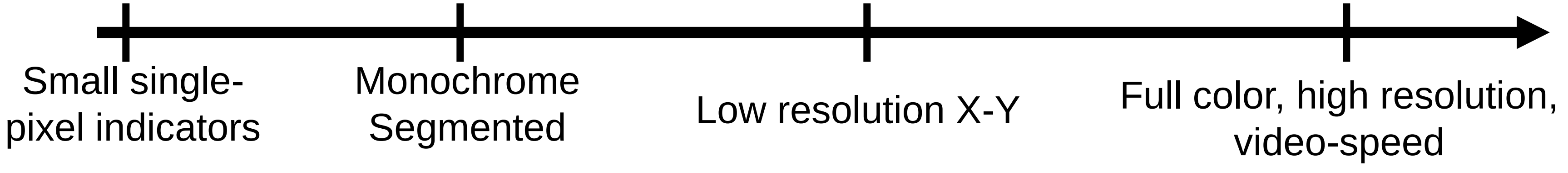
Display power consumption

Technology	Power consumption (W/sq in)
Backlit LCD*	0.27 (2/3 of this is backlight)
CRT*	0.23
Backlit DLP*	0.14
Plasma*	0.36
Eink	~0.03, in TFT w/electronics
Zikon (switching@30Hz)**	0.0005
Zikon (holding)**	0.000 000 5***

Comparison of power consumption of existing technologies to Zikon displays. Of these, only Zikon and E-ink meet ESL low-power requirements.

***Source:** *Draft Efficiency Standards of Televisions*, California Energy Commission, 2008
**Measured in segmented display, no backlight, not accounting for electronics.
We estimate that Zikon power consumption in TFT is comparable to that of eink.
*** calculated 30+ year lifetime from a standard 3V lithium watch battery

Beyond shelf labels



Follow-on products

Tapping the $150B diverse, global display market

When a revenue stream is established in ESL arena, we will branch out further into the ***immense*** *broader display market.*

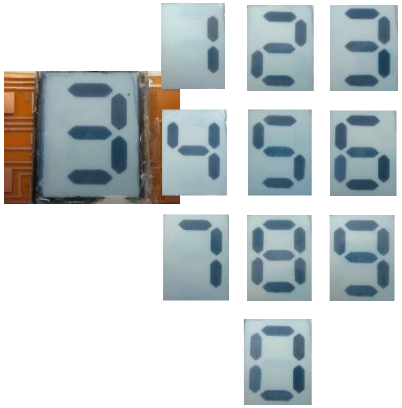
- Flexible displays
- Expanded color and full-color displays
- Wearable displays
- High-resolution text displays
- High resolution, video speed displays
- Large format, sunlight readable displays
- Transmissive displays for HUD and projection

Trends driving next-generation displays aligned with Zikon's technology:

- Flexible substrates
- Printable electronics
- Distributed manufacturing
- "Green" manufacturing
- Easy customization
- Wearable displays
- Sunlight readable
- High contrast
- Low voltage
- Low power consumption
- Low cost

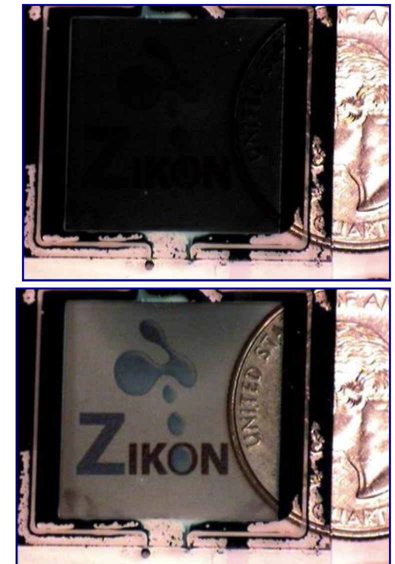
Zikon Displays

We have demonstrated operation in a wide range of displays, including reflective and transmissive modes, and flexible and active matrix substrates.



Seven-segment modular display demonstration

Active dimming sunglasses demonstration



High-contrast light valve demonstration

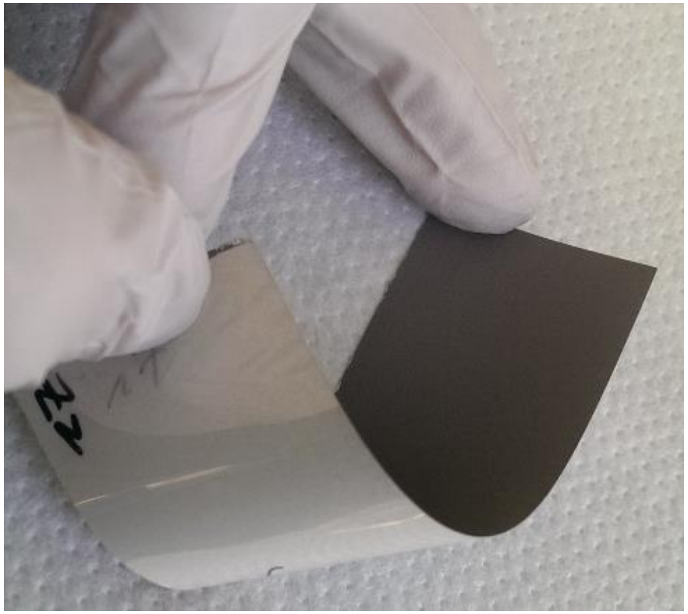
Transmissive active matrix (TFT) display demonstration

High-contrast reflective display demonstration

Custom designs demonstrating small-batch and one-off applications enabled by direct-write patterning of electrodes

Additional demonstration images and videos are available at www.zikon.com/demo

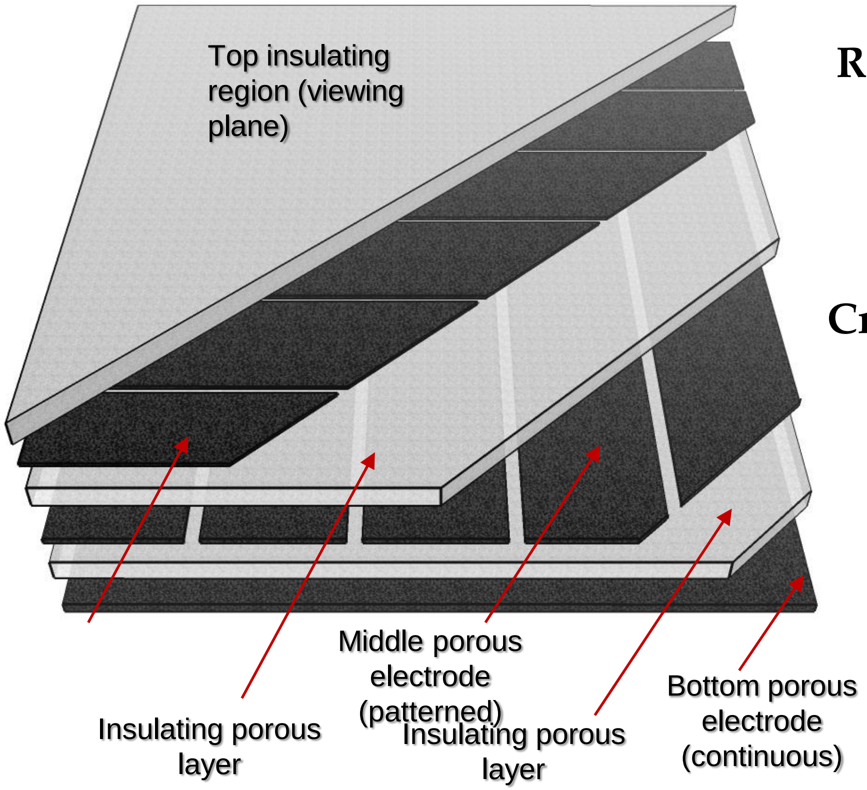
Future Directions: Flexible substrate with carbon backing electrode



Conductive carbon layer deposited onto white matrix

Carbon layer can be patterned using CO_2 laser at low power

Passive matrix addressing using embedded porous electrodes



Remove need for active matrix addressing using embedded holding electrodes

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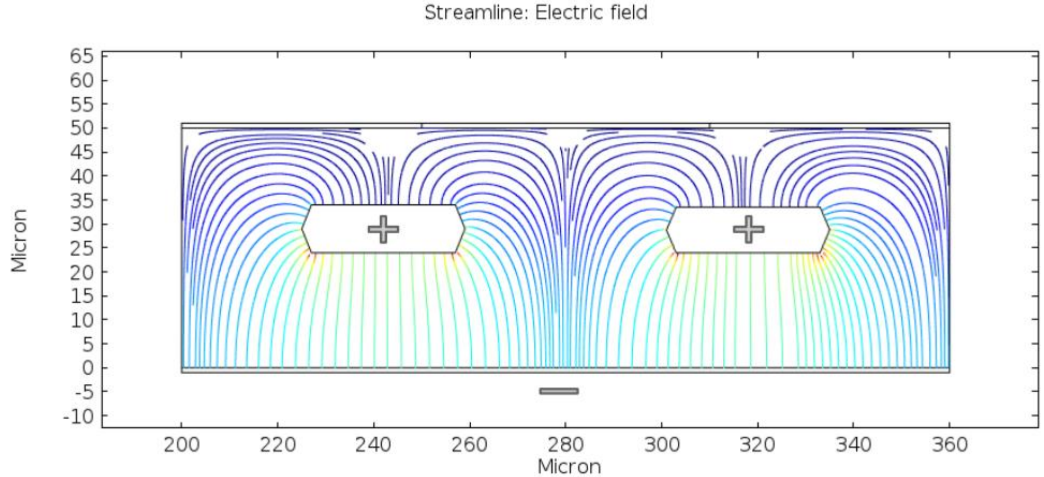
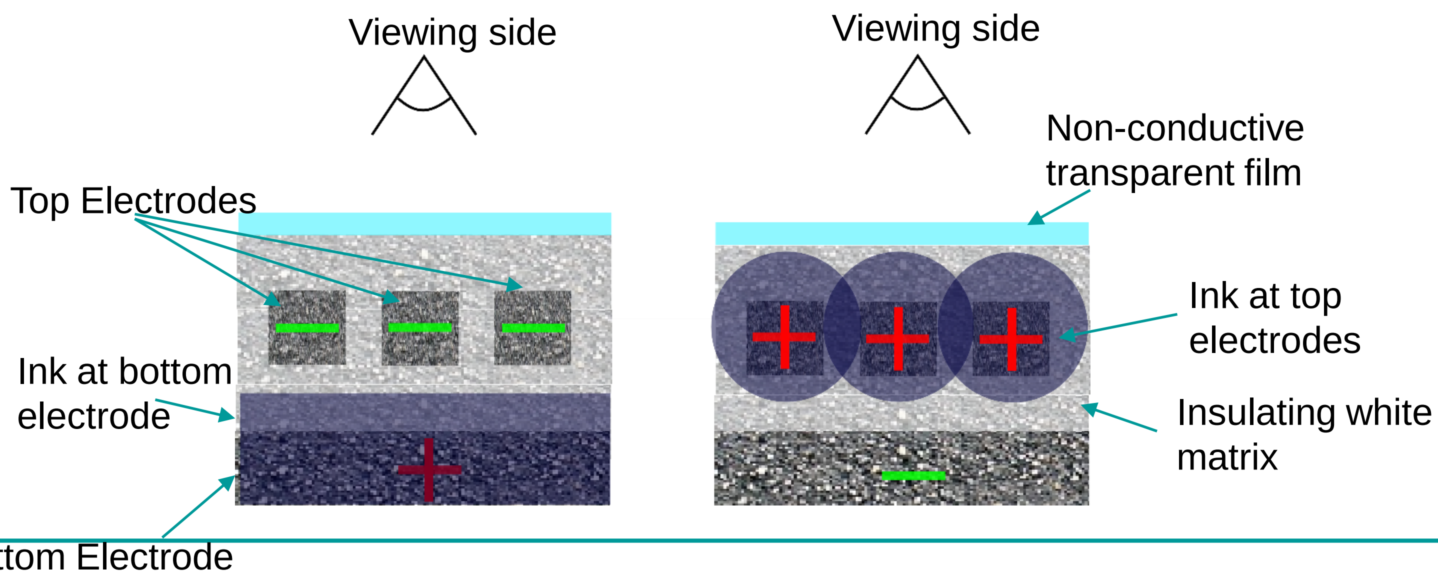
Create easily customizable display formats

Future directions 2: Can we eliminate Indium Tin Oxide?

Transparent ITO electrodes reduce brightness, crack under flexure, and create environmental/supply concerns





White Pixel **Dark Pixel**

Core Team

Core Team

Dr. Remy Cromer is Co-Founder and President of Zikon, with a Ph.D. in chemistry, has extensive expertise in nanotechnology, molecular self-assembly and supra-molecular chemistry. Expertise in colloid, polymer and surface chemistry, chemistry at the nanometer scale, self-assembly, inorganic and materials chemistry. He is intimately familiar with technology-based start-ups.

Dr. Mateusz Bryning, Chief Technology Officer of Zikon, Principal Investigator on this project, is a physicist specializing in emerging technologies in nanotechnology, complex fluids, and advanced materials fields. Dr. Bryning is an entrepreneur with ten years of experience in discovering, developing and transferring new materials technology into application. He is an Adjunct Faculty at San Jose State University, where he teaches a laboratory courses on MEMS and microfluidics, and co-advises several students. Dr. Bryning holds a Ph.D. in Physics from the University of Pennsylvania, where his research focused on carbon nanotube networks.

Alexander Fries, Chief Operating Officer, brings over 20 years of progressive experience in founding, funding, and managing global businesses. His recent entrepreneurial experiences include the co-founding of Playspan Inc , SDK Biotechnologies Inc., PURE SWISS AG, and SVOX AG. Mr. Fries is founder of the European-American Angels Club, heads Club Entrepreneur and Ecosystem Ventures, and serves on the Board of the Social Entrepreneurship Initiative

Winston Wang, R&D Engineer, MSME from San Jose State University. His master's thesis “Effect of nanodroplet ink concentration on image contrast for reverse-emulsion electrophoreticdisplays” was partly supported by Zikon’s SBIR Phase I and Phase II NSF awards, and involved hands-on laboratory work and simulations of REED ink in electric fields. Winston Loves to explore outside of his comfort zone to learn and do things that have never been done before.

Advisors & Students

Advisors:

Prof. John Lee leads the subcontracting team at San Jose State University, and is an advisor to Zikon. Prof. Lee is Associate Professor in Mechanical Engineering at SJSU and conducts research primarily in the field of microfluidics. His doctoral work from MIT focused on a novel "three-dimensional printing" process using a variety of ceramic and metal powders, selectively bonded by custom-designed printheads for colloidal silica ink. He is co-inventor of 10 U.S. patents involving micro fuel cell design and fabrication, and is co-author of a book Microfabrication for Microfluidics (2010 Artech House, Boston, MA)

Dr. Daniel Colbert advises Zikon on business strategy, development, and technology. As a Professor of Chemistry at Rice University, Dr. Colbert was a pioneer in nanotechnology, with over 50 patents and over 50 research papers. He co-founded a leading nanotech startup with Nobel Laureate Rick Smalley, and led business development there. He has co-founded three technology startups, and twice been a venture investor in cleantech, materials, and nanotech.

Dr. Leslie Field advises Zikon primarily in technology, competitive landscape, fundraising and strategic partnerships. Dr. Field is the Founder and Managing Member of SmallTech Consulting, LLC and the Founder and CEO of MEMS Insight, Inc. She also serves as a Consulting Professor in Electrical Engineering at Stanford University. Dr. Field earned PhD and MS degrees in Electrical Engineering from UC Berkeley's Sensor & Actuator Center, and MS and BS degrees in Chemical Engineering from MIT.

SJSU Students:

Christopher Rose, Linh Tran, Manuel Ahumada, Sixto Betancourt, Kelly Li Tsui, Michelle Hartono

Summary

- Platform display technology applicable to a broad range of products

- Uses nanotechnology to:
  - Simplify display geometry
  - Reduce manufacturing costs
  - Improve performance
  - Improve energy efficiency

- First product = Electronic shelf labels
  - Low hanging fruit
  - Perfect fit for technology
  - Attractive market