Polyera

SID Bay Area

April 2016

Content

- A few slides on Polyera
- Organic electronics is alive and growing
- Flexible displays are coming
- Polyera status:
  - Flexible Electrophoretic displays
  - Product concept: the WOVE Band
- What is next:
  - Higher performance
  - Organic CMOS & printing
- Key takeaways

Introducing Polyera

- Founded in 2005 as spin-off from Northwestern University
- Three sites:

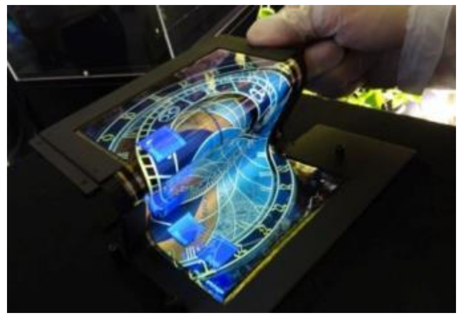
- Unique technology position:
  - Proprietary enabling flexible display backplane materials
  - Complemented by flexible display process technology know-how
  - Unique position in flexible product integration

What does Polyera enable?

Now

Robust flexible
e-paper displays

Next



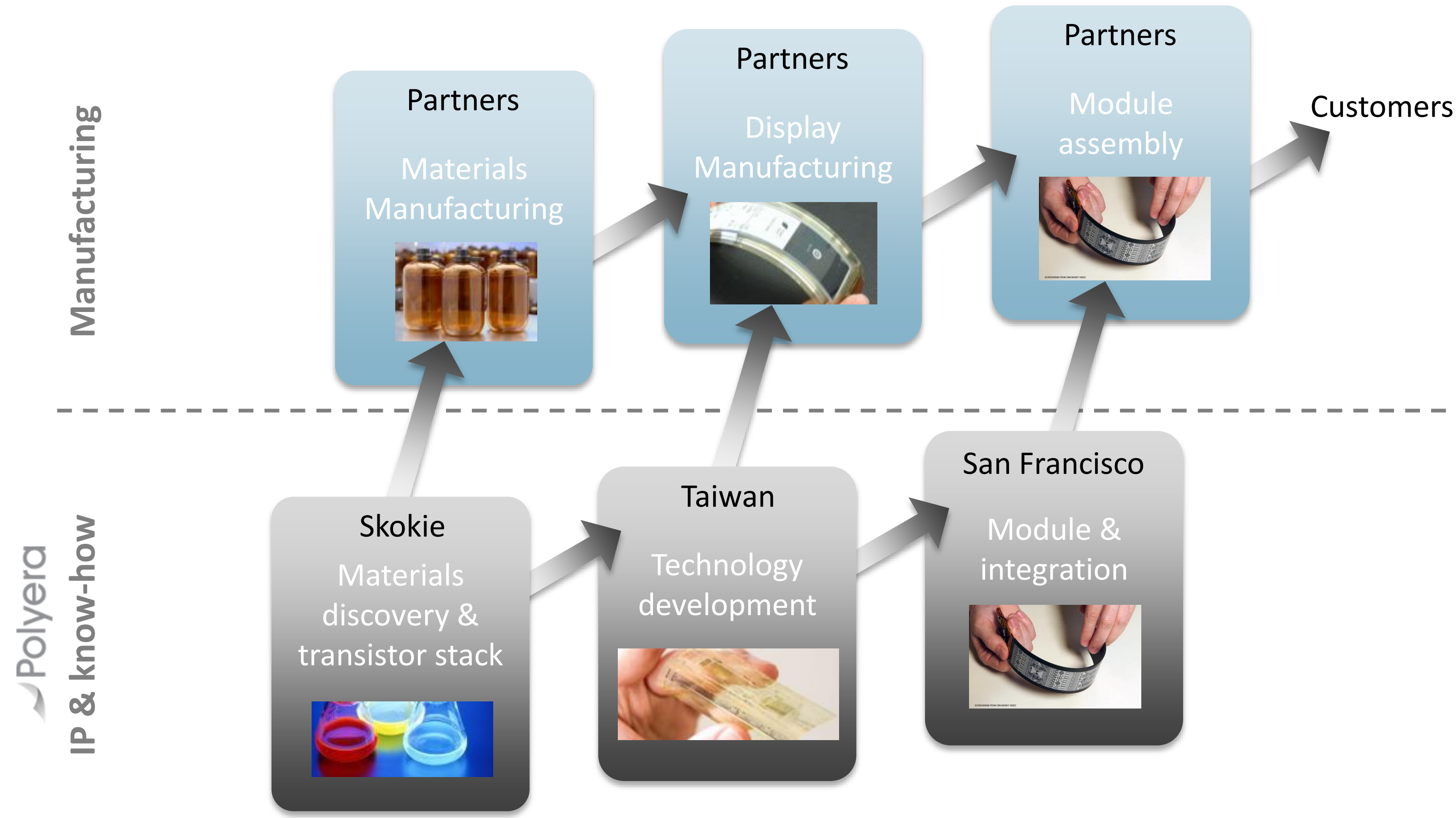
Robust flexible
emissive displays

Final

OCMOS for flexible and
stretchable electronics

- All based on solution processing platforms using organic materials
- The core value lies in mechanical flexibility and strechability of organic materials
- All platforms share the same core technology and build on the current IP portfolio

Fabless model



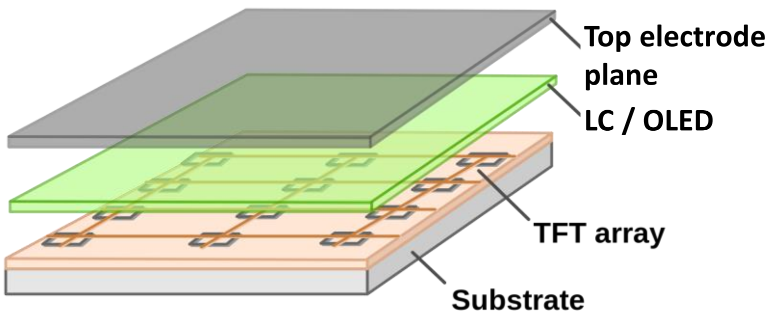
Fabless model:

- Manufacturing of materials and display modules by partners

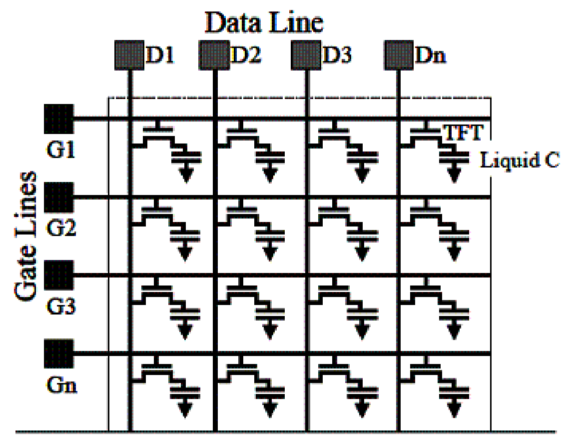
Organic electronics is alive and growing

Introduction: Displays and TFTs

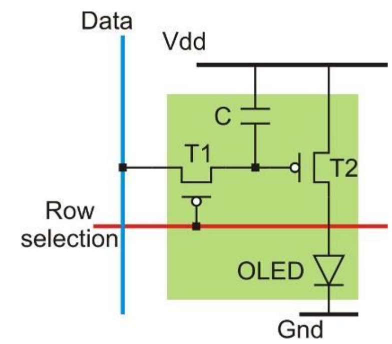
Active-matrix display overview



AMLCD schematic

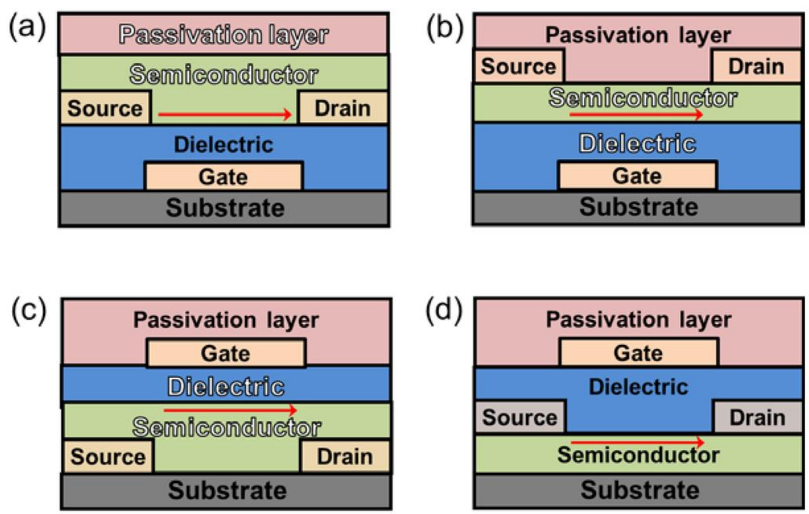


AMOLED schematic



TFT configurations:

(a) Bottom gate – bottom contact
(b) Bottom gate – top contact
(c) Top gate – bottom contact
(d) Top gate – top contact



Semiconductor:
- High mobility & stability
- Processability
- Patternable
- Low cost

Dielectric:
- High resistance
- Low mobile ion content
- High dielectric constant
- Processability / adhesion
- Patternable
- Low cost

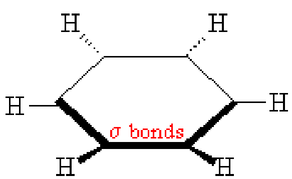
TFT technologies benchmark

Property	Amorphous Si TFT	Polycryst Si TFT (low T)	Oxide TFT	Organic TFT
Mobility (cm^2/Vs)	< 1	10-100	10-50	1-10
Leakage current (A)	10^{-12}	10^{-12}	10^{-12}-10^{-15}	10^{-12}-10^{-15}
TFT stability	Moderate	High	High	Moderate
Process temperature	250-350°C	<500°C	<250°C	RT-130°C
Manufacturing cost	Low	High	Potentially low	Potentially low
Yield	High	Medium	High	High
Flexibility	Moderate	Low	Moderate	High

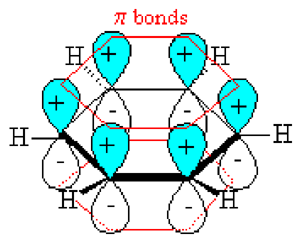
From: Sirringhouse, LOPEC April 2016

What are organic semiconductors?

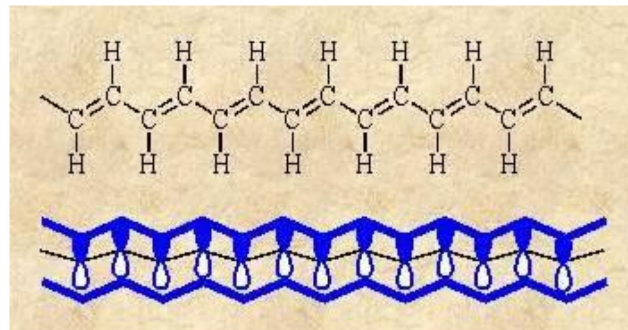
Organic semiconductors have alternating double and single carbon-carbon bonds - π-conjugation



sp^2 orbital overlaps between carbons form the plane of the ring.

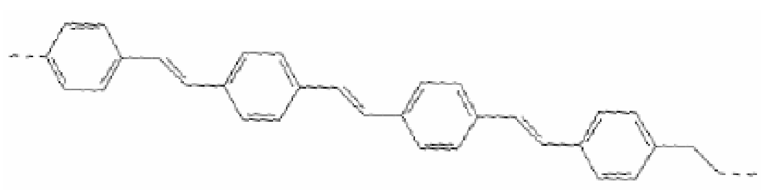


Sideways p orbital overlaps form the π clould above and below the ring.

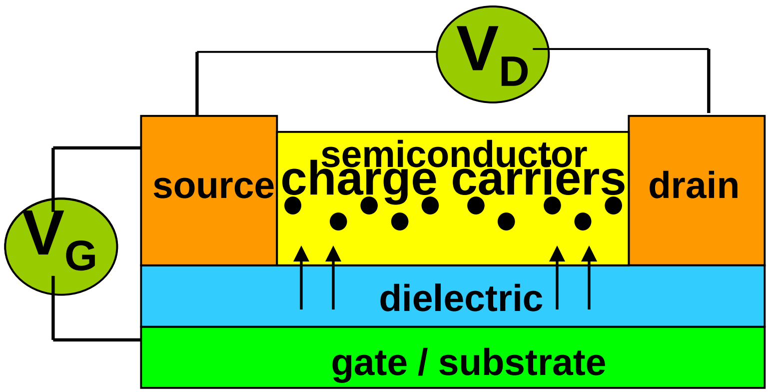


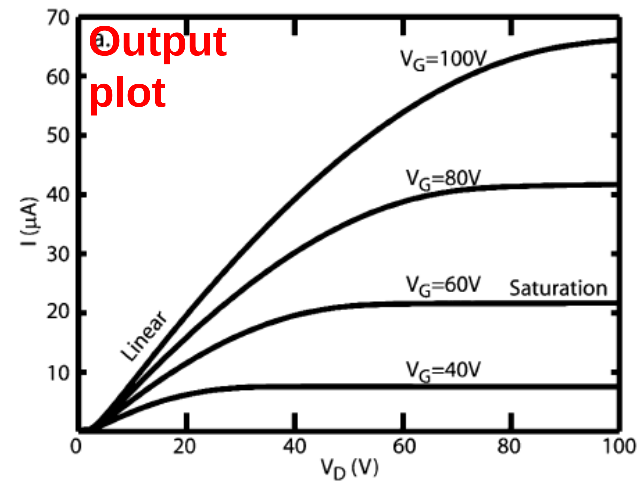
s, p_x and p_y atomic orbitals of the carbon atoms hybridize to sp^2 and form the frame of the molecule/polymer (σ orbitals, bonds).

p_z atomic orbitals form a delocalized π molecular orbital (π-bonds) which extends along the polymer chain as long as the conjugation is preserved.



OTFT Structure and Operation



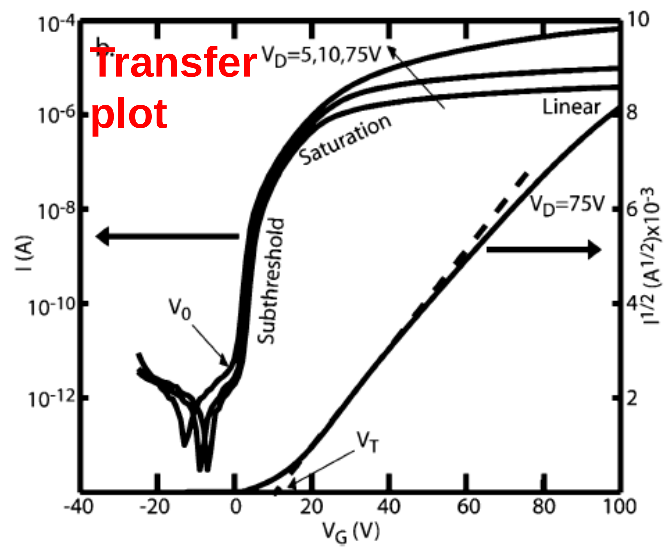


OFF
$V_G = 0$

No charge carriers between S and D => $I_D = 0$

ON
$V_G \neq 0$

Creates charge channel in the semiconductor layer => $I_D \neq 0$

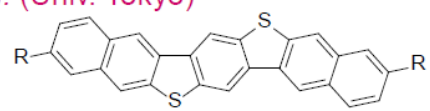


Parameters:

1. Carrier mobility (μ)
2. Current on/off ratio (I_{on}/I_{off})
3. Threshold voltage (V_T)
4. Subthreshold swing (S)

Highest mobility's reported in research

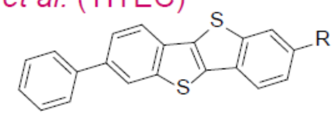
Okamoto *et al.* (Univ. Tokyo)



~16 cm^2/Vs

Adv. Mater. **2014**, *26*, 4546.

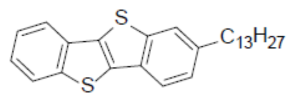
Hanna & Iino *et al.* (TITEC)



> 10 cm^2/Vs
(solution processed, thermally stable)

J. Non-Crystalline Solids, ***2012***, *358*, 2516.

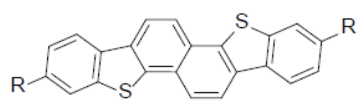
Halik *et al.*



17 cm^2/Vs

JACS **2012**, *134*, 16548.

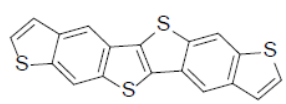
IDEMITSU



> 10 cm^2/Vs (vapor deposited film)

Jpn. J. Appl. Phys. **2013**, *52*, 05DC11.

SAMSUNG

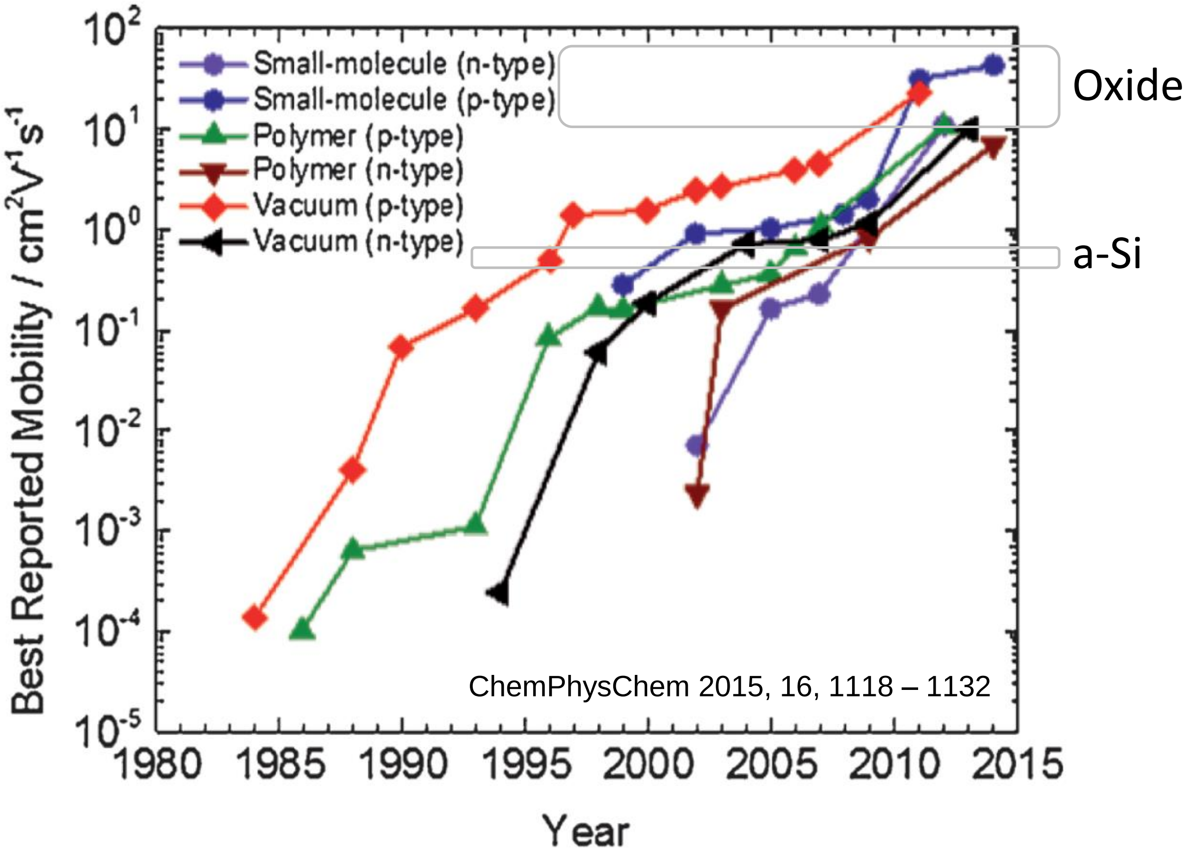


~19 cm^2/Vs (vapor deposited film)

JACS **2015** *Just accepted*
(DOI: 10.1021/jacs.5b01108)

- Like OLED: solution vs vacuum deposition AND small molecule vs polymer
- Both P-type and N-type (more difficult) can be synthesized
- Highest motilities achieved by creating long range molecular order

Performance over the years



- Performance reaching Oxide TFT levels
- Still no products using OTFT on the market

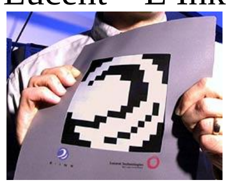
Flexible Displays are coming

Flexible display demo timeline

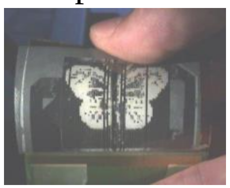
2000 ‘01 ‘02 ‘03 ‘04 ‘05 ‘06 ‘07 ‘08 ‘09 ‘10 ‘11 ‘12 ‘13 ‘14 2015

Philips - PDLC

Lucent – E Ink



Philips – E Ink



Polymer Vision – E Ink

Plastic Logic – E Ink

Fujitsu - CTLC

LG - E Ink

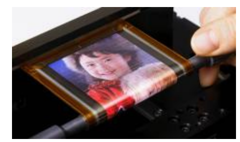
LG - E Ink

Plastic Logic – E Ink

Samsung - OLED

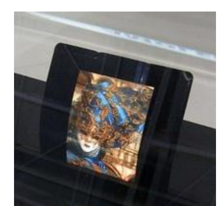
FDC/UDC - OLED

Sony - OLED



Toshiba - LCD

AUO - OLED



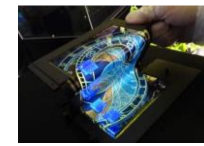
Samsung - OLED

LG - OLED

E Ink

Polyera – E Ink

SEL - OLED



Flex Enable - LCD

BOE - OLED

Royole - OLED

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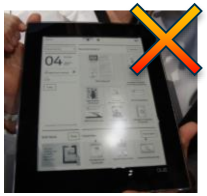
Flexible product timeline

But all still rigid and behind a cover glass

2000 - 2005	2006 - 2010	’11	’12	’13	’14	2015

Plastic Logic Que – E Ink



Fujitsu Flepia - CTLC

Polymer Vision Readius – E Ink

Wexler - E Ink

Yotaphone – E Ink

Samsung Galaxy Round - OLED

LG G Flex - OLED

Samsung Galaxy S4 Edge - OLED

Sony Digital Paper - E Ink

Samsung Gear Fit - OLED

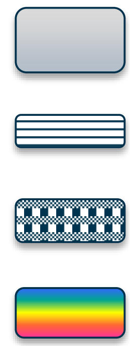
Samsung Gear S - OLED

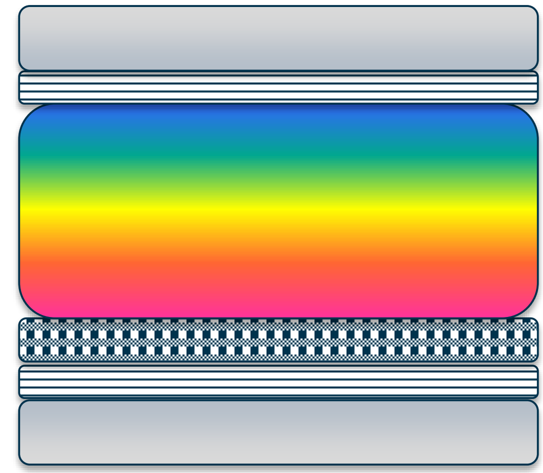
Apple Watch - OLED

Sony Smartband Talk - E Ink

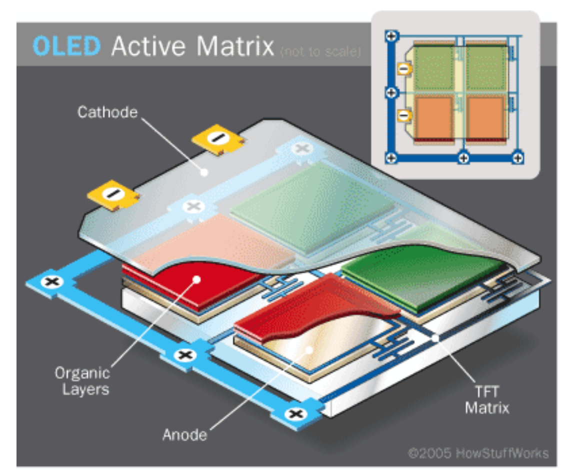
What makes a display flexible?

- It needs to be thin!
- It needs to be impact resistant!

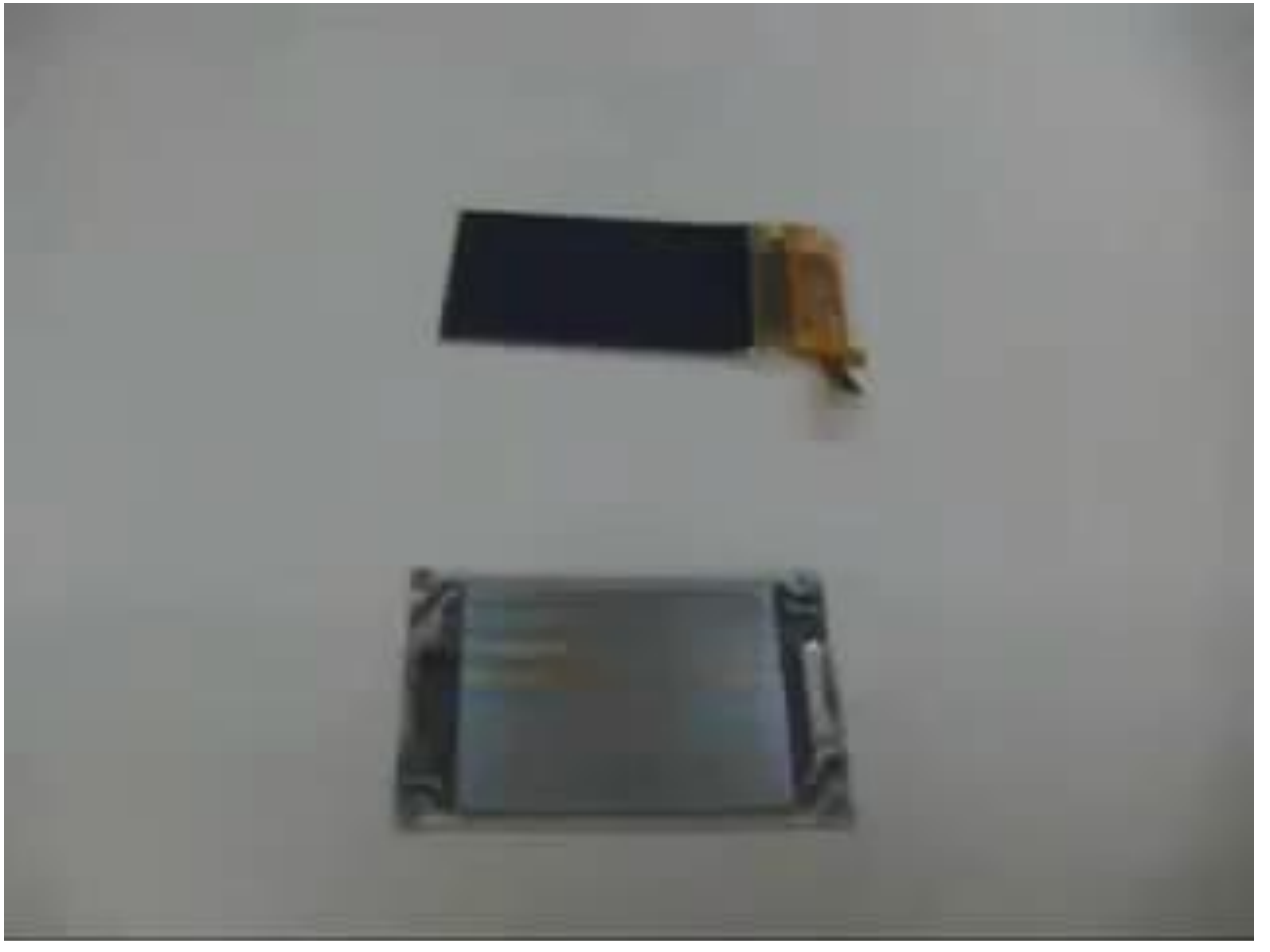




- Four major technology blocks:
  - Flexible substrates
  - Flexible environmental barriers
  - Flexible transistor stack
  - Flexible electro-optical layer



Hammering the display



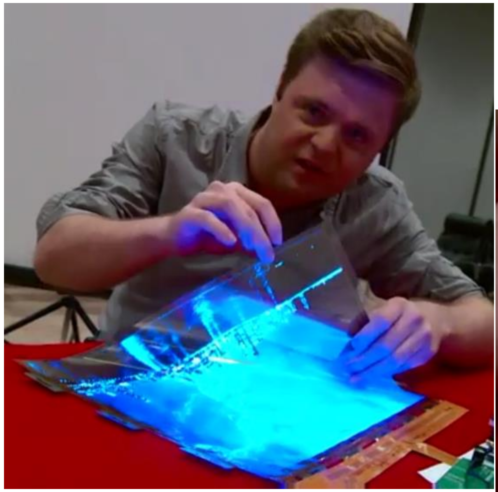
Samsung – 2010

Spectacular but not the most critical test!

Flexing / Rolling the display

Dec 2015: LG announces 18-inch foldable OLED display. Tested by a reporter from the BBC:
http://www.bbc.com/news/technology-35230043

Before rolling



Rolling

After rolling: line defects!

What is missing:

- Robust active matrix backplane that does not crack under bending strain

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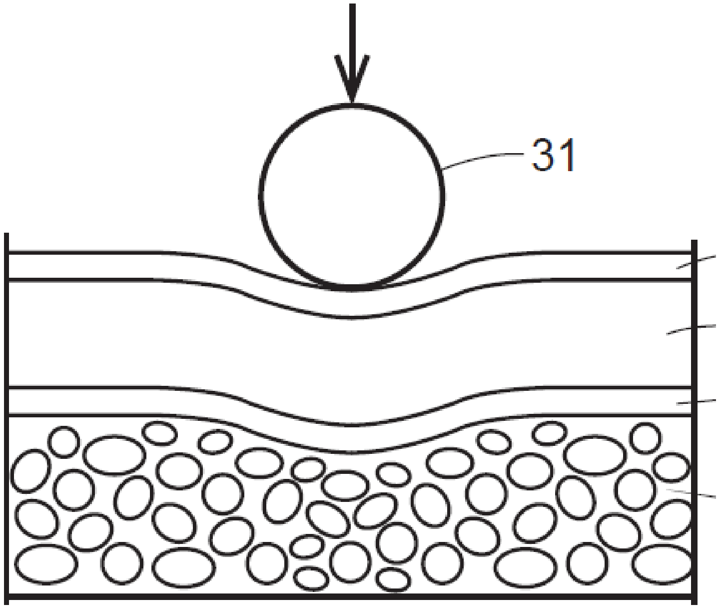
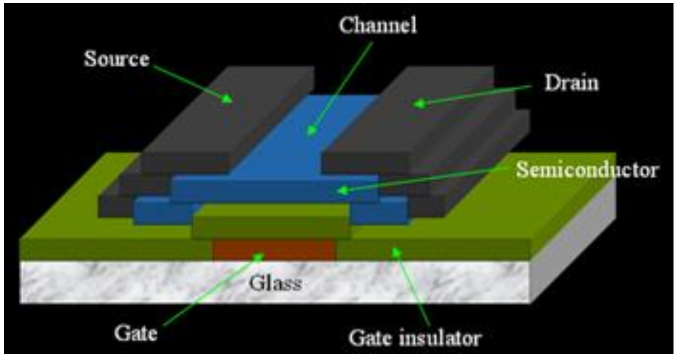
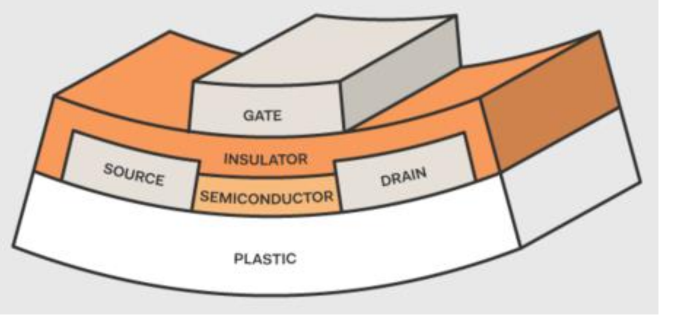
Confidential

What is needed is stretchability

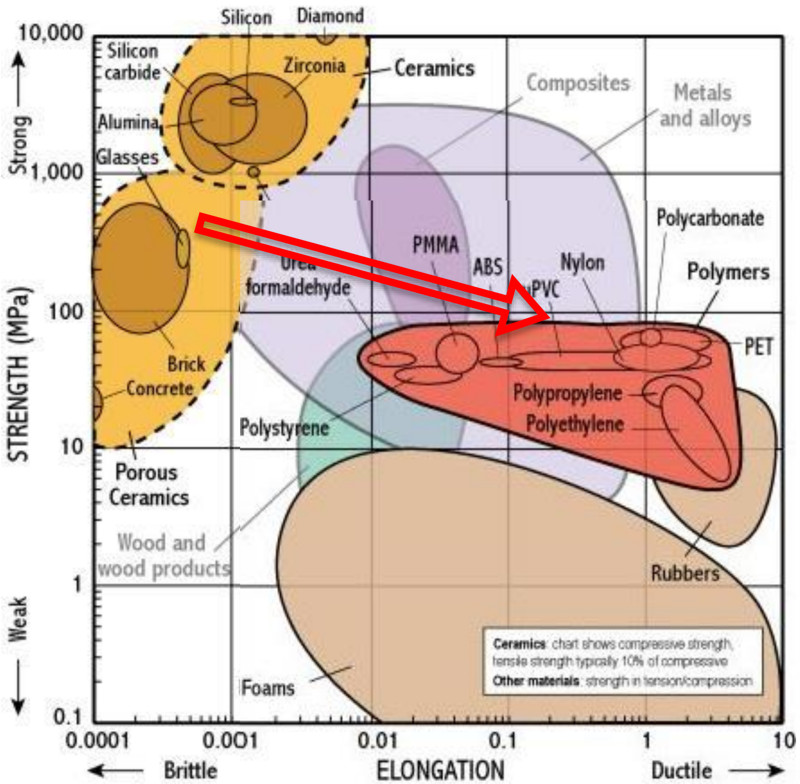


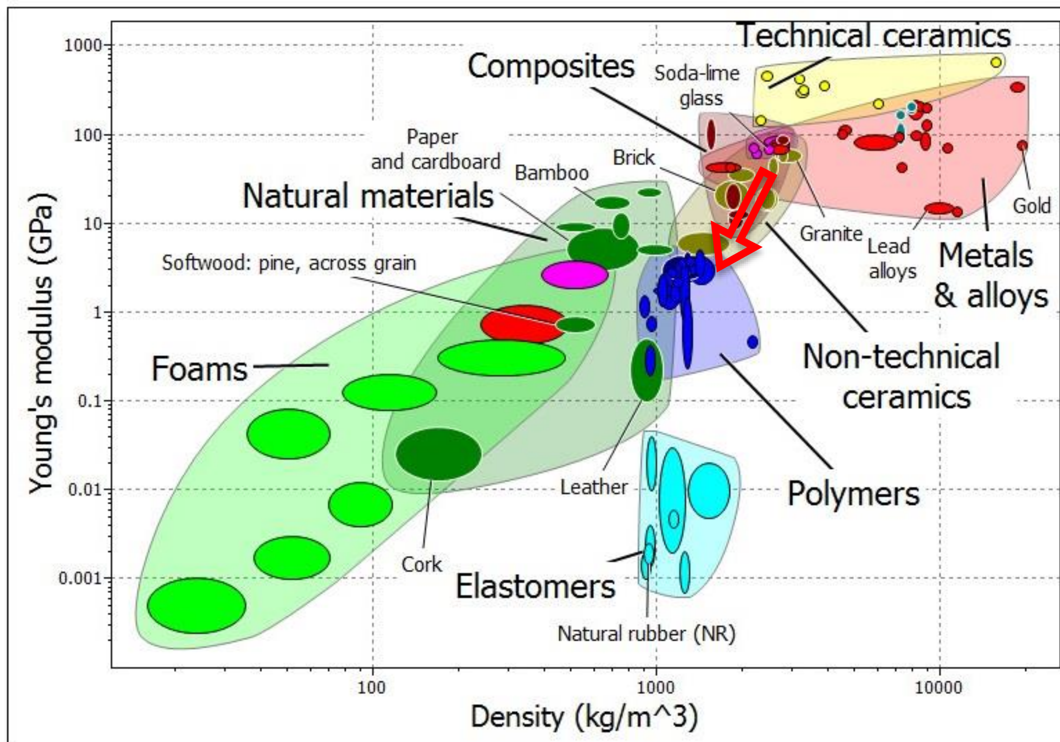




- Object impact / bending requires stretching
- Current Silicon-based transistor stacks break when stretched
- What is needed is a plastic transistor stack that can stretch more

Organic materials for flexible displays





http://www-materials.eng.cam.ac.uk/

- Select the right materials: plastics versus glass / silicon
- Process at low temperatures: avoid build-in temperature stress
- Optimize the position of the neutral plane

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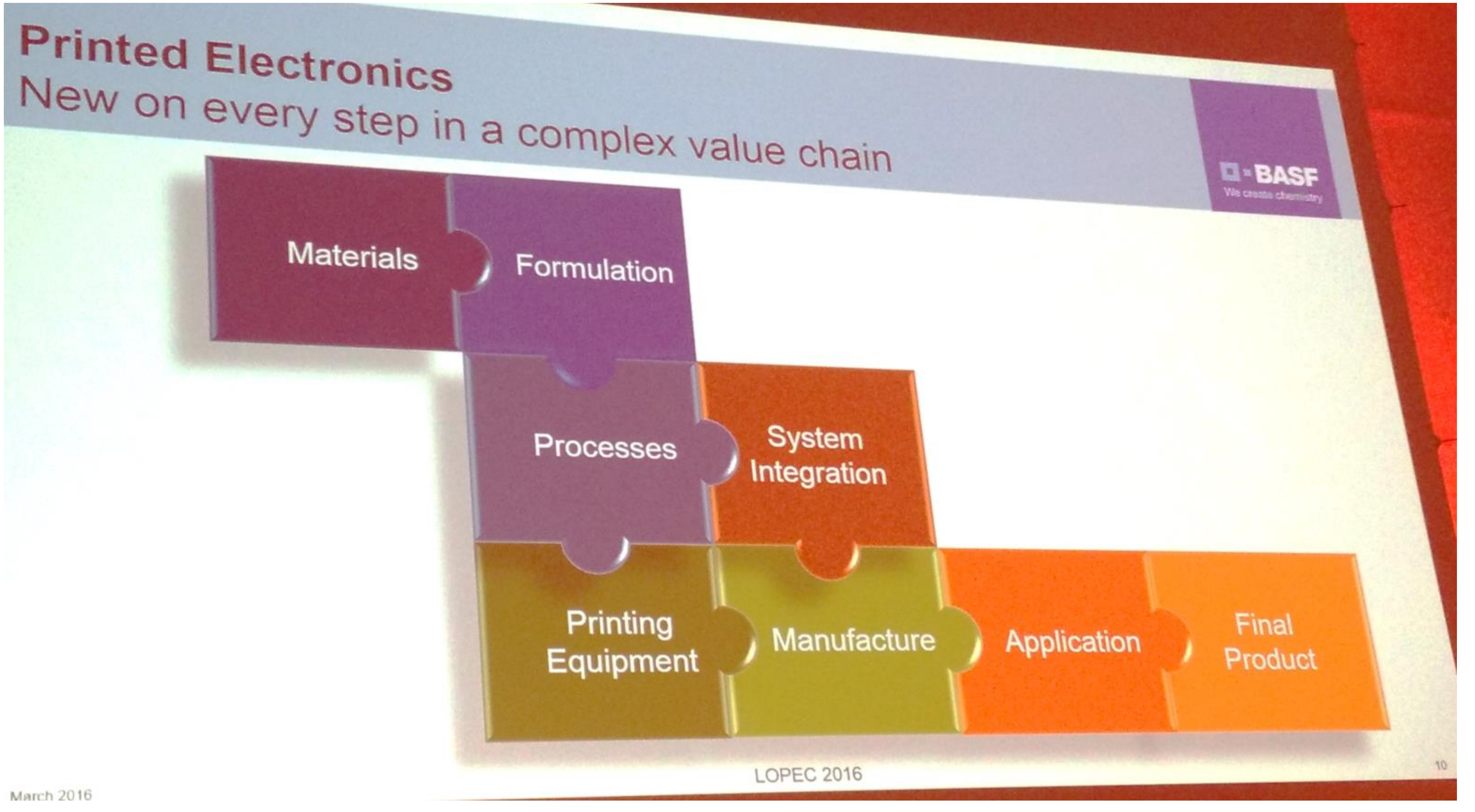
Why does it all take so long?

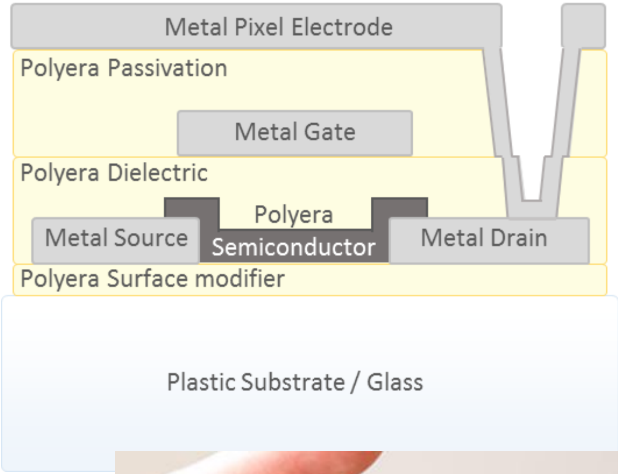


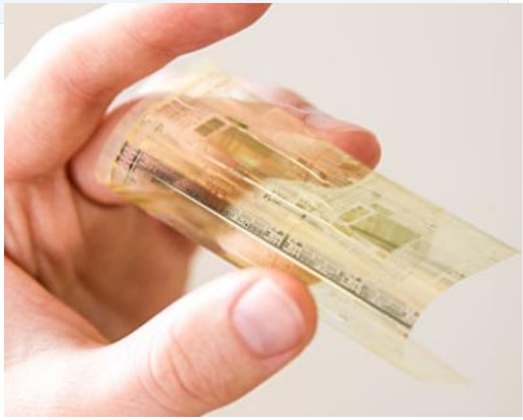
- Although flexible displays using OTFT will enable real flexible products, it requires a whole new value chain
- Polyera is unique in covering all elements [except equipment and manufacturing]

Polyera Flexible Electrophoretic displays

Polyera Flexible OTFT Stack

- Transistor stack:
  - Top gate bottom contact structure
  - Solution processing of the organic layers
  - Sputtering of the metals
- Comparison with a-Si:
  - Already 2x performance in terms of mobility
  - No PECVD used, so reduced cleanroom size and Capex
  - Less processing steps: same mask count but photopatternable dielectrics
  - Lower cost and transparent substrates possible: processing temperature < 150C





Polyera OTFT on 0.025mm PEN

Polyera Gen 1 OTFT Materials set

Semiconductors N-Types

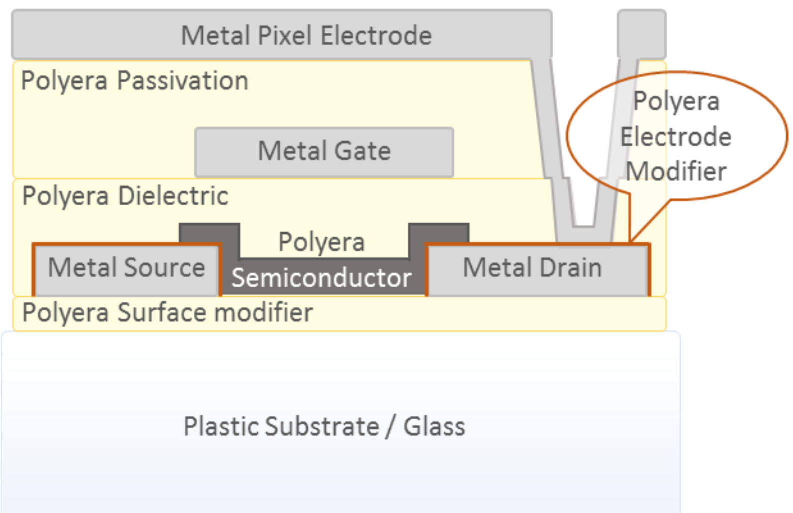
- Mobility: 1 cm^2/Vs now
- Mobility of >3 achievable
- Photo lithography and Inkjet and Gravure printable

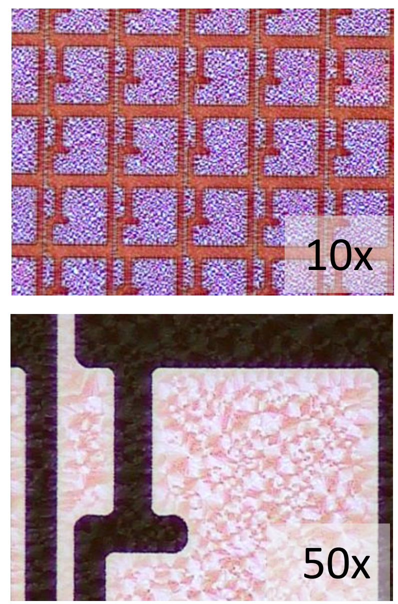
Dielectrics

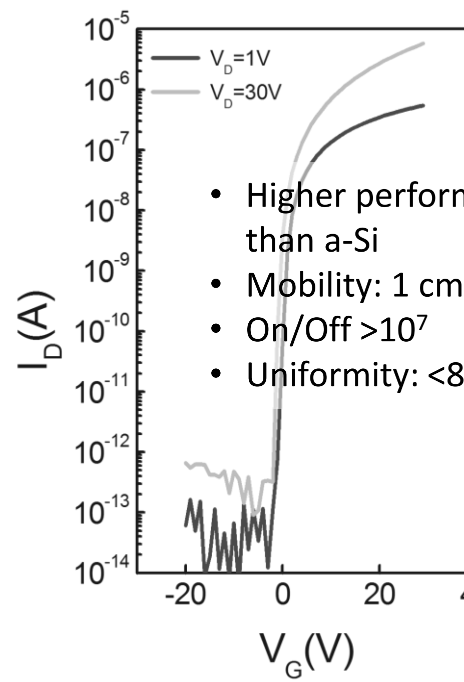
- Compatible with both n- & p-type Semiconductors
- Photopatternable with < 200 mJ/cm^2 dosage and < 8um resolution

Interfacials

- Substrate modifiers for optimal semiconductor deposition
- Electrode modifiers for enhanced injection
- Passivation materials for environmental protection

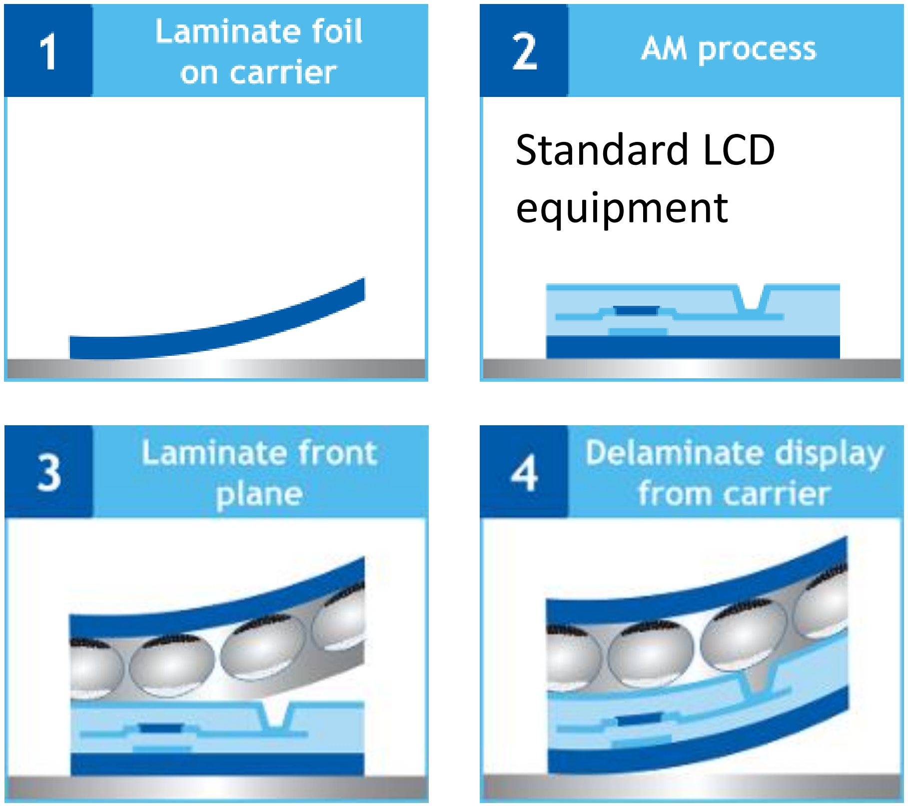


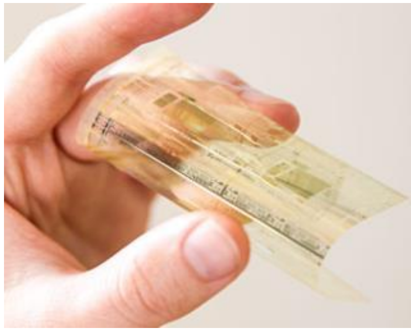


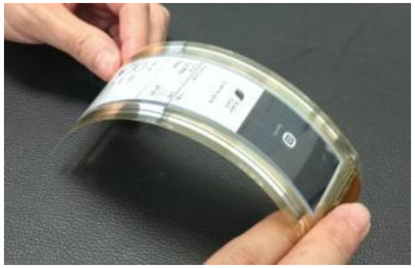


- Higher performance than a-Si
- Mobility: 1 cm^2/Vs
- On/Off $>10^7$
- Uniformity: <8%

Using standard AMLCD equipment

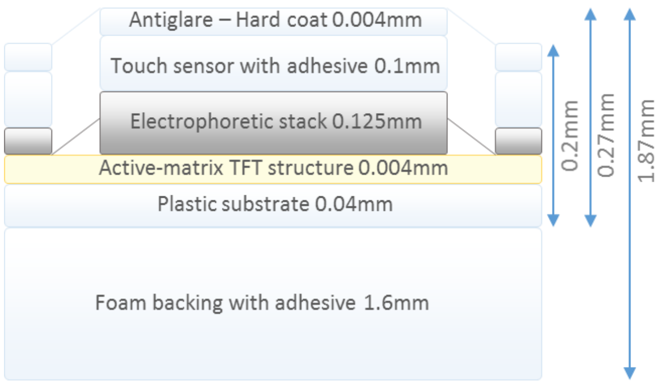






- Using only standard a-Si production equipment
- No printing, ablation, etc; pure photolithography process
- Bond-debond process on standard LCD glass

Flexible Electrophoretic display module



- Polyera OTFT technology combined with E Ink
- Using World's first fully flexible multi-touch sensor using Canatu CNB film with Synaptics firmware

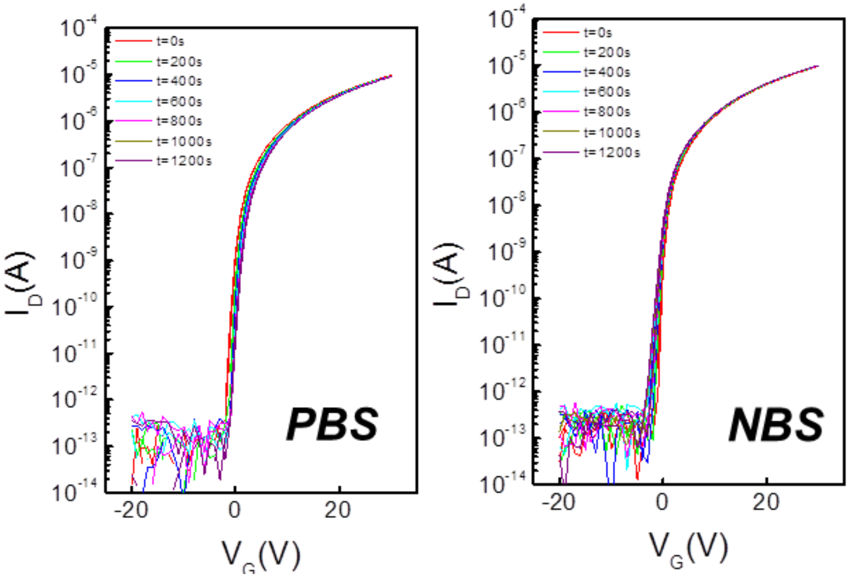
- Transfer to Gen 2.5 on-going (former a-Si line)
- Production start 2016

Pixels:	1040x200
Resolution:	170ppi
Diagonal:	6.25 inch
Touch:	multi-touch
Thickness:	0.27mm
Flexibility:	50k bends @ 15mm

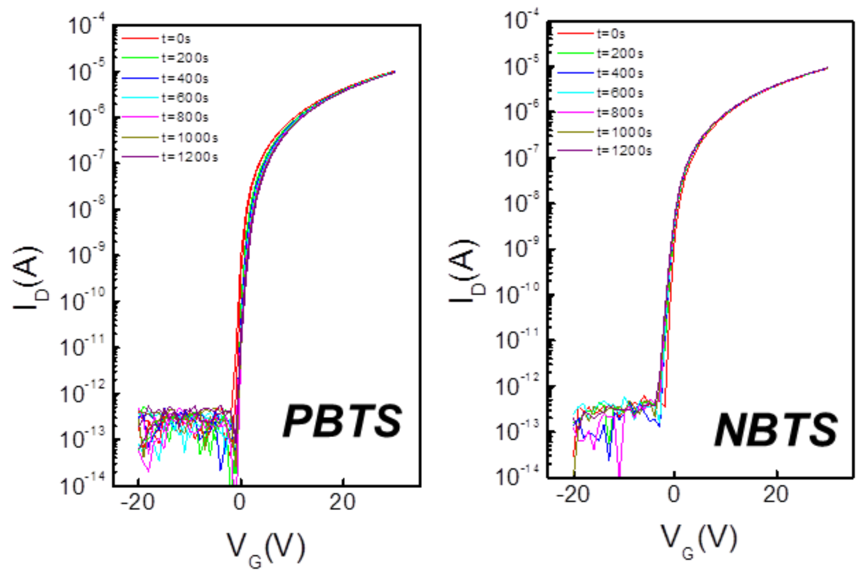
Transistor Performance Stability

- Carrier Mobility ~ 1 cm^2/Vs
- Very stable during stress tests: $\Delta Vth < 1V$
- Enabled by unique organic dielectric material

T=23C
PBS: Vgs=30V; Vds=0V
NBS: Vgs=-30V; Vds=0V



T=60C
PBTS: Vgs=30V; Vds=0V
NBTS: Vgs=-30V; Vds=0V



240 hrs
High temp./High humidity
60C/80%

240 hrs
Low temp.
-25C

100 cycles
Thermal cycling
-25C ->70C-> -25C

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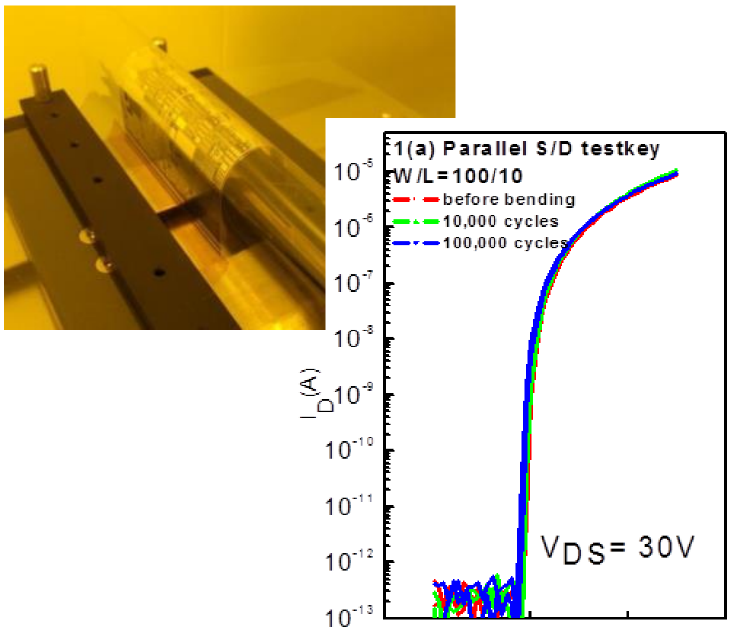
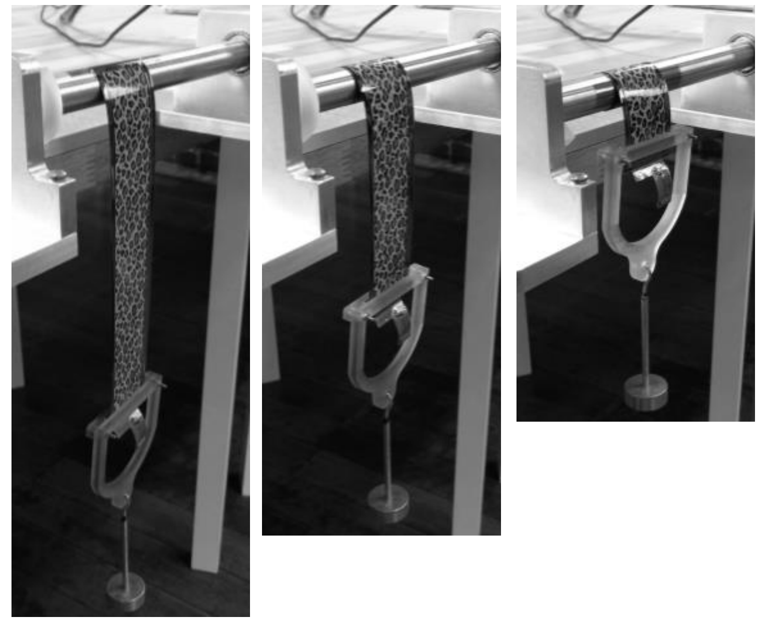
Transistor stack - mechanical

Transistor bending 100.000 times



- Bending radius: 12.5 mm
- No change in TFT performance

Display module bending 50.000 times



- Bending radius: 7.5 mm
- No change in display performance

Ball drop: unmatched performance

Using standard amorphous Silicon for the transistor layer

Fail above 5cm

Using Polyera organic materials for the transistor layer

Pass up to 45cm!

Polyera Product Concepting

The WOVE Band proof of concept

- First ever mass producible flexible display product concept
- Protected by a large patent portfolio
- Two successful build cycles with one of the largest ODMs completed
- Over 200 samples and developer platforms available

WOVE Band specifications

OS	WOVE OS based on Android 5.1
CPU	1.0 Ghz Freescale i.MX7 Dual-Core ARM Cortex A7
Memory	4Gb storage with 512 Mb RAM
Battery	230 mAh
Connectivity	Bluetooth 4.0
Sensors	9 axis Motion sensor
Haptic feedback	ERM Vibration motor
SDKs	Java, HTML5/CSS3/JS and Graphics Tool
Display type	Flexible active-matrix EPD (E Ink)
Display resolution	1040px x 200px, 170 ppi
Display size	156mm x 30mm
Touch	Flexible multi-touch

Display area: 6x Apple Watch!

WOVE Band in the Media

"Polyera has been developing the flexible transistors and display technologies that make it possible for a decade. And the result is undeniably impressive."

"The Flexible Display Band That Puts All Other Smartwatches to Shame"
- Maxim

"The world's first bendable wearable is definitely something you have to see with your own eyes."

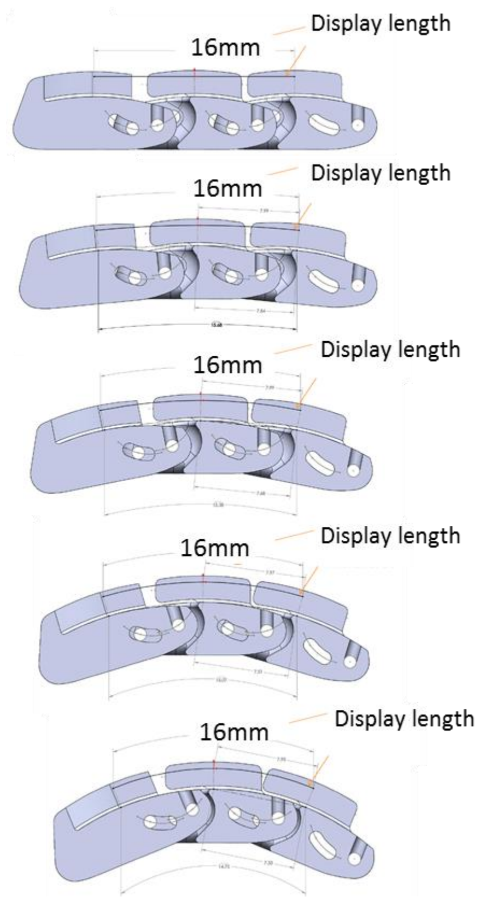
"This is the innovation I haven't seen in the space….it's blowing me away"
- All About Android Postcast

"Wove may be the true fashion-friendly smart bracelet to beat"

"This is exactly what the Pebble Time should have been but isn't."
- Medium

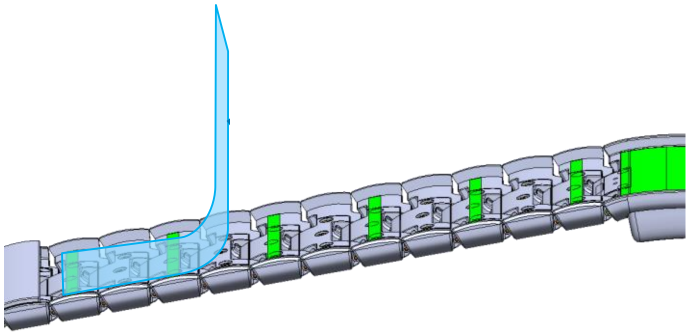
WOVE Mechanics – patents pending

Virtual hinge point; constant display length

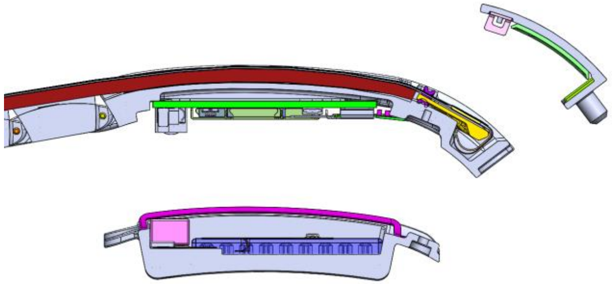


Link design

Display mounting



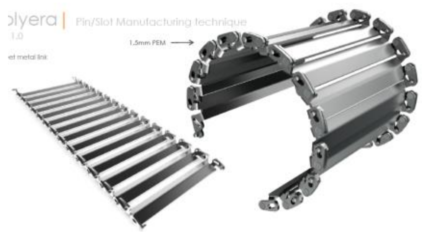
Electronics compartment

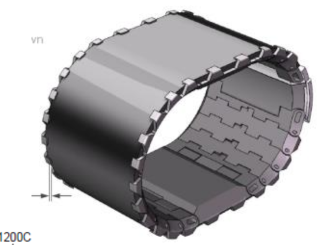


Final assembly

Broad portfolio of mechanical concepts

- Unique enabling flexible product concept families developed
- WOVE mechanical concept selected from a large number of patented directions
- Base patents filed for a complete flexible display product roadmap





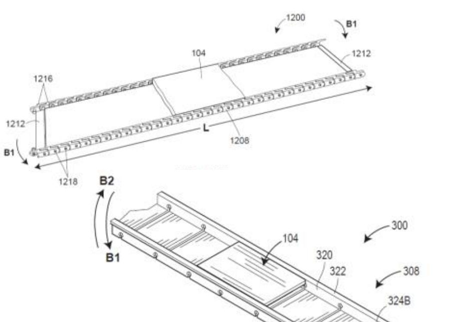
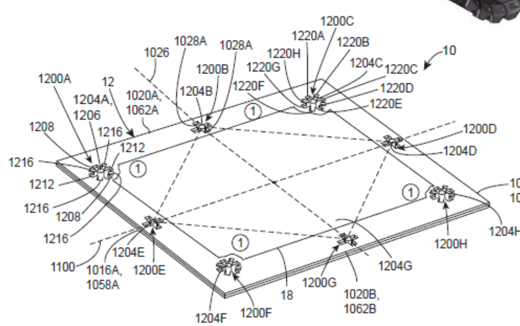


FIG. 4A



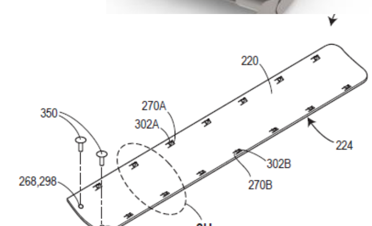
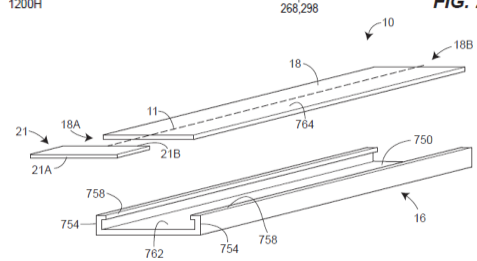
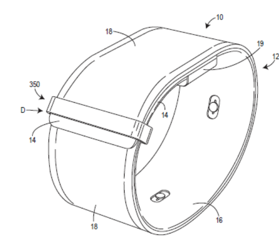


FIG. 2G





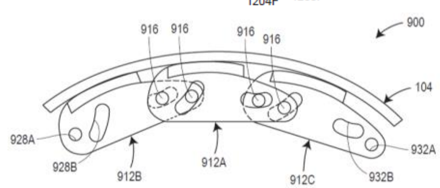
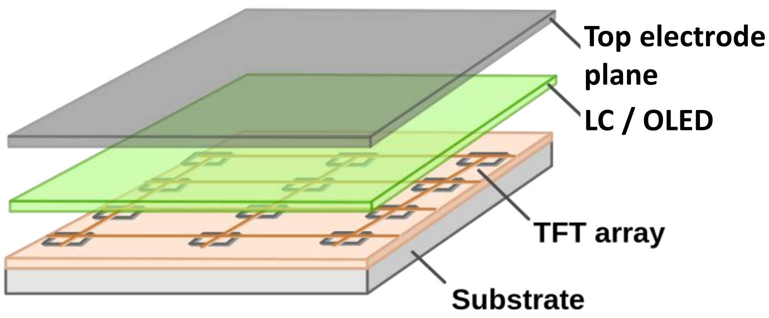


FIG. 8D

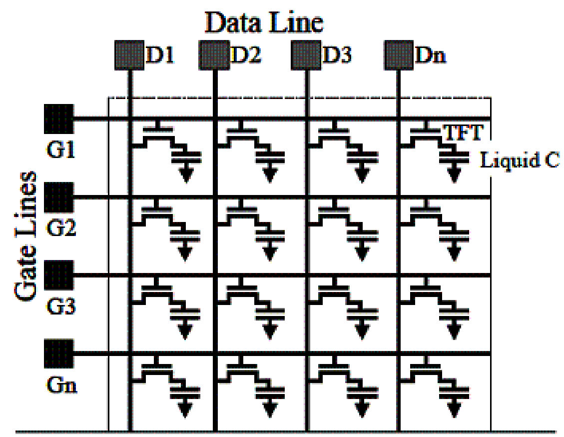
What’s next: higher performance

Introduction: Displays and TFTs

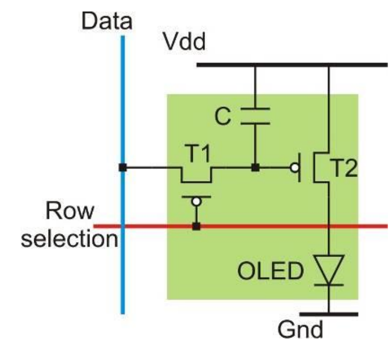
Active-matrix display overview



AMLCD schematic

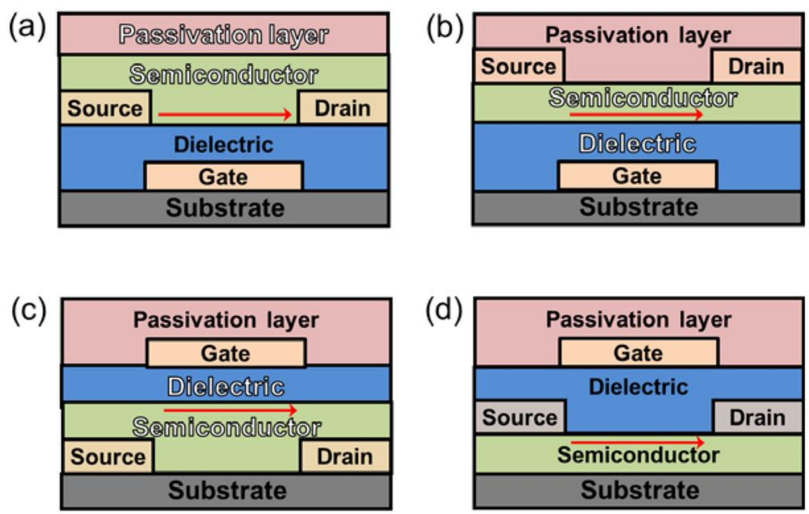


AMOLED schematic



TFT configurations:

(a) Bottom gate – bottom contact
(b) Bottom gate – top contact
(c) Top gate – bottom contact
(d) Top gate – top contact



Semiconductor:
- High mobility & stability
- Processability
- Patternable
- Low cost

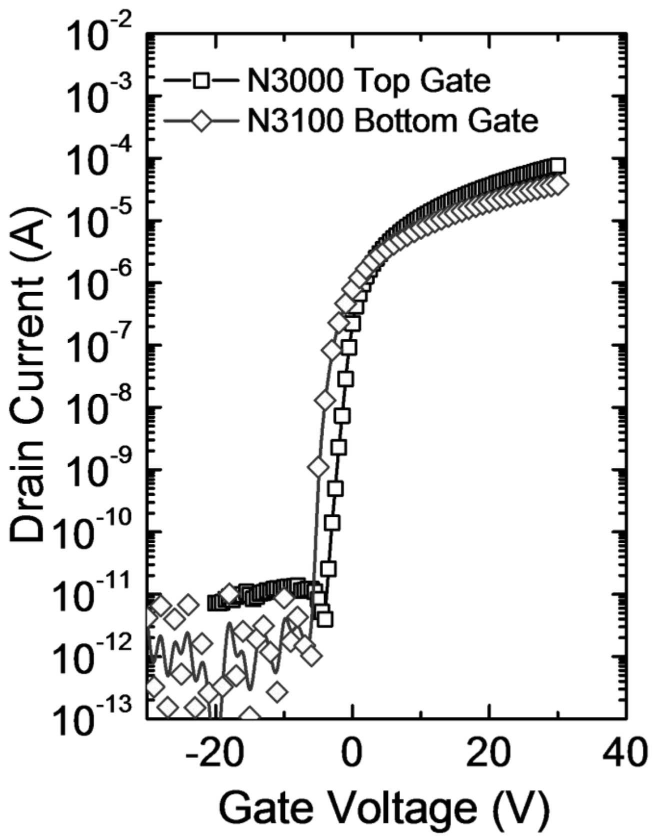
Dielectric:
- High resistance
- Low mobile ion content
- High dielectric constant
- Processability / adhesion
- Patternable
- Low cost

TFT technologies benchmark

Property	Amorphous Si TFT	Polycryst Si TFT (low T)	Oxide TFT	Organic TFT
Mobility (cm^2/Vs)	< 1	10-100	10-50	1-10
Leakage current (A)	10^{-12}	10^{-12}	10^{-12}-10^{-15}	10^{-12}-10^{-15}
TFT stability	Moderate	High	High	Moderate
Process temperature	250-350°C	<500°C	<250°C	RT-130°C
Manufacturing cost	Low	High	Potentially low	Potentially low
Yield	High	Medium	High	High
Flexibility	Moderate	Low	Moderate	High

From: Sirringhous, LOPEC April 2016

Mobility increase for low voltage OLED operation



Small molecule N-type semiconductor N3000 / N31000
Mobility achievable:

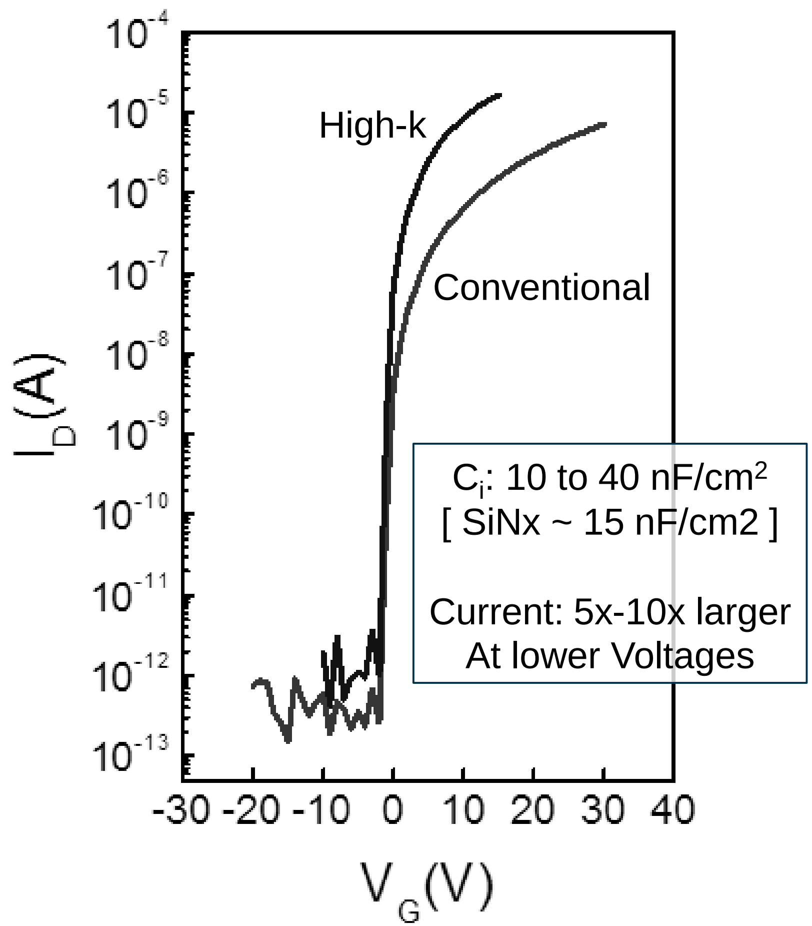
- ~4 cm^2/Vs solution processing
- ~5 cm^2/Vs evaporation

Patents granted for both processing routes

This is still using simple spin-coating or spray coating for deposition

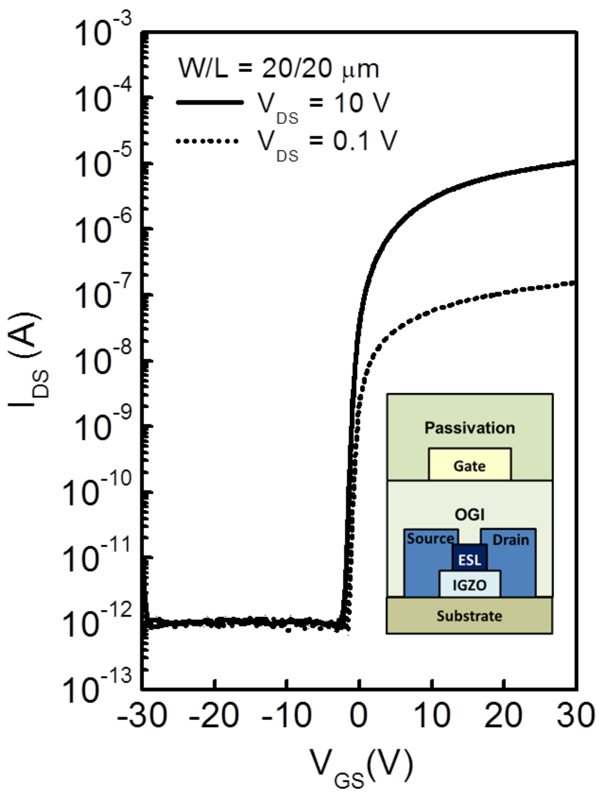
Further enhanced mobility in the coming years is possible by materials optimization

High–k dielectric for low voltage OLED operation



- Typical organic dielectrics have a 3x lower capacitance than SiNx
- Target of high-k dielectrics: exceed the dielectric constant of SiNx
- Resulting in higher currents at lower voltages
- Polyera is first in the World to have this organic dielectric for OTFTs

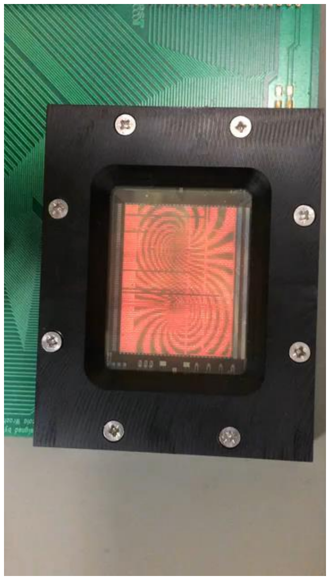
Add organics to the Oxide TFT

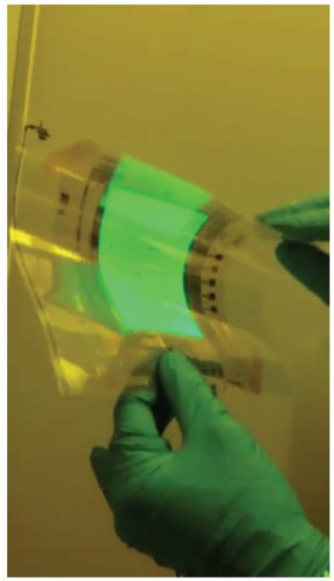


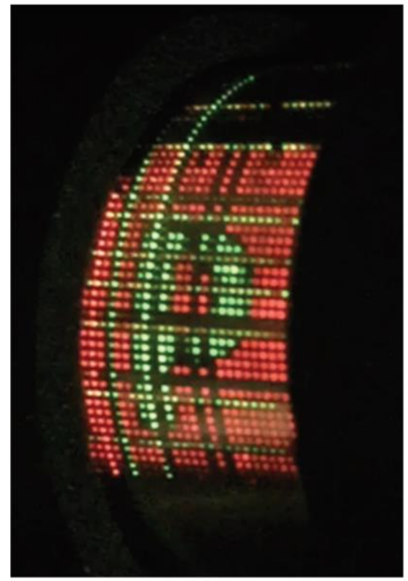
- $\mu \sim 15\ cm^2/Vs$
- S.S < 0.5 V/dec.
- On/off > 10^7
- Negligible hysteresis

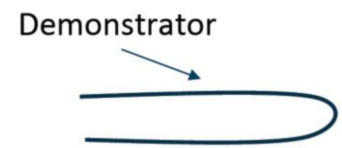
- Solve LG's problem by introducing an organic dielectric into the IGZO TFT
- Unique combination of conventional sputtered IGZO TFT and Organic dielectric
- Advantages:
  - Organic dielectric, can handle >8% strain
  - Spin coated, no vacuum deposition
  - Ideal for flexible OLED products
- Performance:
  - On par with current state-of-the-art Oxide TFTs using inorganic dielectrics

OLED: first Research Demonstrators









Bending radius < 10mm

OTFT V1 OLET demonstrator

Flexible OLED demonstrator using Organic Oxide TFTs

What's next: organic CMOS & printing

Polyera OCMOS Materials set

Semiconductors N- & P- Types

- Mobility: 1 cm²/Vs now
- Mobility of >3 achievable
- Inkjet and Gravure printable

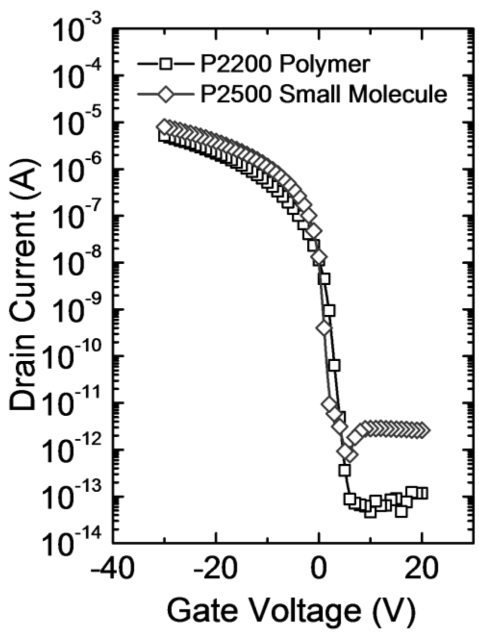
Dielectrics

- Compatible with both n- & p-type Semiconductors
- Photopatternable with < 200 mJ/cm² dosage and < 8um resolution

Interfacials

- Substrate modifiers for optimal semiconductor deposition
- Electrode modifiers for enhanced injection
- Passivation materials for environmental protection

P-type development:



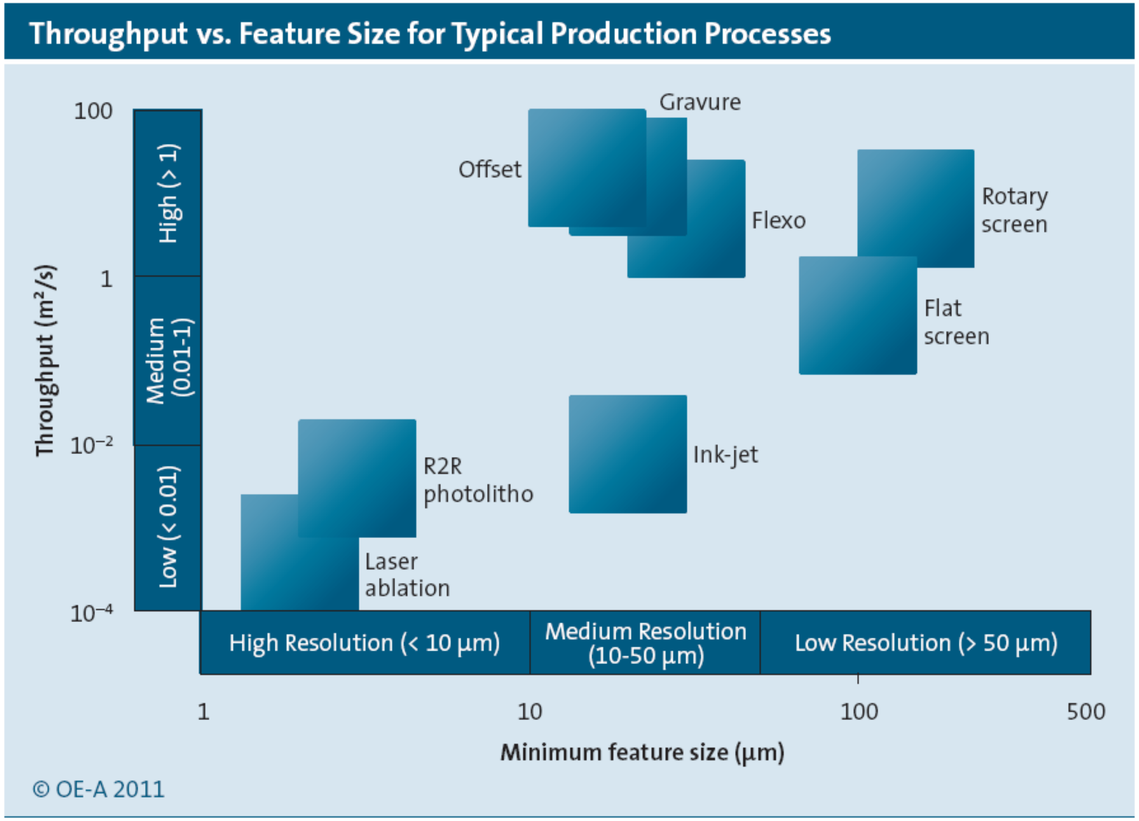
Small molecule and Polymer P-type materials available:

- ~2 cm²/Vs solution processing
- ~3 cm²/Vs evaporation

Patents filed for these materials

N-type layer stack is reused from the other platforms

OTFTs can also be printed



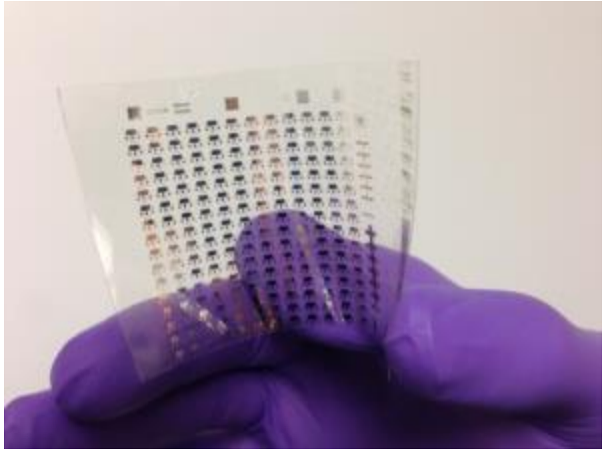
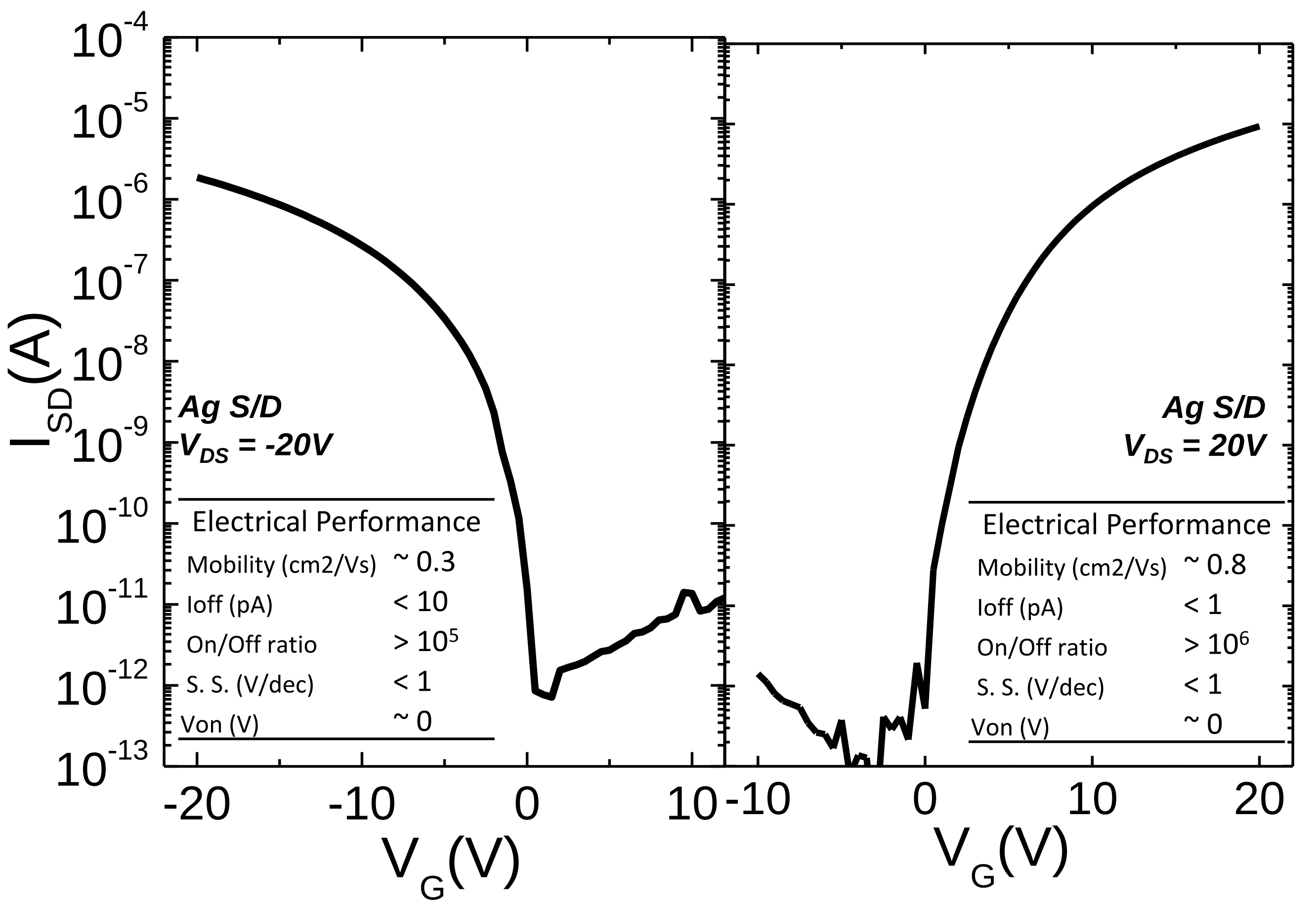


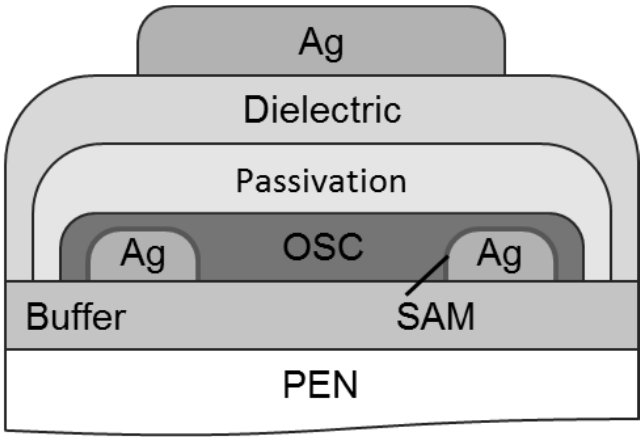
Image of printed TFT array on PEN

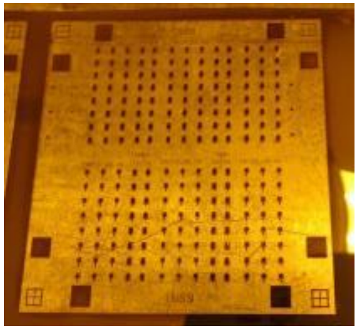
- Gravure: optimum between feature size and throughput
- Inkjet: lower throughput but highly flexible for smaller customized series

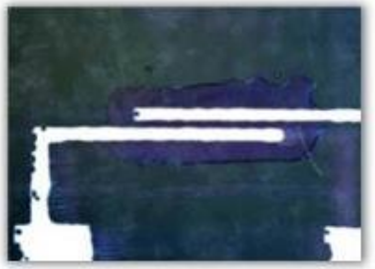
Characteristics of Printed complementary OTFTs: OCMOS



The printed N- and P-type OTFT stack



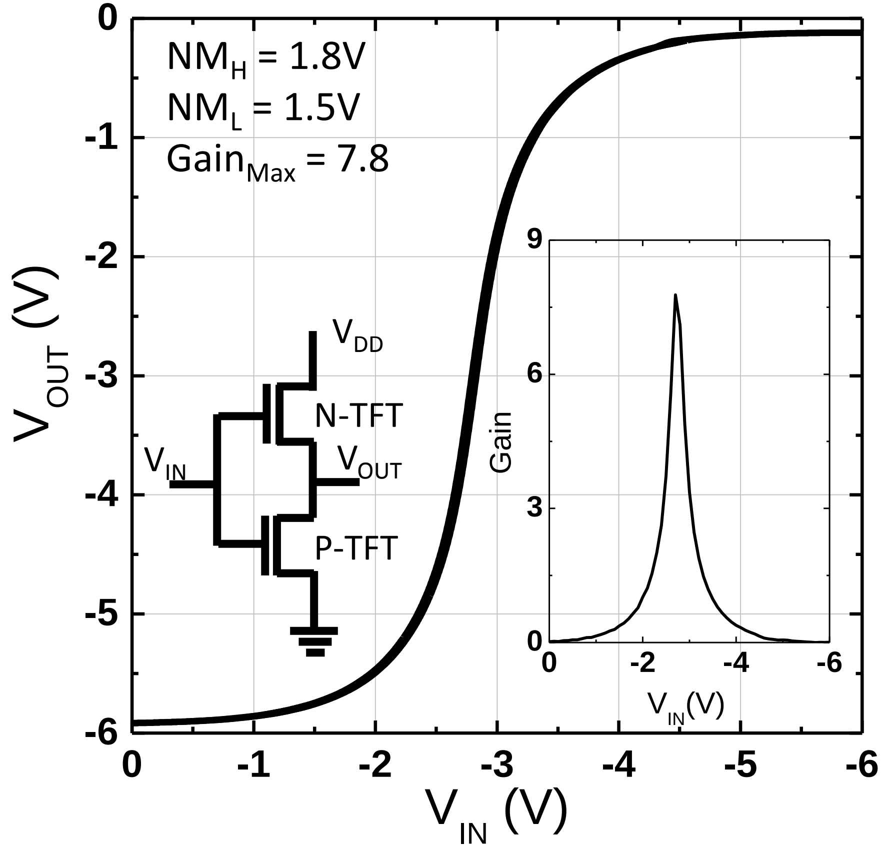




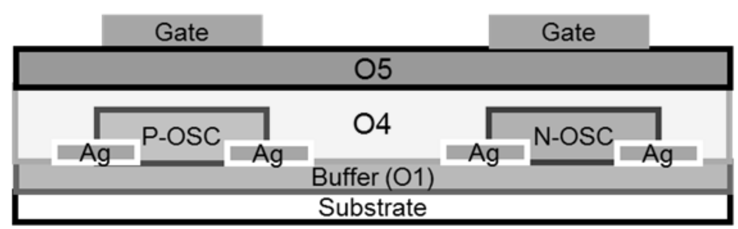
All gravure printed OTFTs:

- Gravure printed metal contacts combined with gravure printed organic layers
- Buffer: proprietary Polyera organic material
- OSC (Organic semiconductor): proprietary N-type or P-type Polyera organic material
- Dielectric: high-k Polyera organic material
- Typical OTFT size: W/L = 1000/60 um

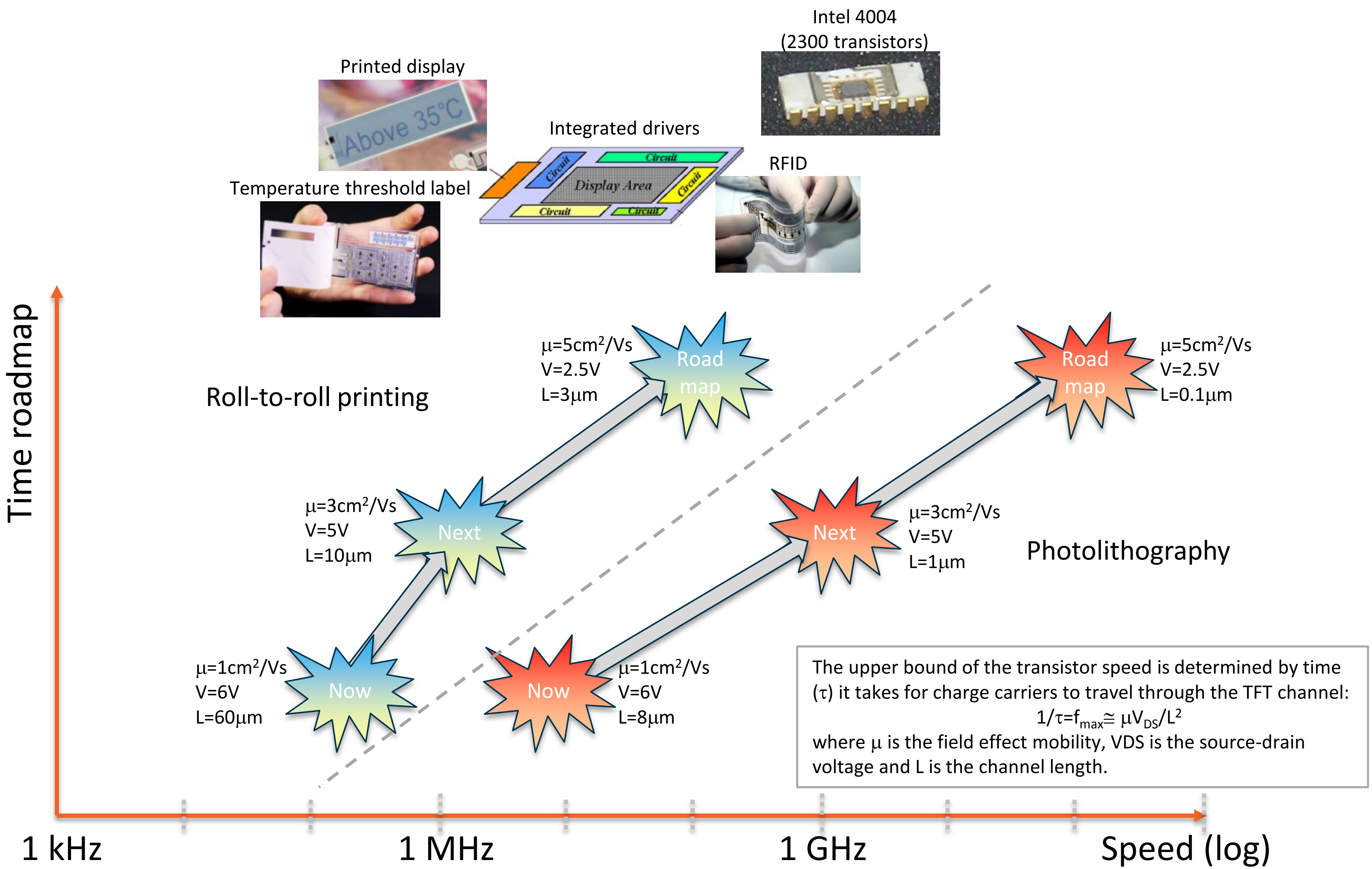
Printed OCMOS Inverter



- Flexible complementary inverter consist of printed P- and N- TFT on PEN.
- Low voltage operation with large signal gain, crossover point close to $V_{DD}/2$, and balanced noise margin.



OCMOS Switching speed considerations



The upper bound of the transistor speed is determined by time (τ) it takes for charge carriers to travel through the TFT channel:

$$1/\tau = f_{max} \cong \mu V_{DS}/L^2$$

where μ is the field effect mobility, VDS is the source-drain voltage and L is the channel length.

The Internet of Everything

Source: TFE

Key takeaways

- Organic electronics is more alive than ever
- Performance in the lab already at Oxide TFT levels
- Performance in the fab a little higher than a-Si
- Polyera is at the forefront of materials development and industrialization of organic TFTs in displays
- Electrophoretic display production starting end of 2016
- Polyera roadmap is going towards OLED and printed electronics using OCMOS