Printed Organic Transistors for Ultraflexible and Stretchable Electronics

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Outline

• **Background & Motivation**
  ✓ Organic integrated circuits on plastics

• **All printed organic transistors**

• **Ultraflexible organic CMOS circuits**

• **Stretchable integrated circuits**

• **Future Prospects & Summary**
Flexible displays

✓ Peri-Xanthenoxyanthene (PXX) derivative
  ➔ Mobility: 0.4 cm$^2$/Vs

✓ Organic driving cells with 2T-1C structure

✓ Resolutions: 121 ppi (432 × 240 × RGB pixels)

✓ Critical bending R = 4 mm

From http://www.sony.co.jp/SonyInfo/News/Press/201005/10-070
## Flexible TFTs on plastic

<table>
<thead>
<tr>
<th>Mobility</th>
<th>Poly-Si TFTs (ref. 1) EPSON</th>
<th>Oxide TFTs (ref. 2) TIT</th>
<th>CNT TFTs (ref. 3) Illinois U.</th>
<th>Organic TFTs (ref. 4) UT</th>
<th>a-Si TFTs (ref. 5) Princeton U.</th>
<th>Organic TFTs (ref. 6) Erlangen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility</td>
<td>&gt;10 cm²/Vs</td>
<td>&gt;7 cm²/Vs</td>
<td>15 cm²/Vs</td>
<td>0.5 cm²/Vs</td>
<td>0.5 cm²/Vs</td>
<td>0.1 cm²/Vs</td>
</tr>
<tr>
<td>Operation voltage</td>
<td>4 V</td>
<td>10 V</td>
<td>20 V</td>
<td>40 V</td>
<td>15 V</td>
<td>2.5 V</td>
</tr>
<tr>
<td>Bending radius</td>
<td>10 mm</td>
<td>30 mm</td>
<td>10 mm</td>
<td>0.5 mm</td>
<td>0.5 mm</td>
<td>2.5 mm</td>
</tr>
</tbody>
</table>


Organic TFTs can easily construct complementary circuits on plastics.  
⇒ Low-process temperatures & stable p-type, n-type semiconductors
Technical challenges for skin-like interfaces

Large-area & flexible active matrix

Sensor arrays (light, pressure, thermal)

Key:1

Key:2

Position-sensing

Large-area Active Matrix

Flexible & conformable
Printed TFT active matrices for displays


Inkjet printing
Semiconductor: PQT
Mobility: \(~0.08\) cm\(^2\)/Vs
340 \(\mu\)m pixel pitch

A. C. Arias, et al., (PARC )

Micro-contact printing
Semiconductor: P3HT
Mobility: \(~0.01\) cm\(^2\)/Vs
127 \(\mu\)m pixel pitch (200ppi)

K. Suzuki et a., IDW’09 (2009) RICOH

Inkjet printing + UV
Semiconductor: Small molecule
Mobility: \(~0.1\) cm\(^2\)/Vs
127 \(\mu\)m pixel pitch (200ppi)

3.2 inch-diagonal
Screen-printing for Large-area electronics

Frame size: 3300 × 3500 mm² (Accuracy ±30 µm)

Tokyo process service Co, Ltd.,
Screen-printing system

Printing area  : 300 × 300 mm²
Repeat accuracy  :  5 µm

Microtec Co. Ltd.
Ag paste with low-drying temperature

Viscosity: 360 Pa·s
➔ very few organic solvents

Resistivity ($\Omega \cdot m$) vs. Drying temp. ($^\circ C$)

- 30 $^\circ C$ (at R.T.)
- 50 $\mu m$ width

Resistivity ($\mu \Omega \cdot cm$)

- 26.4 m$\Omega$/square
High-definition screen-printing

High-viscosity ink

- High-squeezing pressure
- Large-clearance between screen-mask and substrate

This work

Screen-mesh

- Twill-weave mesh for high tensile force (3000 N/mm)

Printed Ag paste

- Finely patterned without ink bleed

18 µm
Organic semiconductor ink

Solution – processable polycrystalline organic semiconductor

- High-mobility (4 cm²/Vs)
- Annealing is not required
- Air-stable

lisicon OSC (Merck Ltd.)

G. Lloyd et al., *Tech Dig* of IDW '08
M. Carrasco-Orozco et al., *Tech Dig* of IDW '09
G. Lloyd et al., *Tech Dig* of IDW '10

Fig. 3 Example lifetime data for a spin coated top gate device stored in normal laboratory conditions.
Transistor fabrication by printing

1. Gate electrode (Ag: 3 μm)
   (Screen printing)

2. Gate dielectric layer
   (parylene: 400 nm)
   (CVD)

3. S/D electrode
   (Ag: 5 μm)
   (Screen printing)

4. Bank
   (Epoxy: 5 μm)
   (Screen printing)

5. Solution-polycrystalline
   Organic semiconductor
   lisicon (300 nm)
   (IJP, Drop-cast)

Substrate (PEN: 125 μm)

Dry at 3 hours in ambient air + Parylene encapsulation
300 x 300 mm²
(14,400 cells: 1mm pitch)
Polycrystalline organic TFT

Mobility : $\sim 0.18 \text{ cm}^2/\text{Vs}$

On/off ratio : $10^3 \sim 10^6$

$V_{DS} = -70 \text{ V}$

$V_{GS} = 0 \text{ to } -50 \text{ V in } -10 \text{ V step}$

$V_{DS} = -70 \text{ V}$

$V_{TH} = -3.2 \text{ V}$

$\mu = 0.13 \text{ cm}^2/\text{Vs}$

On/Off : $> 10^3$

5 days

In air
Bending Test

Flat state (Initial)

Bending state

5 mm

$L=50 \, \mu m$

Flat state

$V_{DS}=-60 \, V$

Bending state

Graph showing $V_{GS}$ (V) vs. $I_{DS}$ (A) with curves for Flat state and Bending state.
Flexible touch-sensor sheet

PET film with Cu electrode

Pressure sensitive rubber

Printed transistor active matrix

Diagram showing layers of PEN film, Cu, pressure sensitive rubber, TFT, and printed transistor active matrix.
Low-voltage operational ultraflexible organic CMOS circuits

TFT structure

Organic semiconductor (30 nm)

Source/Drain electrode (Au: 50 nm)

Gate electrode (Al: 20 nm)

Substrate (Polyimide: 12.5 μm)

Planarization (Polyimide) 500 nm

AlO$_x$ (4 nm)+SAMs (2 nm)

Cross-sectional picture

(FIB/TEM)

Pentacene
SAM (2 nm)
AlO_x (4 nm)
Al (18 nm)
Planarization

20 nm
Organic TFTs on plastic

**P-type**
**DNTT TFT**

![DNTT structure](image)

*JACS* 129, 2224 (2007).
3.0 cm$^2$/Vs
On/off: > $10^5$
80 mV/dec

**N-type**
**F$_{16}$CuPc TFT**

![F$_{16}$CuPc structure](image)

0.02 cm$^2$/Vs
On/off: > $10^4$
150 mV/dec
Bending test

Current // Strain (Parallel)

Current ⊥ Strain (Perpendicular)

Capacitor

Cross-section

W/L = 500/50 (µm)

700 × 100 (µm)

Normalized $I_{DS}$ vs. Bending radius [mm]

$R < 0.5$ mm (13 µm-thick substrate)

$R \sim 4.0$ mm (75 µm-thick substrate)
Organic CMOS circuits

- Inverter
- Ring oscillator

Gain: $\approx 40$

\( R = \infty \) (Initial)
\( R = 300 \ \mu m \)

Stage delay: 4.5 ms
Stretchable integrated circuits on shape-memory polymer
Fine-tube electronics for medical

Helix of organic transistor active matrix

Gate-source voltage
Pressure sensitive rubber (Sensor)
Drain-source voltage

2 mm

Catheter
Tube
Au
Circuits

Pressure sensitive rubber

<table>
<thead>
<tr>
<th>Drain current (A)</th>
<th>Gate-source voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-12}</td>
<td>-3</td>
</tr>
<tr>
<td>10^{-11}</td>
<td>-2.5</td>
</tr>
<tr>
<td>10^{-10}</td>
<td>-2</td>
</tr>
<tr>
<td>10^{-9}</td>
<td>-1.5</td>
</tr>
<tr>
<td>10^{-8}</td>
<td>-1</td>
</tr>
<tr>
<td>10^{-7}</td>
<td>-0.5</td>
</tr>
<tr>
<td>10^{-6}</td>
<td>0</td>
</tr>
</tbody>
</table>

V_{DS} = -3 V

1 kPa
0 kPa
Printed elastic conductor

Resolution: 100 μm
Conductivity: ~100 S/cm
Stretchability: ~140%

Structure for stretchable displays

Data-line $V_{Data}$

Bias-voltage-line $V_{Bias}$

Scanning-line $V_{Scan}$

OLED

$I_{OLED}$

$I_{selector}$

$C$

GND-line

Silicone rubber

Elastic conductor

Pentacene

Source

Polyimide

Gate

Drain

Silicone rubber

Elastic conductor
<table>
<thead>
<tr>
<th>( V_{\text{Scan}} )</th>
<th>+40 V</th>
<th>–5 V</th>
<th>–10 V</th>
<th>–30 V</th>
<th>–40 V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cu wiring</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Control sample)</td>
<td>6.7 nA</td>
<td>1.7 ( \mu )A</td>
<td>35 ( \mu )A</td>
<td>381 ( \mu )A</td>
<td>1.3 mA</td>
</tr>
<tr>
<td></td>
<td>0.0 cd/m²</td>
<td>0.3 cd/m²</td>
<td>6.1 cd/m²</td>
<td>88.3 cd/m²</td>
<td>408 cd/m²</td>
</tr>
<tr>
<td><strong>Elastic conductor</strong></td>
<td>7.0 nA</td>
<td>1.6 ( \mu )A</td>
<td>31.6 ( \mu )A</td>
<td>343 ( \mu )A</td>
<td>1.2 mA</td>
</tr>
<tr>
<td></td>
<td>0.0 cd/m²</td>
<td>0.28 cd/m²</td>
<td>5.5 cd/m²</td>
<td>77.2 cd/m²</td>
<td>364 cd/m²</td>
</tr>
<tr>
<td><strong>Conventional</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>conducting rubber</td>
<td>2.6 nA</td>
<td>280 nA</td>
<td>6.6 ( \mu )A</td>
<td>19.4 ( \mu )A</td>
<td>40 ( \mu )A</td>
</tr>
<tr>
<td></td>
<td>0.0 cd/m²</td>
<td>0.0 cd/m²</td>
<td>1.2 cd/m²</td>
<td>3.4 cd/m²</td>
<td>7.1 cd/m²</td>
</tr>
</tbody>
</table>

\( \Delta 97\% \)
Stretchable active matrix OLED display


50%-stretchability!!

Displays on an egg.
Ultraflexible sensor & lighting for bio/medical applications

Sensing and medical treatment in blood vessel and unconventional surfaces
Stretchable, large-area electronics using organics can cover arbitrary curved surfaces and movable parts, and thus would significantly expand where electronics can be used.
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Summary

✓ All-printed organic transistors
  Solution-semiconductor: $0.18 \text{ cm}^2/\text{Vs}$, on/off ~ $10^6$

✓ Printed transistor active matrix
  $300 \times 300 \text{ mm}^2$ (14,400 cells: 1mm pitch)
  Large-area flexible touch-sensor system

✓ Organic TFTs with SAM gate dielectric on thin films
  P-type DNTT TFT: $3.0 \text{ cm}^2/\text{Vs}$, On/off: $> 10^5$, 80 mV/dec
  N-type $F_{16}\text{CuPc}$ TFT: $0.02 \text{ cm}^2/\text{Vs}$, On/off: $> 10^4$, 150 mV/dec

✓ Ultraflexible Organic CMOS circuits
  Inverter: Gain~40, Ring Oscillator: 4.5 ms (stage delay)
  Medical sensors and display applications

✓ Stretchable electronics
  Stretchable active matrix OLED display on curved surface