Advantages and limitations of printing

**Photolithography**
- Deposit film
- Resist
- Mask

**Digital Inkjet**
- Low-temperature process, low ink consumption (<10μL to cover a 4” wafer)
- Trade-off in resolution and printing speed
  - Inkjet: ~35 micron resolution, web speed ~5 miles/hr;
  - Imprint: ~nm resolution, 20 eight-inch wafers/hr

**Stamp printing**
- Vacuum deposition
- Solution printing in air
Applications for printed sensors

- Scalable to large-area, flexible, tunable materials
  Human-computer interface (touch, imager, etc.)
- Multi-component arrays that increase selectivity
  Low-cost, high-volume for distributed sensing

GE-Avery Dennison


PARC ARPA-E MONITOR
Solution processed sensors comparable to conventional Ge

Tunable organic materials with infrared detectivity comparable to commercial Newport Ge diode

\[ D^* \text{ [Jones]} \]

\( \begin{align*}
1.0 \times 10^8 & \quad 1.0 \times 10^{10} \\
1.0 \times 10^{12} & \quad 600 \\
1.0 \times 10^{10} & \quad 1000 \\
1.0 \times 10^{12} & \quad 1400 \\
\end{align*} \)

wavelength [nm]

Printed TFTs for local sensor control

M x N lines, interconnect takes more space than sensors

With TFTs, M + N lines only

Simple signal conditioning/processing

TFT integrated circuits provides signal conditioning before Si chip
Key challenge for integrated TFT circuits

Challenge for implementation: Designs that tolerate variations in OTFTs

- Variation leads to circuit error
- Controlling variation is key to practical yield

<table>
<thead>
<tr>
<th>TFT variation (1σ std dev)</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>10%</td>
<td>80%</td>
</tr>
<tr>
<td>5%</td>
<td>98%</td>
</tr>
</tbody>
</table>

Monte Carlo Simulation for 100 samples - for a gain + latch circuit with 7 TFTs

Printed vs photolithographic OTFTs

Similar level of variations: main source of variation is semiconductor, less impact from channel W/L

Modify channel surface to adjust $V_T$

- Important to control threshold voltage $V_T$
- Back-channel interface affects $V_T$: electronic dipole, film morphology, etc.

\[
V_{inv} = \frac{V_{DD} + V_T^p + V_T^n \sqrt{\beta^n / \beta^p}}{1 + \sqrt{\beta^n / \beta^p}}, \quad \beta = \frac{W}{L} \mu
\]
Material structures that reduce disorder

Polymers:
Reduce tail states by rigid backbone that reduces torsion

Small molecules:
Suppressing thermal disorder by side chain location

McCoullouch, et al.

J. Anthony, Sirringhaus, et al.
_Nature Communications_ **7**, 10736 (2016)
Reduced variations in printed OTFTs

Uniformity can be improved in both polymer and small molecules

1σ = 40%
Mobility = 0.12 cm²/Vs

1σ = 8-10%
Mobility = 0.6 cm²/Vs

1σ = 12%
Mobility = 0.7 cm²/Vs
From materials to circuit fabrication

Develop ink & devices → Build device models

Design, simulate circuits

Print and test

Other examples of printed circuits

Shift register


Voltage multiplier

Flexible Printed Electronics (2016) 1, 015002.

Temperature dose tag

Desirable to digitize signal near sensor

Amplitude signal prone to attenuation error; frequency signal more reliable

Need to add digitizing circuit near sensor

Attenuation affects amplitude measurement

Same freq as before, will get same readout
Voltage-controlled oscillator

![Organic Oscillator Diagram]

![Graphs showing relationship between supply voltage Vdd and oscillation cycle time]

- 8Vdd: Oscillation cycle time decreases as supply voltage increases.
- 10Vdd: Similar trend observed.

Graphs illustrate the decrease in oscillation cycle time with an increase in supply voltage.
Using printed components to mimic skin mechanoreceptor

In collaboration with Zhenan Bao group
Need to augment spasticity diagnosis

Spasticity - involuntary activation of muscle, very common in patient with neurological disorders such as stroke, traumatic brain injury, cerebral palsy, etc. affect 764K in US; 17M world wide

<table>
<thead>
<tr>
<th>Score</th>
<th>Modified Ashworth Scale (MAS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No increase in muscle tone</td>
</tr>
<tr>
<td>1</td>
<td>Slight increase in muscle tone, with a catch and release at the end of the range of motion (ROM)</td>
</tr>
<tr>
<td>1+</td>
<td>Slight increase in muscle tone, followed by minimal resistance throughout the remainder of ROM</td>
</tr>
<tr>
<td>2</td>
<td>More marked increase in muscle tone through most of the ROM, but affected parts easily moved</td>
</tr>
<tr>
<td>3</td>
<td>Considerable increase in muscle tone, passive movement difficult</td>
</tr>
<tr>
<td>4</td>
<td>Affected part is rigid in both flexion and extension</td>
</tr>
</tbody>
</table>
Issue with reliability in MAS ratings

- 5 patients and 12 tasks: each doctor gave 60 MAS ratings
- Only 27% of the ratings were the same; poor inter-rating reliability, yet dosage is based on this rating

Two doctors’ MAS ratings on the same patients

In collaboration with Dr. Garudadri (Calit2) and Dr. Skalsky at UCSD School of Medicine
Prototype glove to quantify spasticity

Glove worn by the doctor during assessment:
- measure force (printed pressure sensor by Tekscan) and angular velocity (gyroscope)
- Power to move a limb $P = F \cdot v$
Mock patient to calibrate sensor glove

- Calibrate sensor glove with a mock patient with changeable resistance (2-20kg)
  - Load cell to measure force
  - Potentiometer to measure angular velocity
  - The power $P = F \cdot v$ to move the mock limb is recorded
Better resolution than MAS scale

- Quantitative glove measurement allows comparison between rating trials, less dependence on rater perception
- Glove sensor improves the resolution of the spasticity assessment

In press, IEEE-NIH 2016 HI-POCT Proceeding
Summary

• Apply additive printing to demonstrate organic TFT circuits
  1. increase tolerance to device variation issues
  2. integrated local digitizing circuits near sensors

• Example application of printed pressure sensor to achieve quantitative assessment in spasticity diagnosis
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