3d-printed autonomous sensory composites (unpublished)

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Golden tortoise beetle

Self-sustaining, mobile, autonomous
Golden tortoise beetle

Sense $\rightarrow$ Process $\rightarrow$ Respond

dense + freeform 3D integration

Credit: Ken Sproule

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3d-printed autonomous sensory composites (unpublished)
Signal pathway

- Strain sensor
- Amplifier
- Electrochromic element
Example

B. Tee et al., A skin-inspired organic digital mechanoreceptor, Science, 2015

Subramanian Sundaram 3d-printed autonomous sensory composites (unpublished)
1 Natural biological systems

2 Multimaterial additive manufacturing
   - 3d printer
   - UV curable materials
   - Thin films
   - Liquid encapsulation

3 Autonomous sensory composites
   - Schematic
   - Strain sensors
   - Transistors
   - Electrochromic pixel
   - Integration of elements

4 Summary
Drop-on-demand 3d printer

Inkjet printheads, 10 materials, 1080 nozzles

35 $\mu$m lateral resolution, 17 $\mu$m vertical resolution
Filling the voxels

- Array of bitmaps - voxelization
- Control of droplet order
- Multiple materials
- Processing details: UV curing, Heating

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3d-printed autonomous sensory composites (unpublished)
Materials: UV curable polymers

- Acrylic polymer inks: monomer, crosslinker, photoinitiator (365 nm), inhibitor
- Mechanical properties: rigid (637.76 MPa), elastic (678.5 kPa)
- Surface energy: high (45.23 mJ/m²), low (28.65 mJ/m²)
Functional thinfilms

- Inks: PEDOT:PSS, reactive Ag ink
- Heating passes remove solvent
- Surface energy - droplet control

PEDOT:PSS ink/elastic polymer

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Measured contact angle ((\theta)), [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deionized water</td>
</tr>
<tr>
<td>Rigid polymer</td>
<td>60.10 ± 4.54</td>
</tr>
<tr>
<td>Elastic polymer</td>
<td>100.82 ± 1.93</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Probe liquid</th>
<th>Surface energy and components (known), [mJ/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\gamma^L_{LW})</td>
</tr>
<tr>
<td>Diiodomethane</td>
<td>50.8</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>29</td>
</tr>
<tr>
<td>DI Water</td>
<td>21.8</td>
</tr>
</tbody>
</table>

Young equation: \(1 + \cos(\theta)\) \(\gamma^L_{\text{tot}} = 2(\sqrt{\gamma^L_{LW}}\gamma^L_{LW} + \sqrt{\gamma^L_{\ast}}\gamma^L_{\ast} + \sqrt{\gamma^L_{-}}\gamma^L_{-})\)

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Calculated surface energy, [mJ/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\gamma^L_{LW})</td>
</tr>
<tr>
<td>Rigid polymer</td>
<td>41.89</td>
</tr>
<tr>
<td>Elastic polymer</td>
<td>28.33</td>
</tr>
</tbody>
</table>
Liquid encapsulation

- Liquid ink dispensed into polymer wells
- Polymer ink without photoinitiator/solvent based ink
- Sealed by UV curable polymer cap
- Water-glycerol mixture: 4 weeks
Schematic: signal pathway

Strain sensor → Amplifier → Electrochromic element

Strain sensor

$V_1 = 1.5\text{V}$

Common-source amplifier

$M_1$

Electrochromic pixel

$V_2 = -1.5\text{V}$

$V_1 = 1.5\text{V}$

$V_2$

$M_2$

$P_1$

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**Strain sensors**

- Stretchable conductor
- Rigid contacts/elastic matrix
- High $\Delta R/R$

![Diagram of strain sensors](image)

![Graph showing resistance vs. strain](image)

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**Summary**

- Natural biological systems
- Multimaterial additive manufacturing
- Autonomous sensory composites

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**$p$-type depletion mode transistor**

- PEDOT:PSS channel, 0.1M KCl (Water) + glycerol gate
- $L = 1500 \mu m$, $W = 500 \mu m$
- on/off ratio - $9.65 \times 10^3$, transconductance ($g_m$) - 5.61 mS
- Electrochemical switching
  
  $$PEDOT^+PSS^- + M^+ + e^- \leftrightarrow PEDOT^0 + PSS^-M^+$$
$p$-type depletion mode transistor

- Subthreshold swing - 150 $mV/\text{dec}$
- Switching time - 200 $ms$
Diode connected load & amplifiers

Transistor - W/L
W = 500 µm
L = 1500 µm

Diode connected transistor - W/2L

Gain

Input voltage (V)

Output voltage (V)

Gain

Input voltage (V)

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Ag NPs exposed to halide environment - large leakage, slow response
- off-on time is slower (diffusion) - minimizing passive channel length helps¹
- $K^+$ ions worked best here in contrast to ref.²

²D. Khodagholy et al., High transconductance organic electrochemical...
Electrochromic pixel

- PEDOT shows optical contrast - oxidized (transparent), reduced (opaque)
- Low voltage, power
- Response time (~100 ms) and contrast - control electrode area

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Multimaterial additive manufacturing
Autonomous sensory composites
Integration of elements

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Summary

Schematic
Strain sensors
Transistors
Electrochromic pixel
Integration of elements

Strain sensor
Common-source amplifier
Electrochromic Pixel

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3d-printed autonomous sensory composites (unpublished)
Integrating the parts

±1.5V power supply
Summary

- Fully 3d-printed autonomous low-voltage composite
- Tunable surface energy
- Low temperature stretchable conductor and freeform transistors
- Solids, thin-films and encapsulated liquids - mechanical, electrical and optical properties

Biocompatible matrices & programmable lifetimes