Transient Electronics

1) Motivation, Perspective
2) Materials, Device Designs, Manufacturing
3) Ecoresorbable RFID, Electronic Medicines

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SQI and Center for Biointegrated Electronics
The Dominant Future for Electronics: Smaller, Faster, Cheaper

Past  Present  Future

Industrial  Personal

Smaller, Faster Cheaper
An Alternative Future for Electronics: Bio / Eco Resorbable, Transient

Past | Present | Future
---|---|---
Industrial | Personal | Bio / Eco Resorbable

Science 337, 1640 (2012).
Definition – Transient Electronics

*Transient Electronics* – electronic systems that dissolve, resorb or otherwise physically disappear at programmed rates or at triggered times

Transient Electronics – Application Opportunities

1) Zero/Reduced E-Waste Consumer Electronics
2) Temporary Therapeutic / Diagnostic Implants
3) Resorbable Environmental Monitors / Sensors
4) Hardware Secure (non-recoverable) Electronics
5) Hardware Reconfigurable Electronics
Candidate Semiconductors for Transient Electronics

- **Carbon nanotubes:**
  - High mobility
  - ‘Robust’
  - High temp. growth, electr. heterogeneity

- **Polymers:**
  - Solution processing
  - Low performance

- **Small molecules:**
  - Performance similar to a-Si
  - Vacuum dep.

- **Single crystals:**
  - Study of intrinsic charge transport
  - Fragile, challenging integration

- **Carbon nanotubes:**
  - High mobility, ‘robust’
  - High temp. growth, electr. heterogeneity

- **Graphene:**
  - High mobility
  - High temp. growth
  - Semi-metallic
Dissolution of Si Nanomembranes at Phys. pH, Temp.

\[
\text{Si} + 4 \text{H}_2\text{O} \rightarrow \text{Si(OH)}_4 + 2 \text{H}_2
\]

Silicon Can Dissolve by Hydrolysis

Si for Transient Electronics:
- Si thickness: 35 nm (ultrathin, top SOI)
- dissolution time: 10 days
- req’d volume of water: 0.4 mL (~1 cm²)

Si for Conventional Electronics:
- Si thickness: 700 μm (bulk wafer)
- dissolution time: 600 years
- req’d volume of water: 8 L (~1 cm²)
## Current Portfolio of Transient Electronic Materials

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<tr>
<td>ZnO</td>
<td>SiO$_x$</td>
<td>Mg</td>
<td>silk</td>
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<tr>
<td>IGZO</td>
<td>SiN$_x$</td>
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<td>PLGA</td>
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<td>poly-Si</td>
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<td>metal foils</td>
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Transient Si MOSFETS and Logic Gates

\[ \mu \sim 400 \text{ cm}^2/\text{Vs} \]
\[ \text{on/off} \sim 10^6 \]

\[ V_{IN}, V_{OUT}, V_{GND} \]

\[ V_{IN} \]

\[ V_{DD} \]

\[ V_{GND} \]

\[ V_{OUT} \]

\[ \text{Gain} \]

\[ \text{Science 337, 1640 (2012)} \]
Transient Electronics – Test Platform

Si, SiO$_2$, Mg, MgO and silk

Science 337, 1640 (2012).
Science 337, 1640 (2012).
Transient Electronics

Mg ~100 µg, Si ~ 3 µg

Rec. Daily Intake

Mg ~300 mg, Si ~10 mg
Transient, Water-Activated Mg Primary Battery

Discharge current density: 0.1 mA/cm²

Dissolution in Water

Adv Mater (2014)
Transient Battery Power for Radios, LEDs

Adv Mater (2014)
Transient Electronics from a 90 nm CMOS Foundry

Transient SOI CMOS from a Commercial Foundry (X-Fab Intl)

PNAS 114, E5522 (2017).
Rapid, Precise Materials/Device Assembly via Printing

1) Form undercut microdevices, anchored at endpoints
2) Transfer them to a target substrate by printing
3) Interconnect to form systems

Semiconductor Device ‘Printer’
Processing and Printing of AlInGaP μ-ILEDs

AllInGaP μ-ILEDs Printed Onto Plastic (1600; 100% yield)

Science 325, 977 (2009)
Production Scale Transfer Printers
Transient SOI Electronics on Flexible PLGA Substrates

*PNAS 114, E5522 (2017).*
Dissolution / Disintegration of Transient CMOS

Complete dissolution ~20 days: everything except BOX is eliminated in 6 days.

In Vivo Bioresorption of an Array of Transient Devices

- Full dissolution in 45 days.
- No abnormalities or adverse effects.
Printable Transient Conductors: W in Wax for RFID Tags

Intracranial Monitors for TBI

Current

- Non-degradable → Secondary surgery
- Wired operation → Restricted movement
- External interface → Infection / hemorrhage

Future

- Bioresorbable → Eliminate extraction
- Wireless operation → Free movement
- Fully sutured → Safe, minimal risk

http://violetsjourney.blogspot.com/2012/02/icp-monitoring.html
Bioresorbable Intracranial Pressure Sensors for TBI

**In-vivo Wireless Monitoring – Pressure and Temperature**

*In-vivo Results Using A Rat Model*

*Nature 530, 71 (2016).*
Electronic Medicines – Active Project Areas

**Programmable Drug Release** -- therapeutic

**Pacemakers** – recovery

**Intracranial monitors** -- recovery

**Nerve Stimulators** – accelerated healing

**Bone Stimulators** – accelerated healing

**Thermal Therapy** – anti-bacterial
Senior Collaborators

**Engineering Science**
- Prof. Y. Huang (NU) – mechanics
- Prof. P. Ferreira (UIUC) – manuf.

**Clinical Medicine**
- Prof. I. Efimov (GWU) – cardiac
- Prof. R. Murphy (WU) -- TBI
- Prof. Z. Ray (WU) – neuroregen
- Prof. M. MacEwan (WU) -- regen