Transient Electronics

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

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Louis Simpson and Kimberly Querrey Professor

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

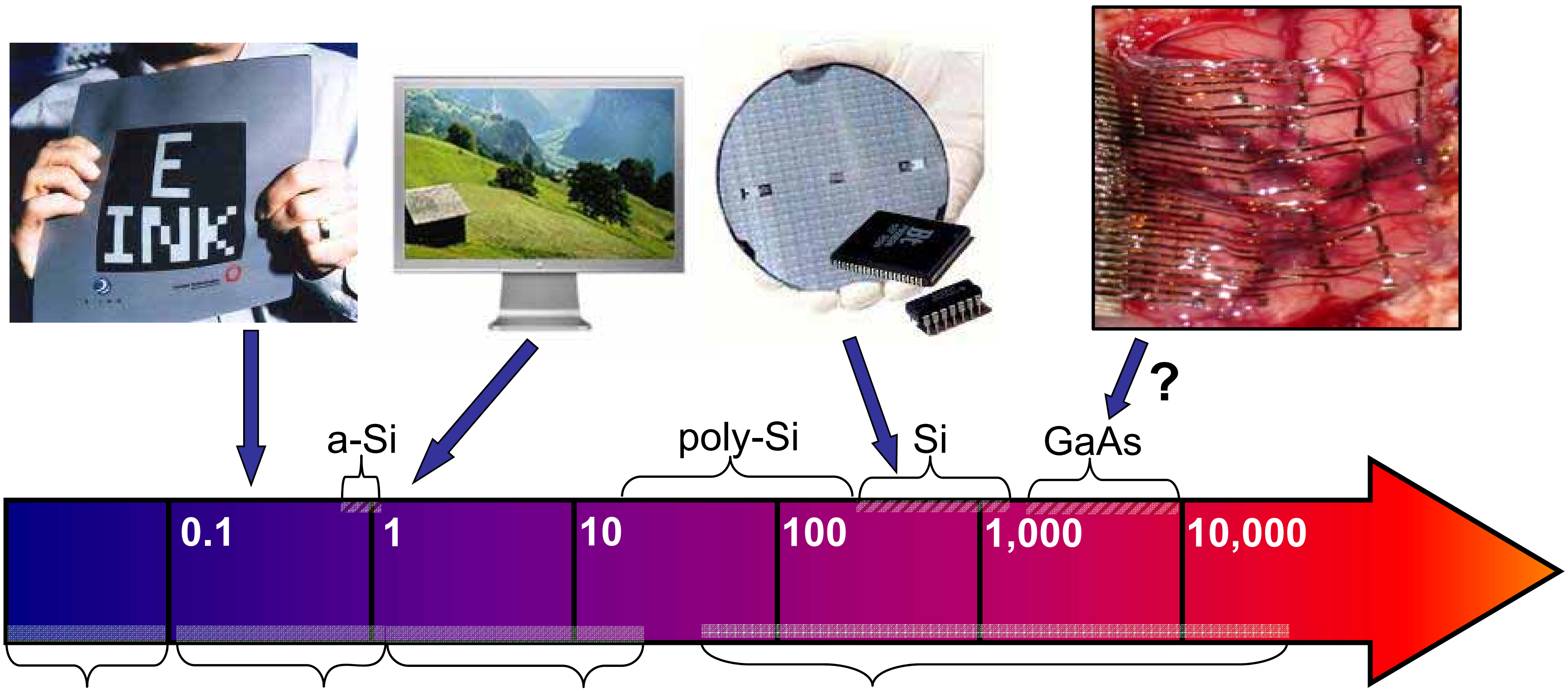
Transient Electronics – electronic systems that dissolve, resorb or otherwise physically disappear at programmed rates or at triggered times

Science **337**, 1640 (2012).

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



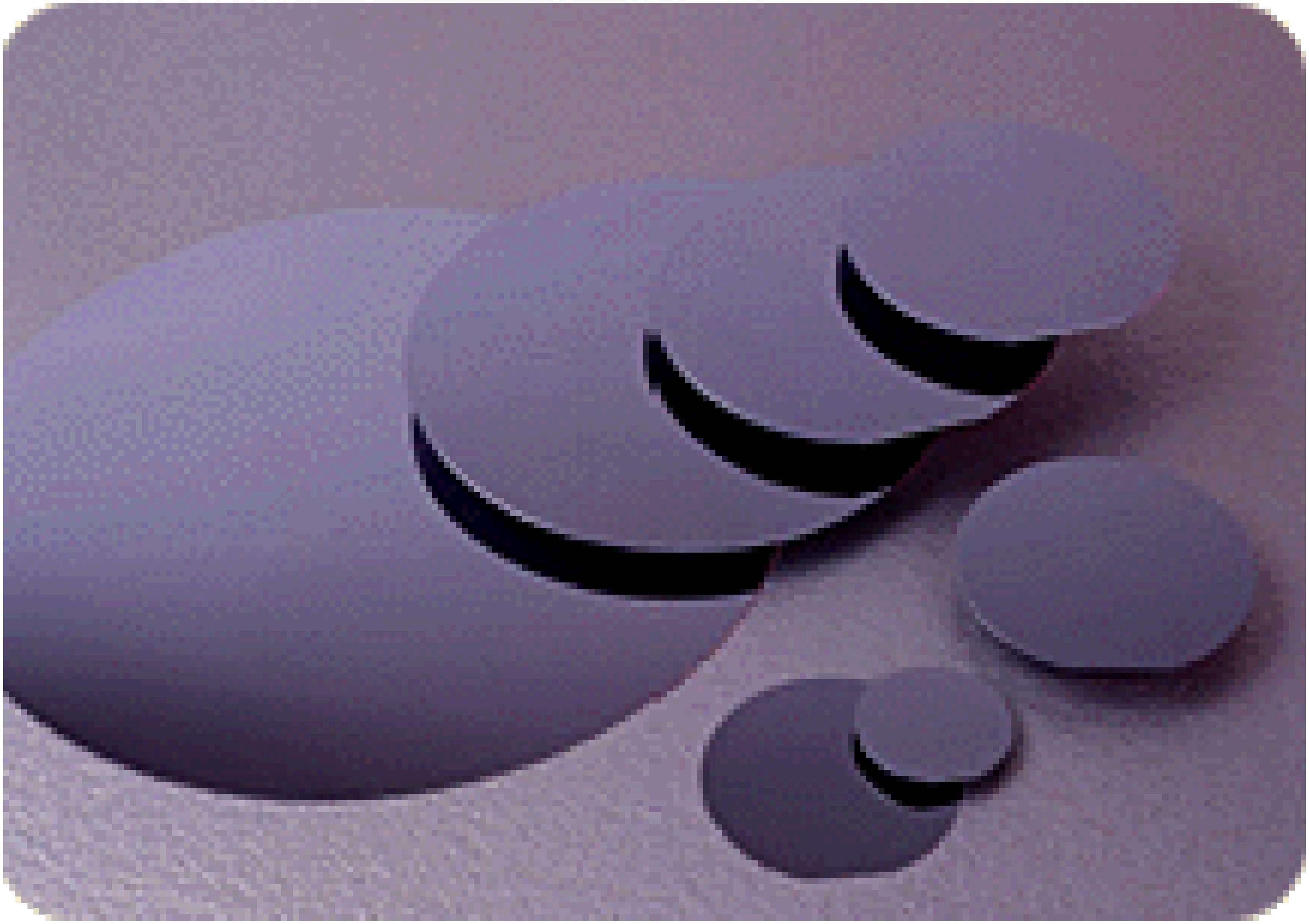
Polymers:
Solution processing
Low performance

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

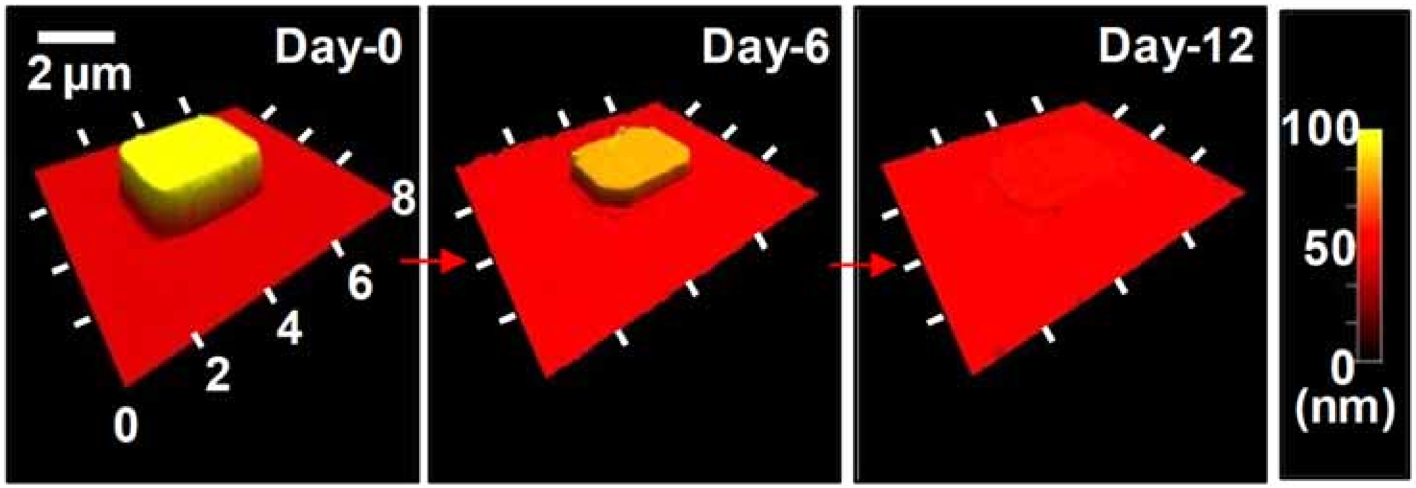
Single crystals:
Study of intrinsic charge transport
Fragile, challenging integration

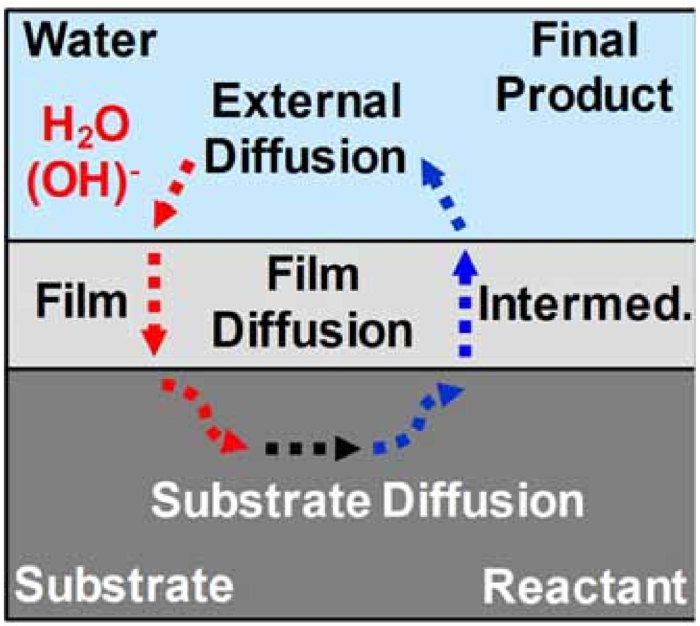
Carbon nanotubes:
High mobility, ‘robust’
High temp. growth, electr. heterogeneity

graphene:
High mobility
High temp. growth
Semi-metallic

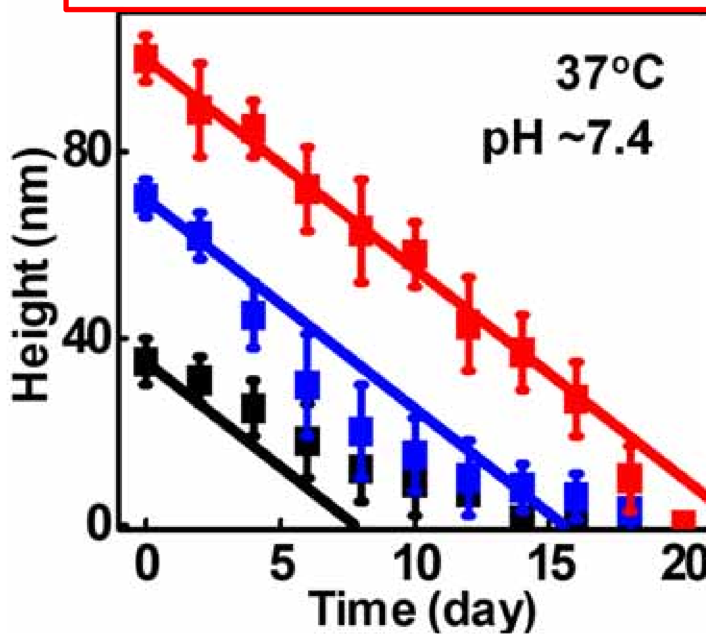


Dissolution of Si Nanomembranes at Phys. pH, Temp.





$Si + 4\ H_2O \rightarrow Si(OH)_4 + 2\ H_2$



Science **337**, 1640 (2012).

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 cm^2)

Si for Conventional Electronics:

Si thickness: 700 μm (bulk wafer)

dissolution time: *600 years*

req'd volume of water: 8 L (~1 cm^2)

Current Portfolio of Transient Electronic Materials

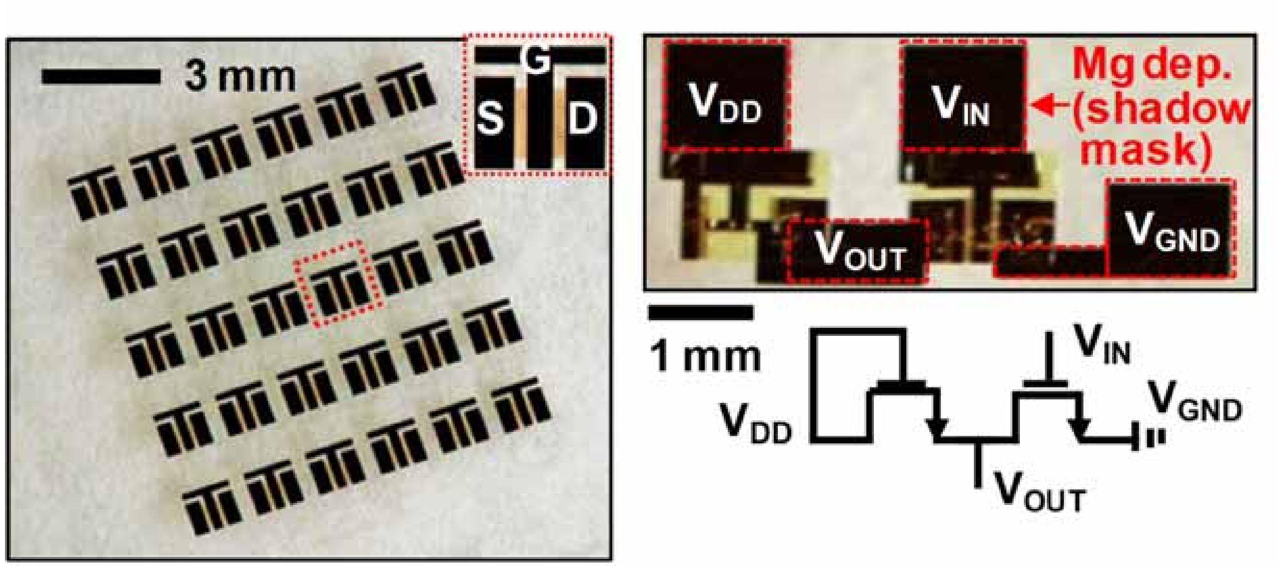
Semic.	Dielectr.	Interconn.	Substr.
ZnO	SiO_x	Mg	silk
IGZO	SiN_x	Zn	PLGA
poly-Si	MgO	W	PLA
a-Si	SOG	Mo	PCL
np-Si		Fe	POC
Ge		pastes	collagen
SiGe			polyanhydride
			metal foils

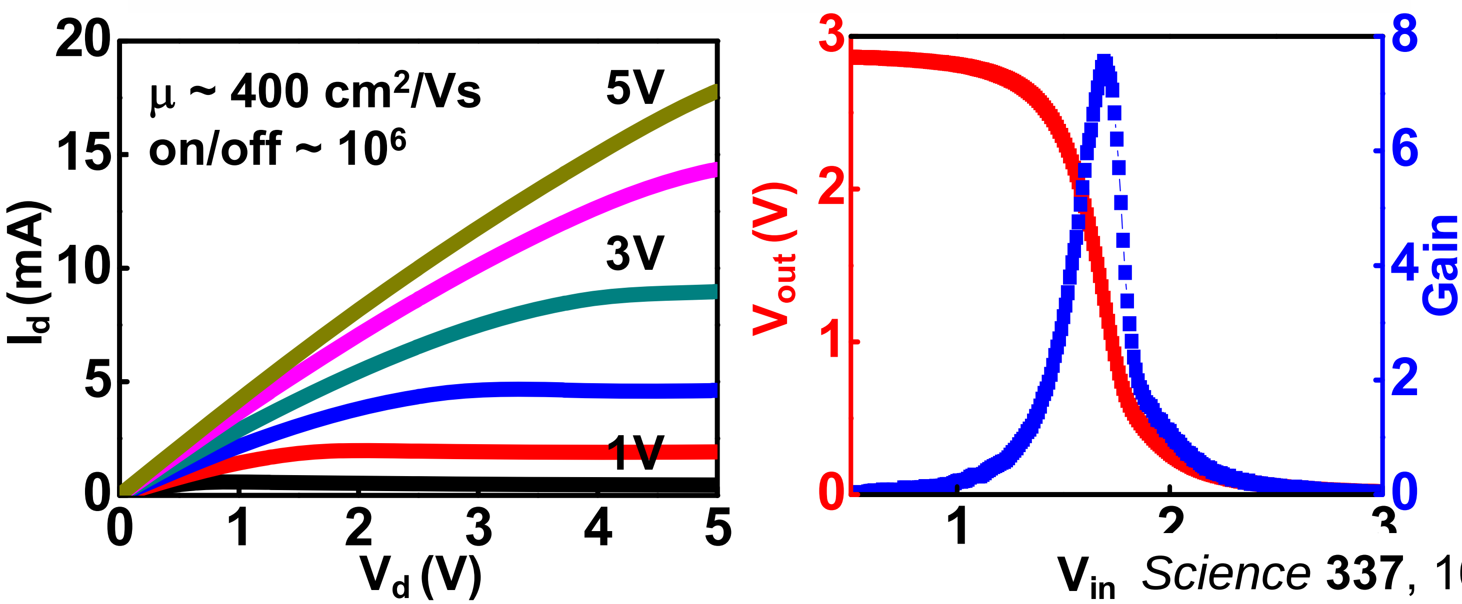
Adv. Mater. **26**, 7637 (2014).
Adv. Mater. **26**, 7371 (2014).
Adv. Mater. **26**, 3905 (2014).
ACS Nano **8**, 5843 (2014).
APL **105**, 013506 (2014)
Adv. Func. Mater. **24**, 4427 (2014).
Adv. Health. Mater. **3**, 515 (2014).
Small **9**, 3398 (2013).
Adv. Mater. **26**, 3905 (2014).
Adv. Func. Mater. **24**, 645 (2014).
Adv. Func. Mater. **23**, 4087 (2013).
Adv. Mater. **25**, 3526 (2013).

Simpson Querrey Institute BioNanotechnology

Northwestern

Transient Si MOSFETS and Logic Gates

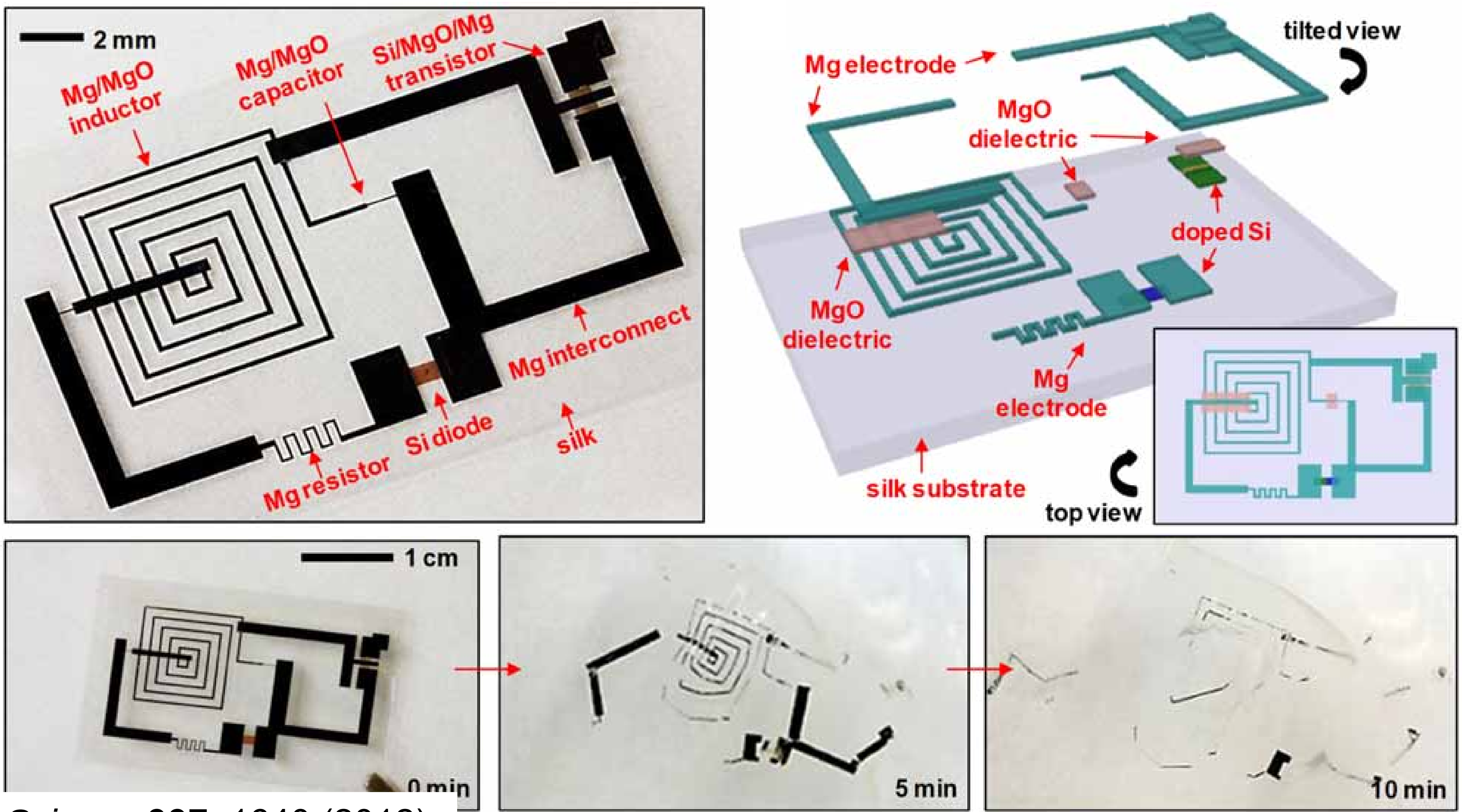




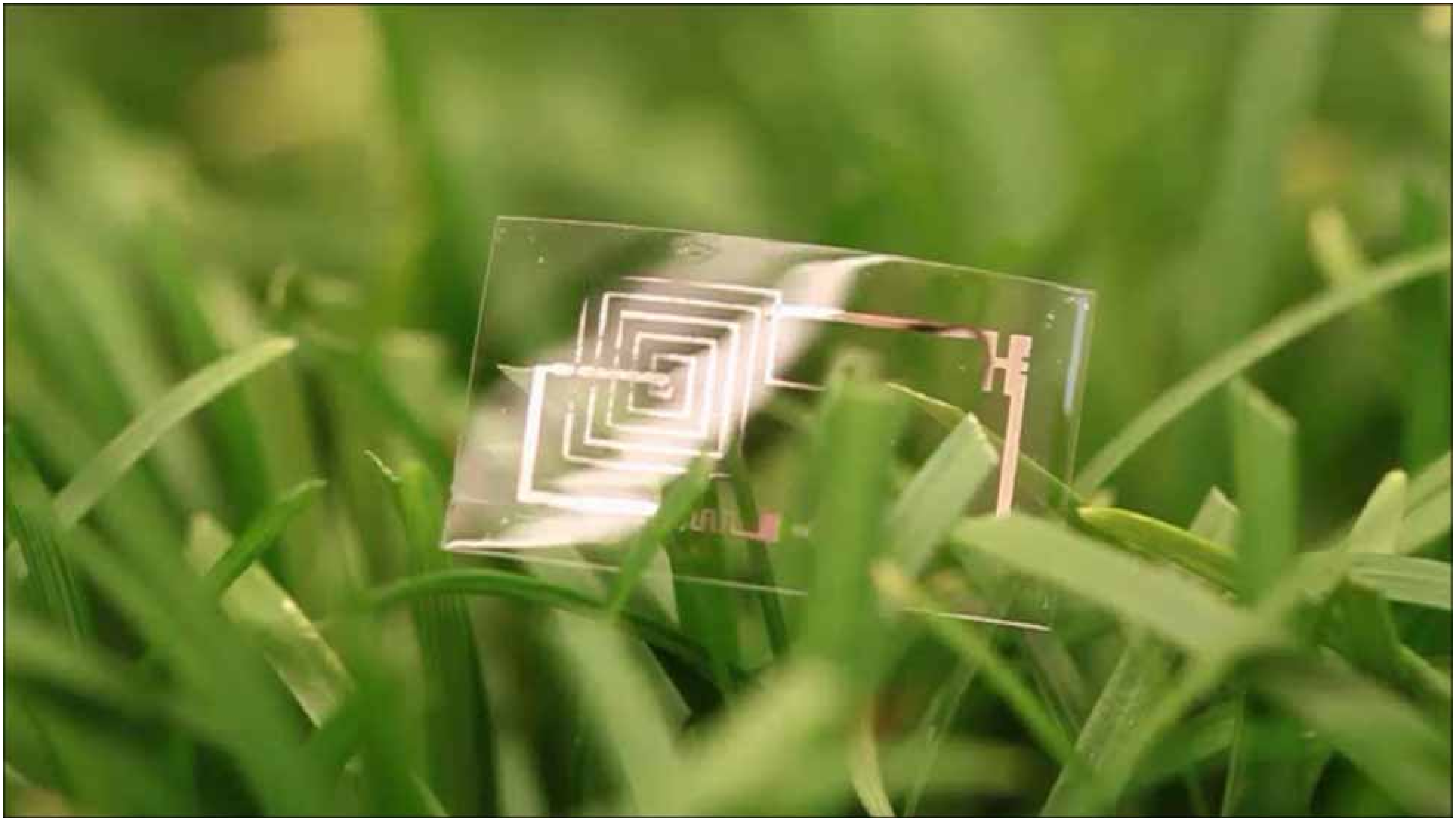
Science **337**, 1640 (2012).

Transient Electronics – Test Platform

Si, SiO_2, Mg, MgO and silk



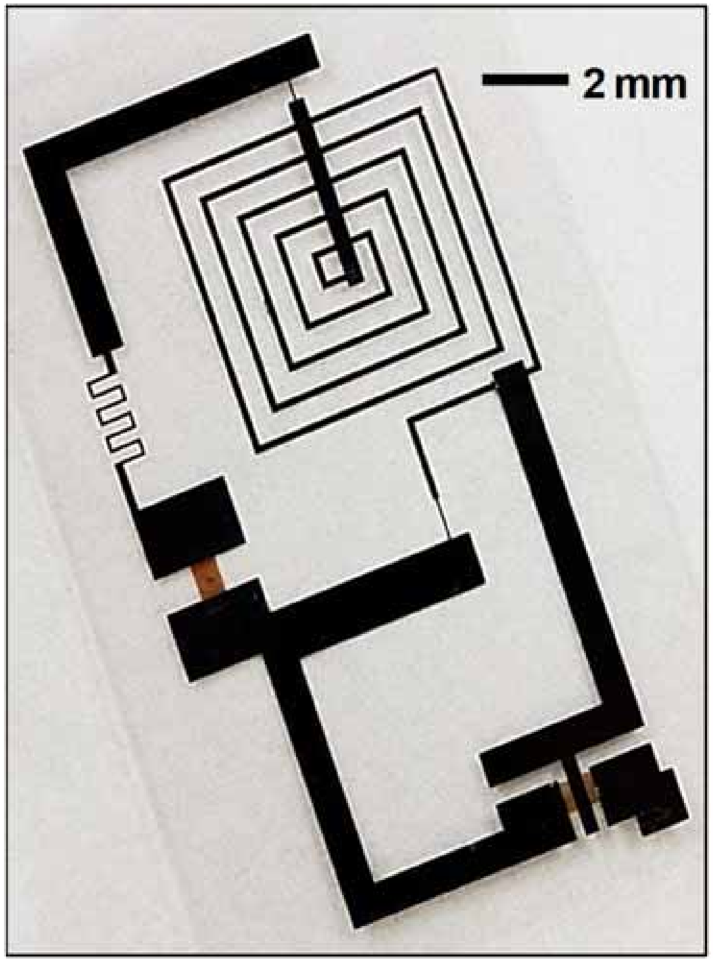
Science **337**, 1640 (2012).



Science **337**, 1640 (2012).

Perspective on Elemental Content

Transient Electronics

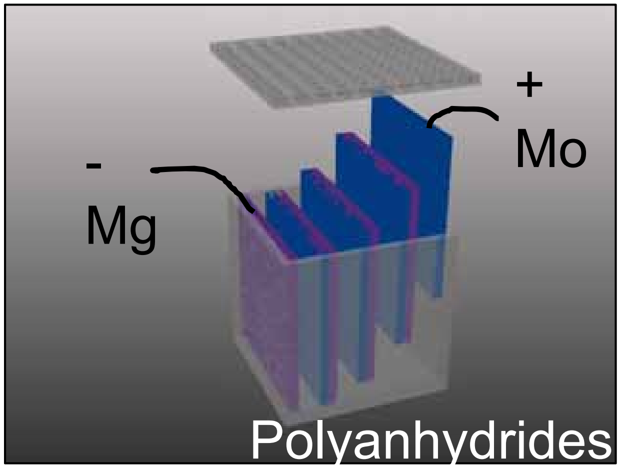


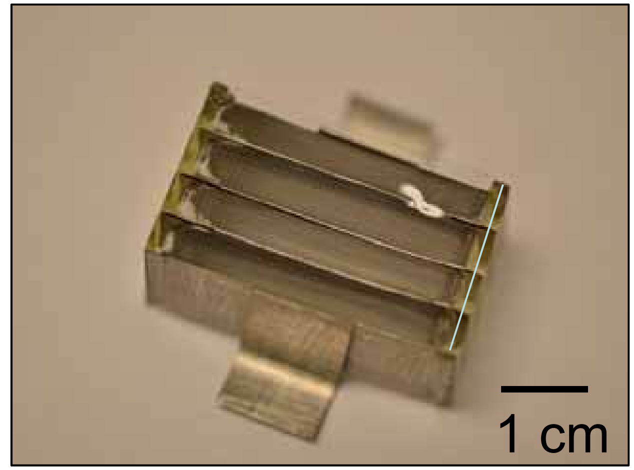
Mg ~100 µg, Si ~ 3 µg

Rec. Daily Intake

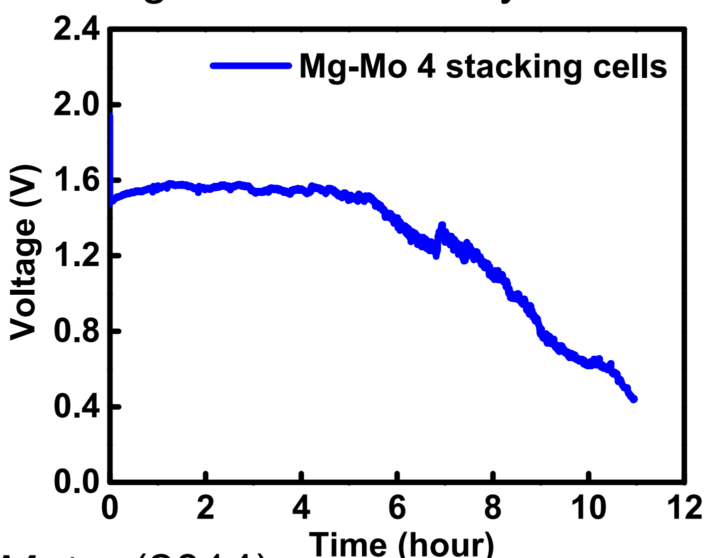
Mg ~300 mg, Si ~10 mg

Transient, Water-Activated Mg Primary Battery

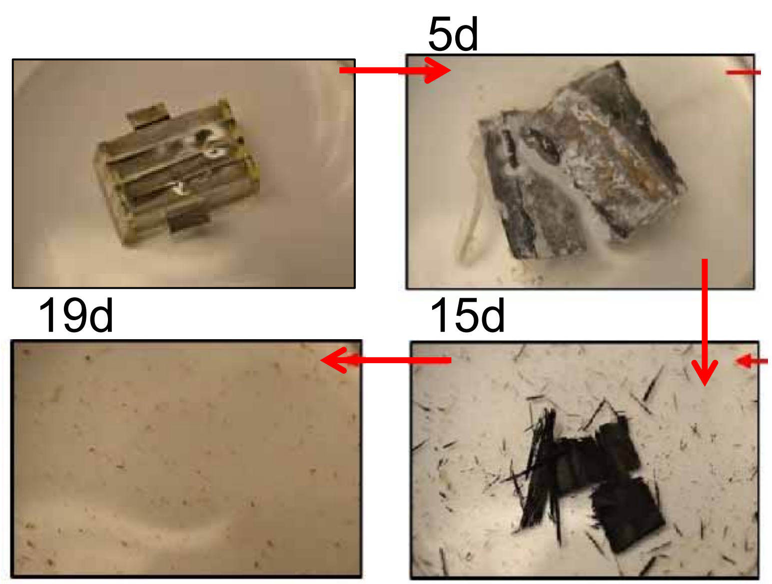




Discharge current density: 0.1 mA/cm^2

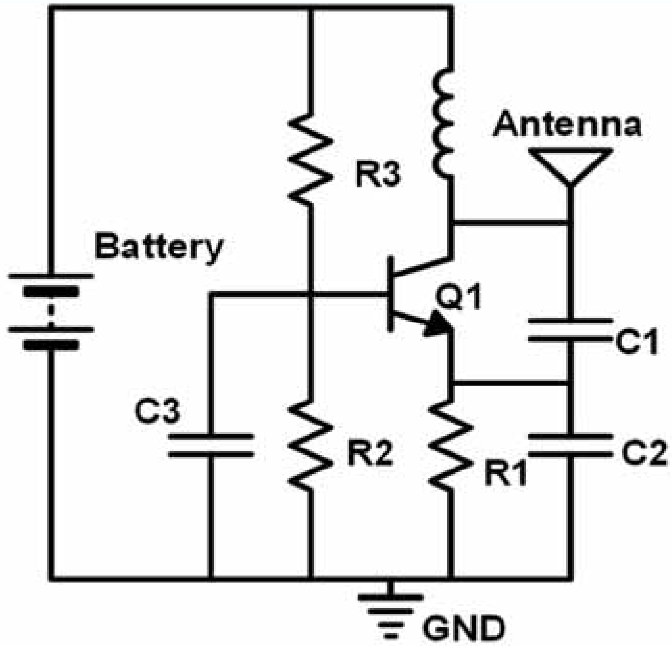


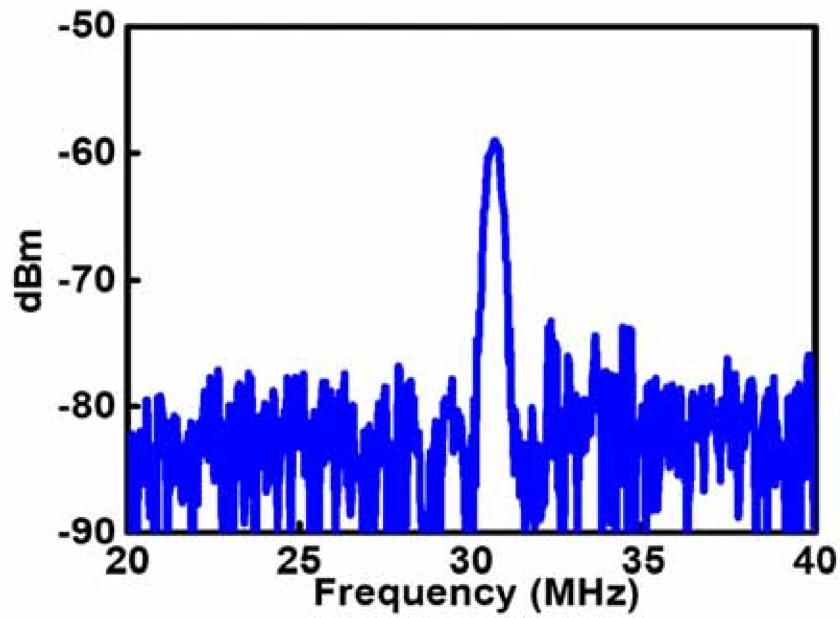
Dissolution in Water

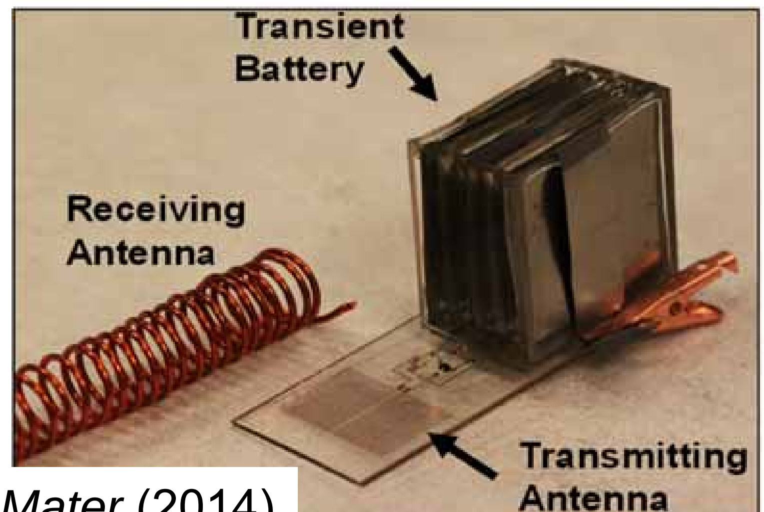


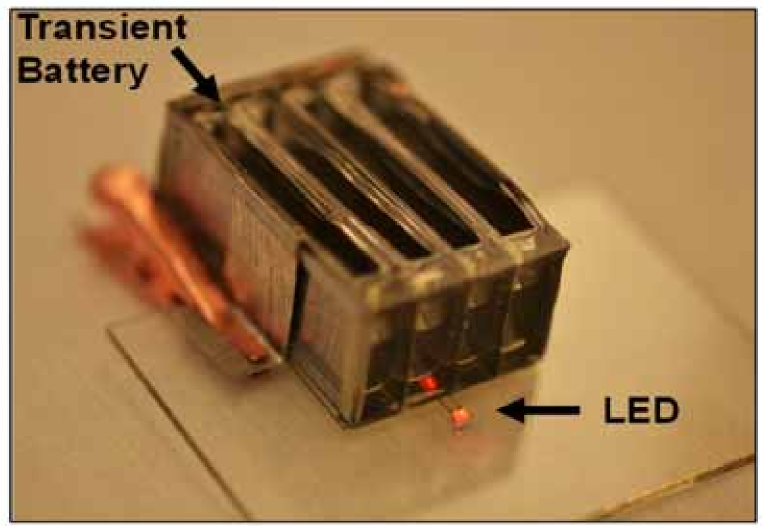
Adv Mater (2014)

Transient Battery Power for Radios, LEDs



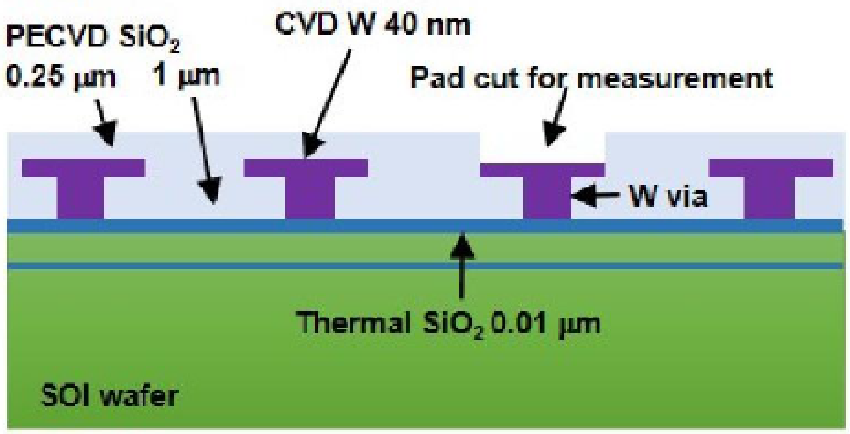


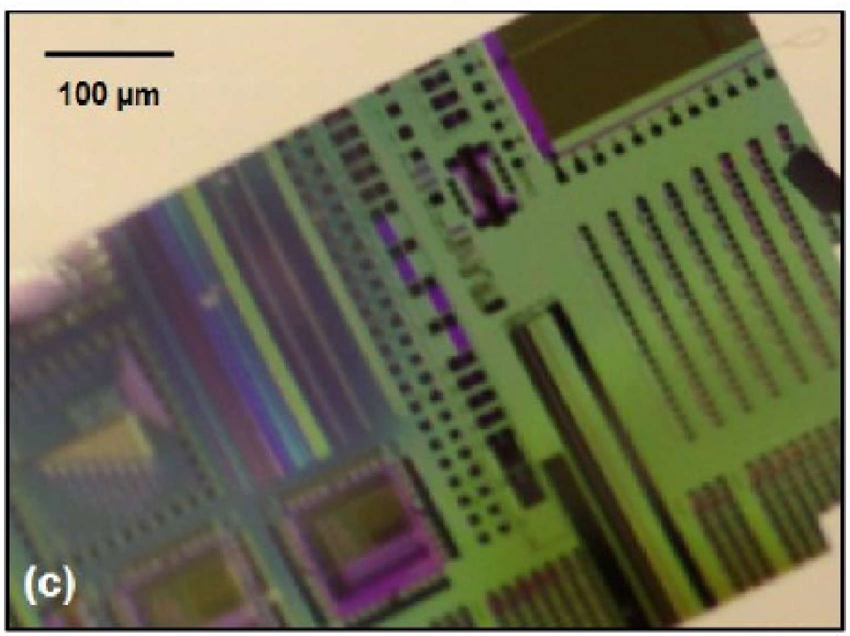


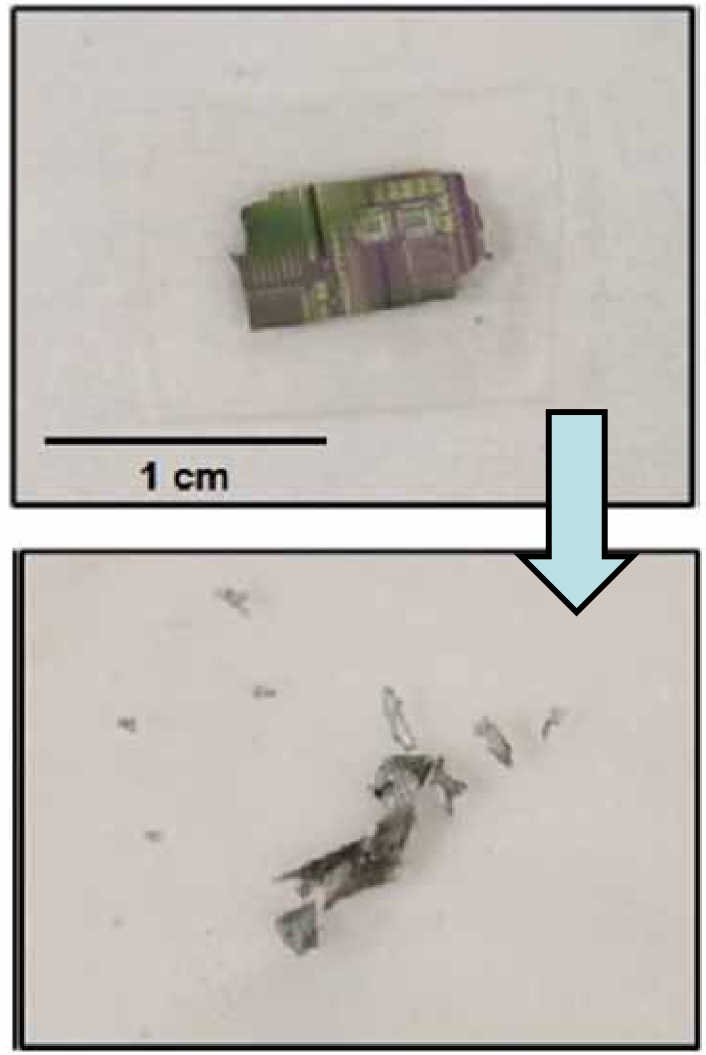


Adv Mater (2014)

Transient Electronics from a 90 nm CMOS Foundry

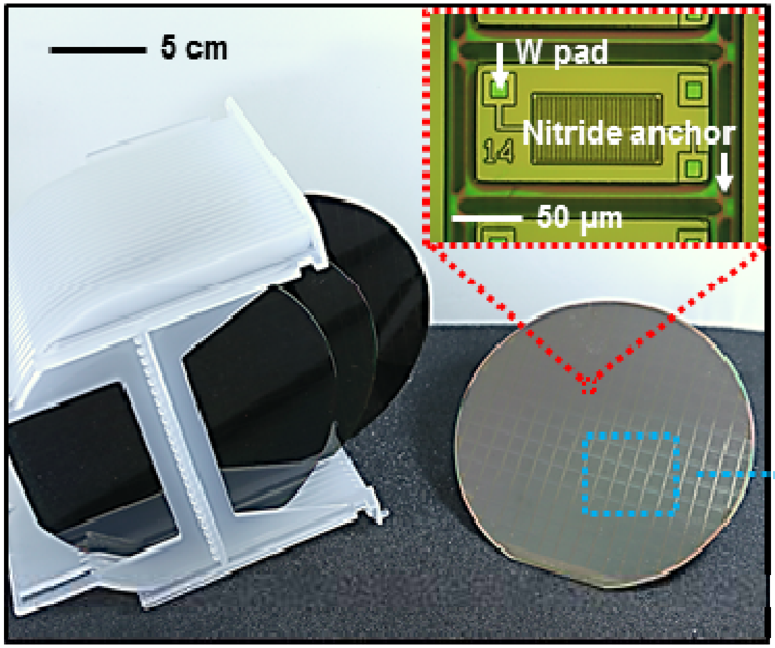


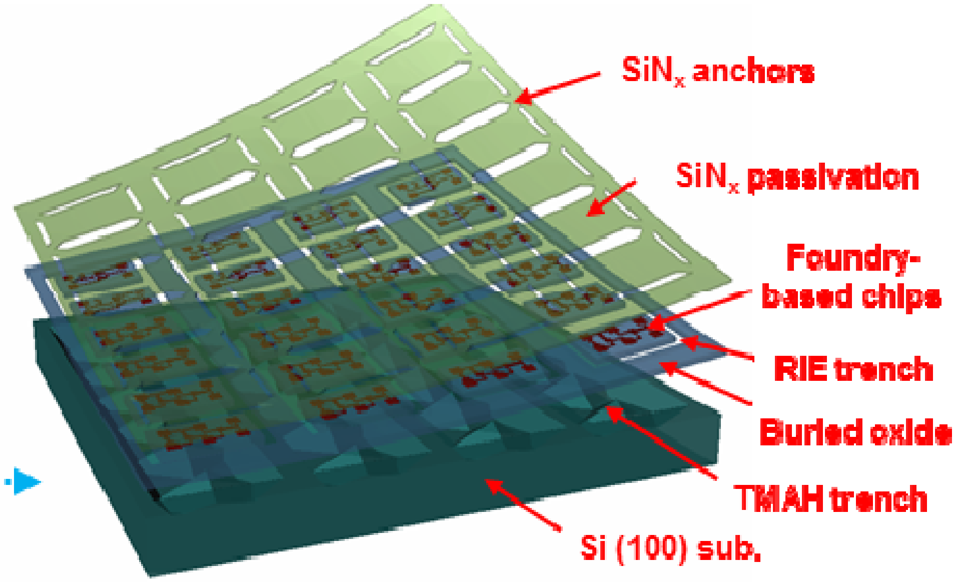




Appl. Phys. Lett **106**, 014105 (2015).

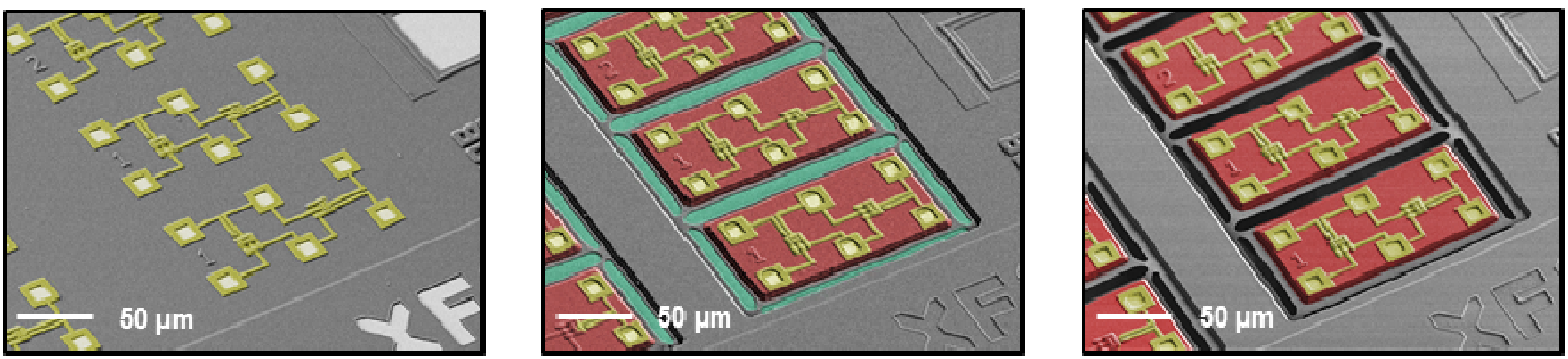
Transient SOI CMOS from a Commerical Foundry (X-Fab Intl)





Foundry-based devices on Si (100) wafer after TMAH etching

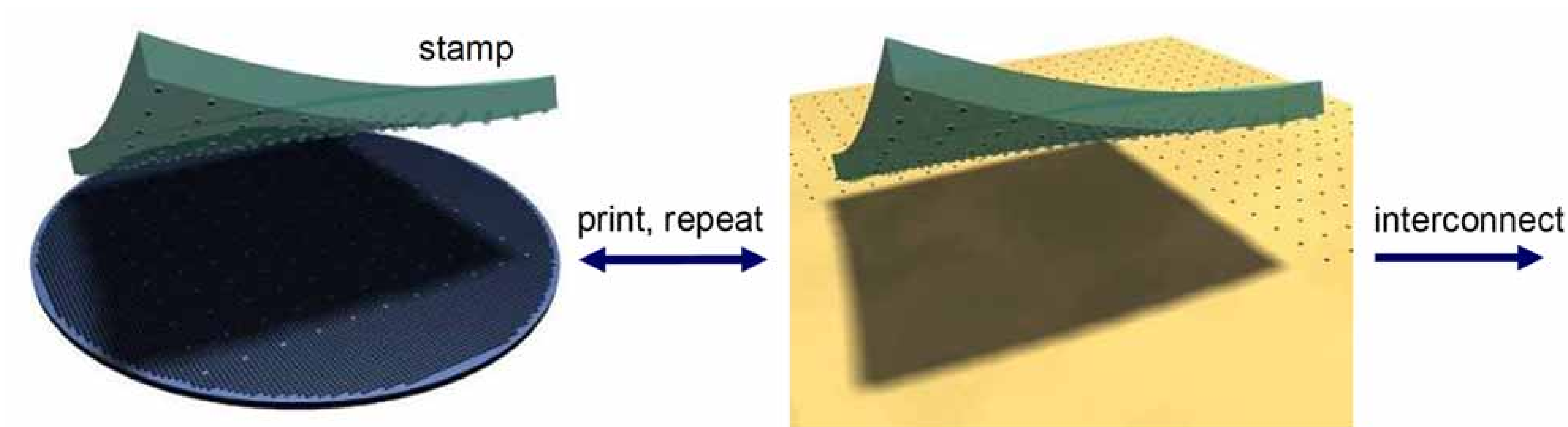
PNAS **114**, E5522 (2017).



Device array on Si (100) wafer → Nitride passivation & trench etch → TMAH undercut

Rapid, Precise Materials/Device Assembly via Printing

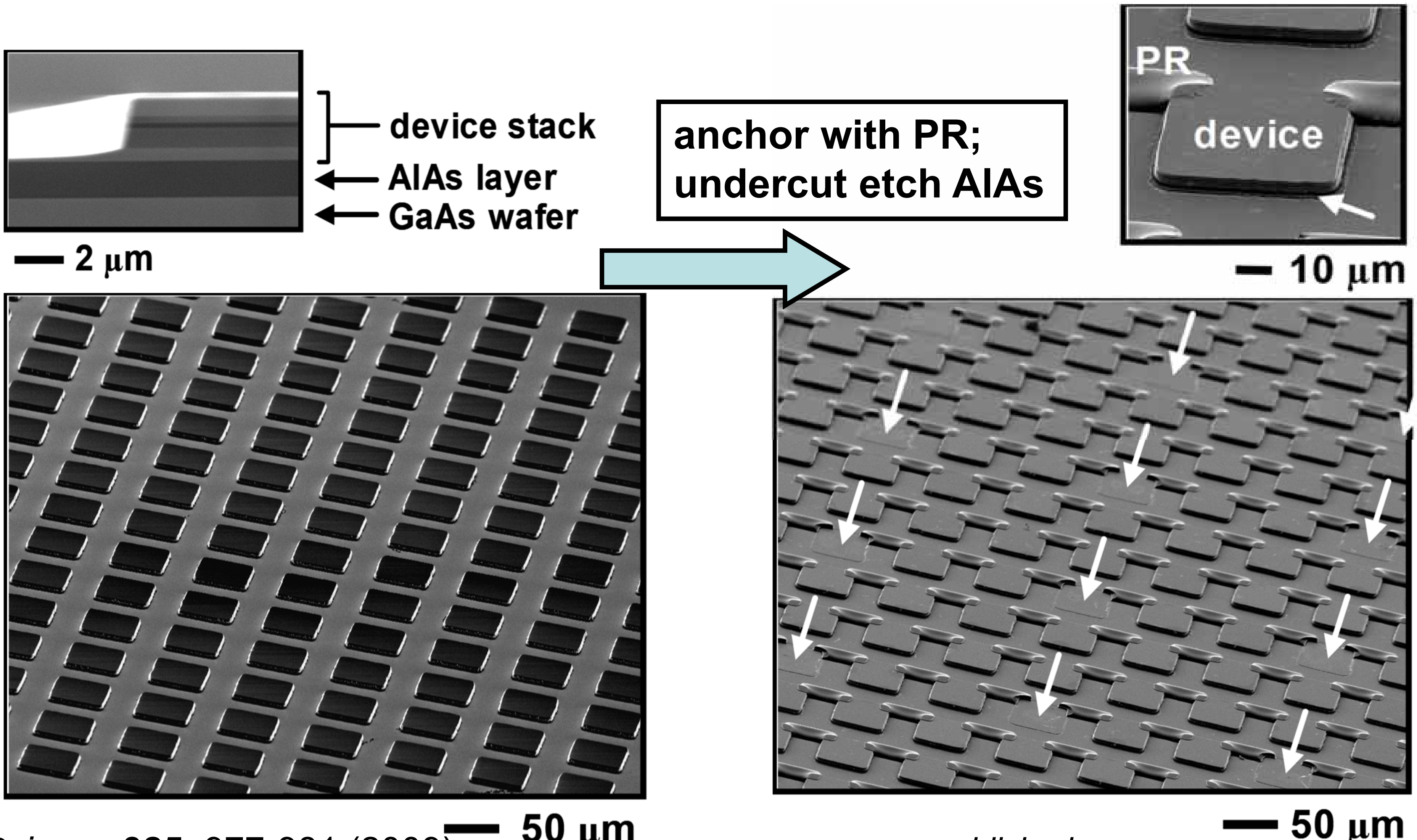
1) **Form undercut microdevices, anchored at endpoints**
2) **Transfer them to a target substrate by printing**
3) **Interconnect to form systems**



Nature Mater **5**, 33 (2006). *PNAS* **107**, 17095 (2010).

Semiconductor Device ‘Printer’

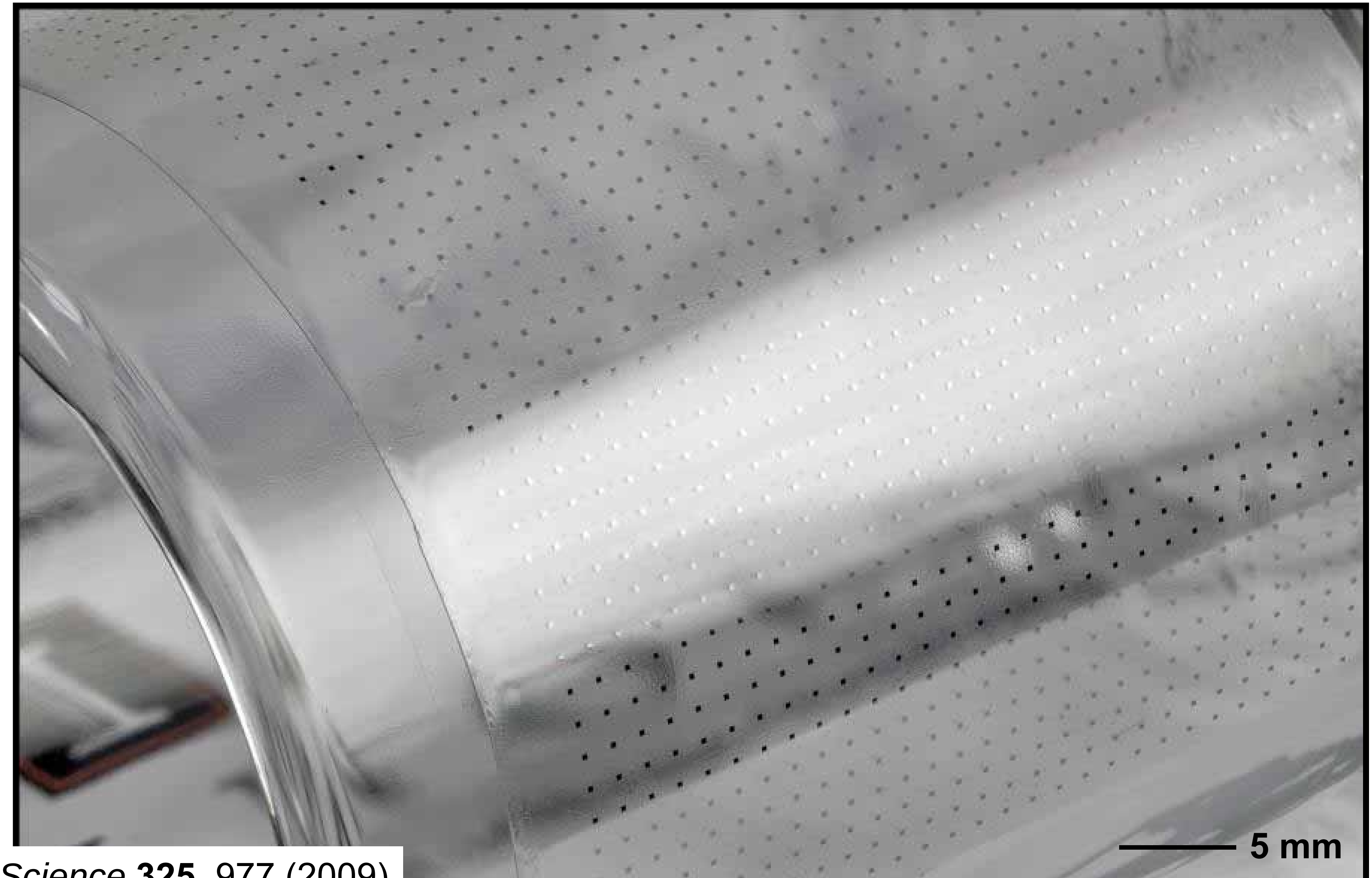
Processing and Printing of AlInGaP μ-ILEDs



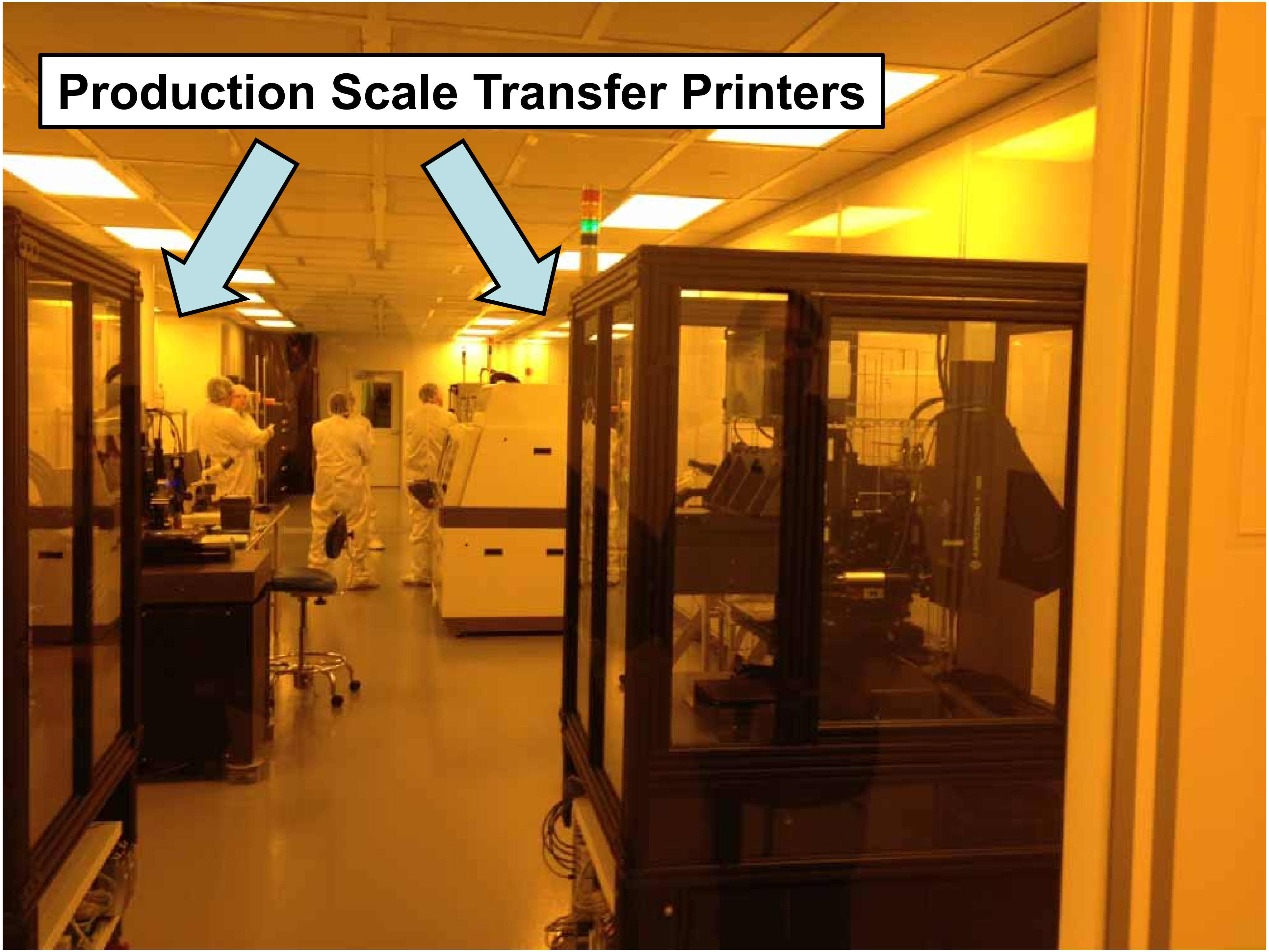
Science **325**, 977-981 (2009).

unpublished

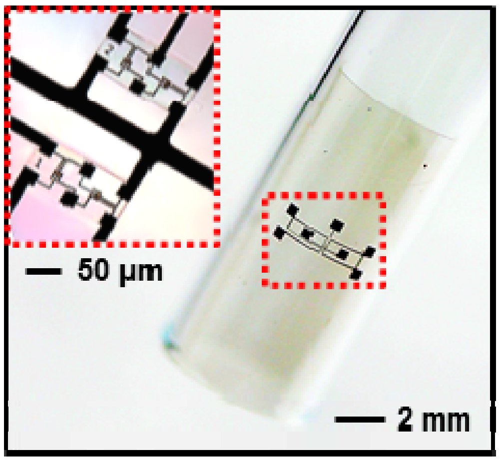
AlInGaP μ-ILEDs Printed Onto Plastic (1600; 100% yield)

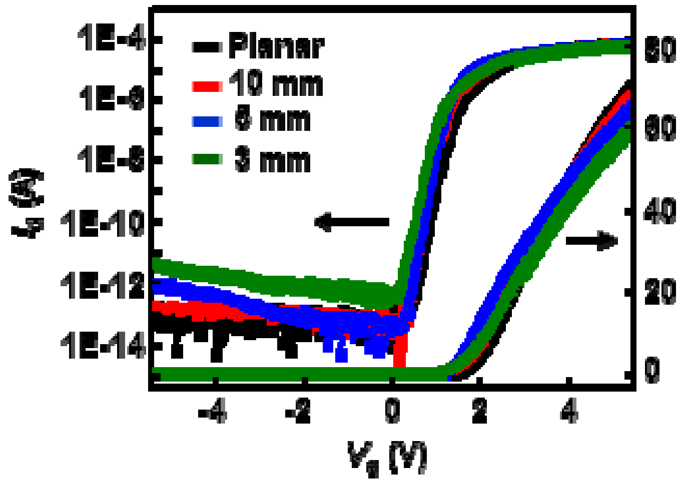


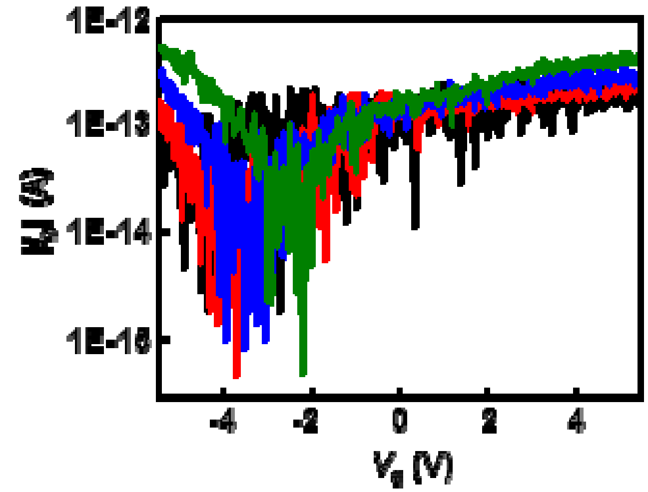
Science **325**, 977 (2009)

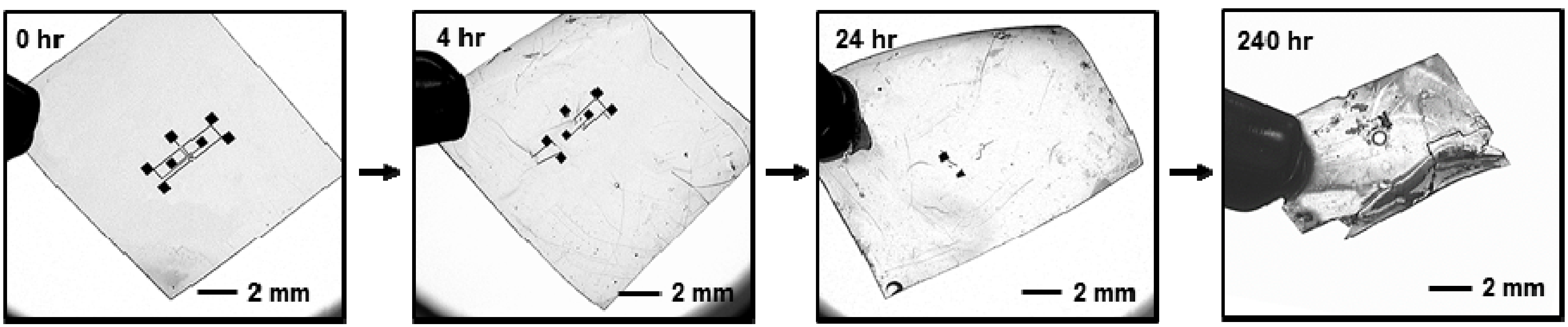

Production Scale Transfer Printers

Transient SOI Electronics on Flexible PLGA Substrates





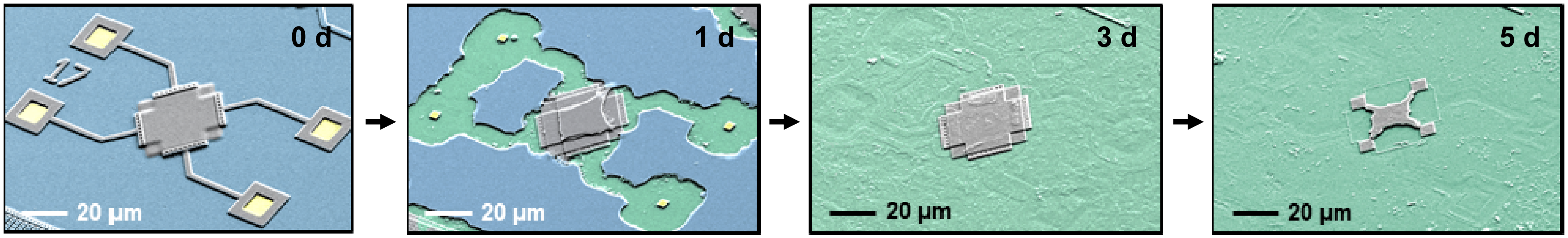


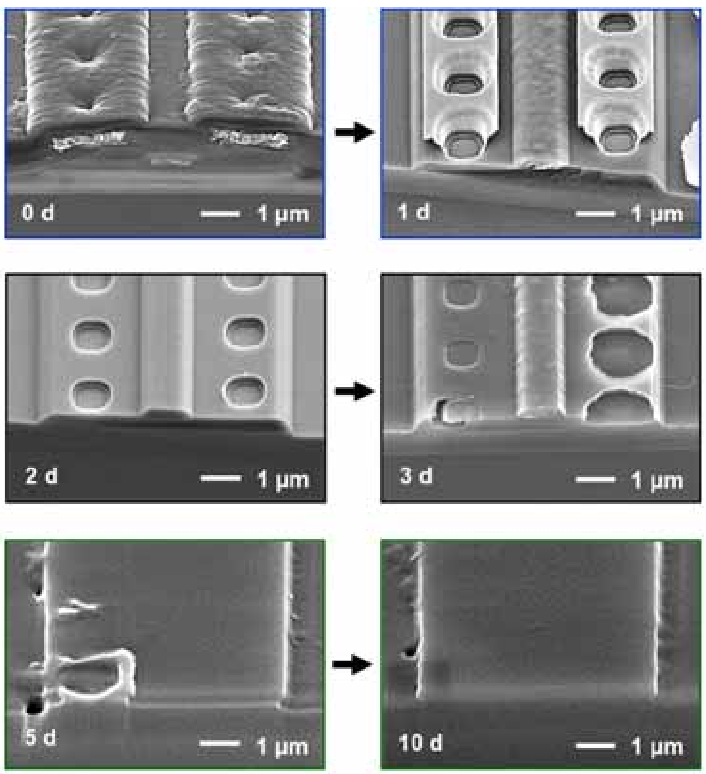


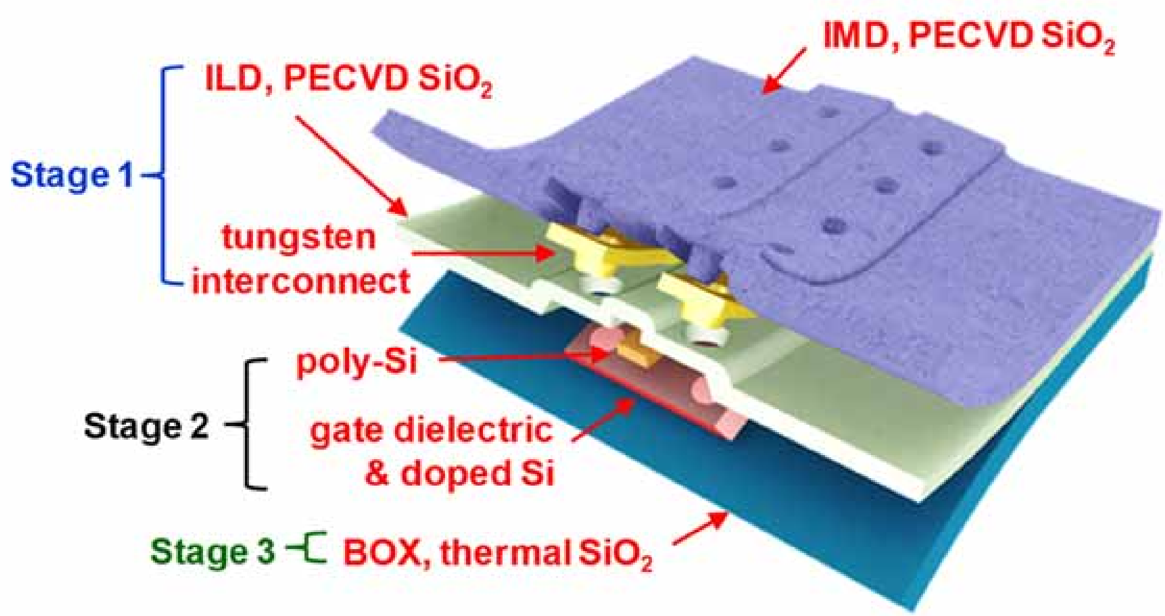
PNAS **114**, E5522 (2017).

Dissolution / Disintegration of Transient CMOS

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

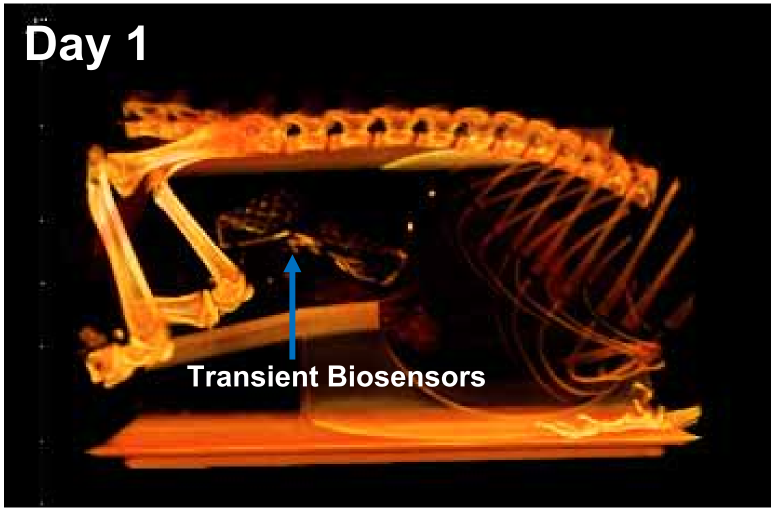


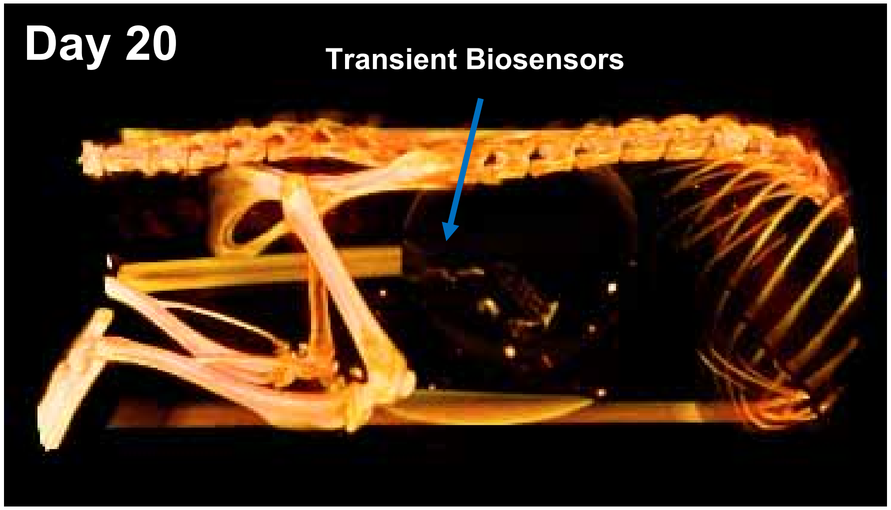


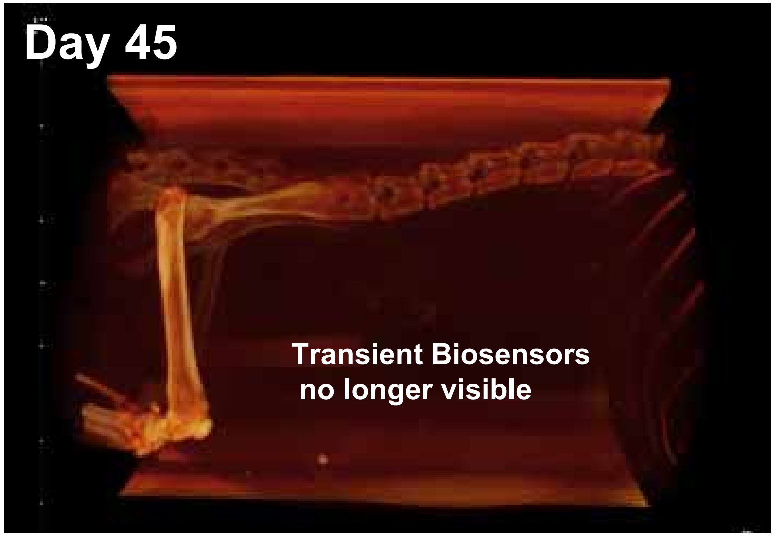


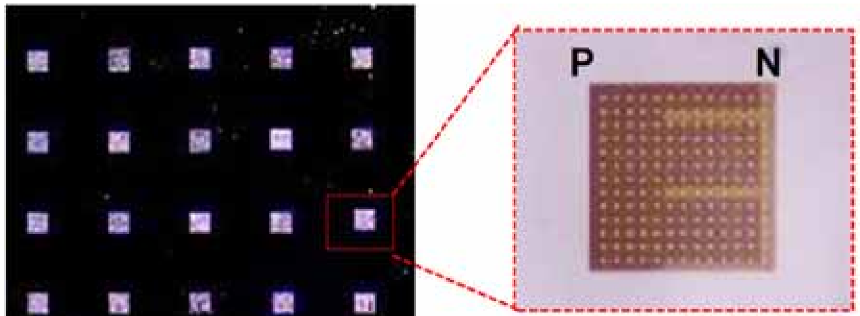
Adv. Mater. **11**, 1704955 (2018).

In Vivo Bioresorption of an Array of Transient Devices





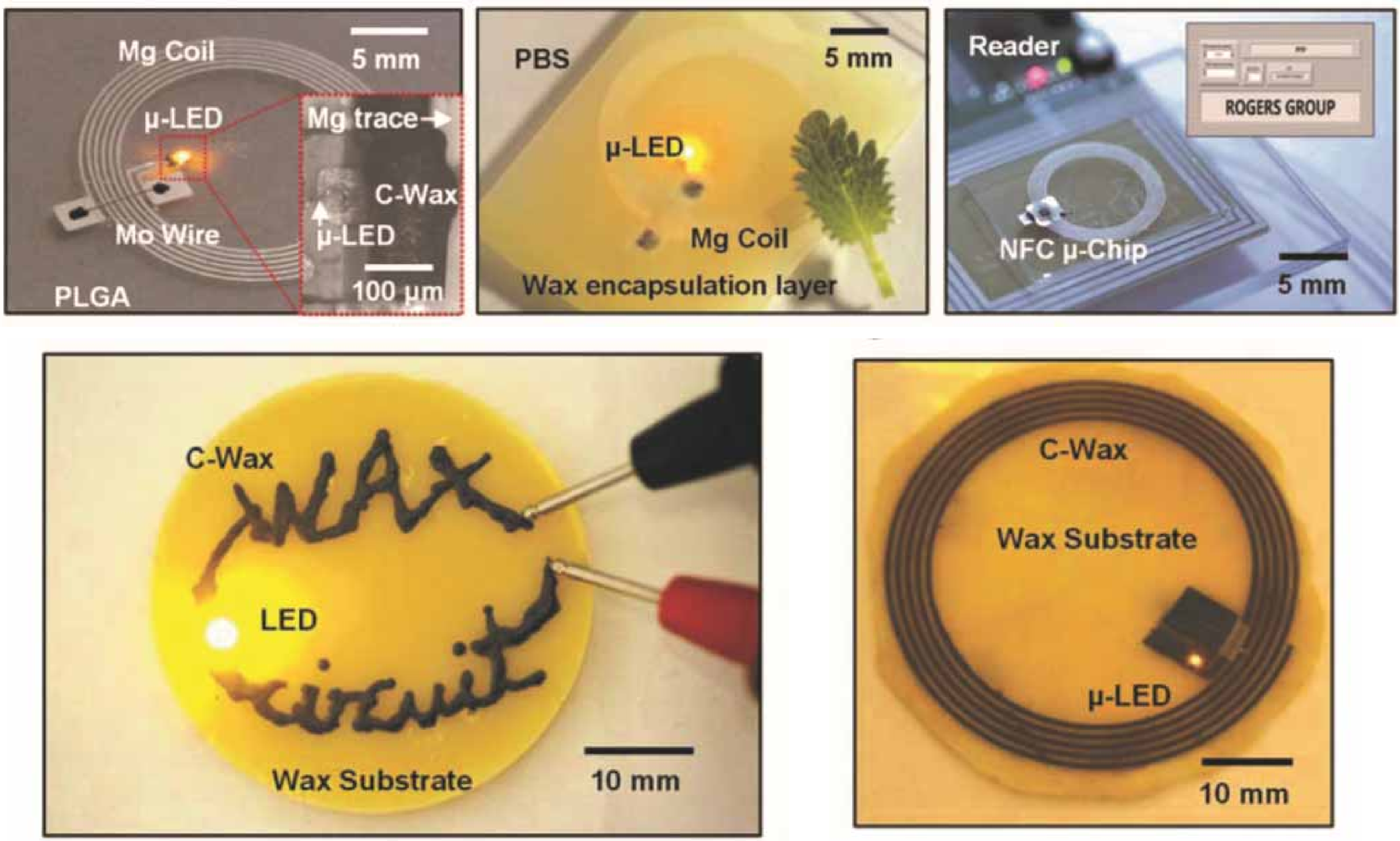




Transient PDs

- Full dissolution in 45 days.
- No abnormalities or adverse effects.

Printable Transient Conductors: W in Wax for RFID Tags



Adv. Func. Mater. **28**, 1801819 (2018).

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

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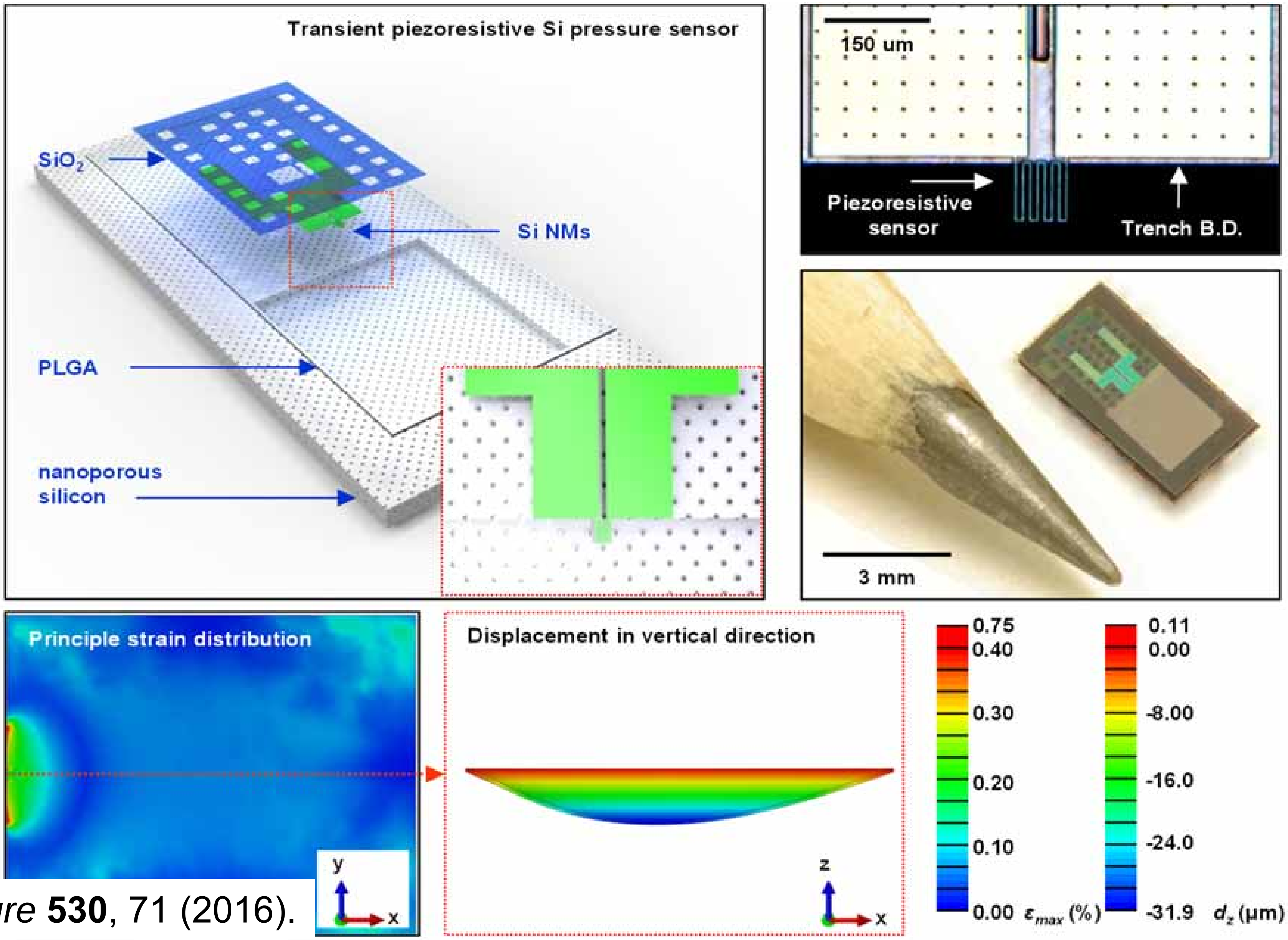
Bioresorbable Intracranial Pressure Sensors for TBI



Nature **530**, 71 (2016).

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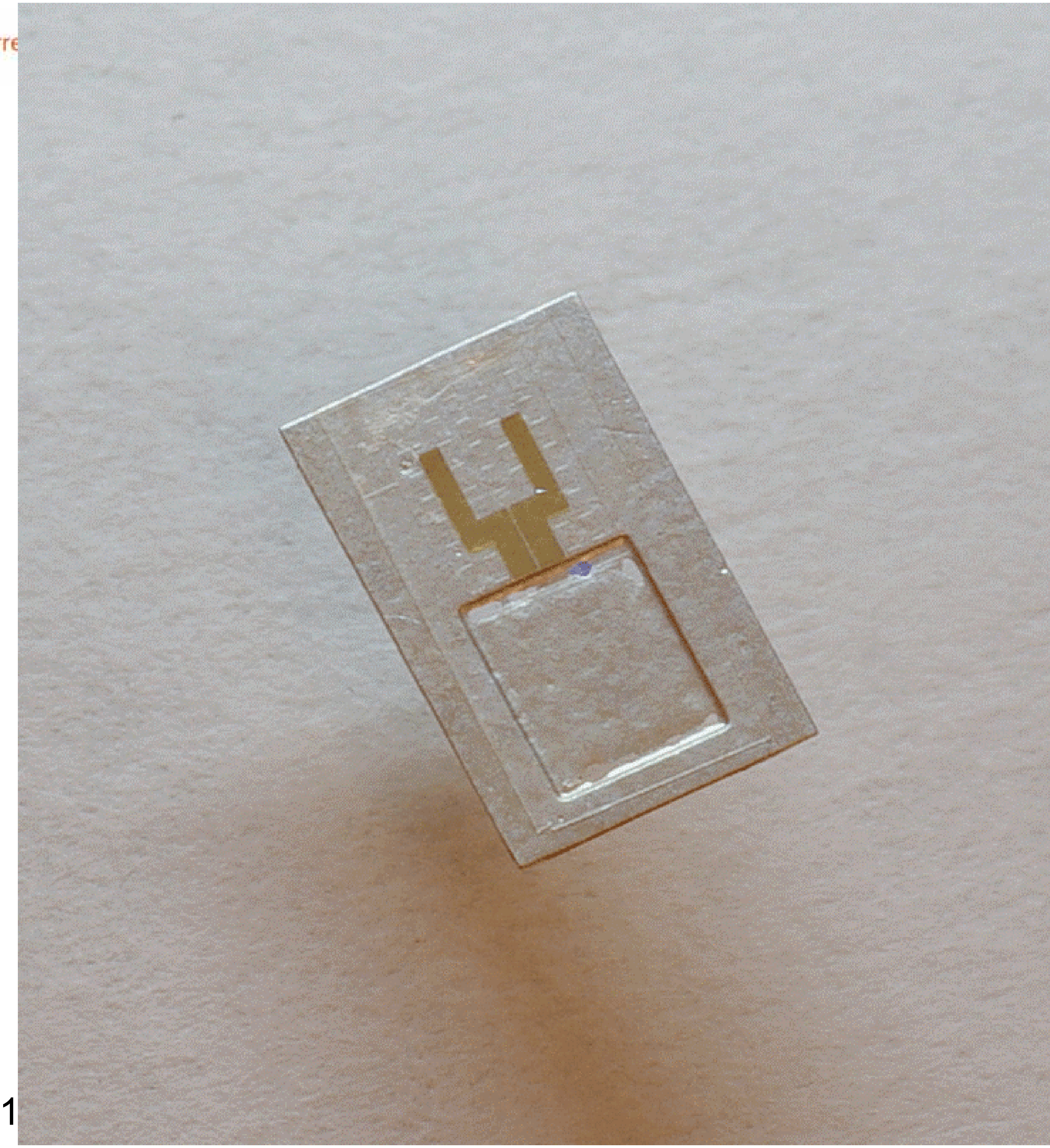
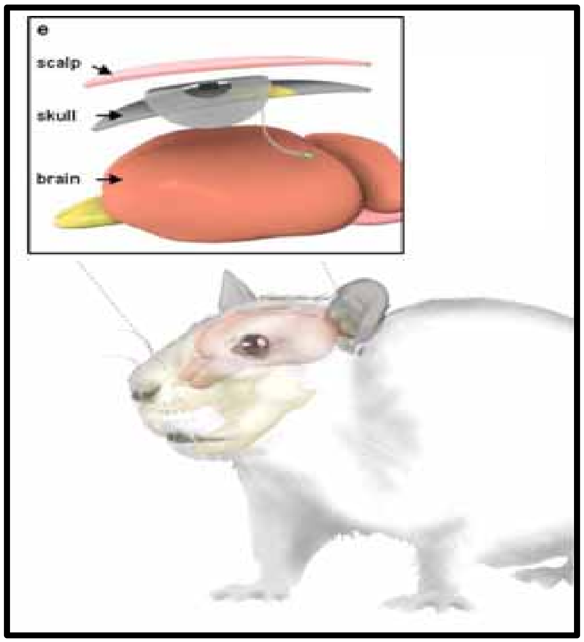
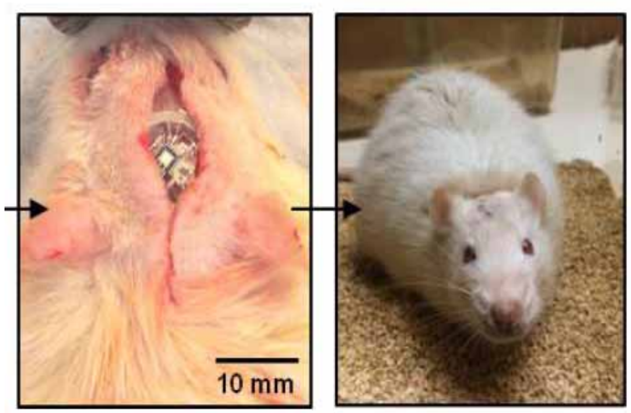


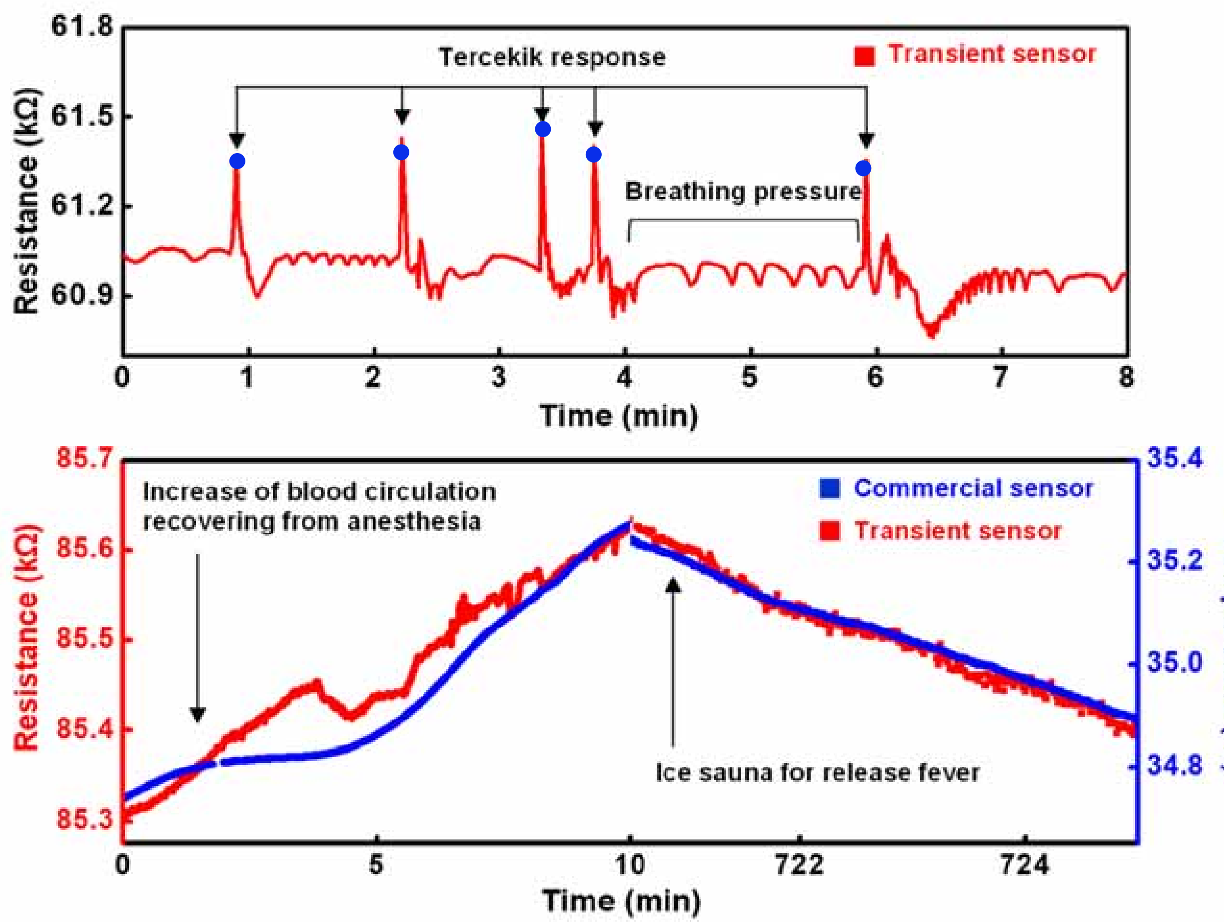
Nature **530**, 71

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.

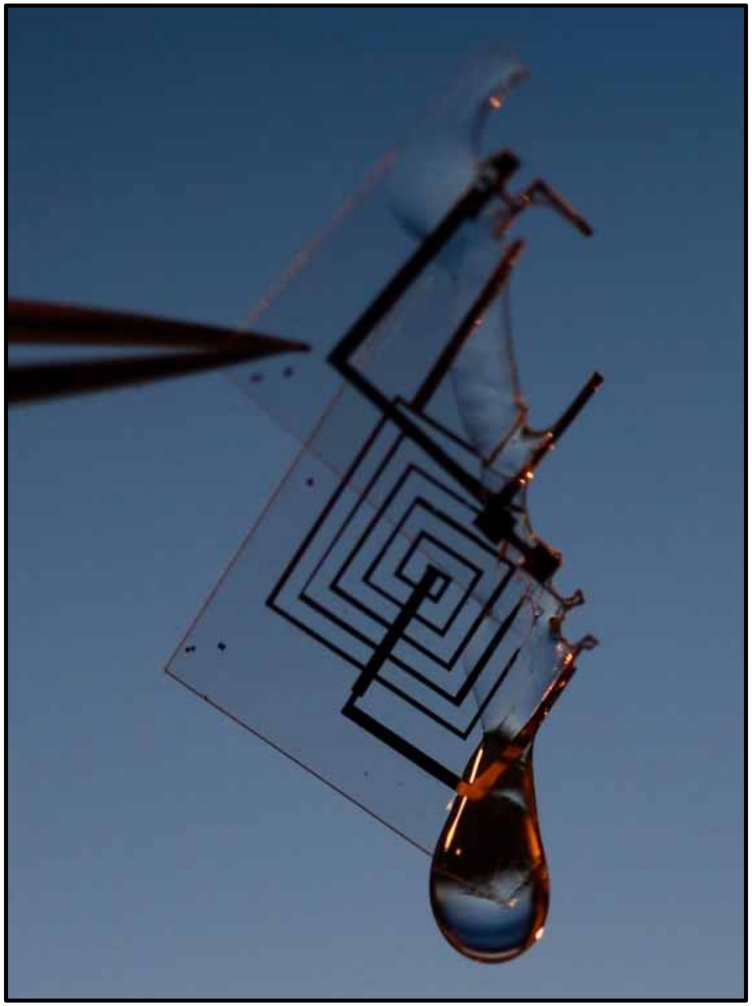
Clinical Medicine

Prof. I. Efimov (GWU) – cardiac

Prof. R. Murphy (WU) -- TBI

Prof. Z. Ray (WU) – neuroregen

Prof. M. MacEwan (WU) -- regen



Research Team