SQI Simpson Querrey Institute BioNanotechnology

Northwestern

Soft Optoelectronic Interfaces to the Brain

1) Soft, Conformal Optoelectronic Systems
2) 3D Mesoscale Electronic Networks
3) Bioresorbable Electronics & Sensors

John A. Rogers – Northwestern University

Departments of Materials Science and Engineering, Electrical and Computer Engineering, Chemistry, Biomedical Engineering, Mechanical Engineering, Feinberg School of Medicine – Neurological Surgery

Louis Simpson and Kimberly Querrey Professor

Director, Center for Biointegrated Electronics

Fundamental Research into the Function of the Brain

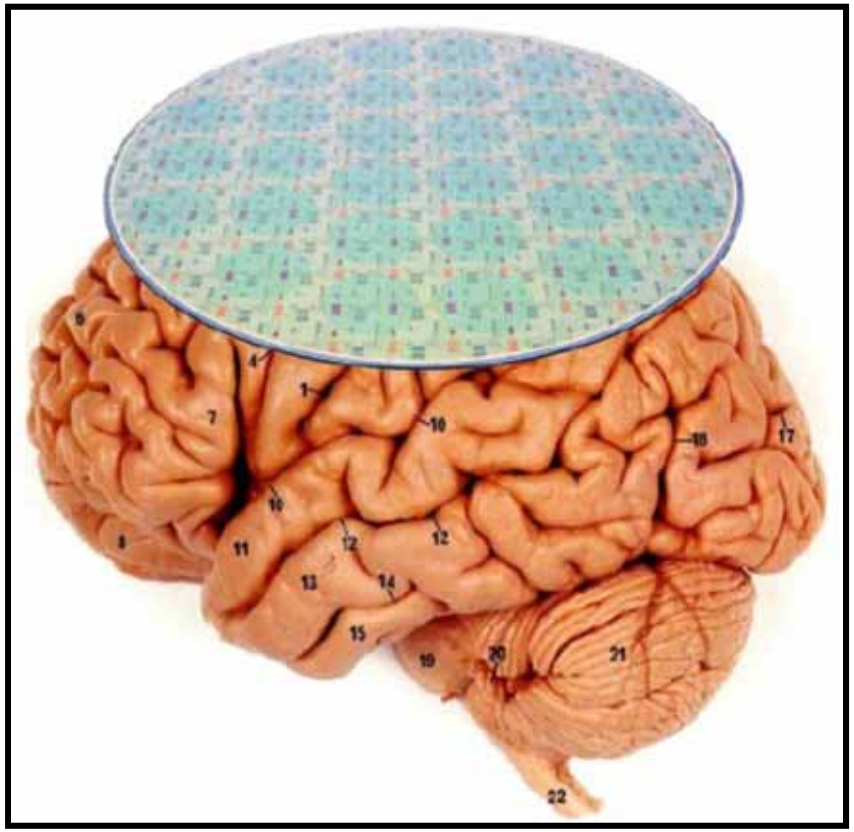
"New directions in science are launched by new tools much more often than by new concepts."

– F. Dyson

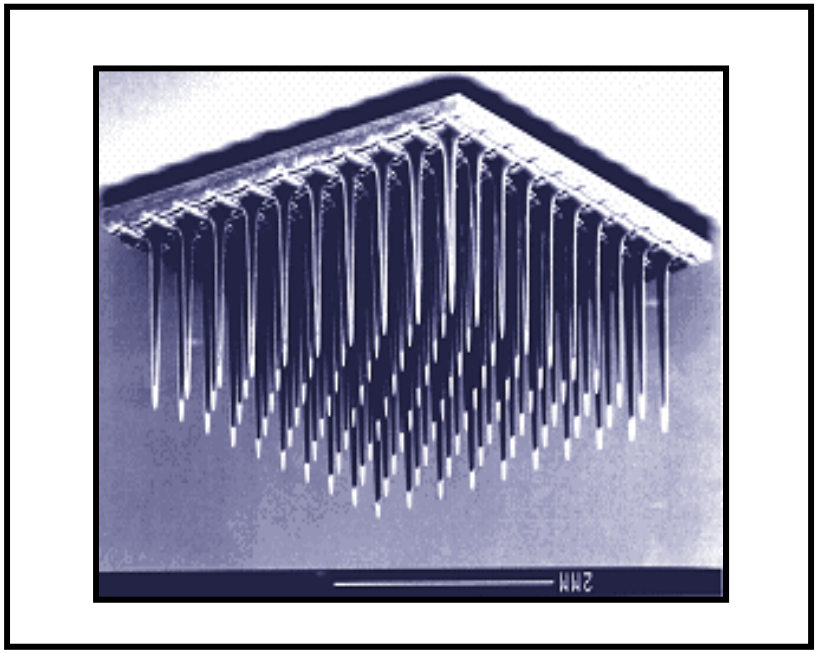
"The Rosetta Stone for the brain will require a new generation of tools that give us the vocabulary, the syntax, and the grammar of the brain." *– T. Insel*

Electronics for the Brain

Challenge ??



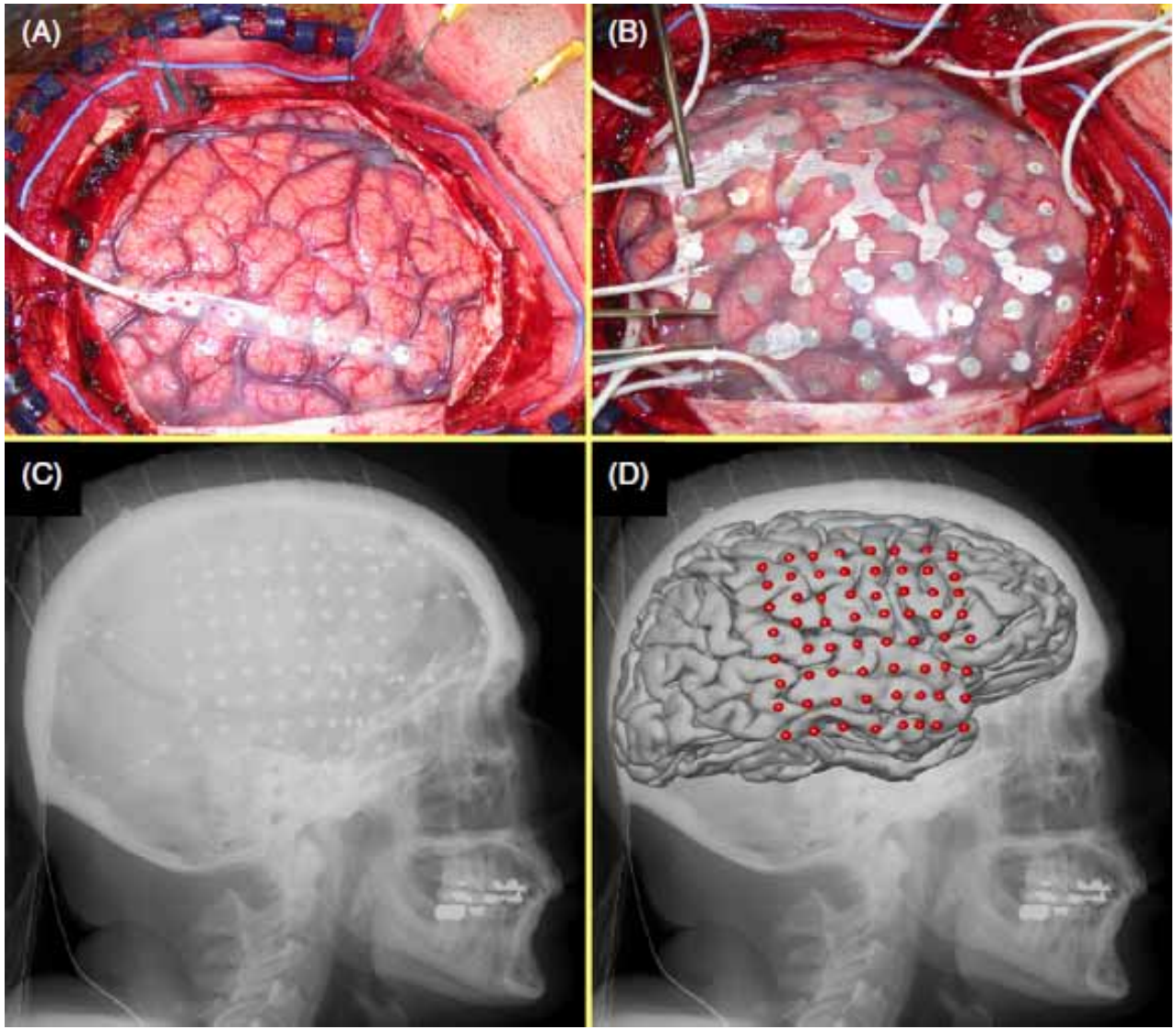
Current *?!*



IEEE Intl. Symp. Ckts & Sys (2008).
J Neurophysiol **111**, 1132 (2014).

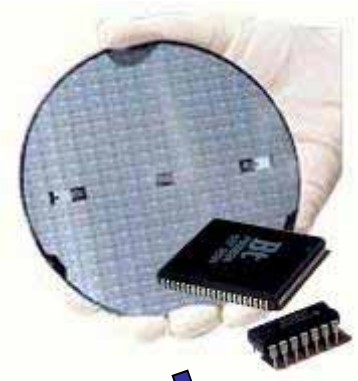
Future – Soft, Shape Conformal, Biocompatible

Diagnostics for Brain Surgery

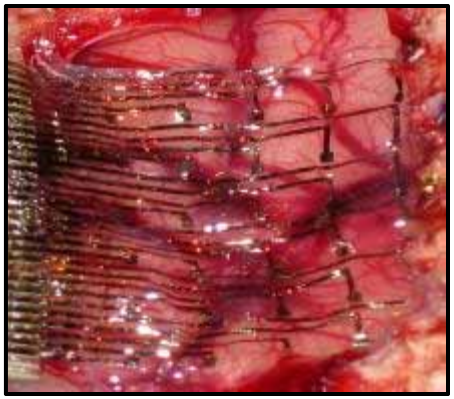


J. Neural Eng. **5**, 75 (2008)

Candidate Semiconductors for Bio-Integrated Electronics



?



a-Si

poly-Si

Si

GaAs

0.1 | 1 | 10 | 100 | 1,000 | 10,000

Polymers:
Solution processing
Low performance

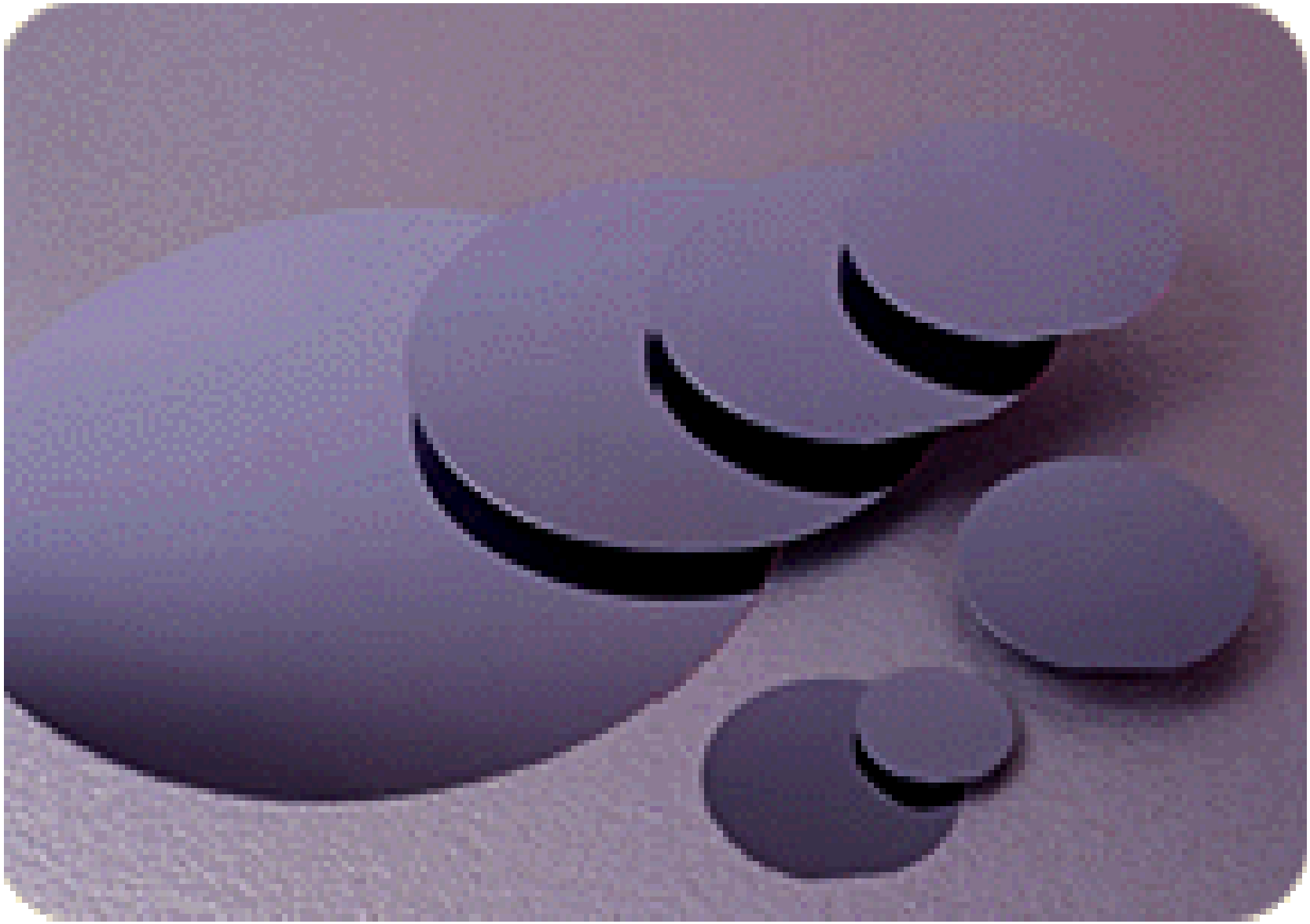
Small molecules:
Performance similar to a-Si
Vacuum dep.

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

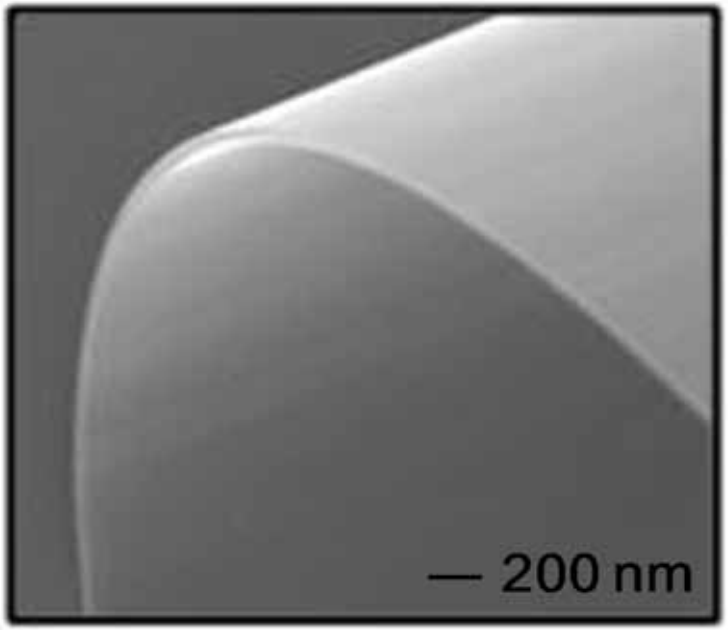
Carbon nanotubes:
High mobility, 'robust'
High temp. growth, electr. heterogeneity

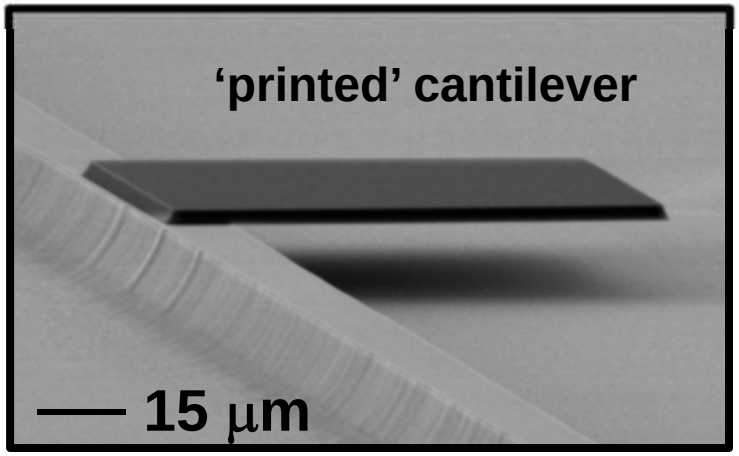
graphene:
High mobility
High temp. growth
Semi-metallic

Materials Challenges

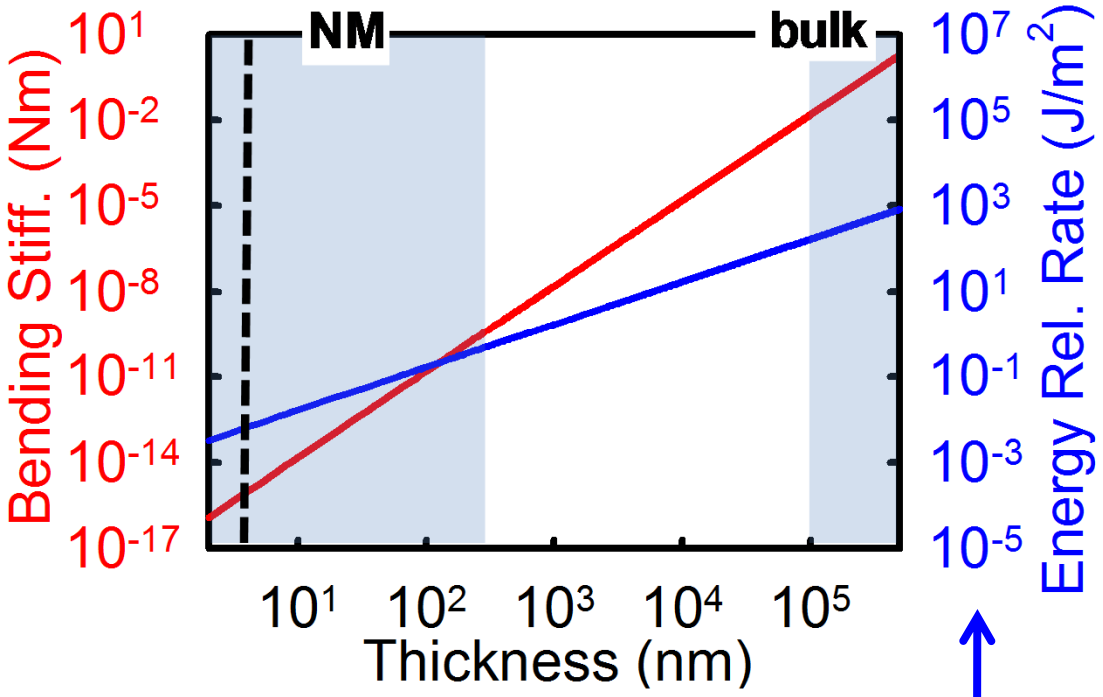


Mechanics of Silicon *NanoMembranes*





$EI \sim Eh^3$ and $\varepsilon_{peak} \sim h / R$

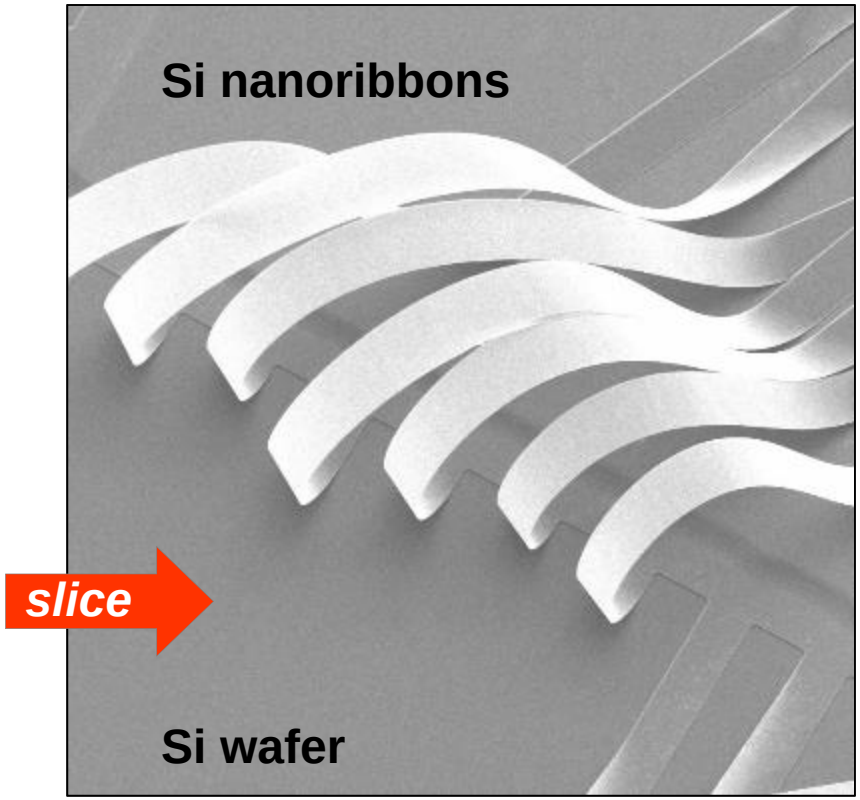


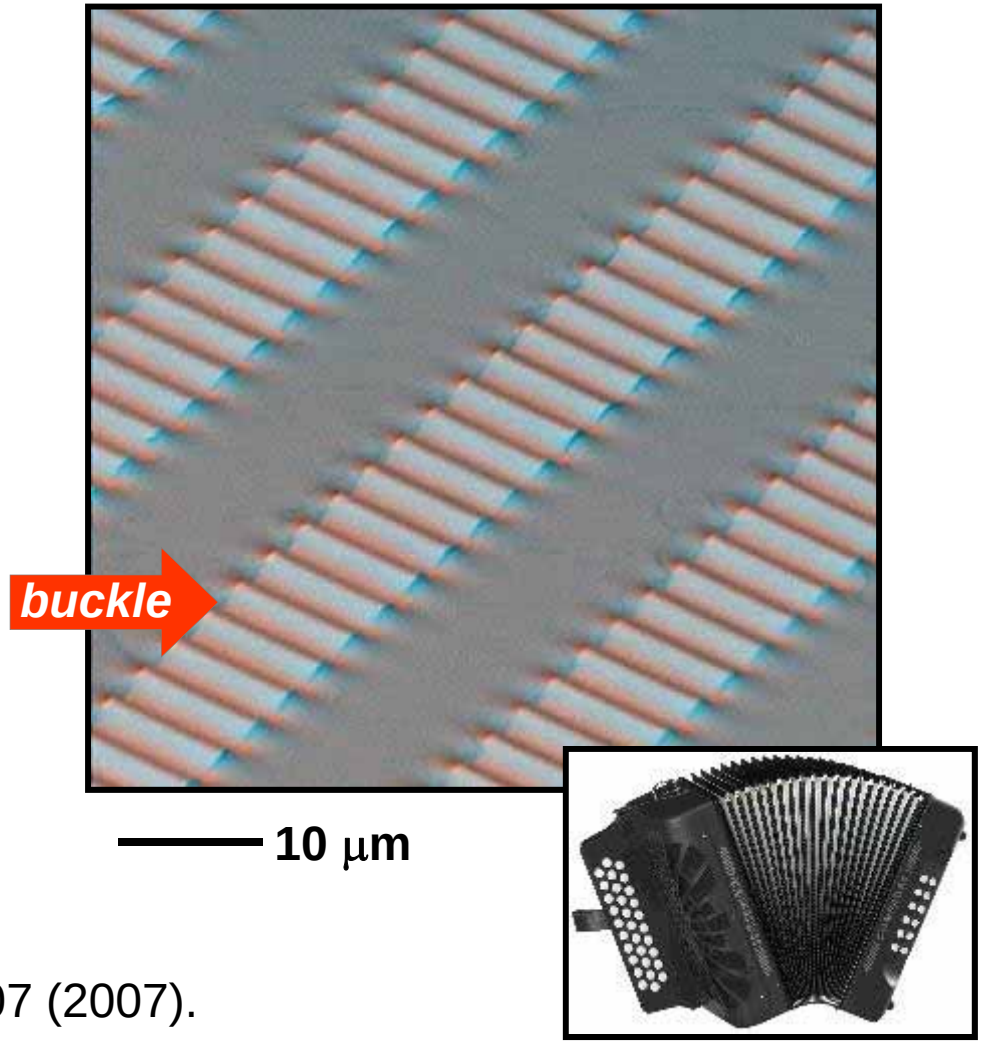
$$G \sim h\left(\alpha_1 - \alpha_2\right)^2 \Delta T^2$$

Nature, **477**, 45 (2011).

Stretchable Silicon

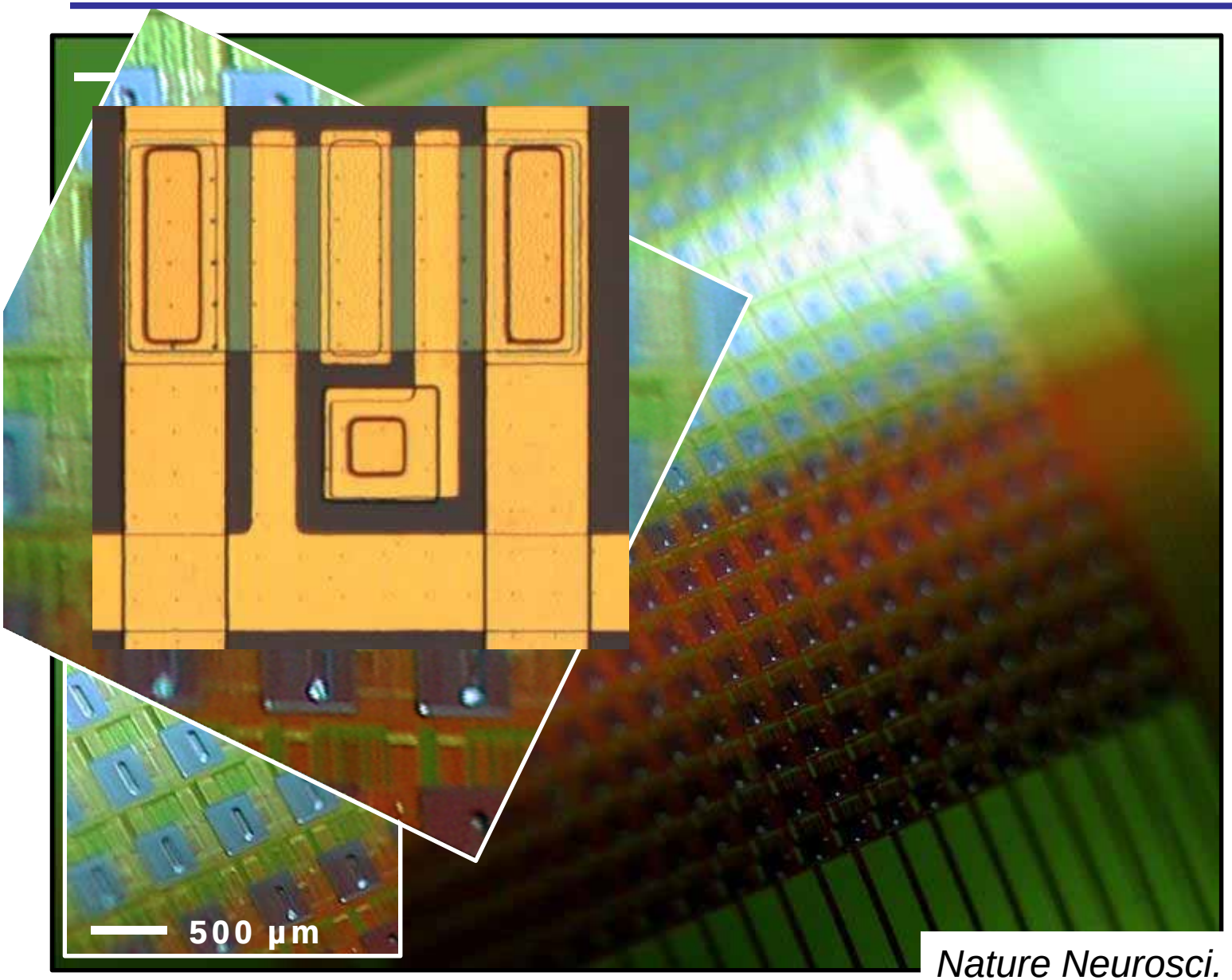
(1): Thin -- *Flexible* → (2): Wavy -- *Stretchable*





Science **311**, 208 (2006); *PNAS* **104**, 15607 (2007).

High-Density Flexible Electronics for Active µECoG

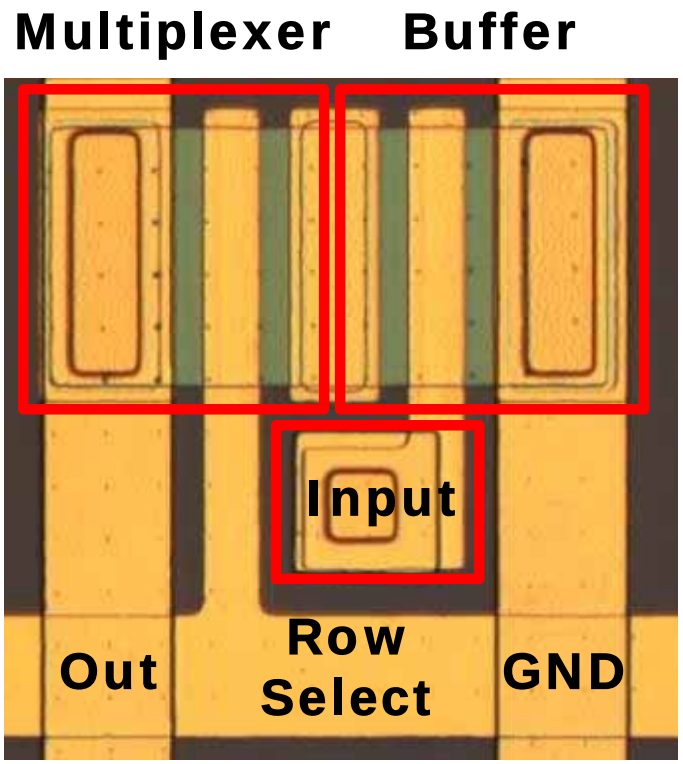


Features

- 360 Electrodes
- 20 × 18
- 500 µm spacing
- 10 x 9mm
- 39 wires

Nature Neurosci. **14**, 1599 (2011).

High-Density Flexible Electronics for Active µECoG

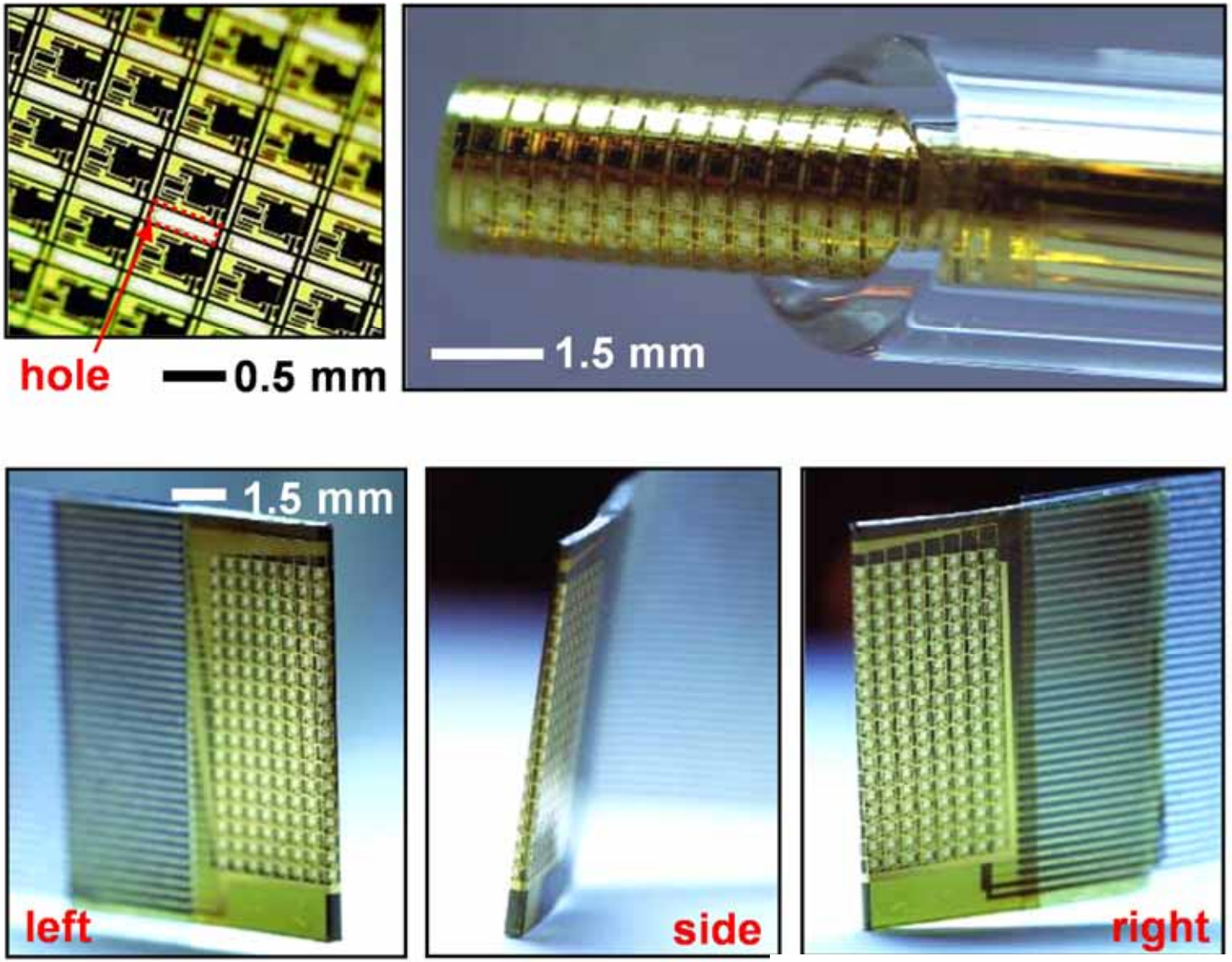


Features

- 360 Electrodes
- 20 × 18
- 500 µm spacing
- 10 x 9mm
- 39 wires

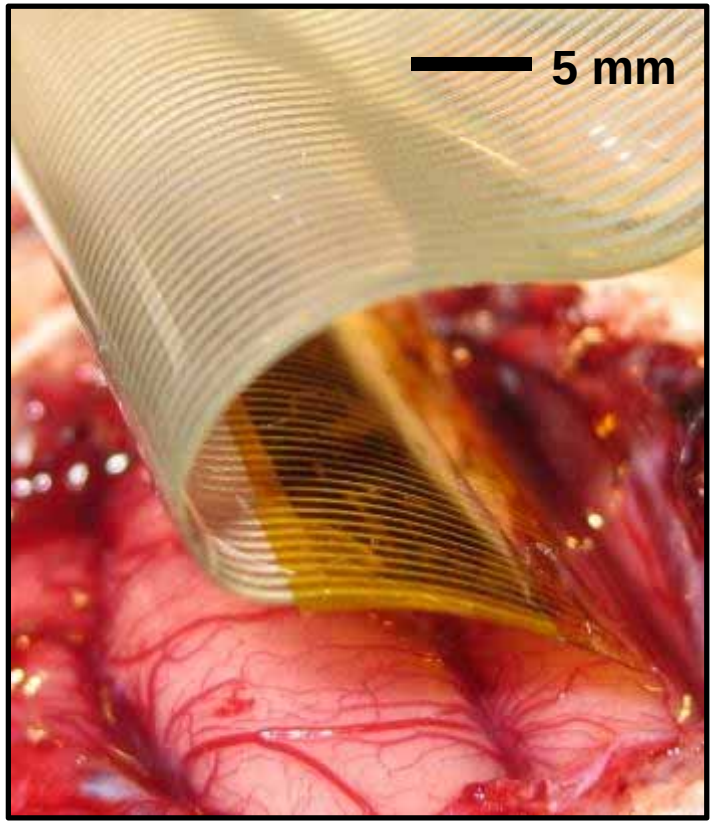
Nature Neurosci. **14**, 1599 (2011).

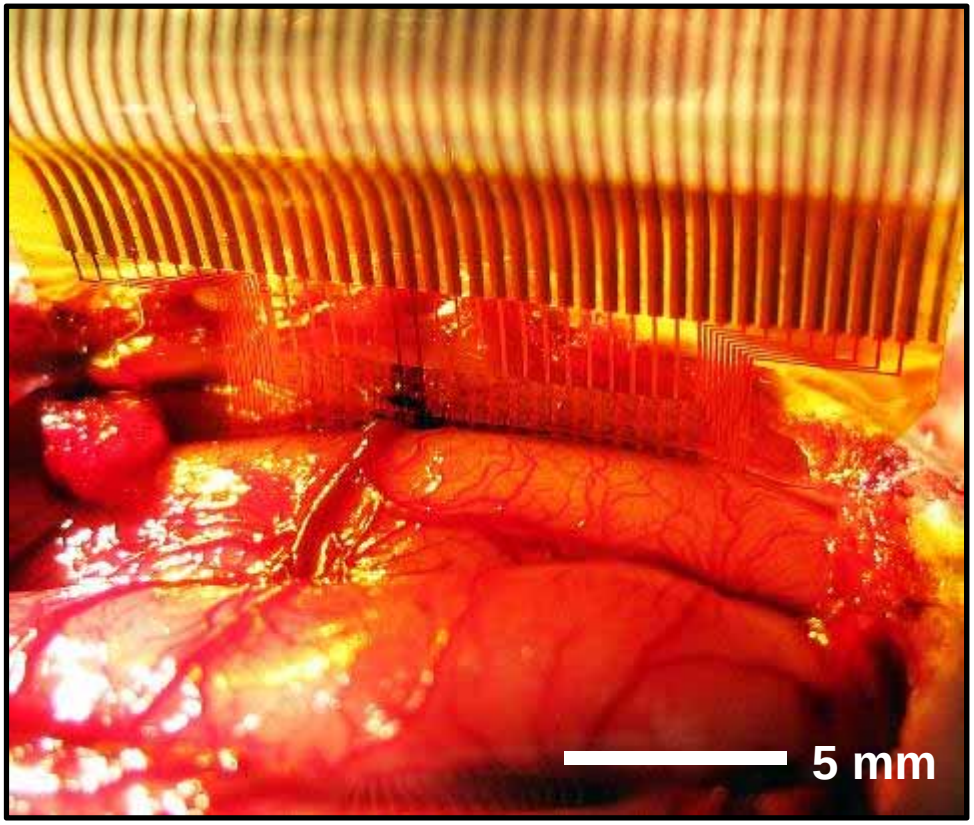
Flexible, Foldable Electronics for Active μECoG



Nature Neurosci. **14**, 1599 (2011).

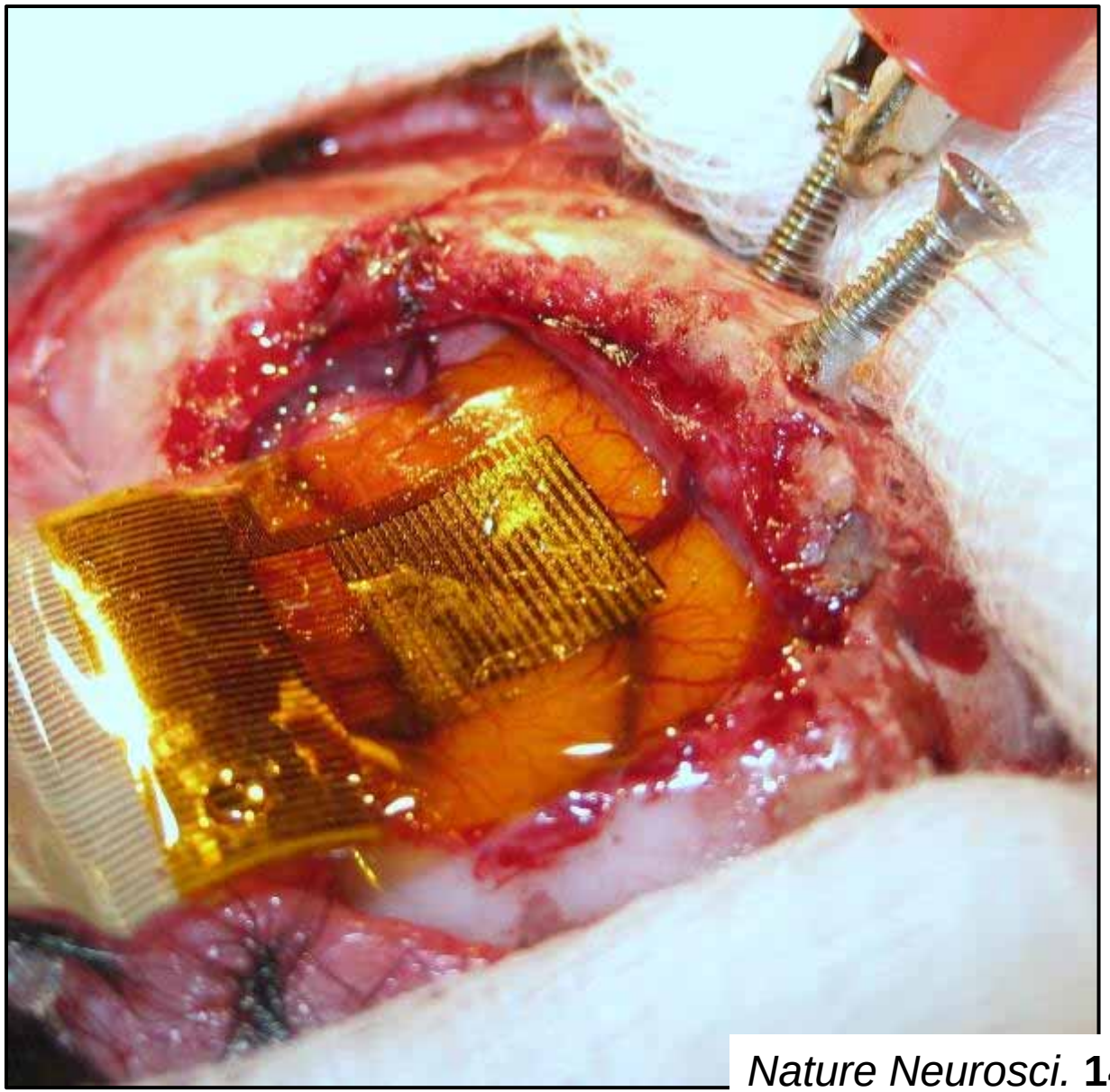
Recording From the Interhemispheric Fissure





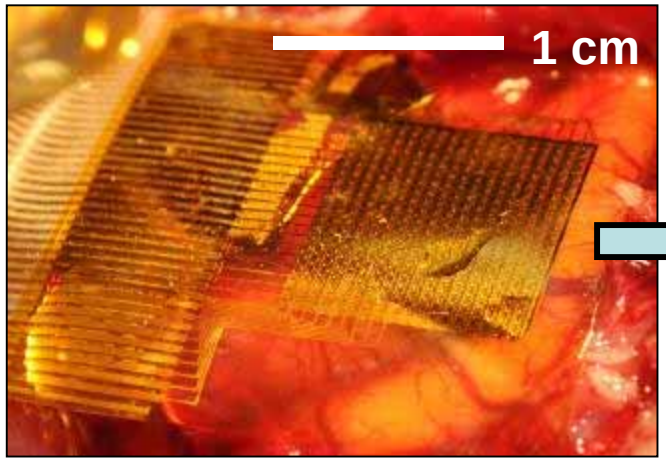
Nature Neurosci. **14**, 1599 (2011).

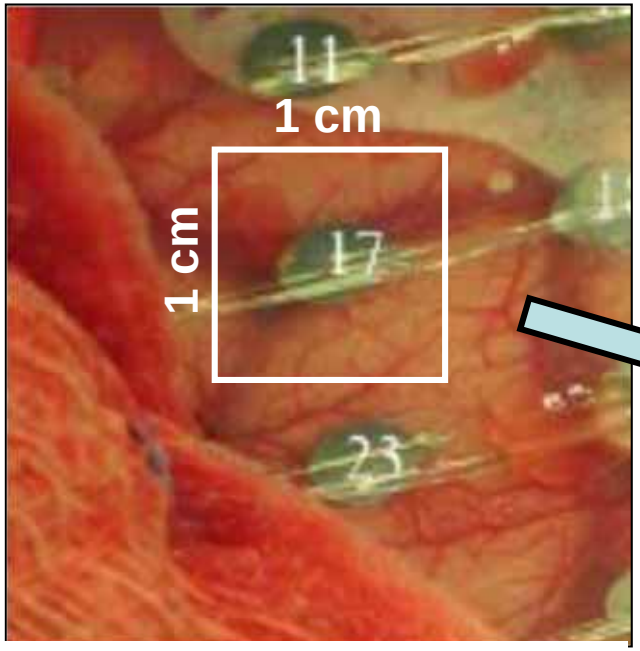
High-Density Flexible Electronics for Active μECoG

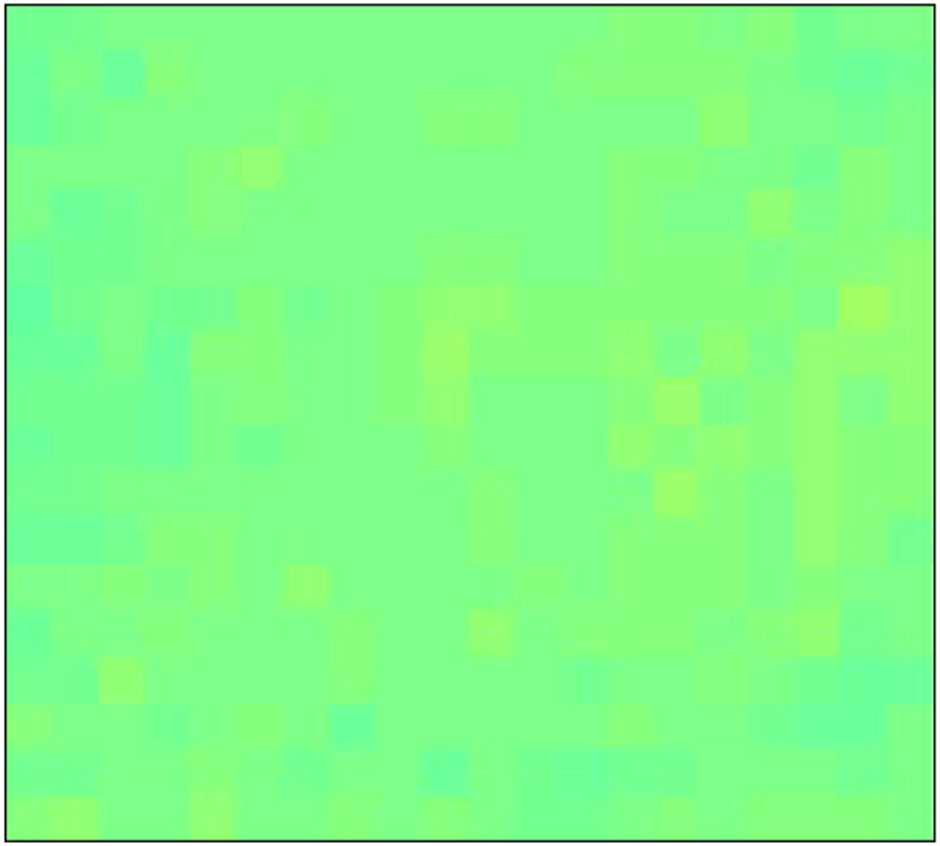


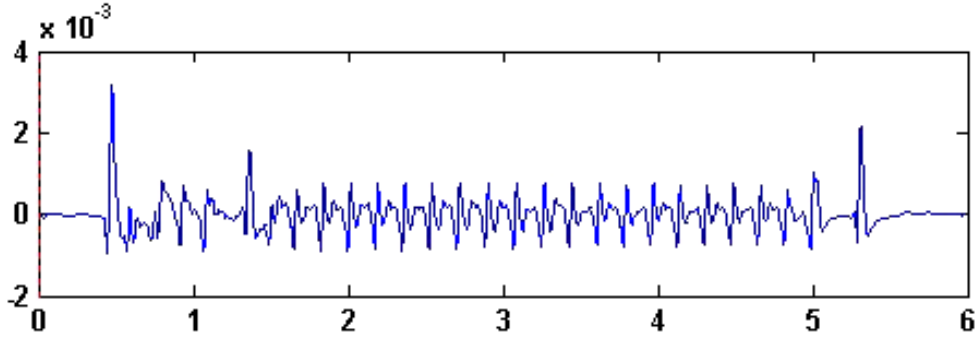
Nature Neurosci. **14**, 1599 (2011).

High Resolution Mapping of a Seizure Event



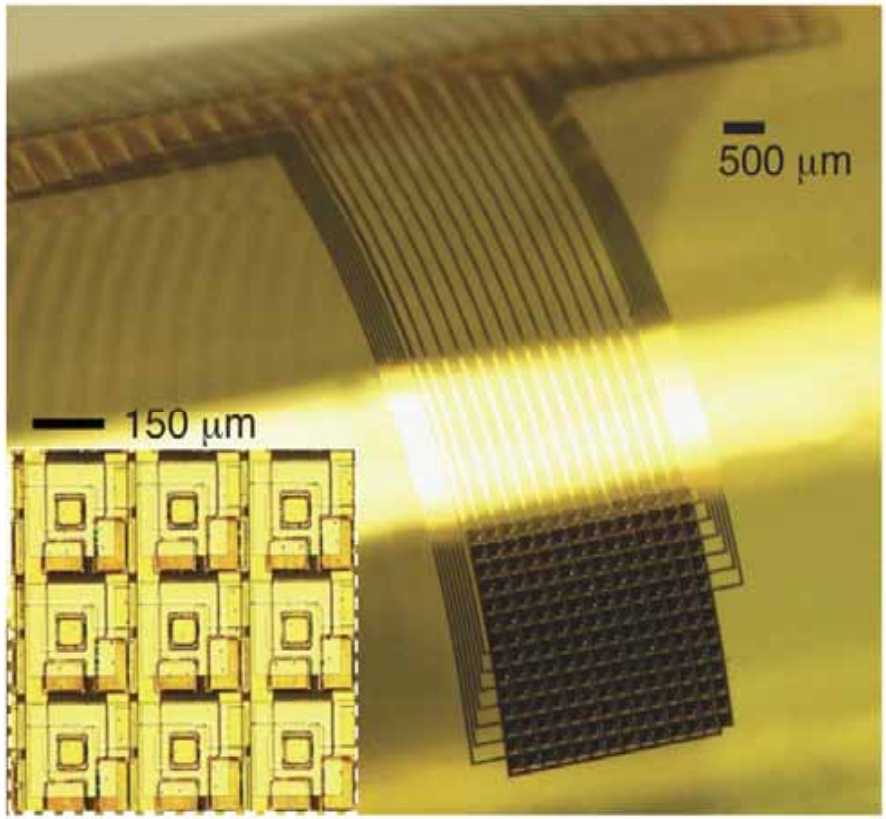


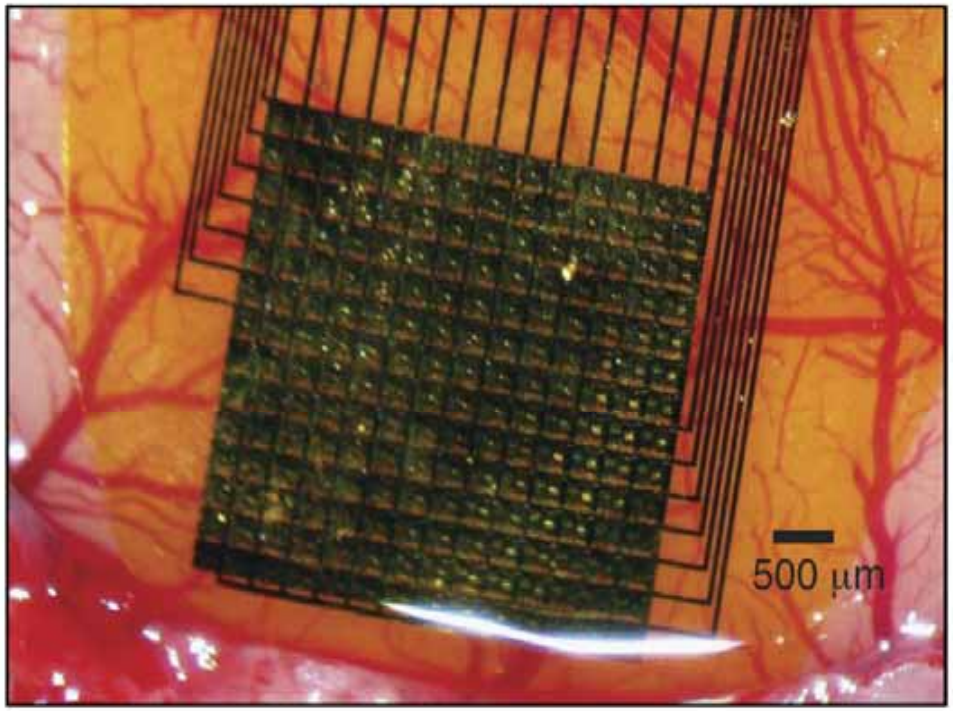




Nature Neurosci. **14**, 1599 (2011).

Higher-Density Flexible Electronics for Auditory Cortex



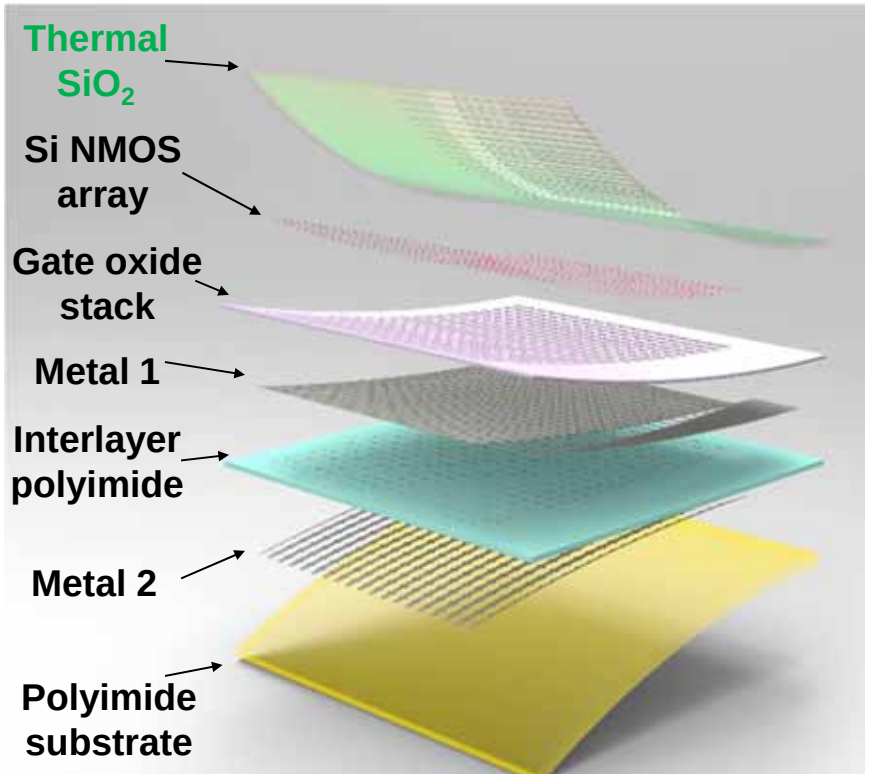


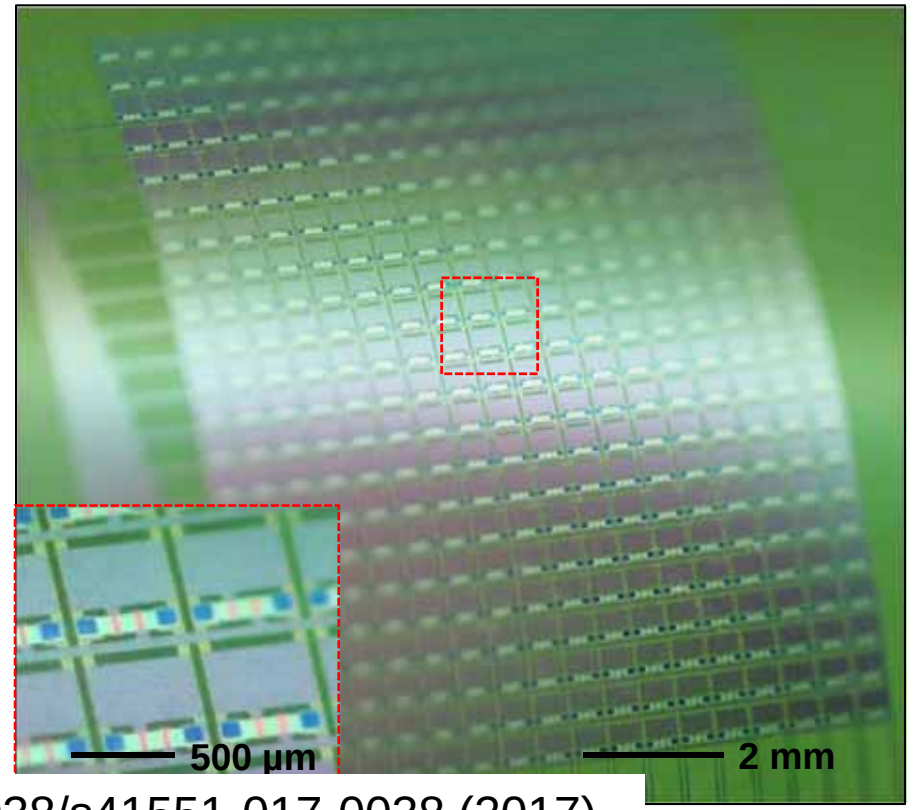
J. Neurophys. **112**, 1566 (2014).

Flexible Bio-Sensing Electronics with Thermal SiO_2 Encapsulation and Chronic Stability

396-ch chronic bio-mapping electronics

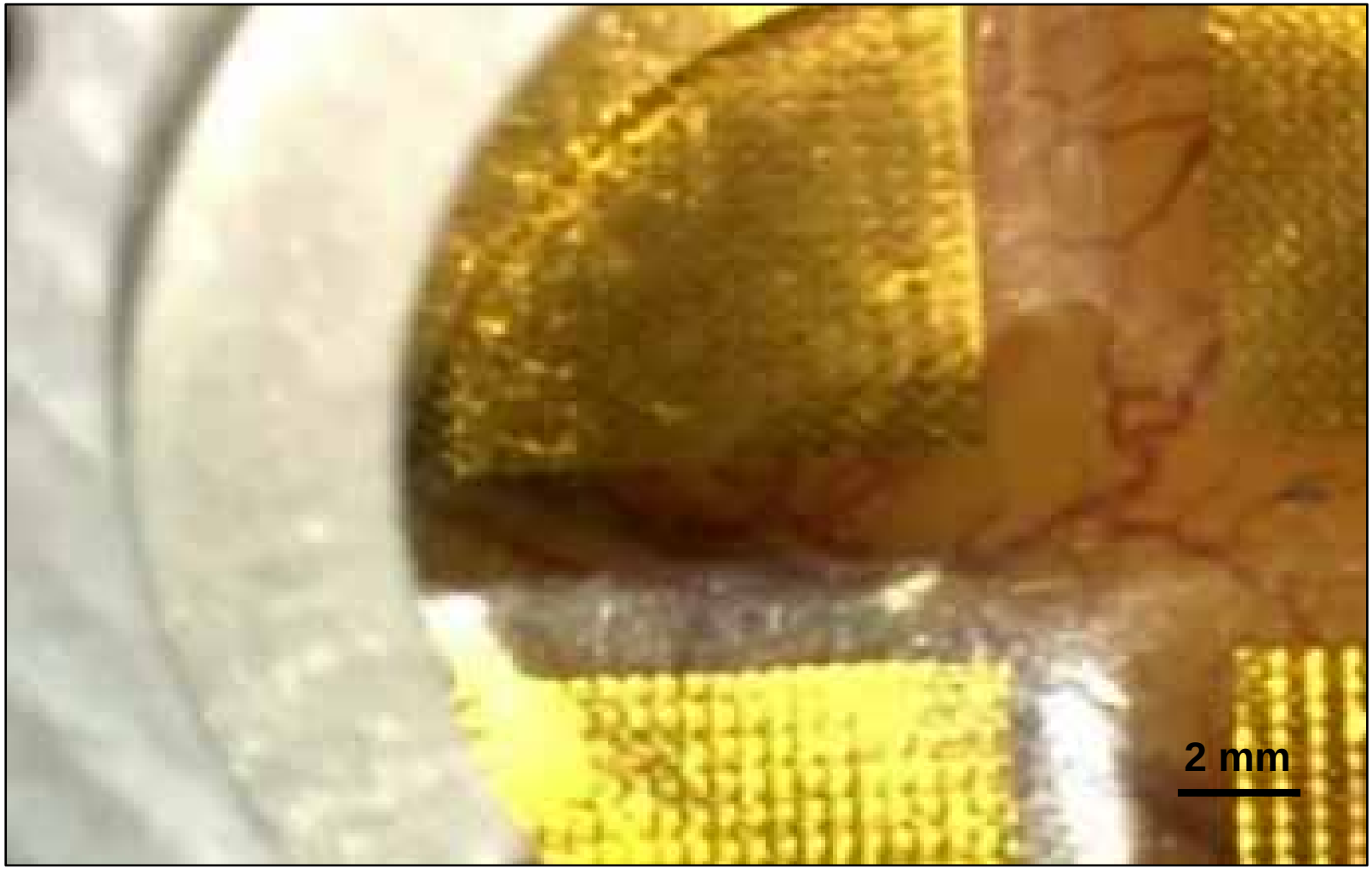
- ❑ **792 Si nano-membrane transistors**
- ❑ **58 wires, 500 μm × 500 μm spatial resolution**
- ❑ **Encapsulated with 900 nm thermal SiO_2**
- ❑ **Capacitive sensing design**





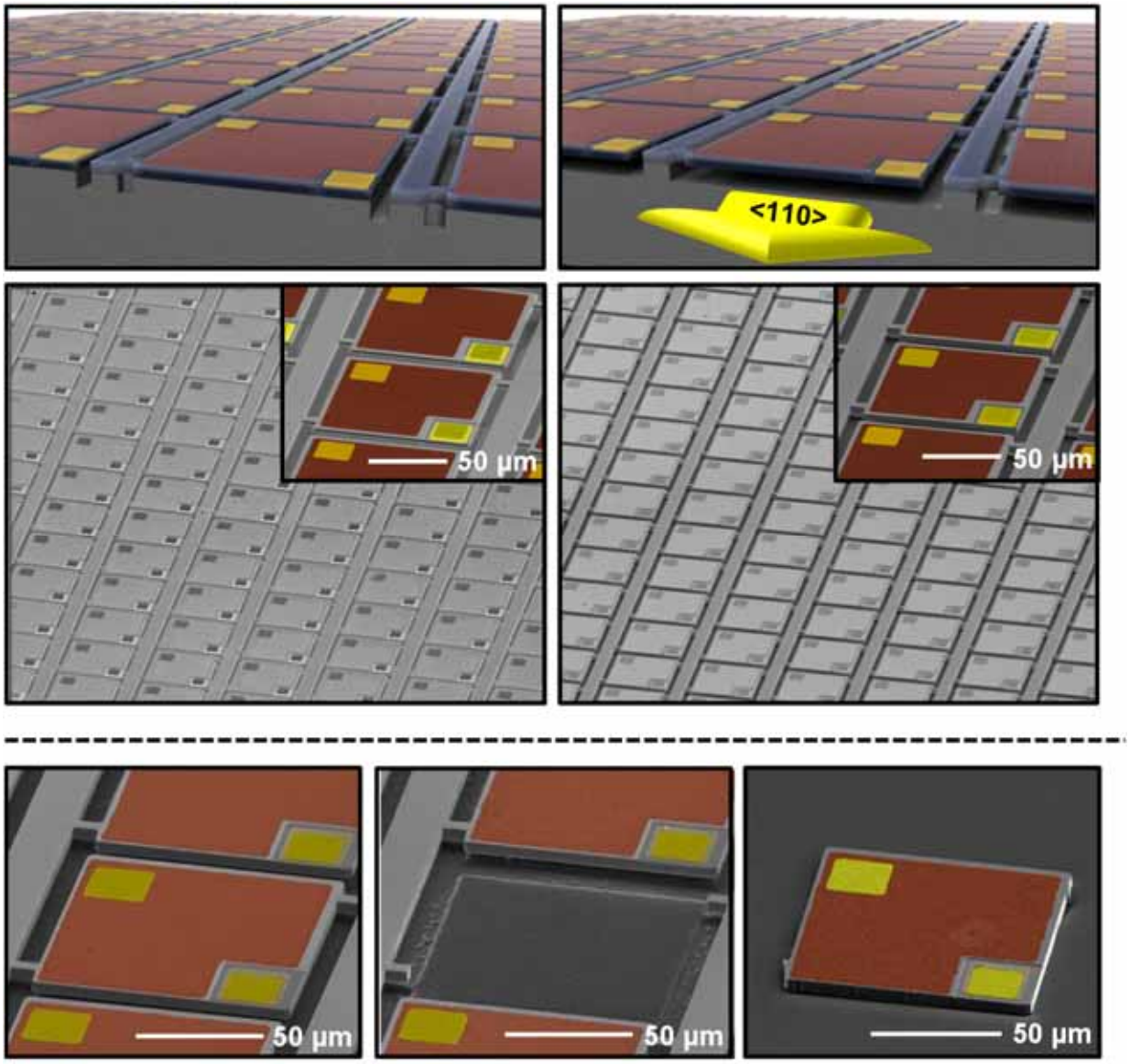
Nature Biomed. Eng. **1**(3), 0038, DOI: 10.1038/s41551-017-0038 (2017).

Chronic Use in NHPs



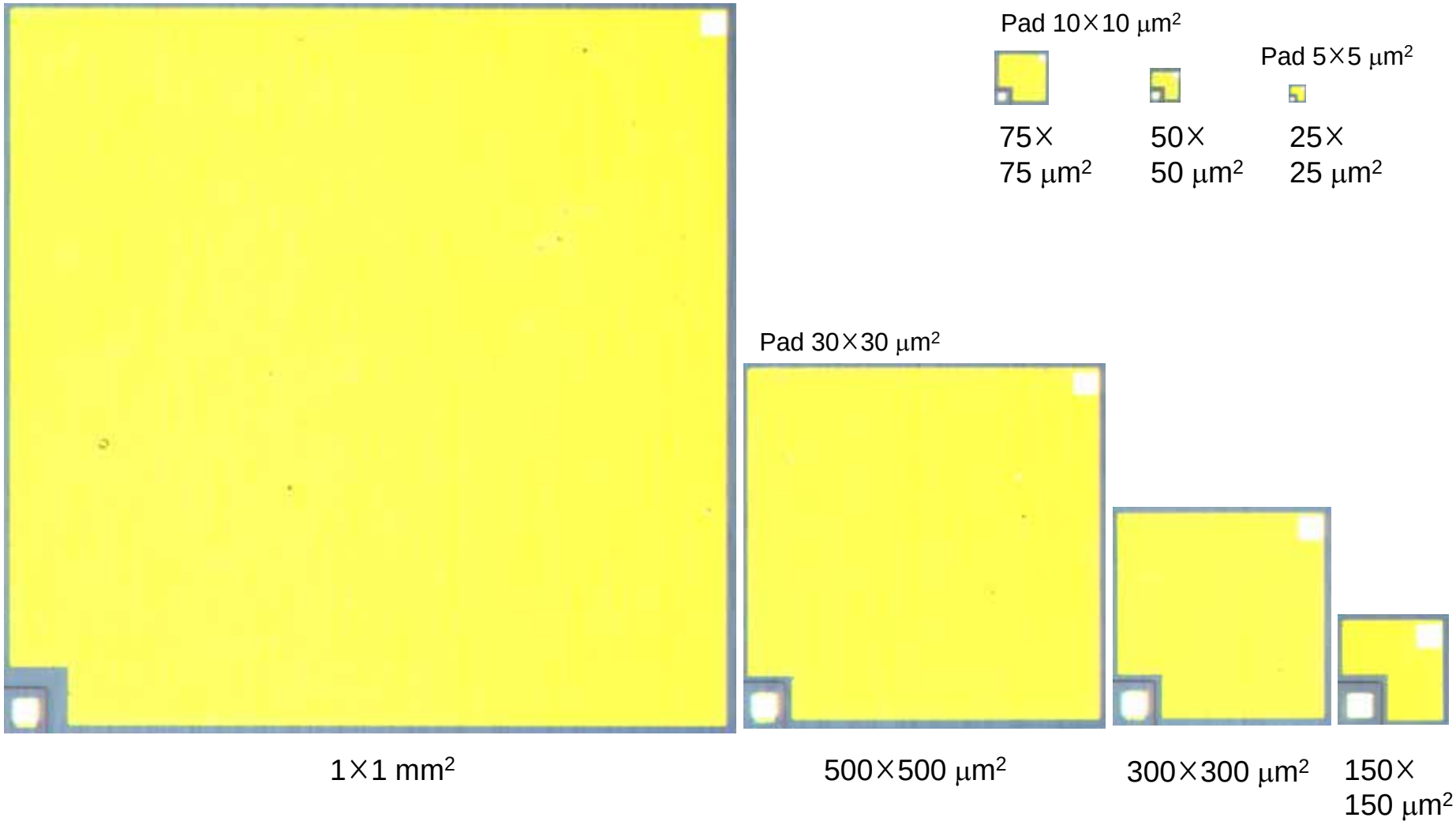
unpublished

Undercut Release of InGaN 'Micro' LEDs



PNAS **108**, 10072 (2011).

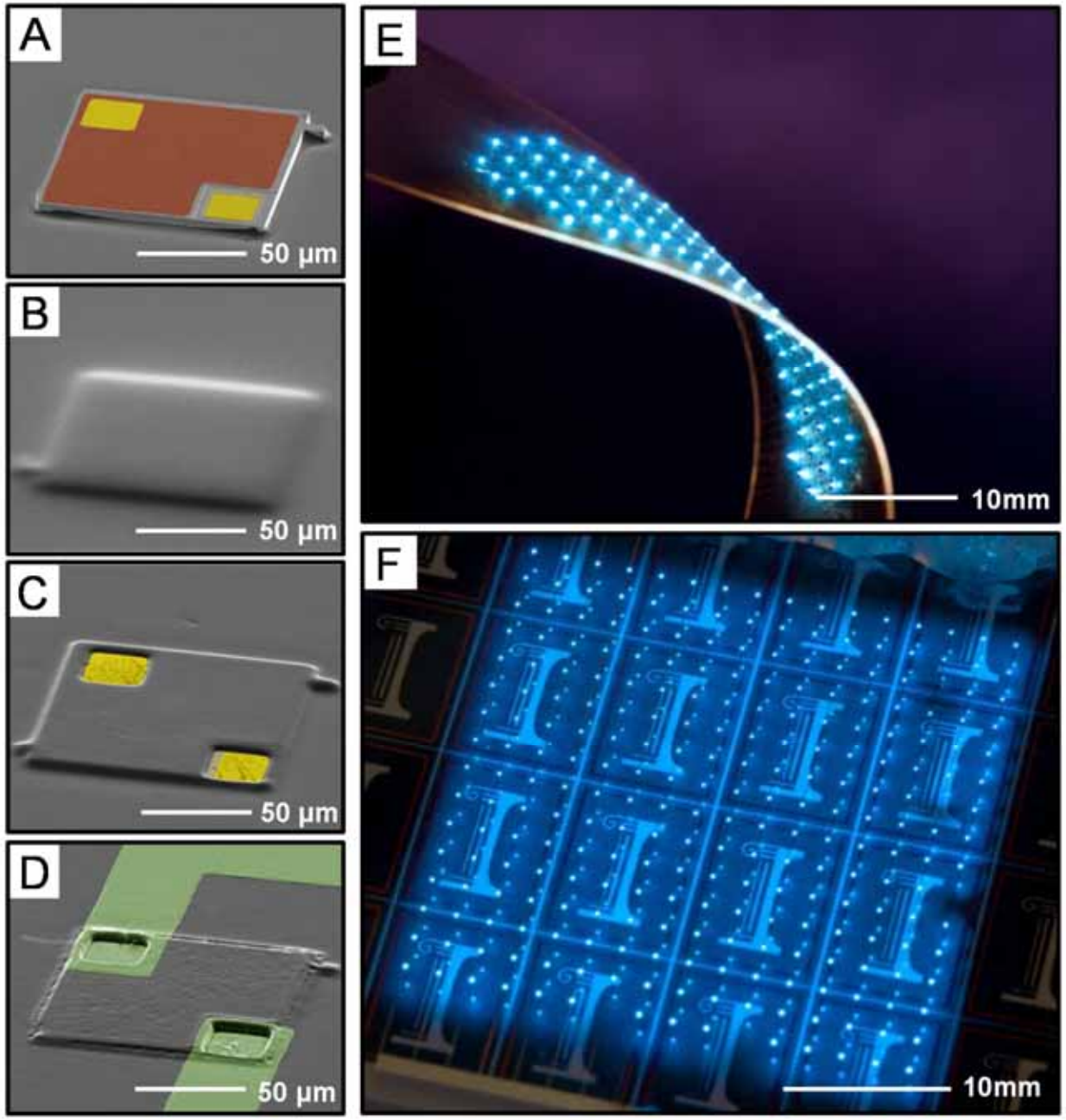
Size Scaling in AlGaN Devices – Thermal, Optical



Max. Size : 1×1 mm² Min. Size : 25×25 μm²

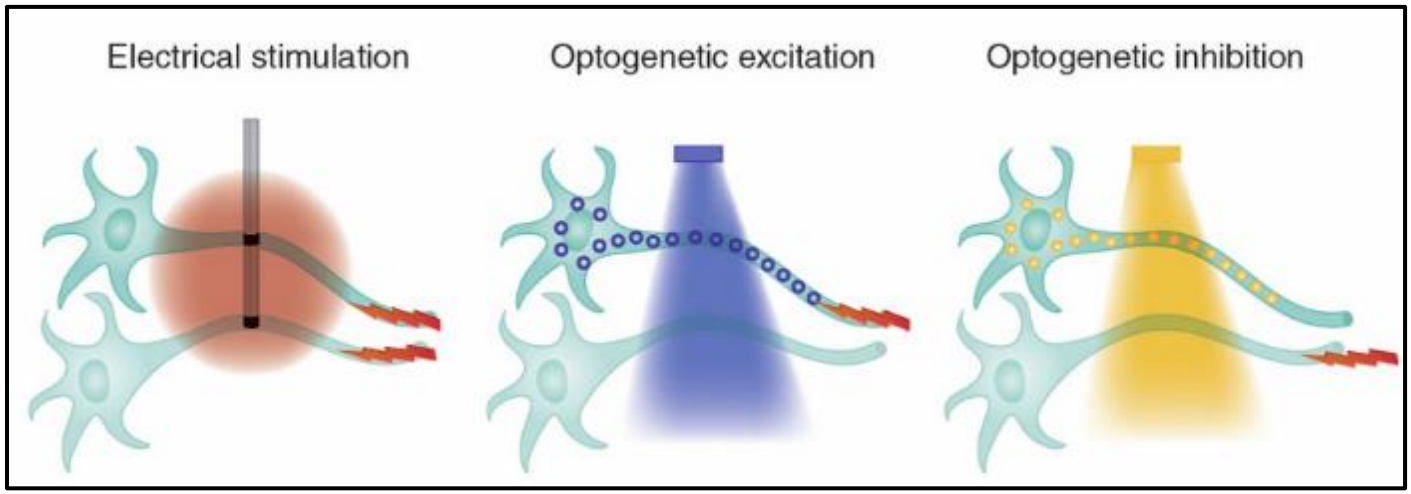
Small **8**, 1643 (2012).

InGaN μ-ILEDs and Lithographic Interconnection Schemes



PNAS **108**, 10072 (2011).

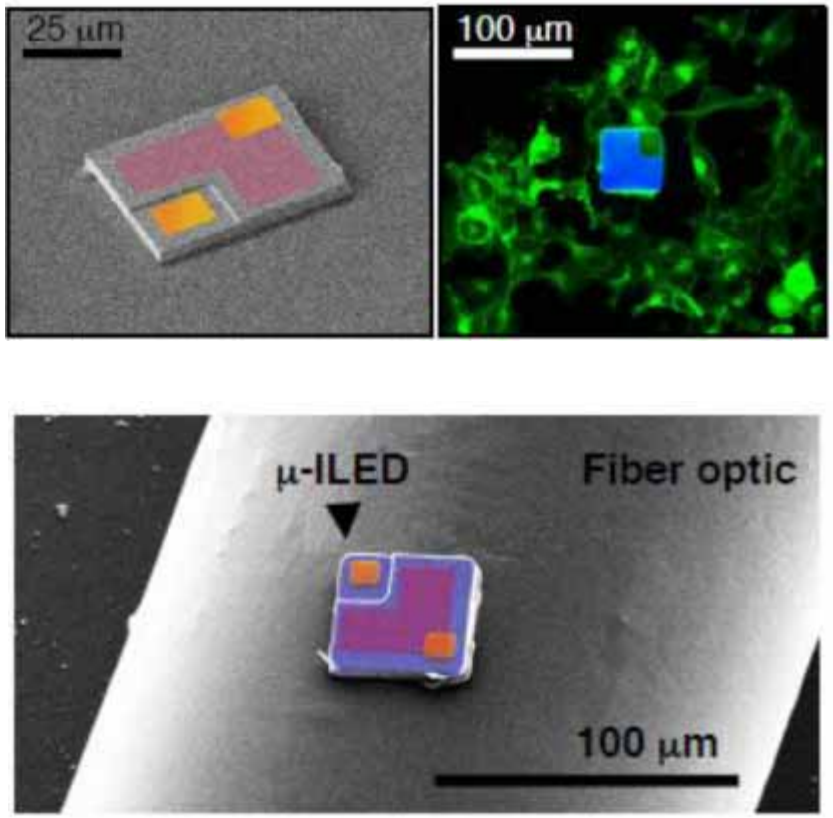
Optoelectronics for the Brain -- Optogenetics

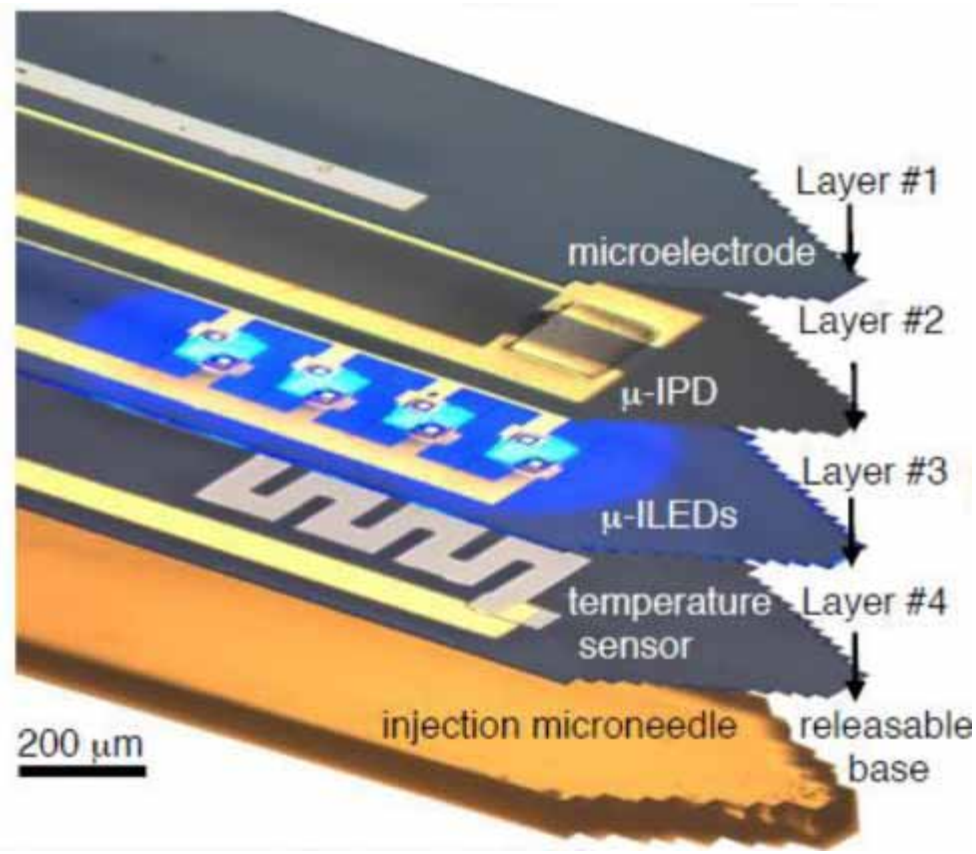


Nature Meth.
8, 26 (2011)

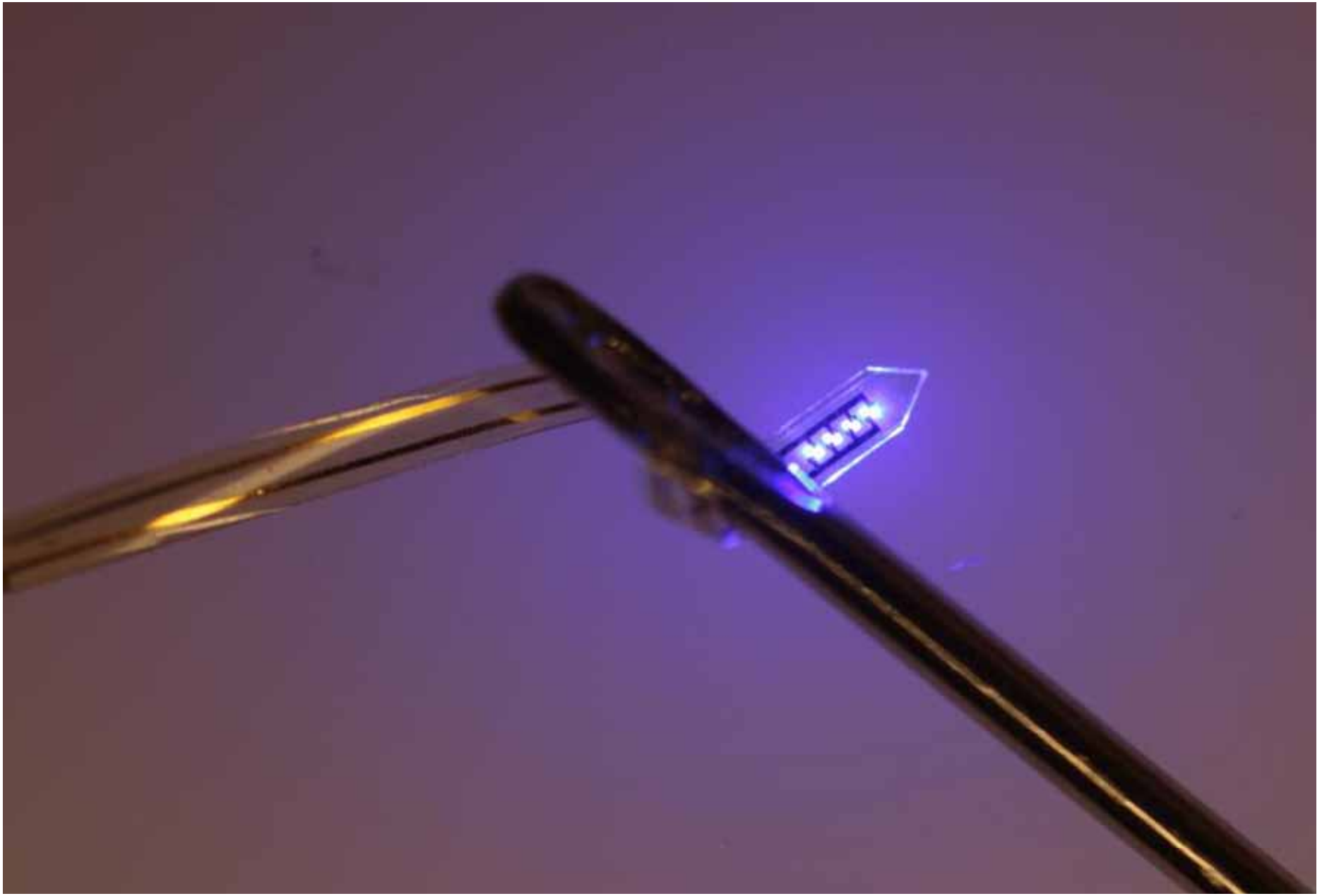
Future – Wireless, Thin, Flexible, Fully Implantable

Multifunctional, 'Cellular-Scale' Optoelectronics

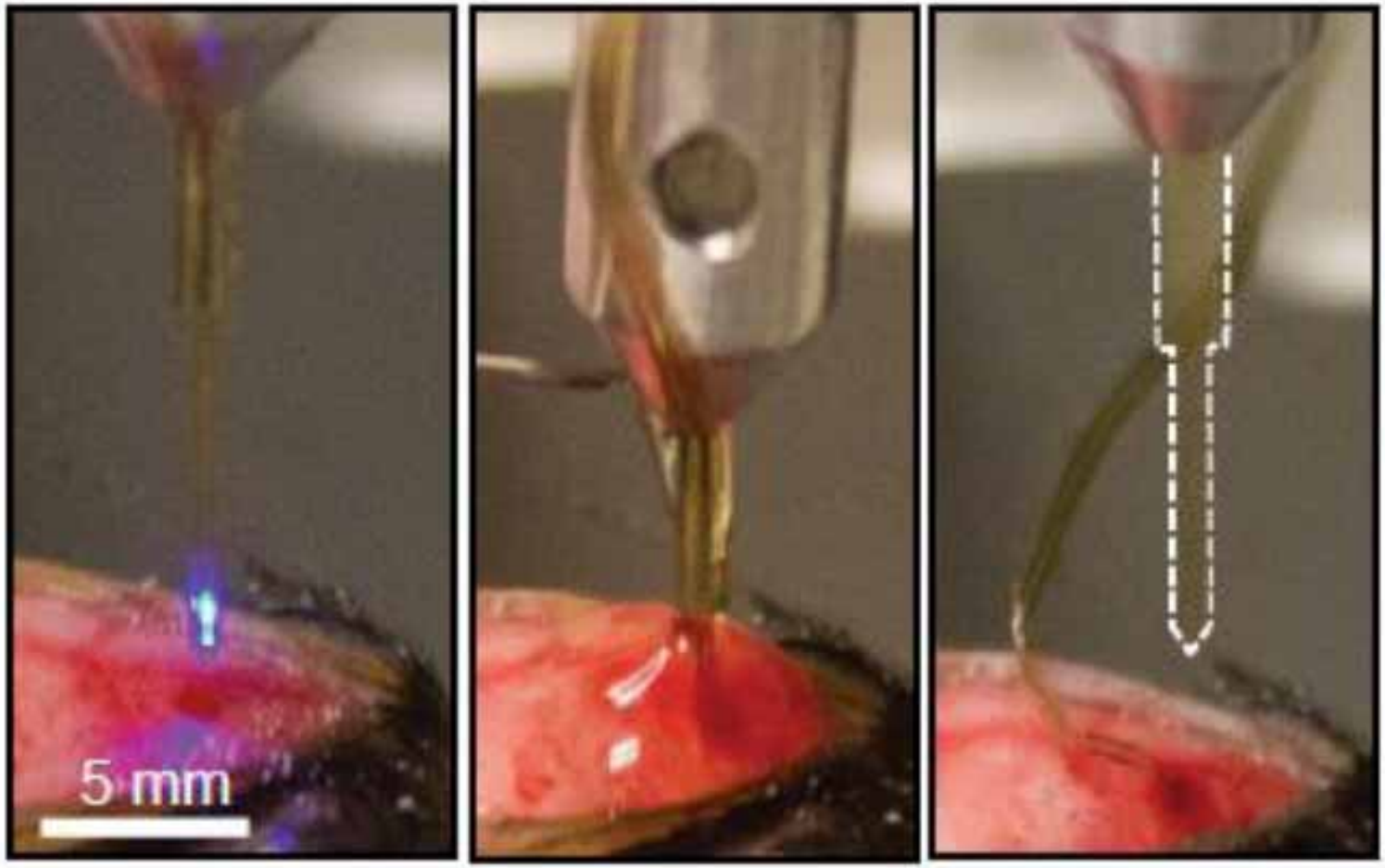




Science **240**, 211 (2013).

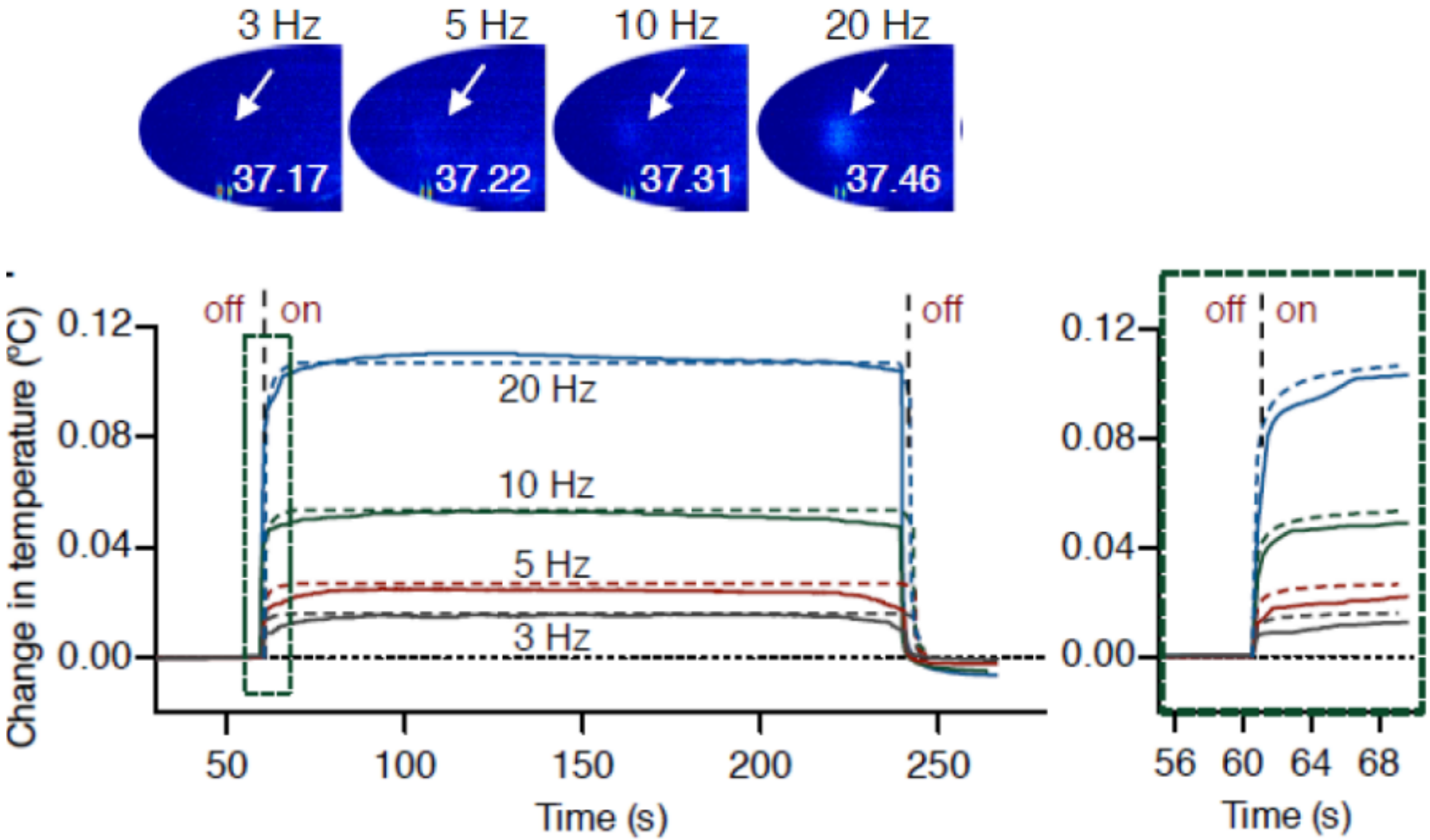


‘Injectable’ Optoelectronics



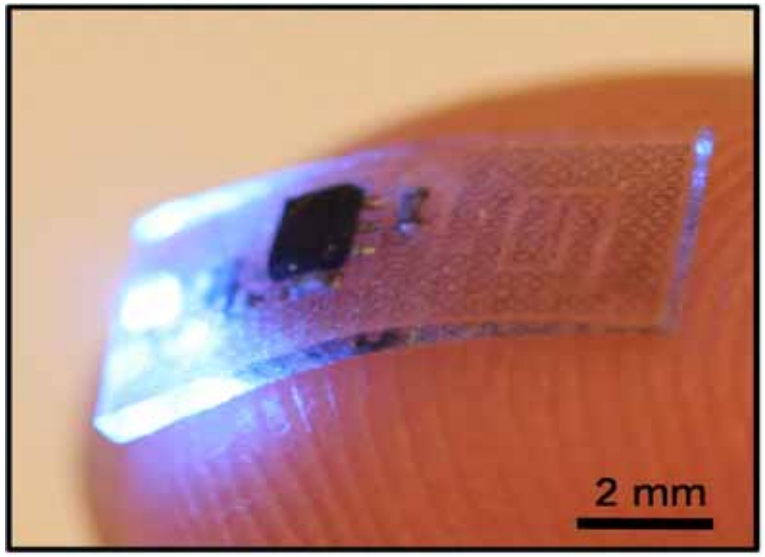
Science **240**, 211 (2013).

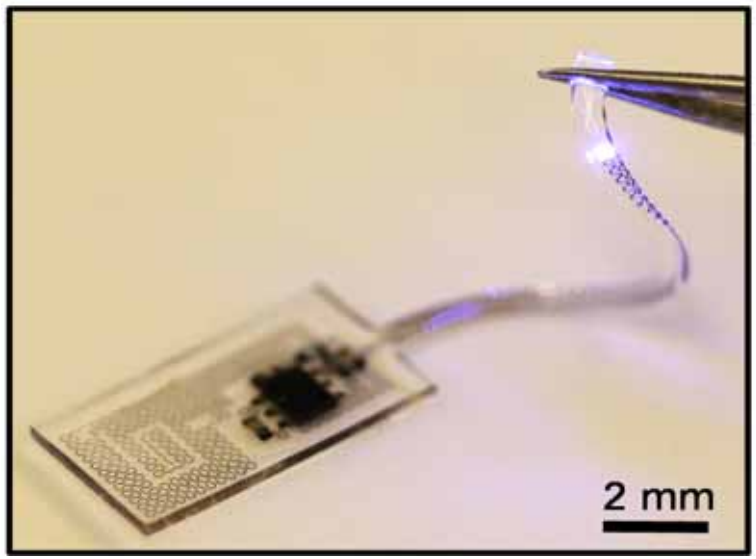
Physics of Heat Flow in the Living Brain

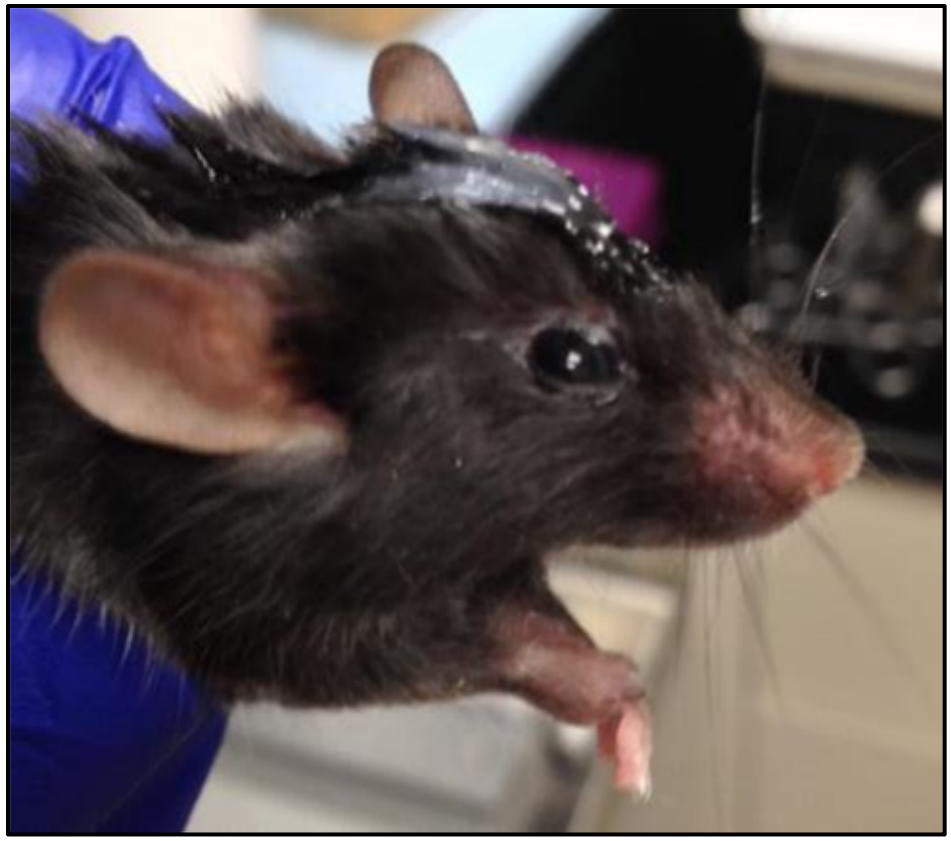


Science **240**, 211 (2013).

Fully Implantable Wireless Optogenetics







Nature Biotechn. **33**, 1280 (2015).

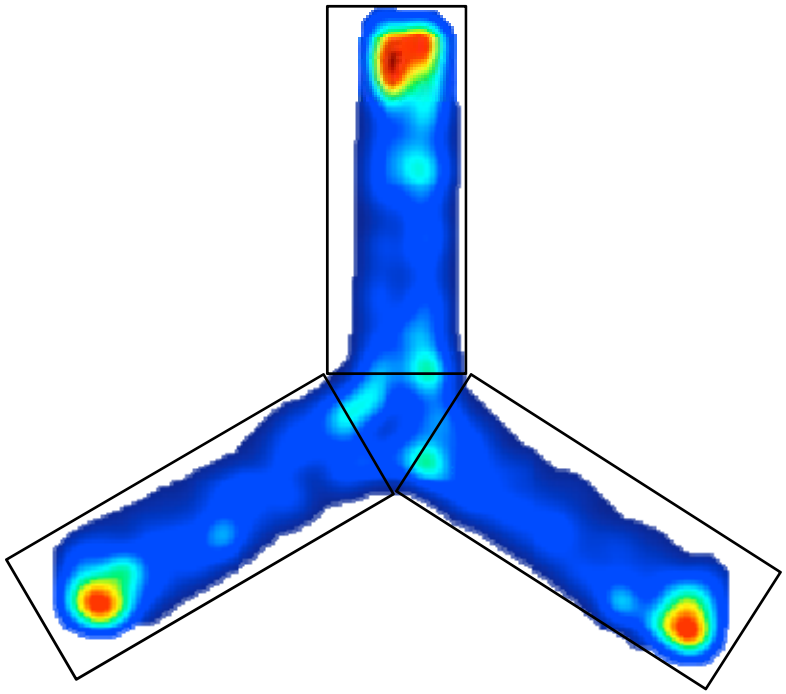
Operation with Multiple Animals in a Place Preference Box

Stimulated **Non-stimulated**

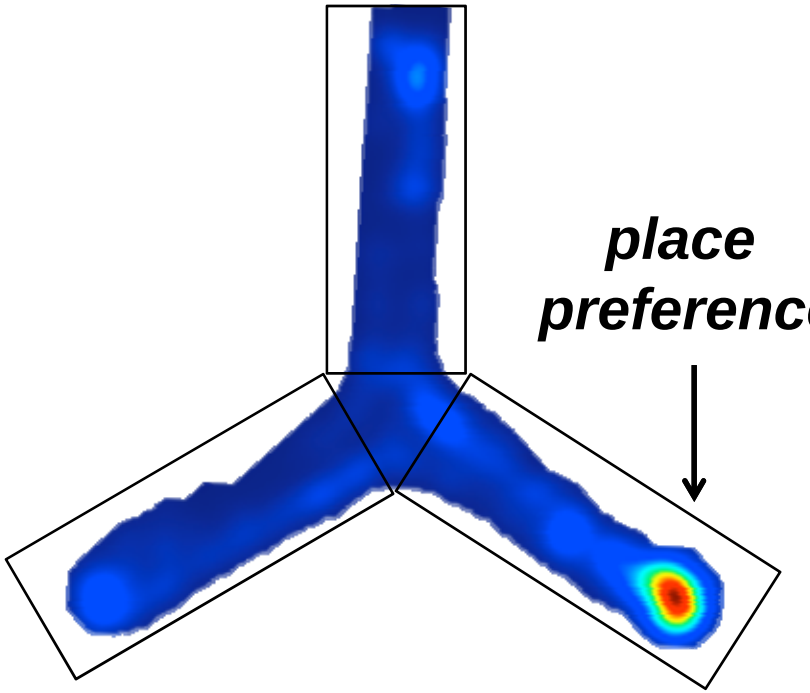
unpublished

Wireless Optogenetics With Freely Moving Mice

Maps of Location in a Y-Maze



untrained

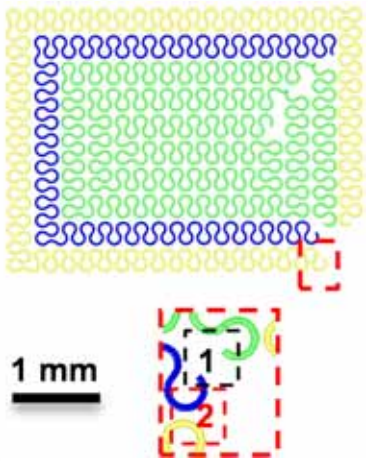


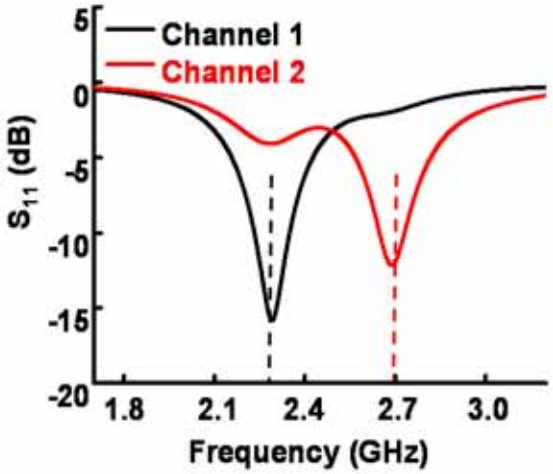
place preference

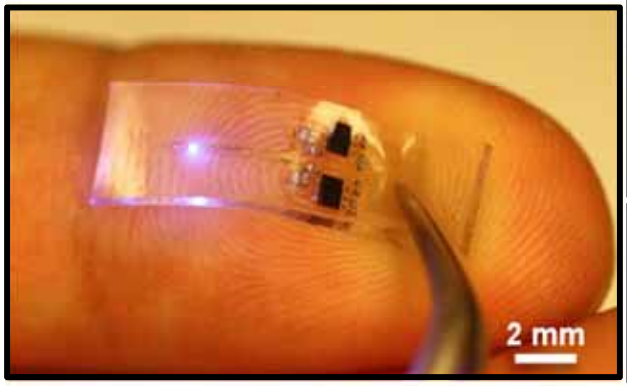
trained using injected, wireless LEDs

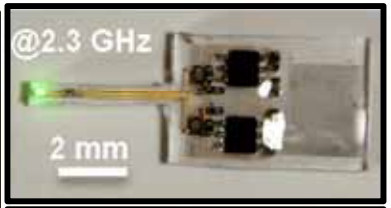
Science **240**, 211 (2013).

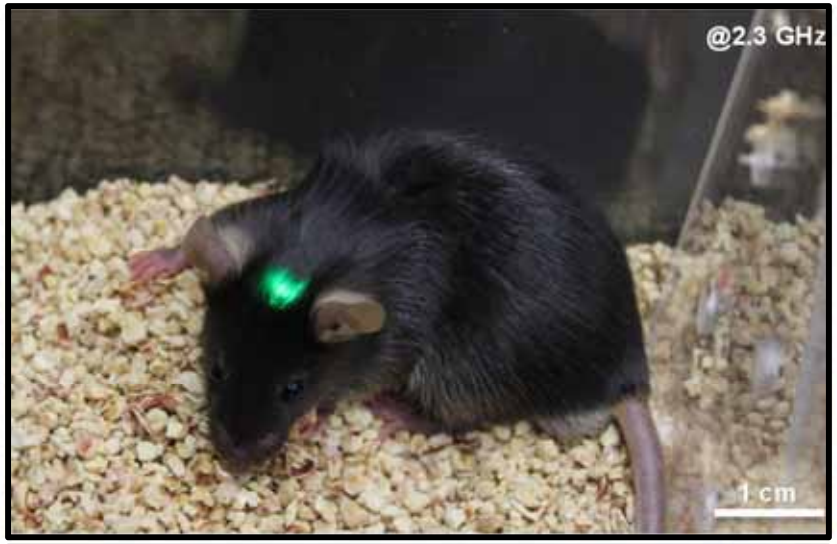
Multi-channel, Multi-Wavelength Wireless Operation

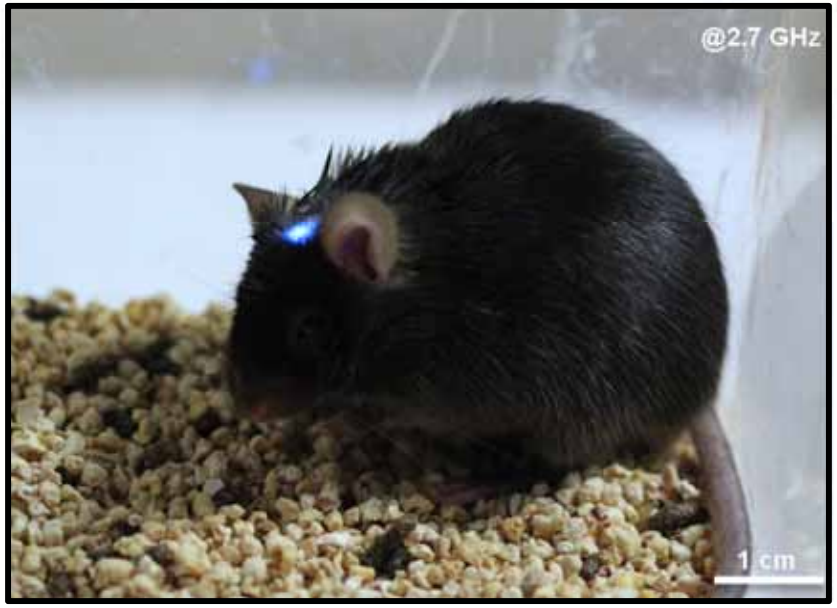








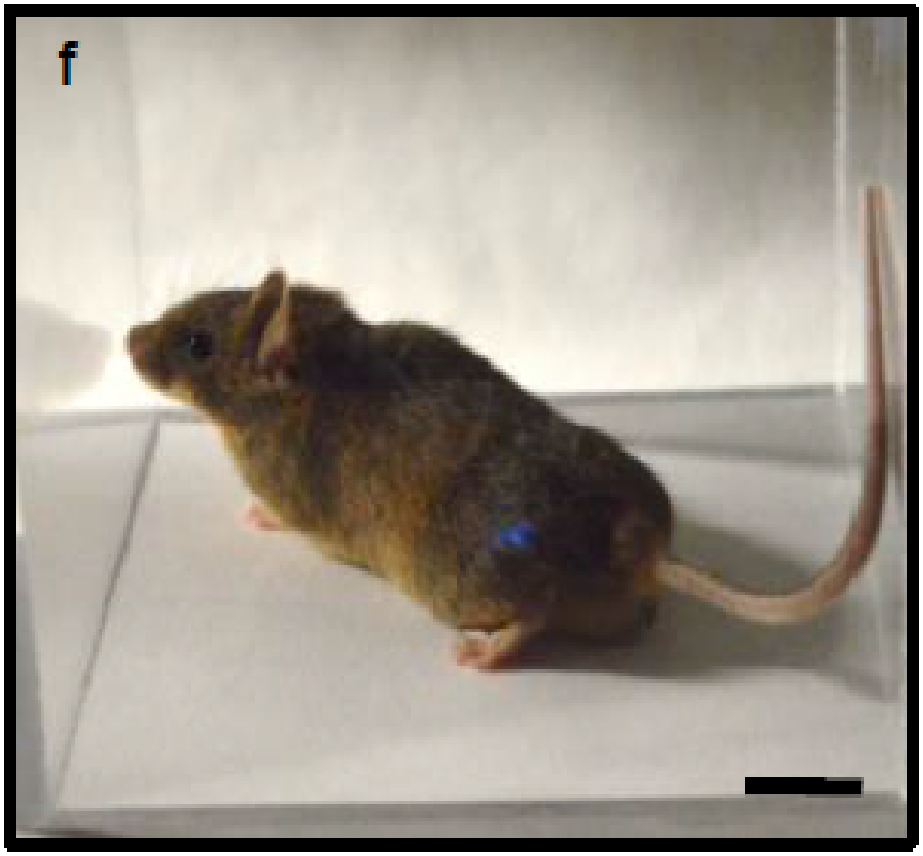




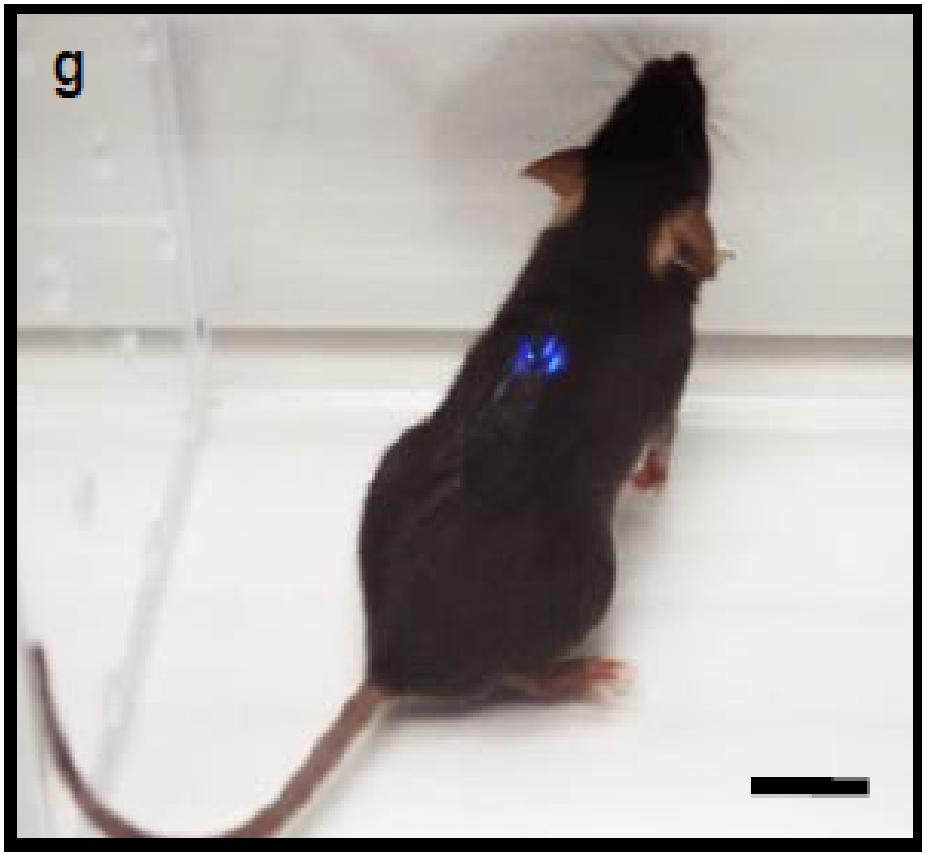
PNAS, in press

Fully Implantable Wireless Optogenetics

Sciatic Nerve



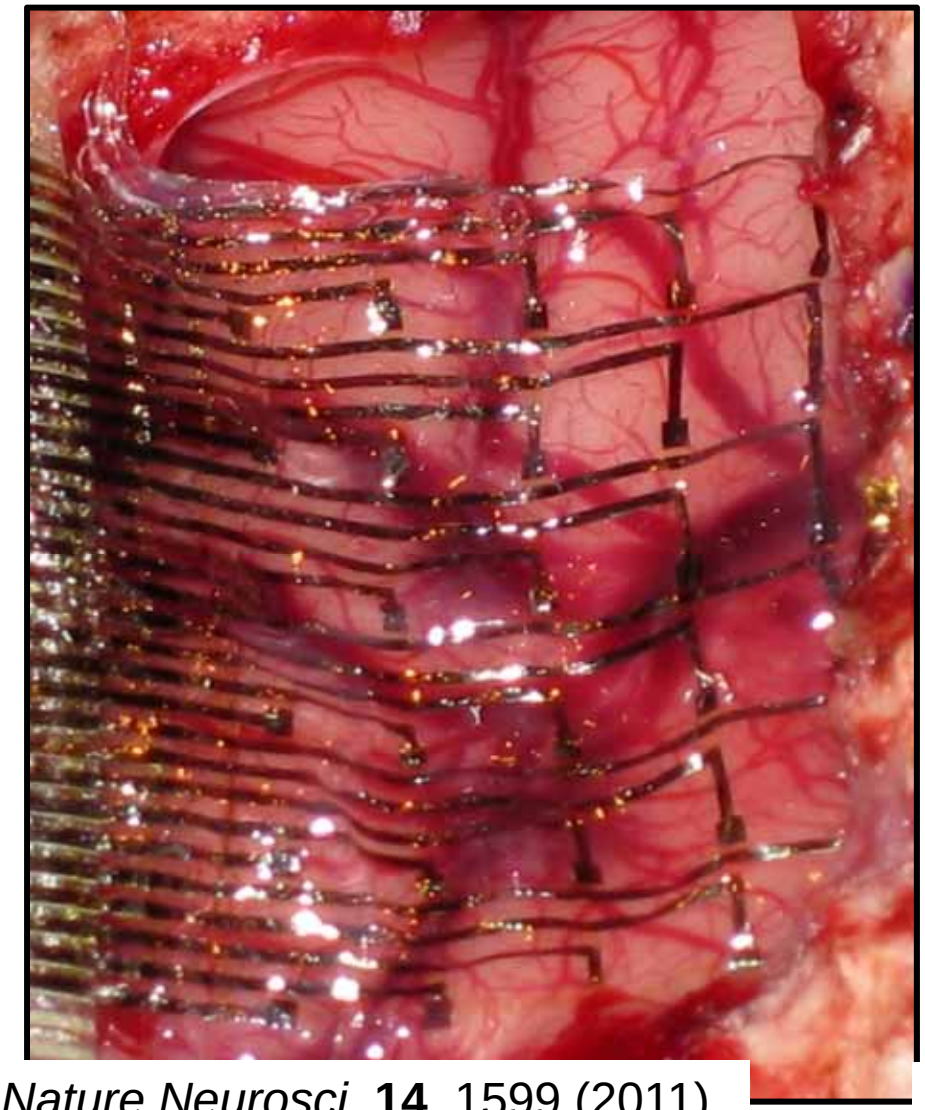
Spinal Cord



Nature Biotechn. **33**, 1280 (2015).

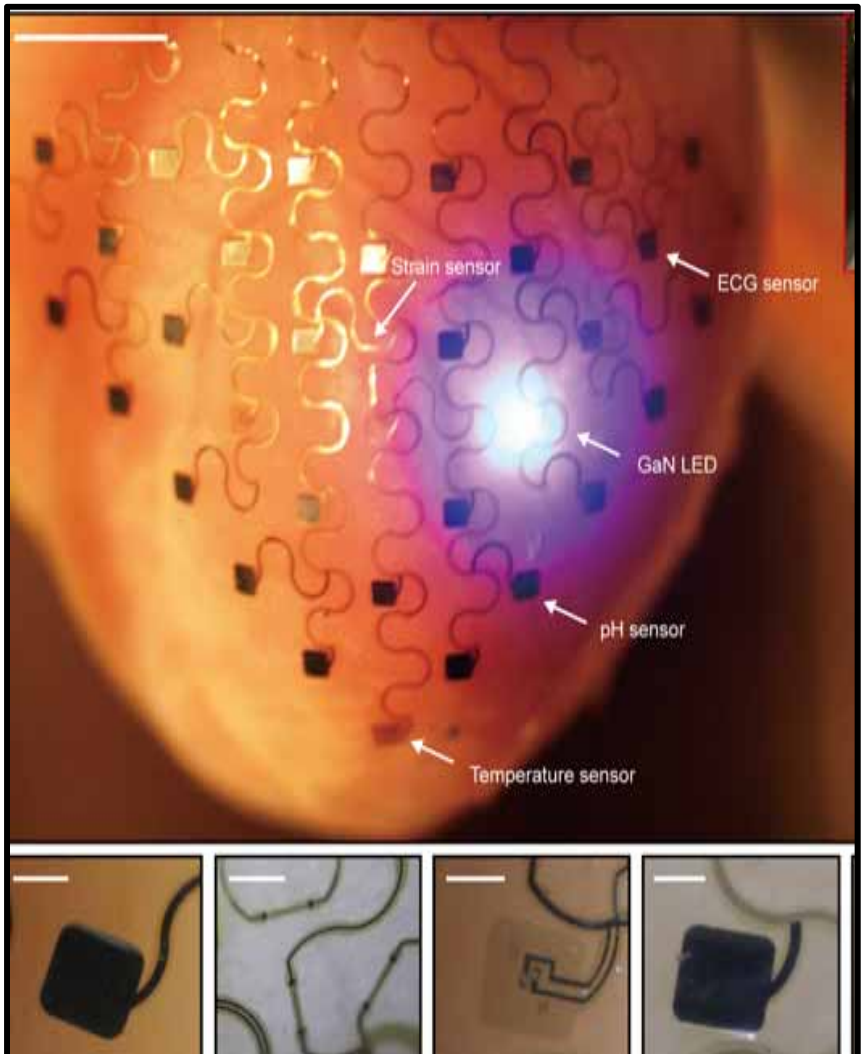
Bio-Integrated Electronics

Brain



Nature Neurosci. **14**, 1599 (2011).

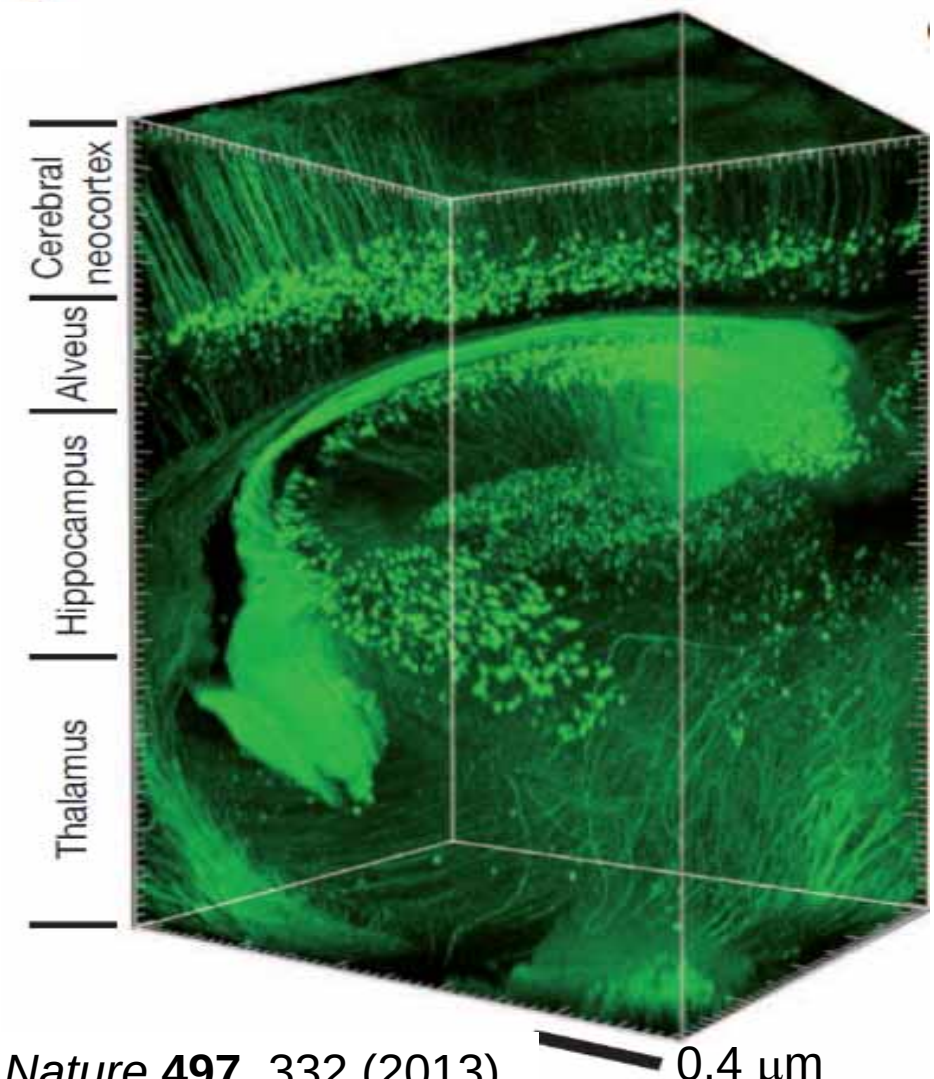
Heart



Nature Comm. 10.1038/ncomms4329 (2014).

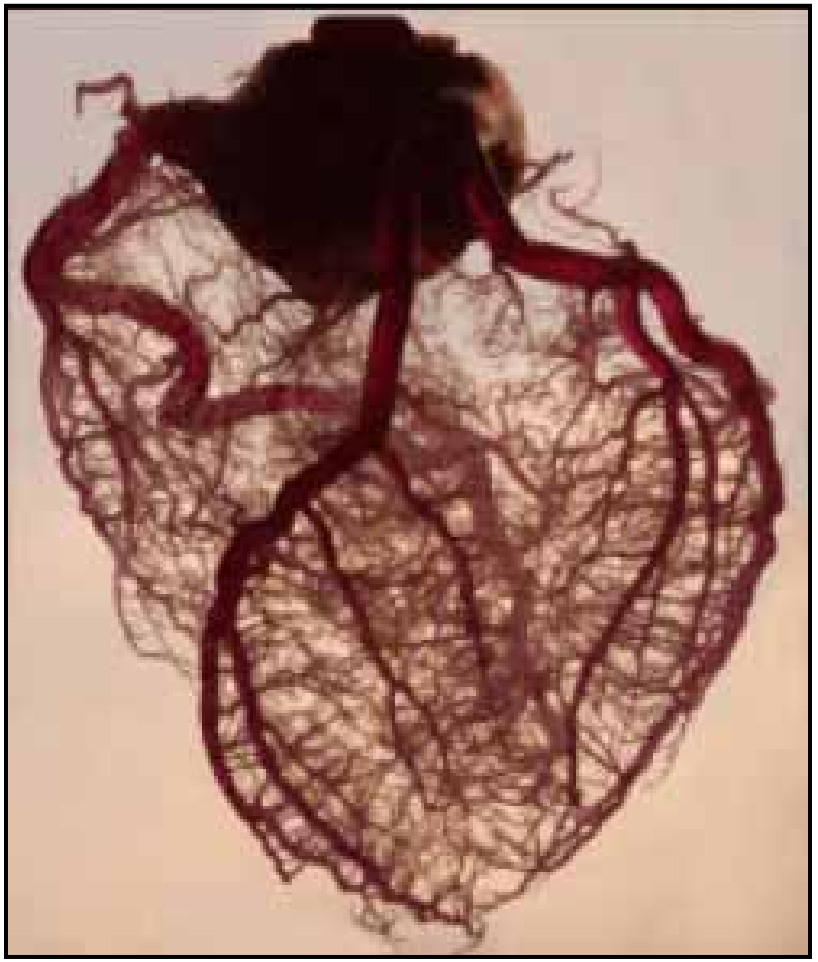
3D Mesoscale Network Structures in Biology

Brain – Neural Circuits



Nature **497**, 332 (2013).

Heart -- Vasculature



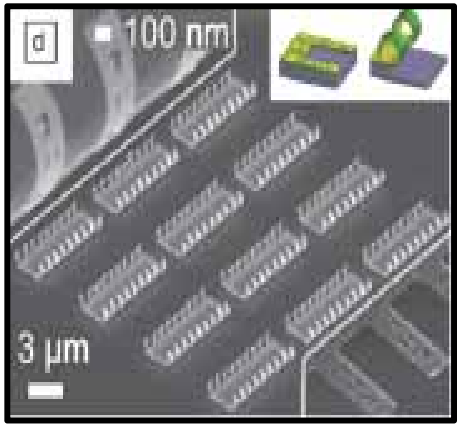
1 cm

MediVisuals

Options in 3D Micro/Nanofab

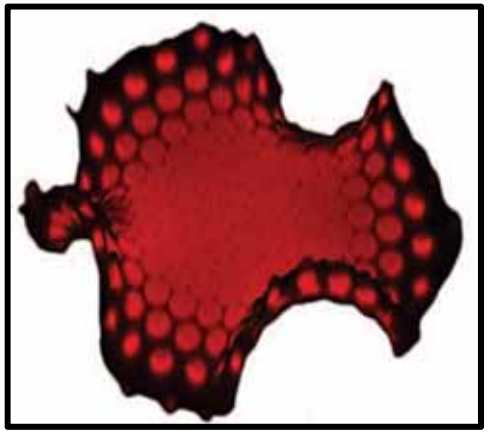
Stress-Induced Bending

Cylinders



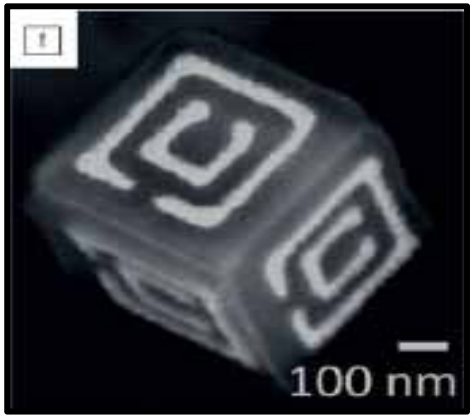
MRS Bull (2012)

Complex Forms



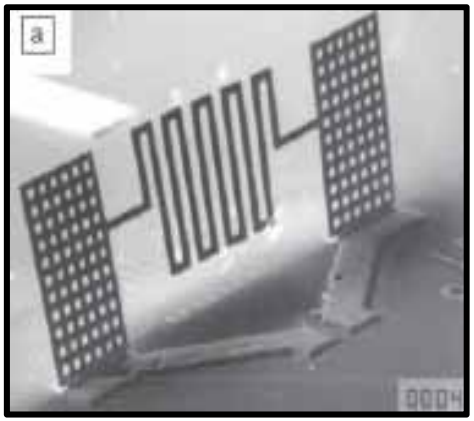
Science (2012)

Polyhedra



MRS Bull (2012)

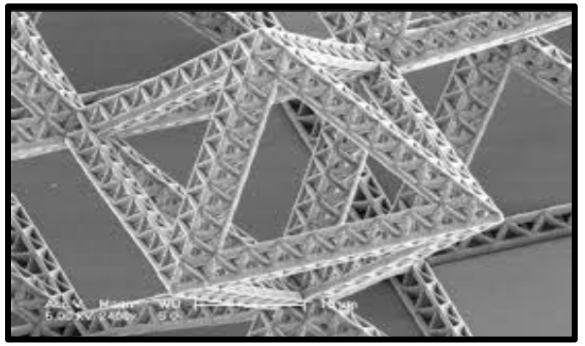
Rotated Plates



MRS Bull (2012)

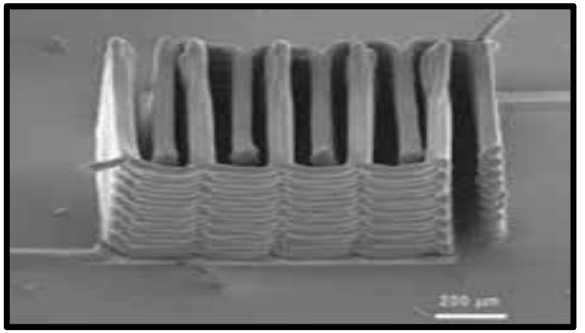
2 Photon Lithography

Science (2014)



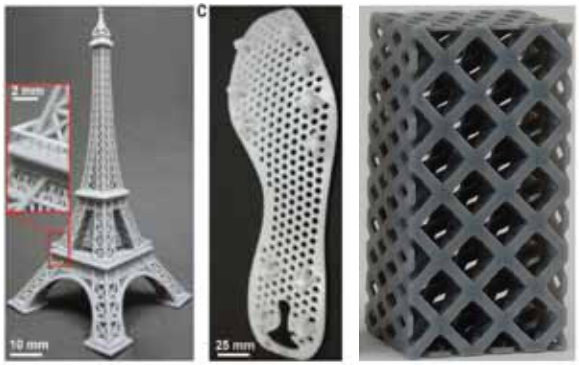
Direct Write Printing

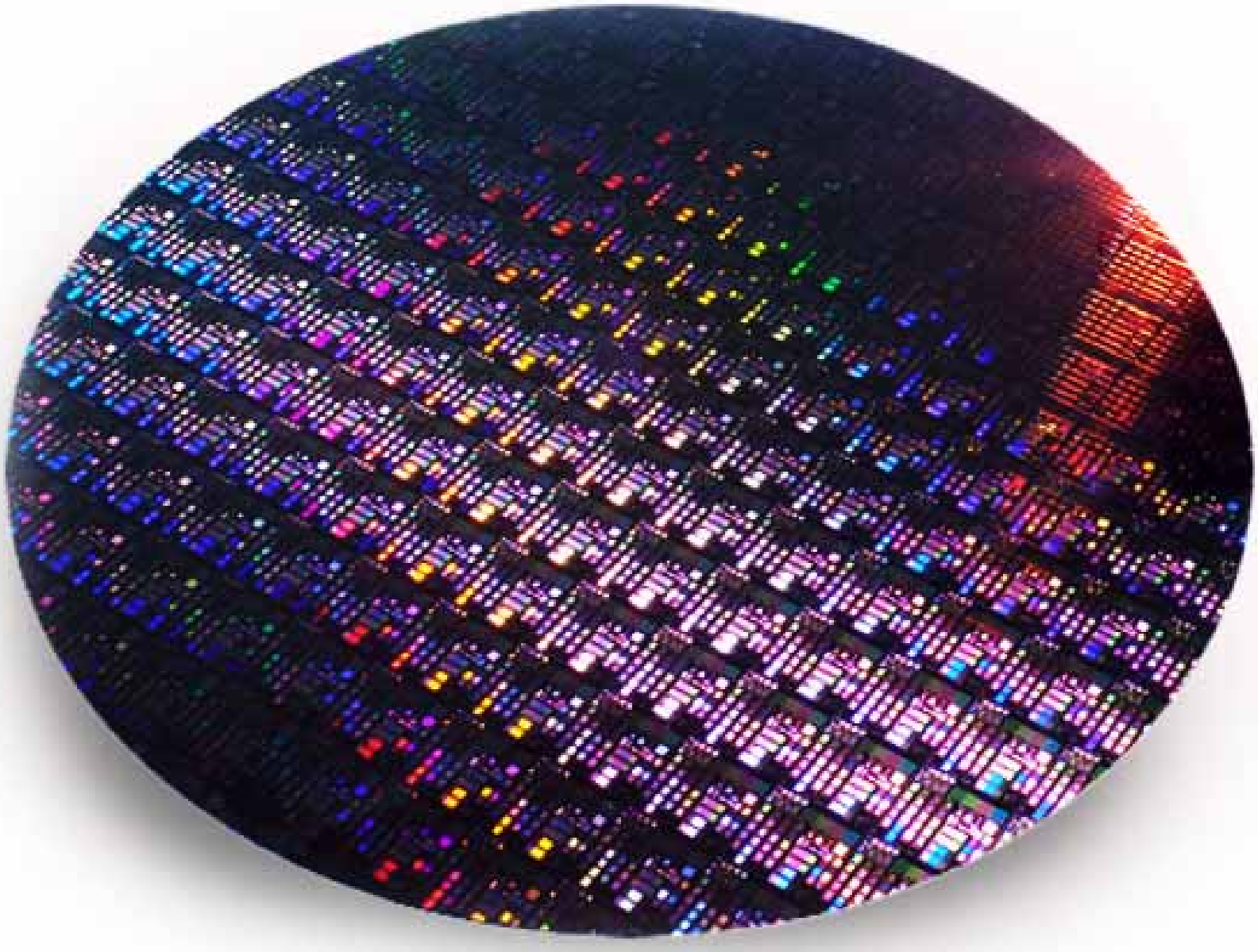
Adv Mat. (2013)



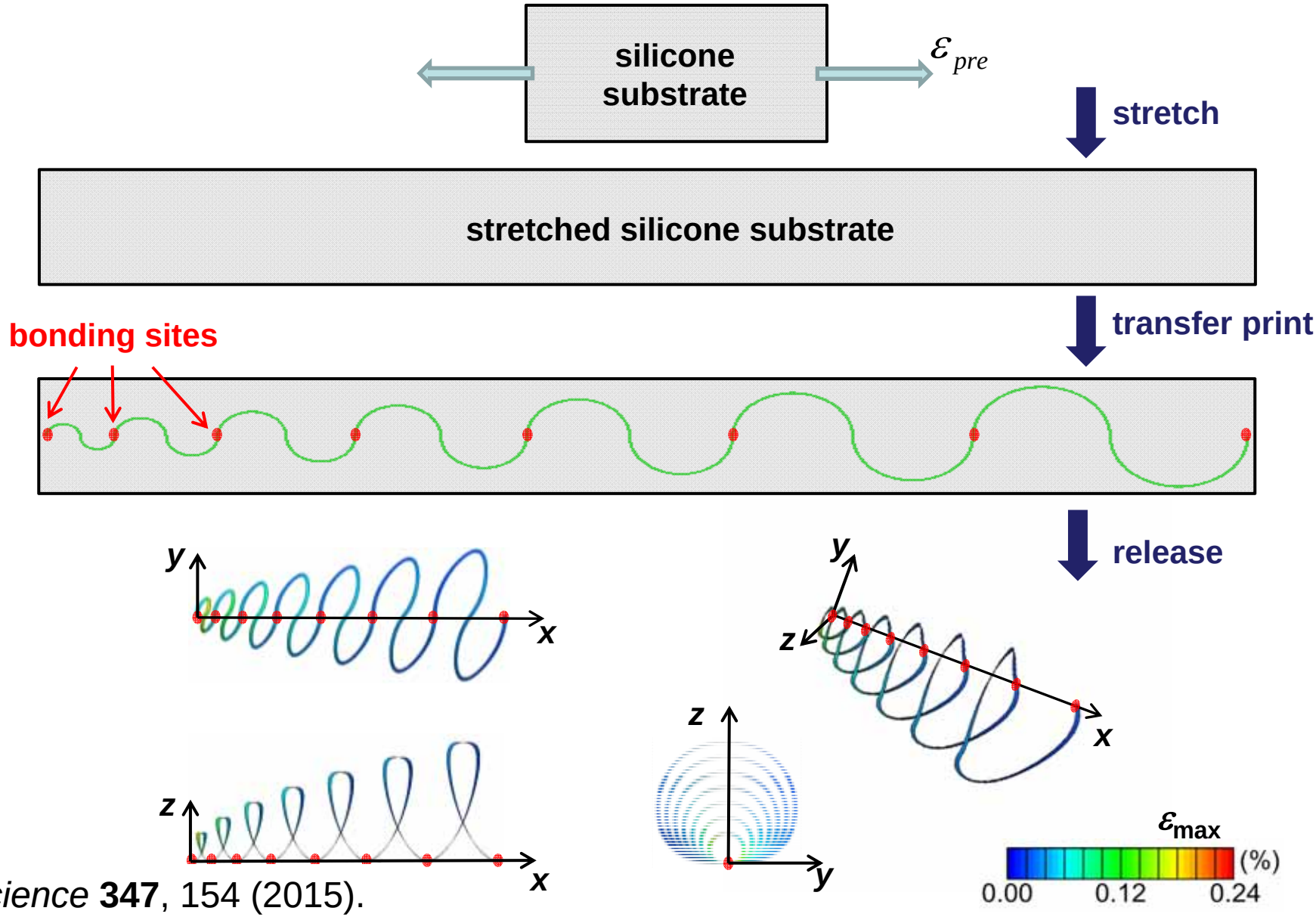
3D Photopatterning

Science (2015)



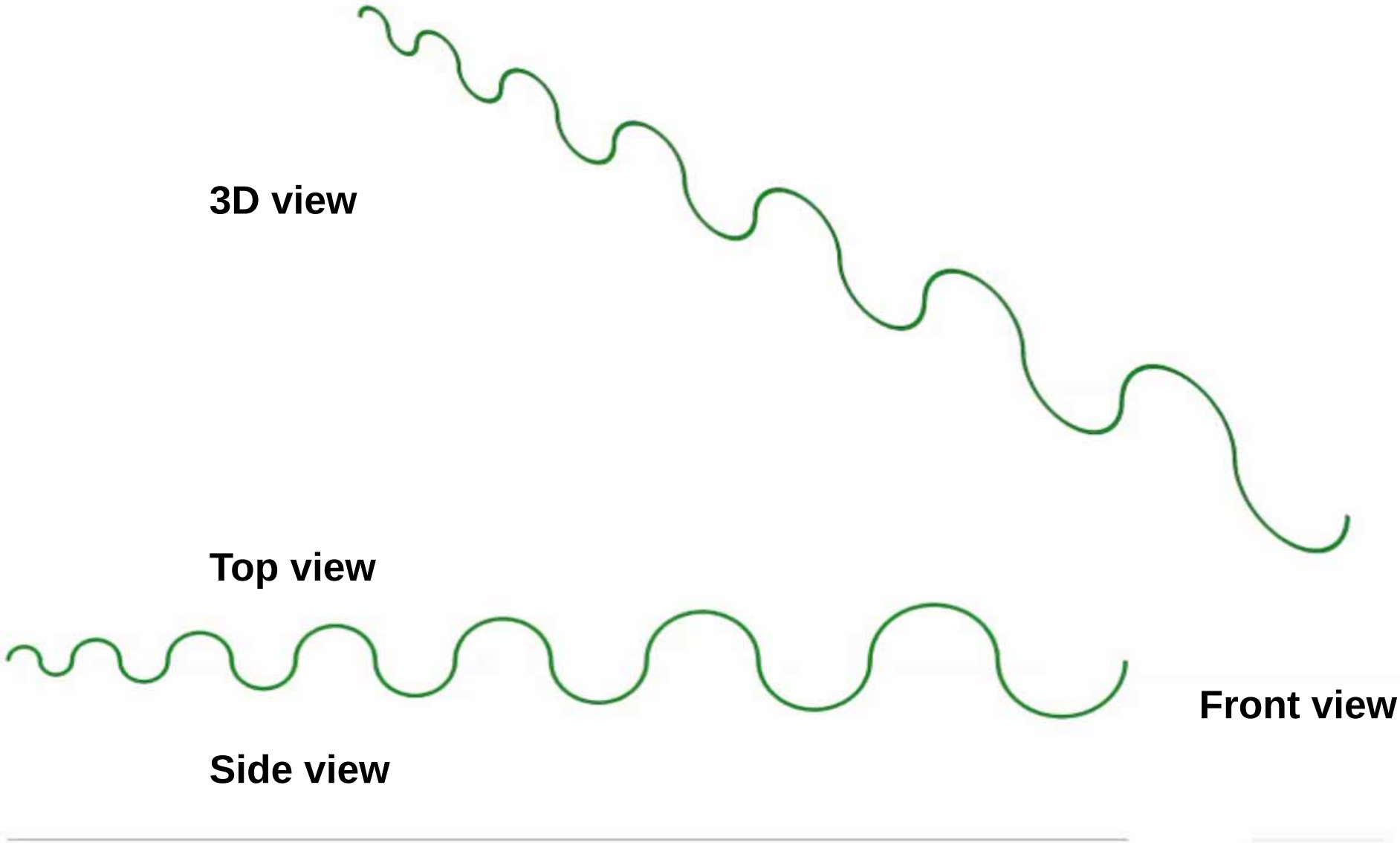


Assembly of a 3D Mesoscale Conical Helix

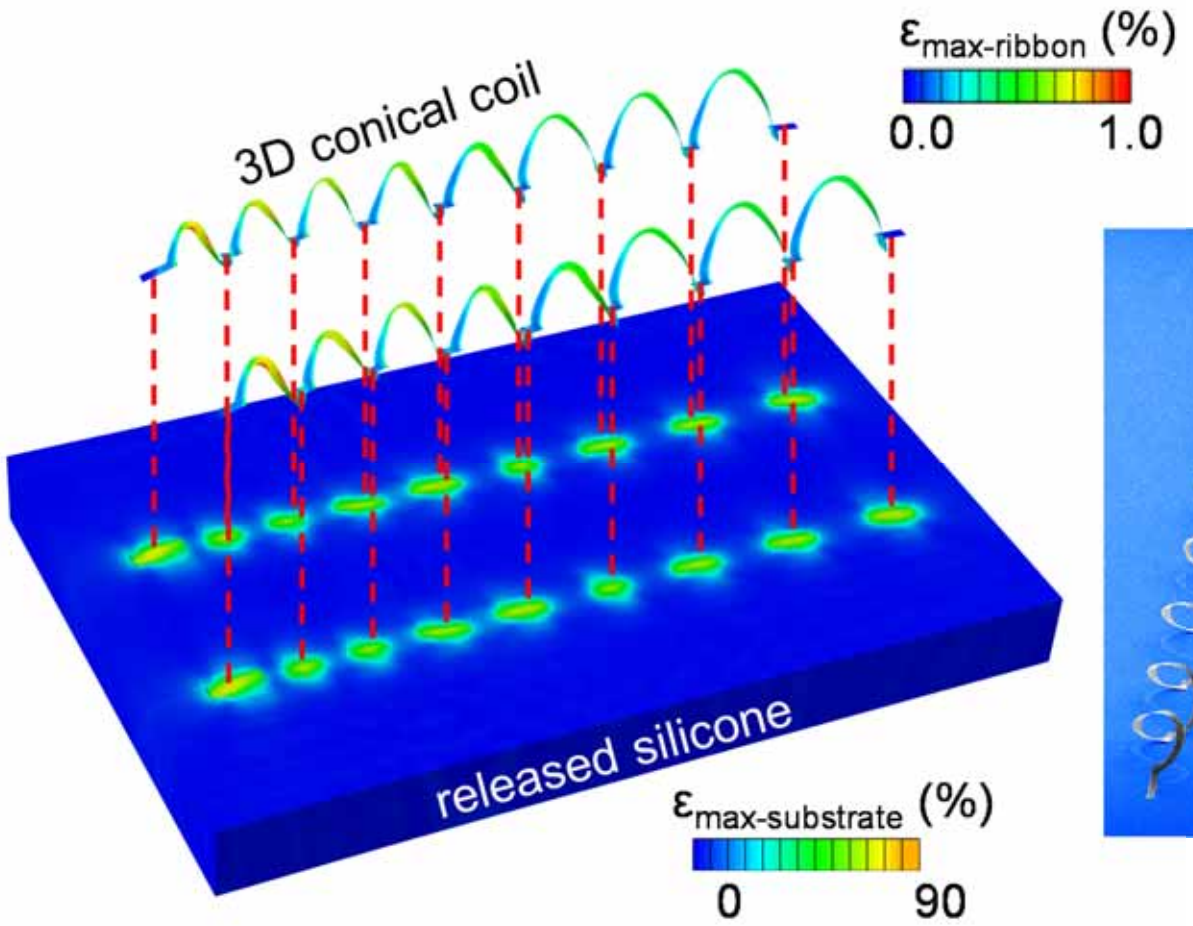


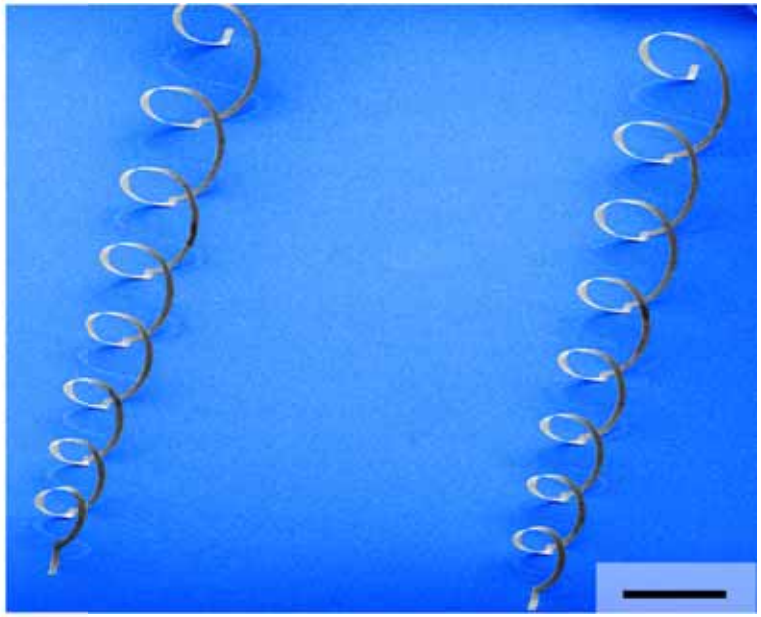
Science **347**, 154 (2015).

Assembly of a 3D Mesoscale Conical Helix



Assembly of a 3D Mesoscale Conical Helix





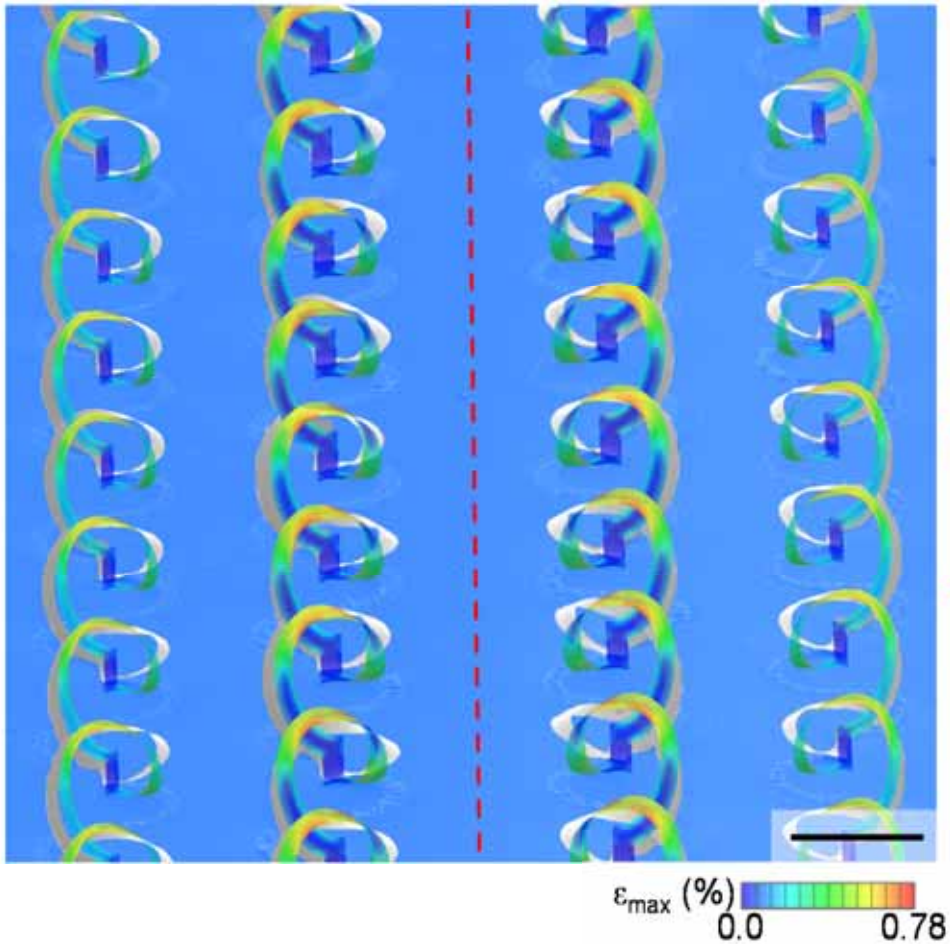
200 μm

Device Grade Silicon

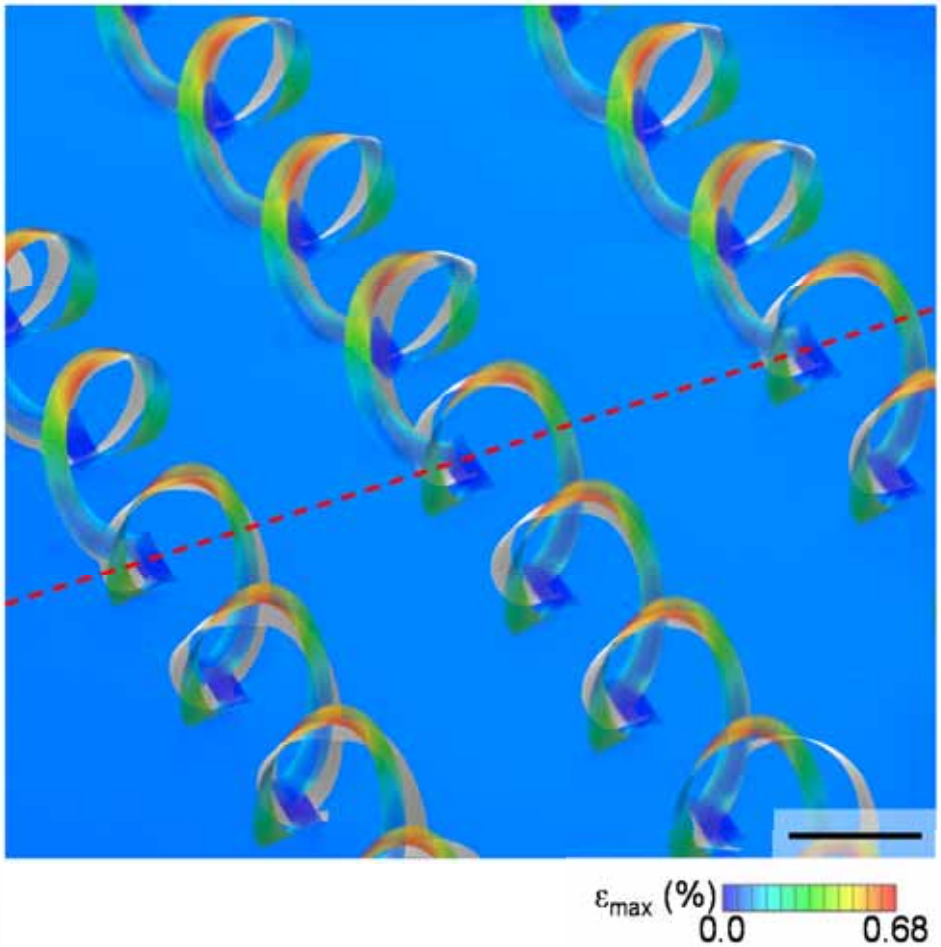
Science **347**, 154 (2015).

Assembly of 3D Helices With Chirality Control

Right and Left Handed Coils

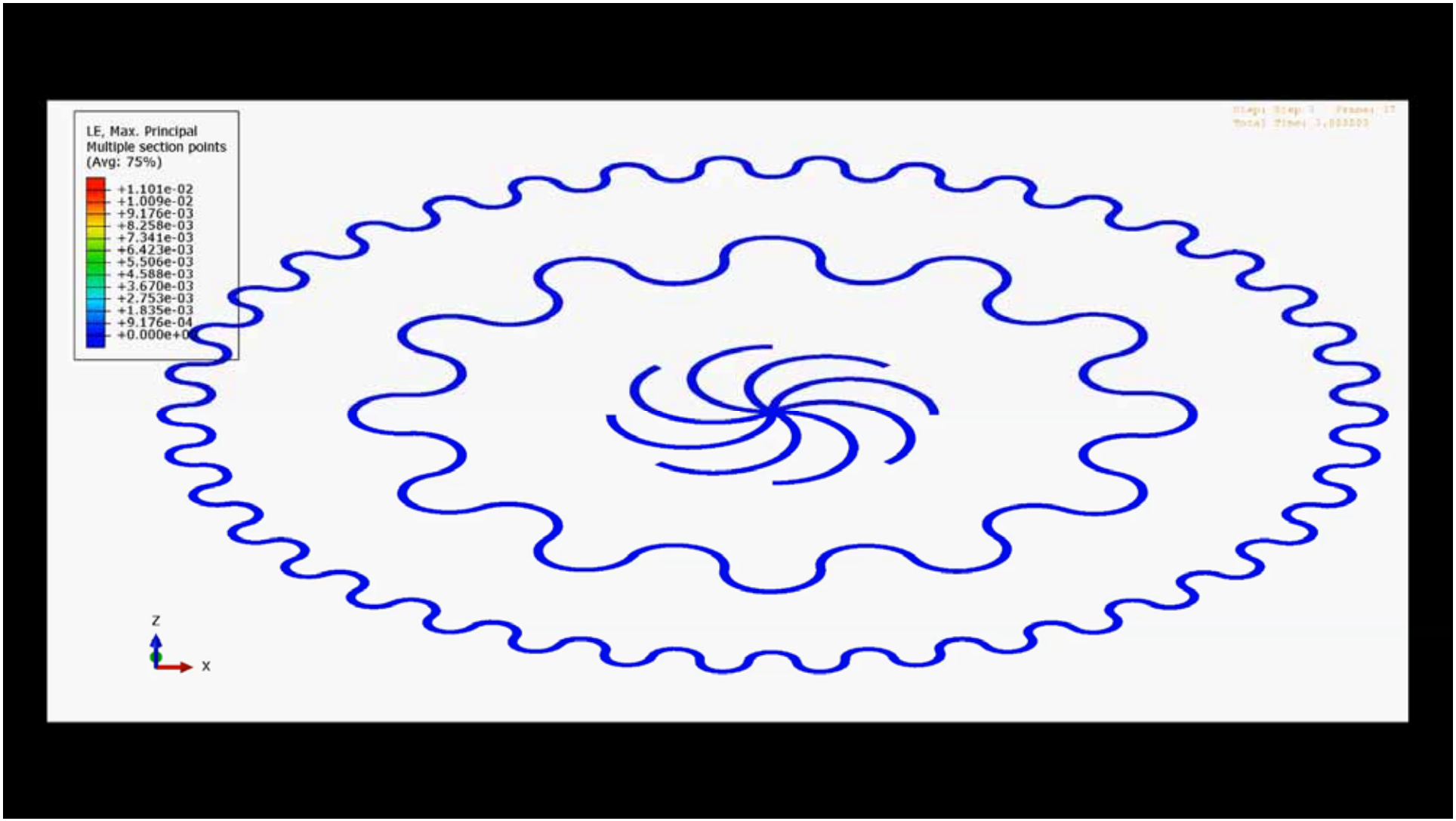


Anti Helmholtz Coils



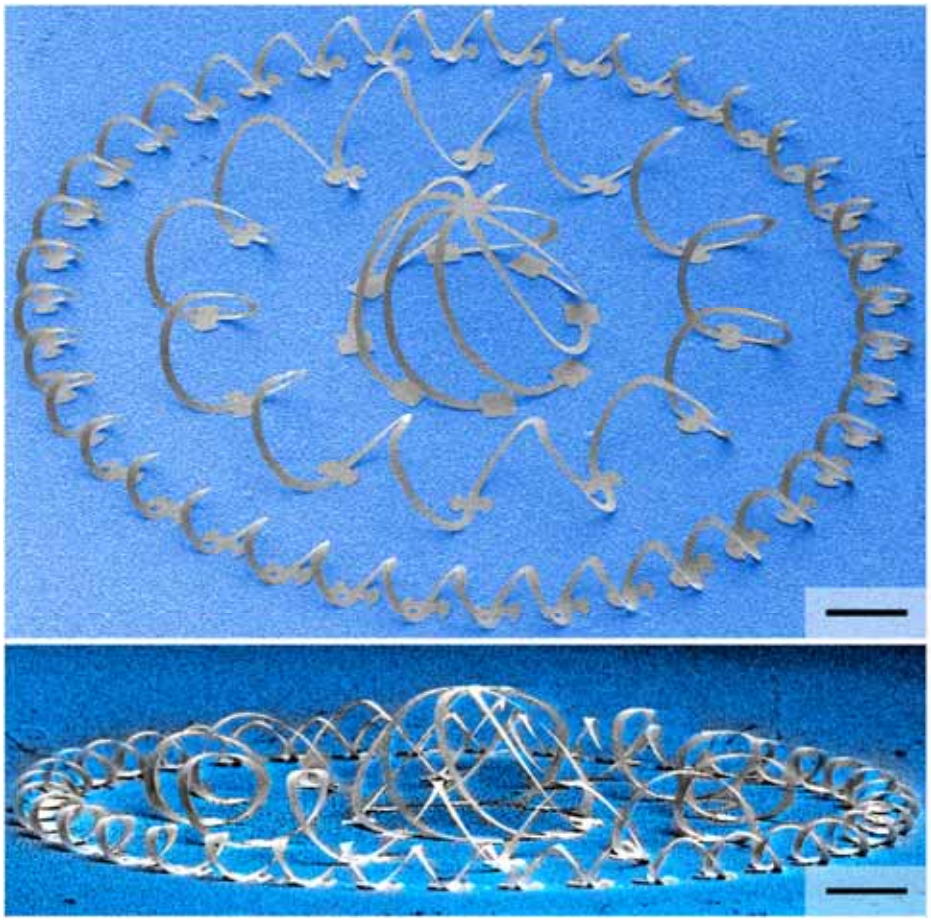
Science **347**, 154 (2015).

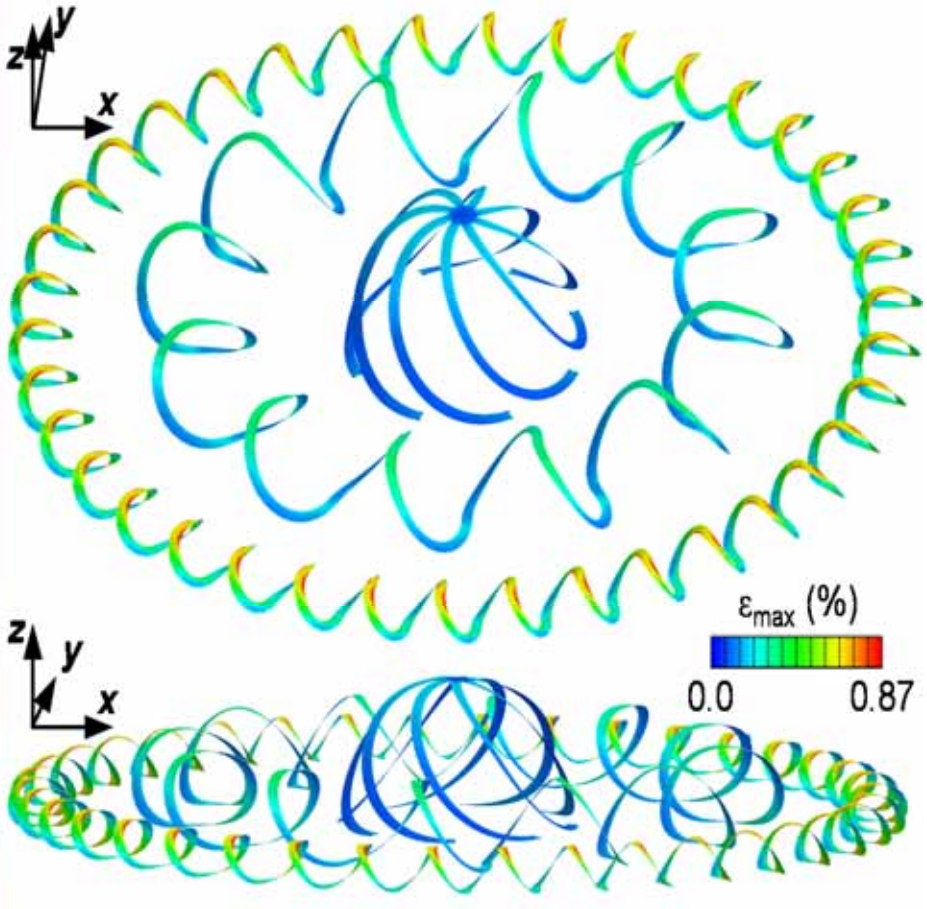
Assembly of 3D, Nested Toroids and Baskets



Science **347**, 154 (2015).

Assembly of 3D, Nested Toroids and Baskets

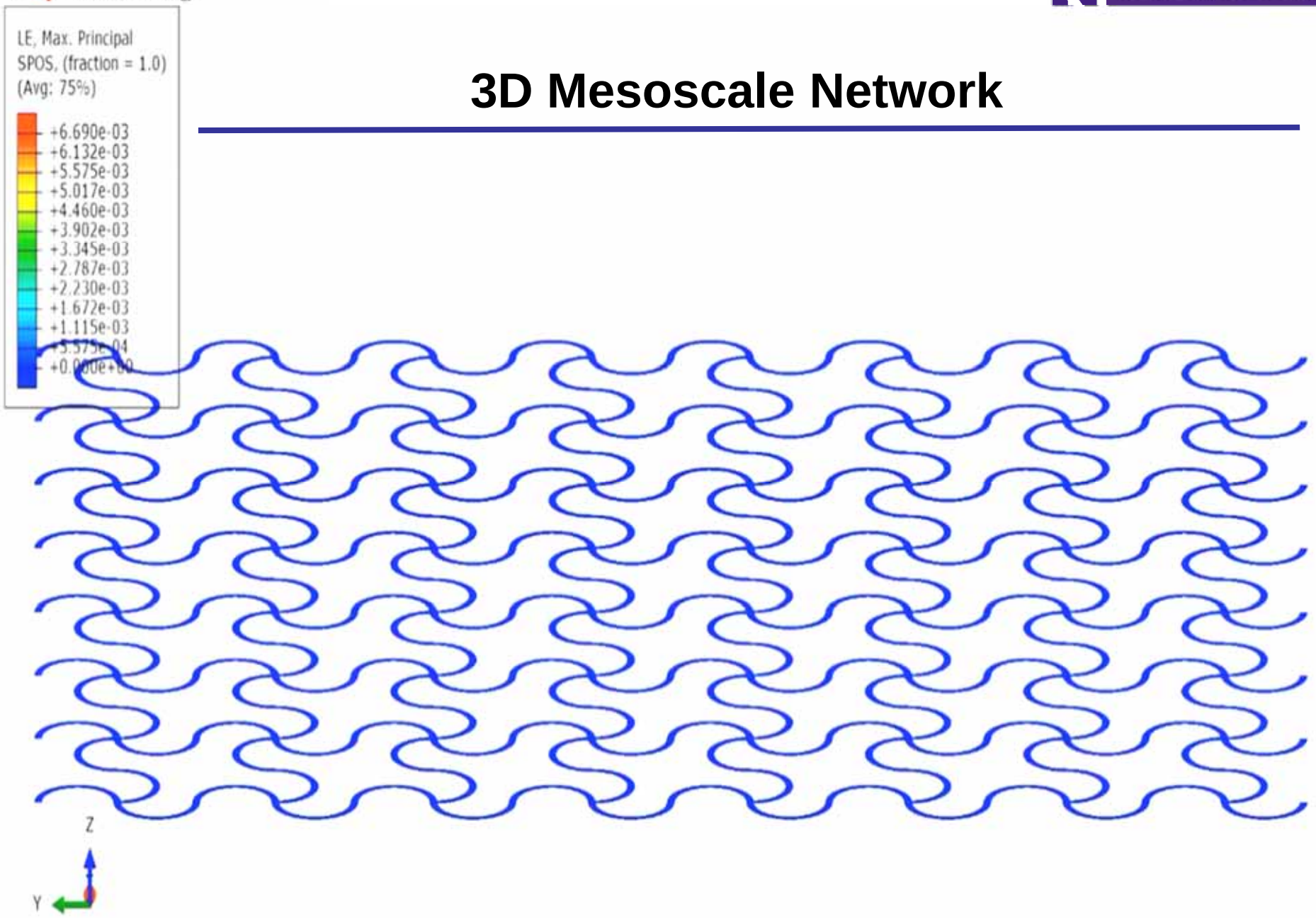




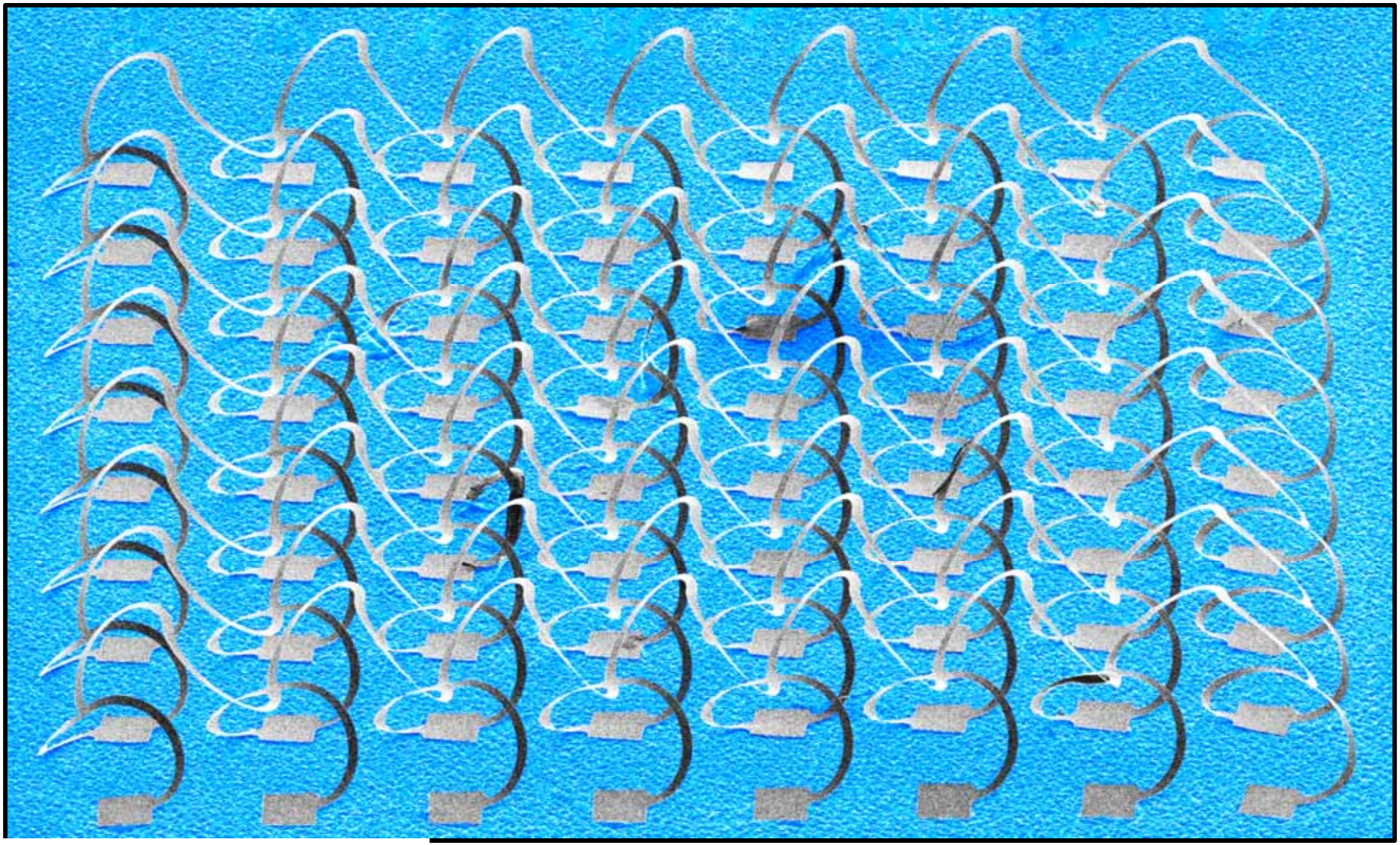
400 μm

Science **347**, 154 (2015).

3D Mesoscale Network



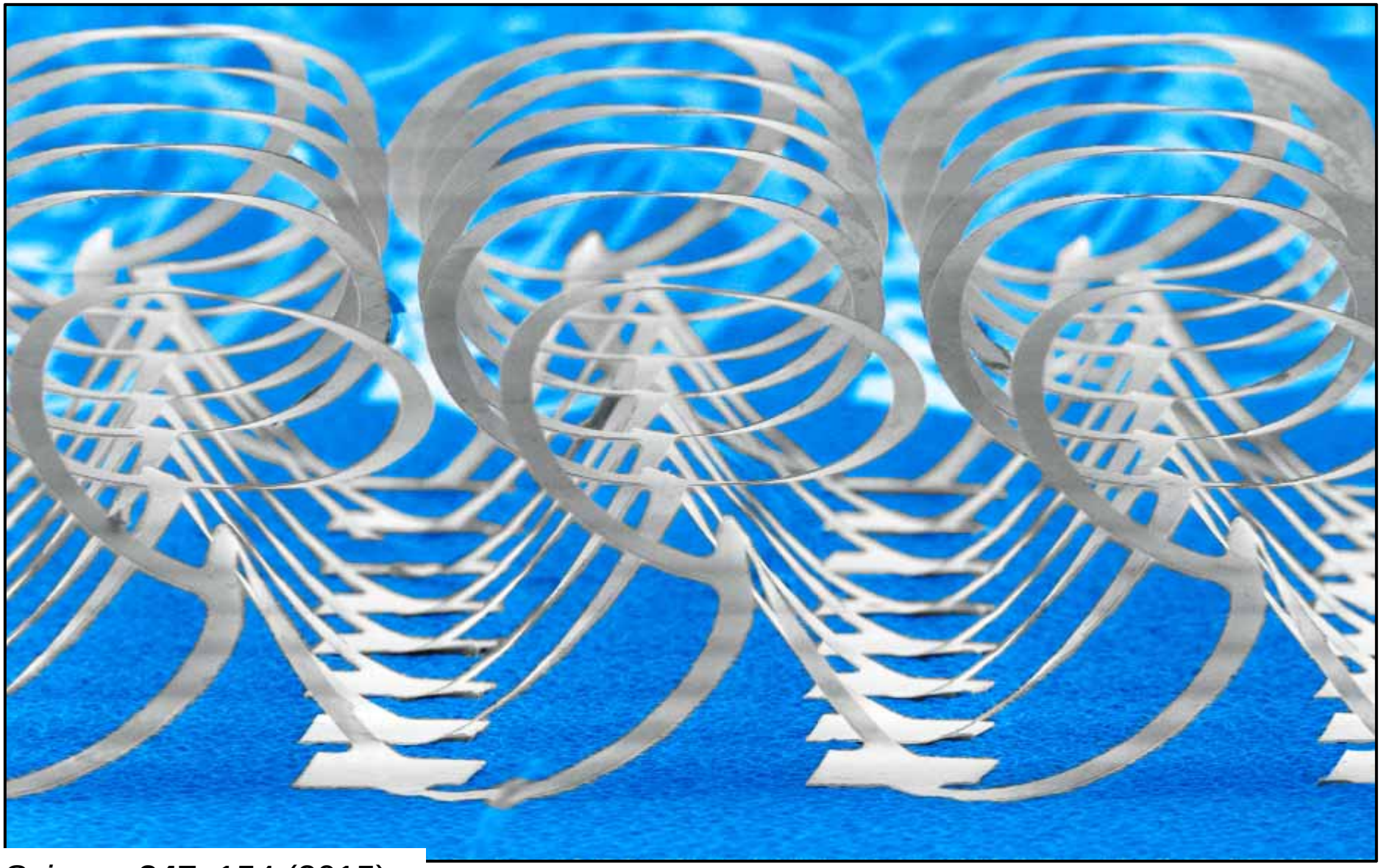
3D Mesoscale Network in Silicon



Science **347**, 154 (2015).

400 μm

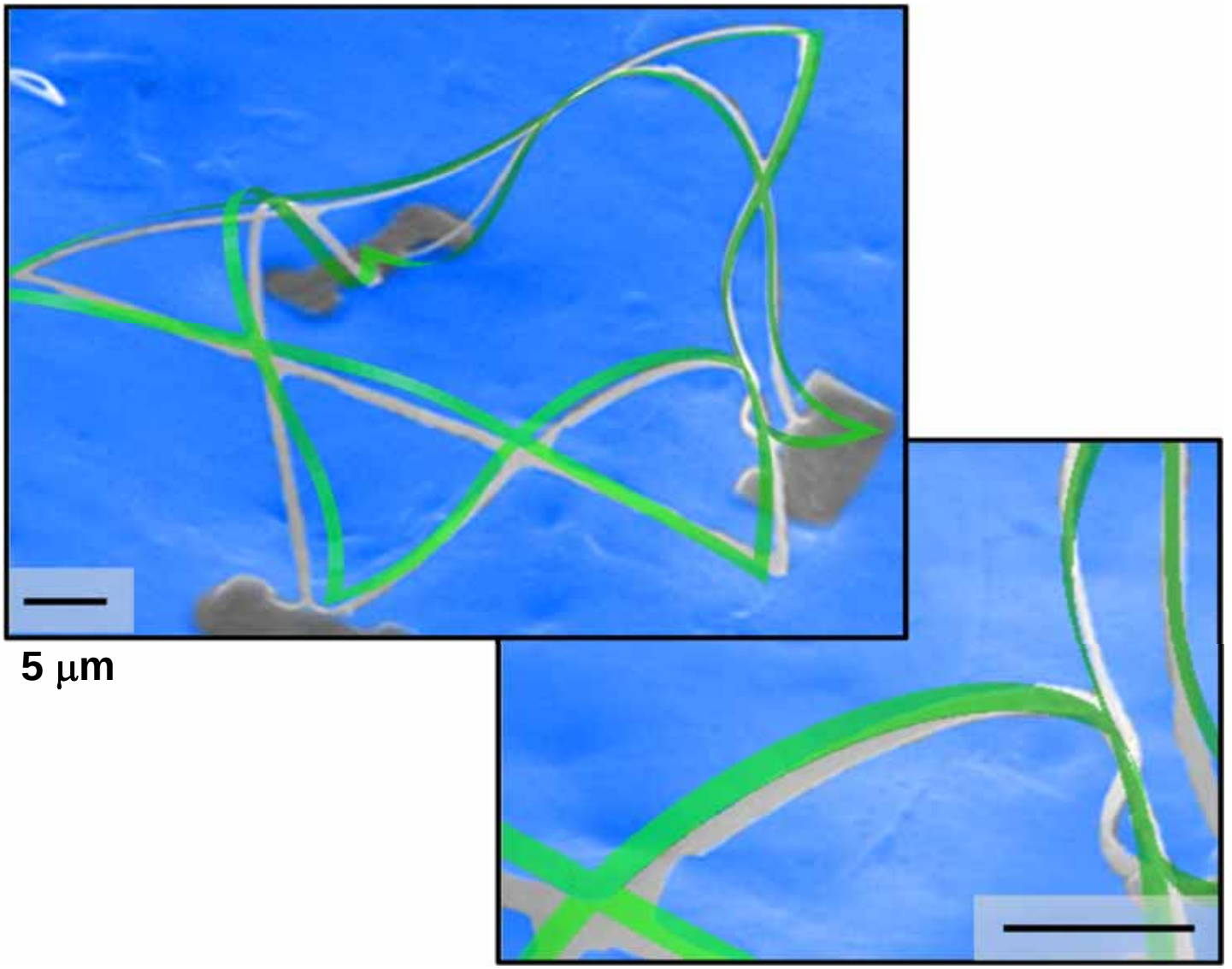
3D Mesoscale Network in Silicon



Science **347**, 154 (2015).

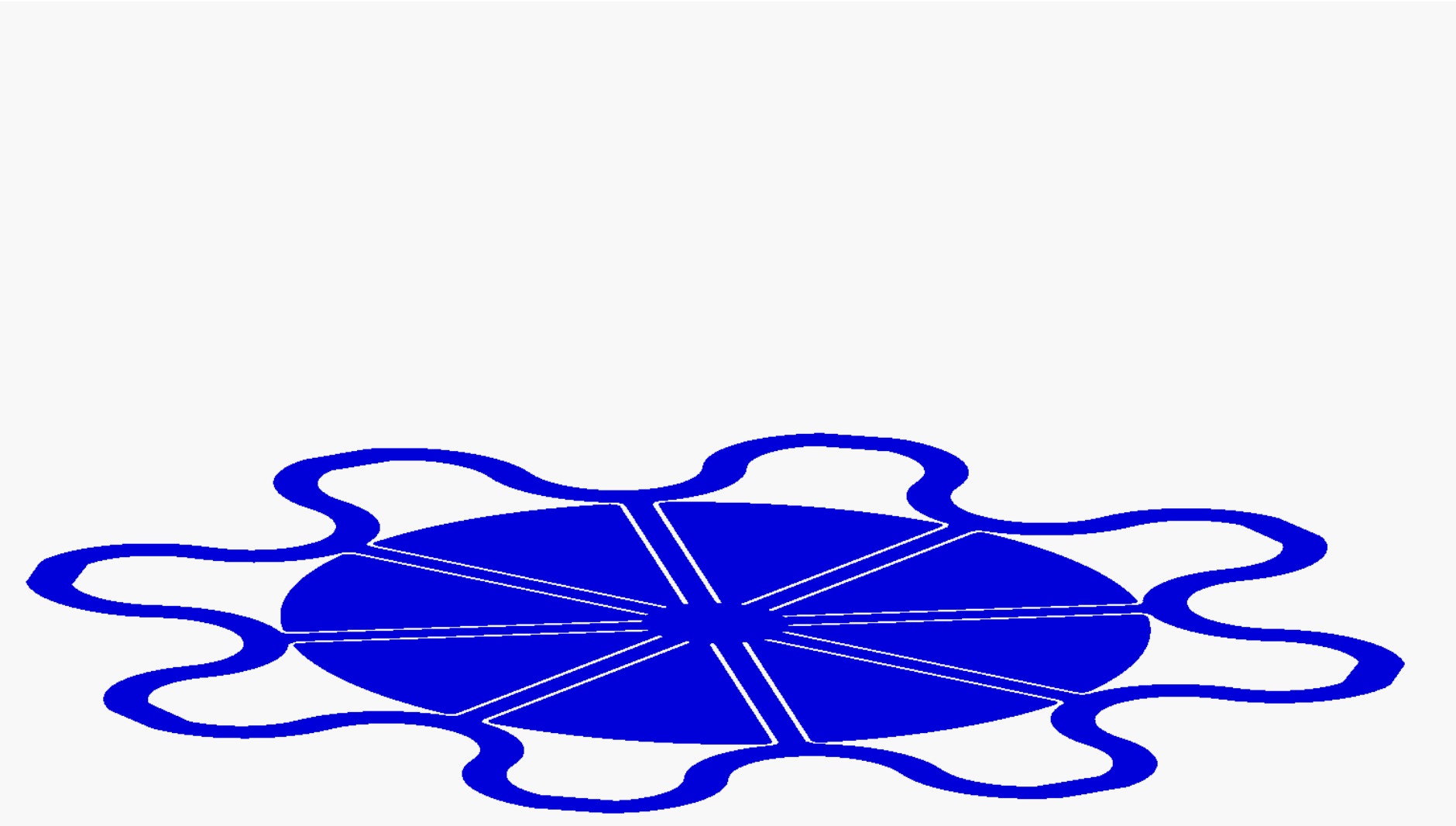
200 μm

3D Nanoarchitectures



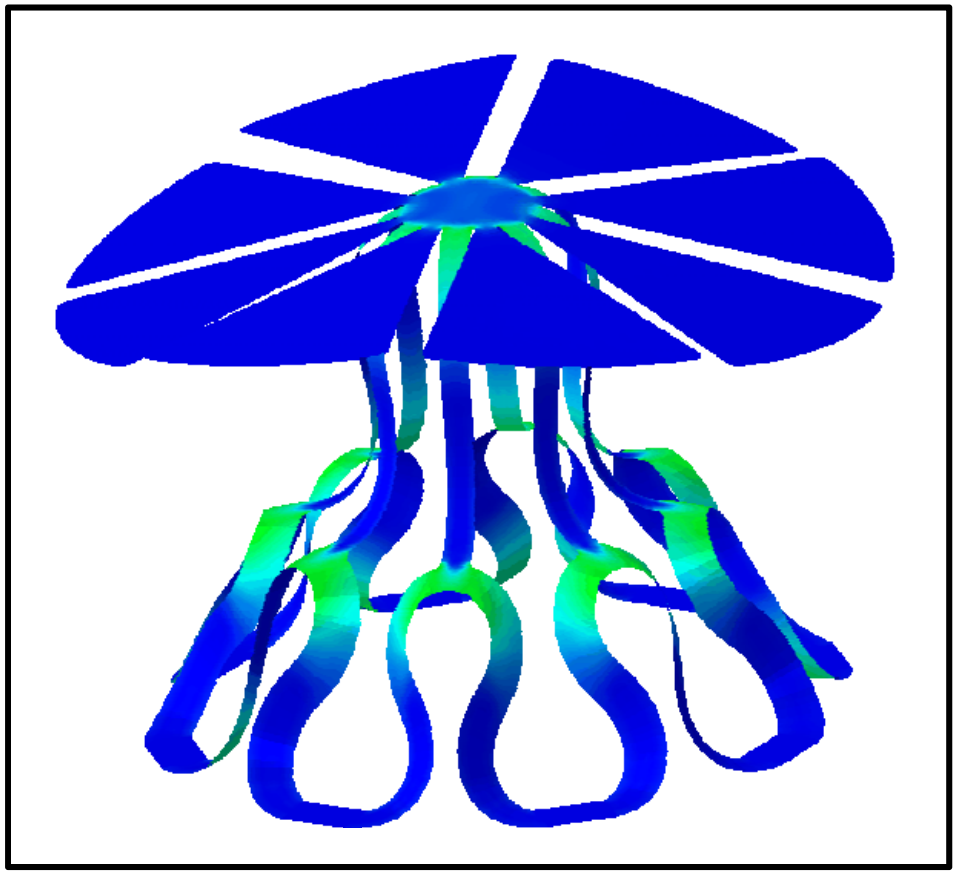
Science **347**, 154 (2015).

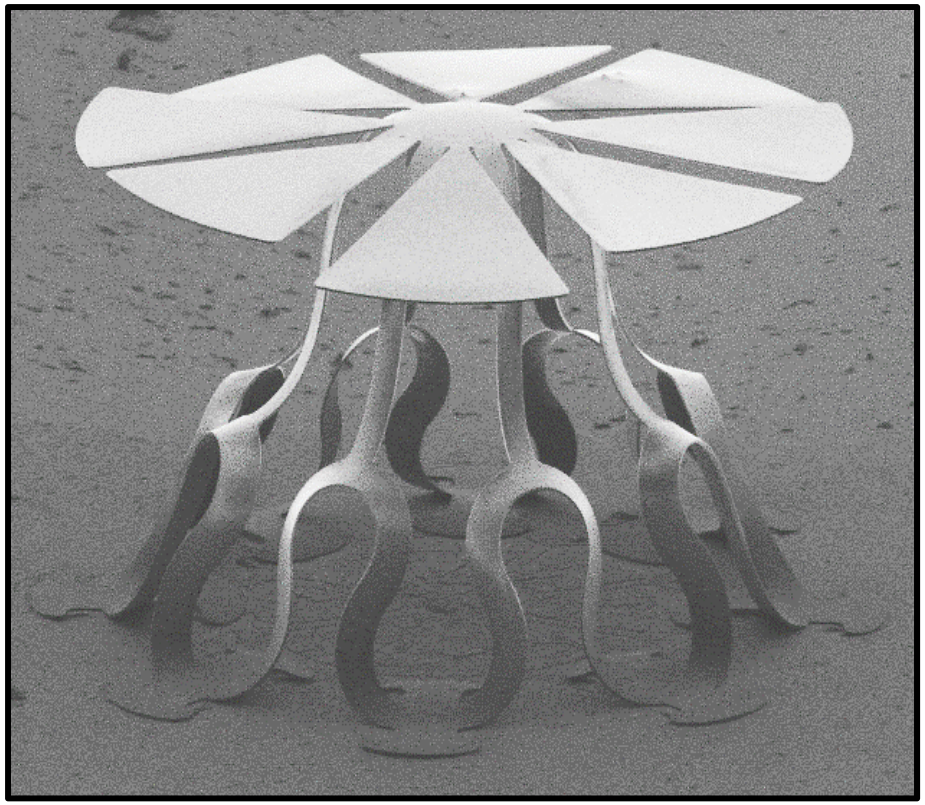
Advanced 3D Architectures – Membranes and Ribbons



PNAS **112**, 11757 (2015).

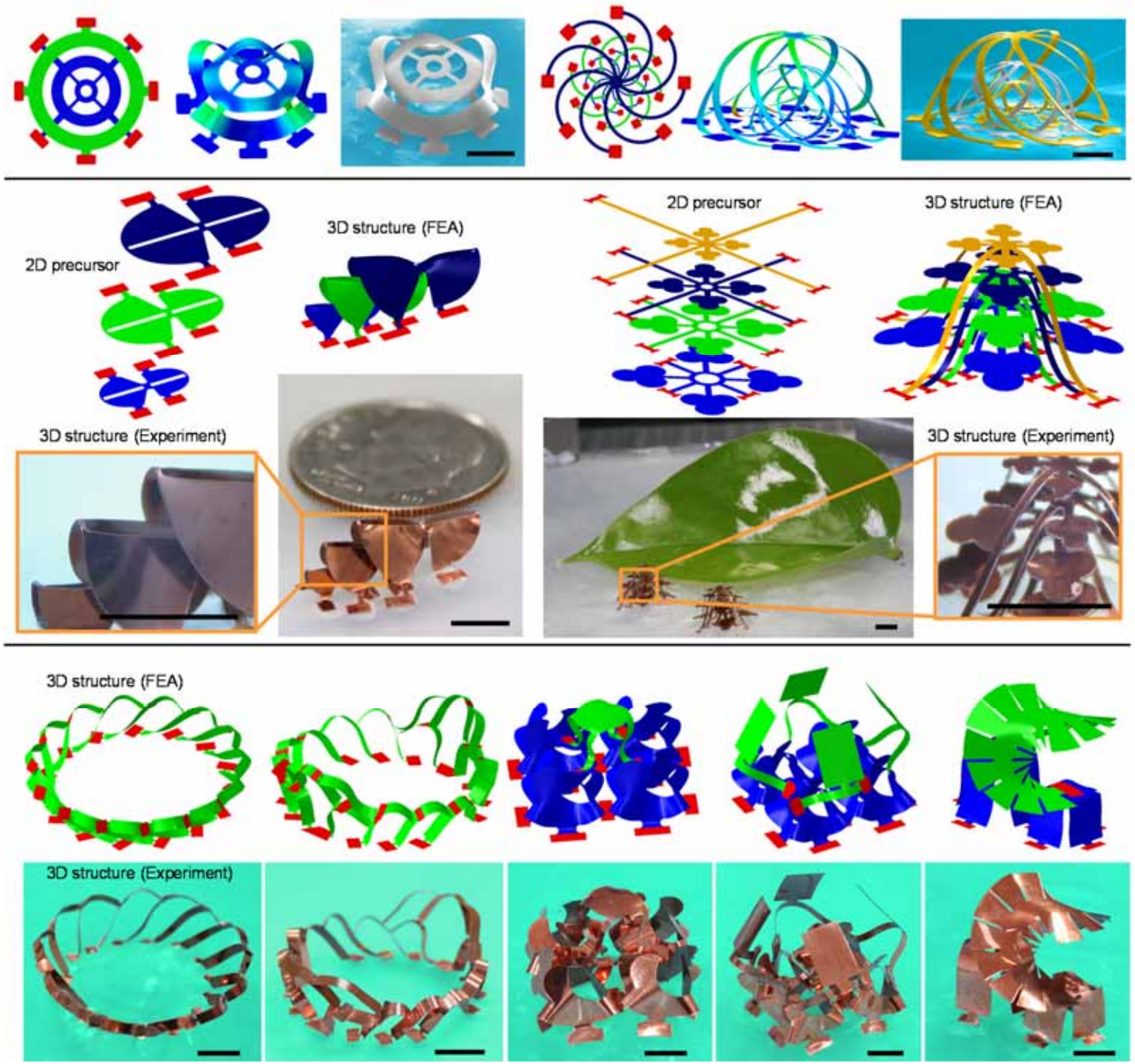
Silicon ‘Kirigami’





PNAS **112**, 11757 (2015).

Nested, Multilayer, Entangled



Science Adv., AOP (2016).

Control Parameters:

2D layouts; bonding configurations

Thickness profiles, cuts

Multilayer configurations

Non-uniform distributions of pre-strain

Residual stresses

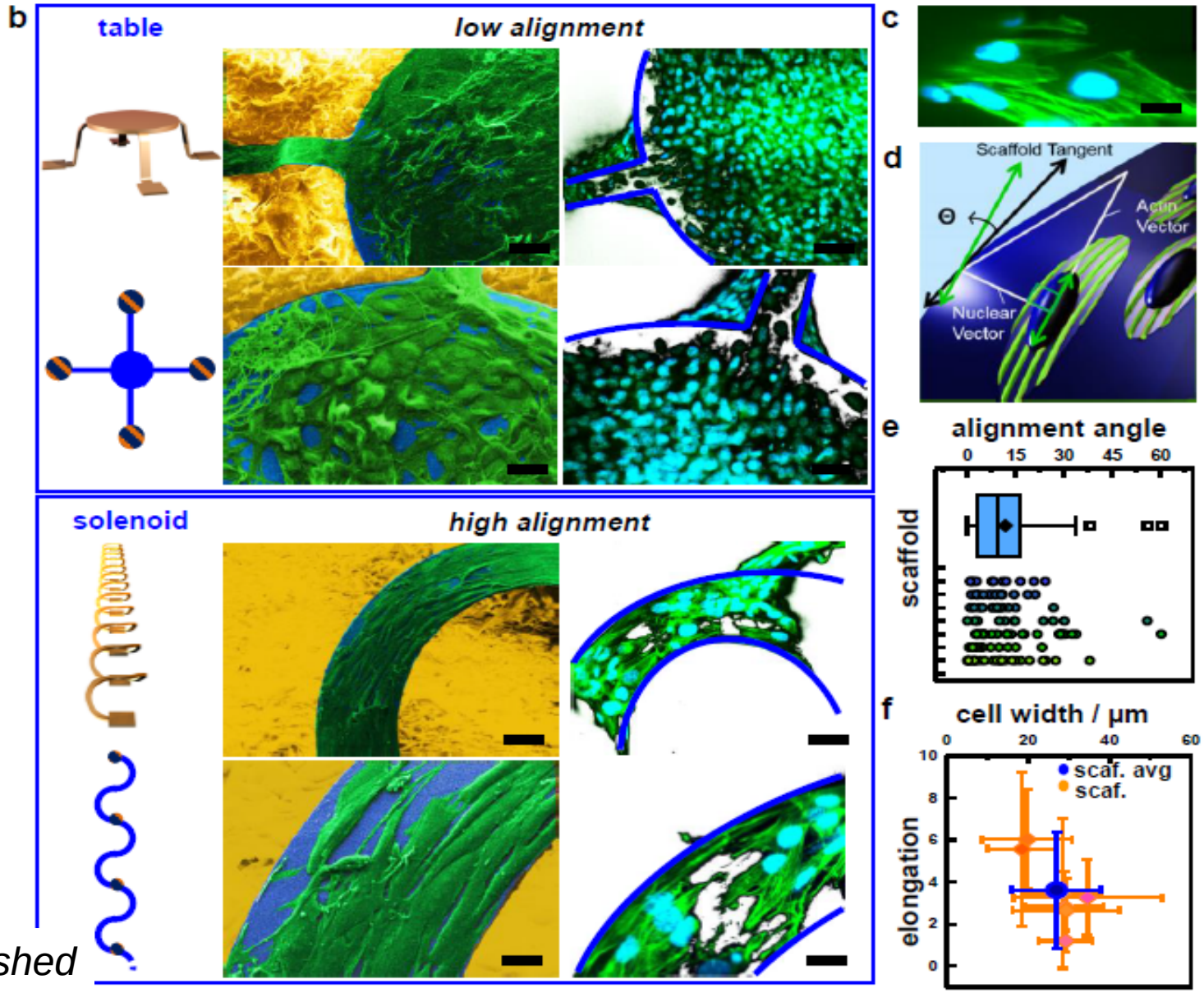
Dissolvable components

Loading path trajectory

What is the range of accessible 3D topologies?
Can we develop inverse design algorithms?
What are the fundamental limits in dimensional scaling?

Is it possible to assemble arbitrary
3D bio-integrated electronic systems, by design?

3D Silicon Scaffolds for Cells



unpublished

Definition

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

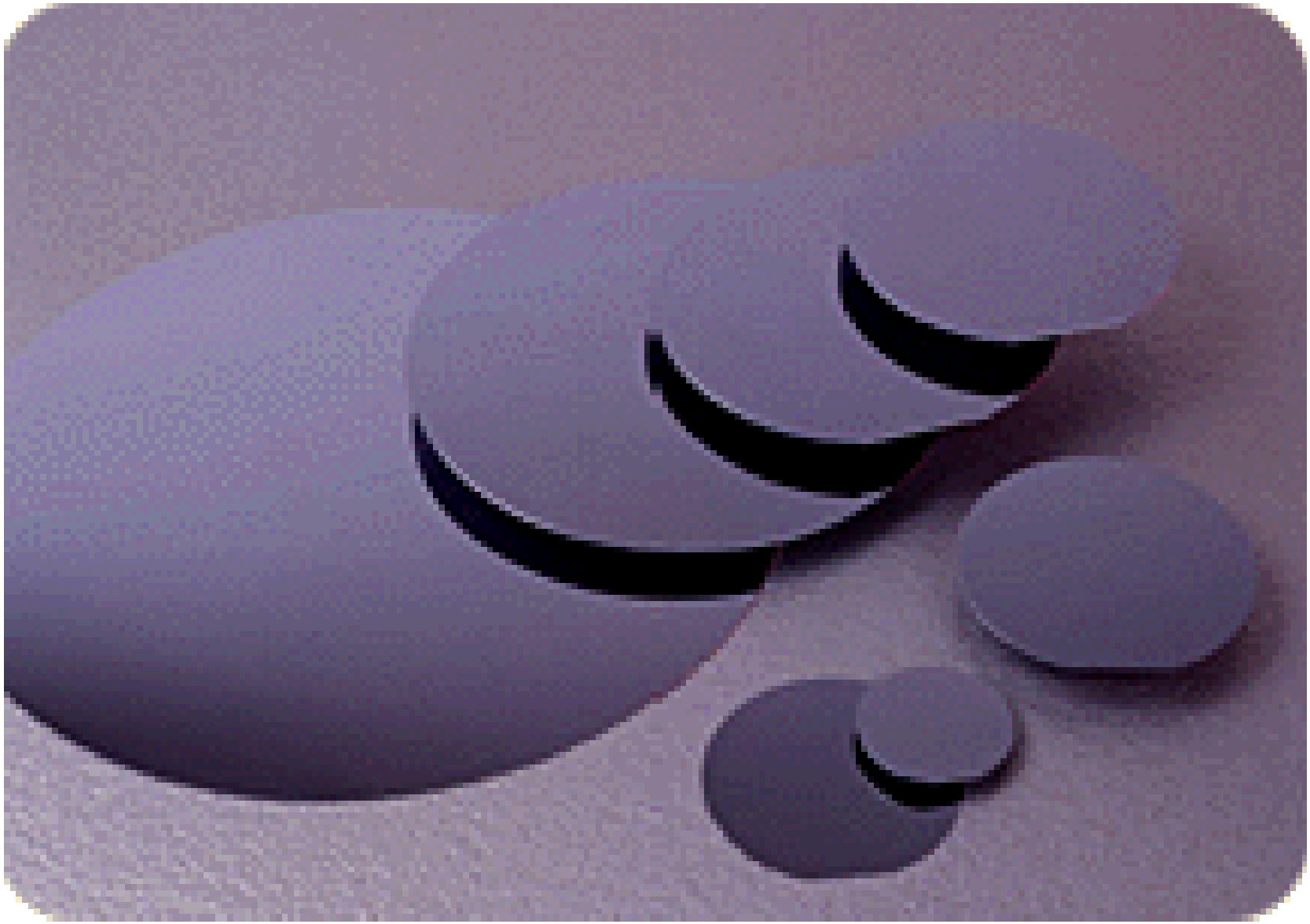
Science **337**, 1640 (2012).

Potential Applications

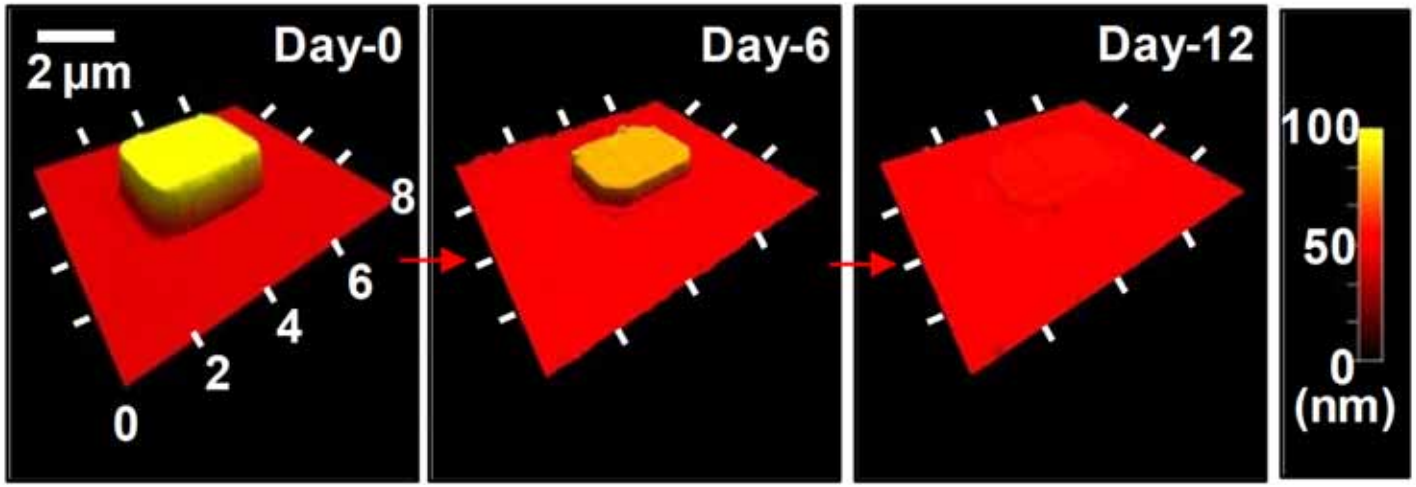
1) **Zero/Reduced E-Waste Consumer Electronics**
2) **Implantable Therapeutics / Diagnostics**
3) **Environmental Monitors / Sensors**
4) **…**

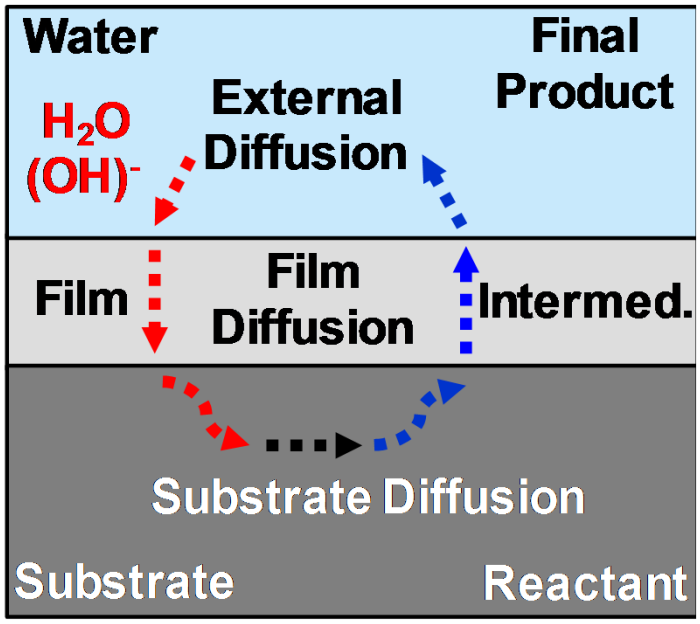
Science **337**, 1640 (2012).

Materials Challenges

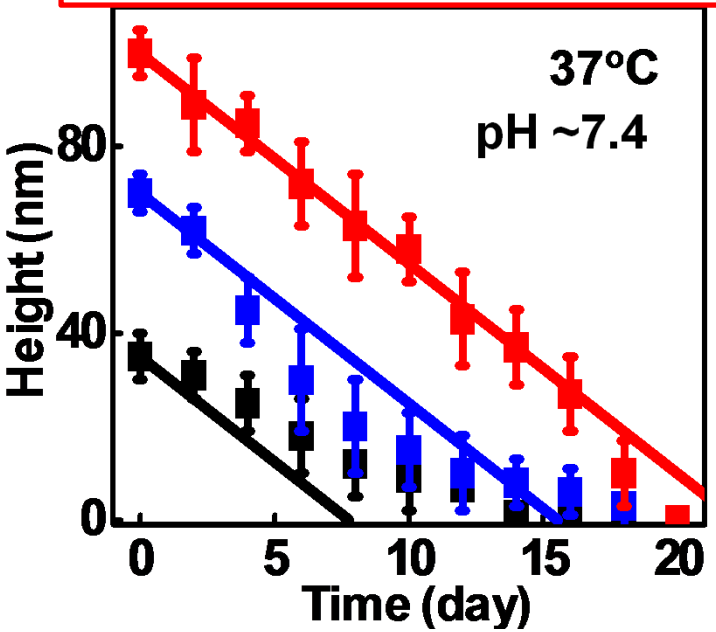


Dissolution of Silicon at Physiological pH, Temp.





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



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

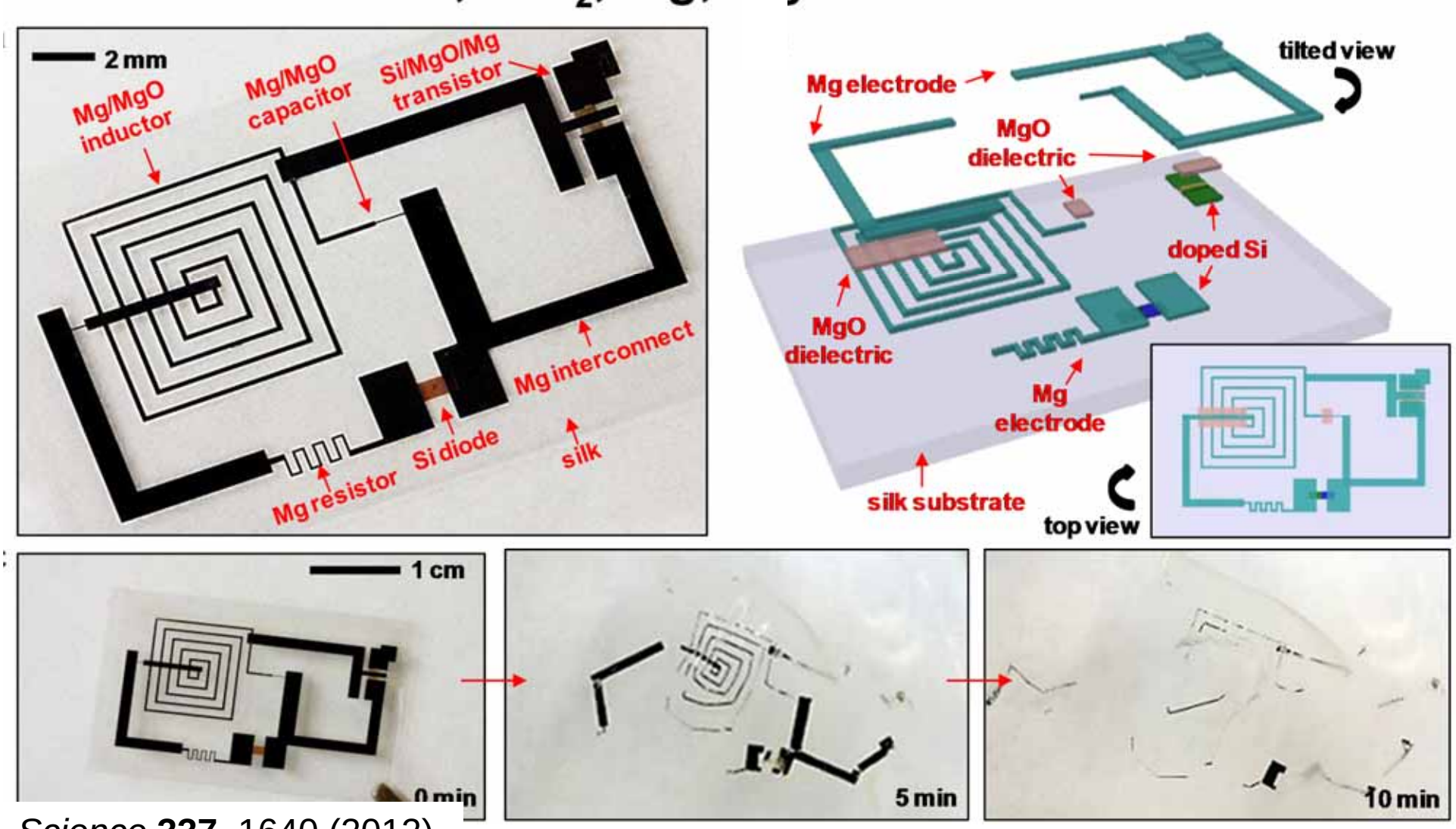
Some Transient Electronic Materials

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

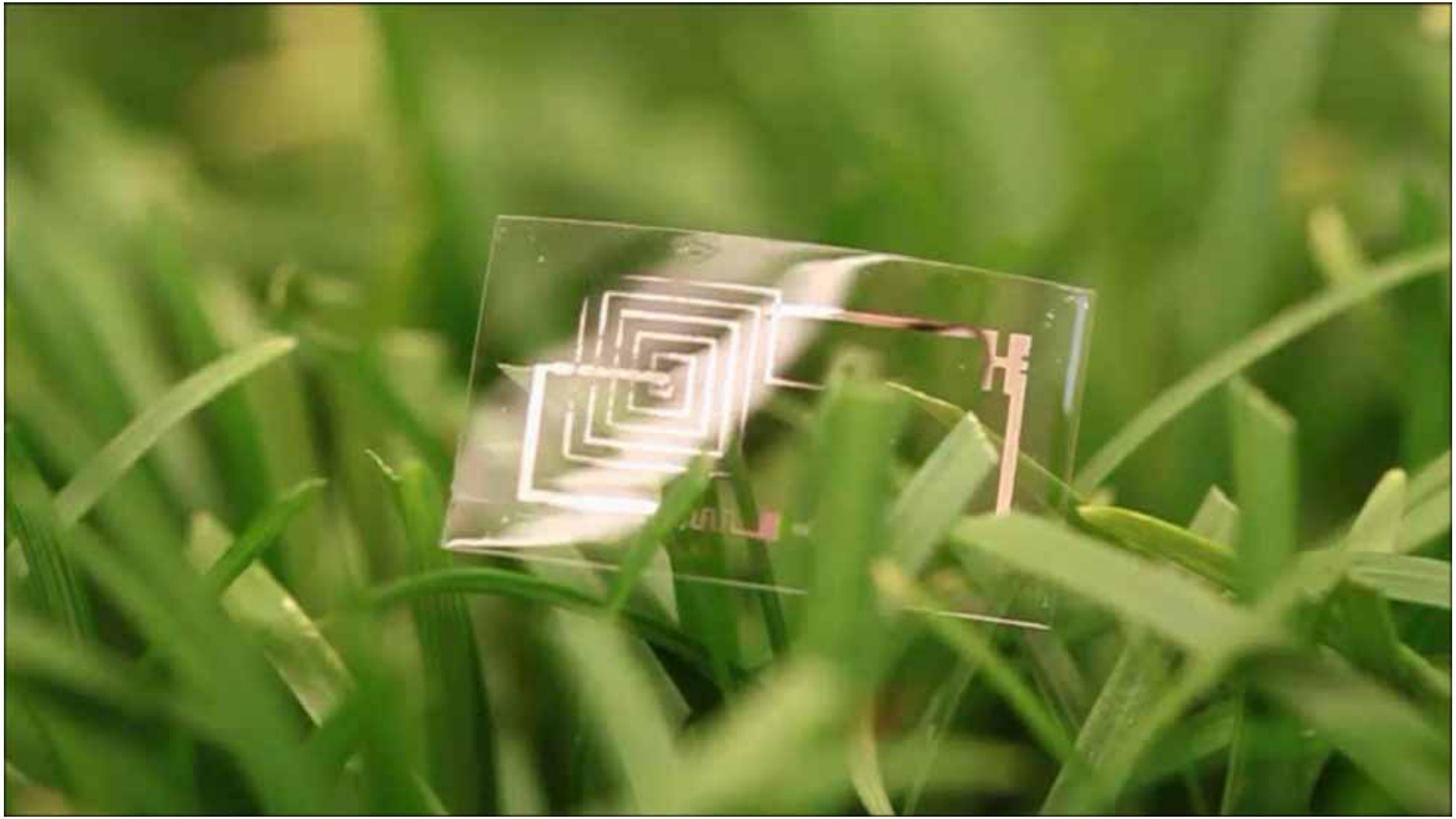
Adv. Mater. **26**, 7637 (2014).
Adv. Mater. **26**, 7371 (2014).
Adv. Mater. **26**, 3905 (2014).
ACS Nano **8**, 5843 (2014).
APL **105**, 013506 (2014)
Adv. Func. Mater. **24**, 4427 (2014).
Adv. Health. Mater. **3**, 515 (2014).
Small **9**, 3398 (2013).
Adv. Mater. **26**, 3905 (2014).
Adv. Func.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

Transient Electronics – Test Platform

Si, SiO_2, Mg, MgO and silk

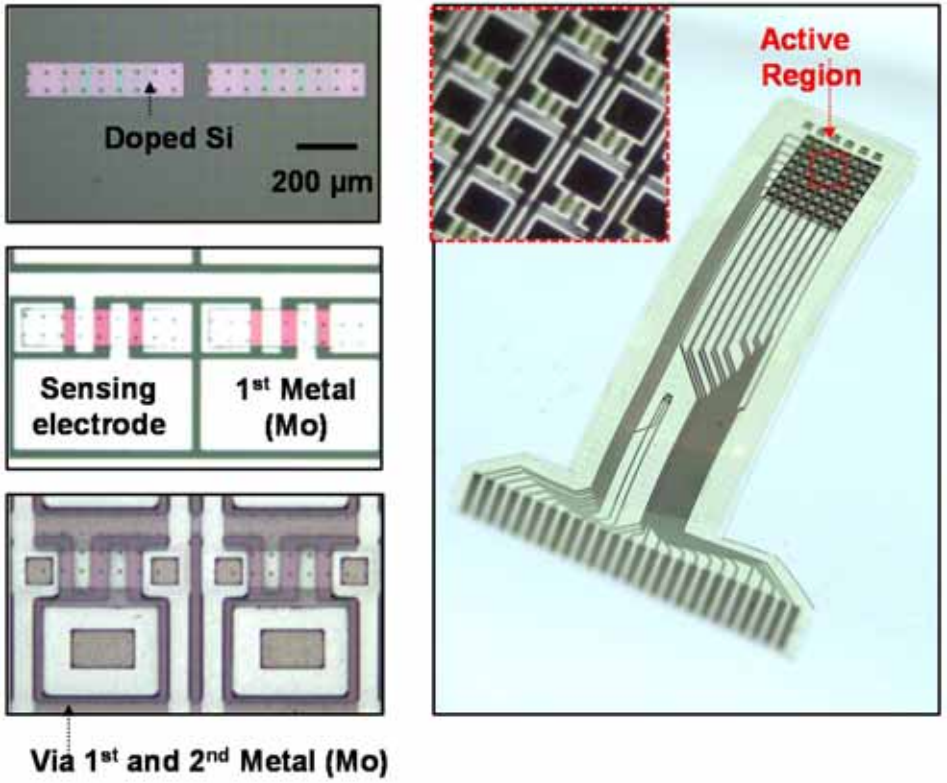


Science **337**, 1640 (2012).

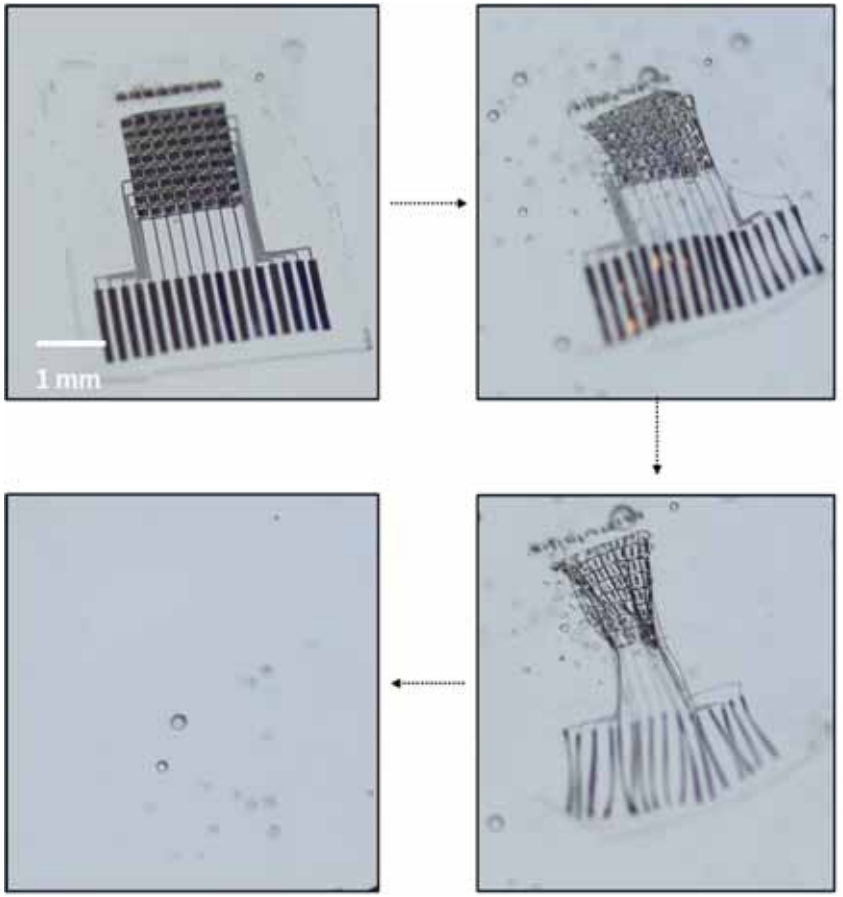


Actively Multiplexed Array

Design



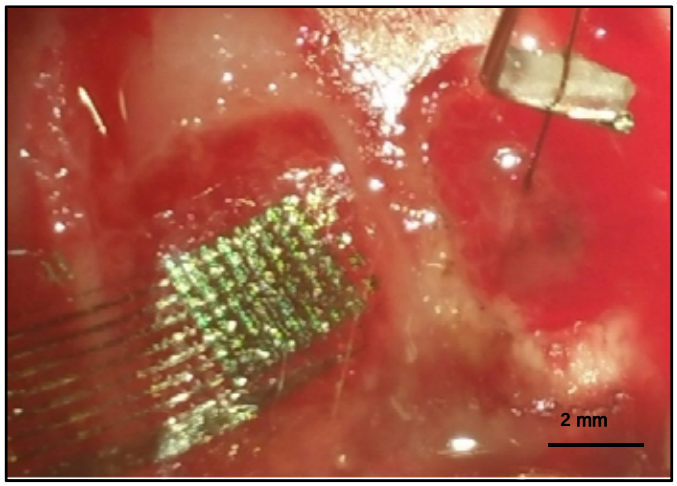
Dissolution



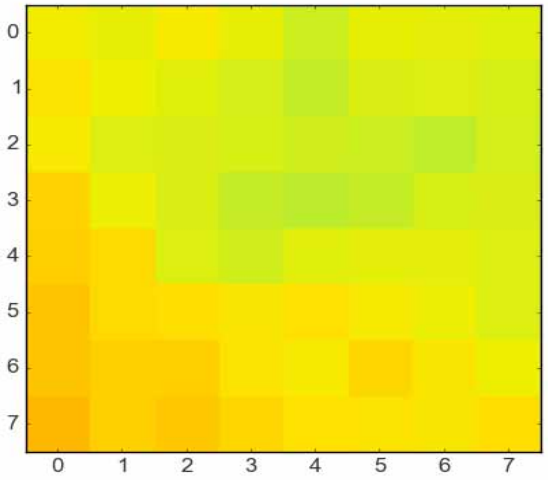
Nature Mater. **15**, 782 (2016).

Epileptic Spiral Activity

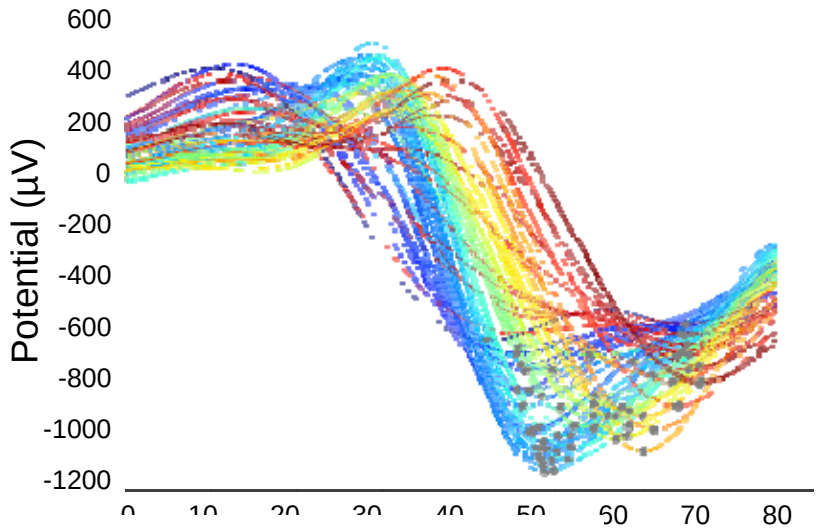
- **Active Electrode on a Rat Brain**

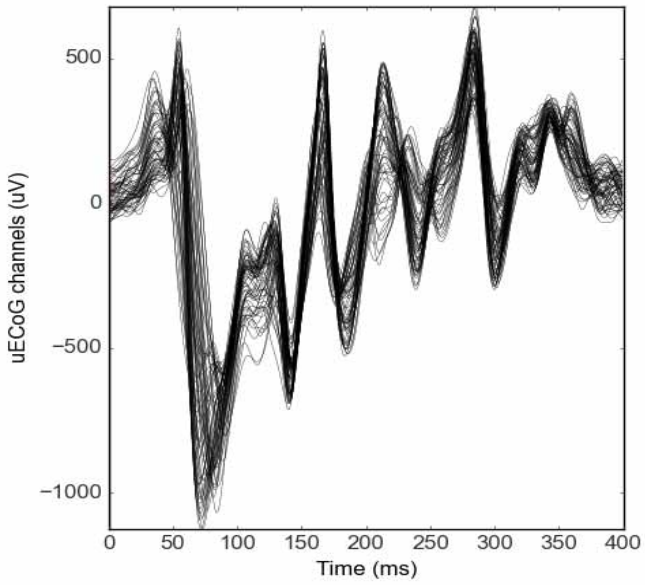


- **Epileptic Activity**



- **Spatial-temporal characteristics**





Nature Mater. **15**, 782 (2016).

Soft, Biocompatible Optoelectronic Interfaces to the Brain

1) Soft, Conformal Optoelectronic Systems

2) 3D Mesoscale Electronic Networks

3) Bioresorbable Electronics & Sensors

Discovery mode *research* in materials & applied physics

New *technologies* for neuroscience & biomedicine

Senior Collaborators

Prof. Y. Huang (NU) – mechanics

Prof. P. Ferreira (UIUC) – manuf.

Prof. X. Li (UIUC) – MOCVD

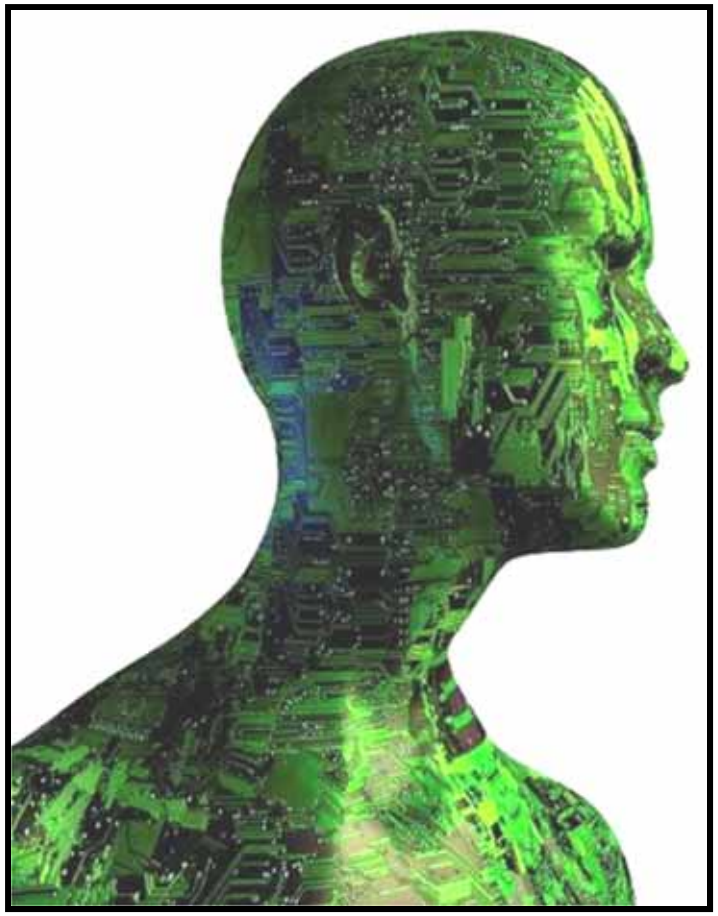
Prof. R. Nuzzo (UIUC) – surf. chem.

Prof. M. Bruchas (WU) – optogen

Prof. B. Litt (U Penn) – epilepsy

Prof. J. Viventi (Duke) – BMI

Dr. R. Murphy (WU) -- TBI



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