QUERREY SIMPSON INSTITUTE FOR BIOELECTRONICS

Northwestern

Semiconductor Nanomaterials in 3D and Transient Electronics

1) Motivation, Perspective, Context
2) Bio/Eco Resorbable Materials, Devices
3) Bioresorbable Electronics for Cardiac Pacing
4) Electronic Microfliers for Environmental Sensing

John A. Rogers – Northwestern University

Departments of Materials Science & Engineering, Electrical & Computer Engineering, Chemistry, Biomedical Engineering and Neurological Surgery

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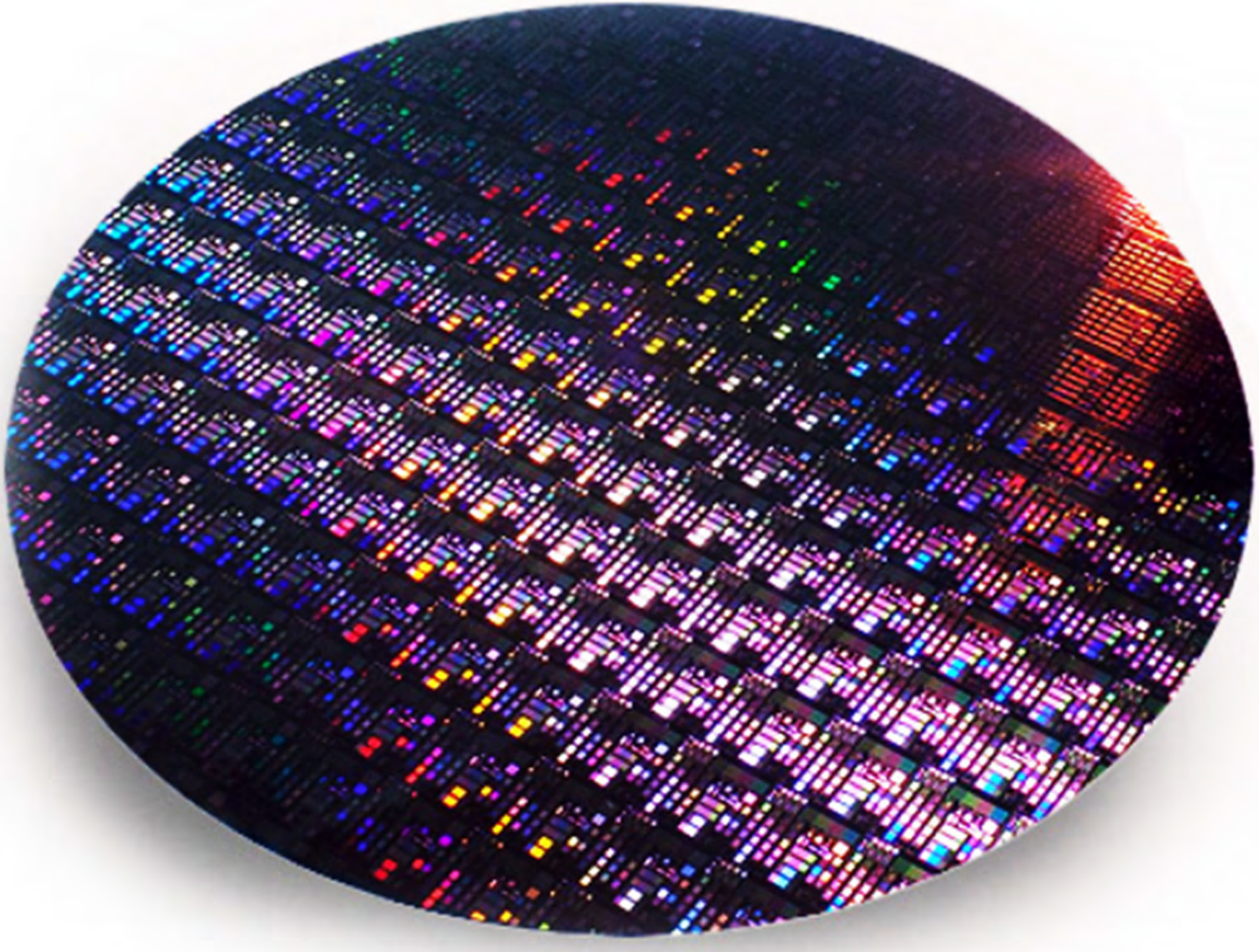
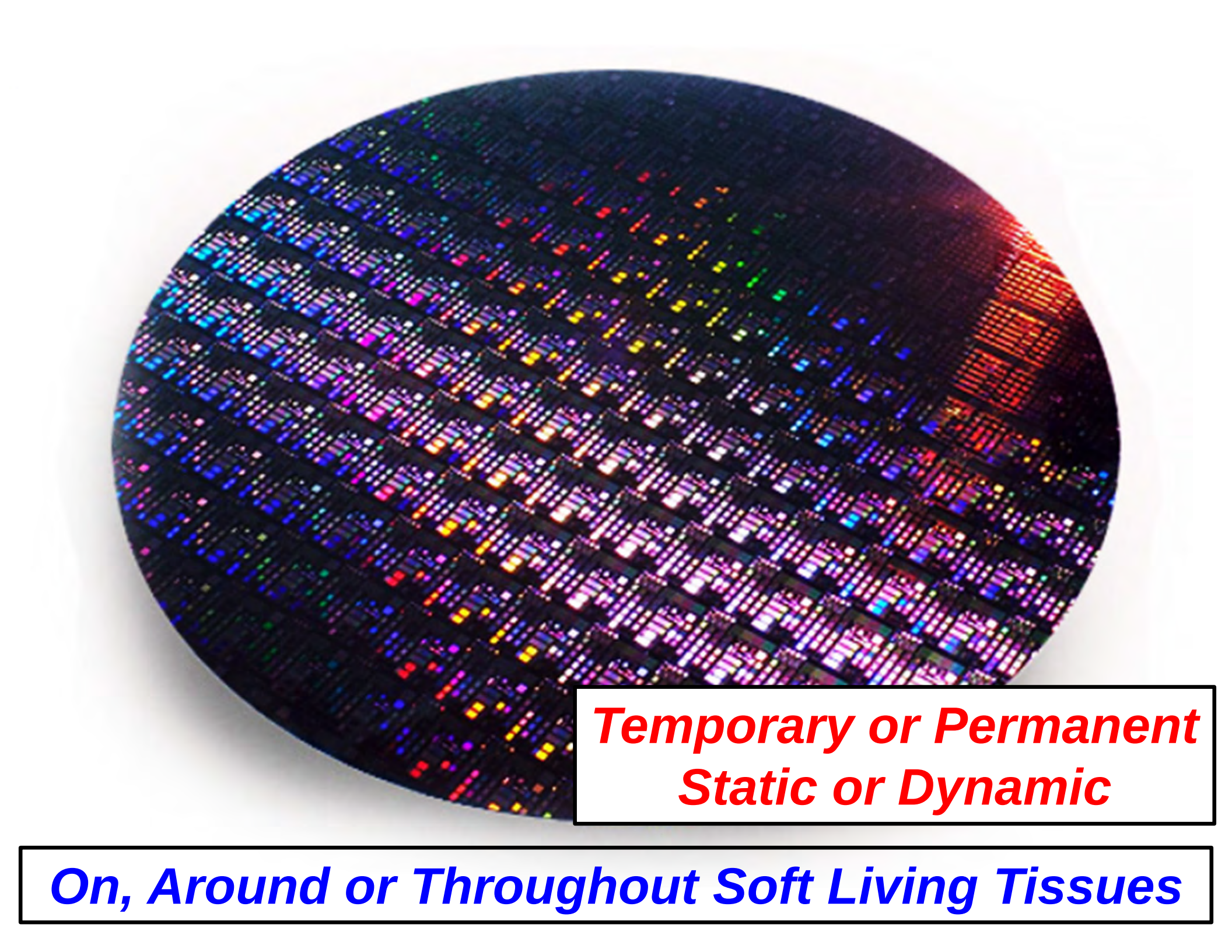


On, Around or Throughout Soft Living Tissues


Temporary or Permanent
Static or Dynamic
On, Around or Throughout Soft Living Tissues

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).

Transient Electronics -- Envisioned Applications

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

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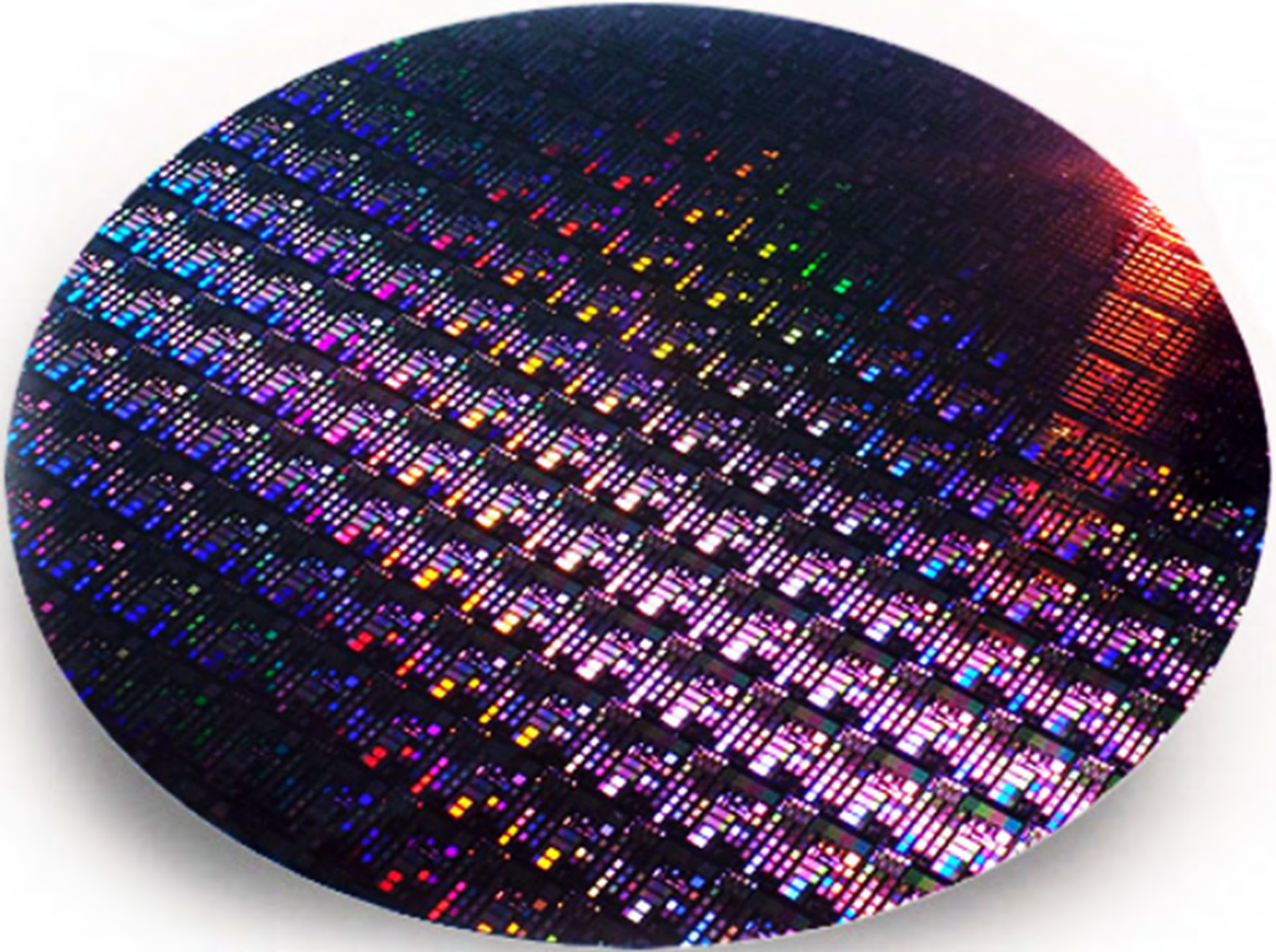
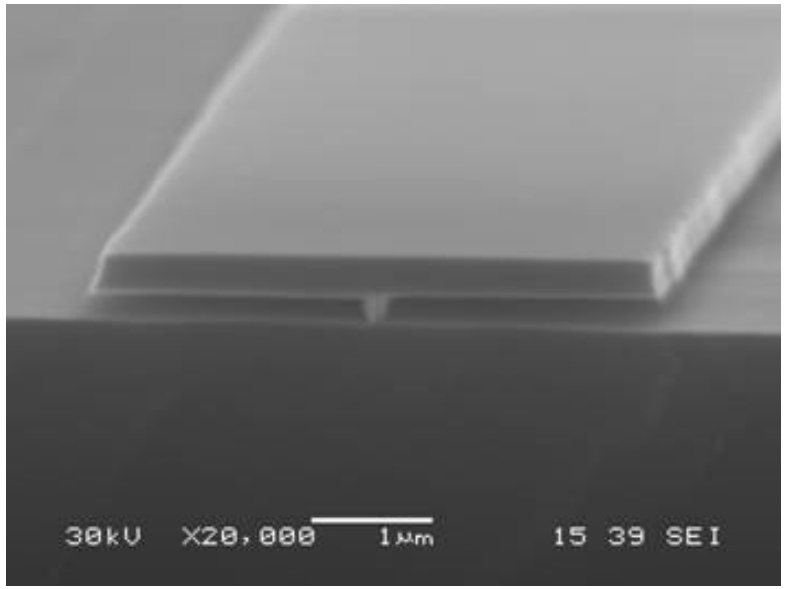


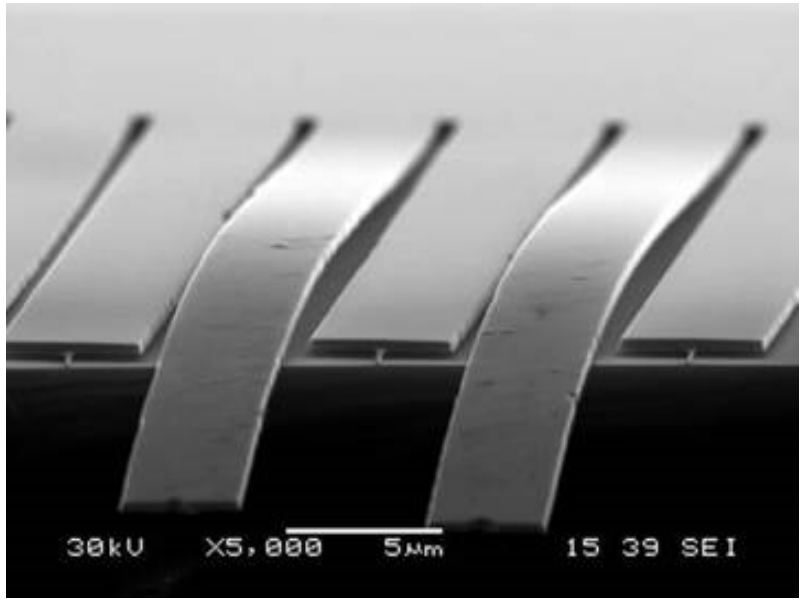
Soluble in Ground Water or Biofluids

Flexible Nanoribbons of Silicon from Bulk Wafers

etch trenches

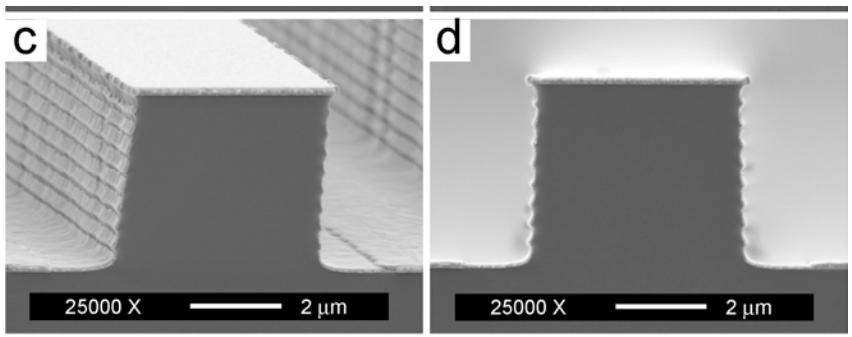
protect sidewalls; etch undercuts

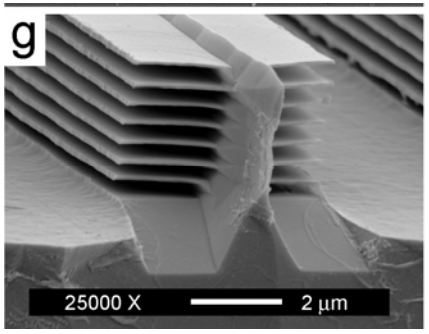


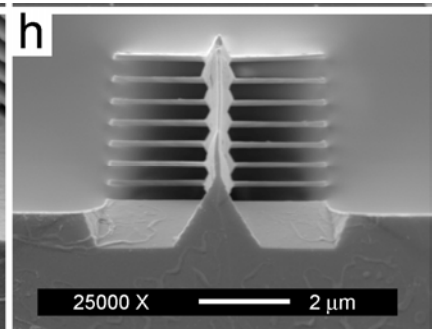


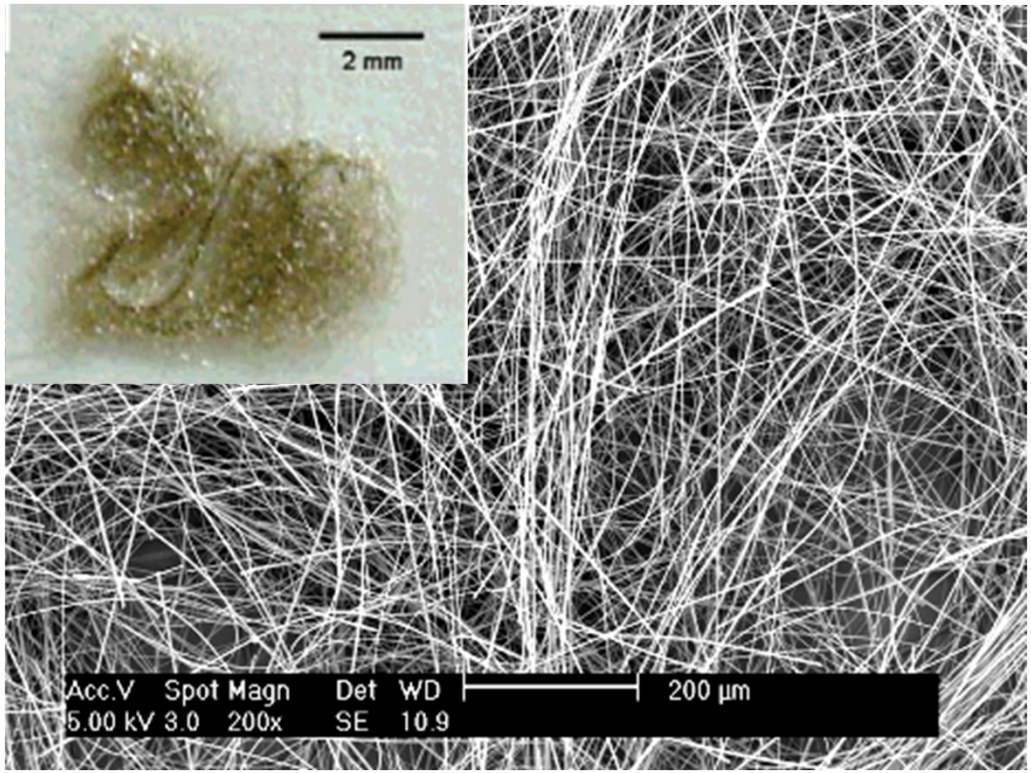
Adv. Func. Mater. **17**, 3051 (2007). *Appl. Phys. Lett.* **88**, 213101 (2006).

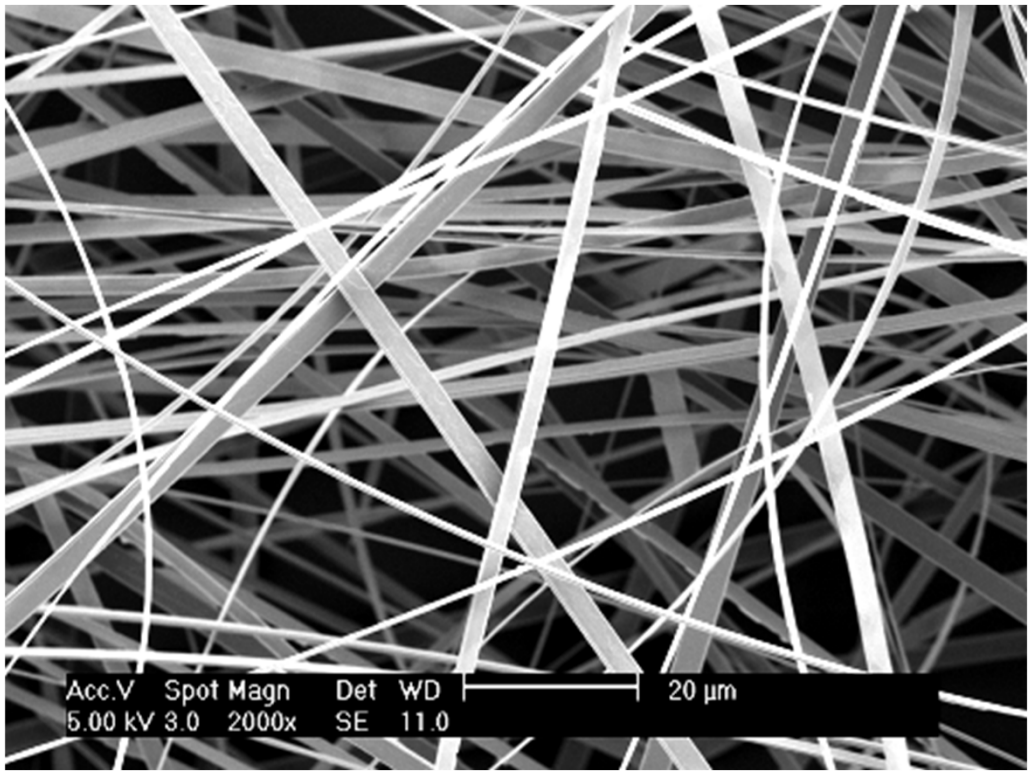
Bulk Quantities of Si Nanoribbons





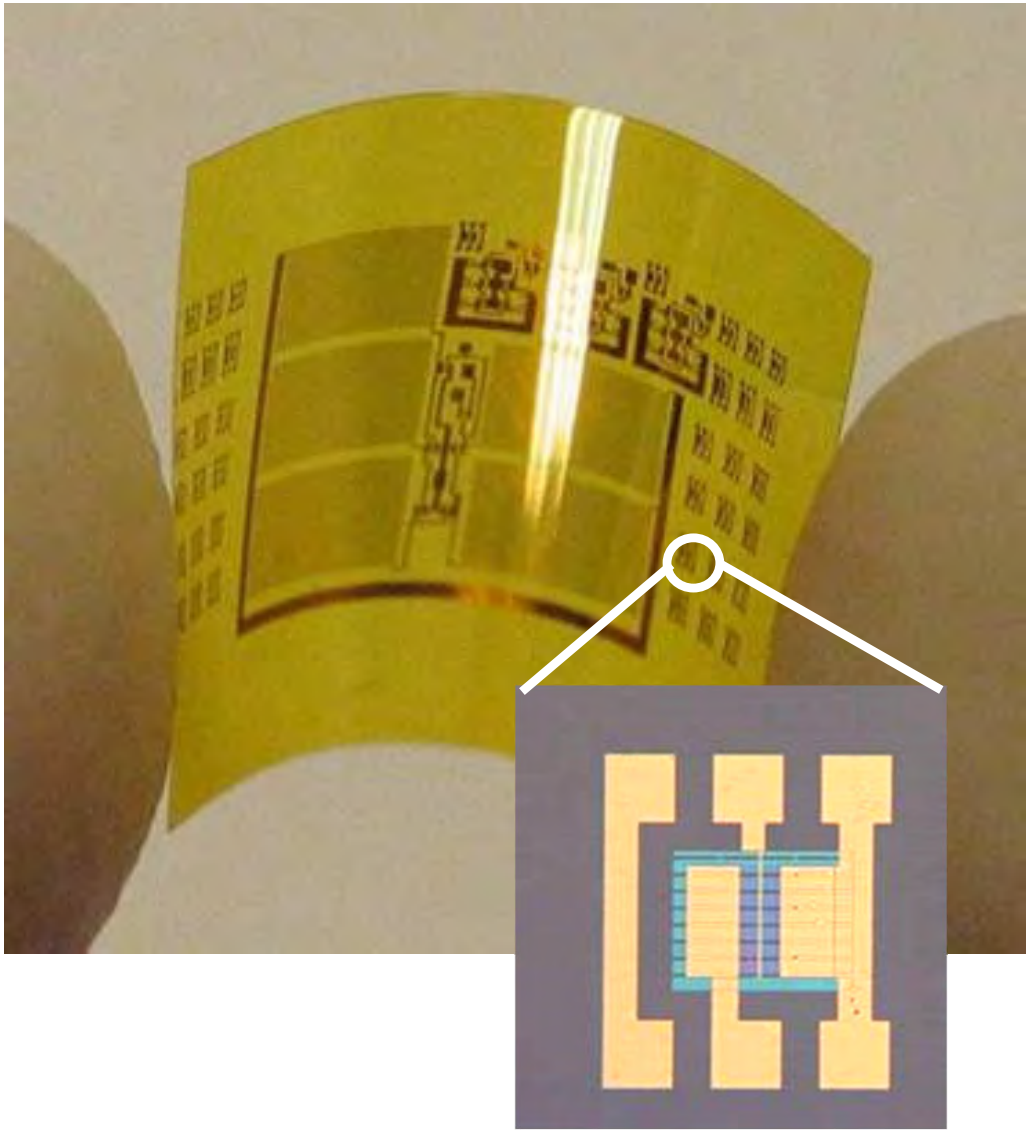




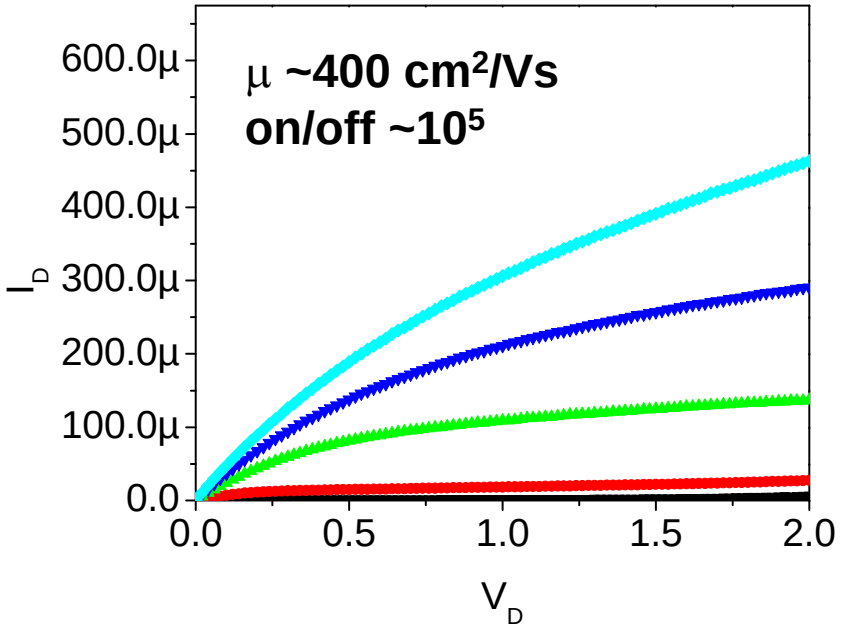


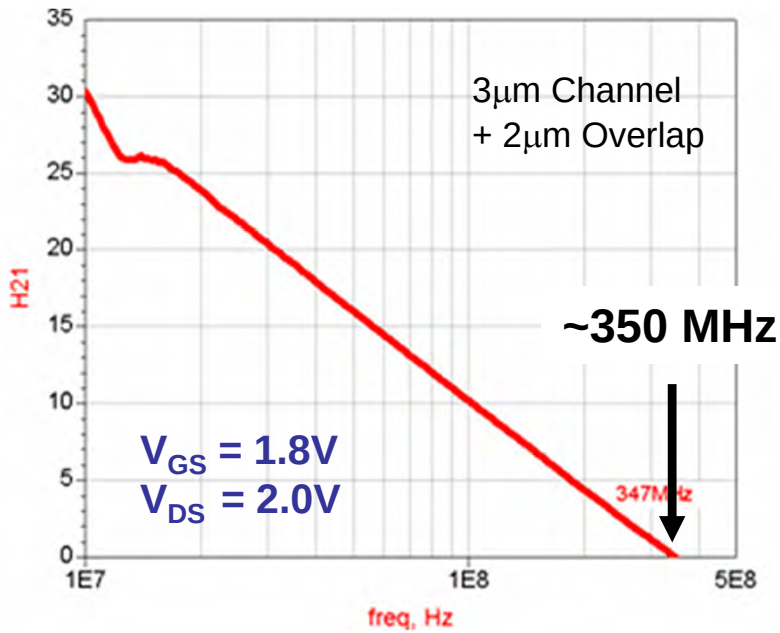
Nano Lett **6**, 2318 (2006).

Single Crystal Silicon TFTs and Circuits on Plastic



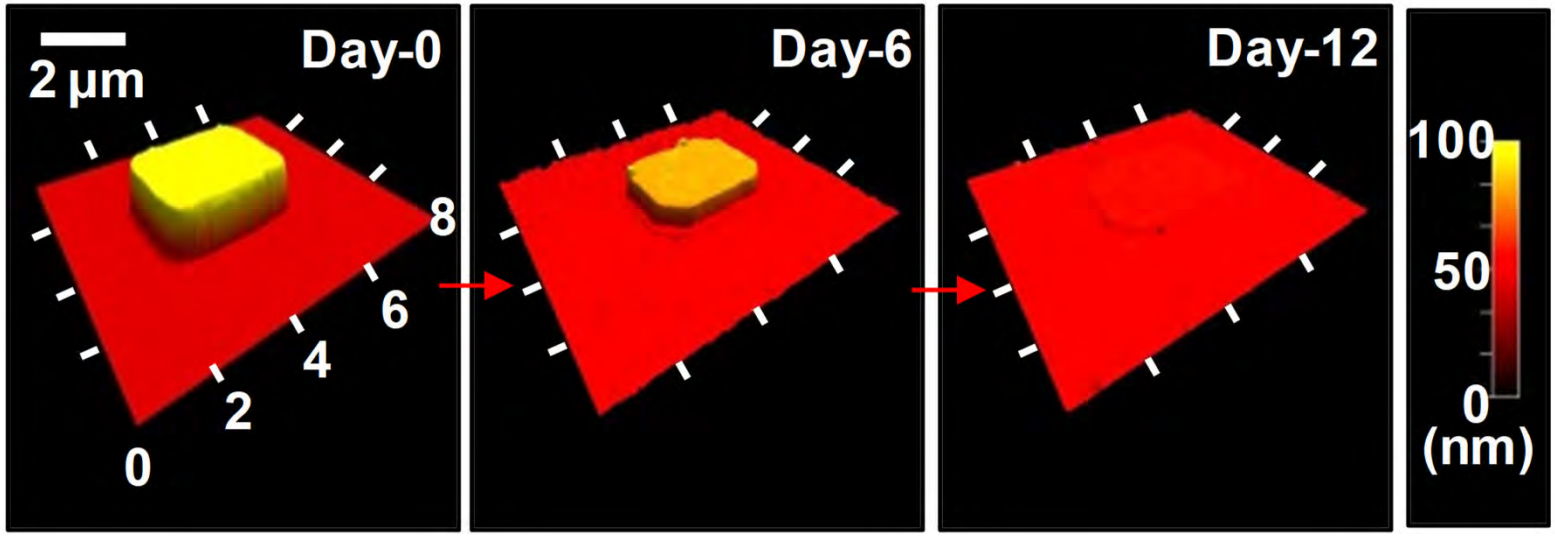
– 10 μm

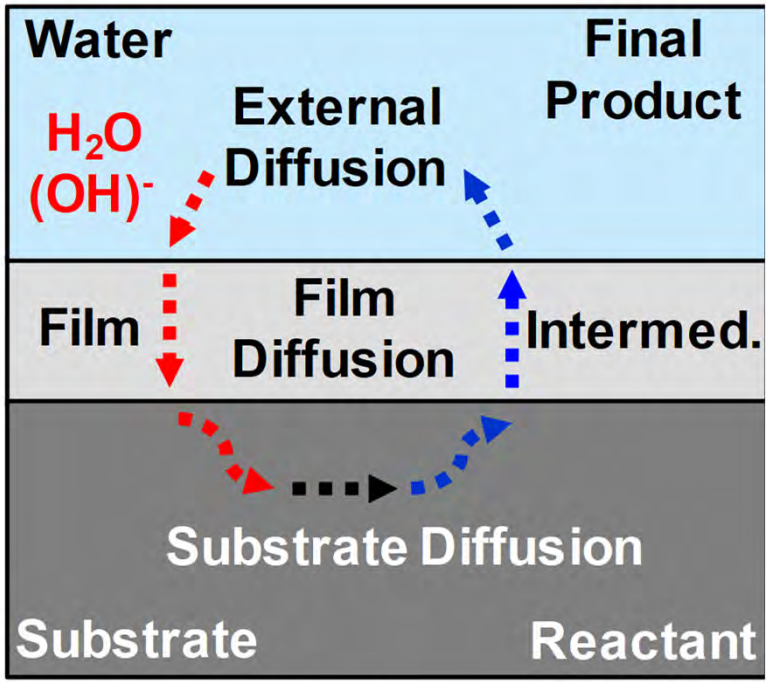




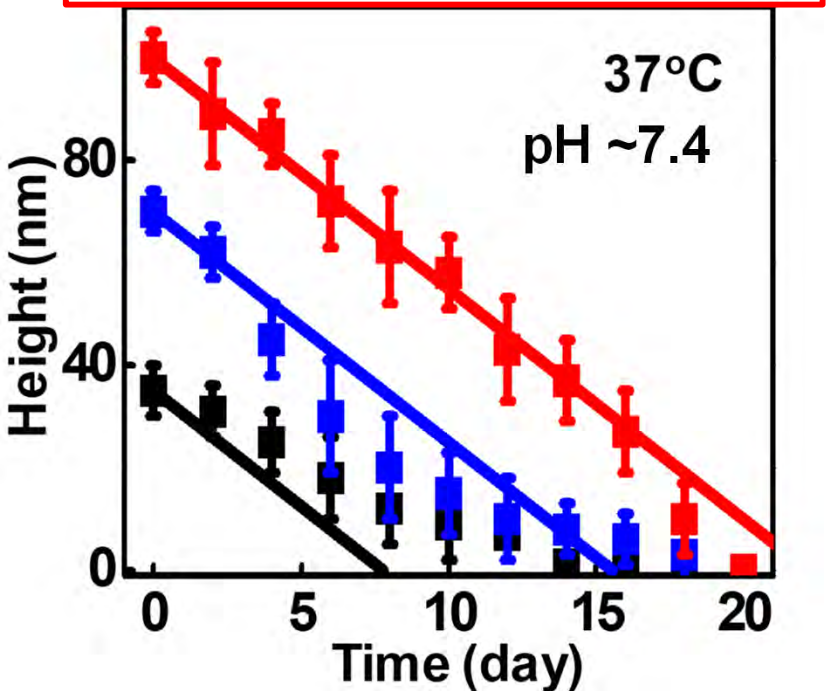
IEEE EDL., **27** 460 (2006); *IEEE EDL* **29**, 73 (2008).

Dissolution of Si at Physiological pH, Temp.





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



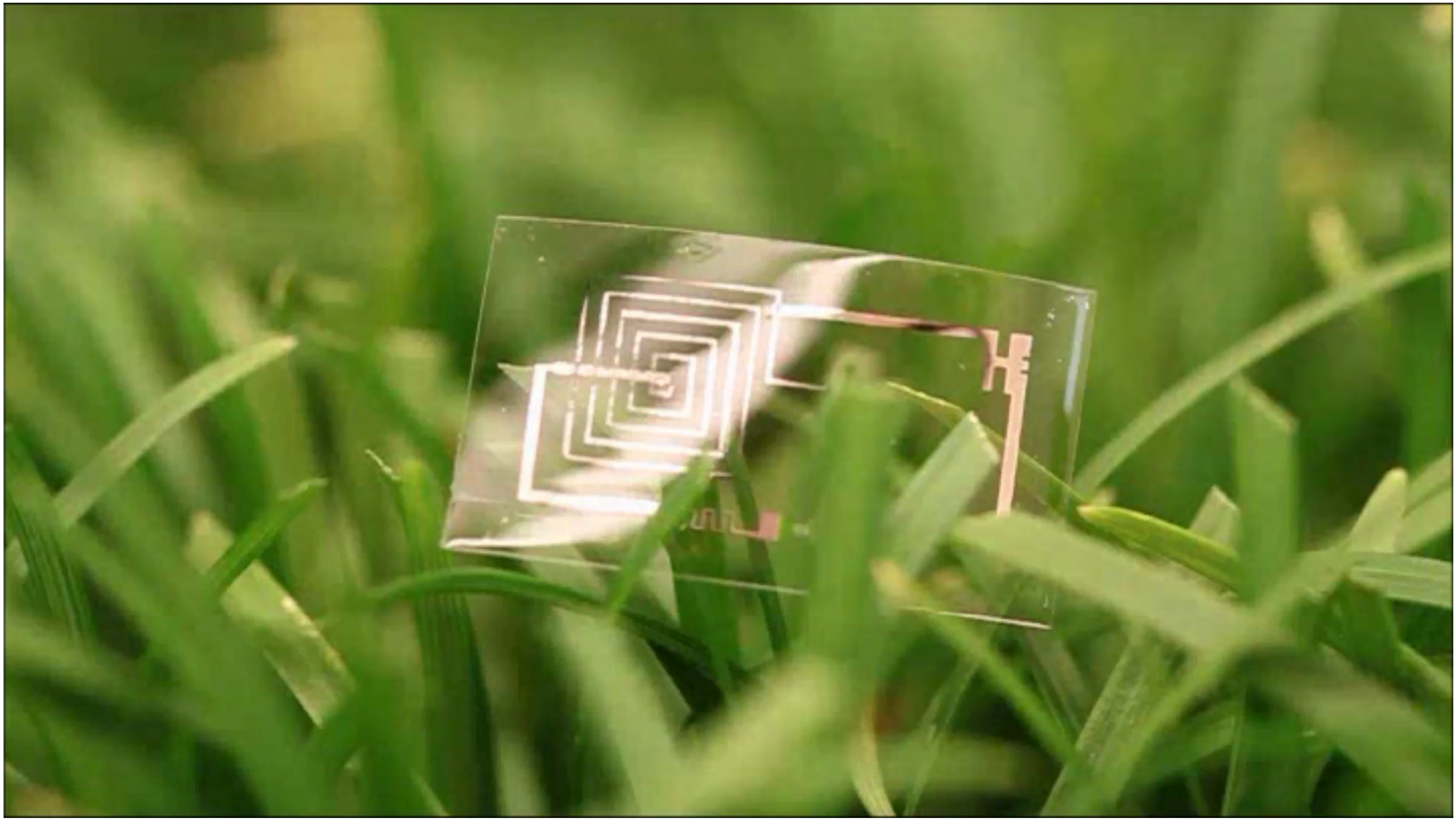
Science **337**, 1640 (2012).

Library of Bioresorbable 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).
Ad 4).
AC (2014).
APL **105**, 013506 (2014)
Adv. Func. Mater. **24**, 4427 (2014).
Adv. Health. Mater. **3**, 515 (2014).
Small **9**, 3398 (2013).
Adv. Func. Mater. **23**, 4087 (2013).
Adv. Mater. **25**, 3526 (2013).

Chemical Reviews **123**, 11722 (2023).



Active Project Areas in Bioelectronic Medicines

Nerve Stimulators – accelerated healing, pain block

Nerve Coolers – pain block

Bone Stimulators – accelerated healing

Cardiac Pacemakers & Diaphragm Control – recovery

Programmable Drug Release – pharmacology

Wound, Cardiac Therapy – accelerated healing

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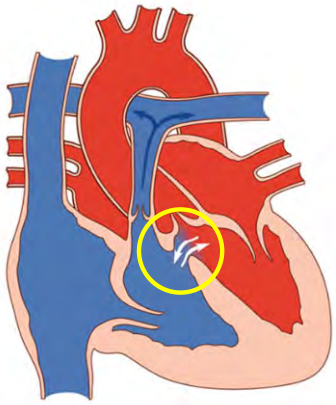
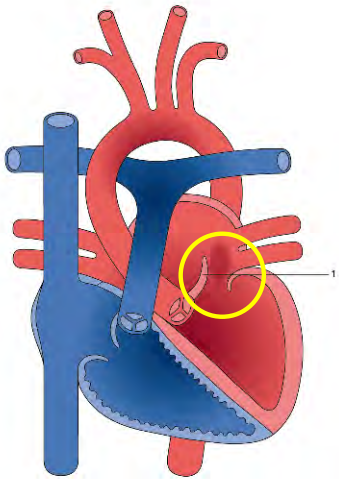
Use in Recovery Following Cardiac Surgery

1. Heart failure
-. Inadequate pumping

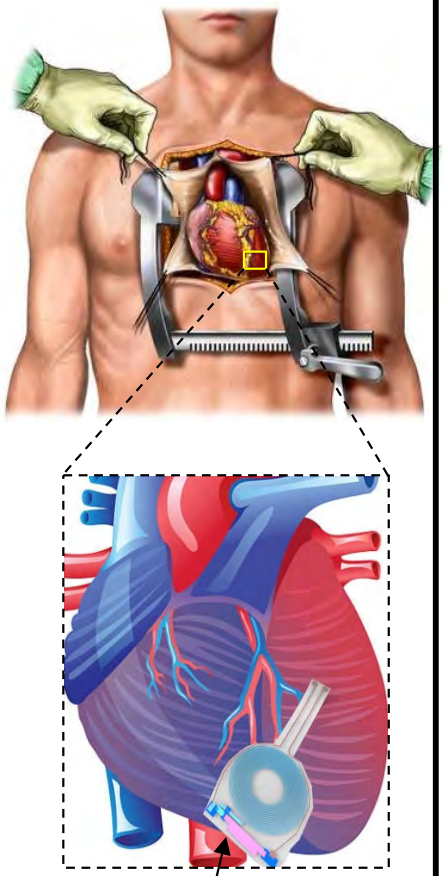
Structure failure



Valve failure



2. Heart surgery & Device implantation

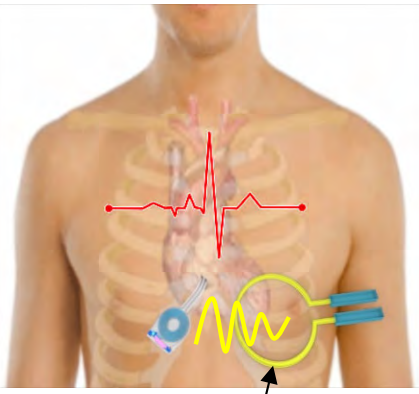


Temporary cardiac pacemaker

3. Temporary pacing

-. Recurring heart failure

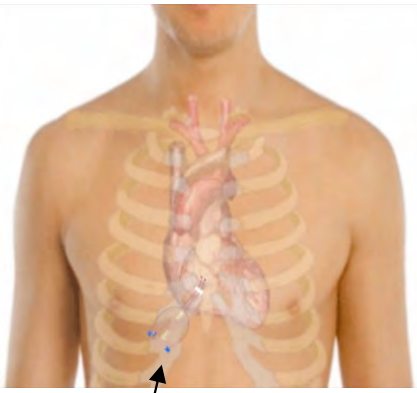
-. Temporary pacing



Post surgery pacing wirelessly

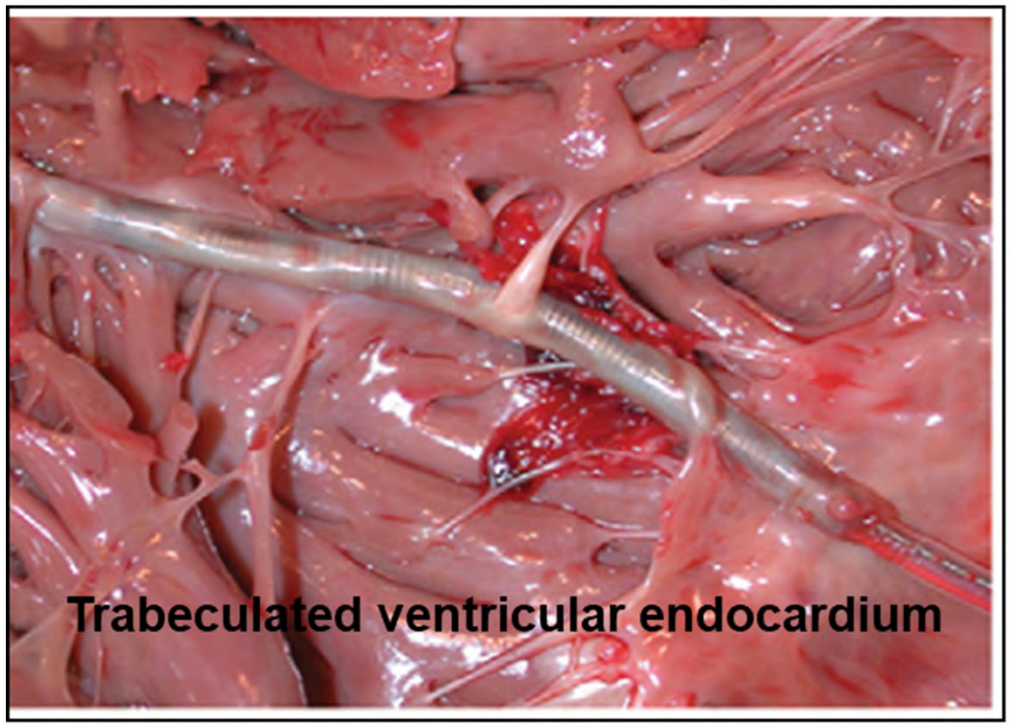
4. Resorbed device

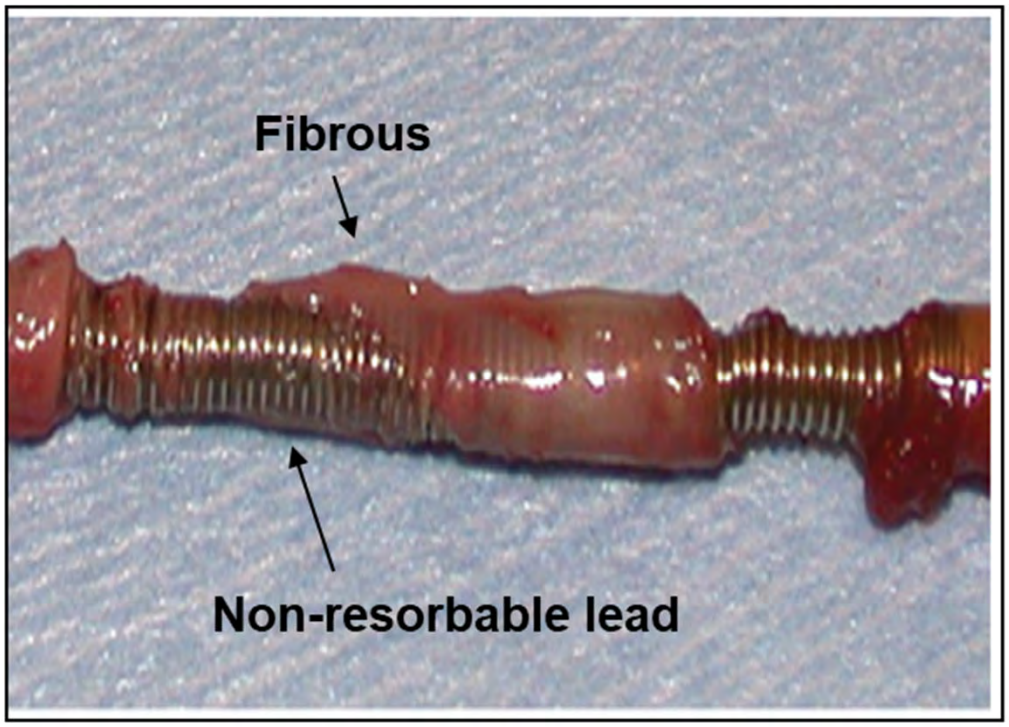
-. No removal surgery



Bioresorbed pacemaker

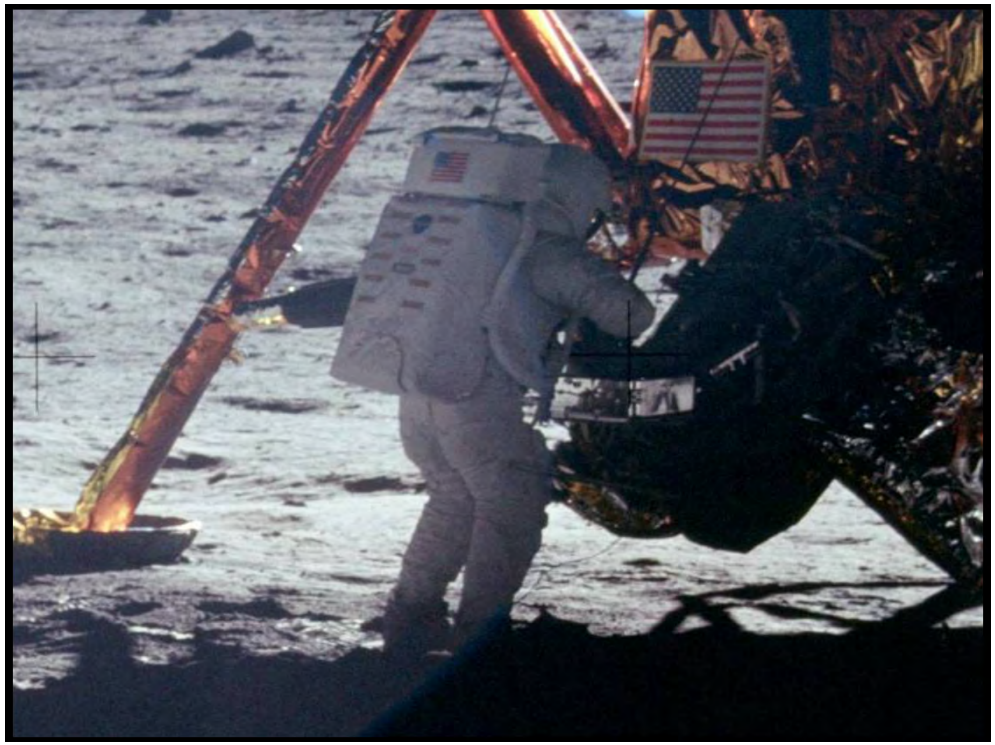
Needs for Temporary Cardiac Pacemakers



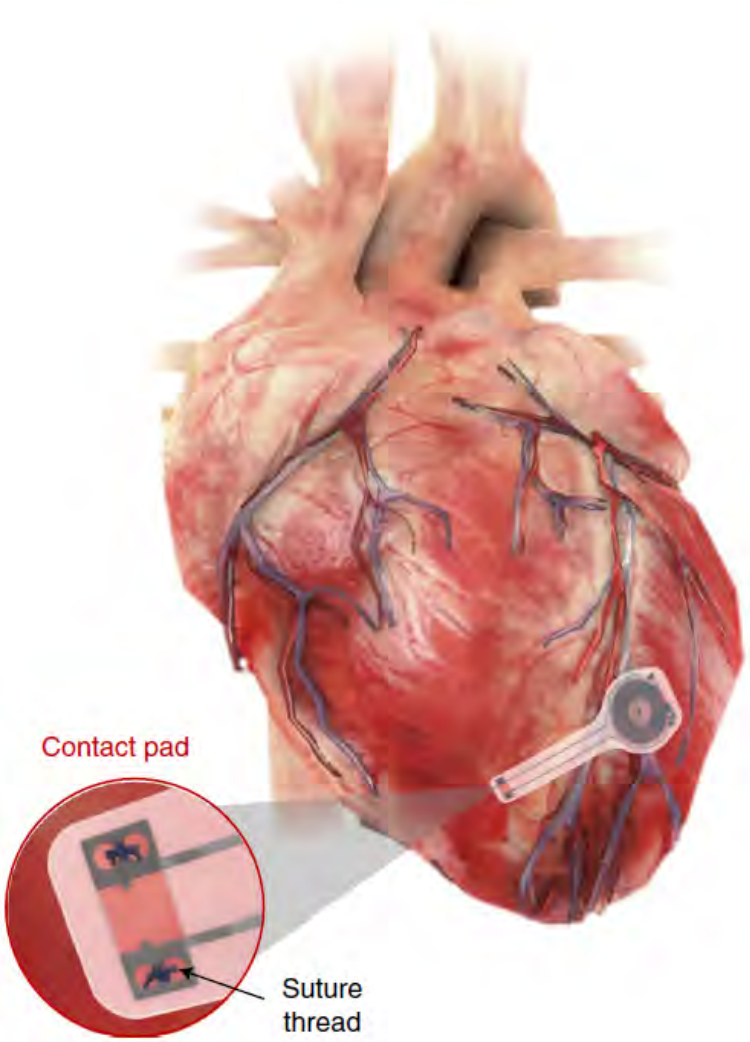


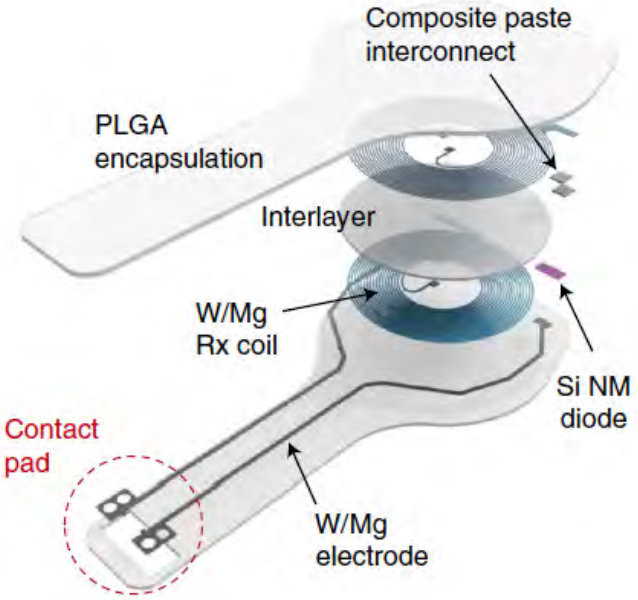
► **Cardiac tissue grows toward implants, difficult to remove**

In July 2019, *The New York Times* reported on details of a medical malpractice suit Armstrong's family had filed. When Armstrong appeared to be recovering from his bypass surgery, nurses removed the wires connected to his temporary pacemaker. He began to bleed internally and his blood pressure dropped.

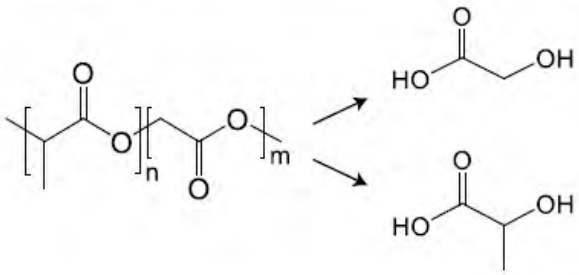


Bioresorbable, Wireless Cardiac Pacemaker

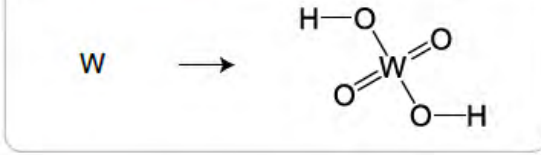




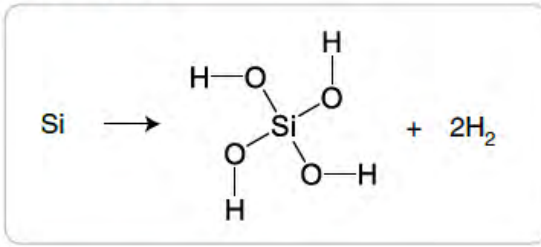
PLGA encapsulation



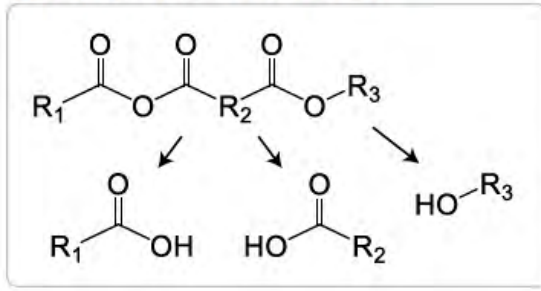
W/Mg electrode



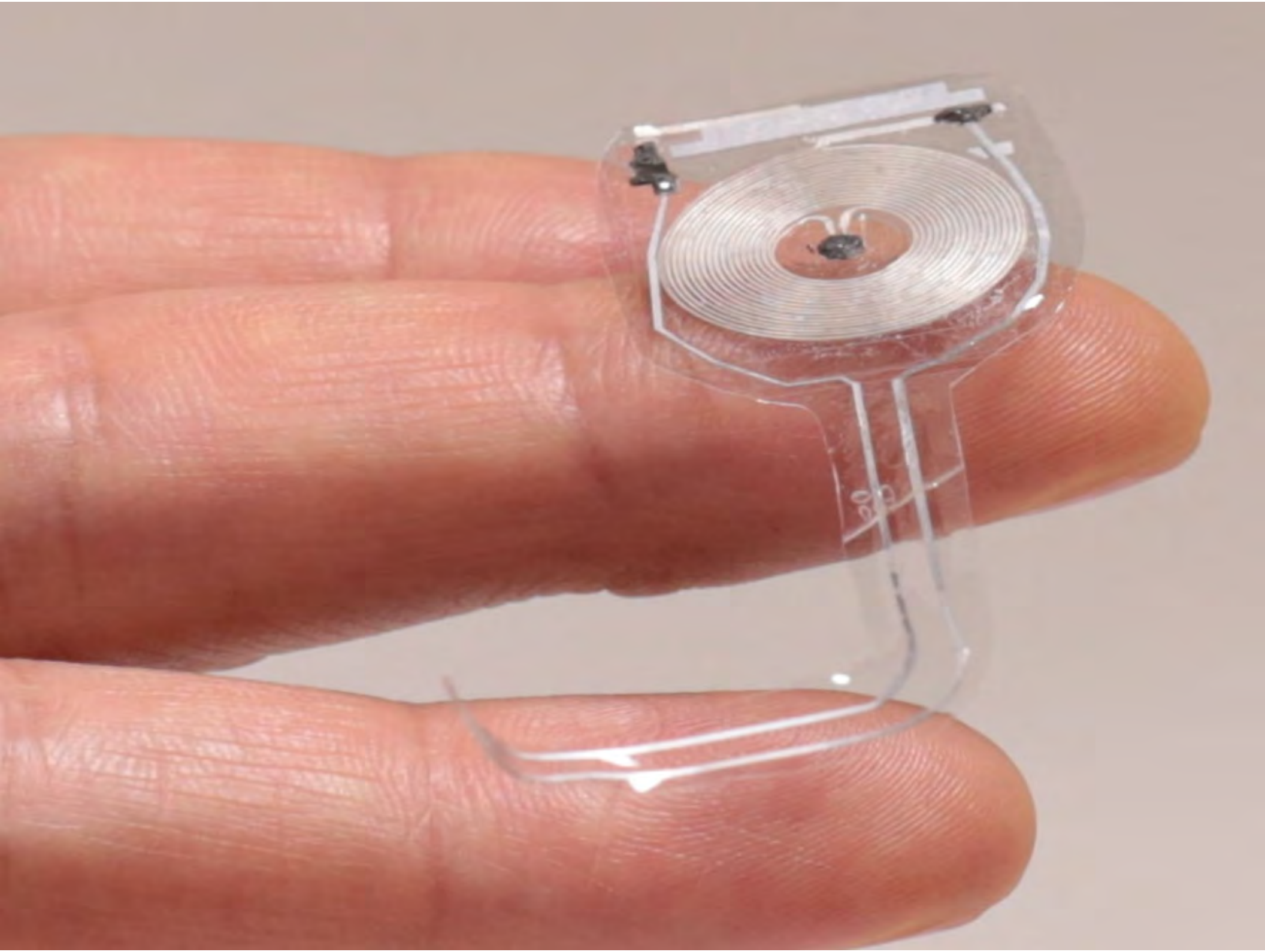
Si NM diode



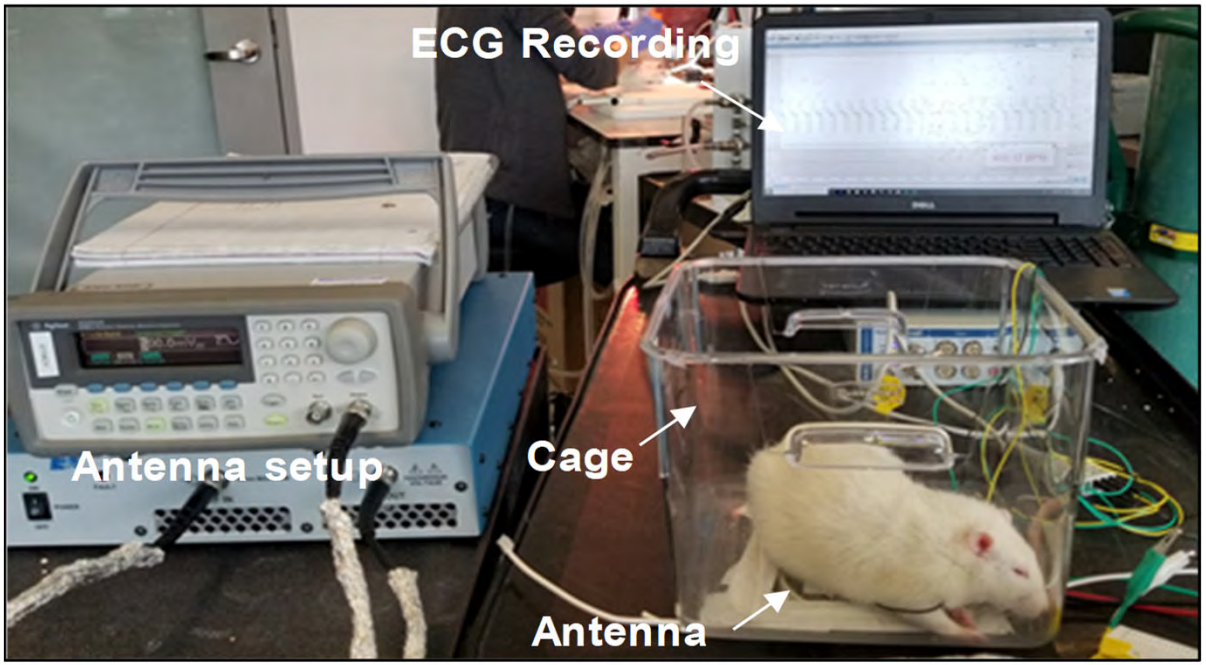
Composite paste interconnect

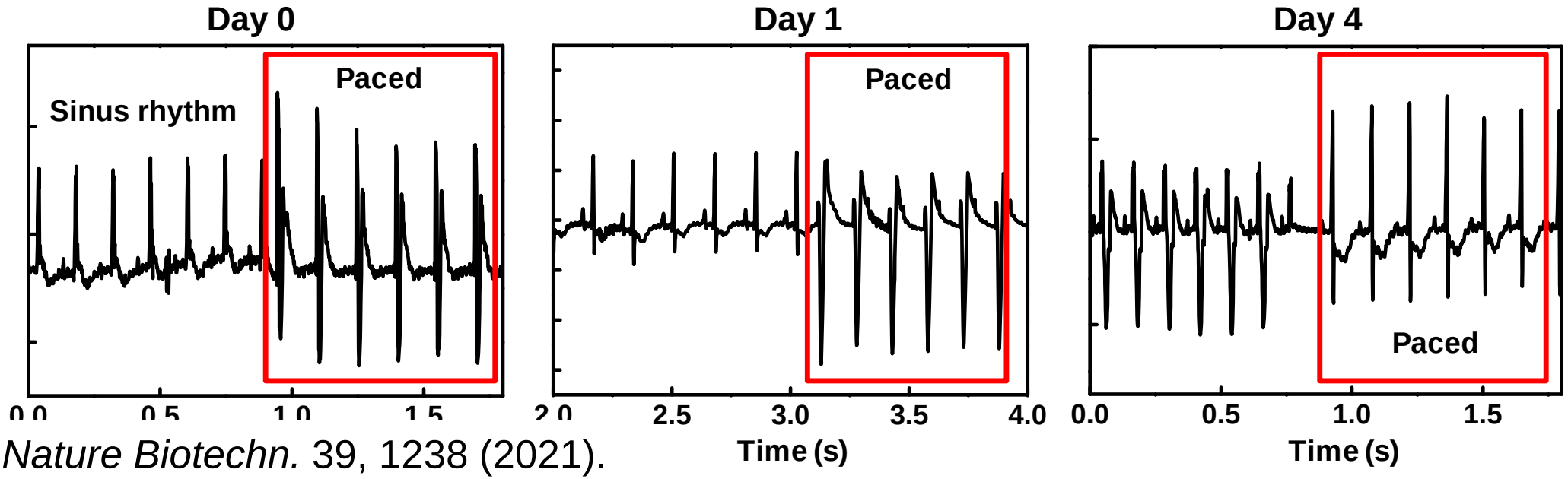


Nature Biotechn. 39, 1238 (2021).



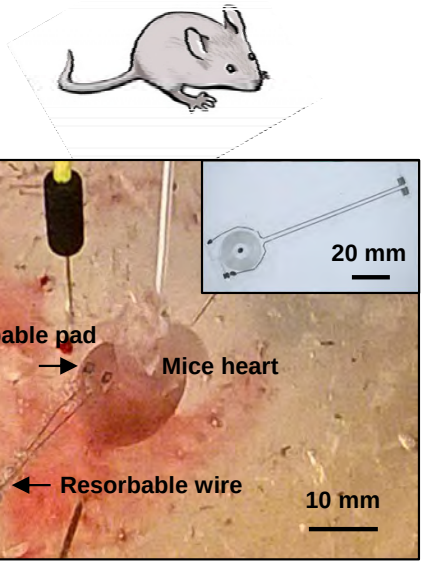
In Vivo Demonstration

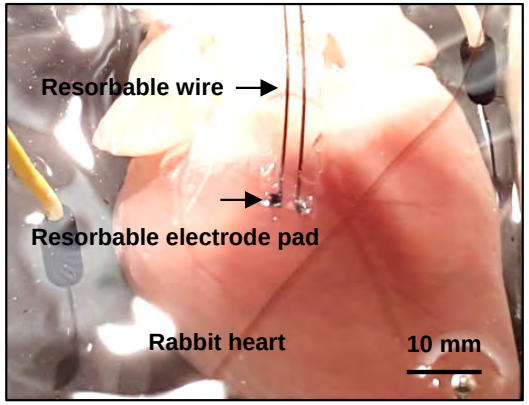


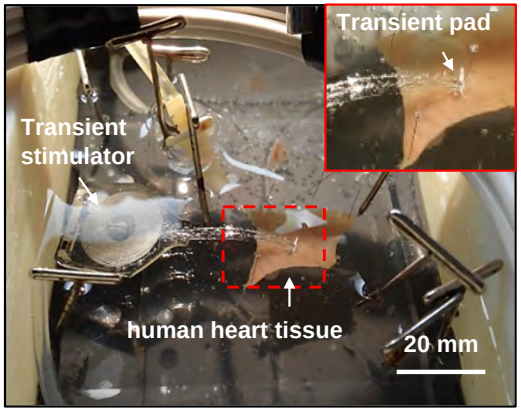


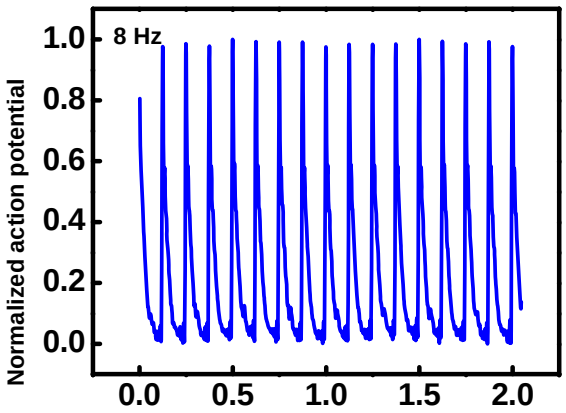
Nature Biotechn. 39, 1238 (2021).

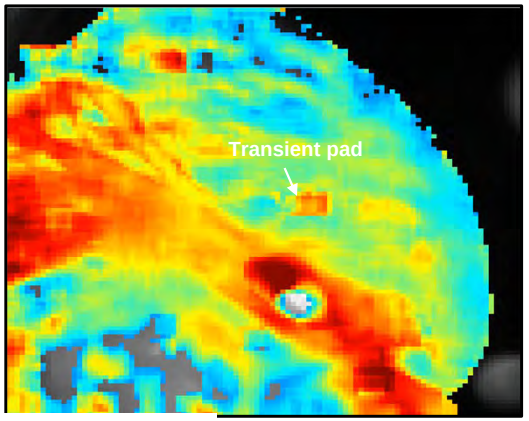
Demonstrations in Various Cardiac Systems

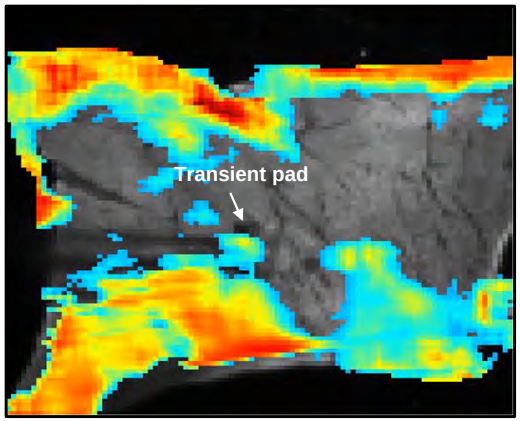












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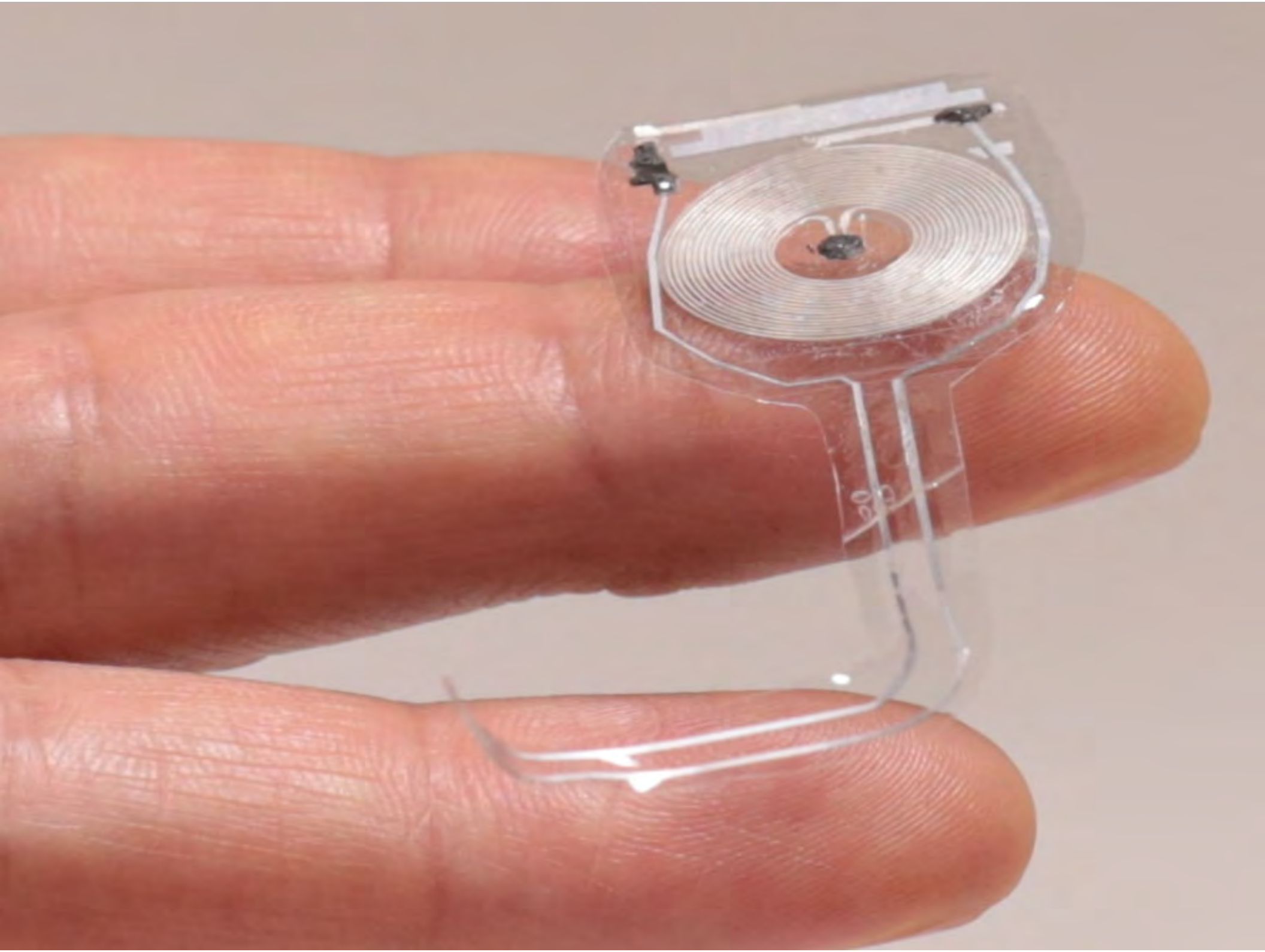
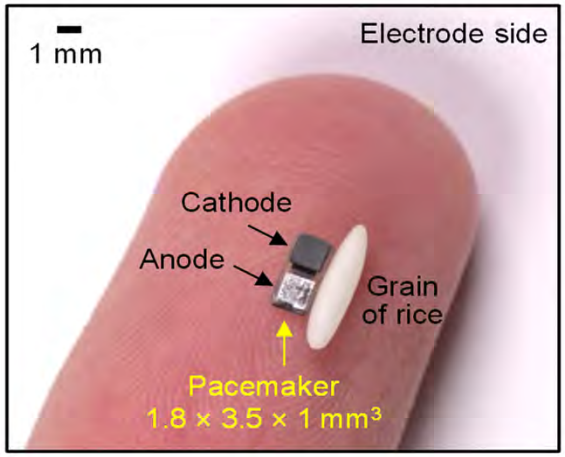
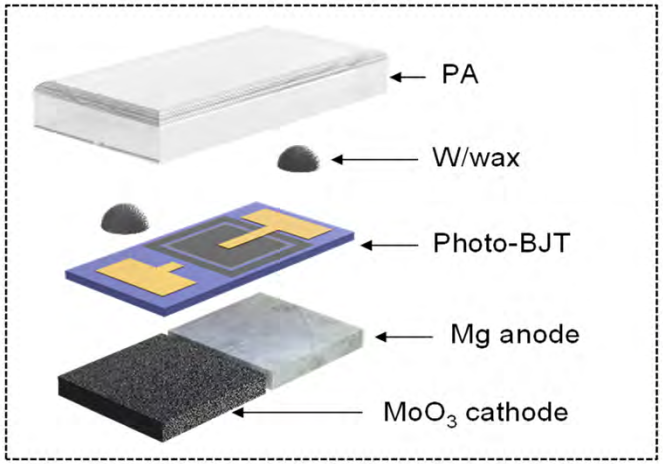
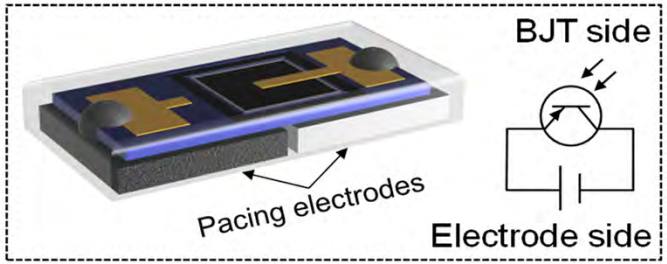
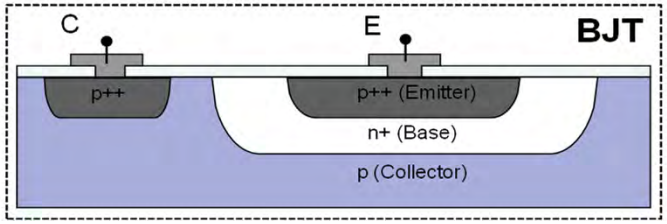


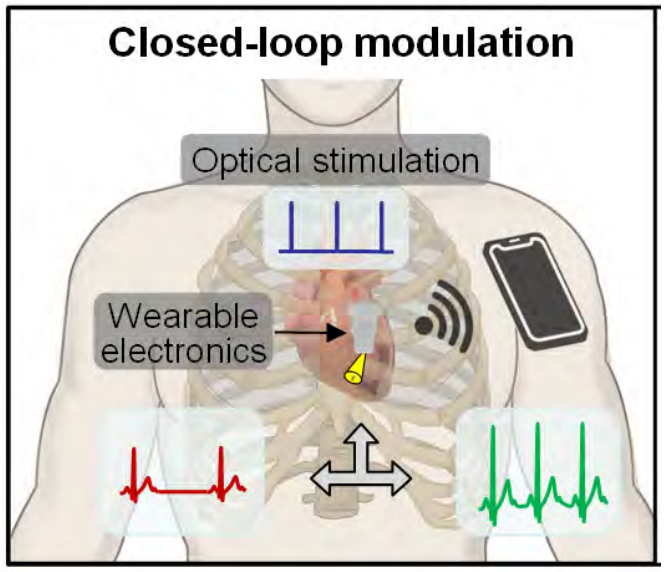
The World's Smallest Pacemaker – Also Bioresorbable

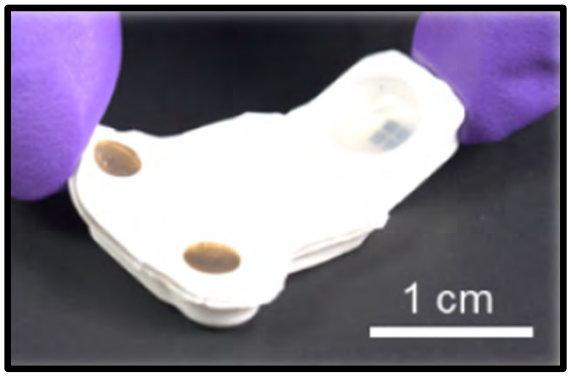


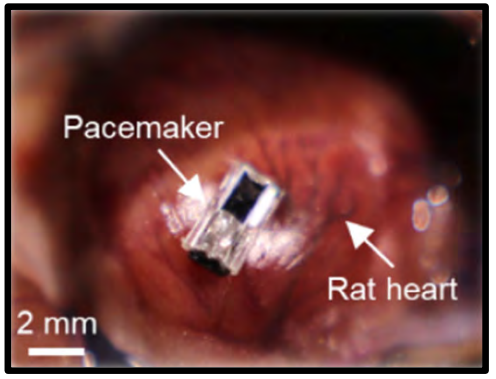


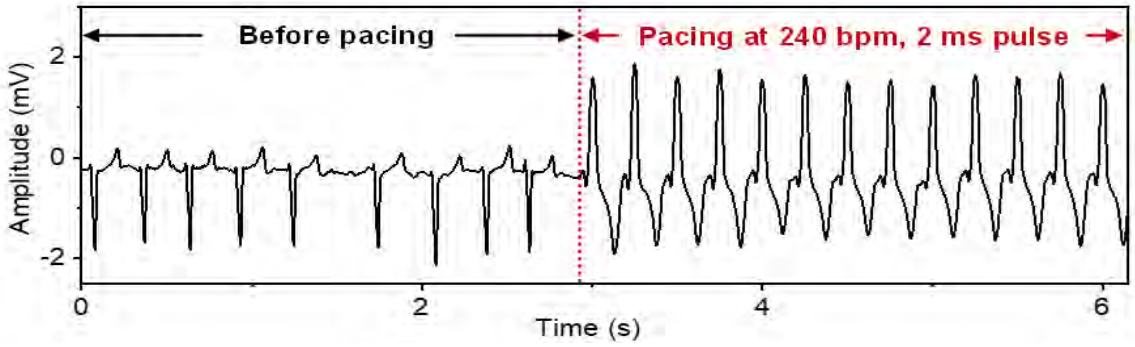












Nature **640**, 77 (2025).

Transient Electronics -- Envisioned Applications

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5) Hardware Reconfigurable Electronics

Health Monitoring – Human Body & the Natural World

Wind Dispersed Seeds

Glider Type

(Source: BBC 2 “Seed aviation, Travelling, The Private Life of Plants”).

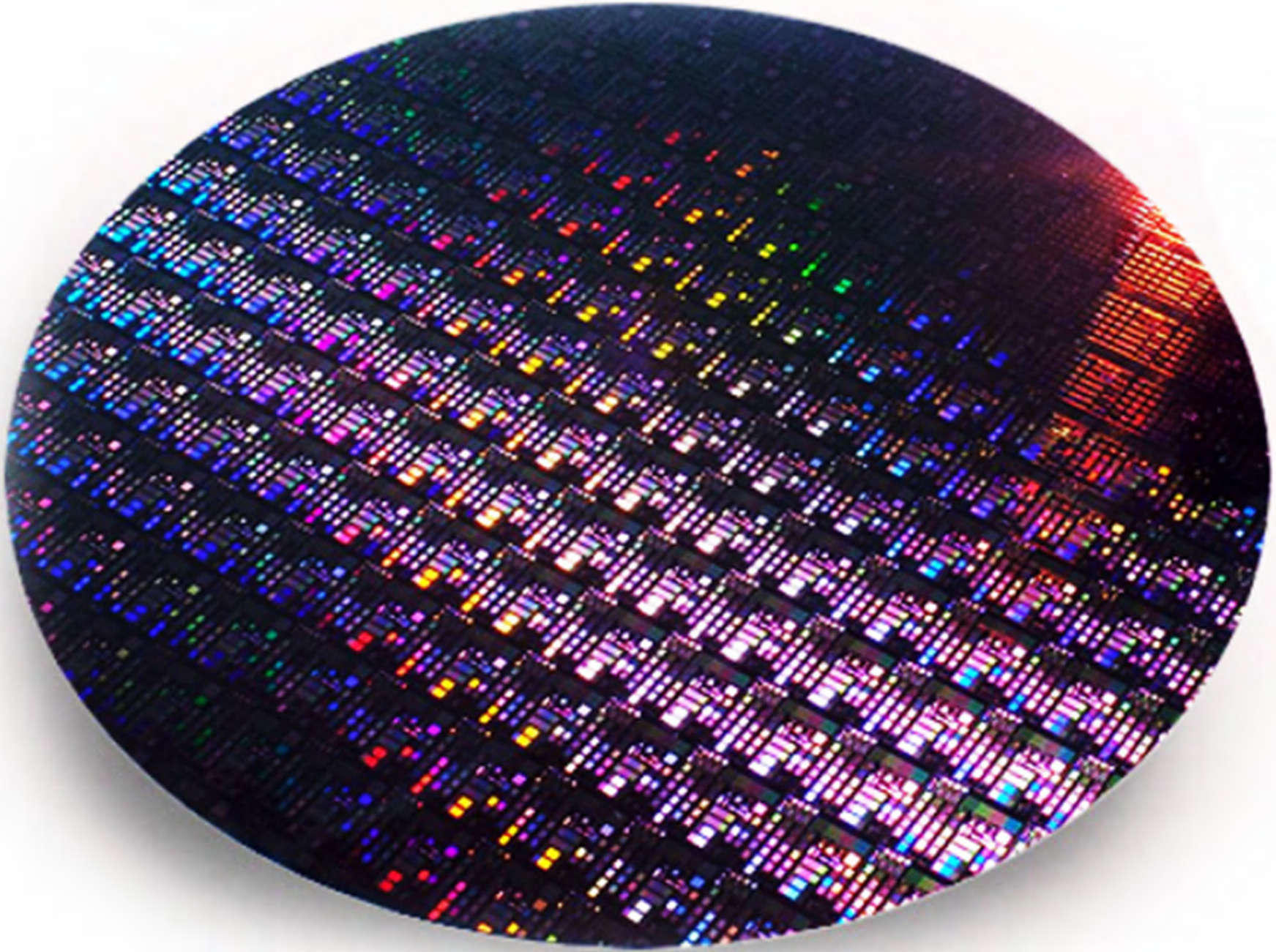
Parachute Type

(Source: New York Times “How a Vortex Helps Dandelions Fly”).

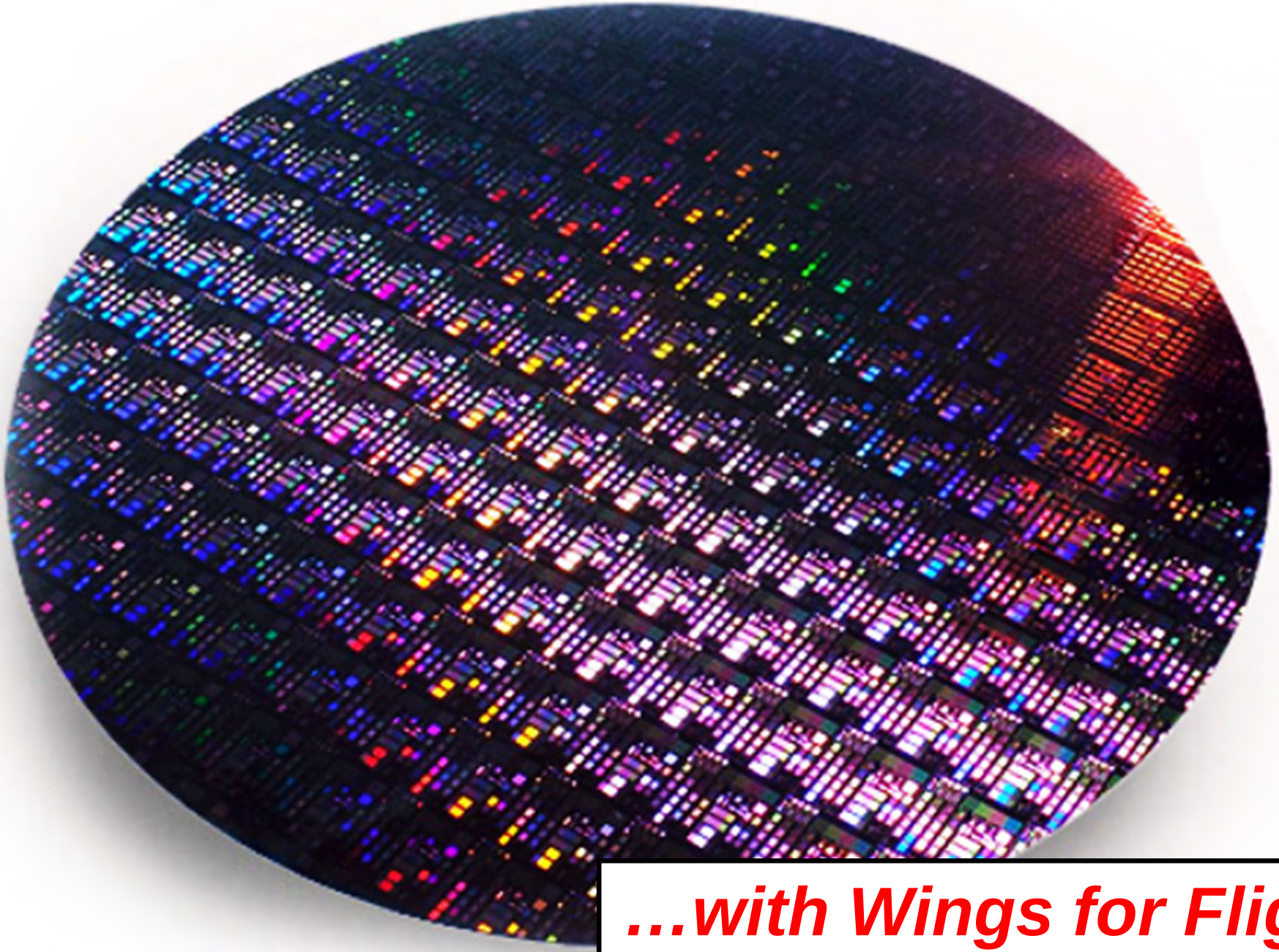
Wind Dispersed Seeds

Helicopter Type

(Source: BBC 2 “Seed aviation, Travelling, The Private Life of Plants”).



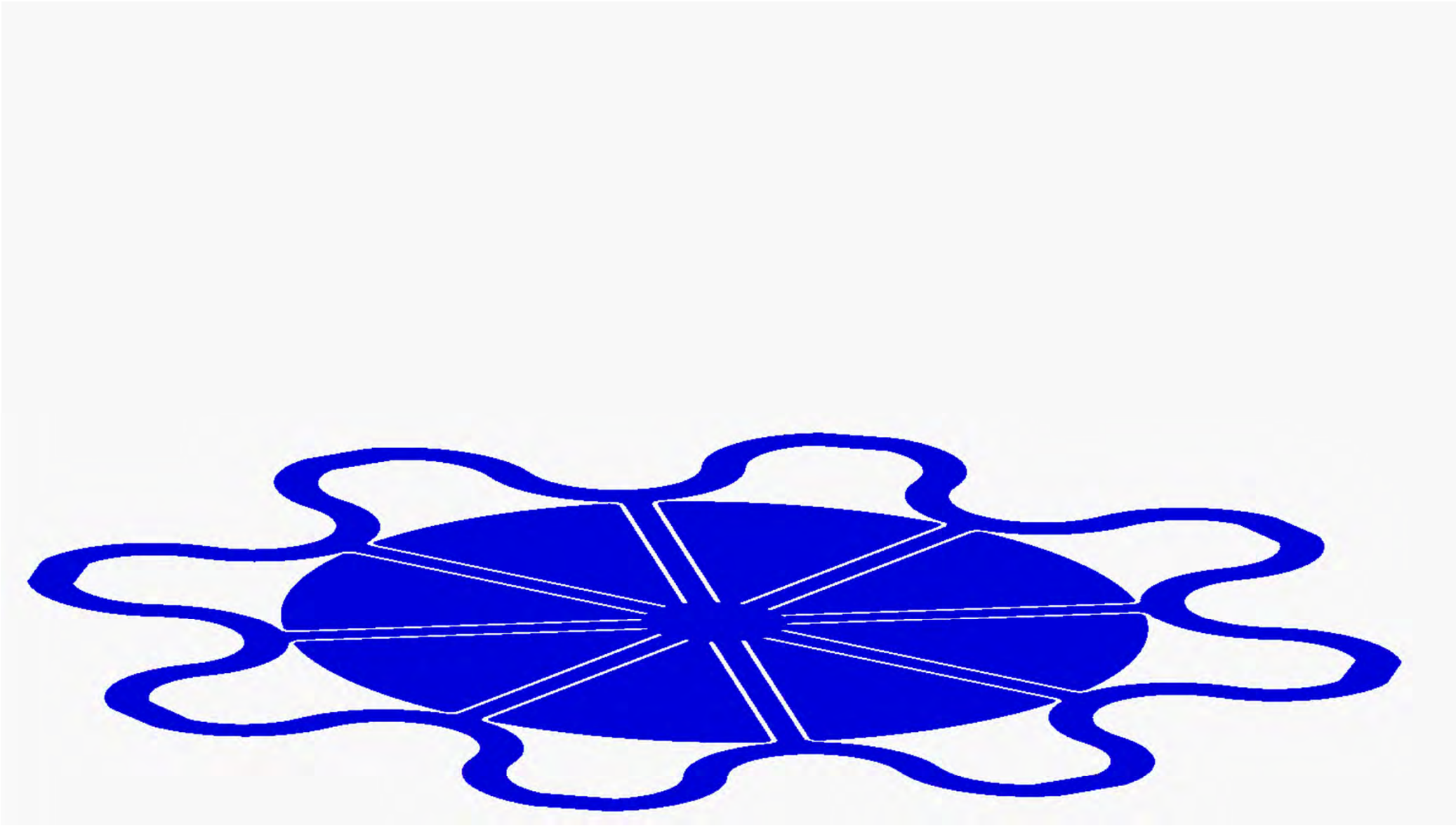
Soluble in Ground Water or Biofluids



…with Wings for Flight

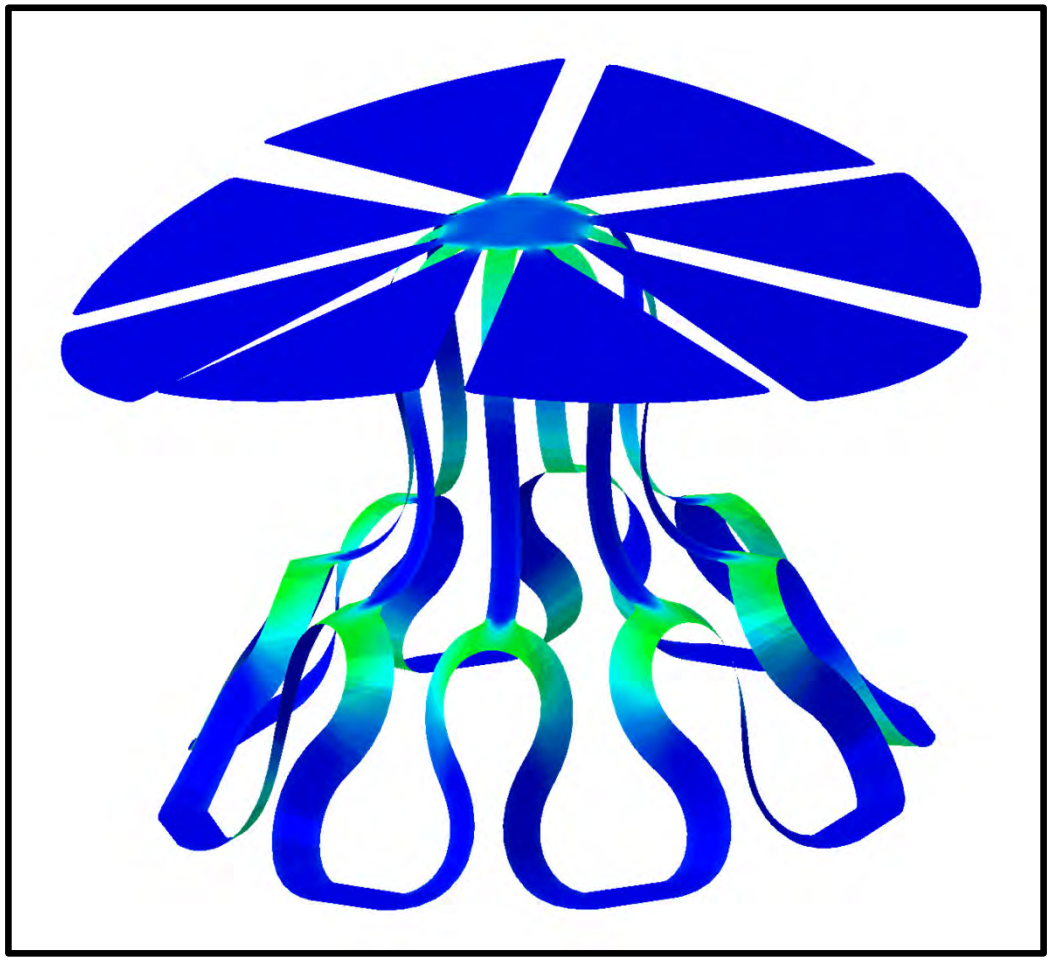
Soluble in Ground Water or Biofluids

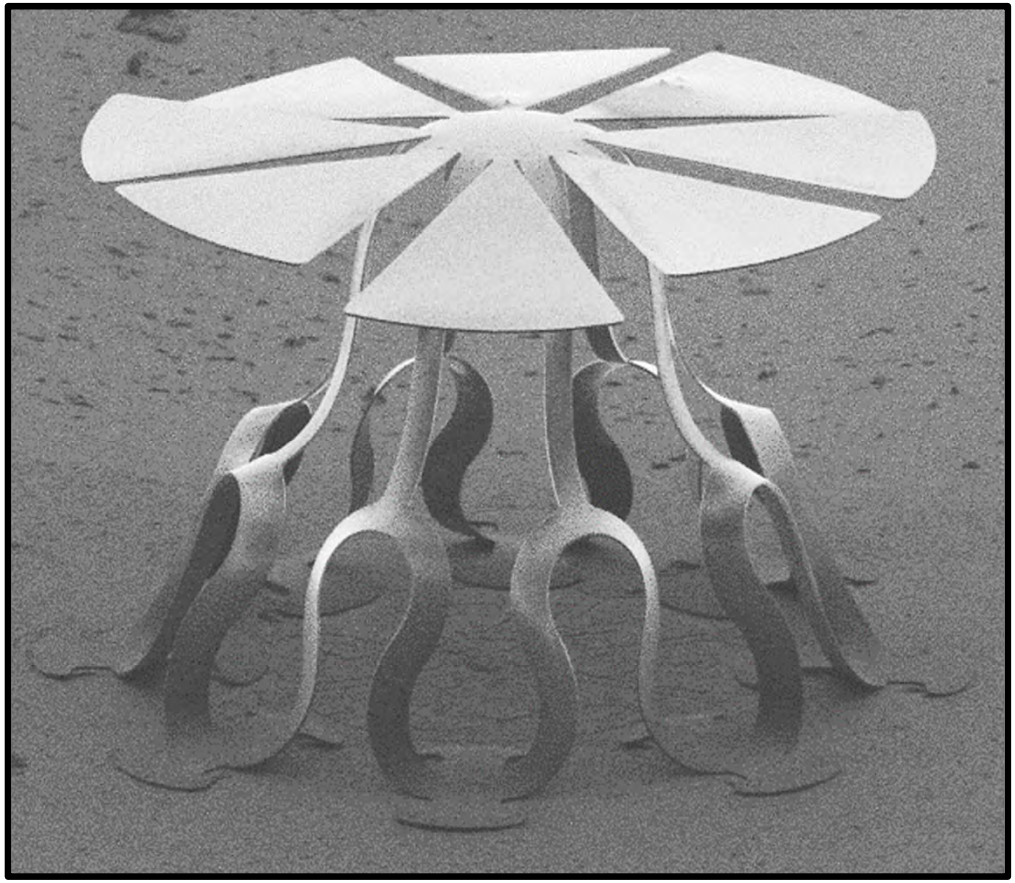
Advanced 3D Architectures – Membranes and Ribbons



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

Silicon ‘Kirigami’

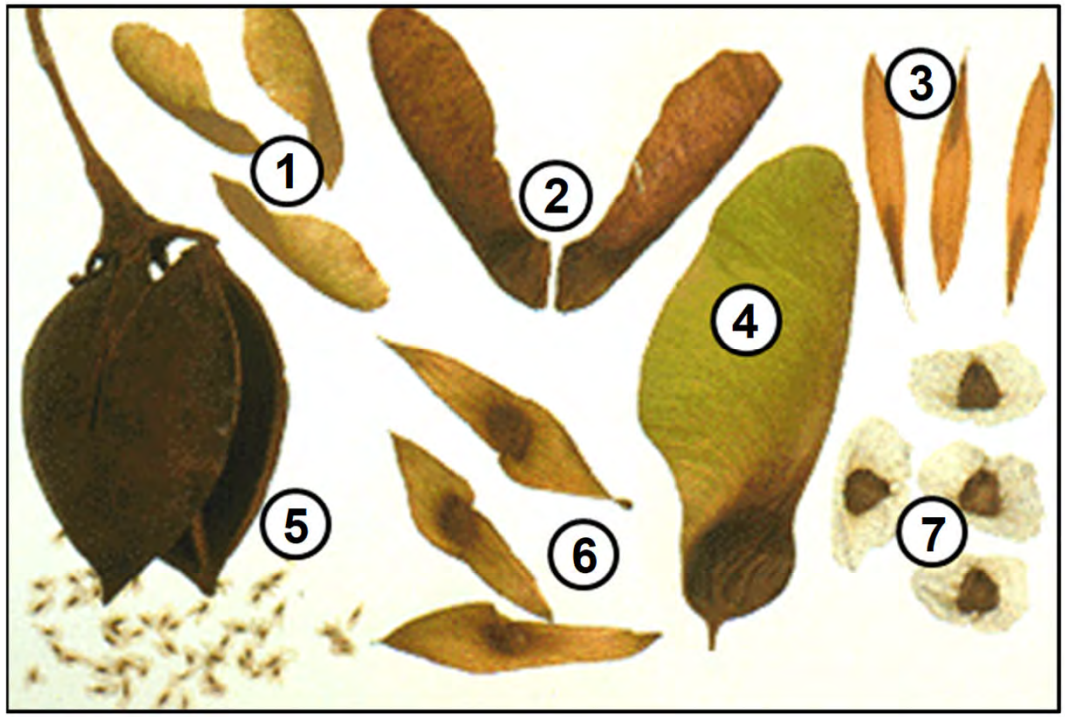


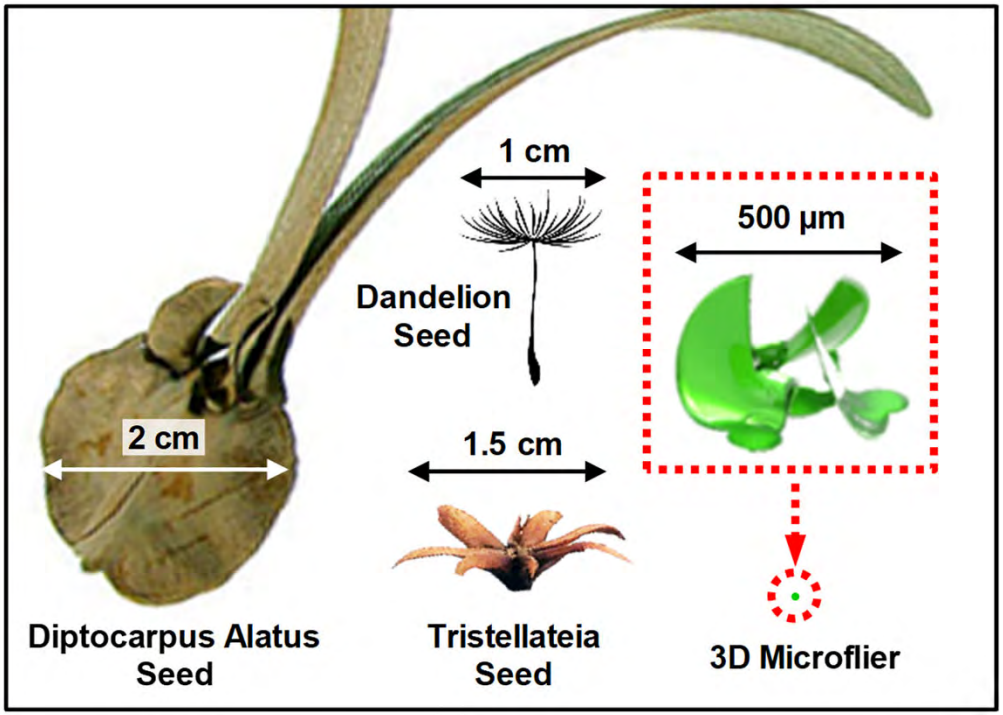


100 μm

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

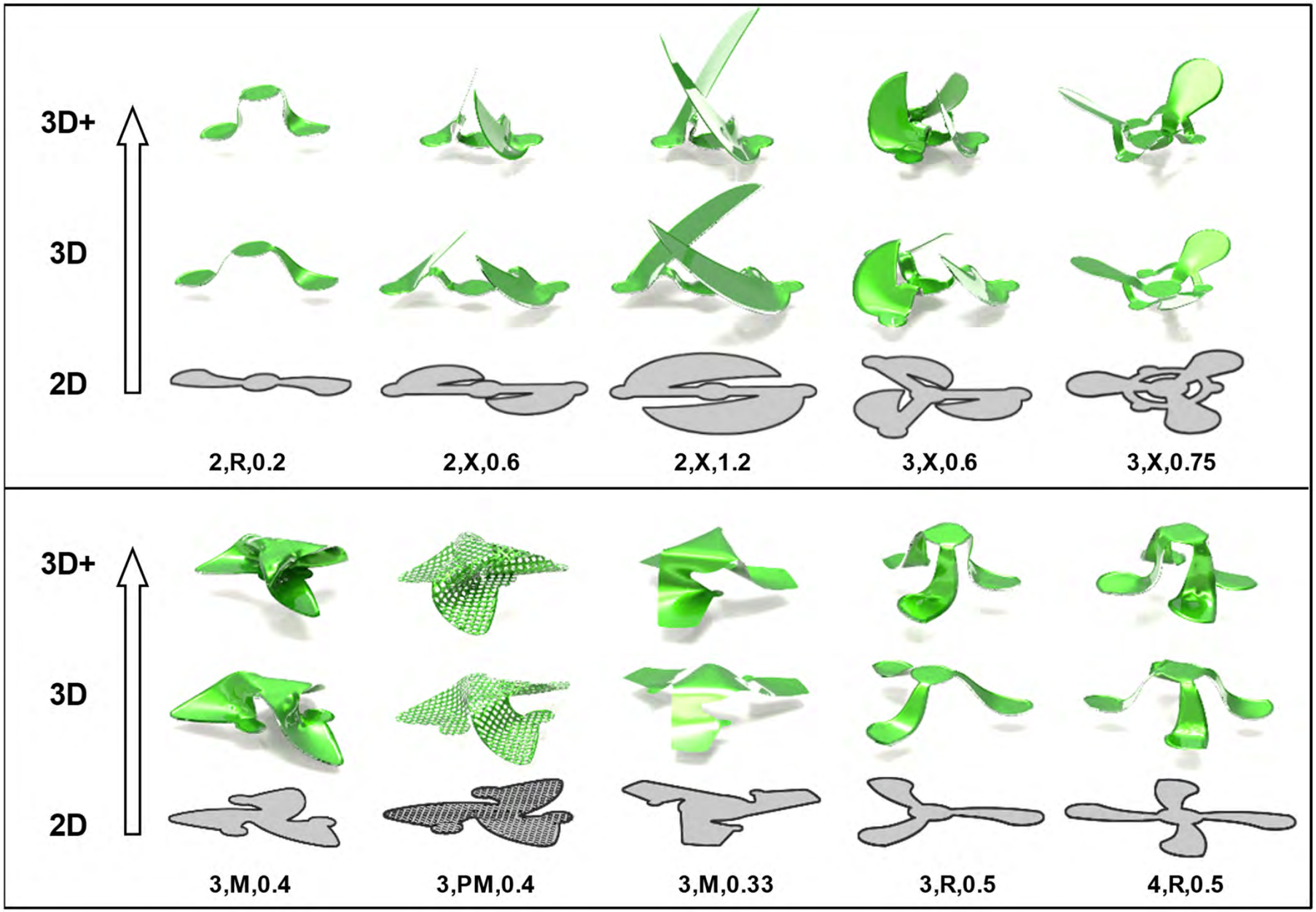
3D Microfliers – Bioinspired by Wind-Dispersed Seeds

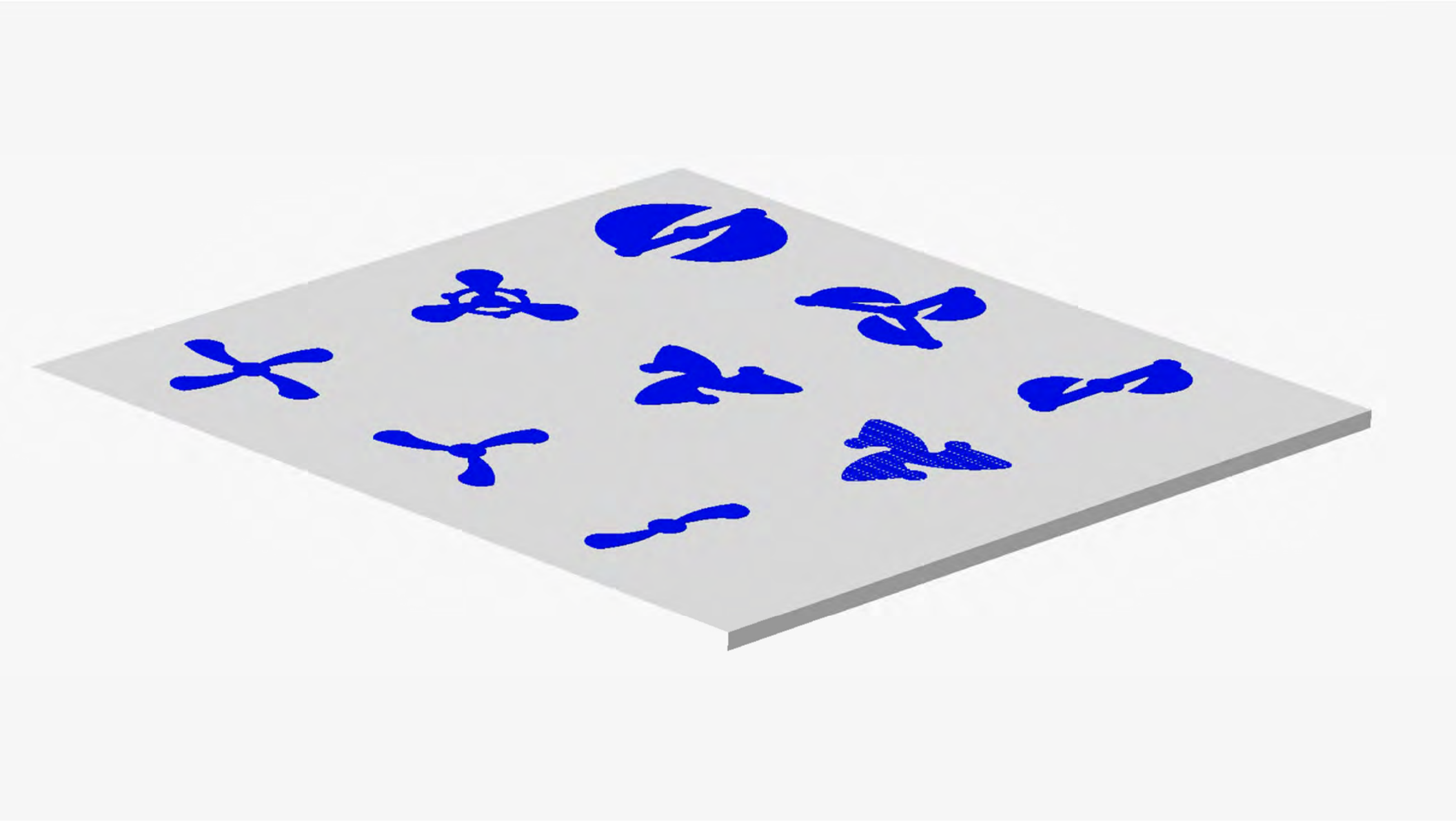




Nature **597**, 503 (2021).

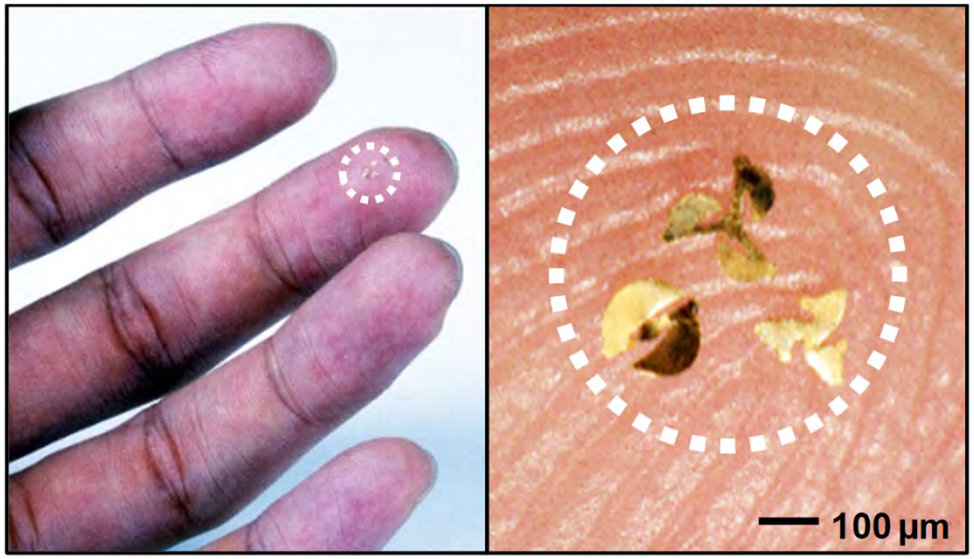
3D Microfliers – Bioinspired by Wind-Dispersed Seeds

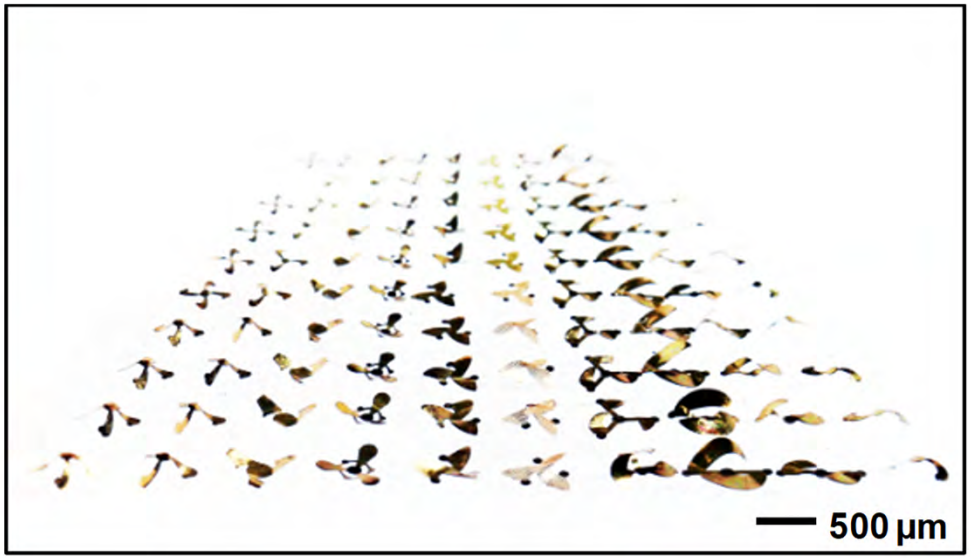


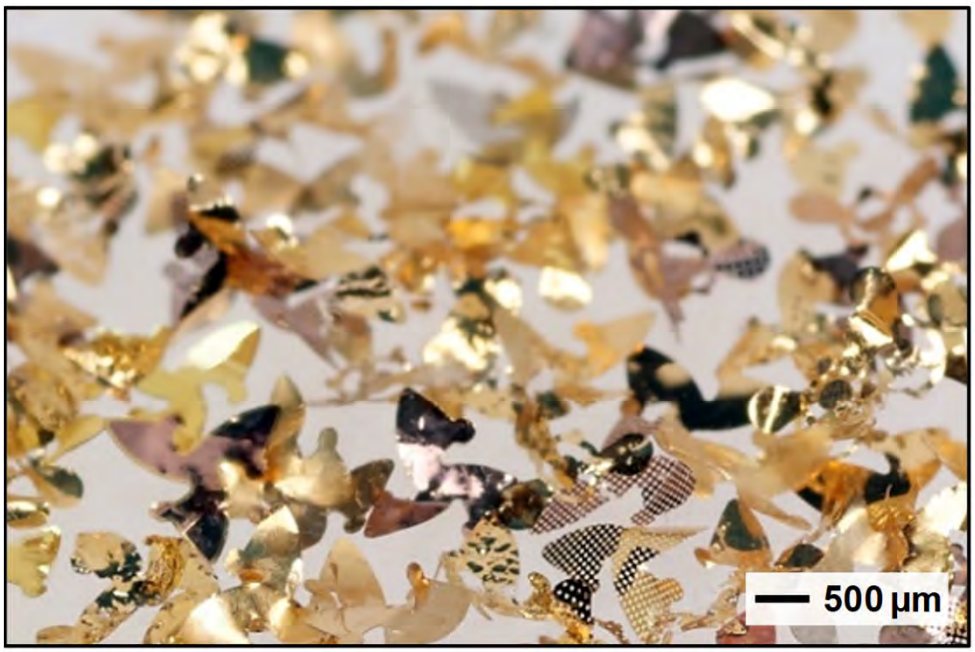


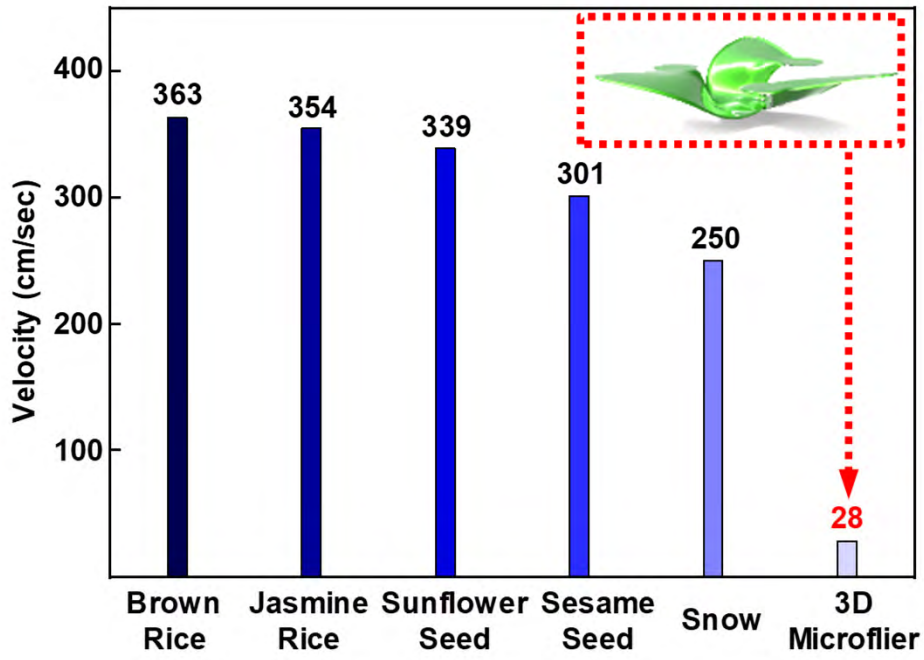
Nature **597**, 503 (2021).

3D Microfliers – Bioinspired by Wind-Dispersed Seeds

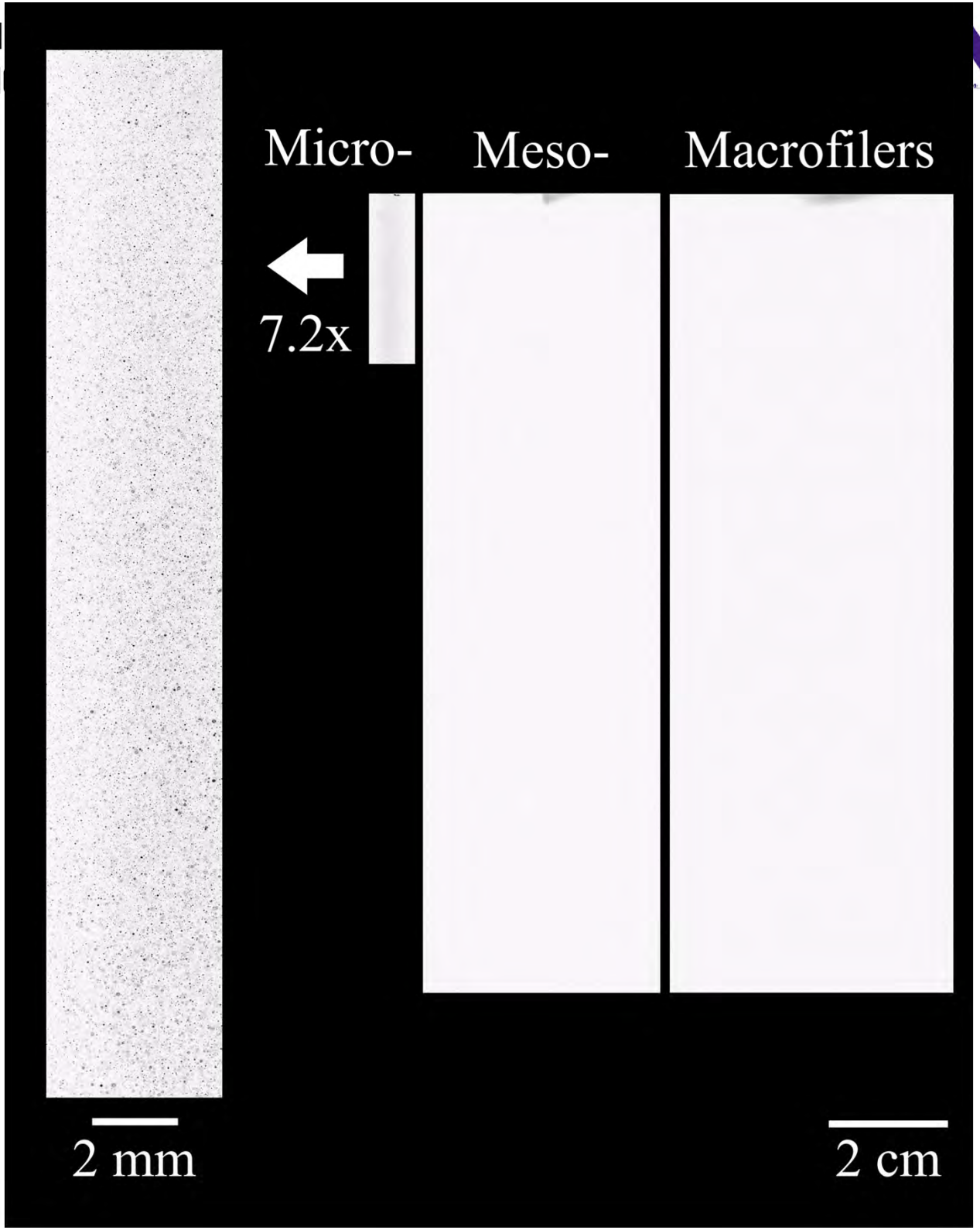






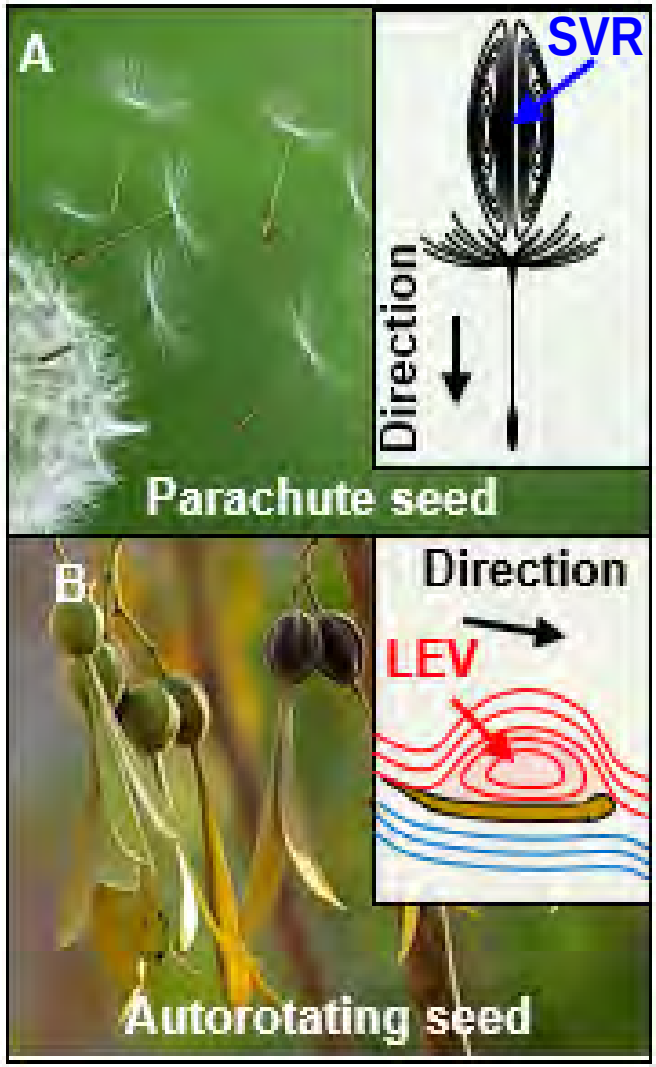


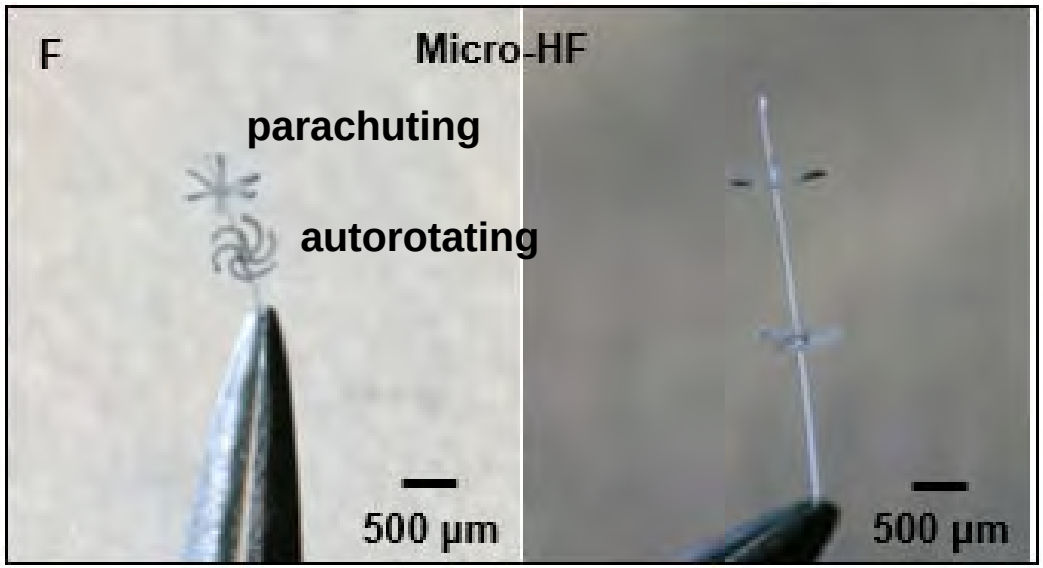
Nature **597**, 503 (2021).

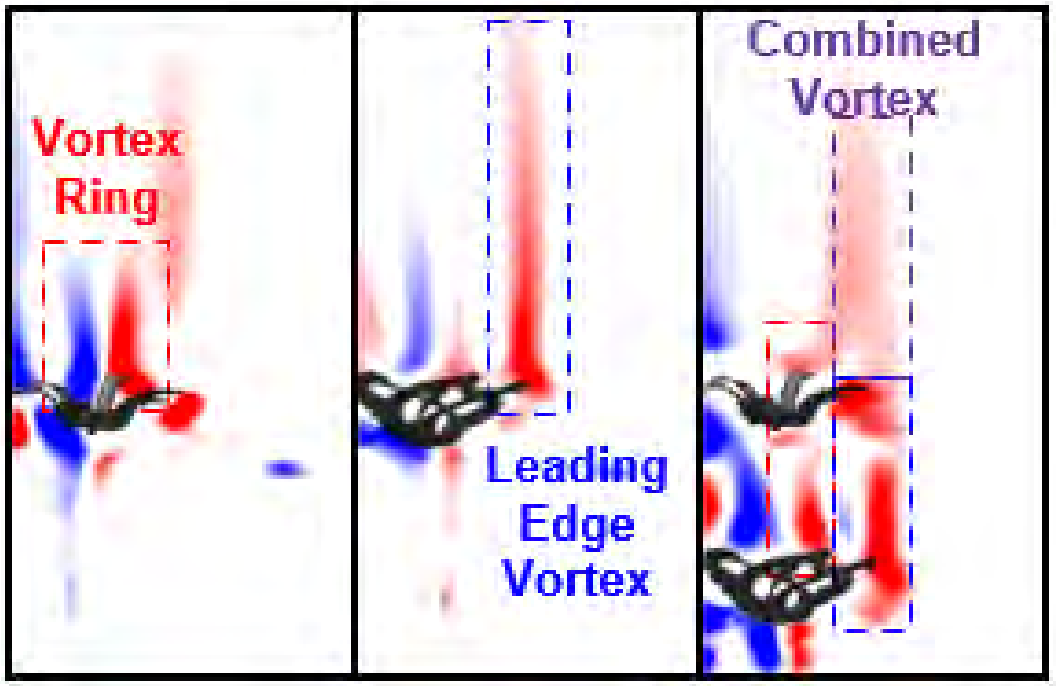


Nature **597**, 503 (2021).

Hybrid Systems – Parachutes and Helicopters







PNAS Nexus **3**(3), 1 (2024).

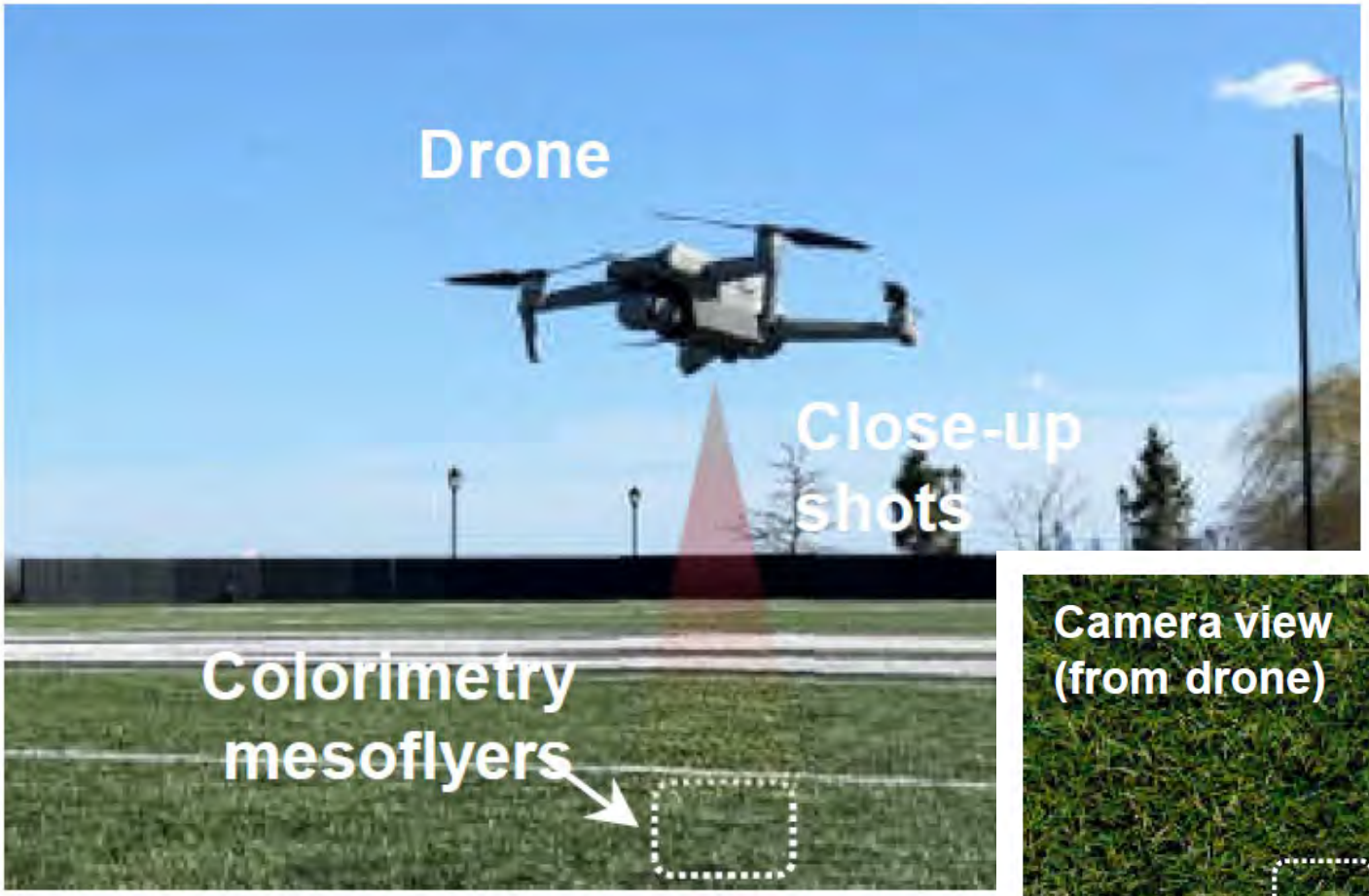
QUERREY SIMPSON INSTITUTE FOR BIOELECTRONICS

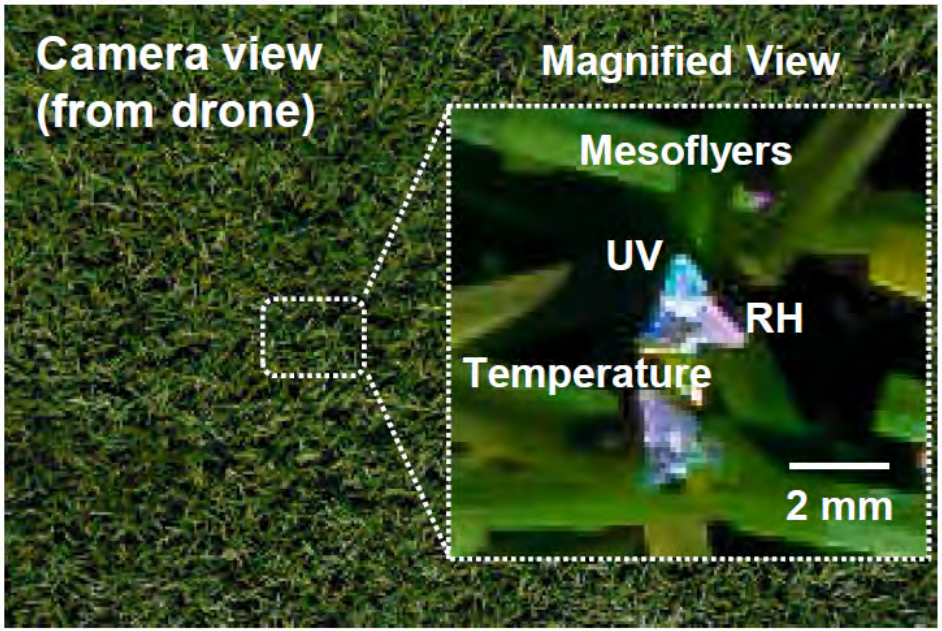
Northwestern

pH Responsive, Degradable Colorimetric Mesoflier

Sci. Adv. **8**(51) eade3201 (2022).

Ongoing Work – Field Studies

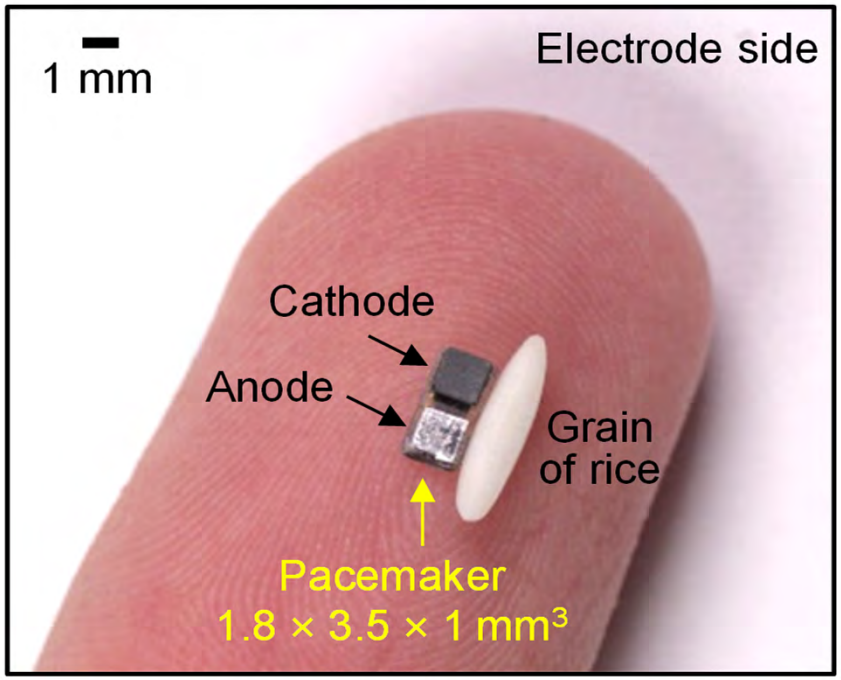


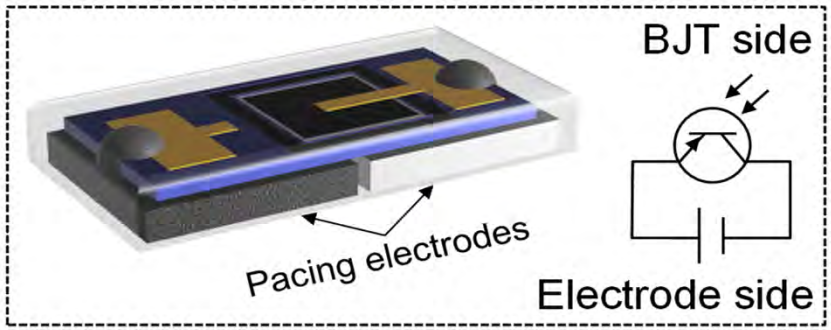


Sci. Adv. **8**(51) eade3201 (2022).

Semiconductor Nanomaterials in 3D and Transient Electronics

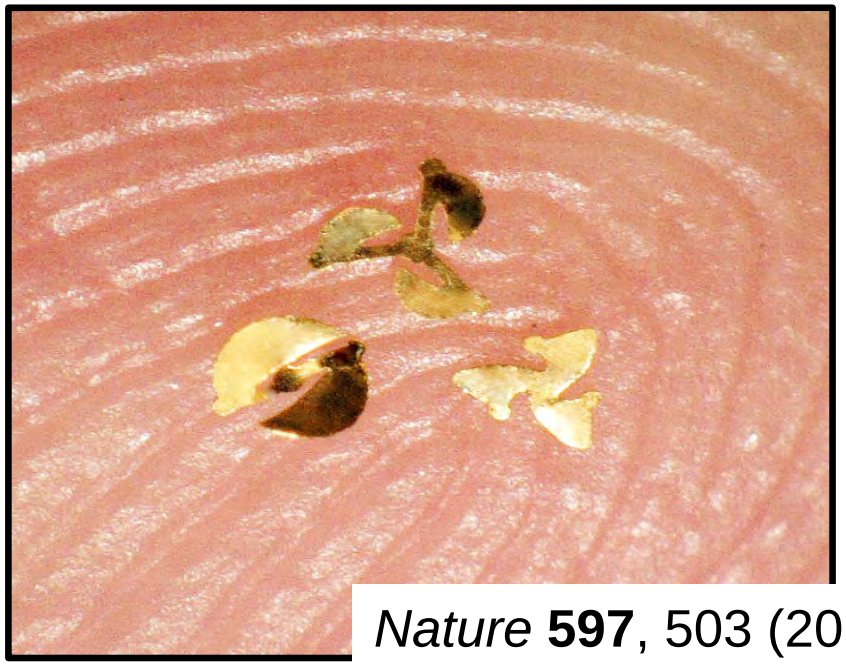
Bioelectronic Medicines





Nature **640**, 77 (2025).

Environmental Sensors



Nature **597**, 503 (2021).

Senior Collaborators

Engineering Science

Prof. Y. Huang (NU) – theory

Prof. P. Ferreira (UIUC) – manuf.

Prof. S. Li (UCLA) – nerve cuff

Clinical Medicine

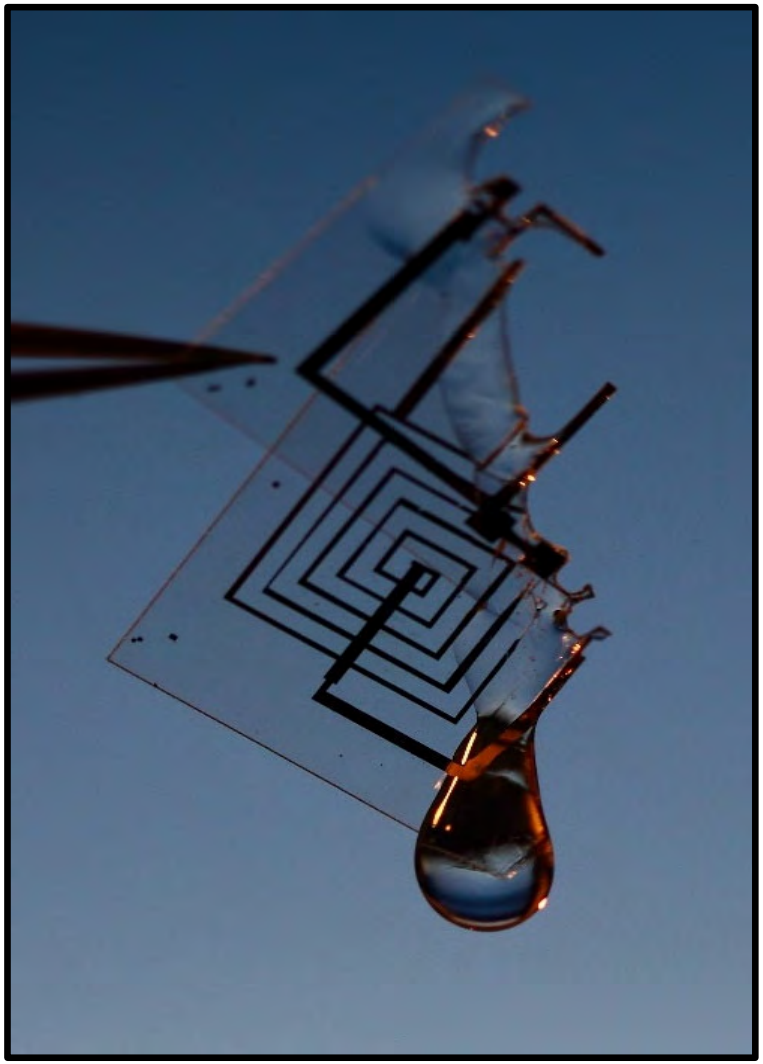
Prof. I. Efimov (NU) – cardiac

Prof. Z. Ray (WUSTL) – neuro

Prof. C. Franz (SRAL) - neuro

Prof. R. Arora (NU) – cardiac

Prof. A. Bharat (NU) - diaphragm



QUERREY SIMPSON INSTITUTE FOR BIOELECTRONICS

Northwestern

Research Team

Undergraduates, MS Students, MD Students
PhD Students, Postdocs, Senior PIs

DARPA NSF Office of Basic Energy Sciences Serving the Present, Shaping the Future BARDA Biomedical Advanced Research and Development Authority NIH NICHD Bill & Melinda Gates foundation