Skin-Inspired Organic Electronics

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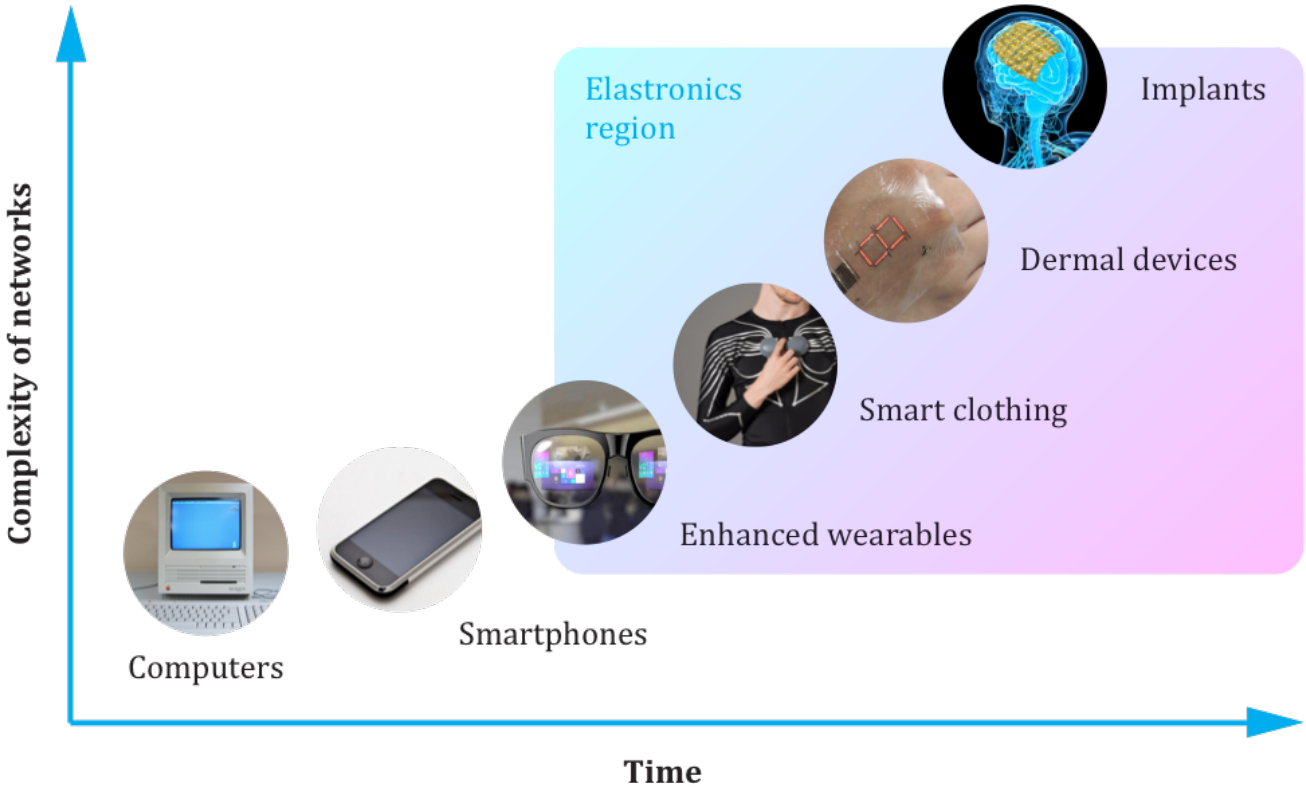
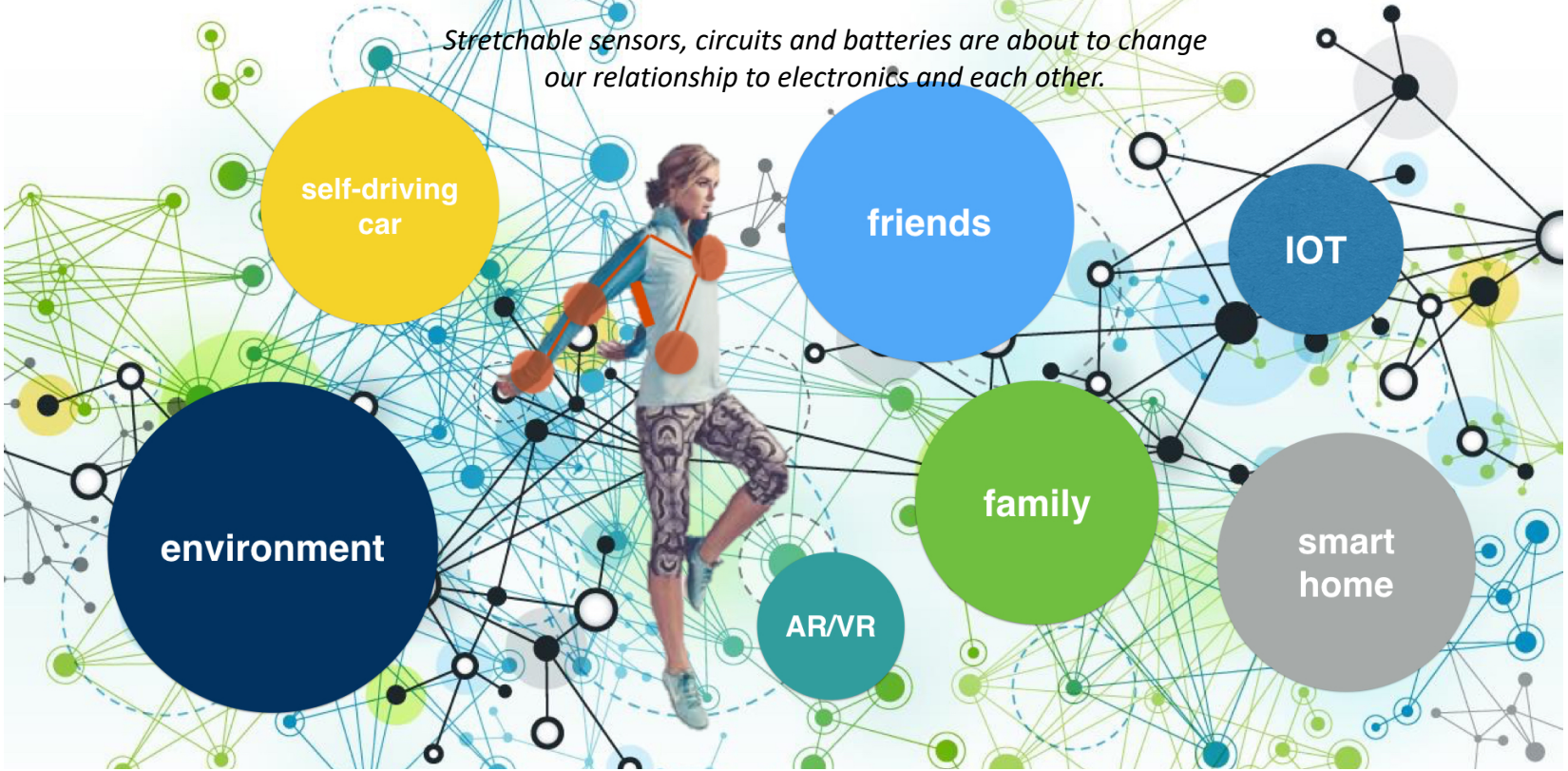
A world beyond smartphones



Chu, Chang, Burnette, Bao, **Nature**, September 21, 2017

Skin-like electronics (*e*-Skin): connecting digital world to physical world

Stretchable sensors, circuits and batteries are about to change our relationship to electronics and each other.



Chu, Chang, Burnette, Bao, **Nature**, September 21, 2017

nature
Comment
September 21, 2017

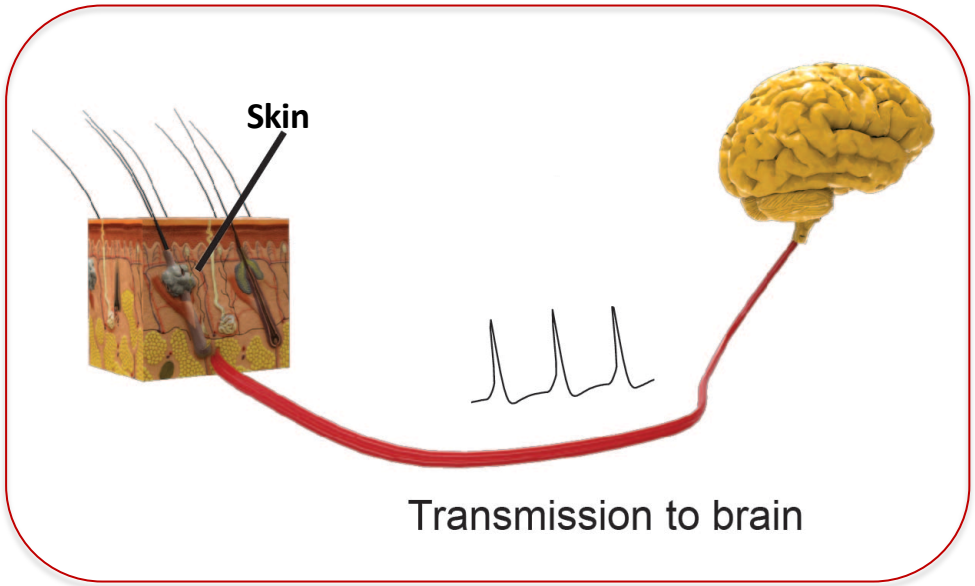
Unobtrusive ‘elastronic’ transistors can behave like skin and stretch without tearing. Credit: Bao Lab

Bring on the bodyNET

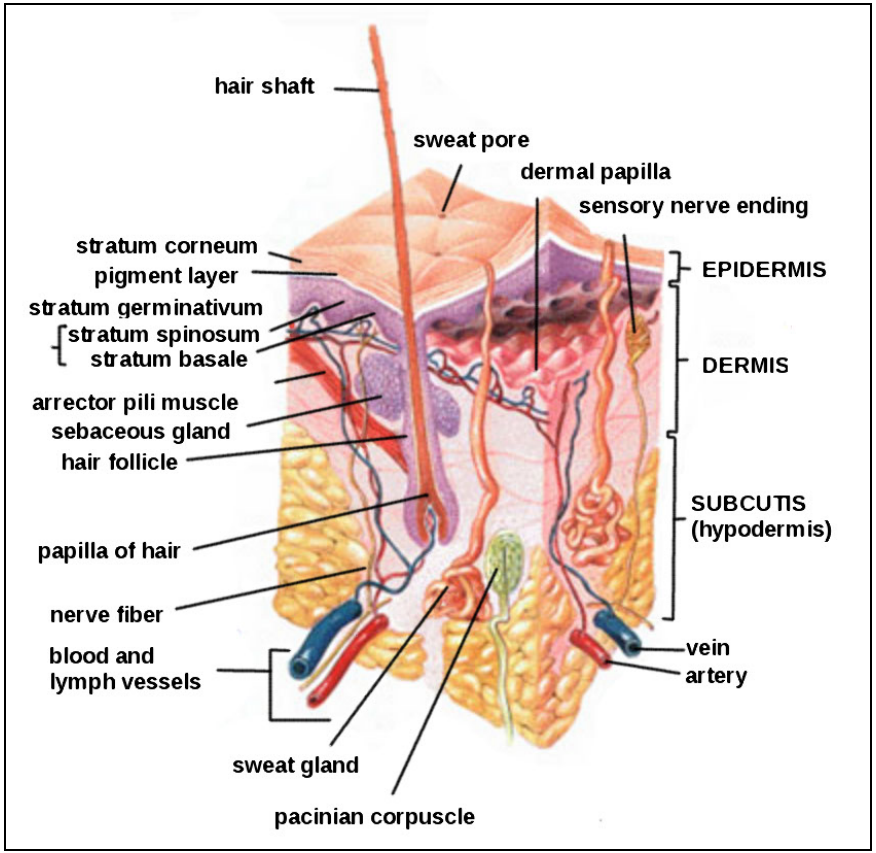
Stretchable sensors, circuits and batteries are about to change our relationships with electronics and each other

Skin-inspired electronics - skin as an inspiration

Sensing
Signal processing/transmission
Bio-interface



Skin-inspired electronic materials



wikimedia.org

Sensing Functions:

- Touch
- Temperature
- Humidity

Material Properties

- Flexible
- Stretchable
- Biodegradable
- Self healing

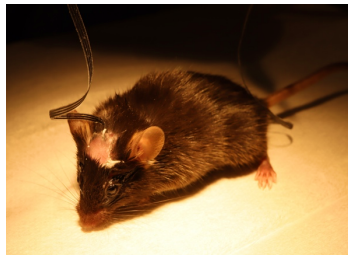
Skin-like form factor

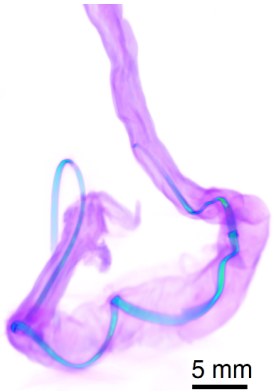
Rigid and brittle electronics

Minimal signal attenuation

Robust under deformation

Minimal invasive reactions





Soft and stretchable skin-like electronics

"as a part of human"

Re-invent electronics with intrinsically stretchable materials

Questions we address

1. How do we design and build an e-skin that mimics skin functions?

2. How do we design skin-like electronic materials?
- Without compromising electronic properties

3. What unique applications can we apply e-skins to?

Stretchable semiconductor and transistors

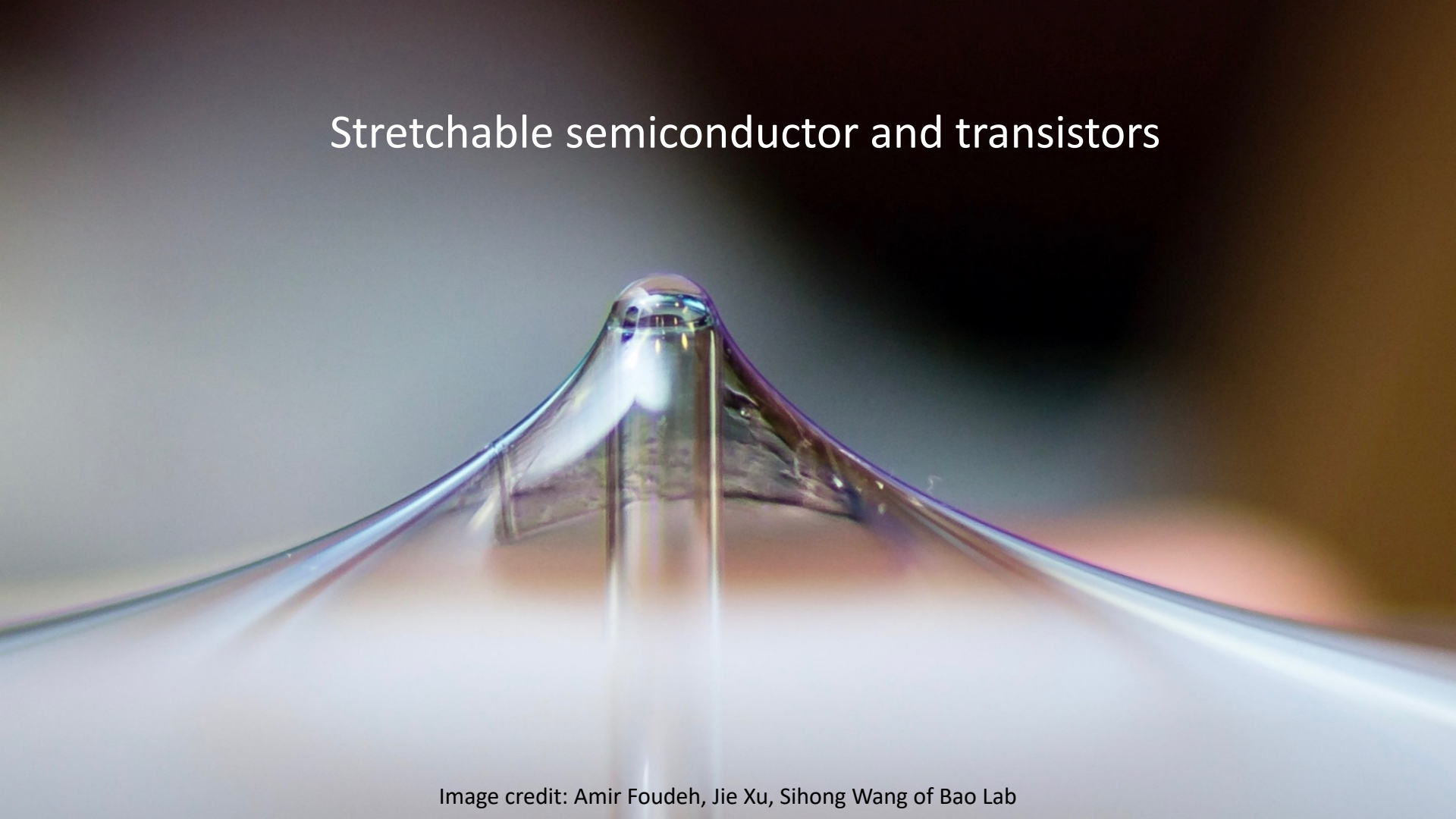
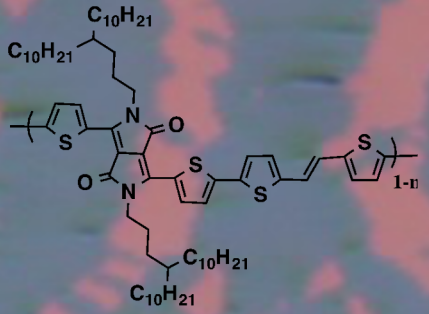


Image credit: Amir Foudeh, Jie Xu, Sihong Wang of Bao Lab

Cracks !

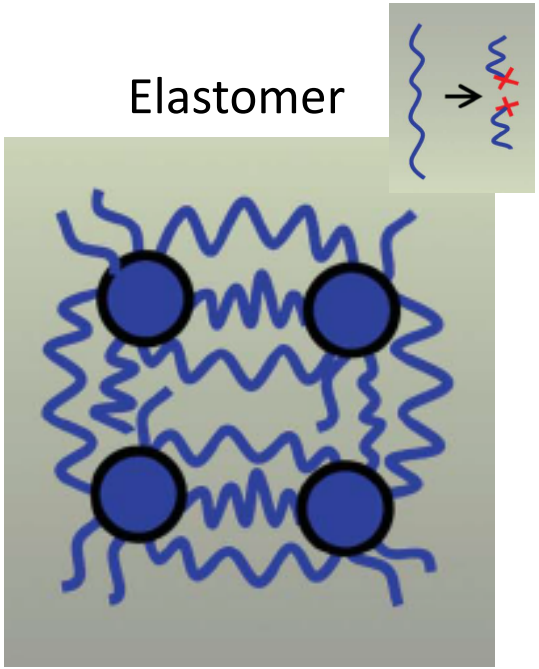
Typical polymer semiconductor under 20% strain



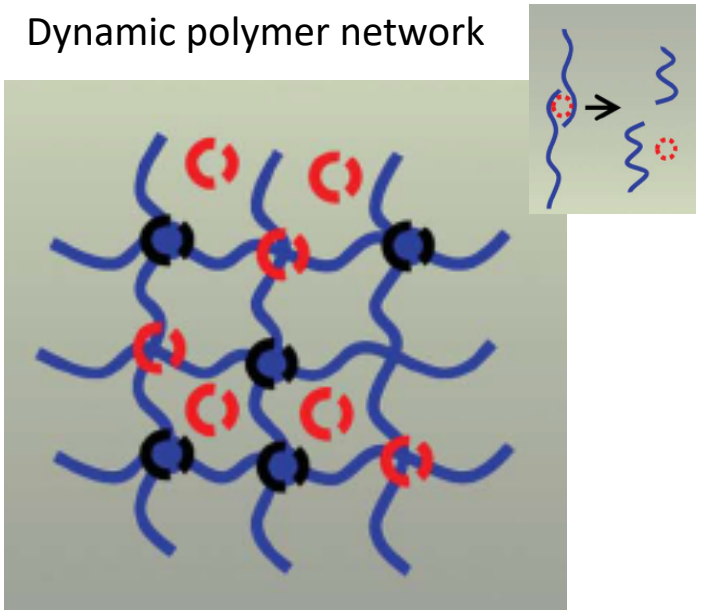
20 µm

Covalent vs. dynamic crosslinked polymer network

Elastomer



Dynamic polymer network



Total fracture energy $\Gamma = \dfrac{\Gamma_0}{1 - \alpha \cdot h_{\max}}$

Γ_0: Intrinsic fracture energy

$h_{\max}$: Max. dissipation/max. work

Zhang, Zhao et al., **Extreme Mech. Lett.**, 4, 1, 2015.

Dynamic polymer network

Dynamic Covalent Chemistry

C-C

C-N

C-S

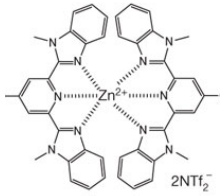
B-O

S-S

W. Zhang et al., Chem. Soc. Rev. 42, 6634 (2013)

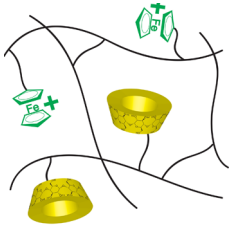
Non-covalent Chemistry

Metal Ion Complexes



Rowan and Weder et al. Nature, *472*, 334-337 (2011).

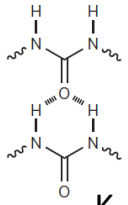
Guest-host



Harada et al. Nature Comm. 2011

Hydrogen Bonding

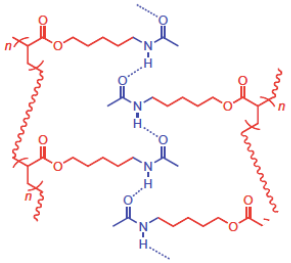
Urea groups



$K_a \sim 1$

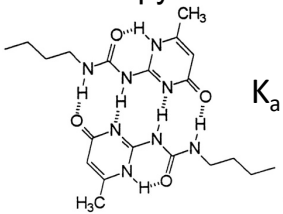
L. Leibler et al. Nature 451, 977–980 (2008).

Amide brushes



Z. Guan et al. Nat Chem 4, 467–472 (2012).

Upy



$K_a \sim 10^5$

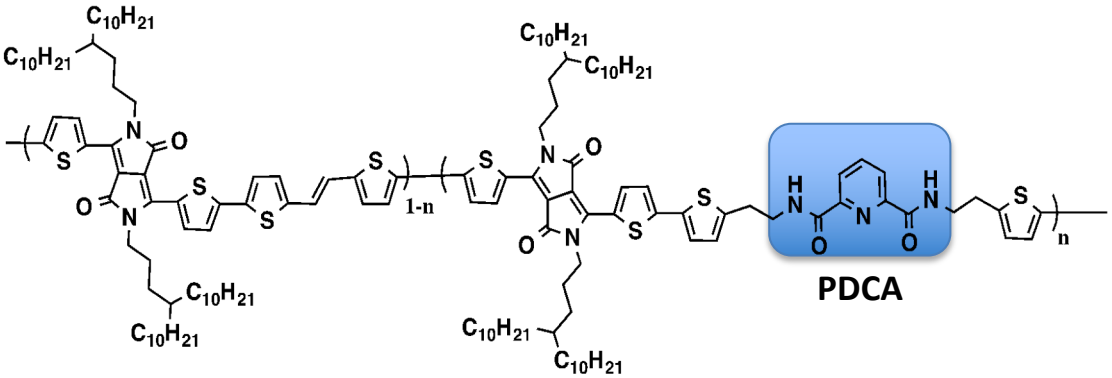
E.W. Meijer et al. Science 278, 1601 (1997)

Our stretchable polymer semiconductor design

Simon Rondeau-Gagné

Yu-Cheng Chiu

Jinyoung Oh

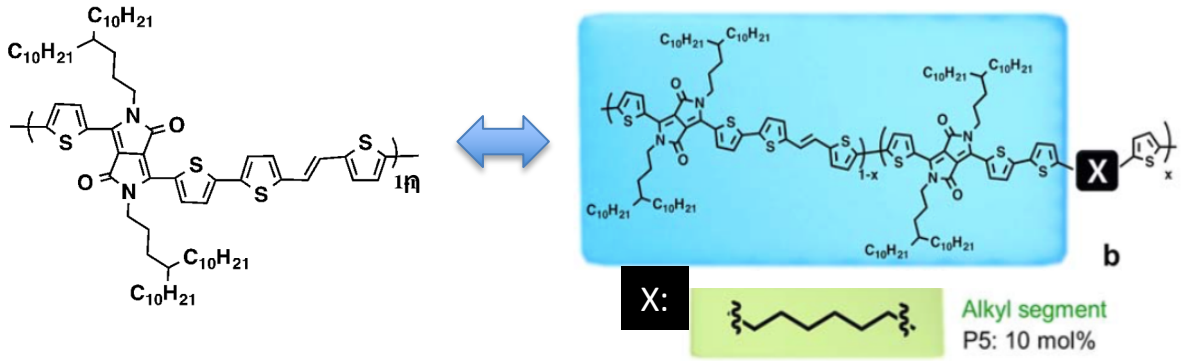


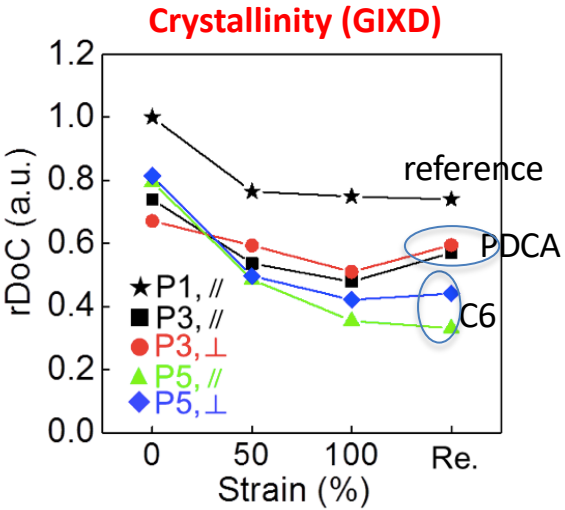
Increase disorder, more amorphous domains: partial break of conjugation

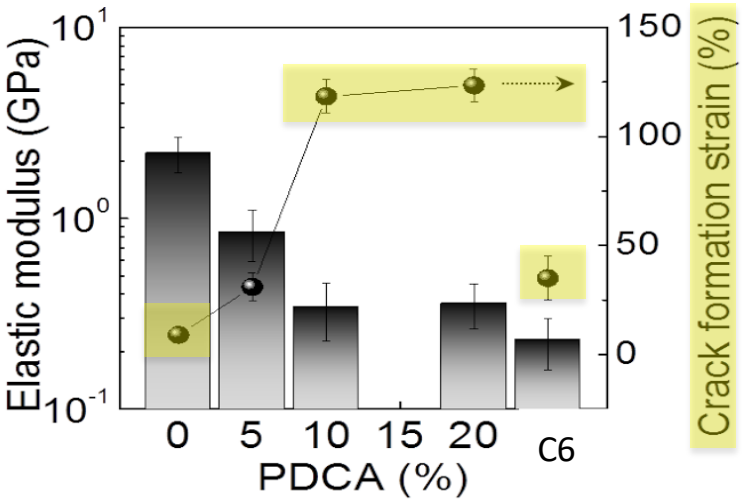
Add energy dissipation mechanism: H-bonding sites

Oh*, Rondeau-Gagne*, Chiu*, Bao, **Nature**, 2016.

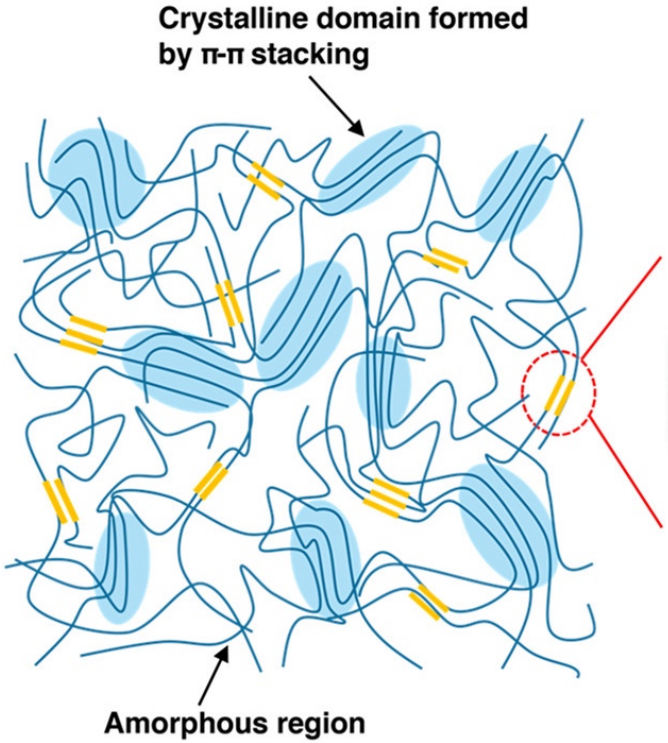
Break conjugation: increase crack onset strain

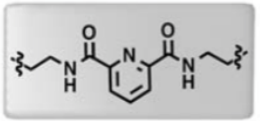


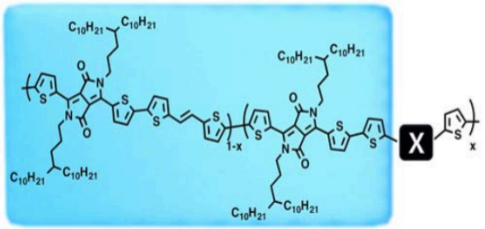


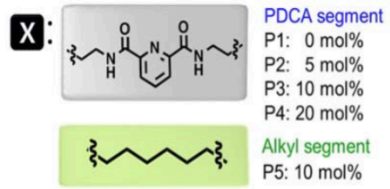


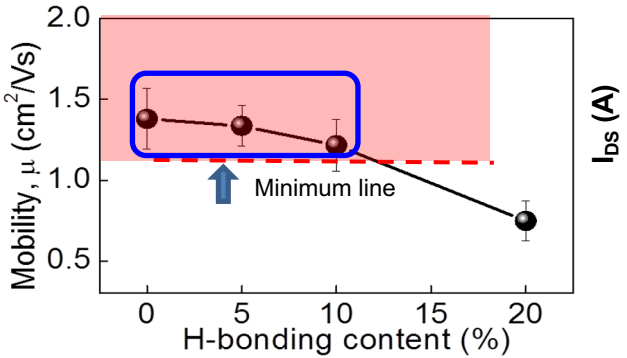
Maintain good charge transport



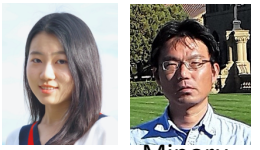




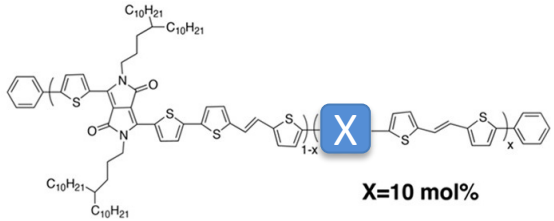




H-bonding strength



Yu Zheng Minoru Ashizawa



	Alkyl-chain	Ether-chain		
Urea			K_a ~ 1.2	40%
Amide			K_a ~ 0.3	30%
Urethane			K_a ~ 0.1	30%
Carbonate				20%

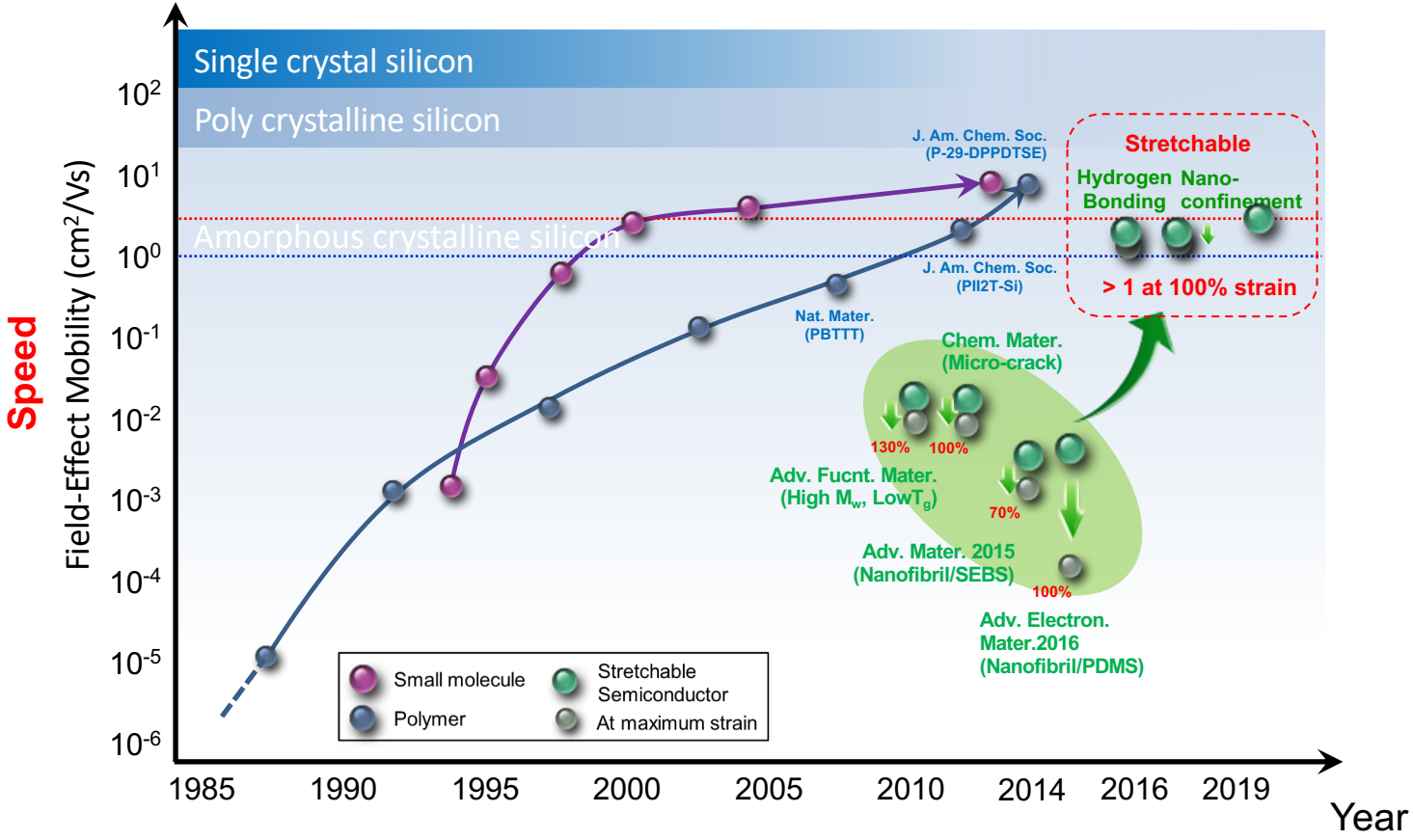
Association constant

Crack onset strain

More flexible structure

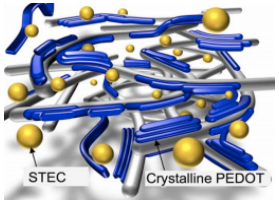
Zheng, Ashizawa, Bao et al. **Chem. Mater**. 2020

Stretchable polymer semiconductors have comparable mobility as best organic semiconductors



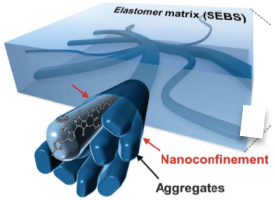
Skin Inspired Electronic Materials

Flexible → Stretchable → Self-healing → Biodegradeable



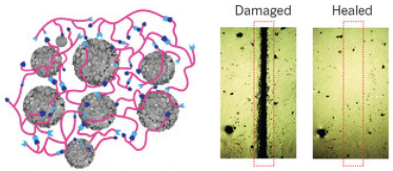
Science Advances, 3, 3, 2017
Nature Biomedical Engineering,

conductor



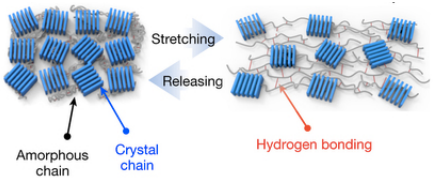
Science, 355, 59, 2017
Nature Materials

Semiconductor



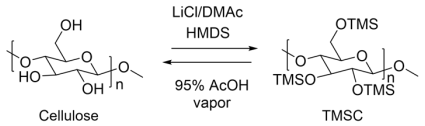
Nature Nanotech. 7 , 825, 2012
Nature Nanotech.

conductor



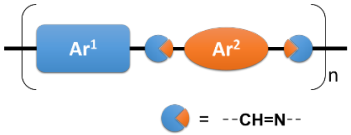
Nature, 539, 411, 2016

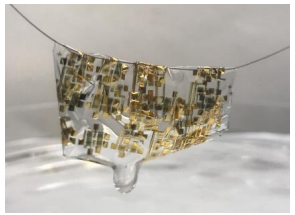
Semiconductor



Substrate

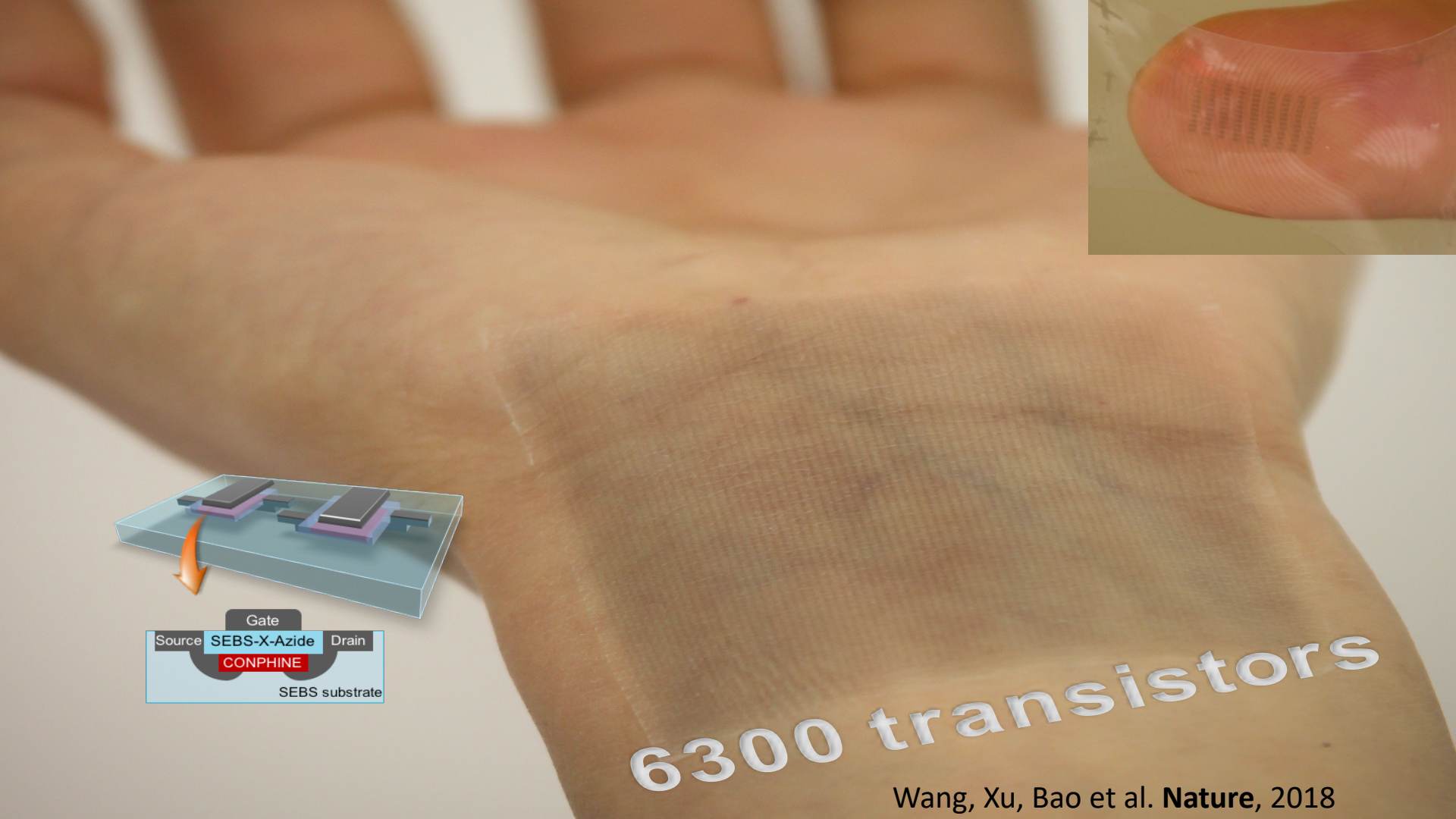
PNAS, 2017





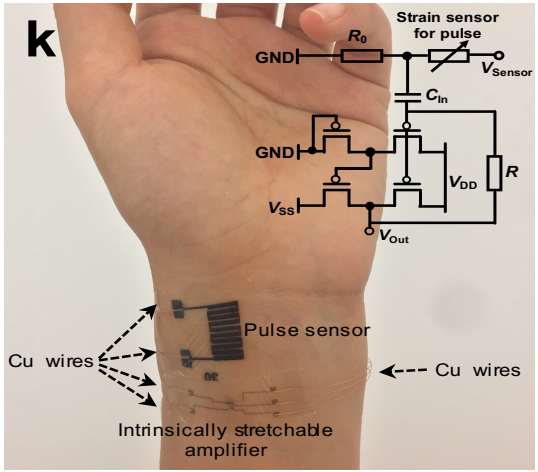
PNAS, 2017 ACS Central Science 2019

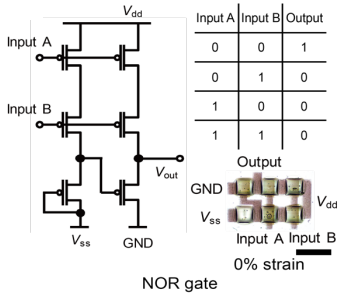
Semiconductor



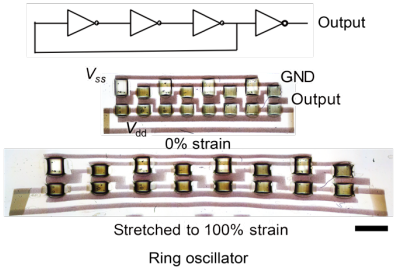
Wang, Xu, Bao et al. **Nature**, 2018

Stretchable circuit blocks

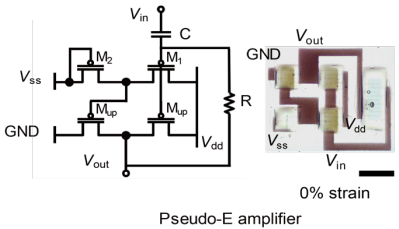




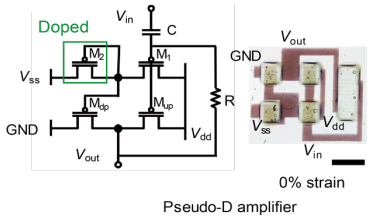
NOR gate



Ring oscillator



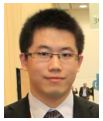
Pseudo-E amplifier



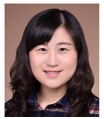
Pseudo-D amplifier

Zhu, Murmann, Bao et al. **Nature Electronics** 2019
Wang, Wang, Bao et al. **Nature Electronics**, in press.

Weichen Wang



Sihong Wang



Chenxin Zhu

Murmann

Tactile *e*-skin

Wang, Xu, Bao et al. **Nature**, 2018

Morphing Electronics: MorphE

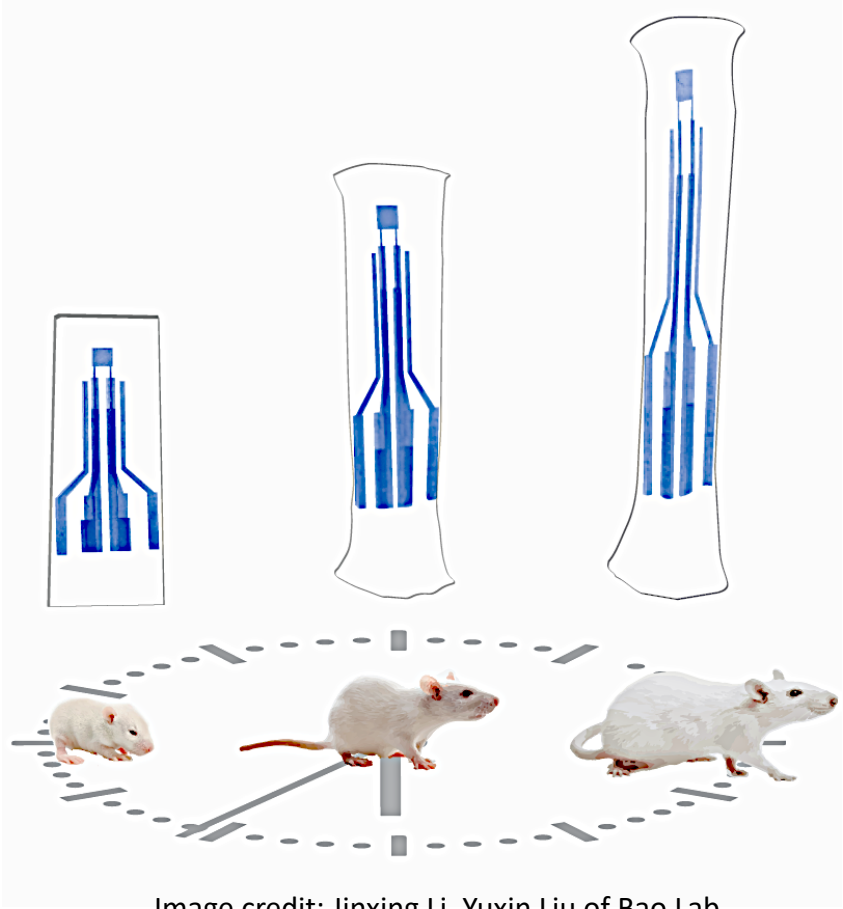
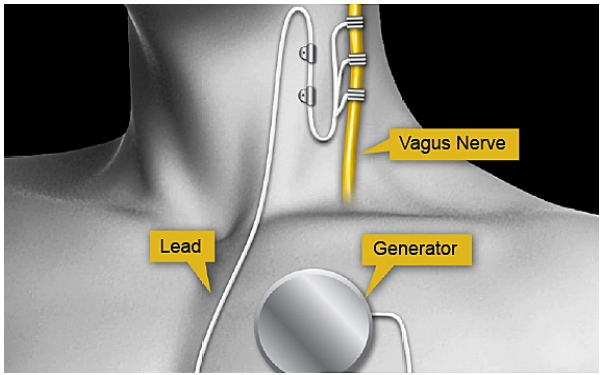


Image credit: Jinxing Li, Yuxin Liu of Bao Lab

Rigid implants constrain tissue growth

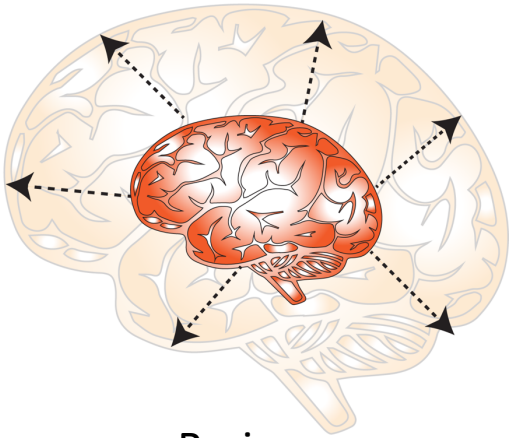
Nerve growth rate (~ 2×10^{-5} %/s in rat)
Multiple times increase in size

Diameter increase



Vagus Nerve

Volume Expansion

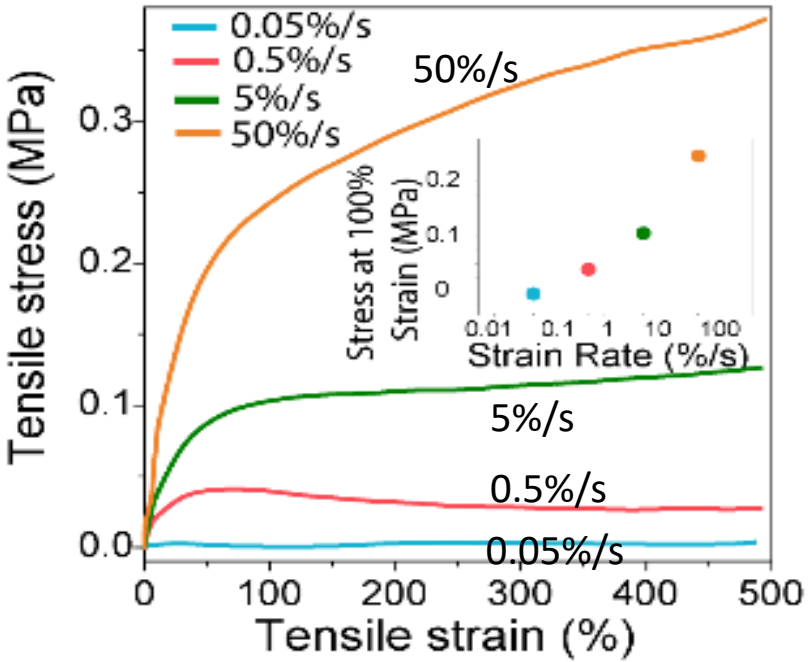


Brain

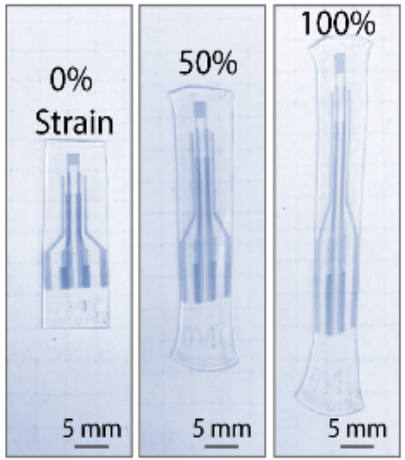
Electronics for growing tissue: morphing electronics MorphE

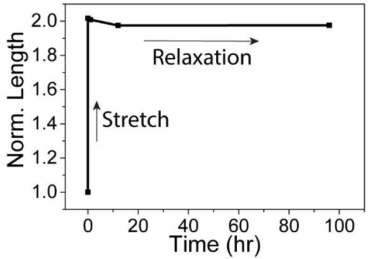

Yuxin Liu


Jinxing Li



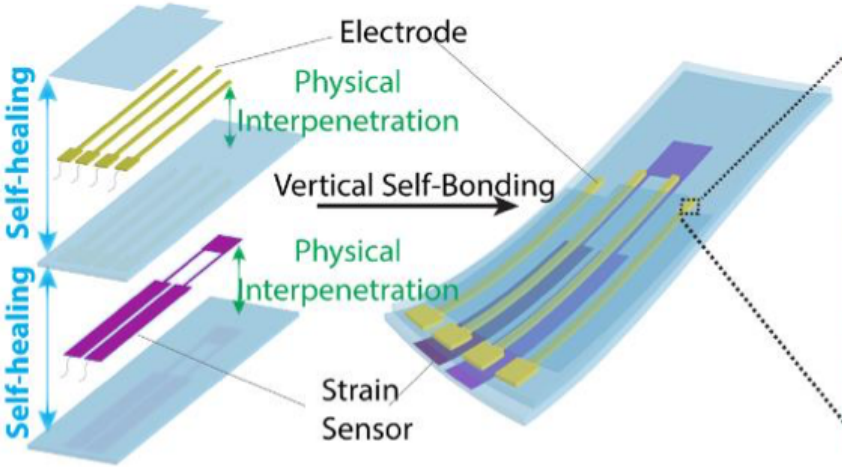
Morphing cuff



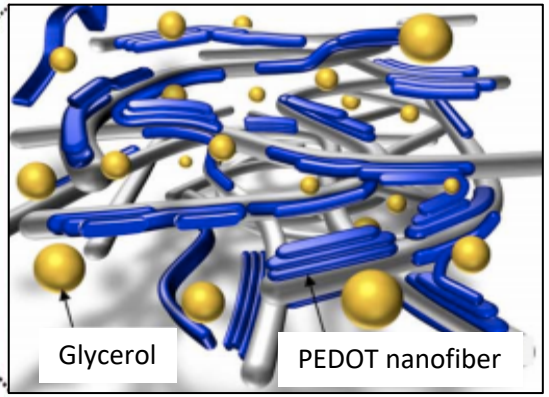


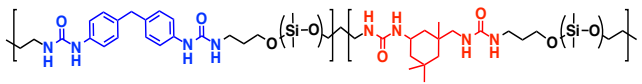
Y. Liu J. Li*, S. Song* P. George, Z. Bao et al Nature Biotechnology, 2020*

Morphing electronics: neuro stimulator



Conducting polymer
(PEDOT:PSS/Glycerol)





MPU0.4 IU0.6

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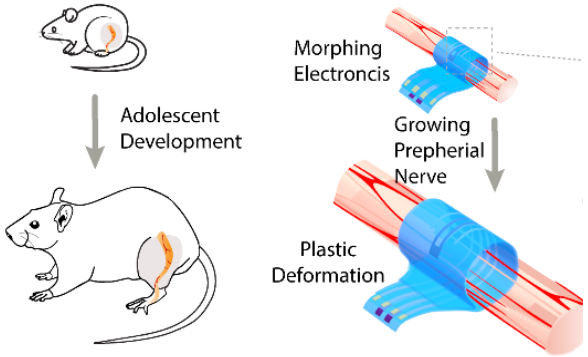
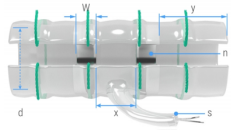
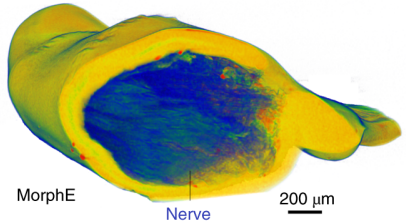
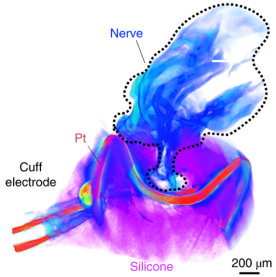
Implanted morphing electronics

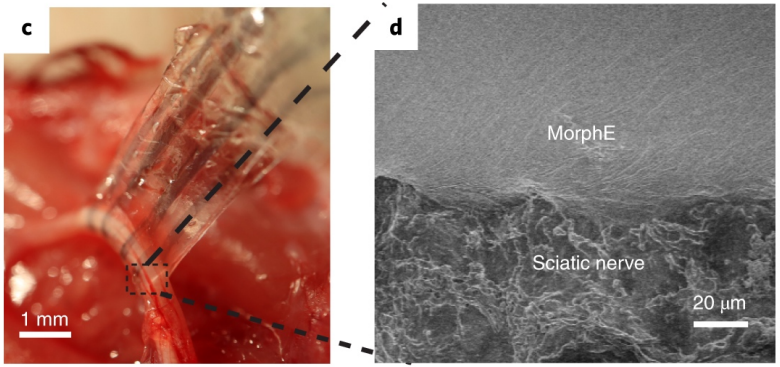


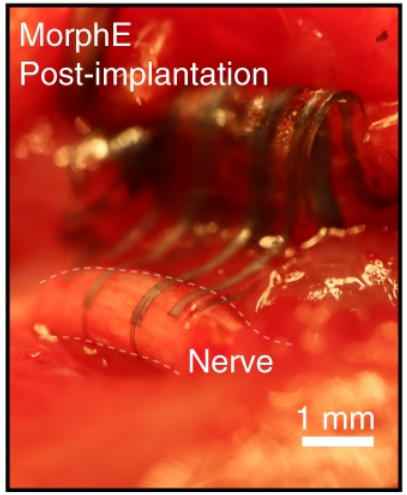


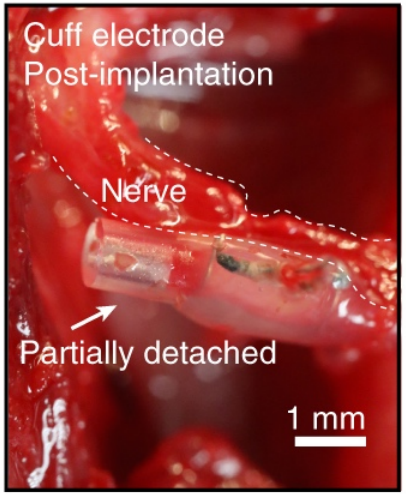




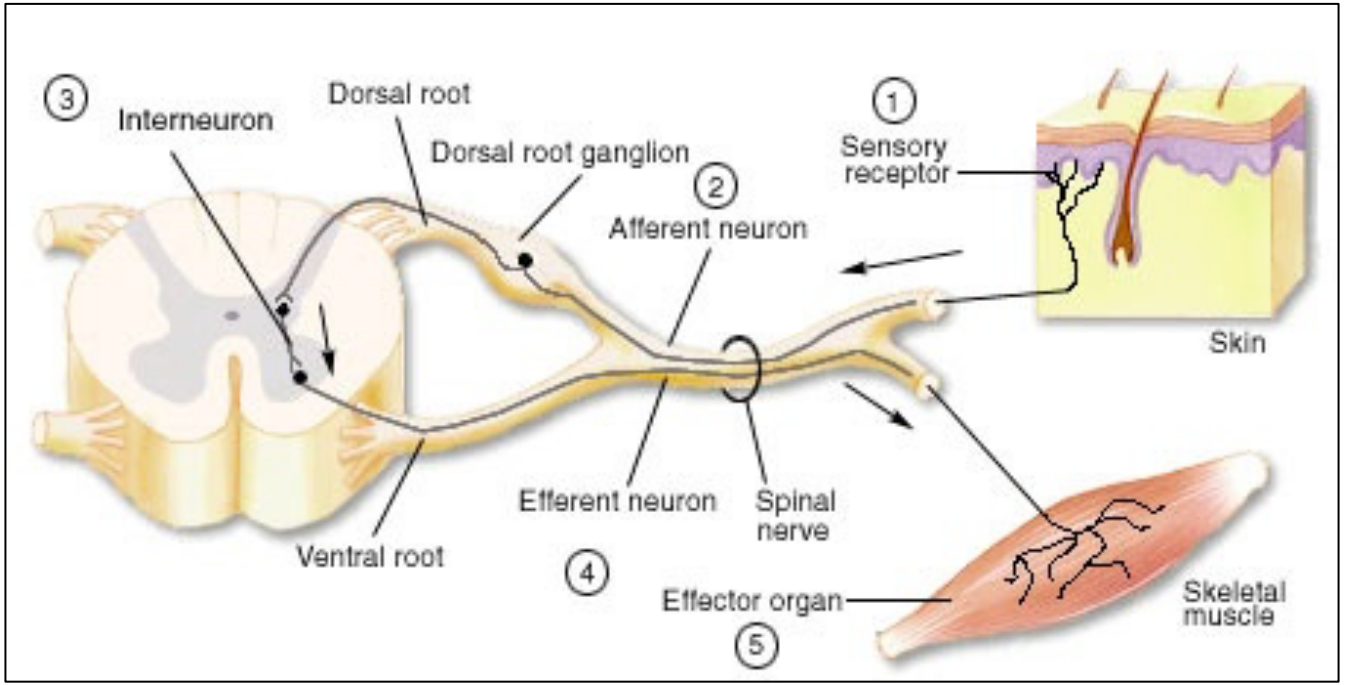
Immediate after implanting







Interface with sensory and motor nerve fibers



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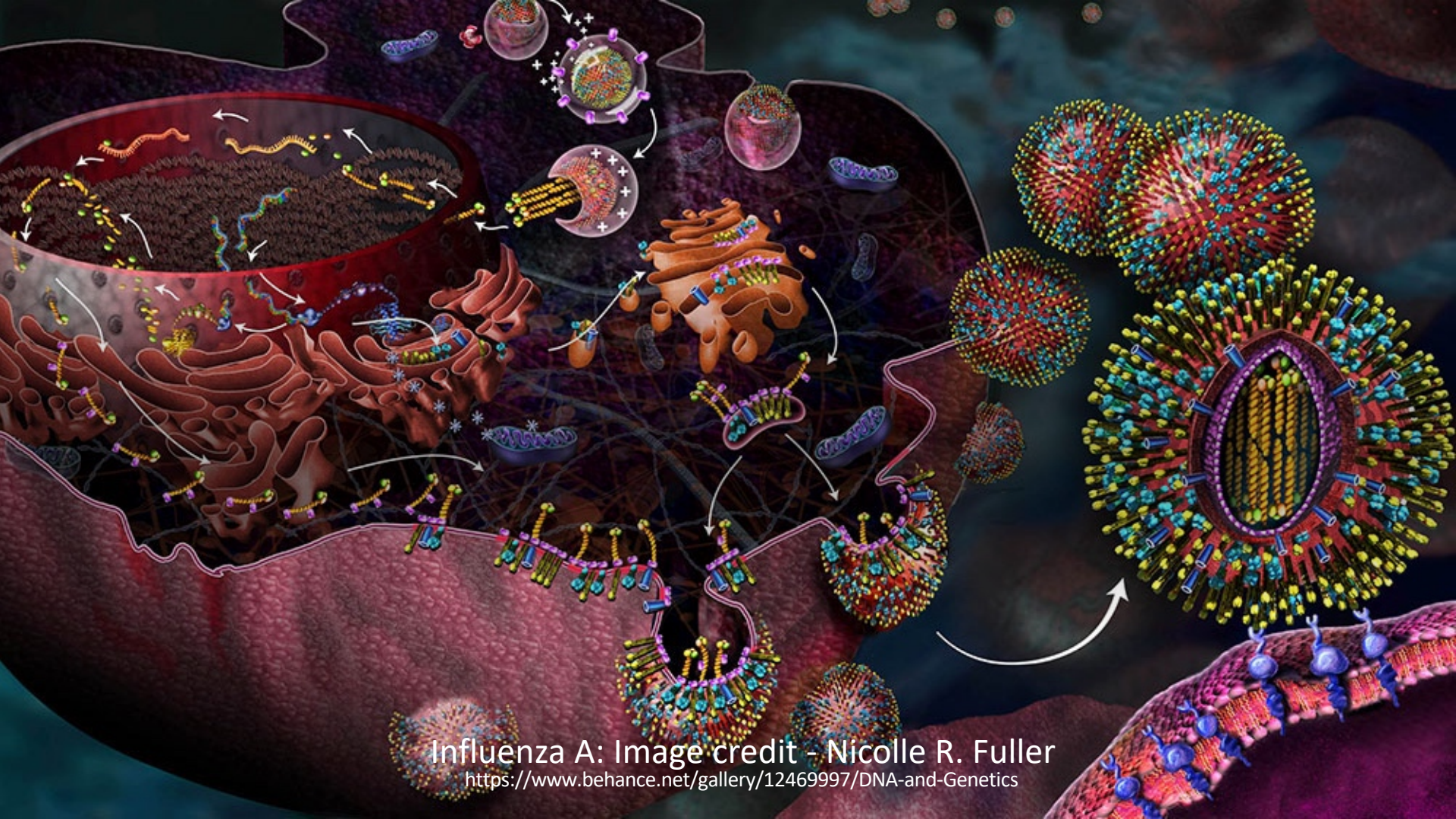


Influenza A: Image credit - Nicolle R. Fuller
https://www.behance.net/gallery/12469997/DNA-and-Genetics

Optogenetics

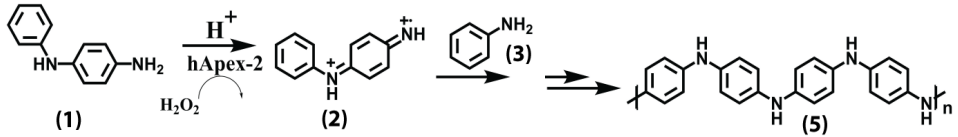
Karl Deisseroth

Image credit: Deisseroth Lab

Genetically-targeted chemical assembly

Image credit: ELLA MARU STUDIO AND YOON SEOK KIM/JIA LIU, DEISSEROTH/BAO LABORATORIES

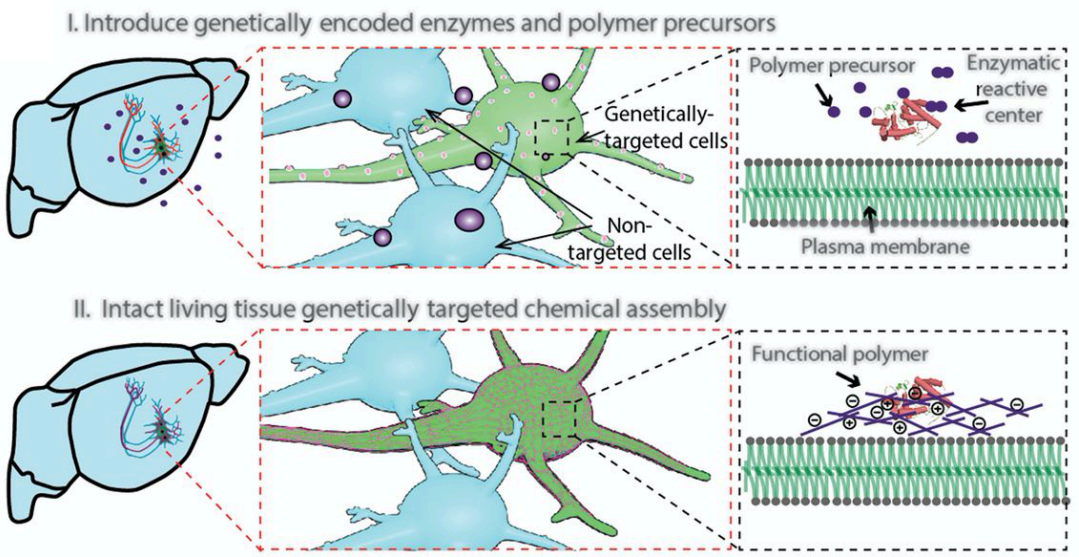
Genetically-targeted chemical assembly (GTCA)

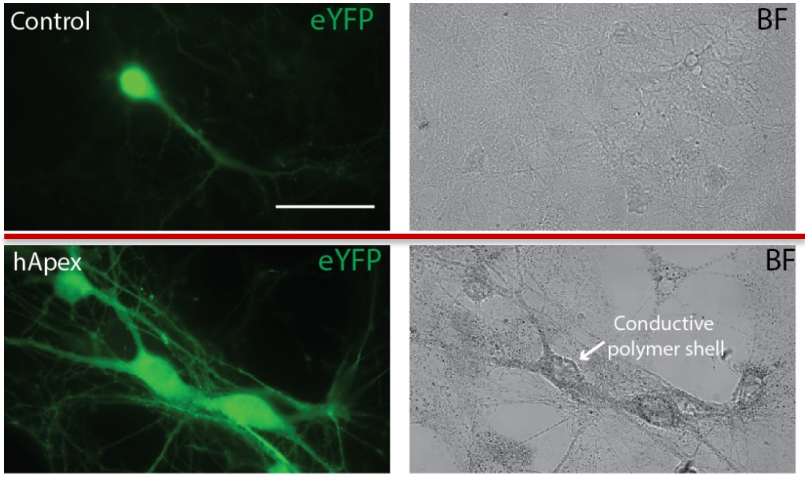



Jia Liu


Yoon Seok Kim


Karl Deisseroth





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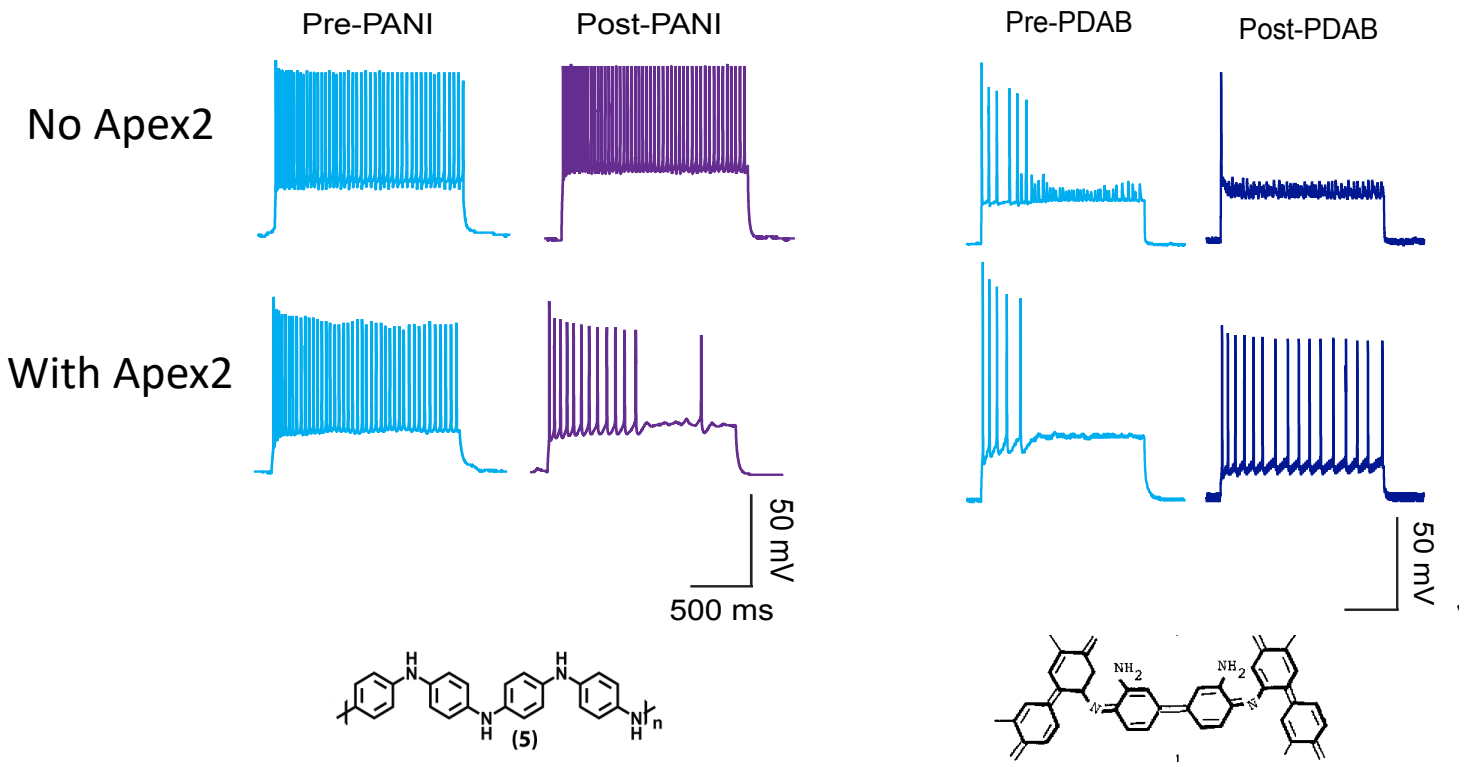
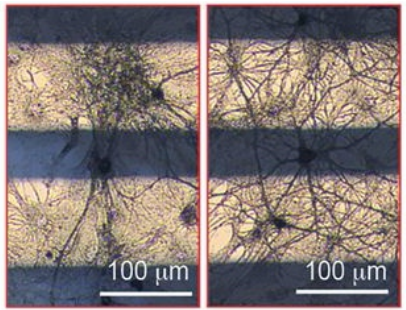
GTCA changes neuron firing pattern

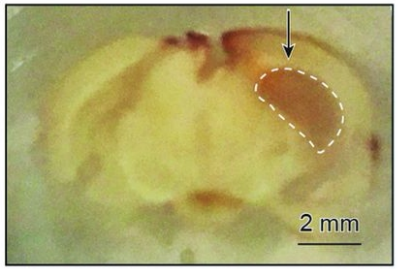


GTCA of conducting polymer assembly on cells, organ, live organism

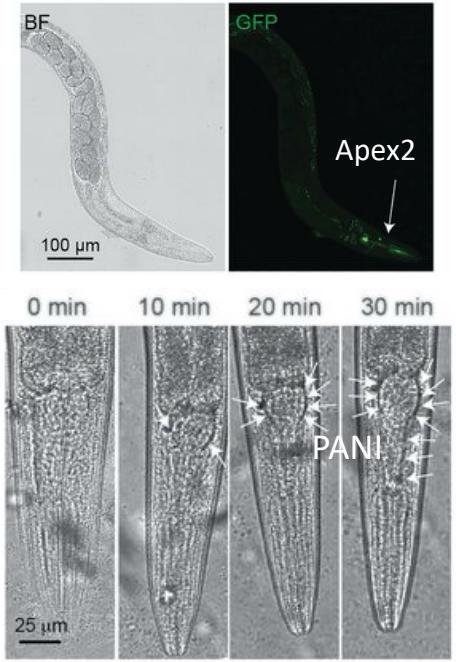
Neuron

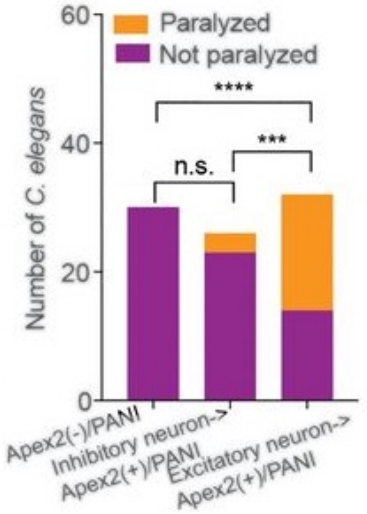


Brain slice



Live C. eleganse





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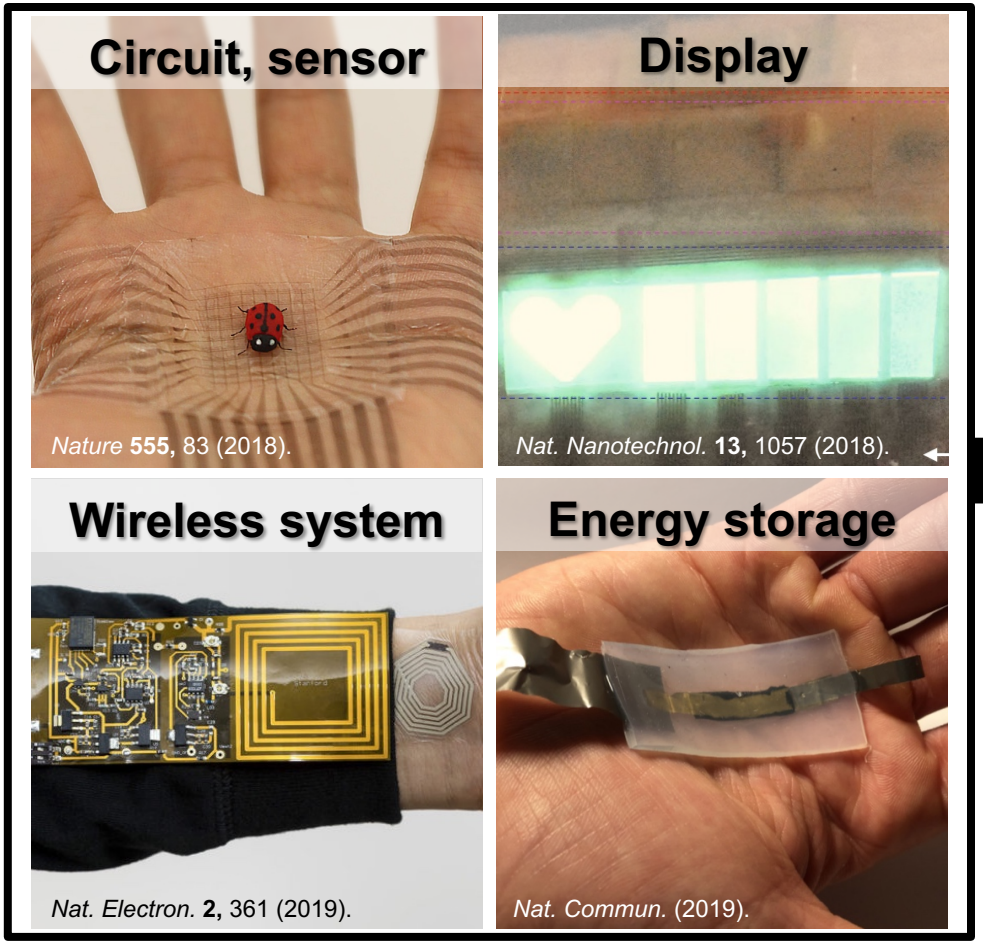
Stretching chemistry to ultimate wearables



nature
Comment

Unobtrusive 'elastronic' transistors can behave like skin and stretch without tearing. Credit: Bao Lab

Bring on the bodyNET

Stretchable sensors, circuits and batteries are about to change our relationships with electronics and each other

Chu, Chang, Burnette, Bao, **Nature**, September 21, 2017

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Stanford Precision Health and Integrated Diagnosis (PHIND)
Stanford Precourt Institute for Energy
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Thank you