The 16th U.S.-Korea Forum on Nanotechnology

Wireless Electronic Tattoos

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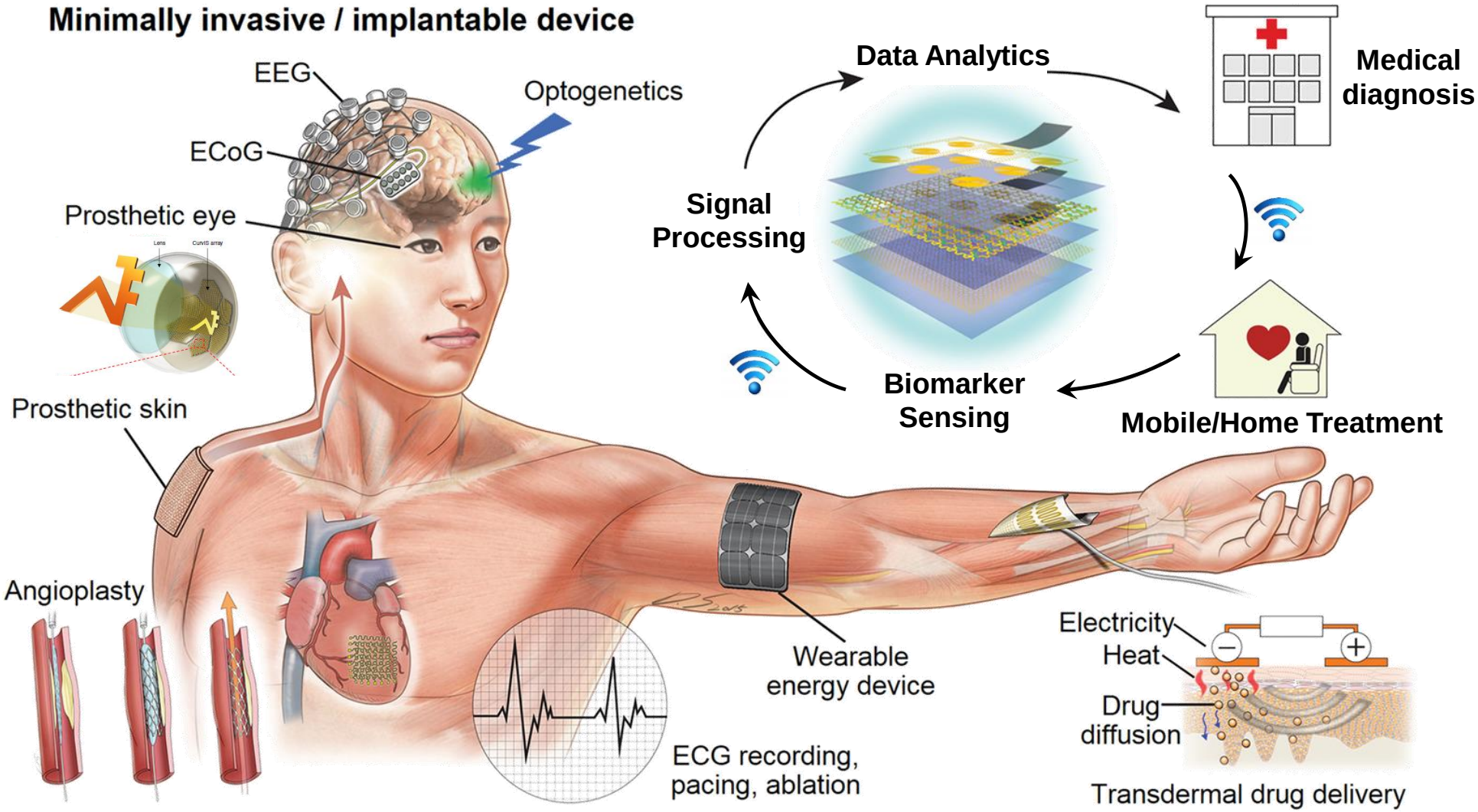
Bioelectronics – Closing the Loop for Internet of Health (IoH)

Prof. Dae-Hyeong Kim
Seoul National Univ.



Choi, Kim*, *et al.*, *Adv. Mater.* 28, 4203 (2016).

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Example Applications of Wearable Electronics

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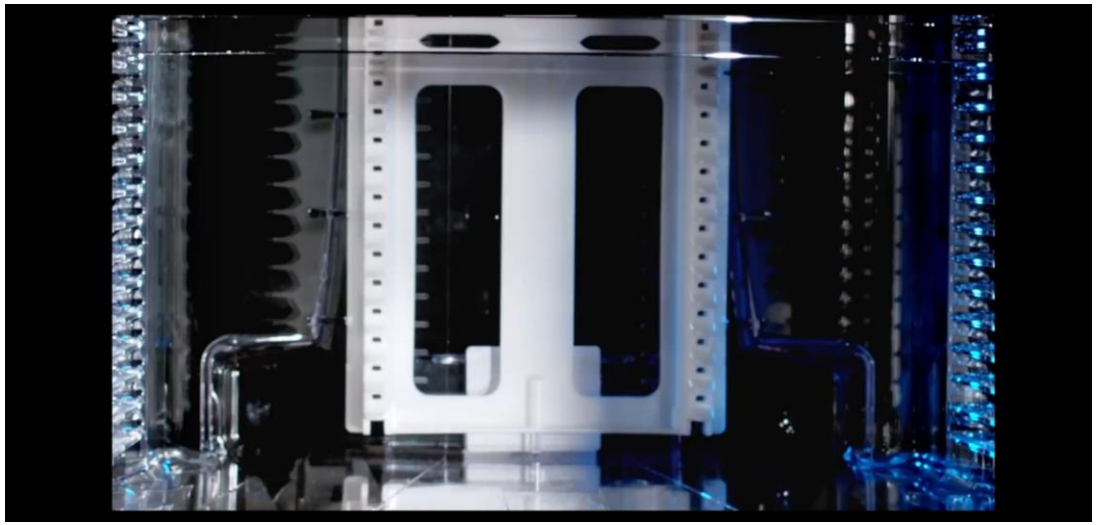
Silicon vs. Skin – A Mechanical Challenge

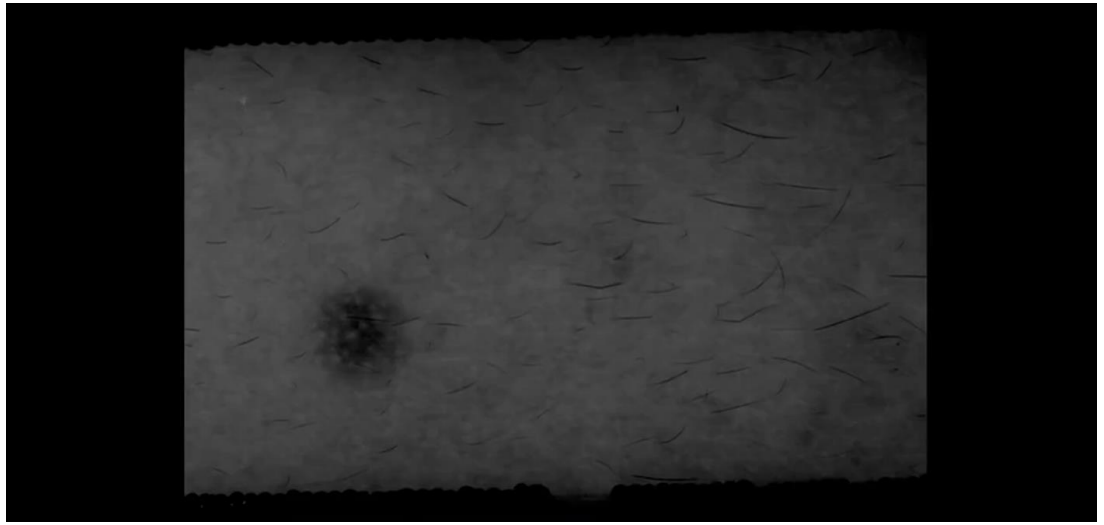
E_{Si} = 130 GPa, ε_{frac} = 1%



Credit: Intel

Hard
Planar
Fragile

E_{Skin} = 130 kPa, ε_{ouch} = 20%



Credit: ICTGraphicsLab @ USC

Soft
Curvilinear
Dynamic

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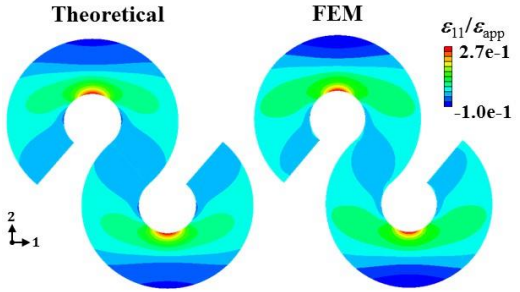
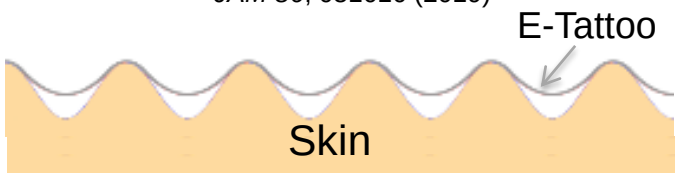


Mechanics of Flexible and Stretchable Structures

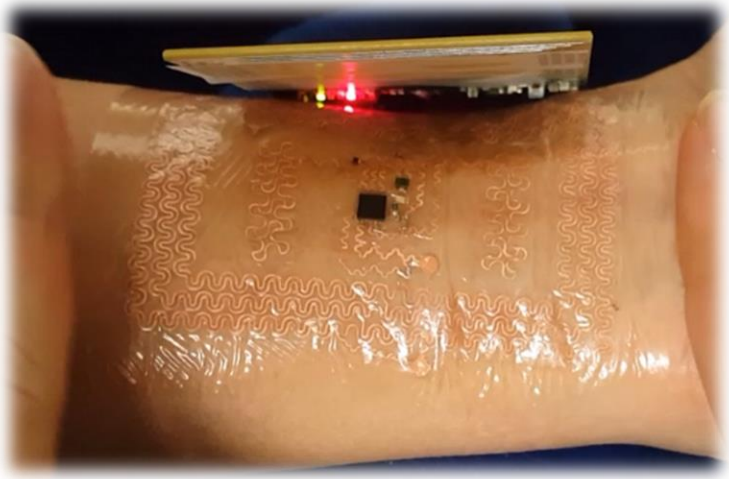
Sensors 13, 8577-8594 (2013)
IJSS 51, 4026-4037 (2014)
IJF 190, 99 (2014)
Nat. Photonics 8, 643–649 (2014)
ACS Nano 8, 12265–12271 (2014)
EML 2, 37-45 (2015)
Curr. Opin. Solid St. M. 19, 149-159 (2015)
IJSS 87, 48-60 (2016)
Smart Mater. Struct. 25, 035037 (2016)
JAM 84, 021004 (2017)
Light 7, e17138 (2018)
JAM 86, 051010 (2019)



Bio-Electronics Interface

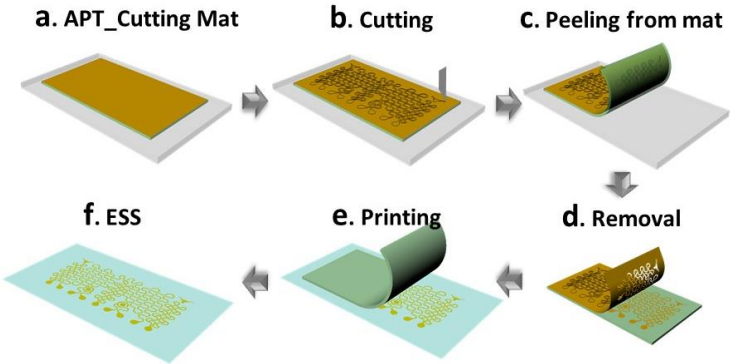
JMR 30, 2702-2712 (2015)
Adv. Healthc. Mater. 5, 80-87 (2015)
JAM 83, 041007 (2016)
Soft Robotics 3, 99-100 (2016)
Adv. Funct. Mater. 26, 3207-3217 (2016)
JAM 84, 111003 (2017)
EML 15, 130 (2017)
J. Roy. Soc. Interface 14, 20170377 (2017)
Soft Matter 14, 8509 (2018)
EML 30, 100496 (2019)

Lu Research Group



Soft Bioelectronics

Nature Nanotech. 9, 397–404 (2014)
Adv. Mater. 27, 6423-6430 (2015)
ACS Nano 9, 5937-5946 (2015)
Nature Nanotech. 11, 566-572 (2016)
Sci. Transl. Med. 8, 86 (2016)
ACS Nano 11, 7634–7641 (2017)
Nature Comm. 8,1664 (2017)
npj Flexible Electronics 2, 6 (2018)
Sensors 18, 1269 (2018)
Micromachines 9, 170 (2018)
Adv. Funct. Mater. 1808247 (2019)
Adv. Mater. Tech. 1900117 (2019)
Adv. Sci. 1900290 (2019)
NPG Asia Materials 11, 43 (2019)



Freeform Manufacture

Adv. Mater. 27, 6423-6430 (2015)
EML 2, 37-45 (2015)
ACS Nano 11, 7634–7641 (2017)
Adv. Mater. Tech. 1800600 (2019)
Adv. Mater. Tech. 1900117 (2019)

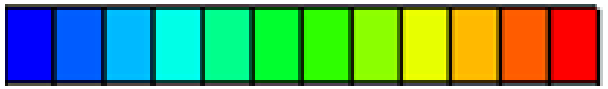
2D Materials & Devices

Adv. Mater. Interface 2, 1500176 (2015)
Nano Lett. 15, 1883–1890 (2015)
Nature Nanotech. 11, 566-572 (2016)
EML 13, 42-77 (2017)
ACS Nano 11, 7634–7641 (2017)
Nano Lett. 17, 5464 (2017)
npj 2D Materials and Applications 2, 19 (2018)
PNAS 115, 7884 (2018)
PRL 121, 266101 (2018)
Nature 567, 71 (2019)
2D Materials, accepted (2019)
JMPS, revision submitted (2019)

Serpentine Ribbons – 2D Springs

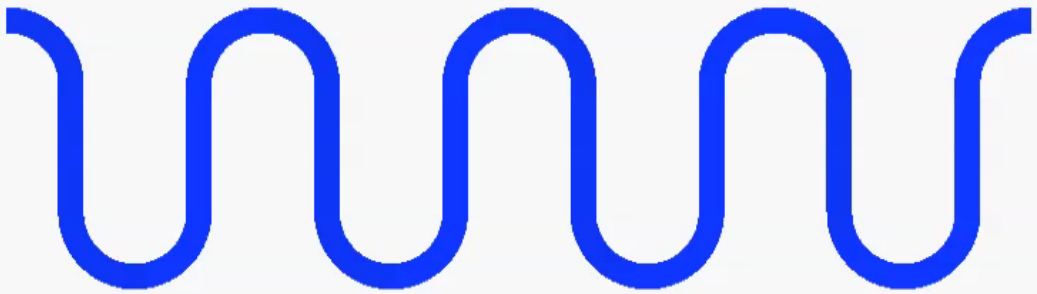
Stretchability and compliance can be achieved by serpentine structures of ANY material.

ε_{max}



0 2%

ε_{app} = 114%



Widlund, Yang, Hsu, Lu*, *IJSS* 51, 4026 (2014).
Yang, Lu*, *et al*, *IJF* 190, 99 (2014).
Yang, Lu*, *et al*, *EML* 2, 37 (2015).
Yang, Qiao, Lu*, *JAM* 84, 021004 (2016).
Liu, Ha, Lu*, *JAM* 86, 051010 (2019)

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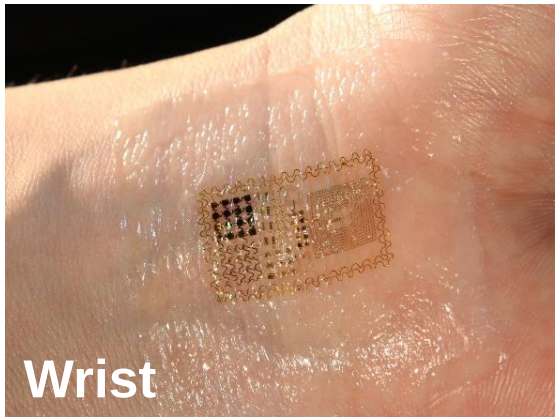
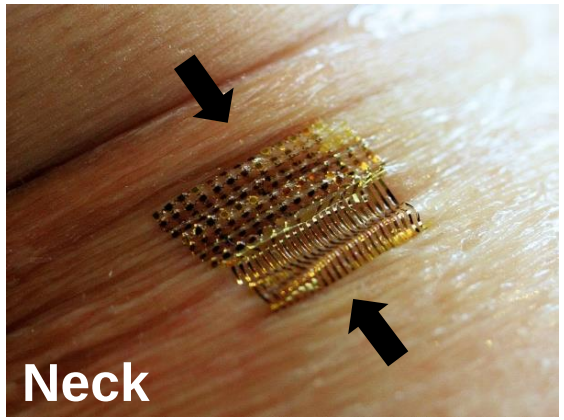
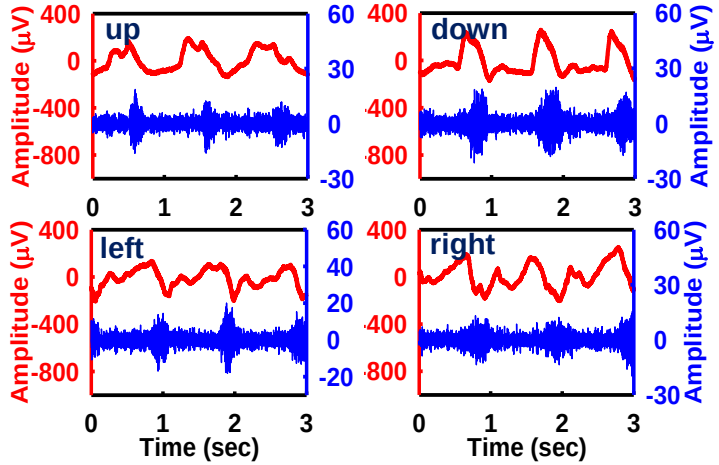
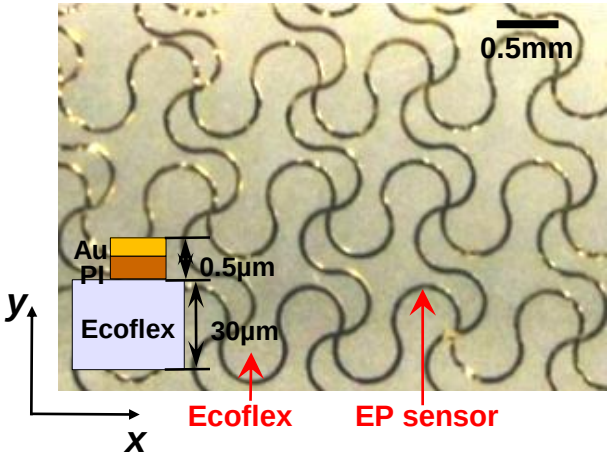
Epidermal Electronics (E-Tattoos)

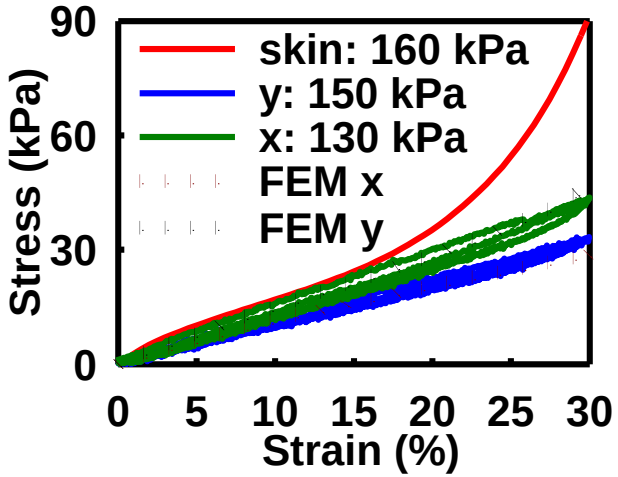
Ultrathin, ultrasoft, noninvasive, stretchable and multifunctional

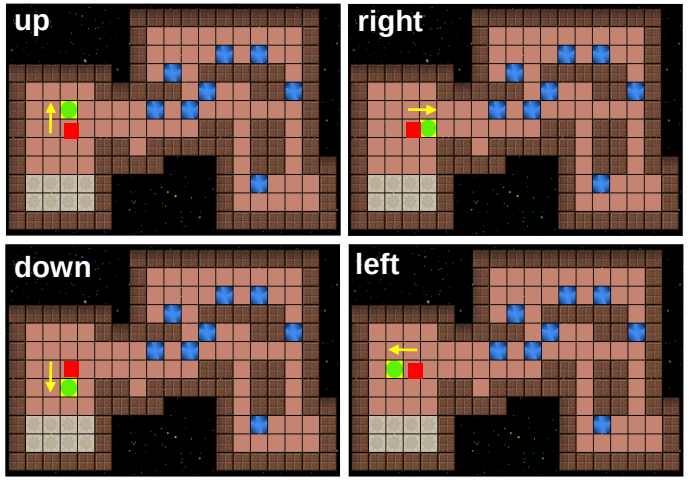












Kim†, Lu†, Ma† (†equal contribution), Rogers*, *et al.*, *Science* **333**, 838, (2011).

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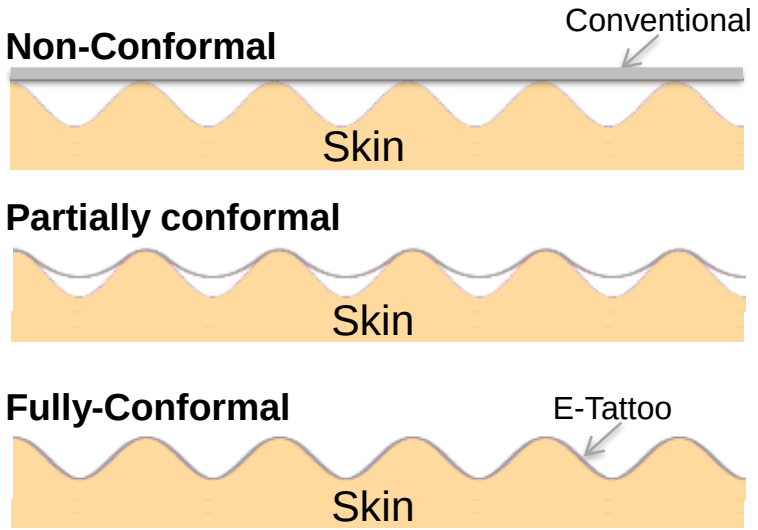
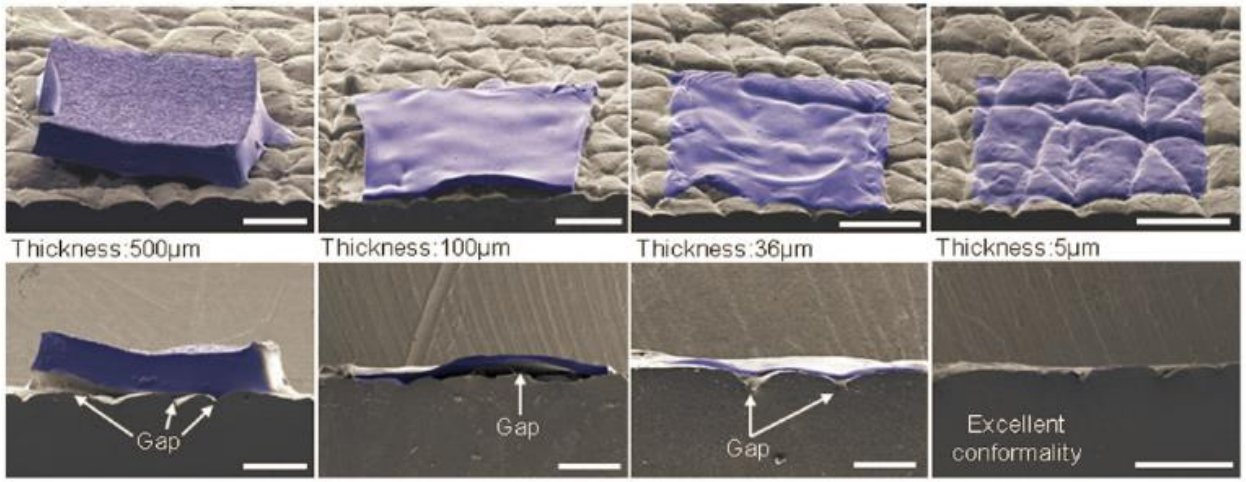
Ultra-Soft & Ultra-Thin → Ultimate Conformability

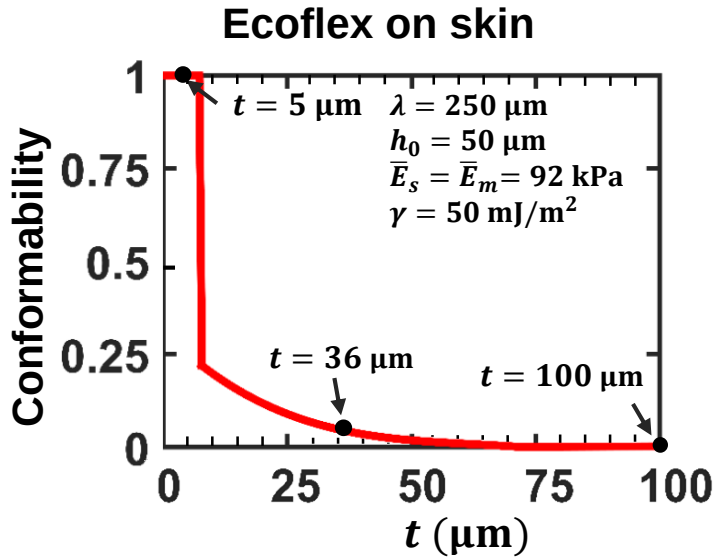


Conformable contact ensures

- Low interface impedance → higher signal to noise ratio
- No slippage → less motion artifacts, more accurate measurement of skin deformation
- Better heat or mass transfer across the skin-tattoo interface



Jeong, Rogers* *et. al.*, *Adv. Mater.* 25, 6839 (2013).



Wang, Lu*, *JAM* **83**, 041007 (2016).

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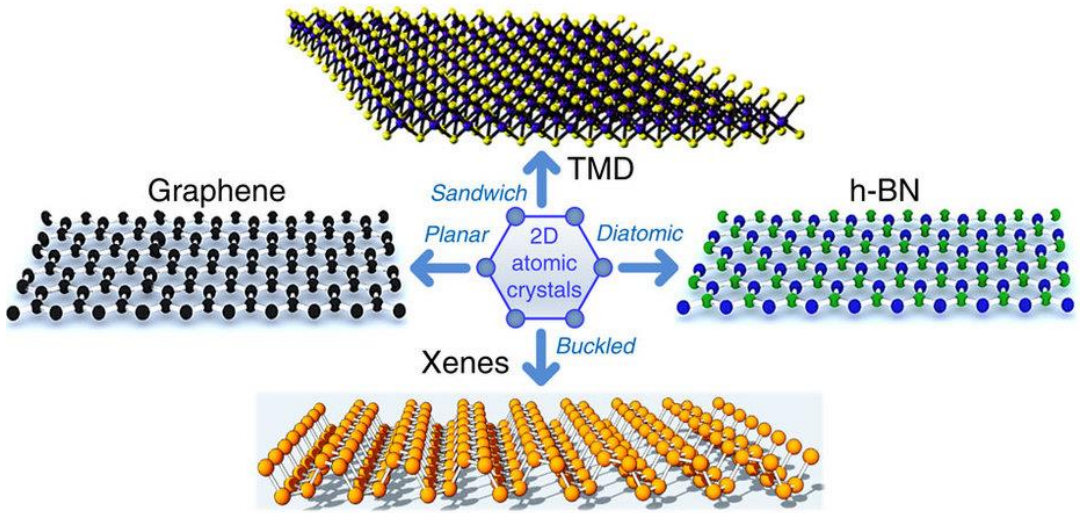
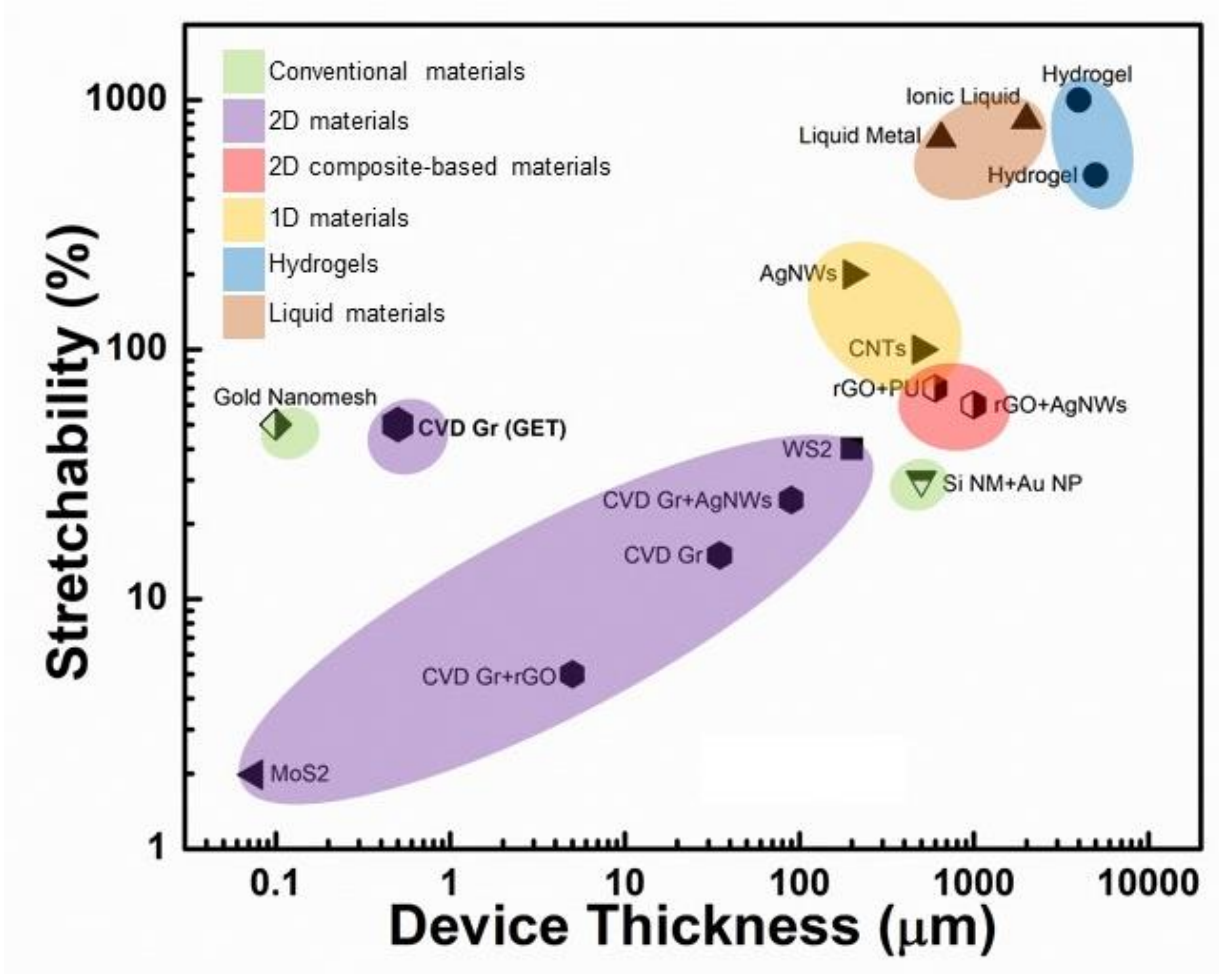
World's Thinnest Materials – 2D Materials



- Electronically functional
- Atomically thin (nm)
- Optically transparent
- Mechanically robust (cuttable)
- Chemically inert
- Potentially low cost



Jang, Lu*, *et al.*, *npj 2D Materials and Applications (invited review)*, in preparation (2019).

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Cut-and-Paste Manufacture of Graphene E-Tattoo Sensors (GETS)

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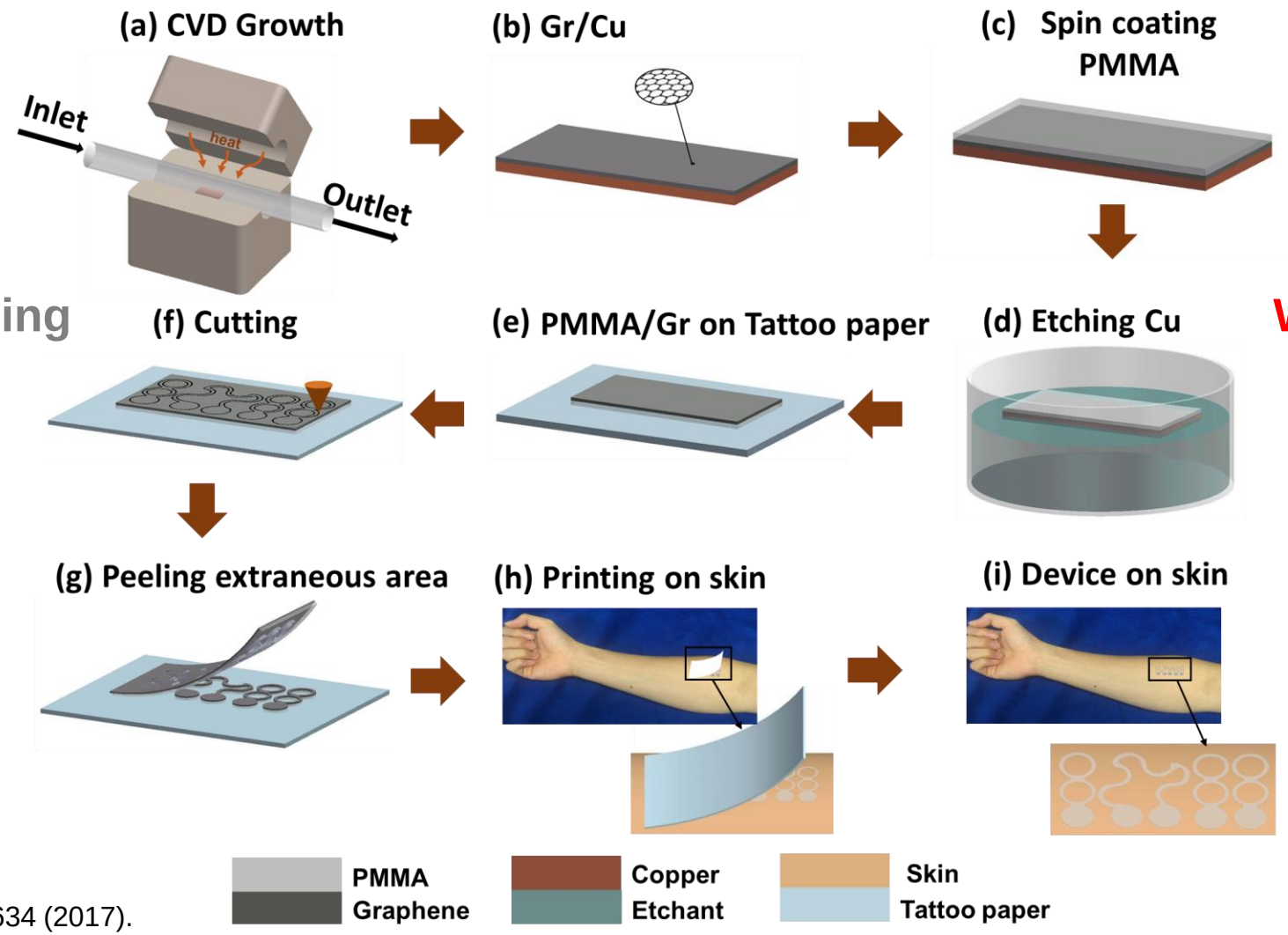
UT-Austin ECE

Dr. Shideh K. Ameri
UT-Austin ECE
(Queen's University, Canada)



ECCS-1541684

Wet transfer

Ameri, Akinwande*, Lu*, *et al.*, *ACS Nano* 11, 7634 (2017).

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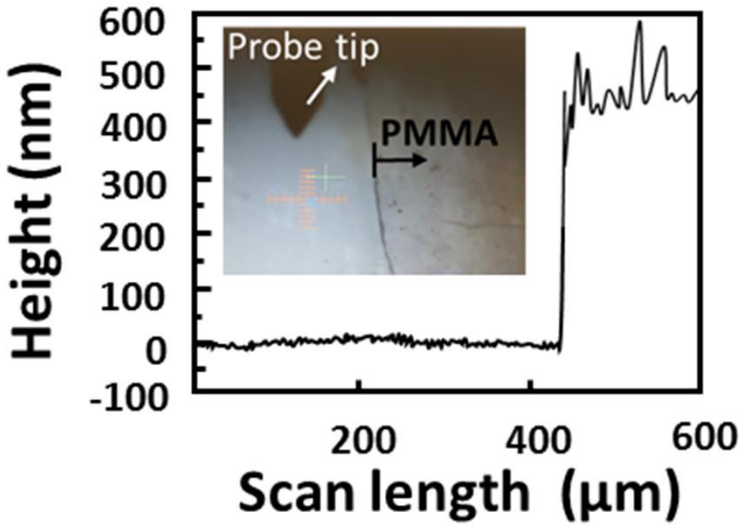
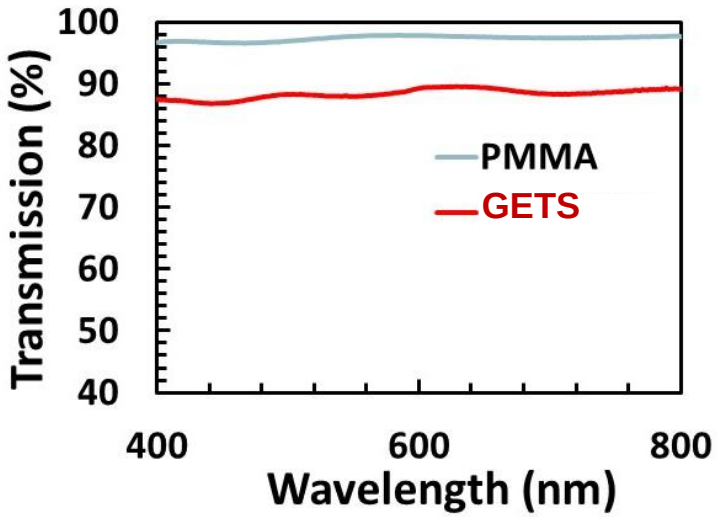
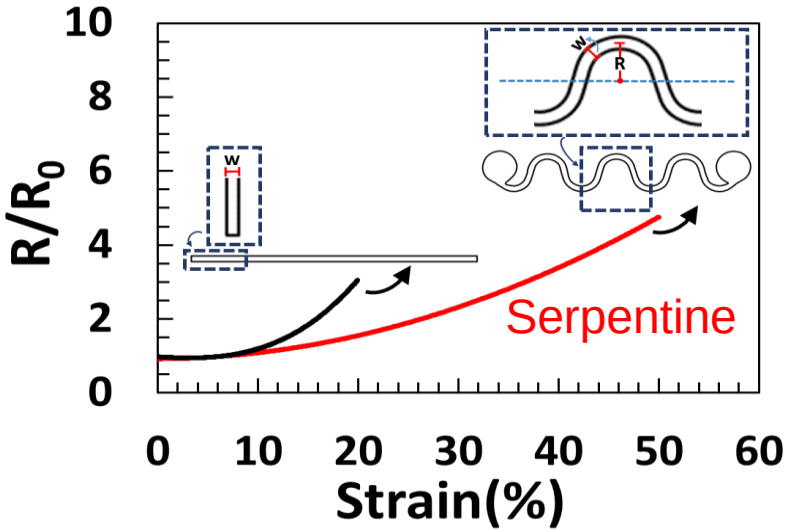
GETS Characterization







Ameri, Akinwande*, Lu*, *et al.*, *ACS Nano* 11, 7634 (2017).

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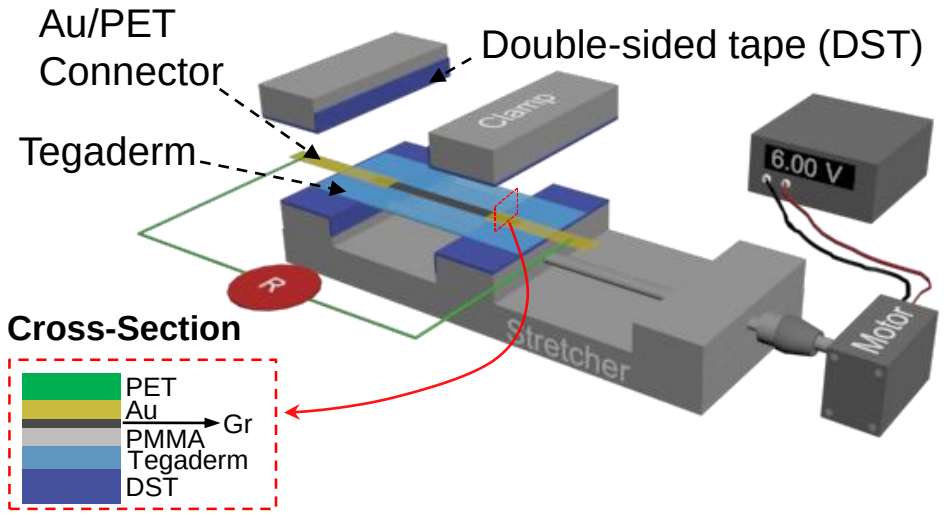
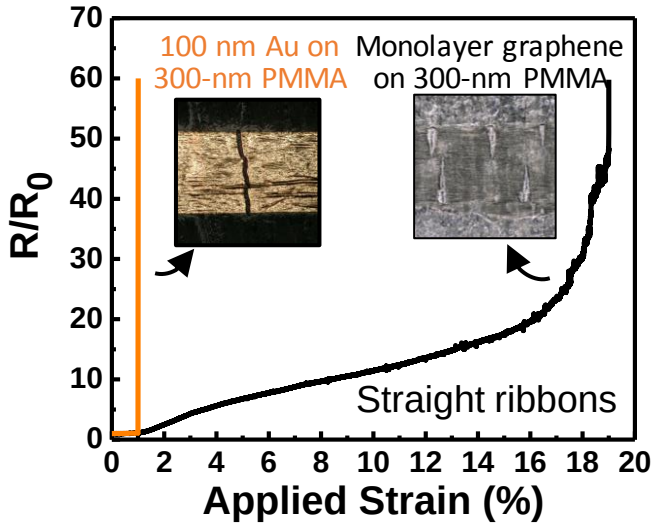
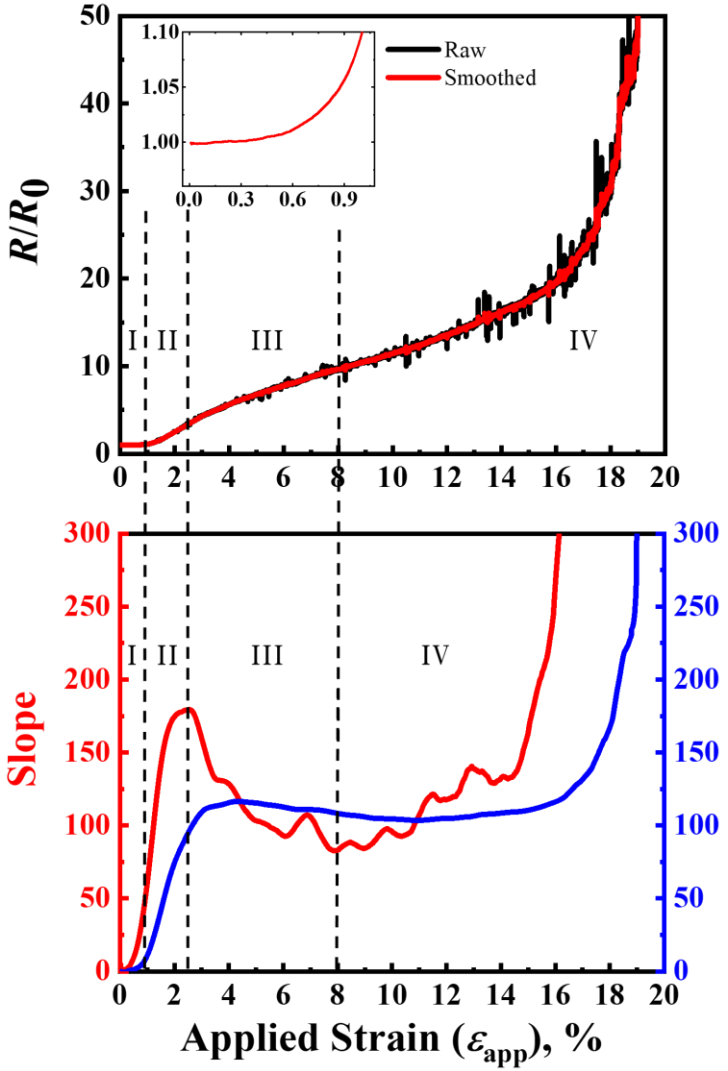
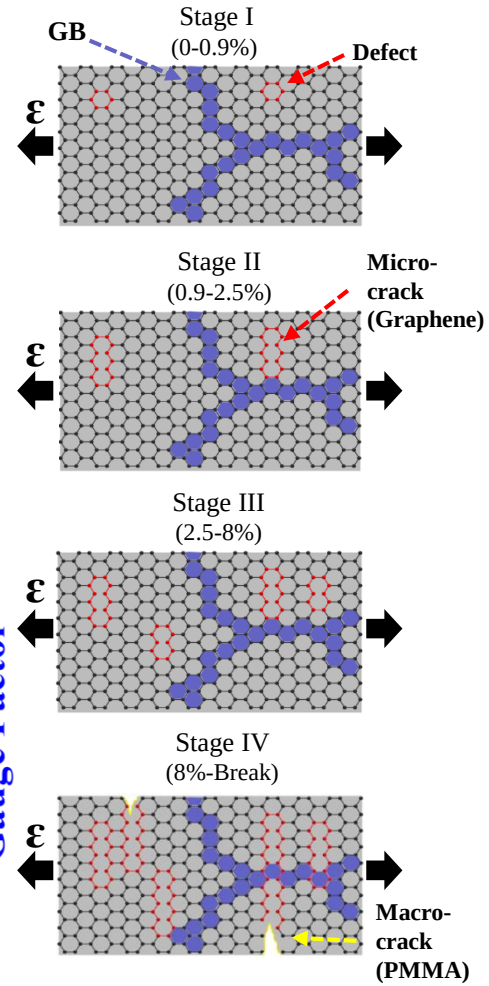
Stretchability of Graphene/PMMA





Jang, Lu*, *et al.*, *2D Materials*, accepted (2019).





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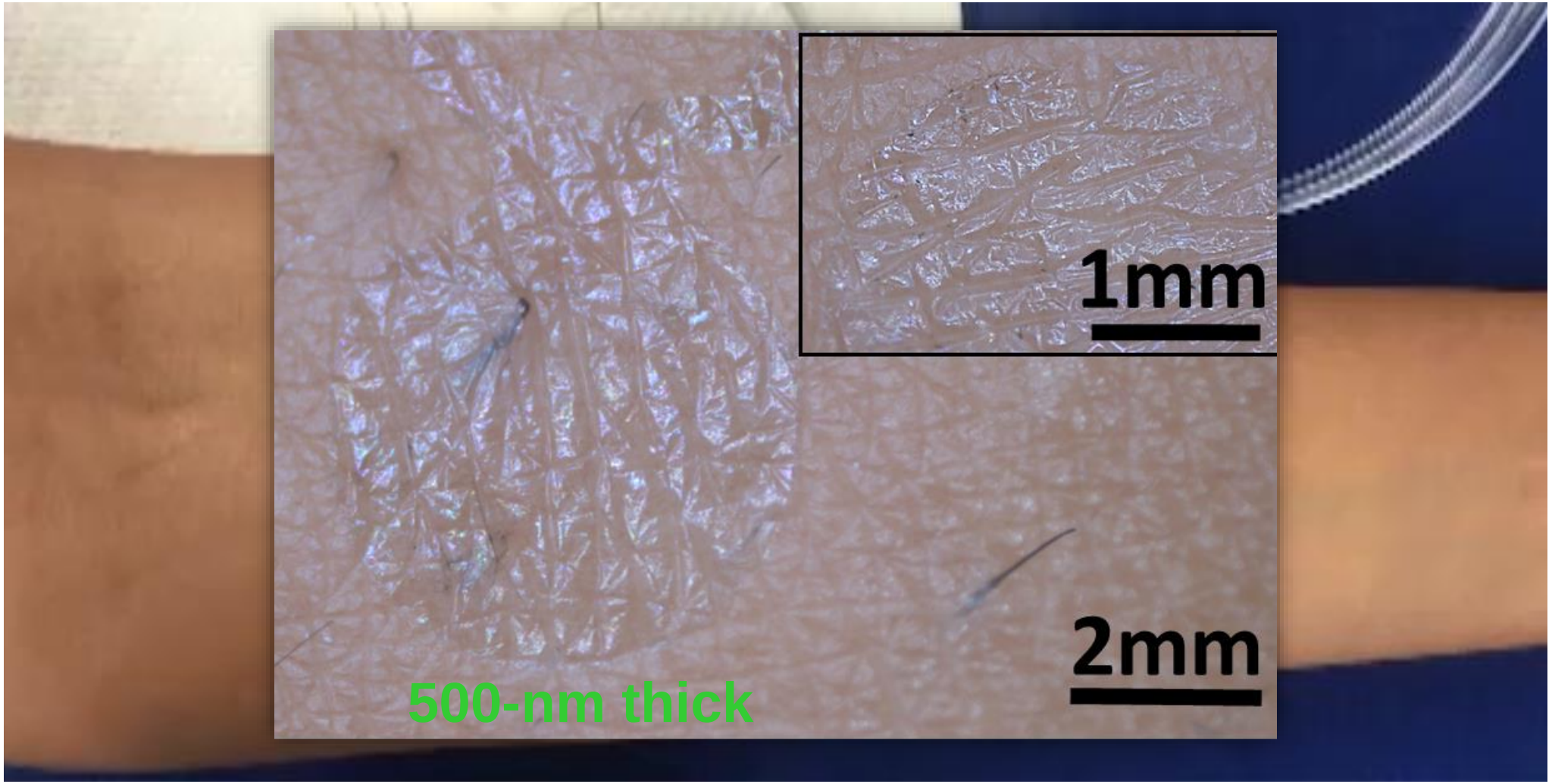
GETS Are Fully Conformable to the Skin



Ameri, Akinwande*, Lu*, *et al.*, *ACS Nano* 11, 7634 (2017).

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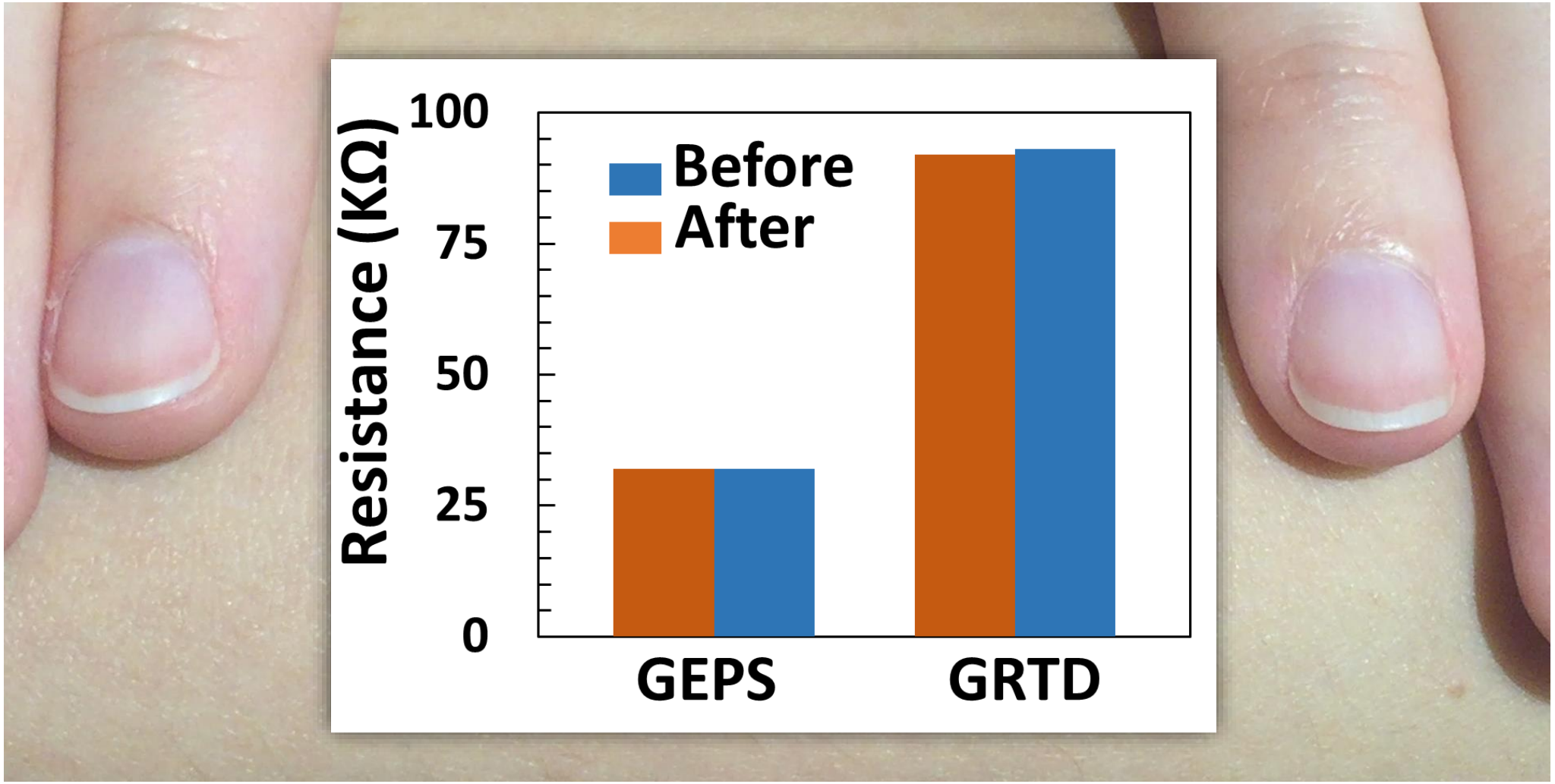
GETS Are as Deformable as Skin



Ameri, Akinwande*, Lu*, *et al.*, *ACS Nano* 11, 7634 (2017).

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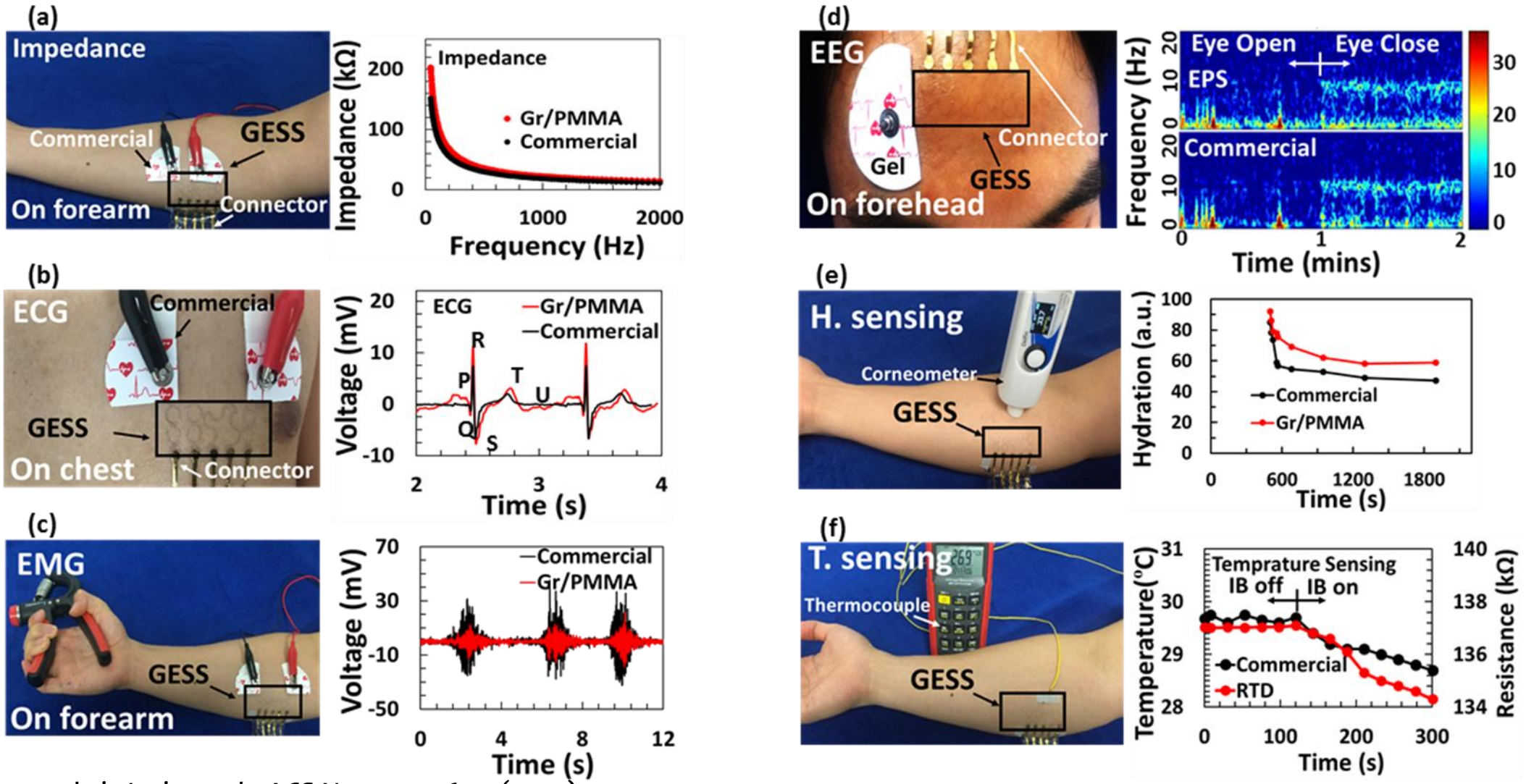
Multifunctional GETS



Ameri, Akinwande*, Lu*, *et al.*, *ACS Nano* 11, 7634 (2017).

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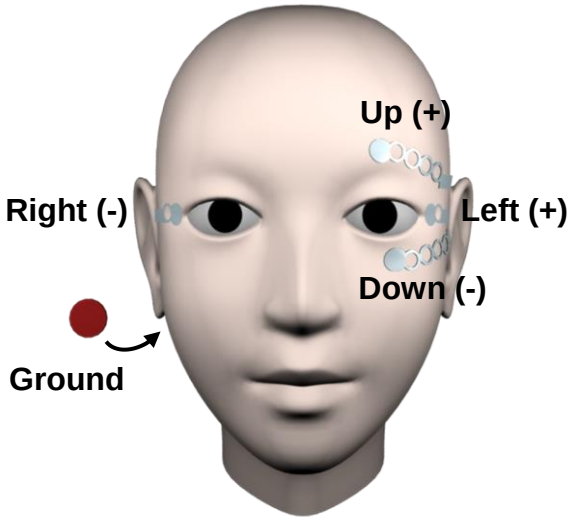
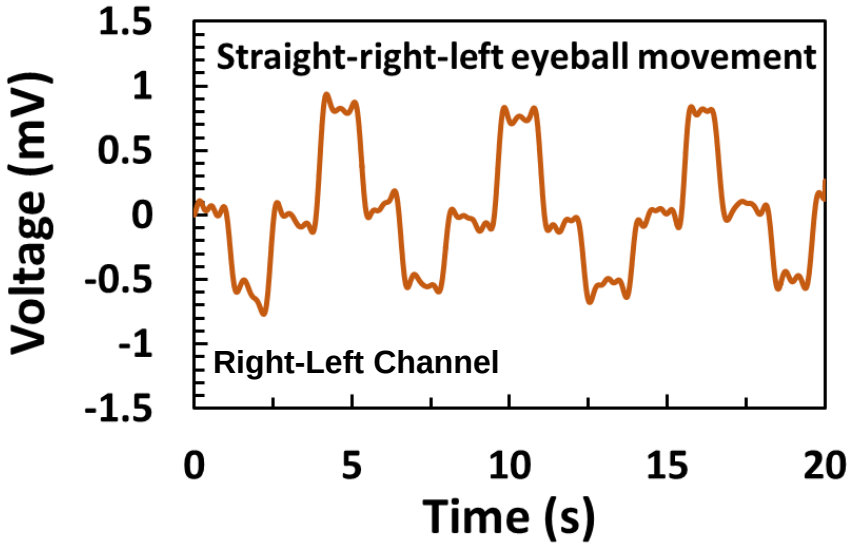
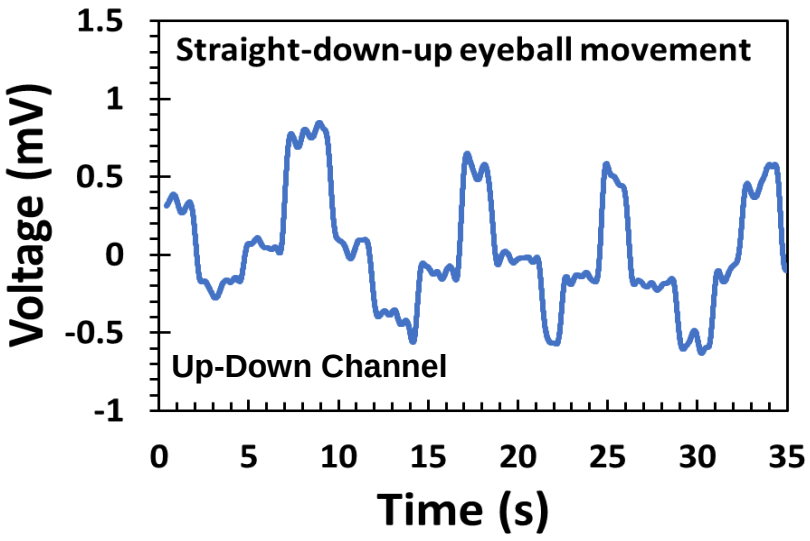
Transparent GETS for Electrooculogram (EOG)







Ameri, Akinwande*, Lu*, *et al.*, *npj 2D Materials and Applications* 2, 19 (2018).

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Imperceptible Human Robot Interface (HRI) by GETS

Ameri, Akinwande*, Lu*, *et al.*, *npj 2D Materials and Applications* 2, 19 (2018).

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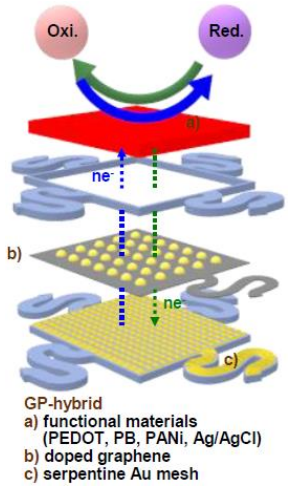
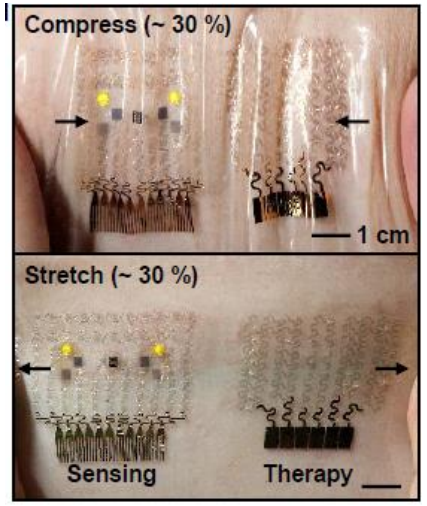
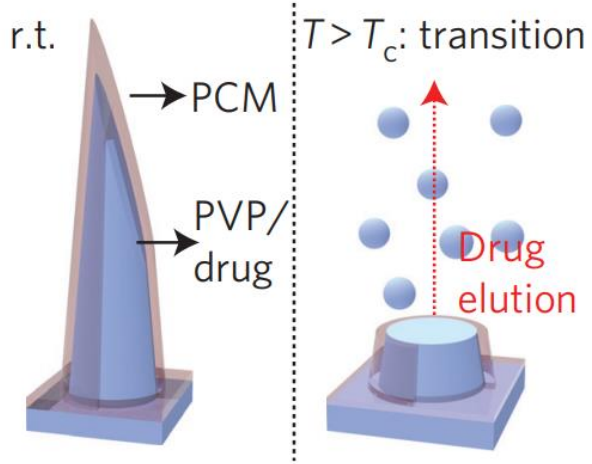
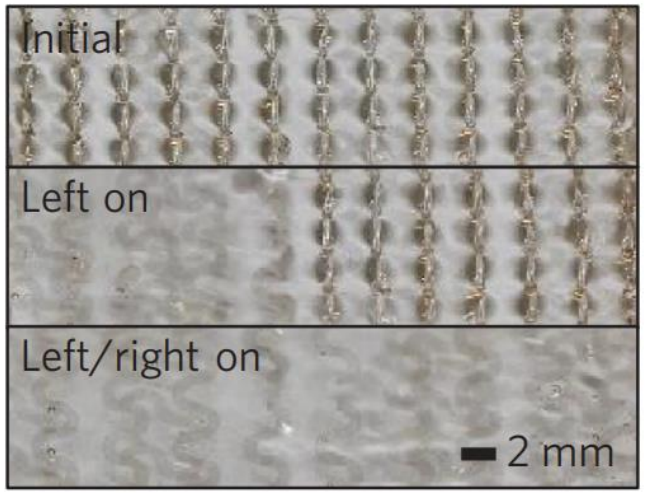
Graphene-Based E-Tattoo for Diabetics

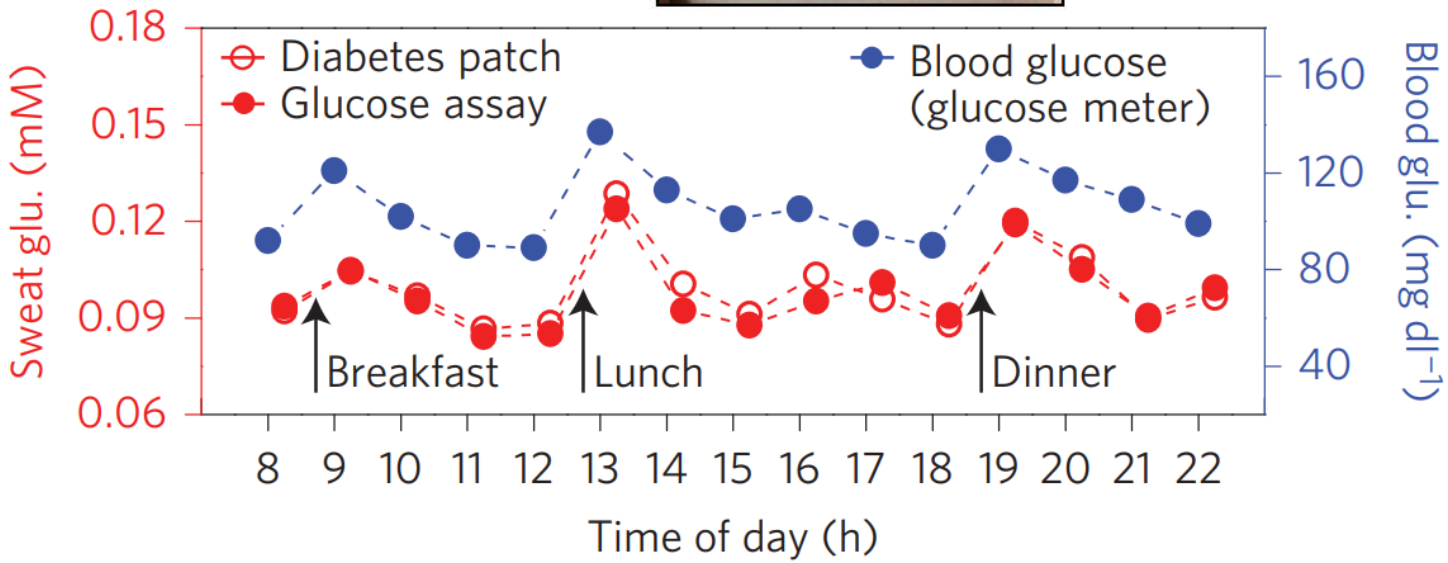
Prof. Dae-Hyeong Kim
Seoul National Univ.

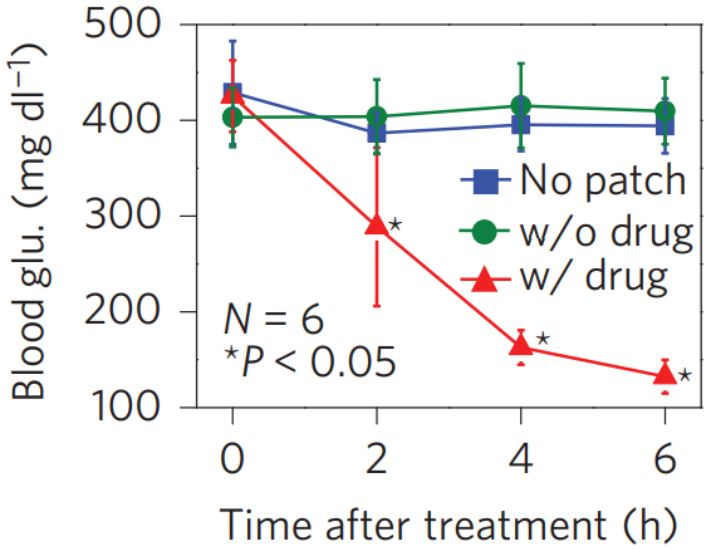












Lee, Lu, Kim*, *et al.*, *Nat. Nanotech.* 11, 566-572 (2016).

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Going Wireless – Near Field vs. Far Field Technology

Near Field (Induction)		Far Field (Radiation)	
Advantage	**Disadvantage**	**Advantage**	**Disadvantage**
• Less power consumption	• Data transfer rate : 424 kpbs	• Data transfer rate : 3 Mbps	• Battery powered
• Passive mode without battery	• Operating range : ~10 cm	• Operating range : ~10 m	

$$\frac{1}{r^6}$$

DOMINANT TERMS
IN THE REGION
(**Power density** attenuation)

r : distance

$$\frac{1}{r^2}$$

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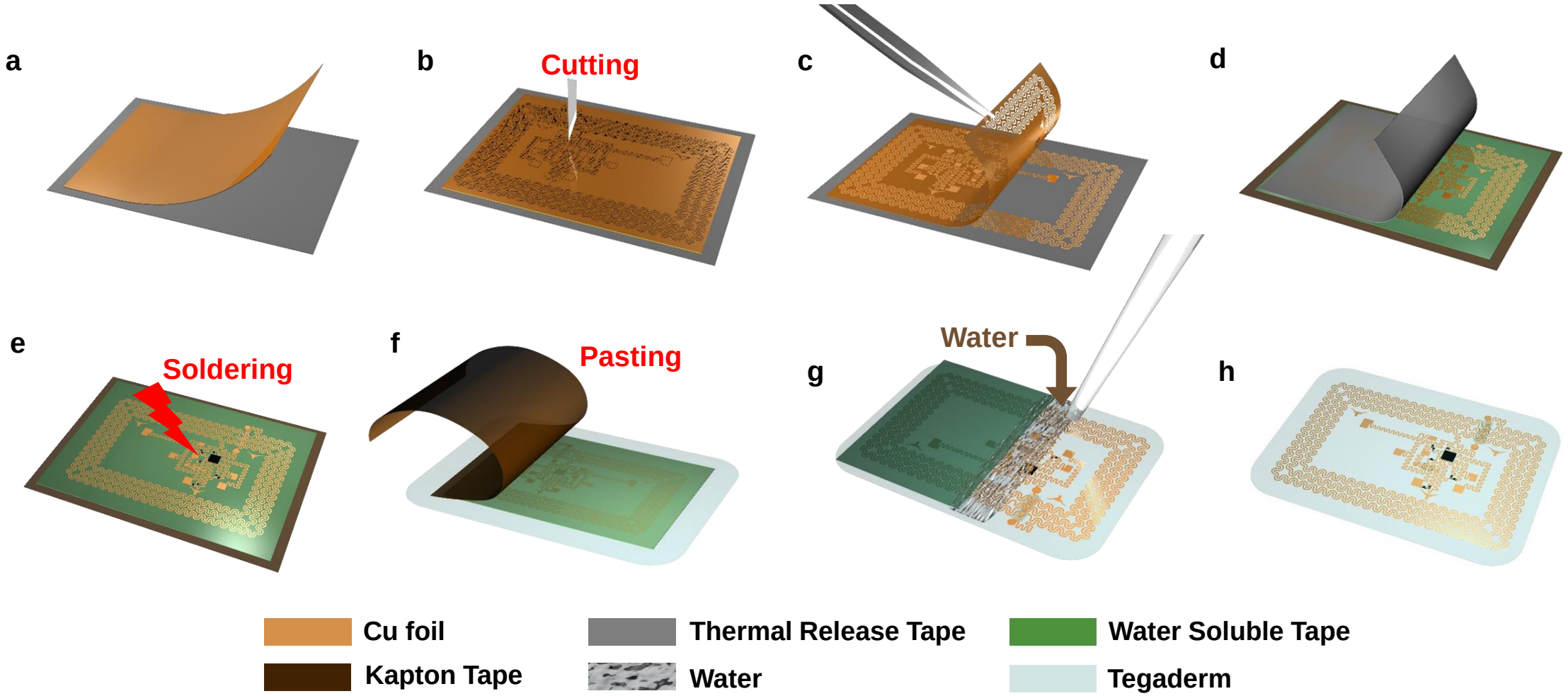
“Cut-Solder-Paste” Method for Integrating ICs on E-Tattoos



Jeong, Lu*, *et al.*, *Adv. Mater. Tech.* 1900117 (2019).

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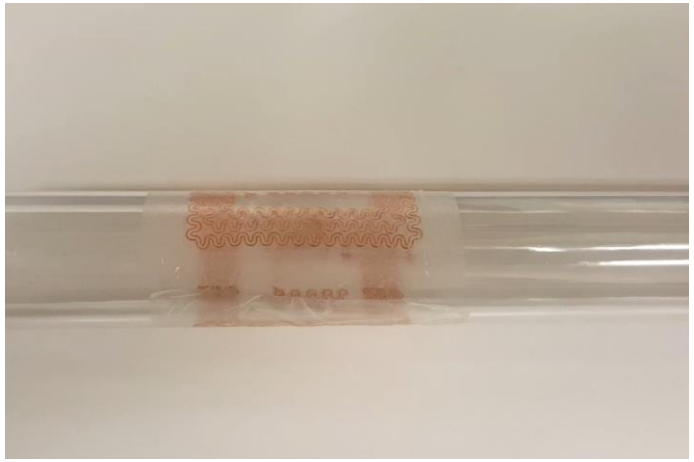
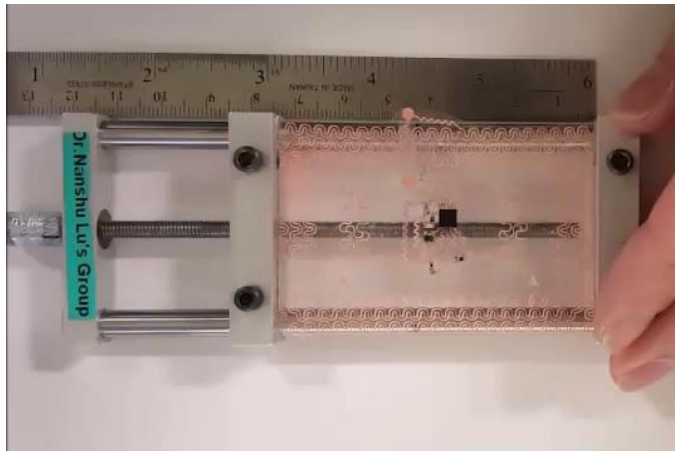
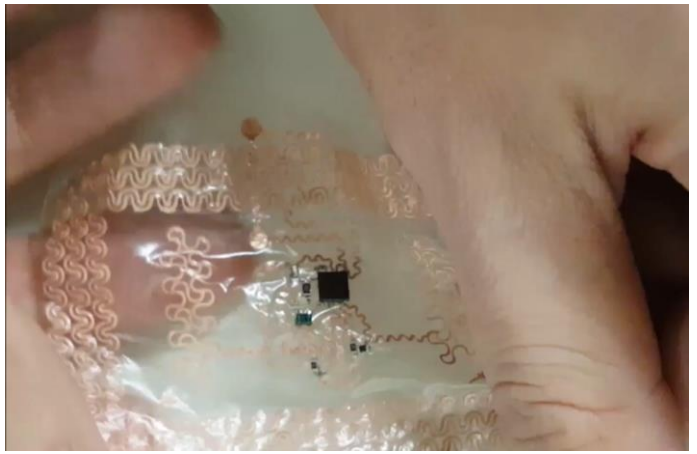
Robustness of Wireless E-Tattoos







Jeong, Lu*, *et al.*, *Adv. Mater. Tech.* 1900117 (2019).

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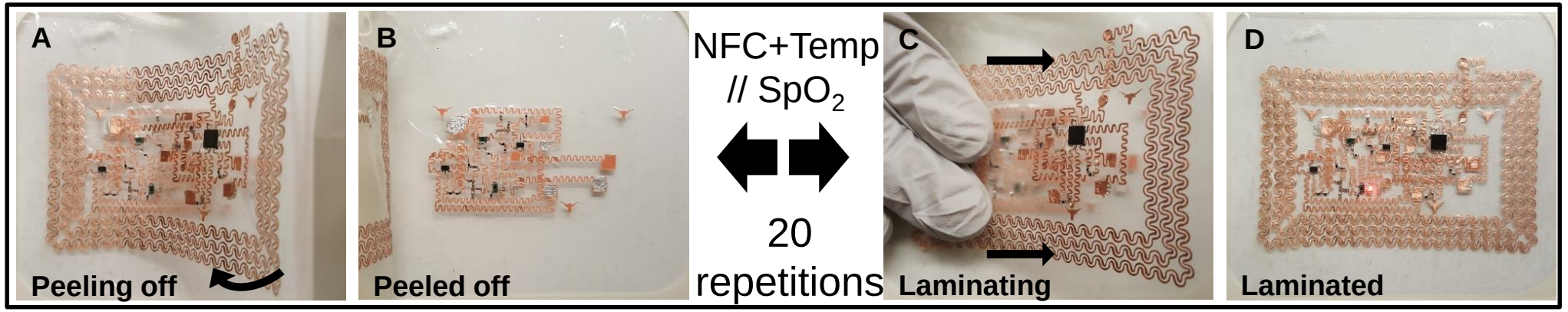
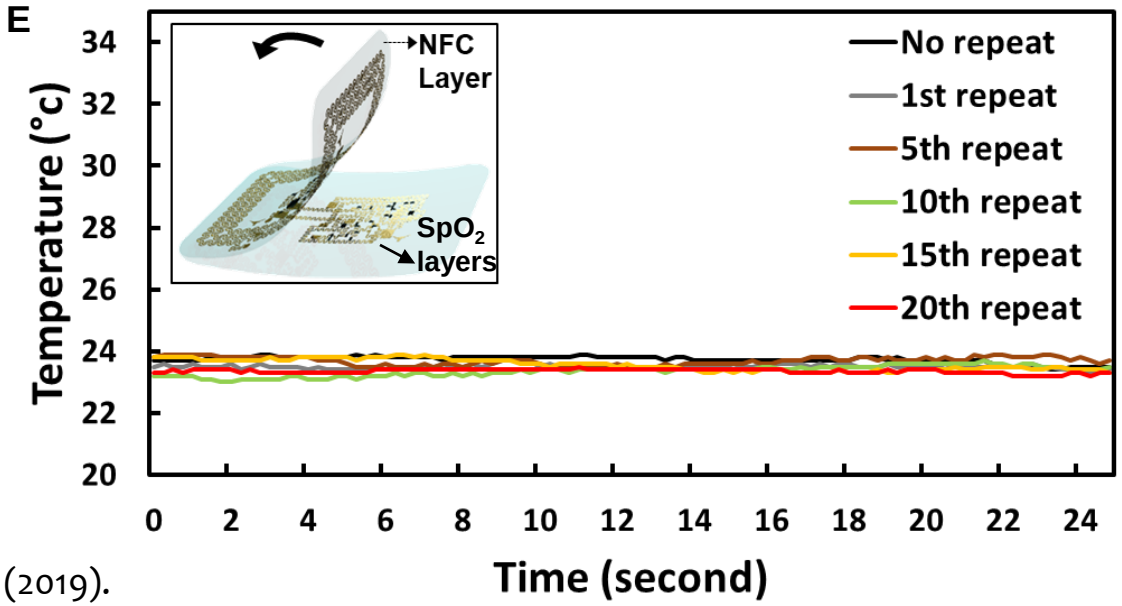
Assembly and Disassembly up to 20 times





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Acknowledgement

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