Sensor Devices for Mobile and Wearable Applications

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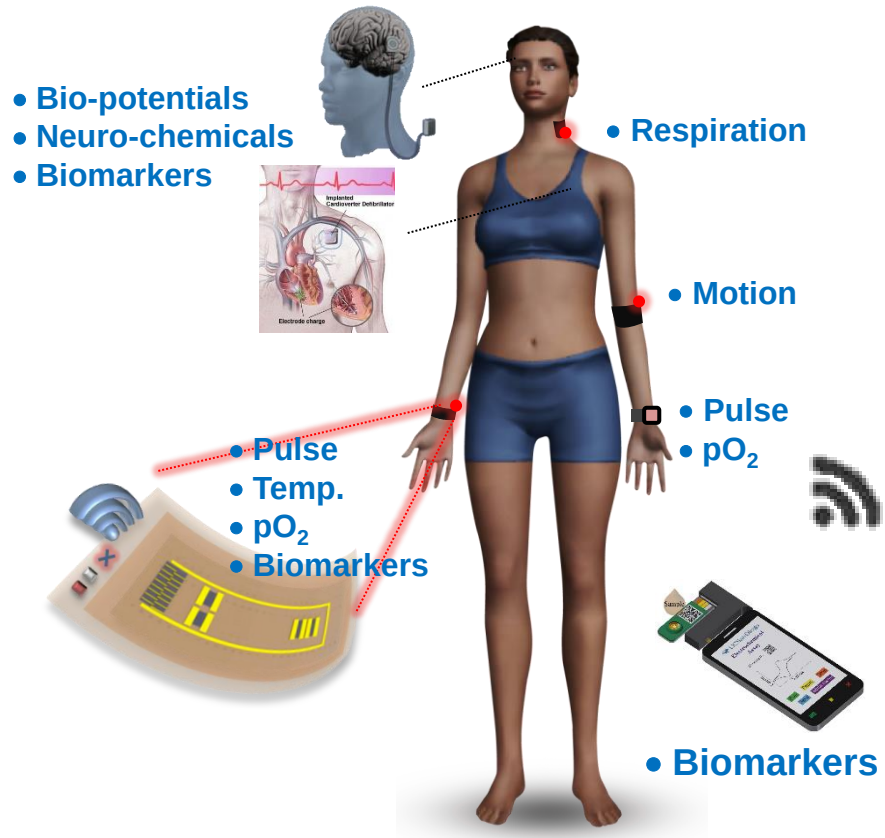
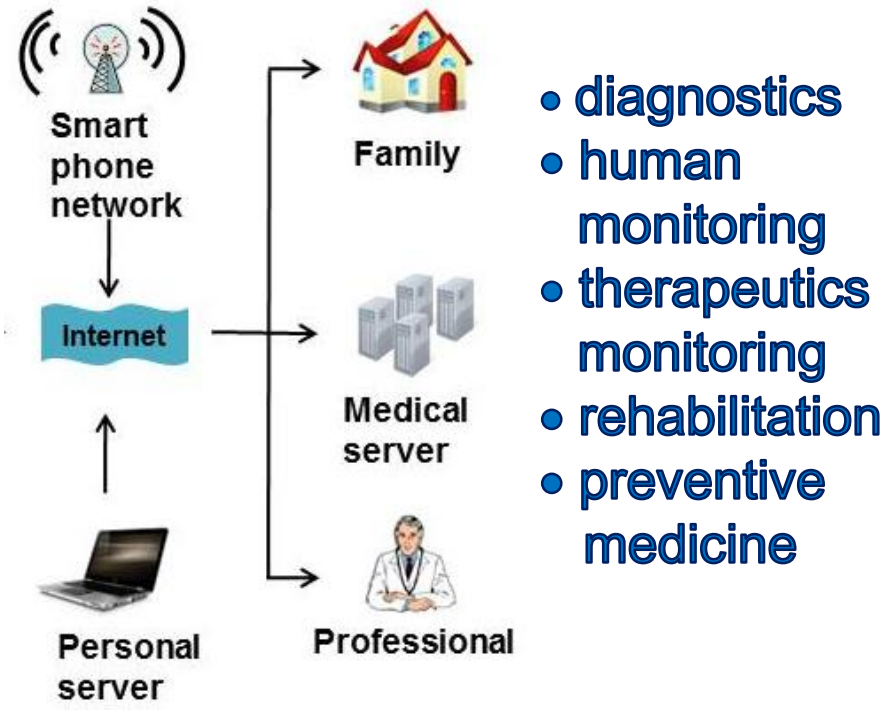
SAINT SKKU Advanced Institute of Nanotechnology

SAIHST Samsung Advanced Institute for Health Sciences and Technology

Sungkyunkwan University (SKKU) Korea

Personalized smart healthcare technology





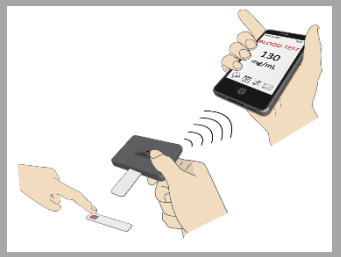
Sensor-integrated mobile and wearable systems which can monitor physiological and clinical parameters at point-of-care or home are promising for personalized smart healthcare technology.

Mobile and wearable POCT (point-care-testing) systems for personalized healthcare

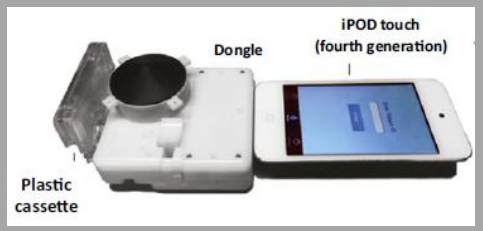
m POCT

w POCT

Standalone IOT



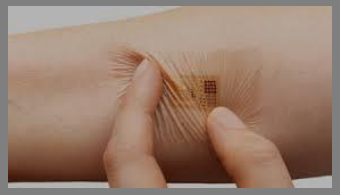
Smartphone-integrated



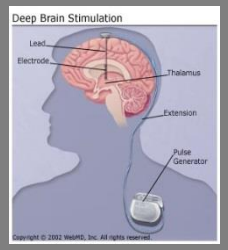
dressable

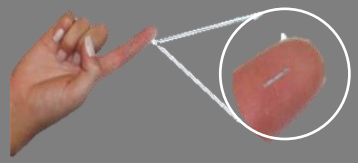
accessary

skin-attachable



implantable





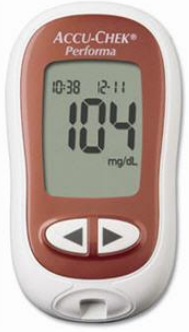
UNOBTRUSIVE

Mobile point-of-care testing (mPOCT) systems

Portable PoCTs : limits in connectivity and personalization

iSTAT
Abbott Labs

Blood analyzer
Alere



Accu-Check
Roche

Coagucheck
Roche

Stratus troponin analyzer
Siemens

mPOCTs : advantage in connectivity (spatiotemporal mapping, epidemic demography, preventive healthcare) but limit of low accuracy and no standardization

Glucometer
iHealth

LFA reader
CELLMIC

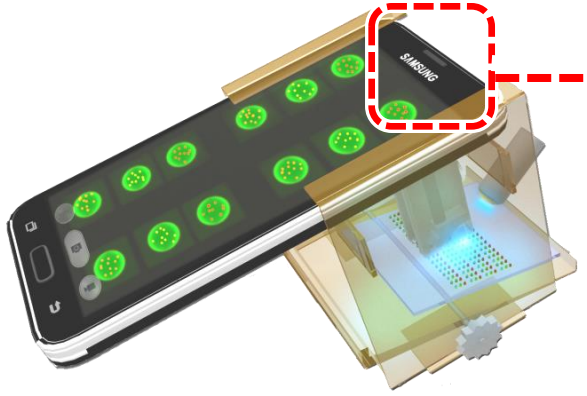
SAW biosensor
OJbio

Heart monitor(ECG)
Alivecor

Fluorescence imaging-based high accuracy biosensing for *m*POCT

ELISA is a gold standard in immunoassays

Spectrophotometer



Smartphone

CMOS Image Sensor (CIS)

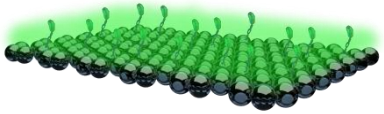
Rough exposure time control / low SNR

Issue : Low Accuracy

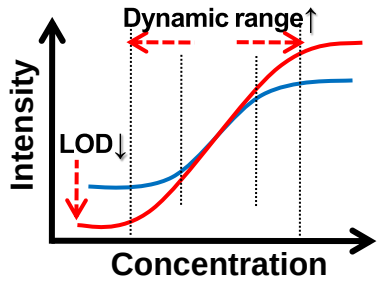
Smartphone-based “seesawed” fluorescence imaging for high accuracy apta-assay

Signal to noise ratio ↑

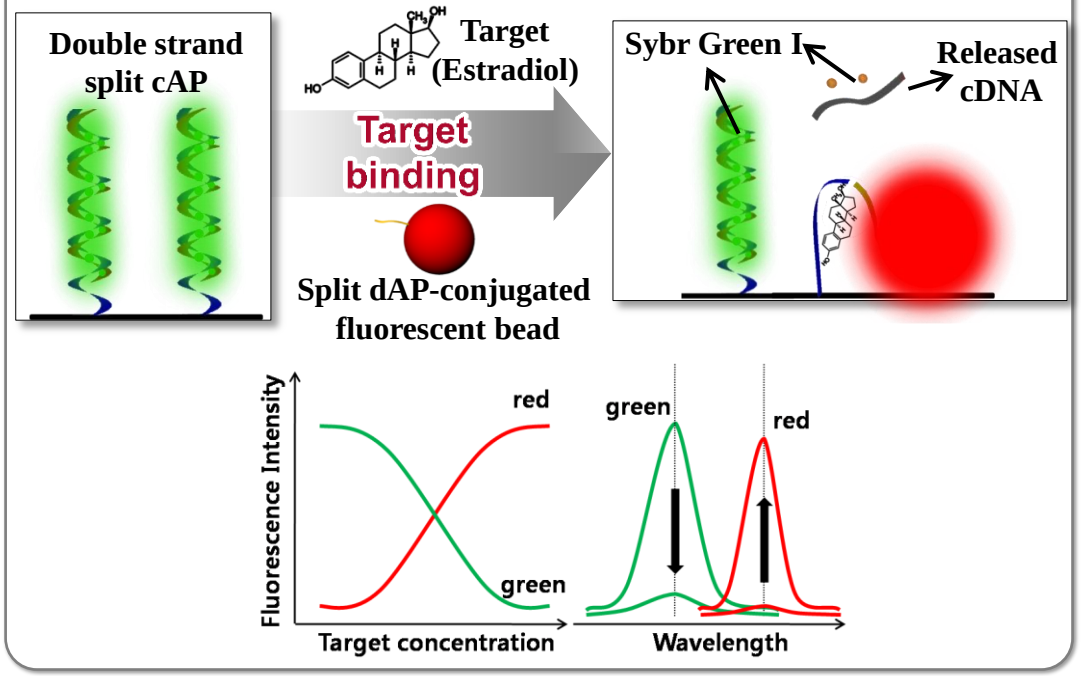
Metal-enhanced fluorescence substrate



- **LOD ↓ / dynamic range↑**



“Seesawed” fluorescence

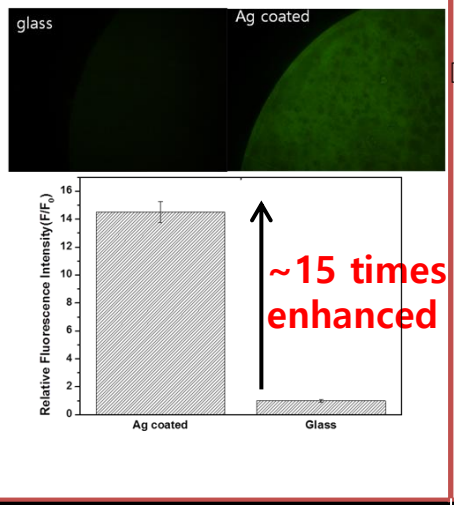


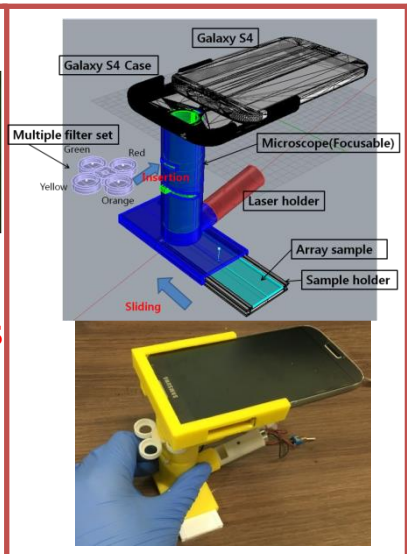
False-negatives (FN) ↓
Sensitivity (TP/(FN+TP)) ↑

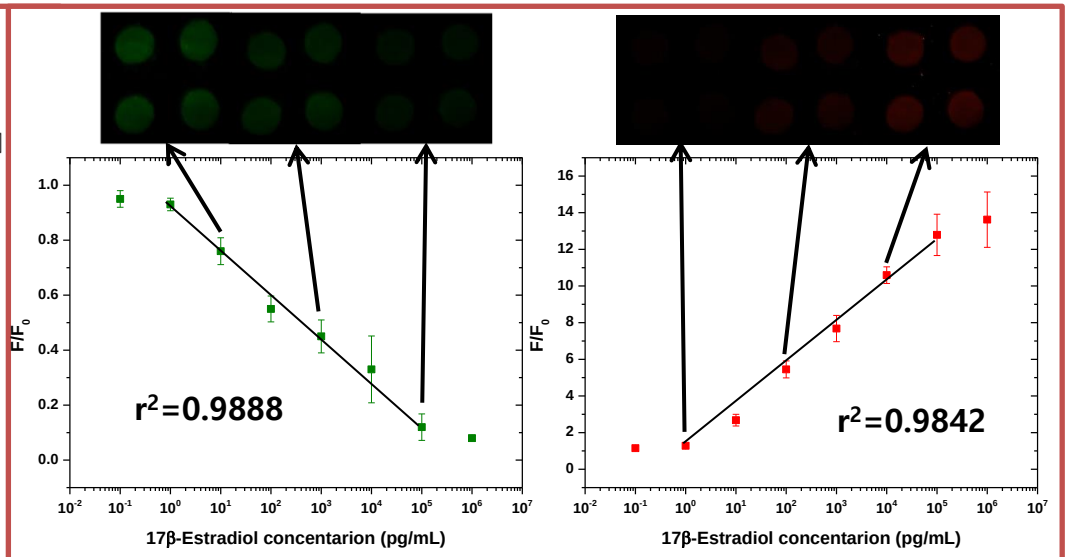
False-positives (FP) ↓
Selectivity (TN/(FP+TN)) ↑

W. Lee et al., Biosensors and Bioelectronics 94(2017) , 643

Smartphone-based “seesawed” fluorescence imaging for high accuracy apta-assay



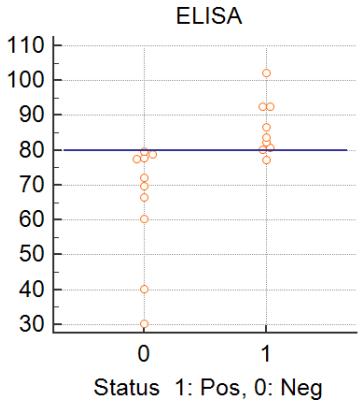




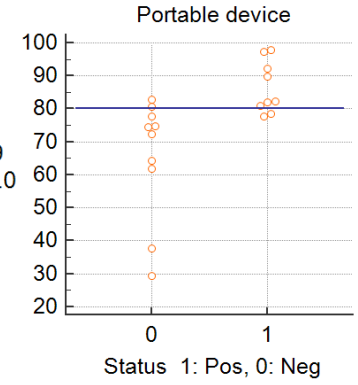
MEF(Ag)→SNR ↑

Prototyping of using 3D printing

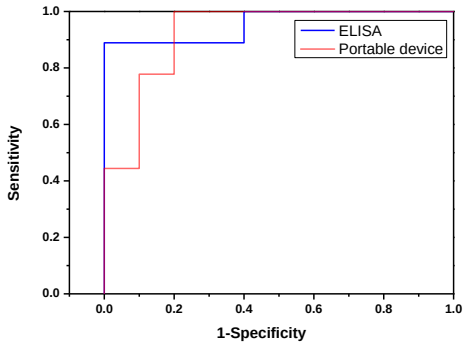
Calibration curve for 17β-estradiol with smartphone fluorescence microscope



>80
Sens: 88.9
Spec: 100.0



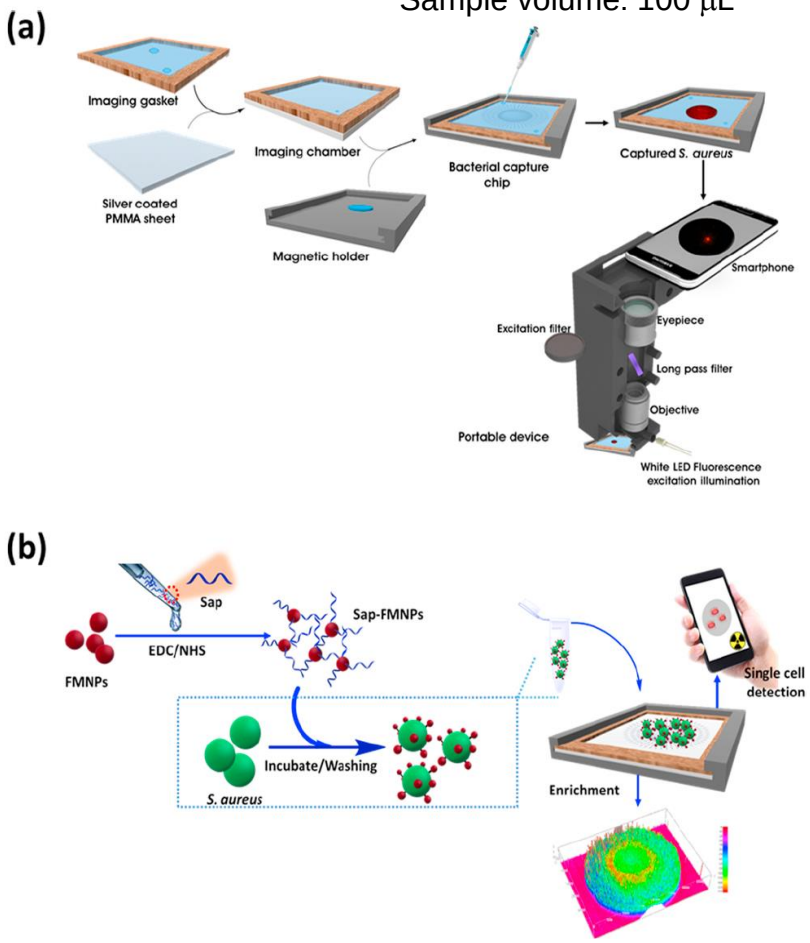
>80
Sens: 77.8
Spec: 80.0

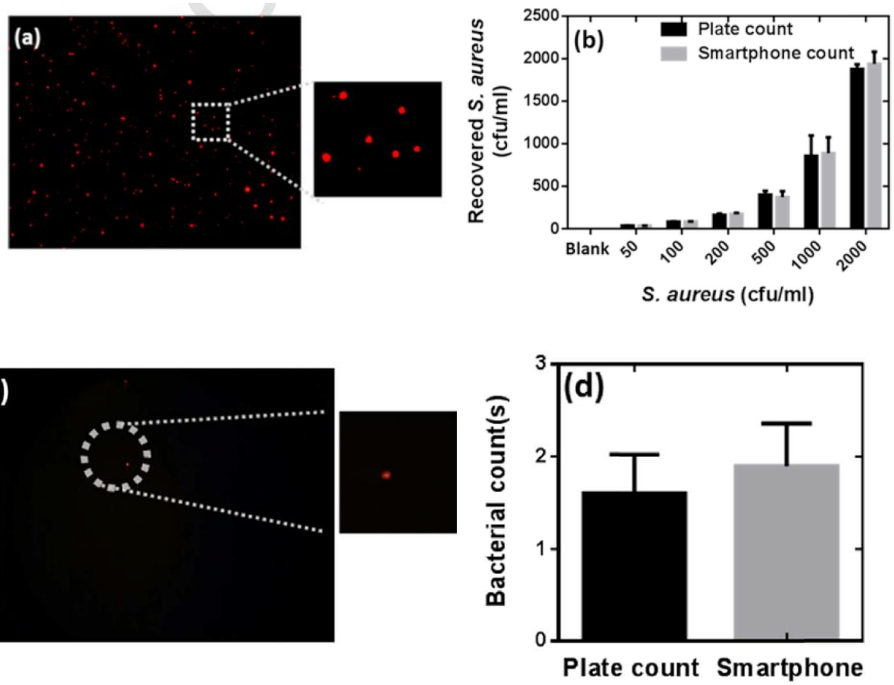


Statistical accuracy test of target analyte spiked wastewater	Area under ROC curve
ELISA	0.956
Mobile biosensor	0.922

Smartphone-based fluorescence imaging of pathogenic bacteria for on-the-spot detection

Sample volume: 100 μL



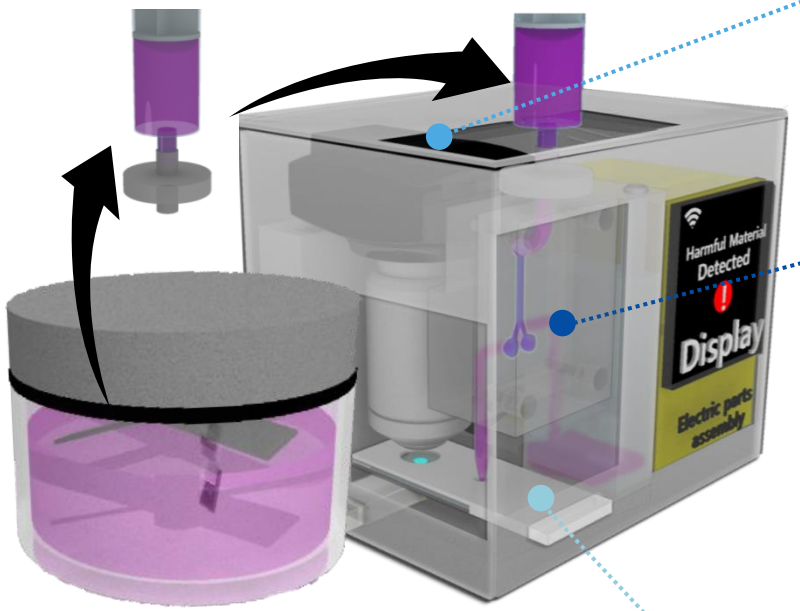


10 CFU/mL (single bacterial cell in 100 μL) detectable

But, typical target concentration in blood (sepsis) and food safety: 1~10 CFU/mL

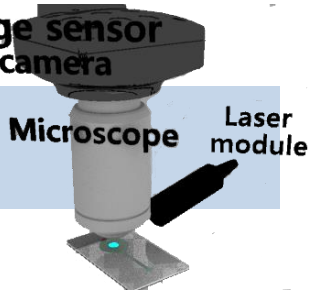
S. Shrivastava et al., Biosensors and Bioelectronics, 95 (2018)

Fluorescence imaging-based IOT-enabled on-the-spot POCT system

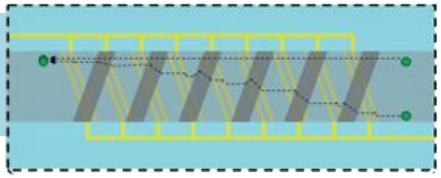


IOT-enabled system

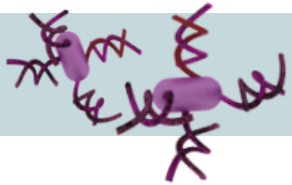
Fluorescence imaging based biosensing

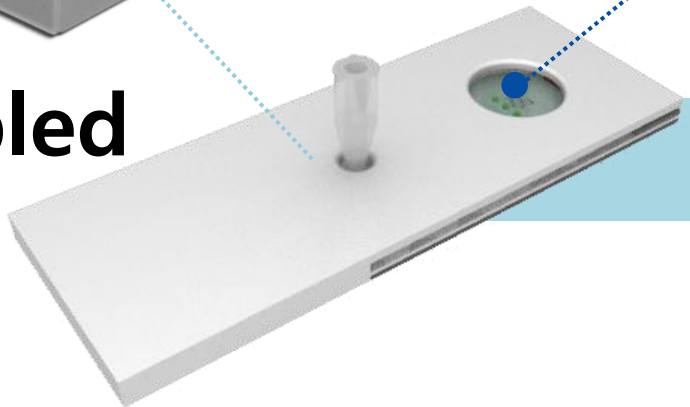


Bacteria separator/concentrator



Probes for bacteria and toxin





Cartridge integrated with MEF substrate

Skin-attachable sensor patches for wearable electronics

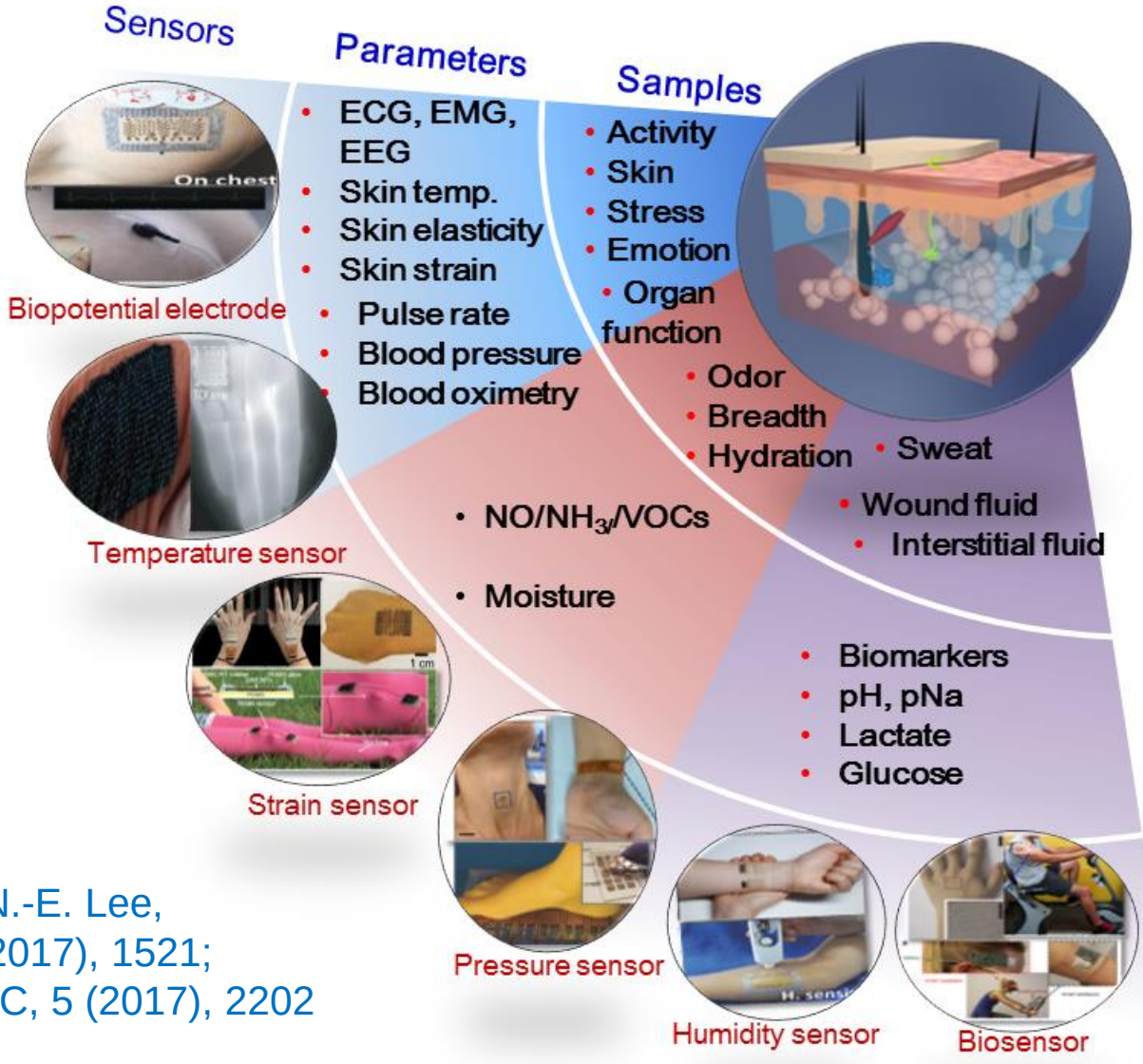
Accessary : non-invasive but limit in unobtrusive monitoring

Patch: non-invasive and unobtrusive monitoring, high SNR due to conformal contact with skin

Biostamp
MC10

S-patch
Samsung

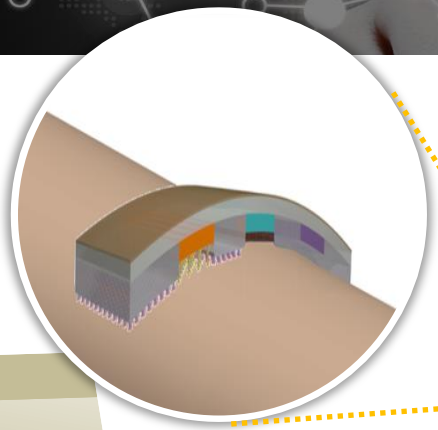
What can be measured by skin-attachable sensor patches?



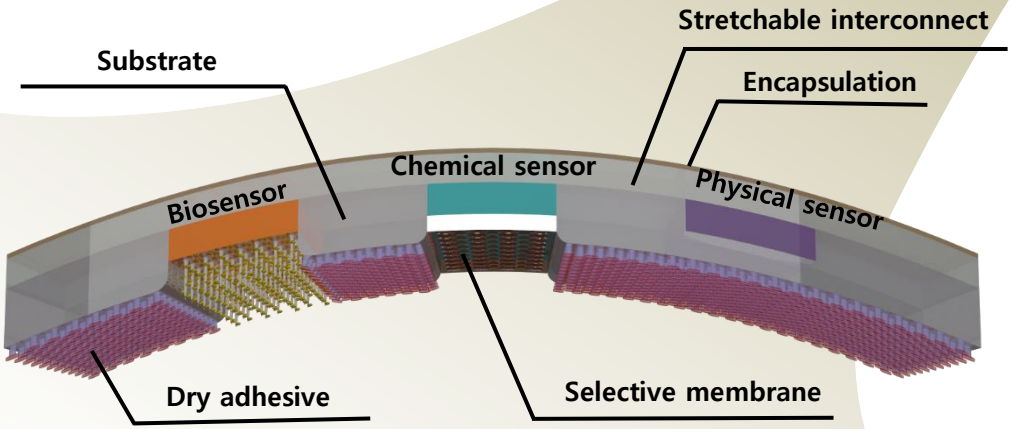
T.Q. Trung and N.-E. Lee,
Adv. Mater. 29 (2017), 1521;
J. Mater. Chem. C, 5 (2017), 2202

Engineering of skin-attachable sesnor patches

Stretchable materials	Sensing materials, electrodes, electrochemical electrodes, dry biopotential electrodes
Devices	Stretchable sensors, energy harvesters, energy storage devices
Packaging	Substrate, dry adhesives, interconnect, encapsulation



Stretchable materials & devices

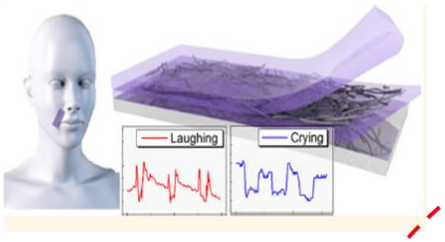


Sensor-integrated systems

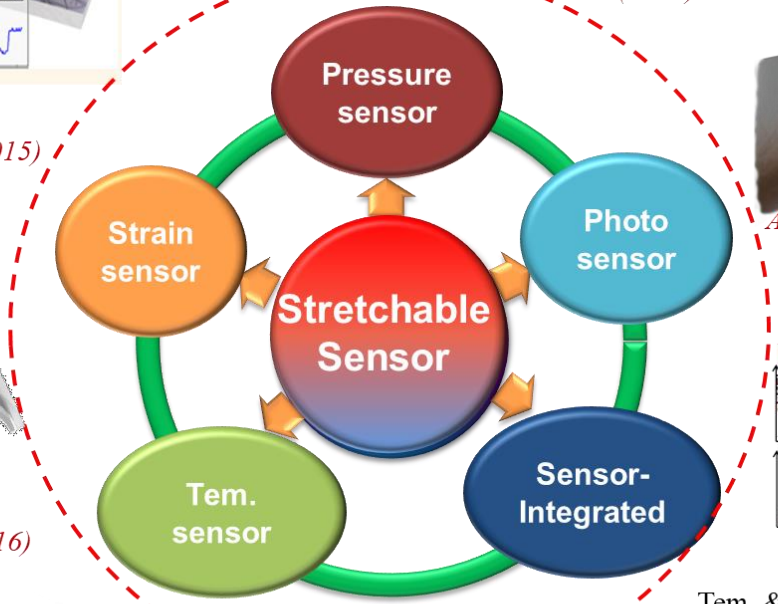
Circuits	Signal acquisition, power management , data handling
S/W	Applications, big data, AI
Clinical	New applications, clinical evaluation, services

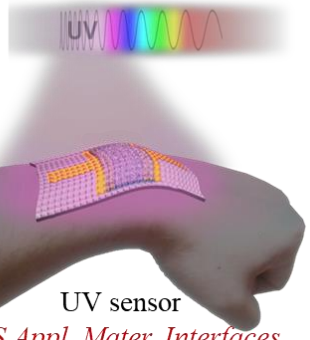
Stretchable physical sensors for skin-attachable patches

Pressure sensor
Adv. Mater. 29, 1703004 (2017)

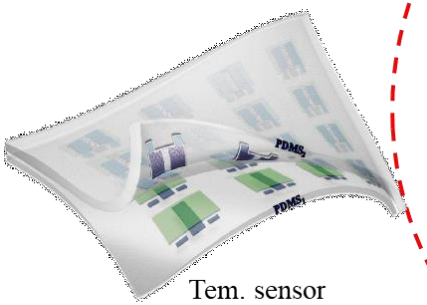


Strain sensor
ACS Nano , 11, 6252 (2015)

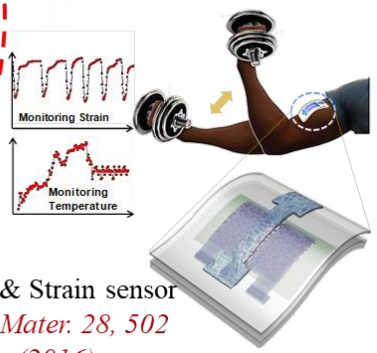




UV sensor
ACS Appl. Mater. Interfaces. 9, 3598 (2017)

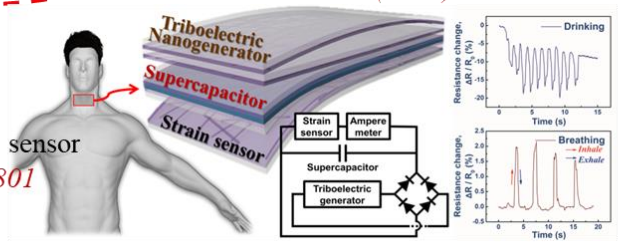


Tem. sensor
Adv. Mater. 28, 502 (2016)



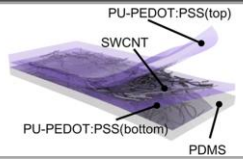
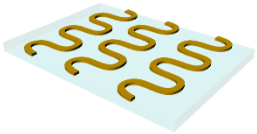
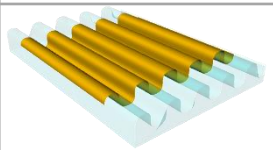
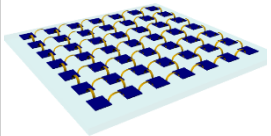
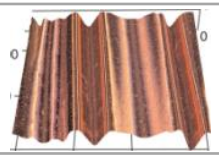
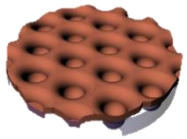
Tem. & Strain sensor
Adv. Mater. 28, 502 (2016)

Self-powered stretchable piezoelectric sensor
Adv. Energy Mater. 8, 1701520 (2018)



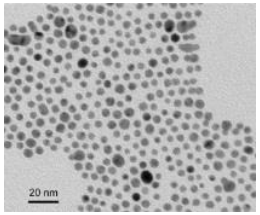
Self-powered strain sensor
ACS Nano 9, 8801 (2015)

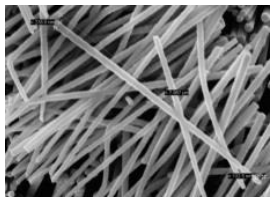
Approaches for stretchability

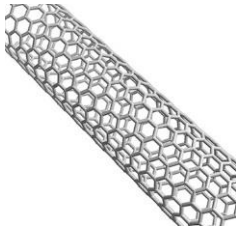
Materials	Strategies	Designs	Process methods	Stretchable direction
Intrinsically stretchable components	Using intrinsically stretchable materials	 **Elastomeric nanocomposites**	Spin-coating, printing, spraying, electropsinning *ACS Nano* **2015**, *9*, 6252	Omni-direction
Geometric engineering of compliant materials	In-plane, geometric engineering	 Serpentine routing	Patterning *Appl. Phys. Lett.* **2014**, *104*, 021908	Uniaxial
	Out-of-plane, geometric engineering	 Wavy structure	Pre-stretching and release *J. Vac. Sci. Technol. A* **2009**, *27*, L9	Uniaxial, Biaxial
		 Island-bridge	Transfer printing *IEEE Trans. Compon. Packag. Manuf. Technol.* **2015**, *PP*, 1	Biaxial
		 Imperceptible	Transfer on pre-strained ultrathin substrate *Adv. Mater.* **2015**, *27*, 34	Unixial
	Out-of-plane, 3D structuring	 Bio-mimicking	Soft lithography *Adv. Sci.* **2015**, *2*, n/a	Multi-direction, but not fully stretchable
		 **Microstructrured pattern**	Soft lithography spin coating, printing, spraying	Omni-direction

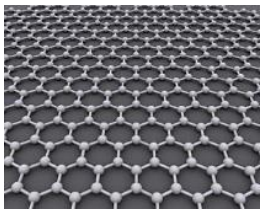
Approach 1: Intrinsically stretchable elastomeric nanocomposites

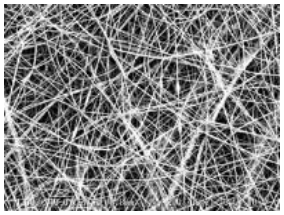
Nanomaterials











piezoelectric
pyroelectric
piezoresitive
chemresistive
thermoresistive
photoresponsive
electroactive

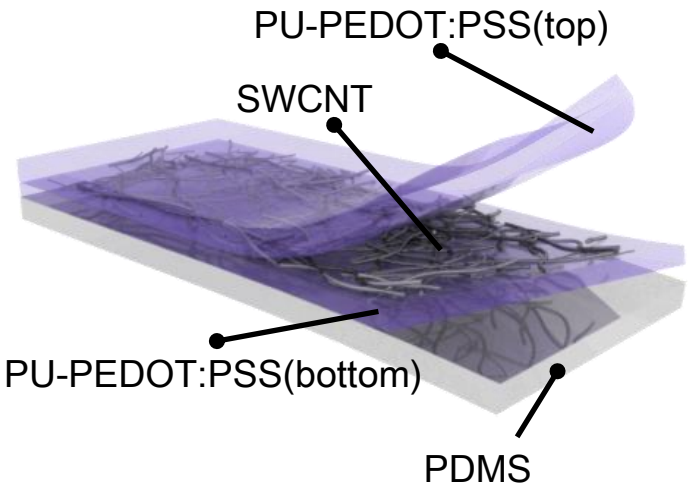
+ Elastomer

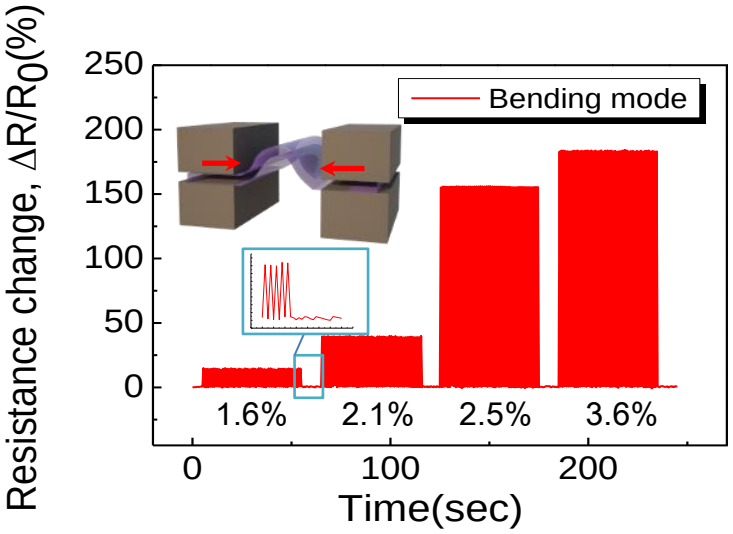
Transparent

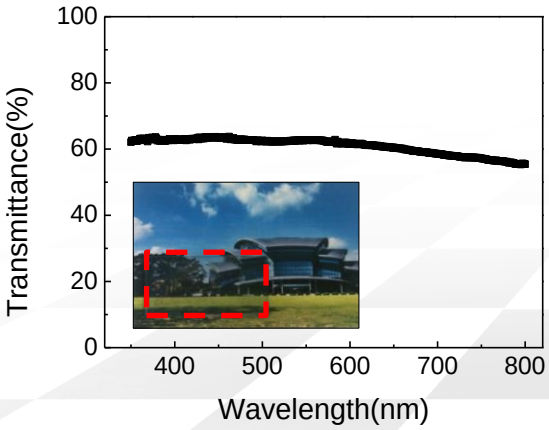
- Thin films
- Sheets
- Nanofibers
- Microfibers

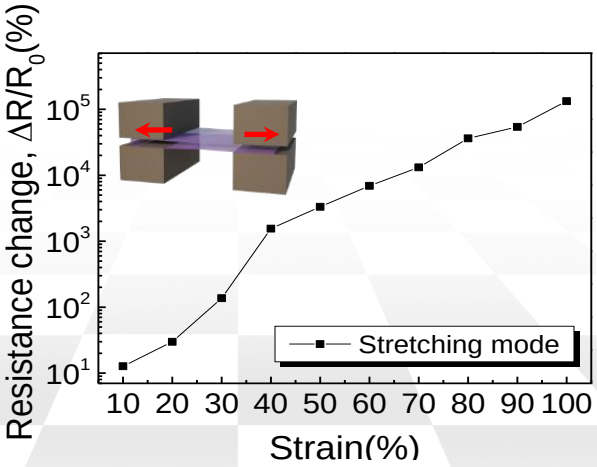
Stretchable

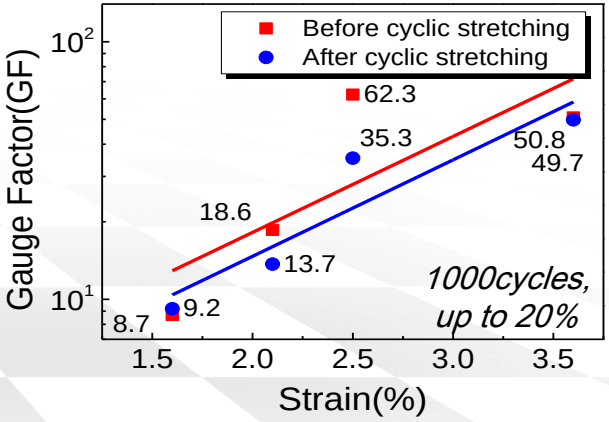
Stretchable, transparent and ultrasensitive strain sensor for emotion detection





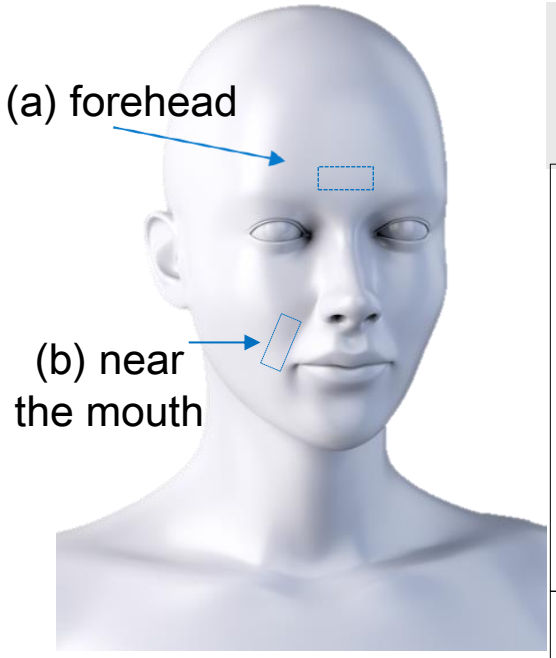


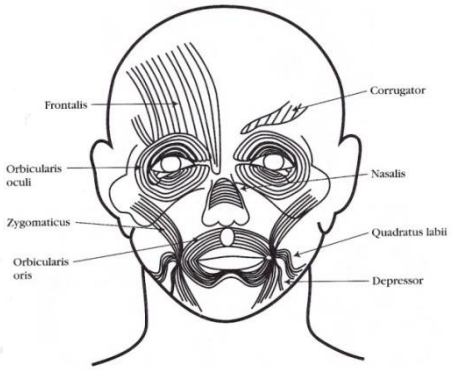


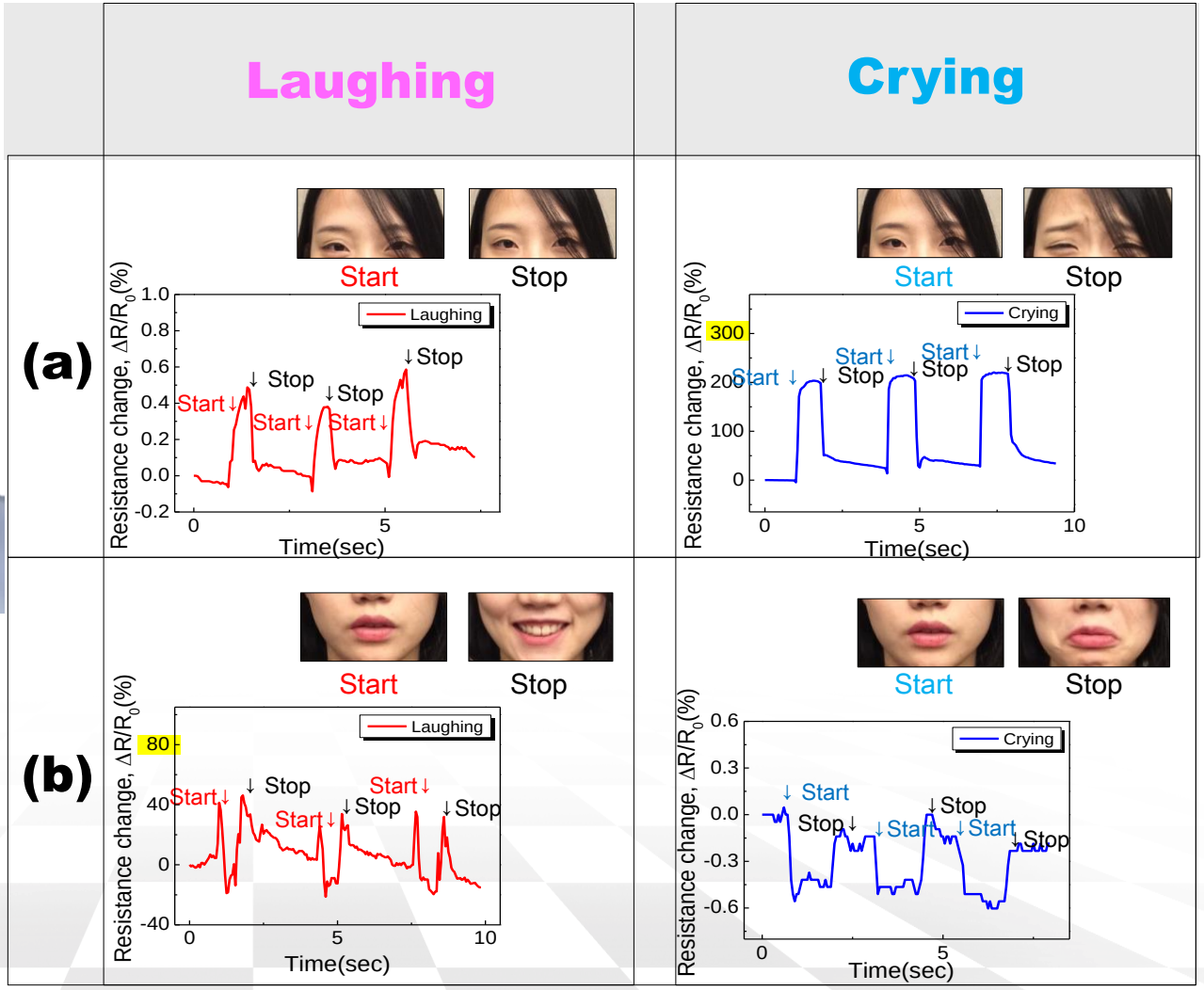


Roh et al., ACS Nano 11 (2015) 6252

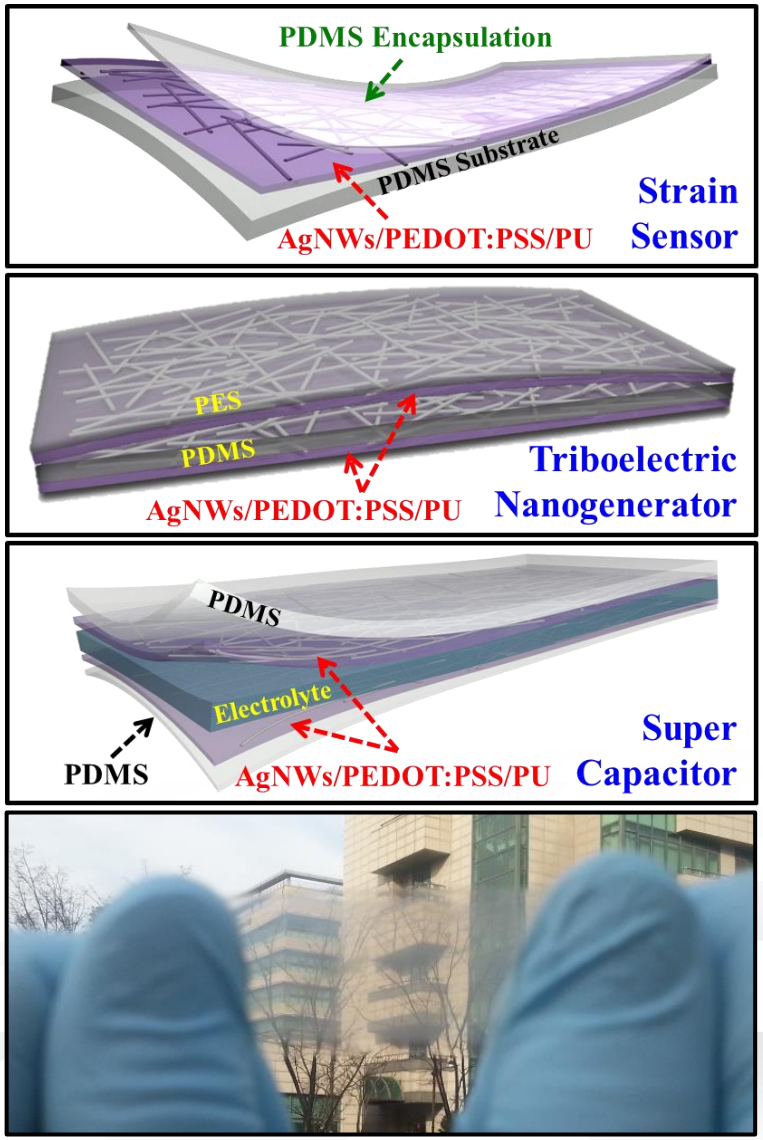
Stretchable, transparent and ultrasensitive strain sensor for emotion detection



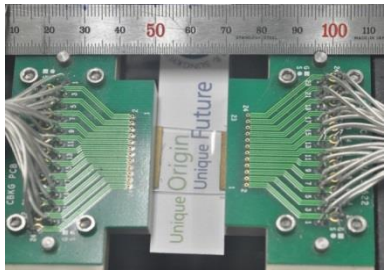


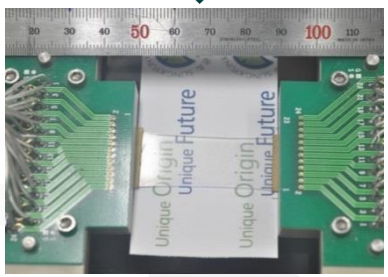


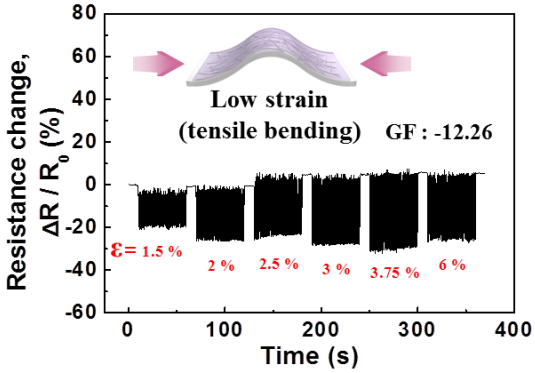
Stretchable, transparent, ultrasensitive, self-powered strain sensor for activity monitoring

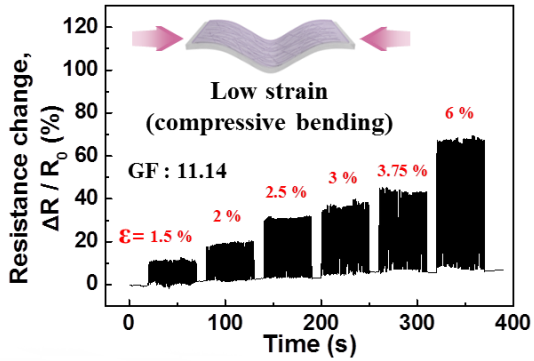


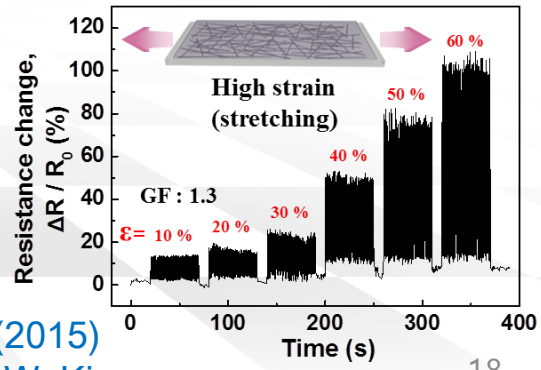
Evaluation





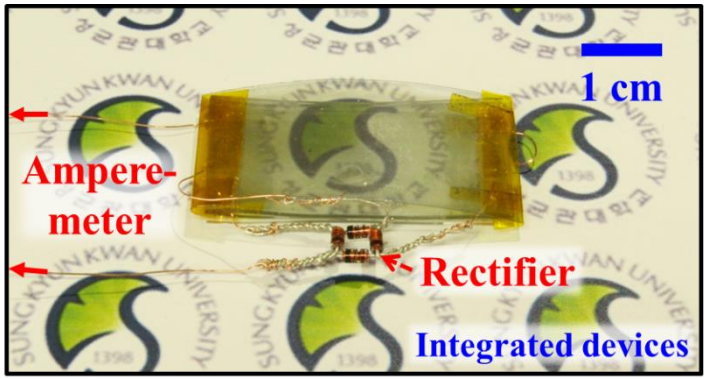




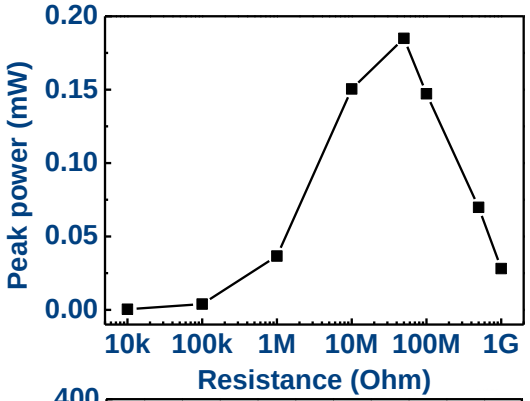


Hwang et al., ACS Nano 9 (2015) 8801, collaboration w/ prof. S.W. Kim

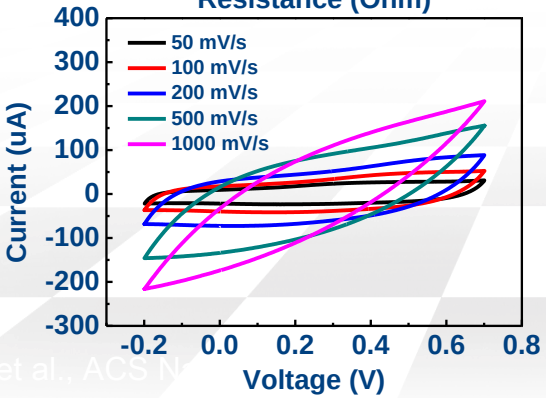
Stretchable, transparent, ultrasensitive, self-powered strain sensor for activity monitoring



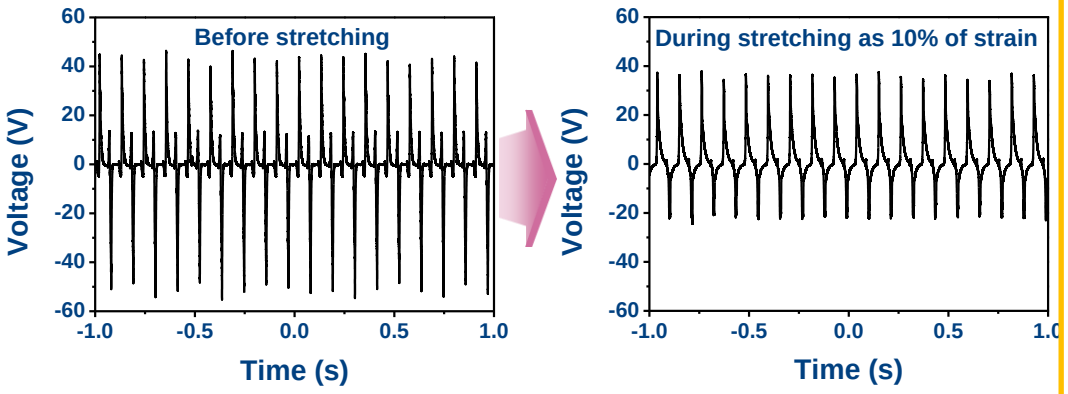
TENG



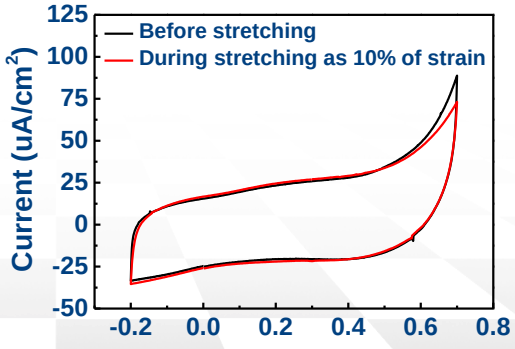
SC



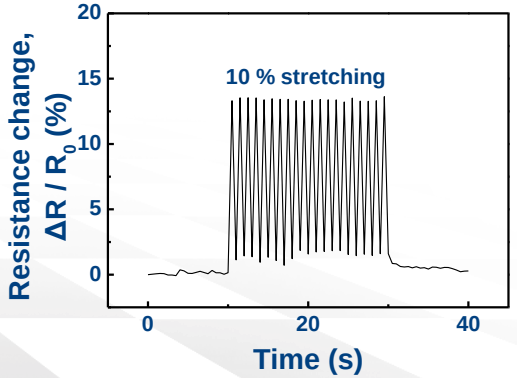
Electrical performance of integrated devices during stretching as 10% of strain



Triboelectric nanogenerator

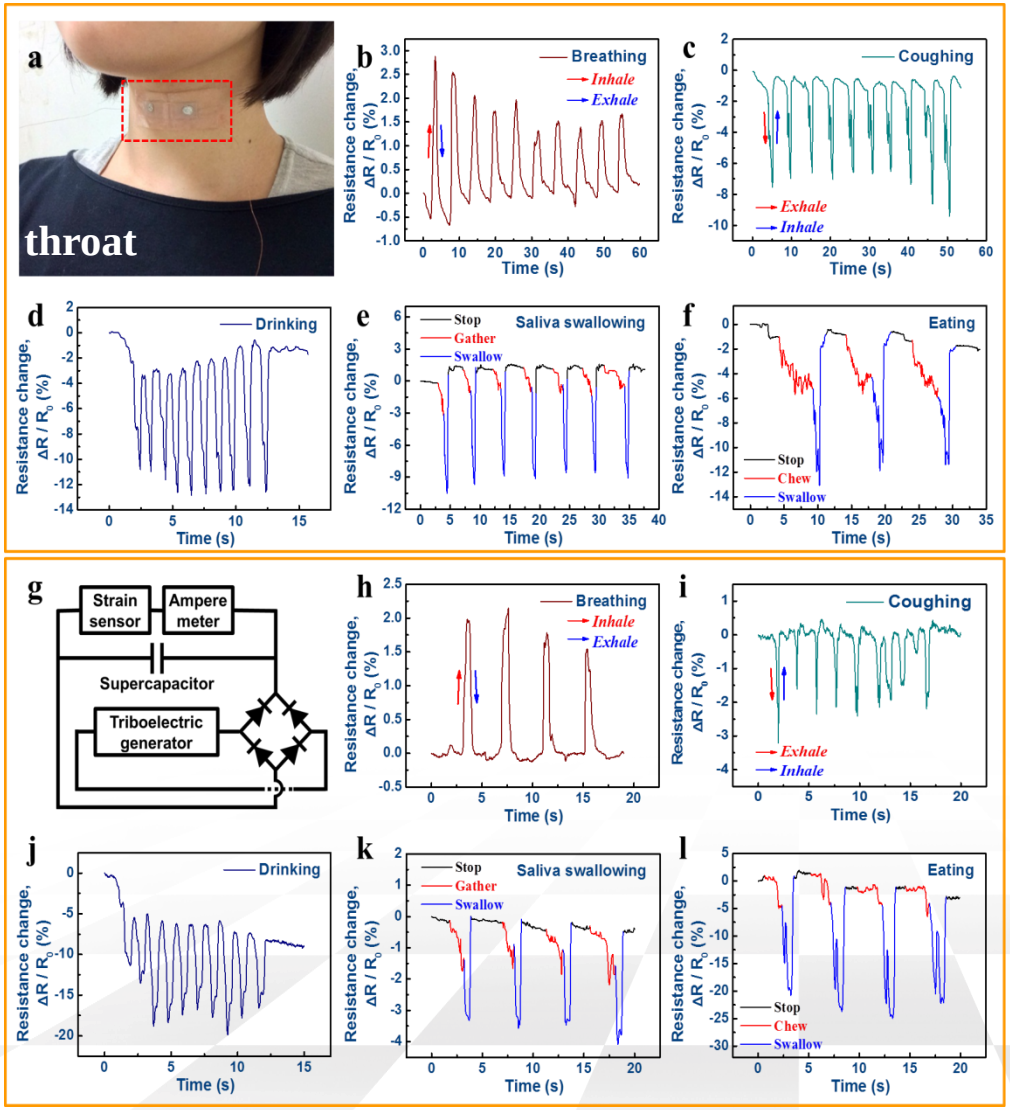


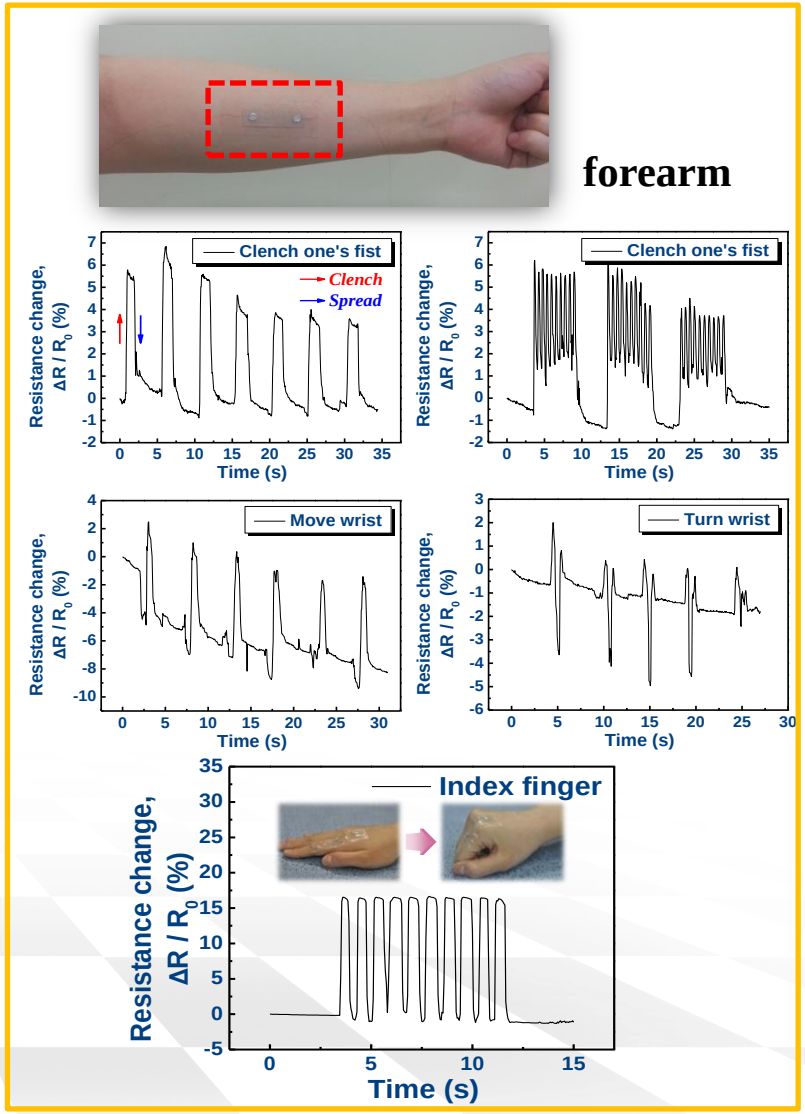
Supercapacitor



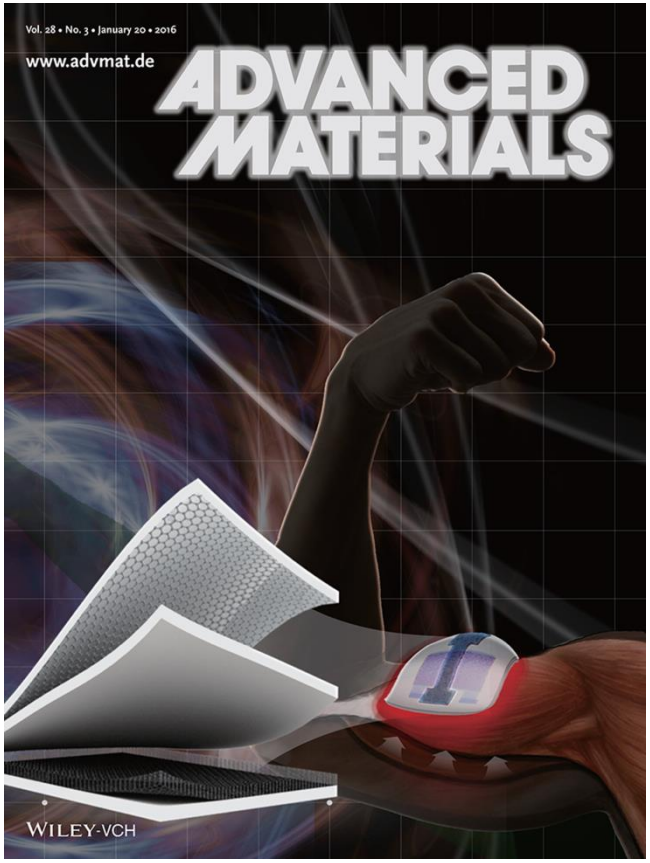
Strain sensor

Stretchable, transparent, ultrasensitive, self-powered strain sensor for activity monitoring

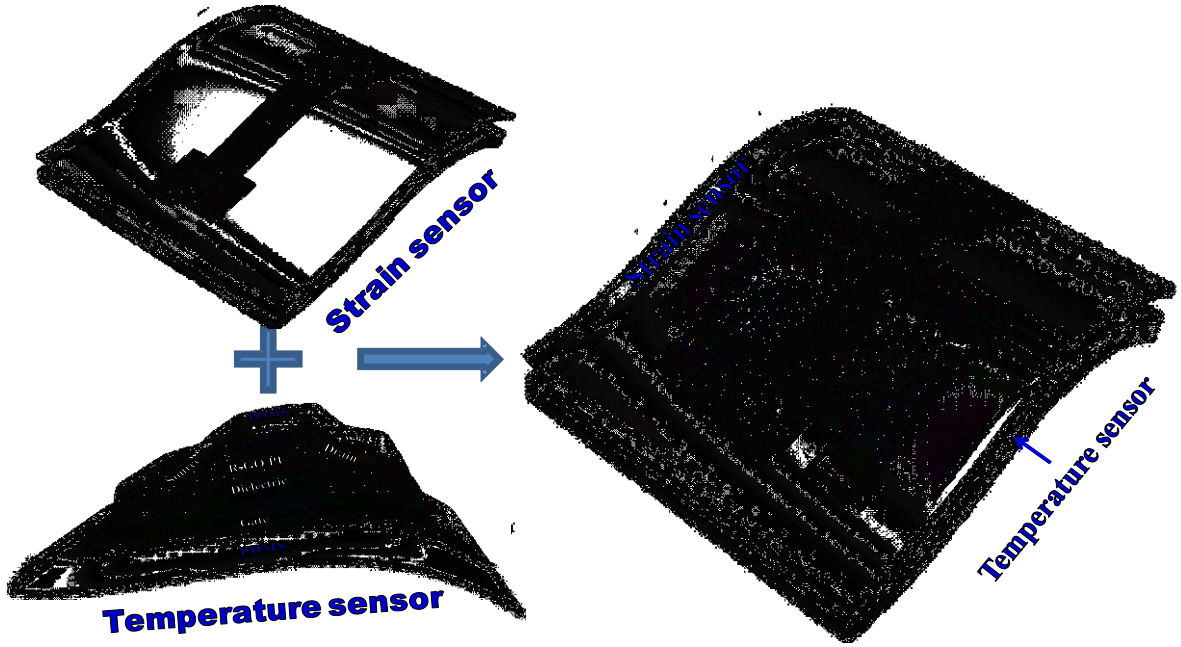




All-elastomeric transparent and stretchable multi-sensors for activity monitoring



AgNWs/PEDOT:PSS-PU resistor

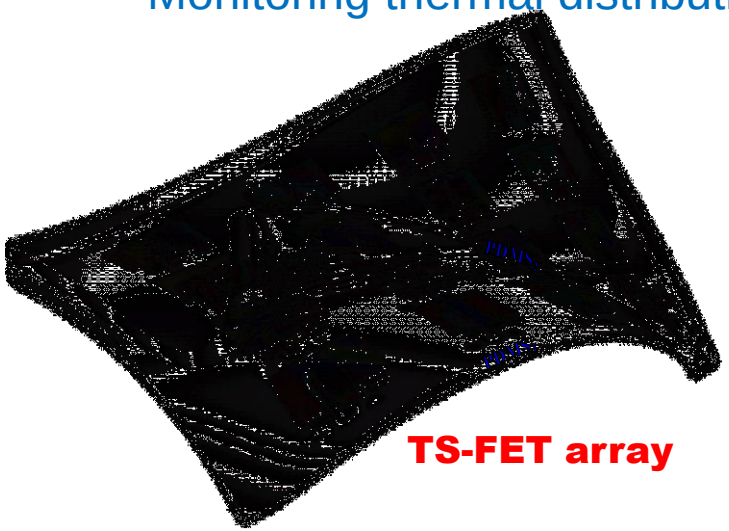


Reduced graphene oxide-PU channel, PU gate dielectric and PEDOT:PSS-PU electrode

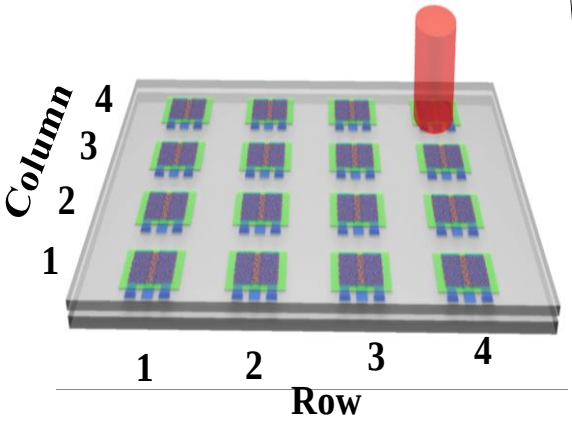
Trung et al., Adv. Mater., 28(2016) 502

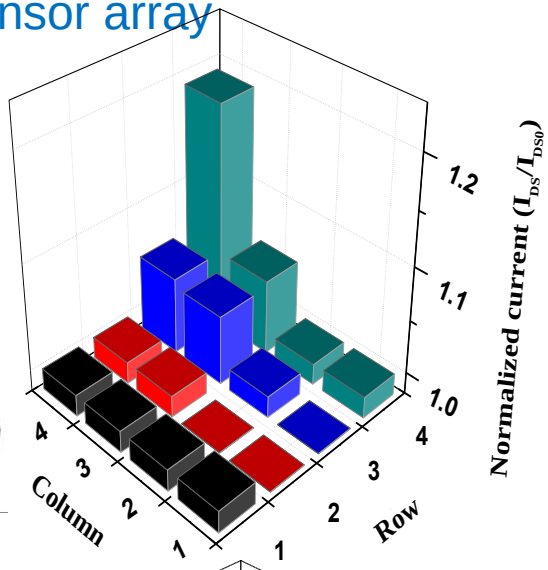
All-elastomeric transparent and stretchable multi-sensors for activity monitoring

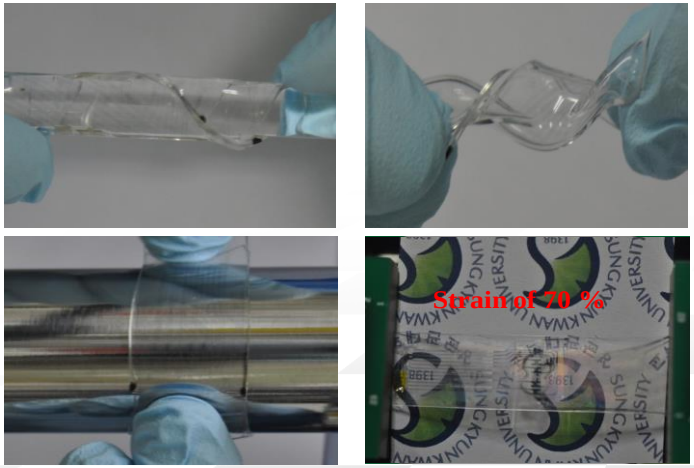
Monitoring thermal distribution by FET temperature sensor array

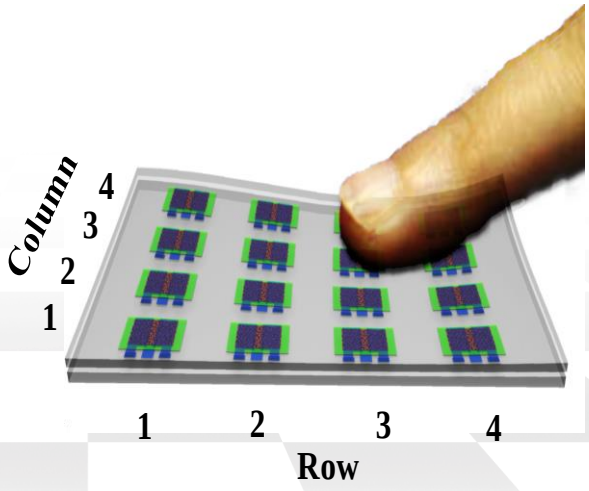


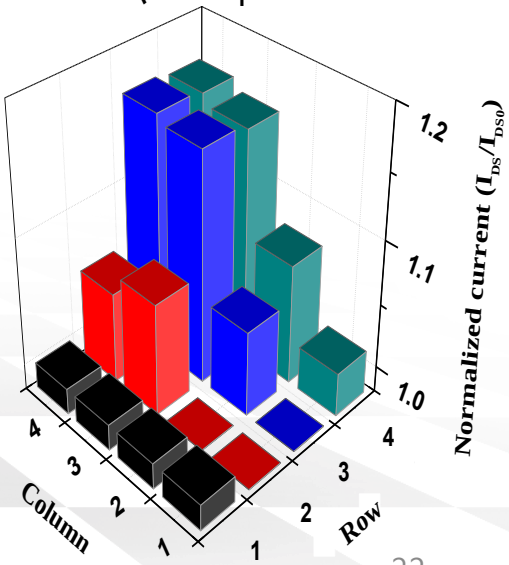
Hot object





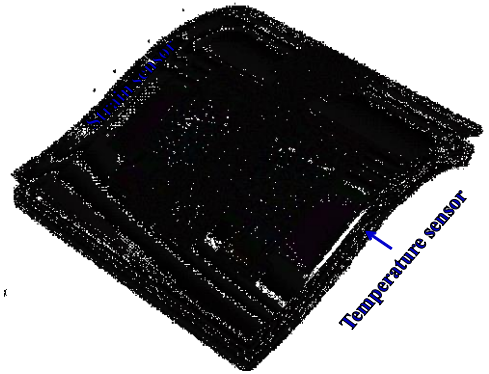


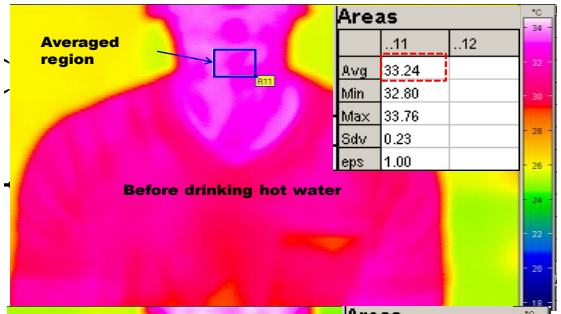


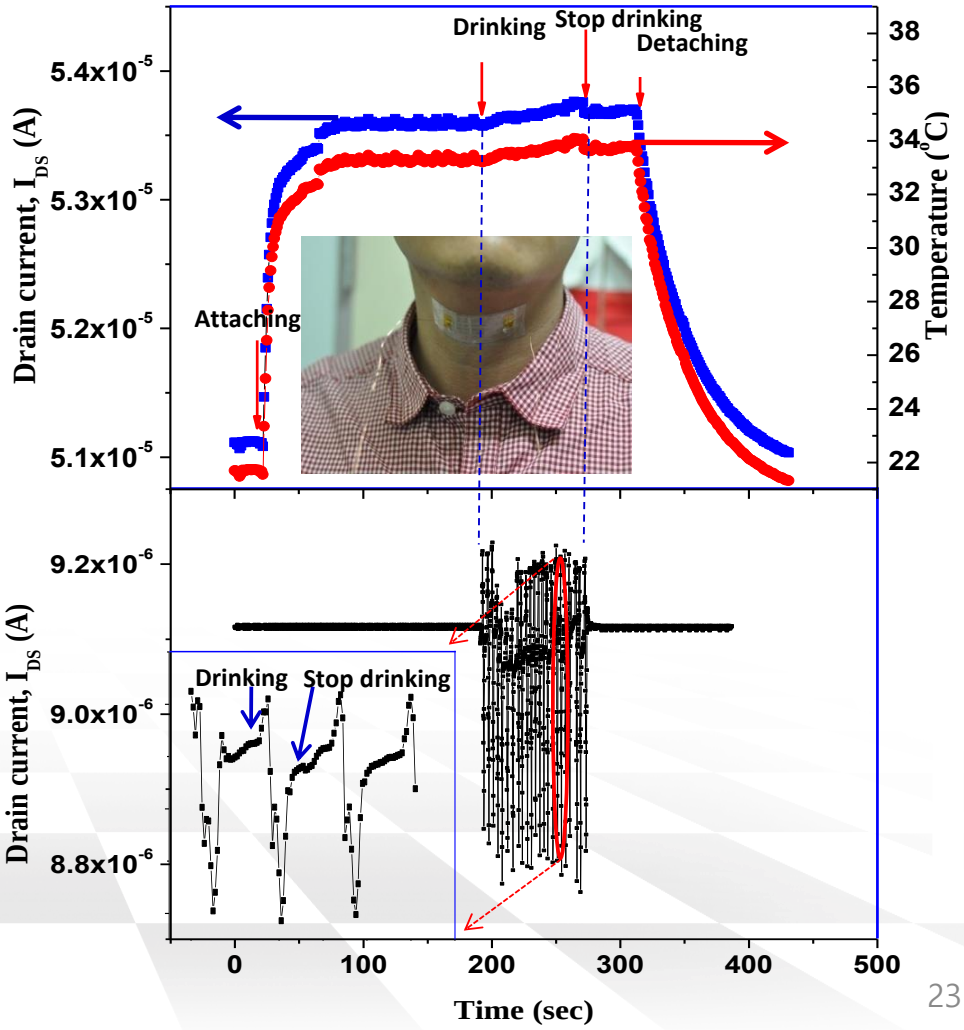


All-elastomeric transparent and stretchable multi-sensors for activity monitoring

Simultaneous monitoring skin temperature and muscle movement during drinking hot water

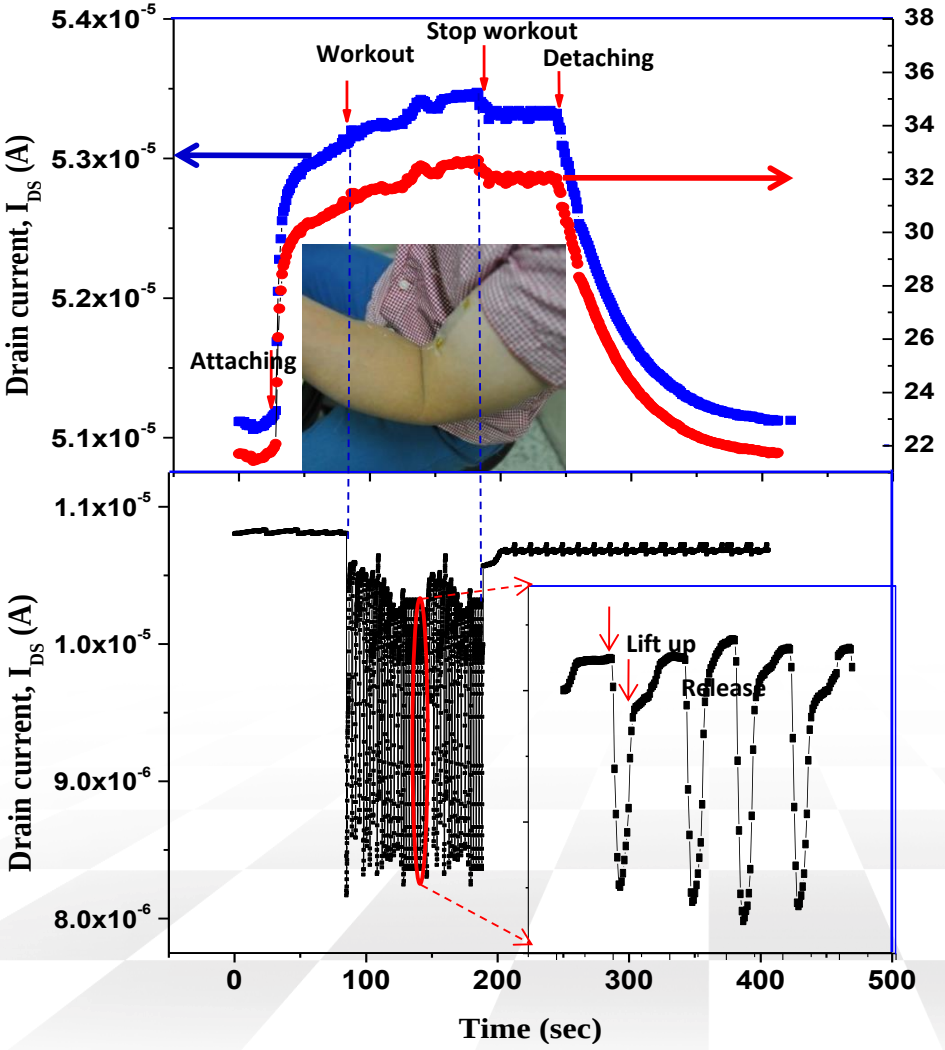


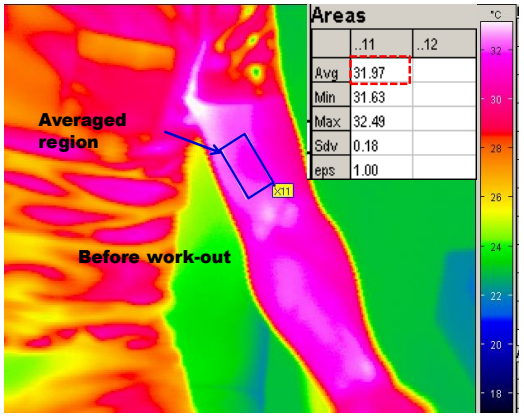


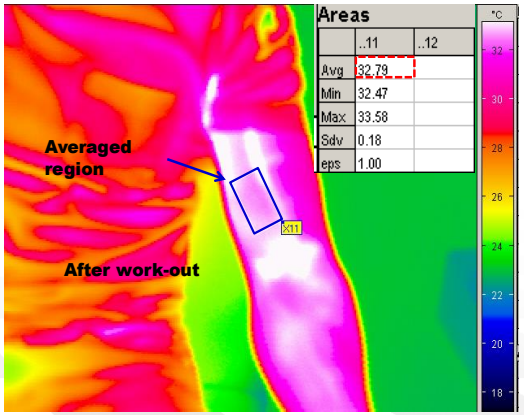


All-elastomeric transparent and stretchable multi-sensors for activity monitoring

Simultaneous monitoring skin temperature and muscle movement during workout

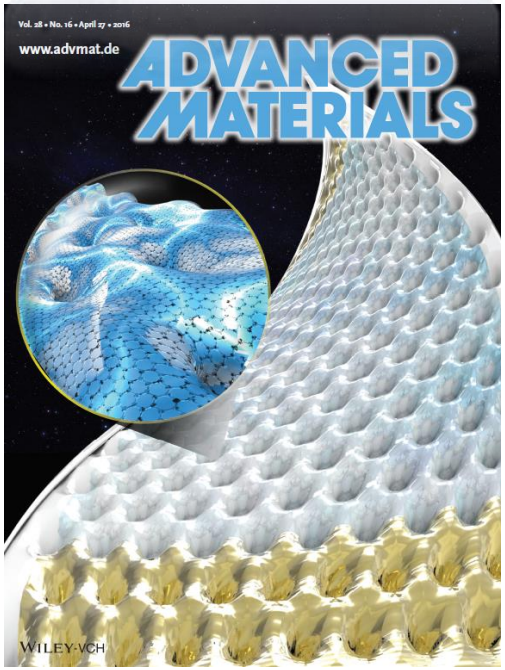


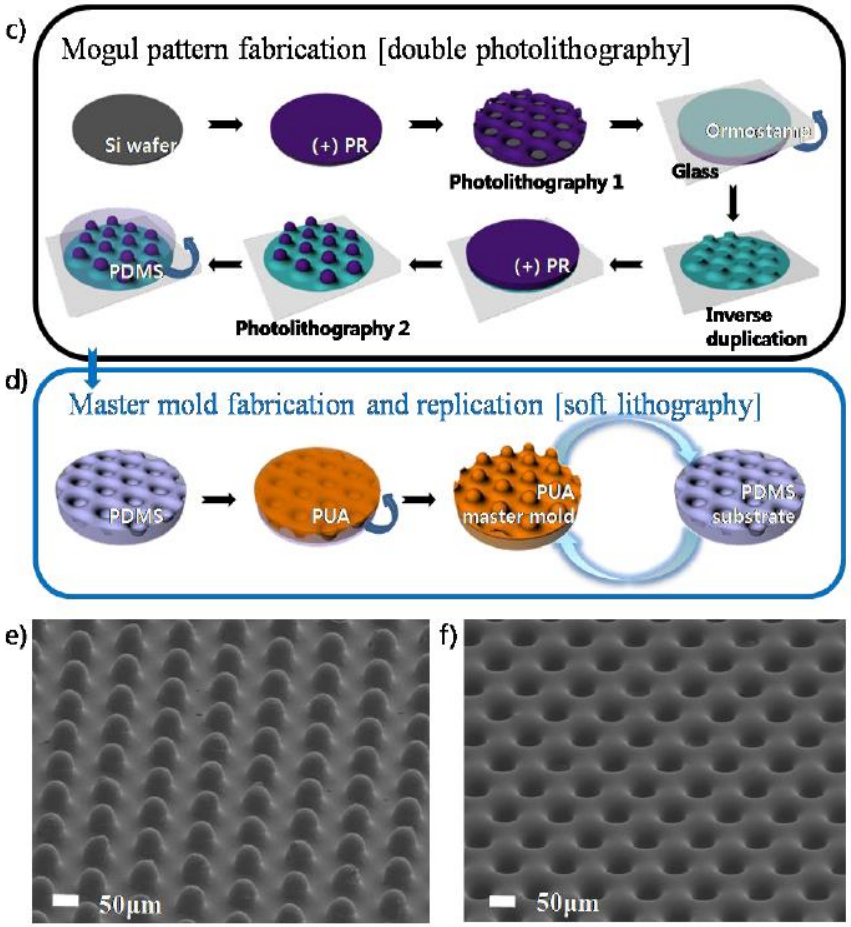




Approach 2: Mogul-patterned elastomeric substrate for stress-relieving

A versatile substrate for stretchable electronics

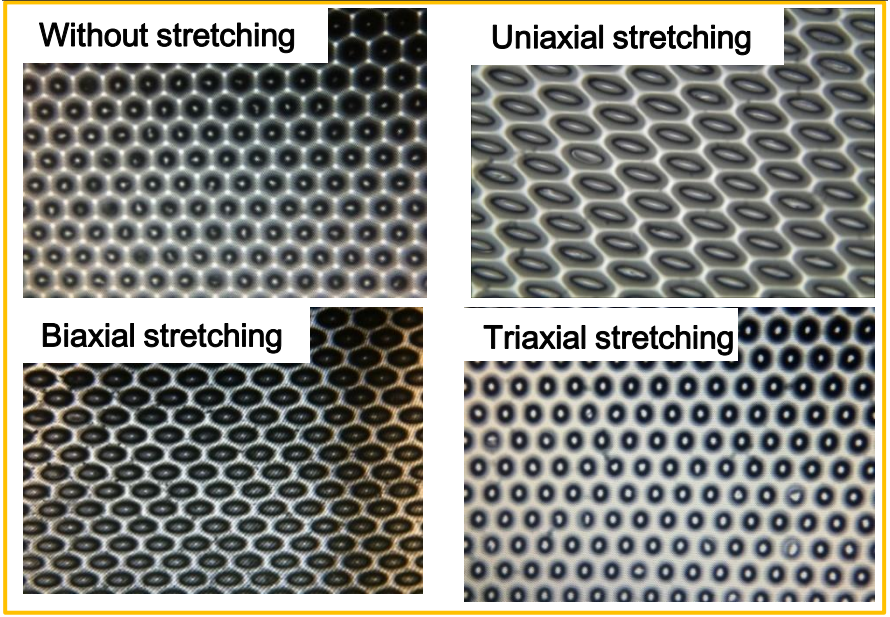




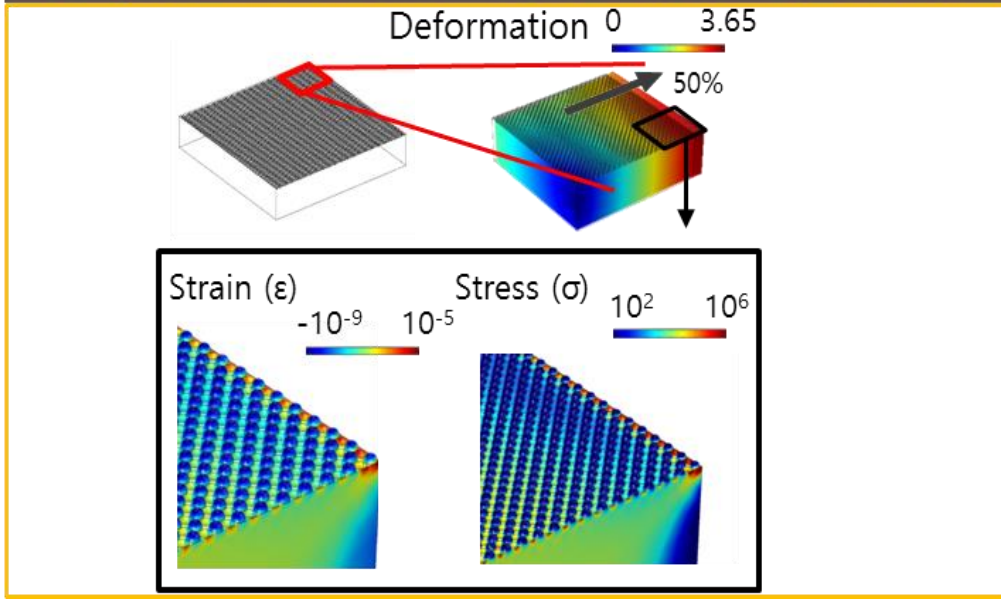
H.B. Lee et al., Adv. Mater., 28 (2016) 3086

Approach 2: Mogul-patterned elastomeric substrate for stress-relieving

Optical image depending on stretching direction



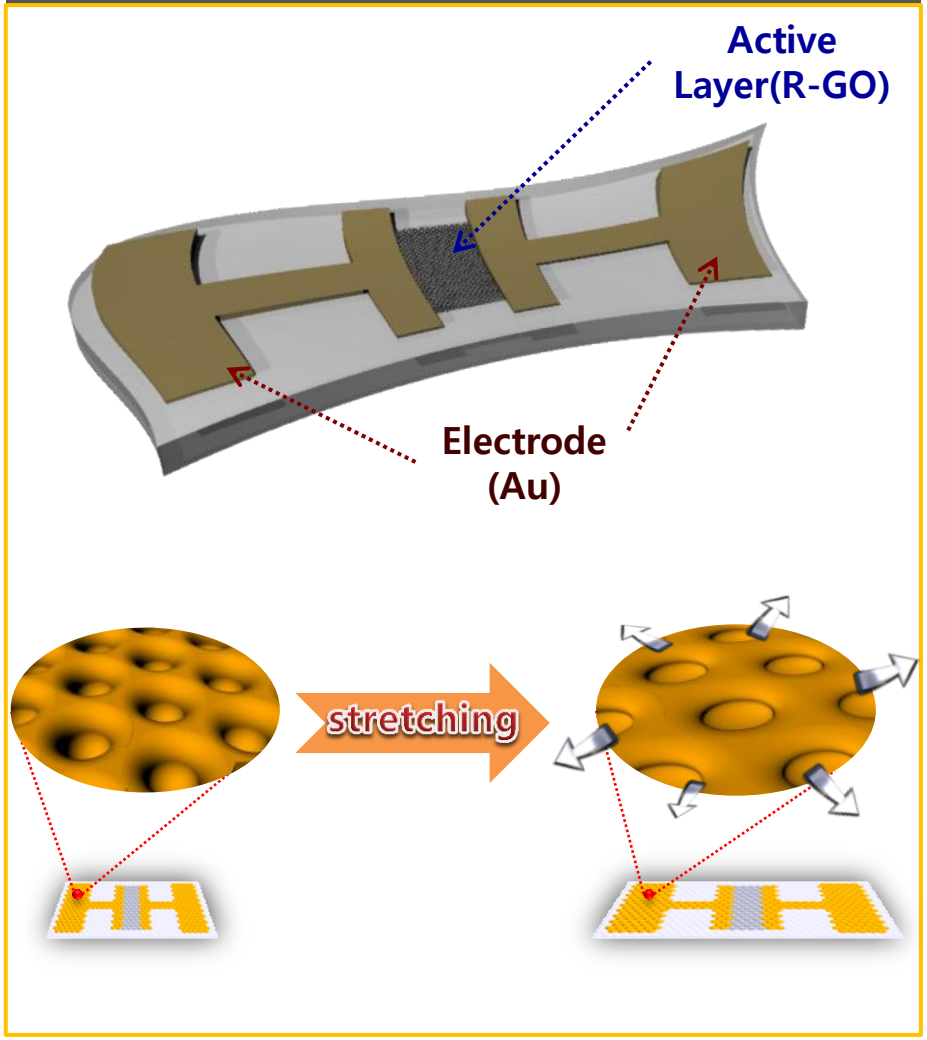
Computer simulation for deformation, strain, and stress



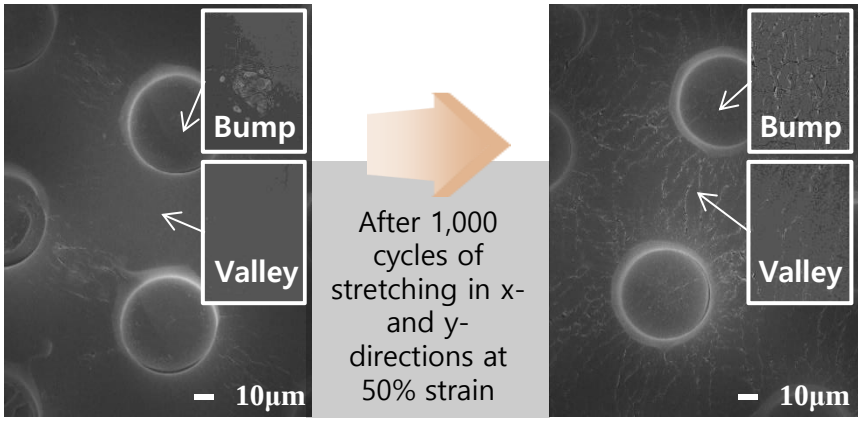
- **Omniaxially stretchable and stress of the layers are readily relived.** [7]
- **Conventional processing (CVD, PVD, ALD, spin coating, spray coating, printing etc) can be used to form the layers directly on the substrate**
- **Multi-layer stacking is possible by forming layers directly on the 3D micro-pattern**

Omniaxially stretchable R-GO gas sensor on mogul-patterned elastomeric substrate

Structure



Stability of Au electrode (70nm)

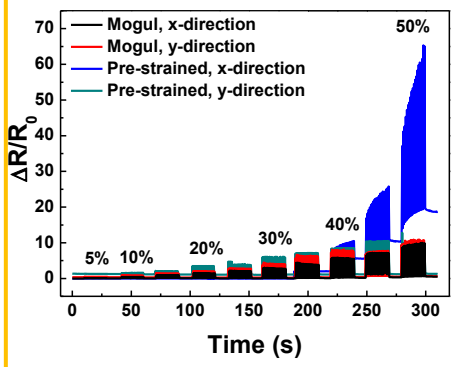


Omniaxially stretchable R-GO gas sensor on mogul-patterned elastomeric substrate

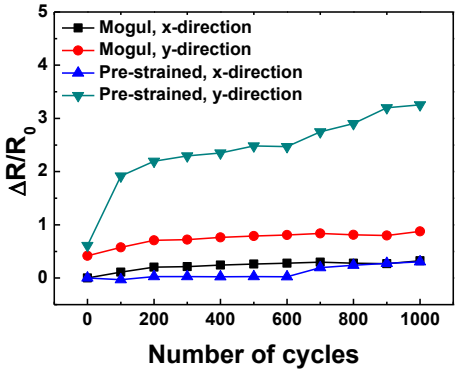
Investigatiion of electrical stability

Electrical stability of Au electrode

[Dynamic test]

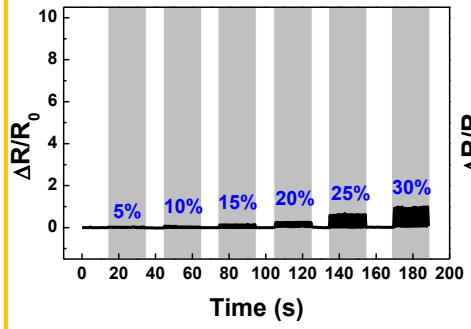


[Cyclic test]

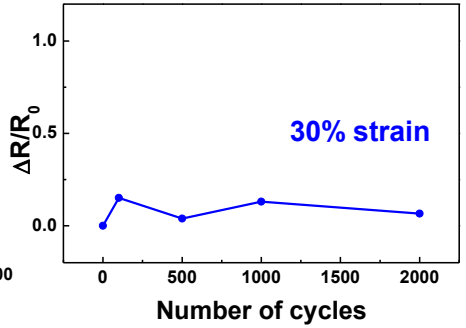


Electrical stability of chemical sensor

[Dynamic test]

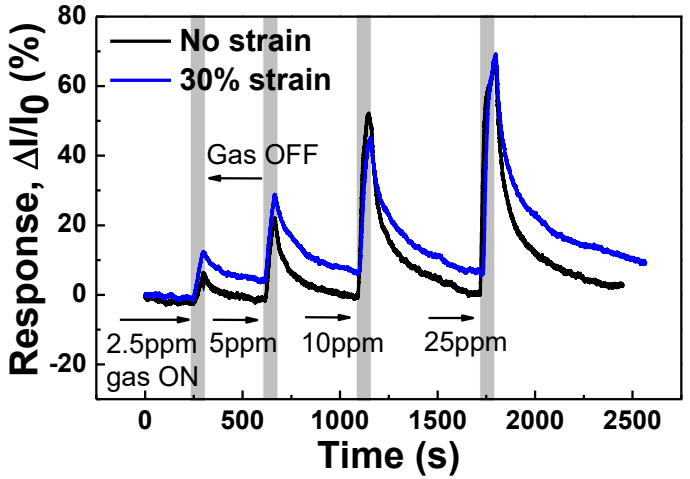


[Cyclic test]



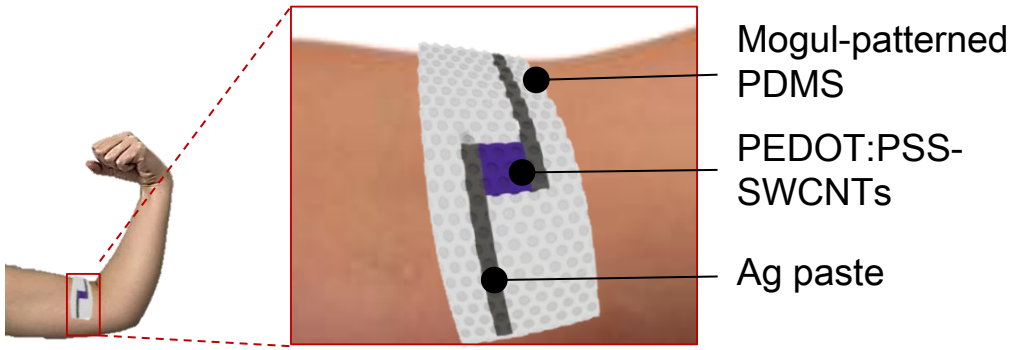
NO_2 sesning

Under stretched condition



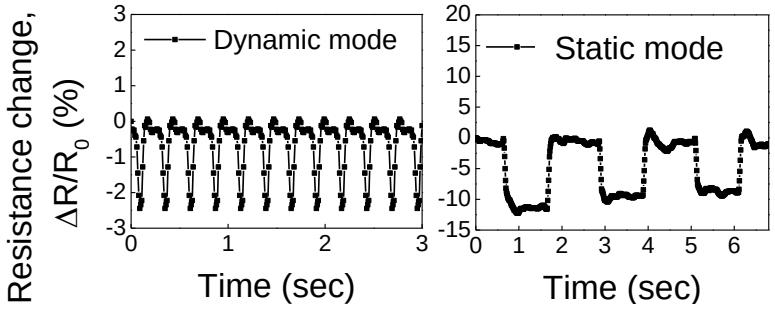
Omniaxially stretchable piezoresistive pressure sensor on mogul-patterned substrate

Device Structure

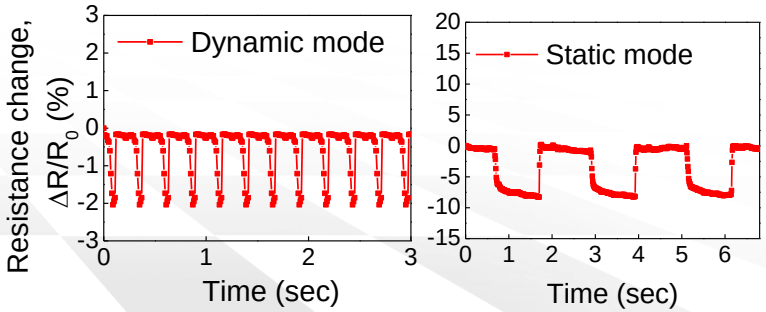


Pressure responsivity

✓ Unstretched state

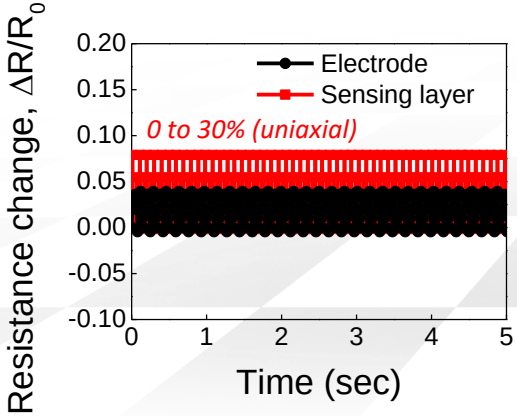


✓ Under 30% stretching state

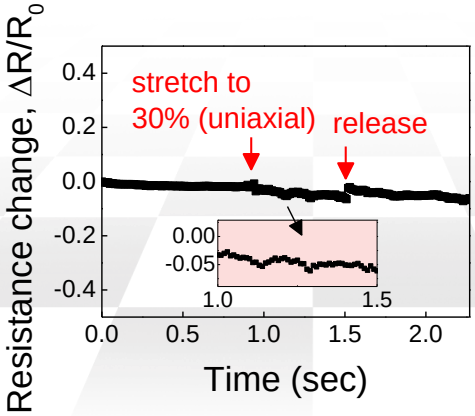


Stability under stretching

✓ Materials stability under stretching



✓ Device stability under stretching

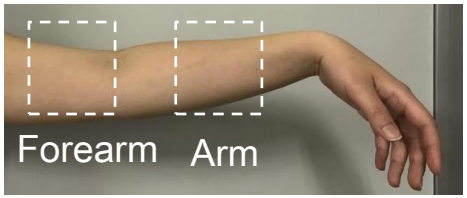


E. Roh et al., Adv. Mater., 29 (2017) 1703004

Omniaxially stretchable piezoresistive pressure sensor on mogul-patterned substrate

Demonstration : Tremor detection

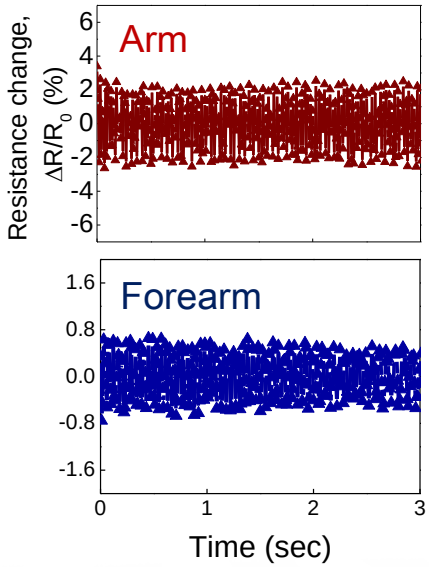
✓ Skin area



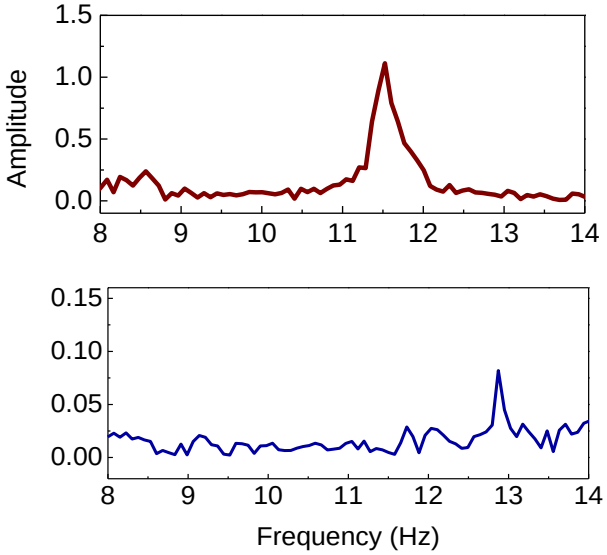
✓ Demonstration setup

Experimental mixer for vibration

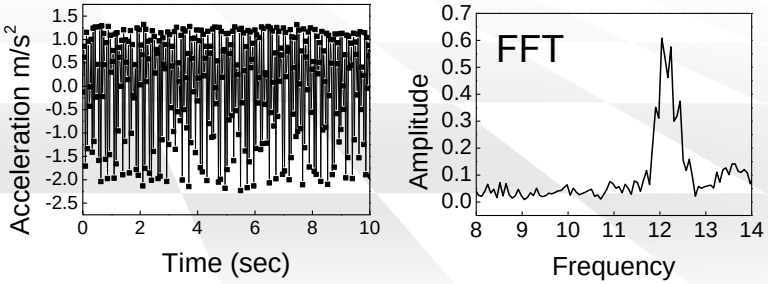
✓ Vibration detection using the device



✓ FFT (fast Fourier transform)



✓ Vibration detection using the accelerometer in smartphone

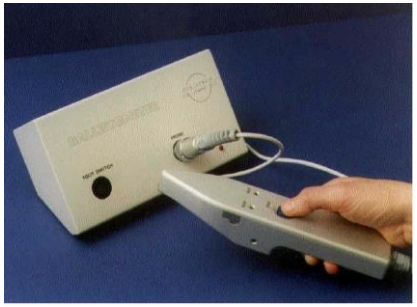


Omniaxially stretchable piezoresistive pressure sensor on mogul-patterned substrate

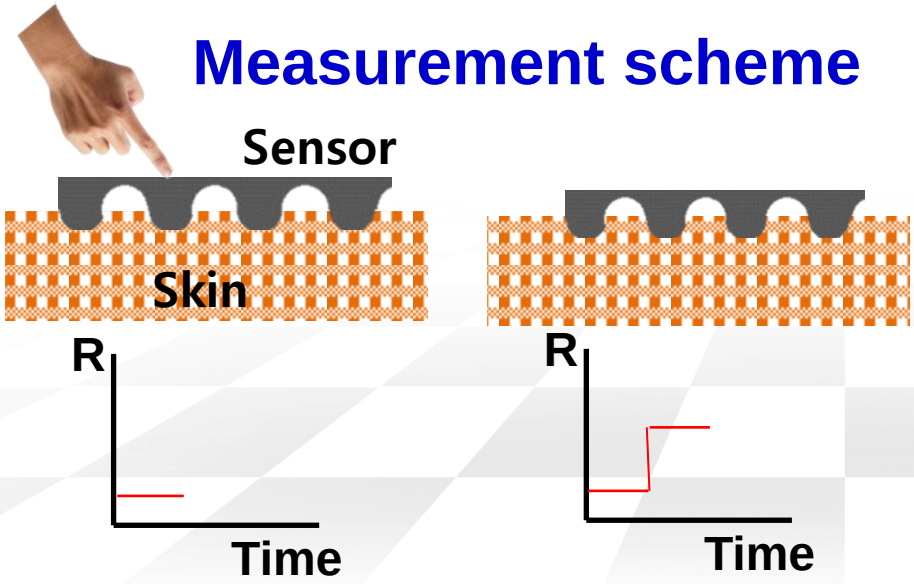
Skin elasticity evaluation

Cutometer

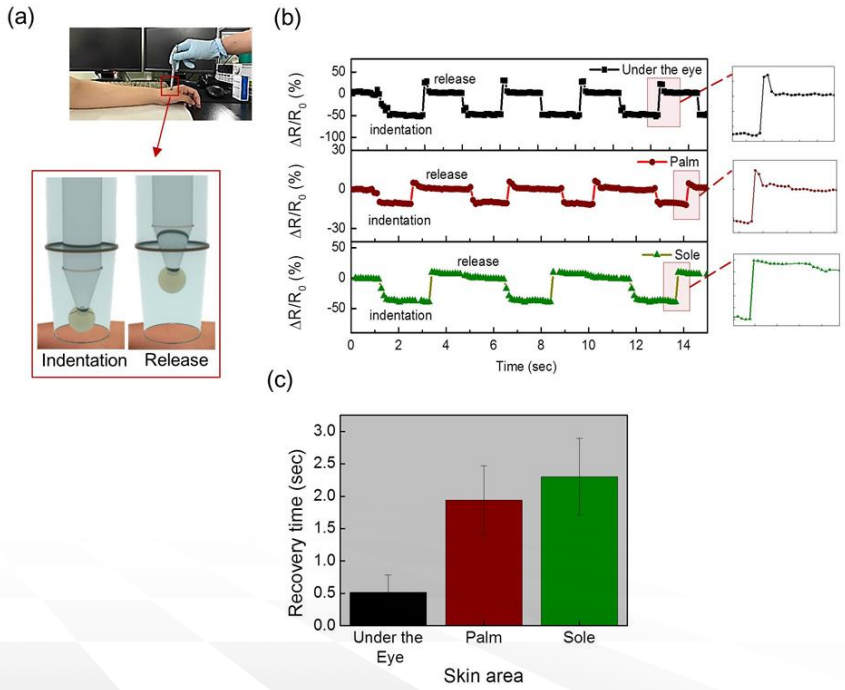
Ballistometer



Measurement scheme

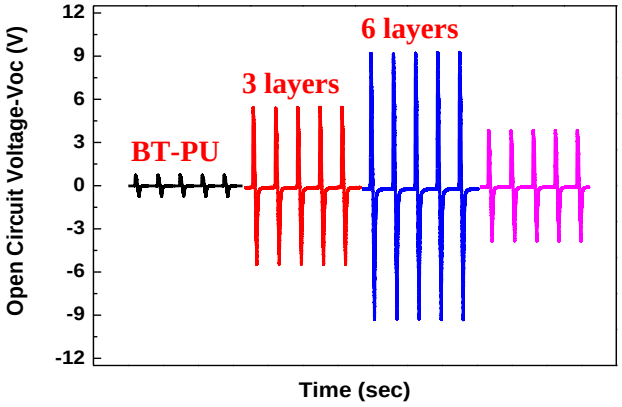


Relative skin elasticity



Omniaxially stretchable self-powered piezoelectric sensor

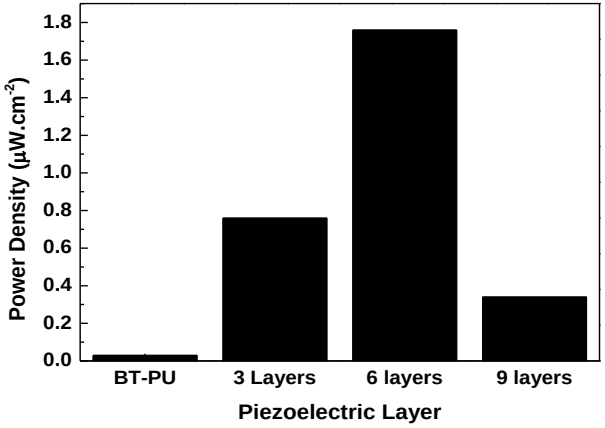
Output during stretching

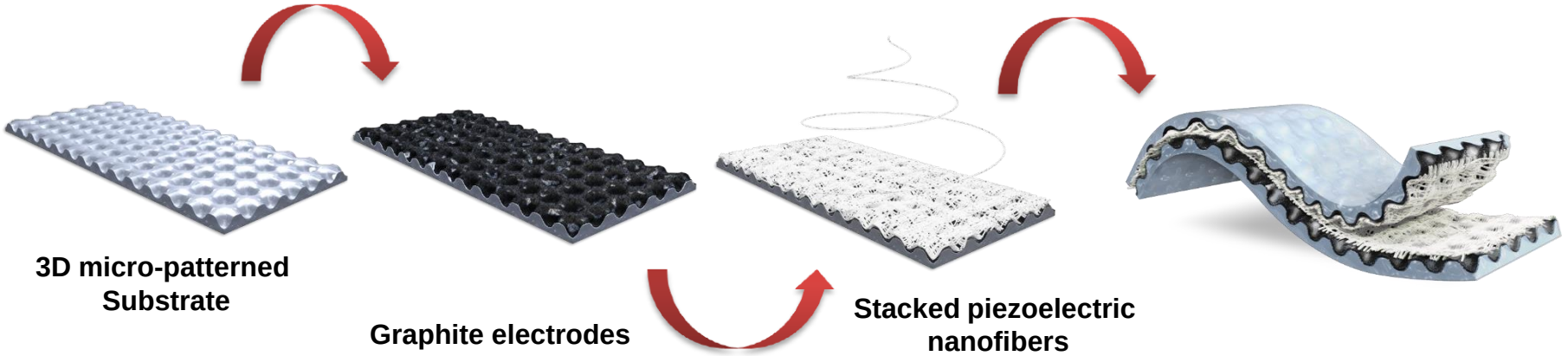


Key Issues for Stretchable Sensors

- Low stretchability
- Poor stability of electrode under stretching
- Complicated process
- High cost

Output power at 40% stretching

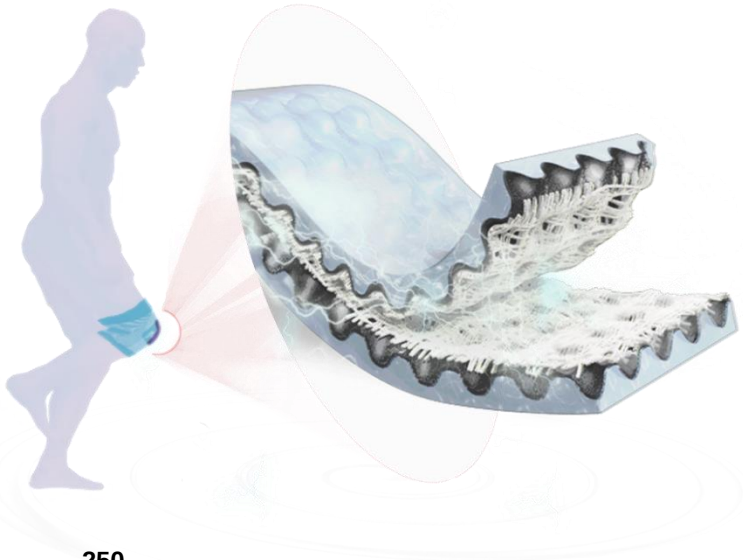


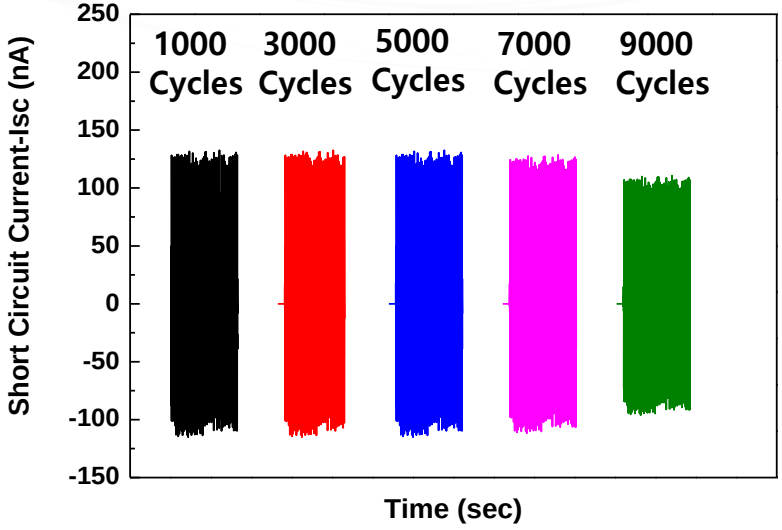


Stacked mat of BT NPs-PU nanocomposite and P(VDF-TrFE) nanofibers on stress-relieving mogul-patterned elastomeric substrate

S. Siddiqui et al., Adv. Energy. Mater. 8 (2018) 1701520

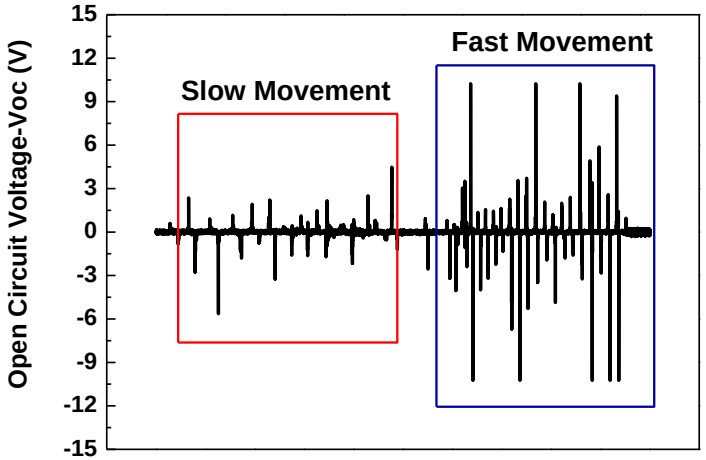
Omniaxially stretchable self-powered piezoelectric sensor



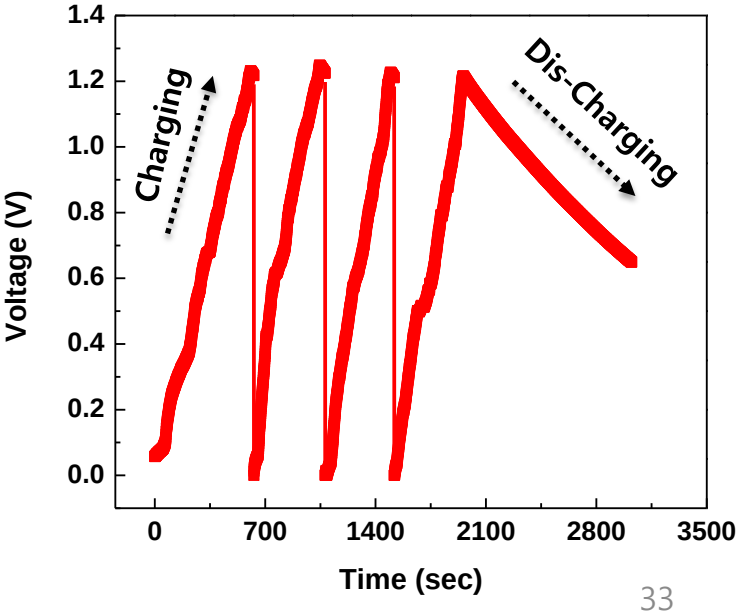


Stability at 30% stretching strain

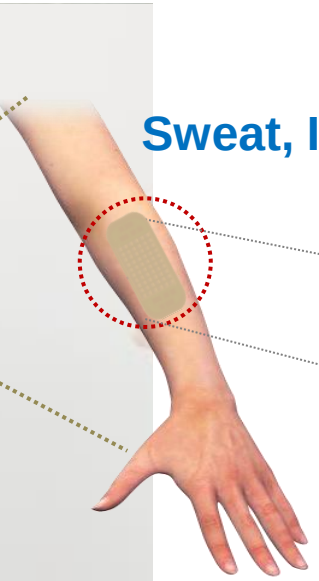
Walking Pattern Detection



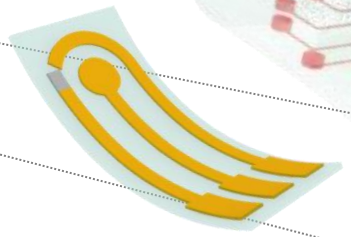
Charge Storage during walking

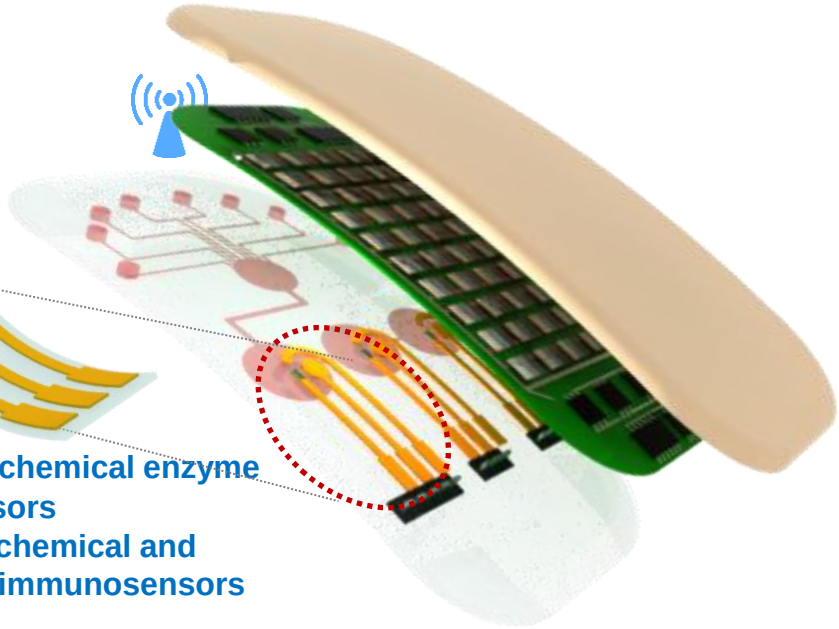


Disposable stretchable biosensor patches for *m*POCT

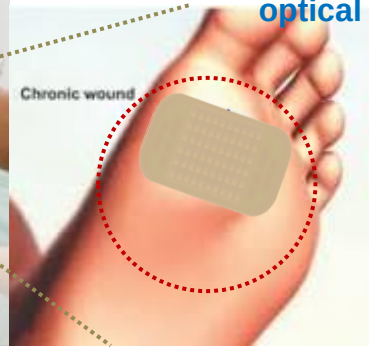


Sweat, ISF



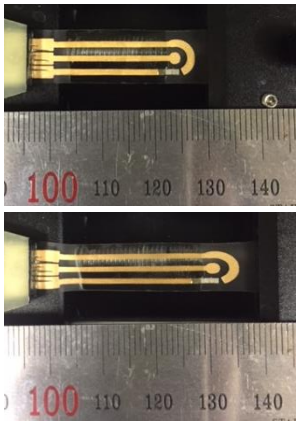


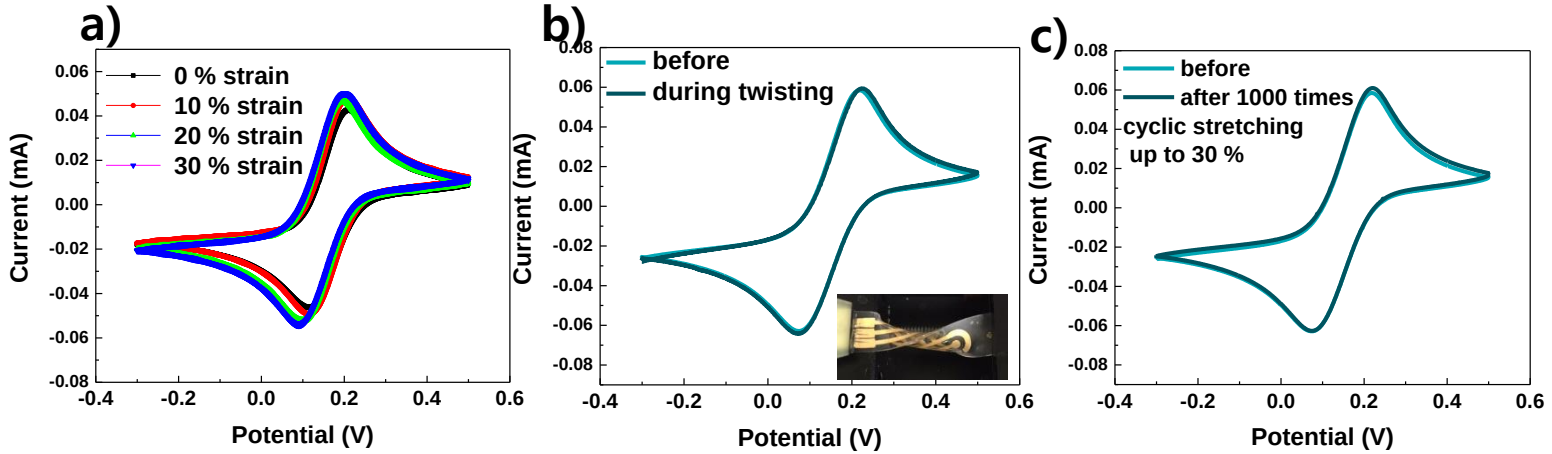
- **Electrochemical enzyme biosensors**
- **Electrochemical and optical immunosensors**



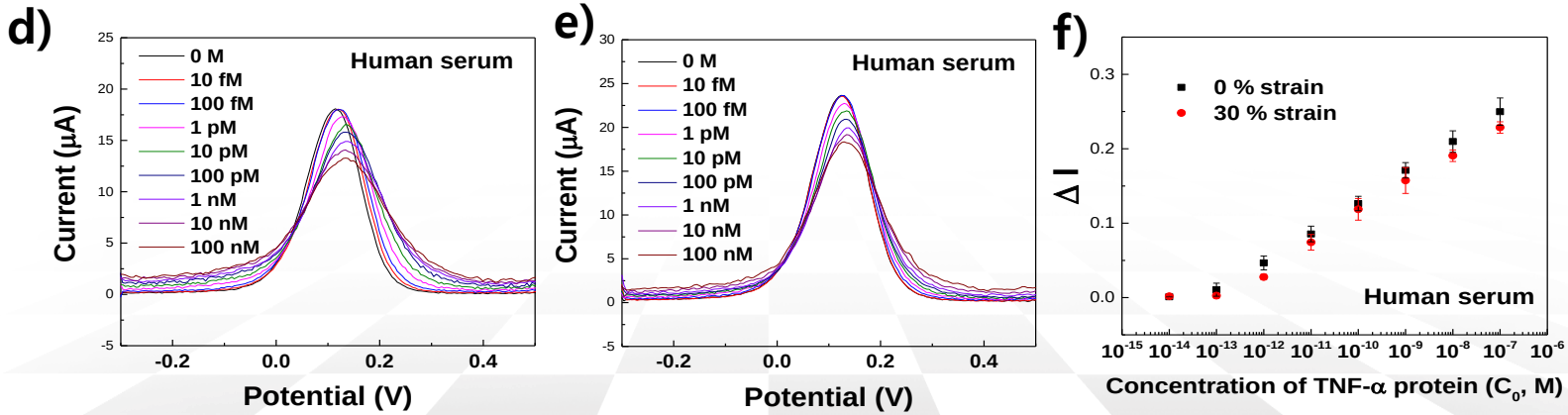
Wound fluid

Disposable stretchable label-free electrochemical immunosensor for wound monitoring





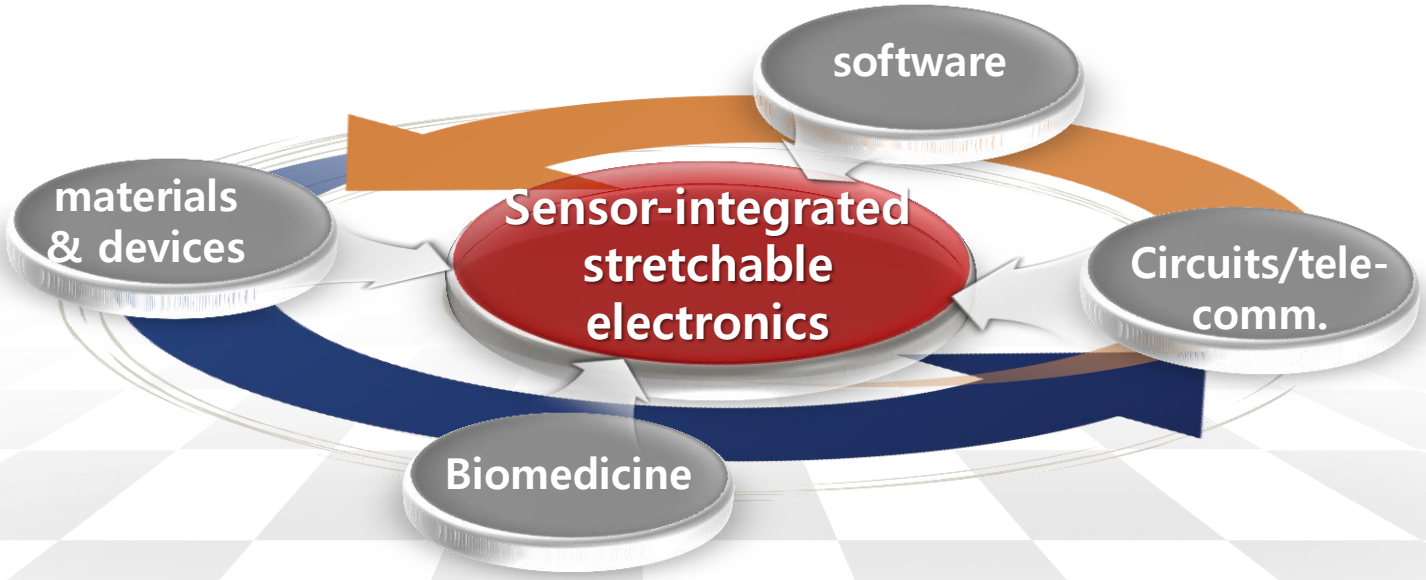
- **Cyclic voltammograms of a device under a) a non-stretched and 10, 20, and 30% stretched condition, b) without twisting and under twisting, and c) before cyclic stretching and after cyclic stretching 1000 times at 30% strain**



- **Differential pulse voltammograms of immunoreaction of TNF-α protein under 0 % (d) and 30 % (e) strain and calibration curve (f) in human serum**

Perspectives

- Efforts toward the improvement of stability and reliability of the sensing nano-materials are required for real applications.
- Sensor-integrated systems need to be developed by considering the specific needs and service scenario.
- Collaborative research is essential for success.



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