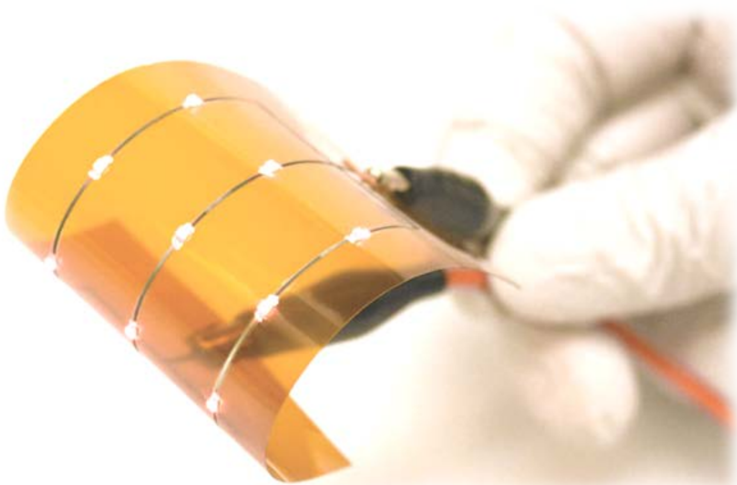
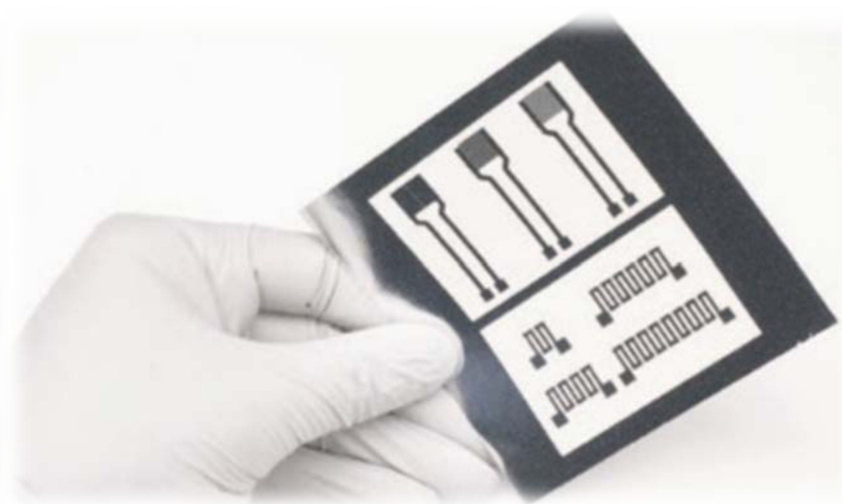
Laser processing and printing of multilayer films for inexpensive and flexible microsystems

Purdue University

Birck Nanotechnology Center

Rahim Rahimi



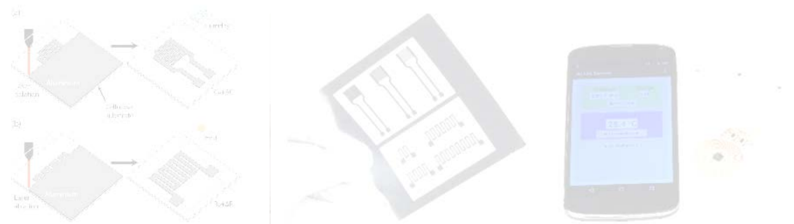


2/28/2018

Outline

- **Introduction**
- **Laser carbonization**
  - Laser-induced porous carbon
  - Functionalization

- **Laser ablation**
  - Selective etching of multilayer films
  - CO_2 vs Nd:YAG



- **Printed-electronics**
  - Health-care
  - Precision agriculture

- **Future work**

Flexible electronics on arbitrary substrates

Food packaging

Energy Harvesting

Health monitoring

Battery

Wound monitoring

Flexible displays

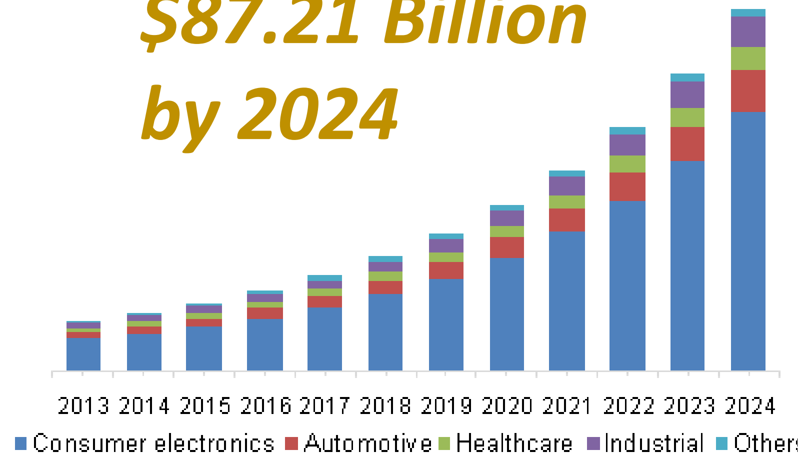
Robotics

Wearable devices

Global initiative with growing market

Flexible electronics market : $20.85 Billion in 2015

$87.21 Billion by 2024

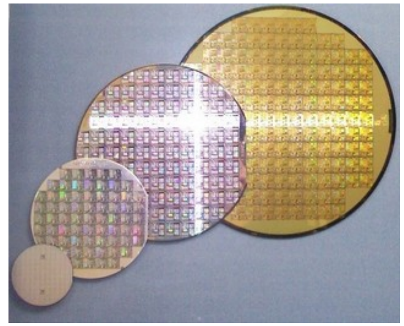


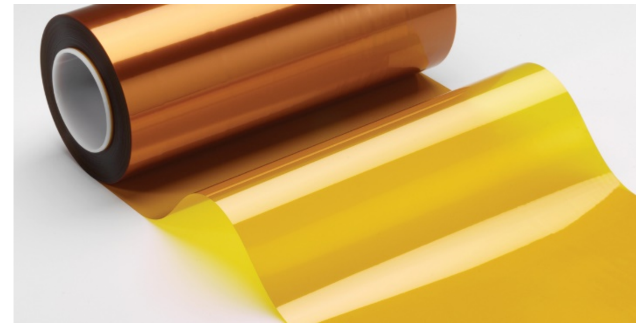
**IDTechEX research*

- Main ***manufacturing and material supplier*** companies for flexible and printed electronics.
- ***3,000 companies and organization*** work in this area and related areas

Materials

- Plastic substrates
  - Thermal budget
  - Chemical restrictions



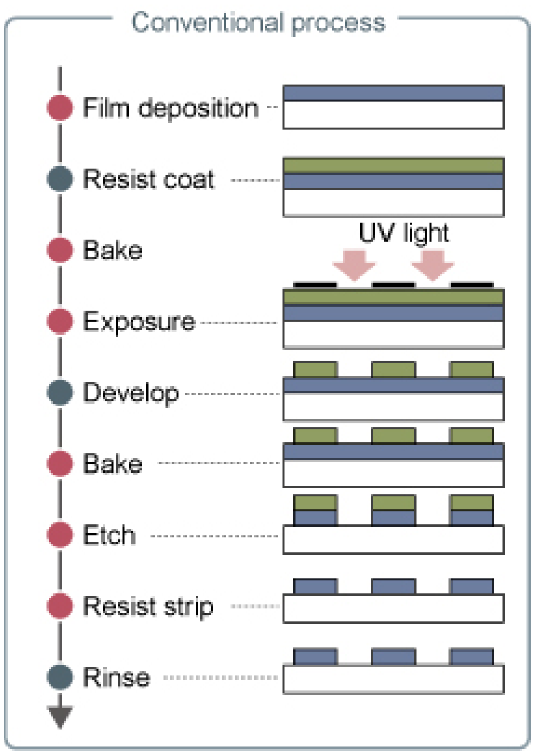


Material	Young's Modulus (Mpa)	Bio-compatible	Spin-coatable	Stretchable	Flexible	Hydrophilic	Glass transition temperature (°C)	WVP × 10^10 *
PDMS [a]	0.360-1.24	Yes	Yes	Yes	Yes	Yes	-125	72000
Poly(vinyl alcohol) (PVA) [b]	49.5±3.2	Yes	Yes	No	Yes	No	85	9.03-4190
Whatman filter paper [c]	460-1700	Yes	No	No	Yes	Yes	–	989-8140
PTFE [d]	500	Yes	Yes	No	Yes	Yes	130	8.45
polylactide (PLA)[e]	1030-4000	Yes	Yes	No	Yes	No	55-60	200**
PET [f]	2500	Yes	No	No	Yes	Yes	85	151
Polyimide [g]	3200	Yes	Yes	No	Yes	Yes	>400	417-5040
Parylene [h]	4000	Yes	No	No	Yes	Yes	80-100	9.25**

IEEE Review 2014

Fabrication methods

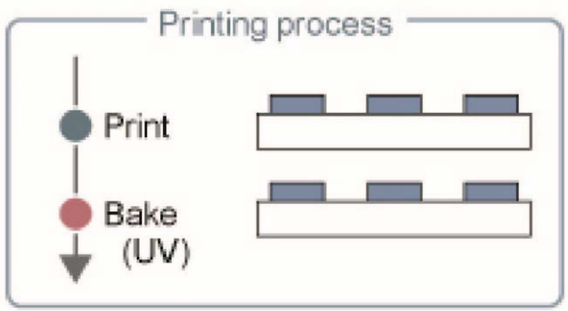
Conventional process

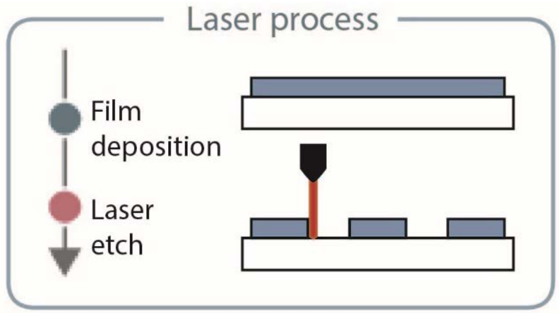


Direct process

Transfer process

Low-cost scalable manufacturing



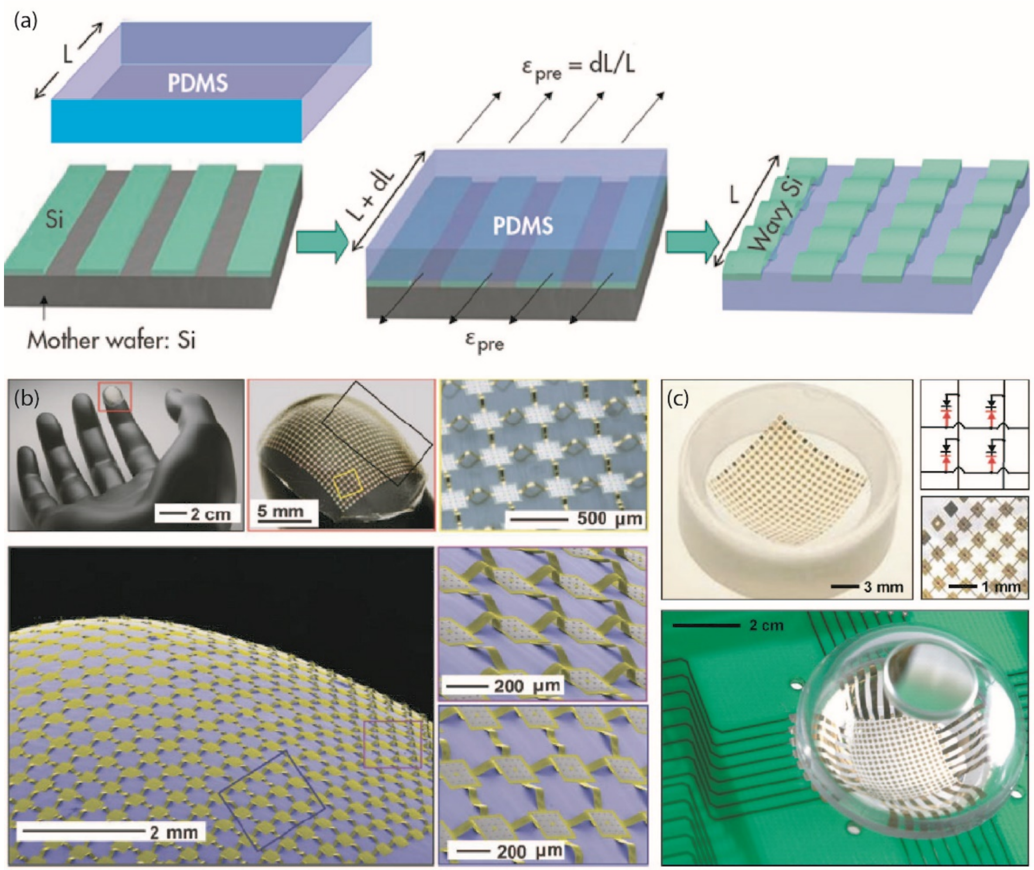


Inkjet printing

Laser-assisted deposition

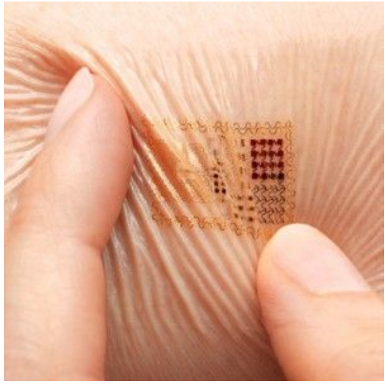
a. Environmentally friendly process
b. Increased production speed
c. Reduction in material loss
d. Lower manufacturing costs
e. Scalable manufacturing

Cleanroom assisted technology

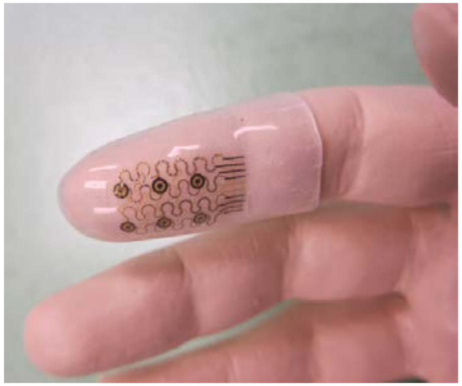


D.H. Kim *Adv. Mater.* (2008)

- Great performance
- Wide range of applications
- Complex, expensive, and time consuming steps
- Incompatibility with large scale manufacturing



D.H. Kim *Science*. (2011)



M. Ying *Nanotechnology*. (2012)

Low-cost and Disposable

Smart packaging

Food-waste

1/3 of food produced in world

1.3 billion tonnes

Worth **US$990** billion

Sources of food-waste

Improper **packaging**

'Best before' date has passed

Healthcare

Chronic wounds

6.5 Million infected in US

$25 billion to treat on an annual basis

Snowballing Threat

Aging population

Increasing numbers of **Obesity and diabetes**

Precision agriculture

Soil fertilizers

40-60% of crops are grown with the use of different fertilizers.

More than **50% synthetic** fertilizers.

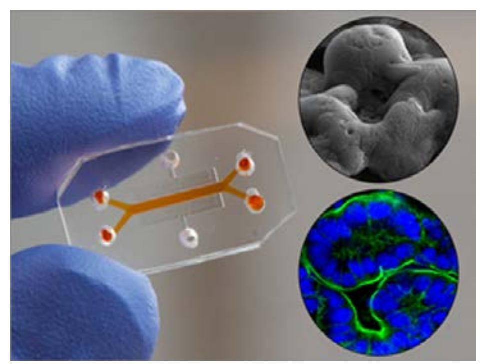
Problems of Overusing

Root Burn, Environmental Issues

Diminished Plant Health

Pests and Diseases

Biology/drug discovery



Antibiotic-resistance

2 Million infected in US

23,000 people die each year

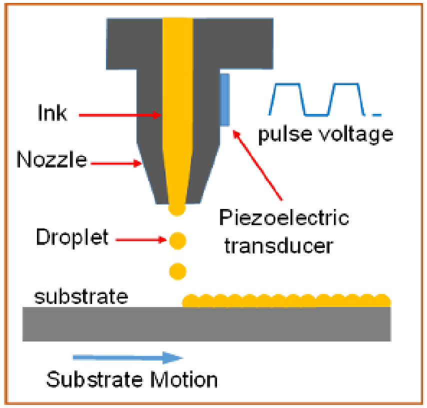
Drug Development

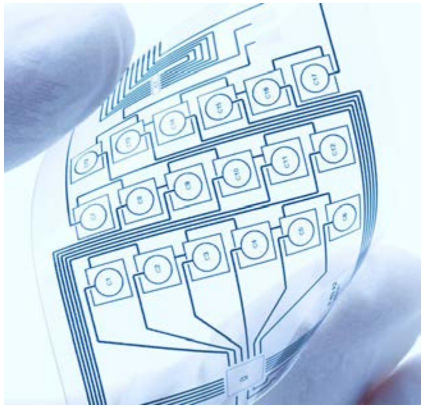
$2.6 Billion cost of developing a new drug

145% increase over the past decade

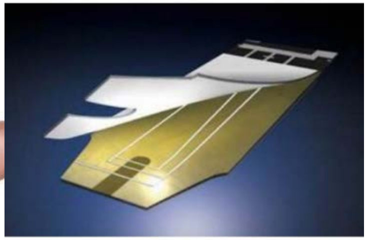
Printed Electronic

- Unique non-contact and mask-less patterning process extensive number of materials in a solution form:
  - Conductive polymers
  - Ionic conductors
  - CNT/graphene
  - Metallic nanoparticles
- Challenges:
  - High sintering temperatures at 200–350°C or required special functionalized substrates.
  - Nanoparticles agglomeration
  - Clogging of the equipment nozzle
  - Viscosity range of 8–15 cP
  - Conductive inks limited to costly noble metals e.g. silver and gold





Laser-Enabled Manufacturing



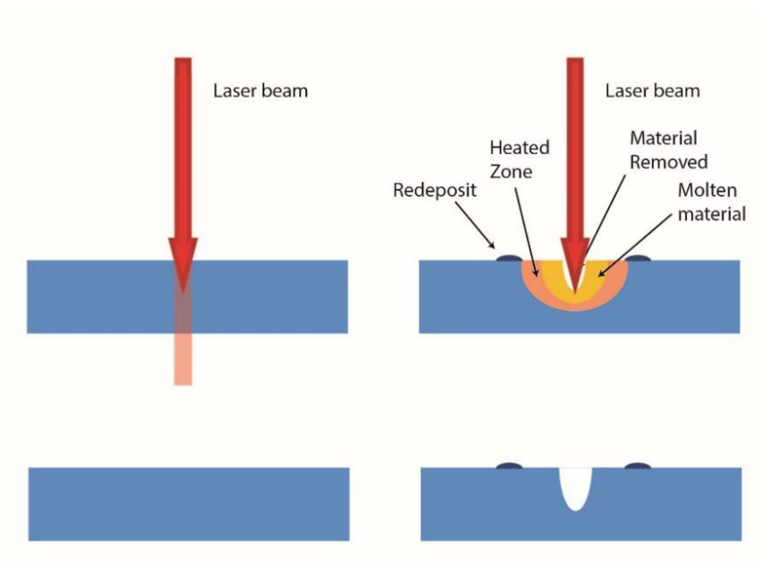
Global laser processing market size was valued at 10.36 billion USD in 2015

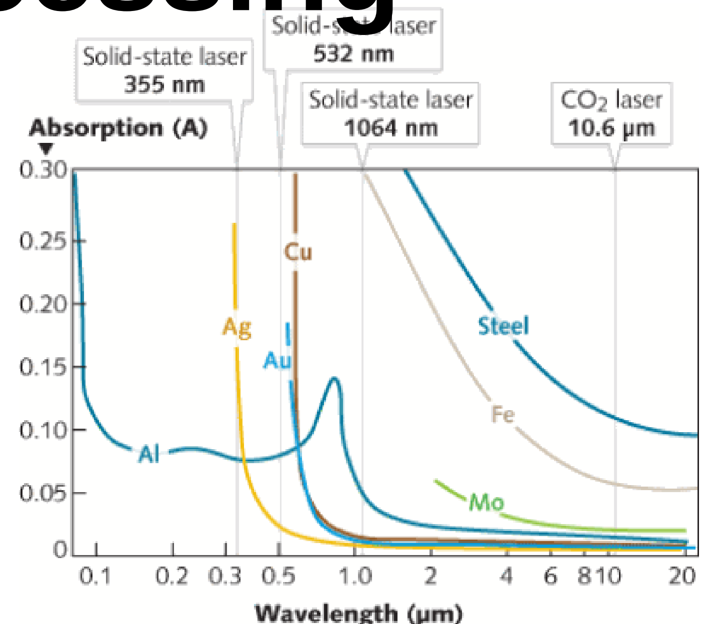
CO_2 and Nd:YAG **$60,000**

30W CO_2 Laser Engraver/cutter **$339.99**

2W Miniature Laser Engraving Machine **$62.99**

Laser material processing

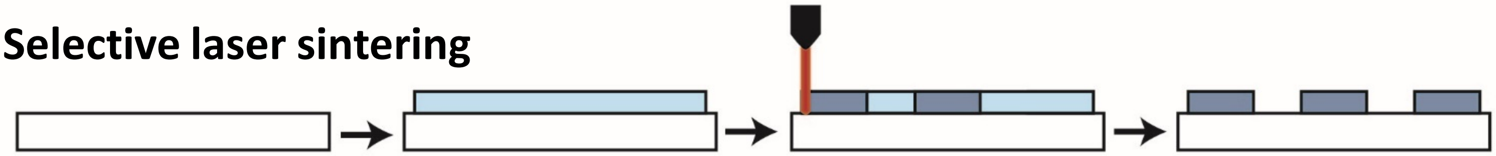


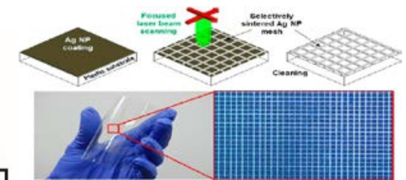


- Monochromatic light through an optical amplification process
- Commercial systems
  - **10.6 μm CO_2 laser** (typical powers of 30–150 W) suitable for cutting polymers
  - **1.06 μm Nd:YAG fiber laser** (typical powers of about 40-90 W)
- Required ablation energy densities:
  - 10 to100 J/cm^2 for metals
  - 0.1 to10 J/cm^2 for organic materials

Flexible electronics

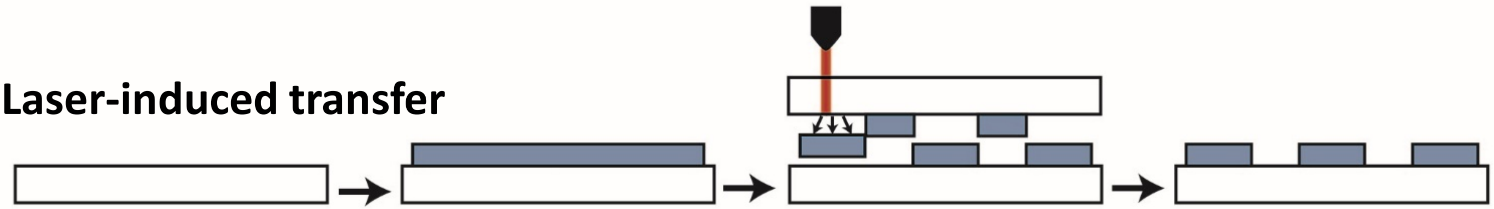
Selective laser sintering

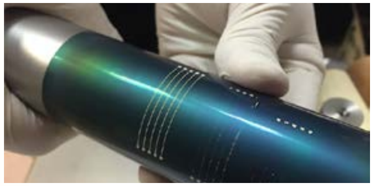




Hong, Sukjoon, et al. ACS nano 7.6 (2013)

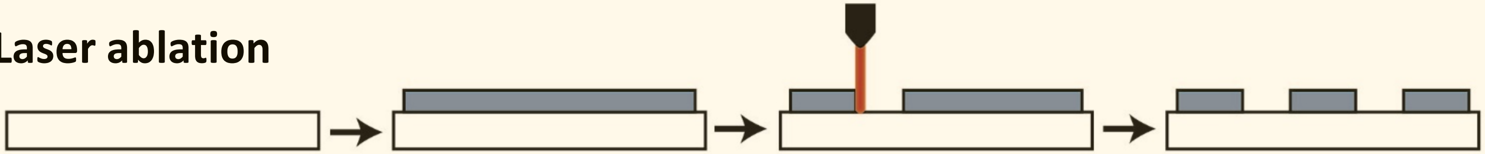
Laser-induced transfer

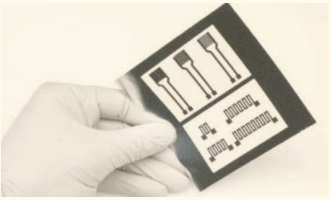




Y. Chen, et al. Physics Procedia (2016)

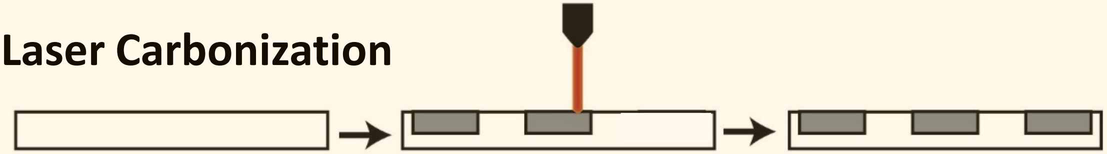
Laser ablation

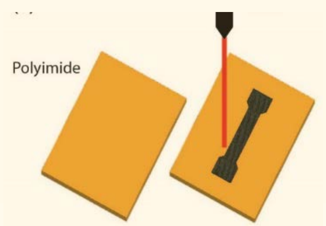




R. Rahimi, et al. ACS applied materials

Laser Carbonization





R. Rahimi, et al. ACS applied materials (2015)

Outline

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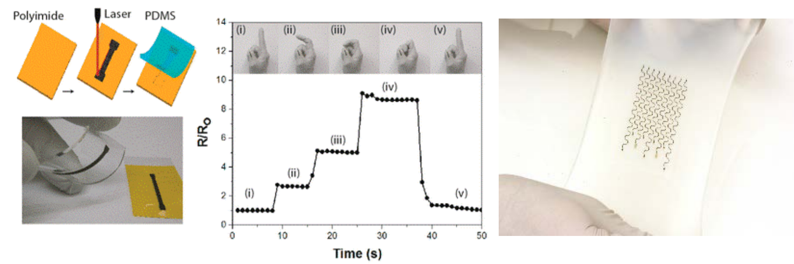
  - Laser-induced porous carbon
  - Functionalization



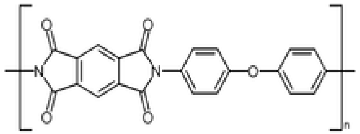
- Laser ablation
  - Selective etching of multilayer films
  - CO_2 vs Nd:YAG

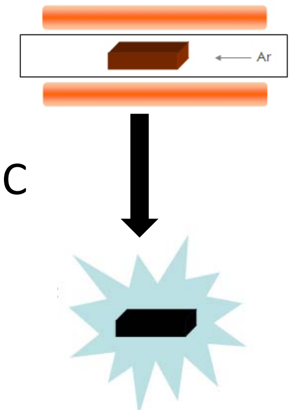
- Printed-electronics
  - Health-care
  - Precision agriculture

- Future work

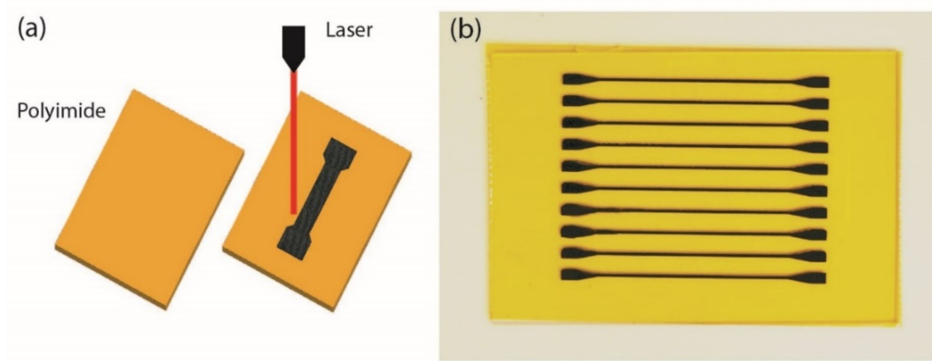
Laser carbonization

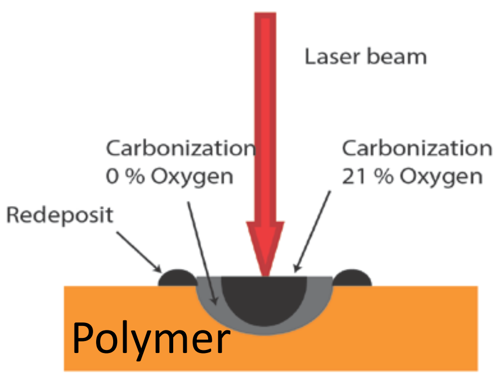
Polyimide (Kapton)



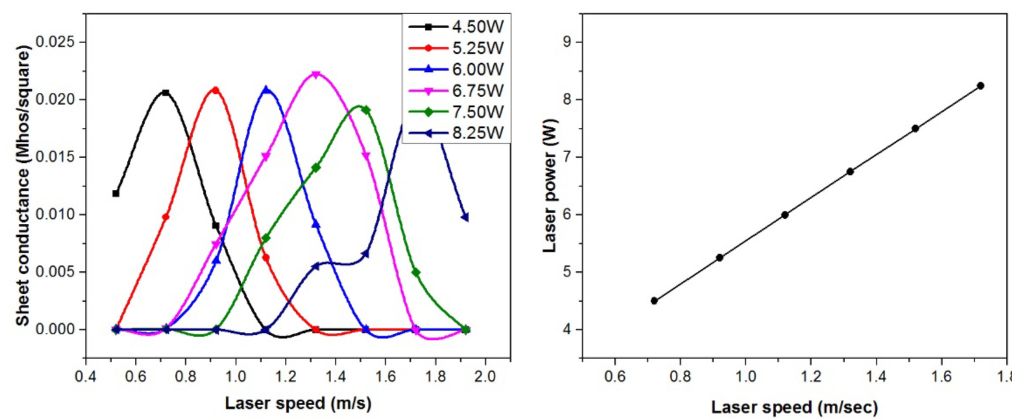


Pyrolysis
400–1800°C
3–7 hours





Localized heating using laser



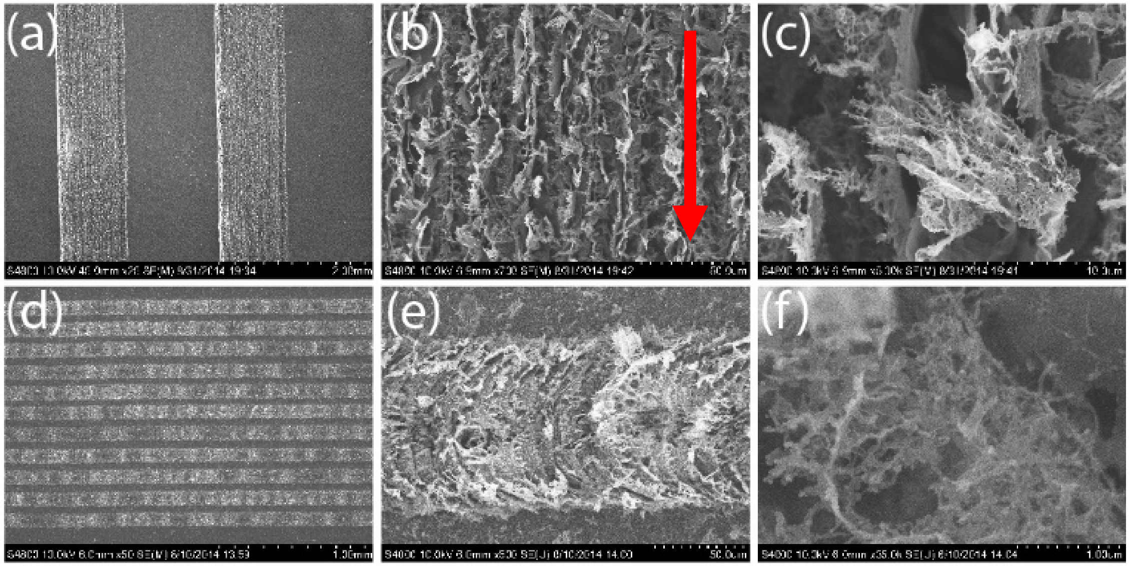
Laser process yields porous carbon

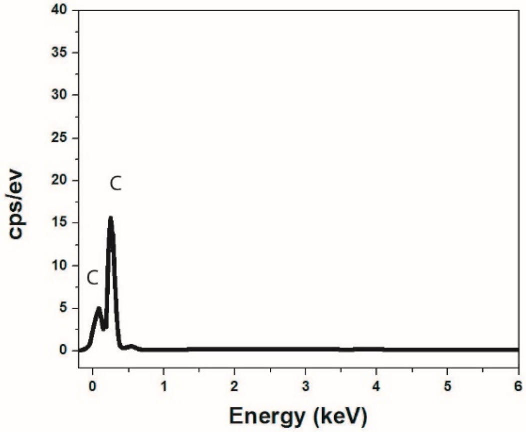
- Maximum conductivity of ~0.02Mhos/sq with 6.75 W and 1.3 m/sec
- Optimal energy density (6200 J/m^2)

R. Rahimi, et al. ACS applied materials (2015)

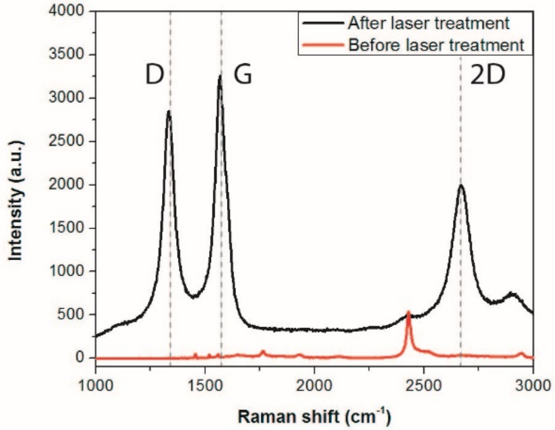
Laser carbonization

- Smallest features
  - (width × pitch = 90 µm × 120 µm) achievable with our laser system
- Partially oriented carbon flakes
  - ~70 nm wide
  - ~2 µm length
- EDX spectra
  - 0.25 keV corresponding to high concentration of carbon material
- Raman spectra
  - G-band lattice stretching in C−C
  - D-band disorder and defects in the graphitic lattice
  - I_D/I_G(~0.8) to quantify the amount of defects in the graphitic material
  - 2D-band layers of carbon
  - ($I_{2D}/I_G \approx 0.7$) mostly three carbon layers





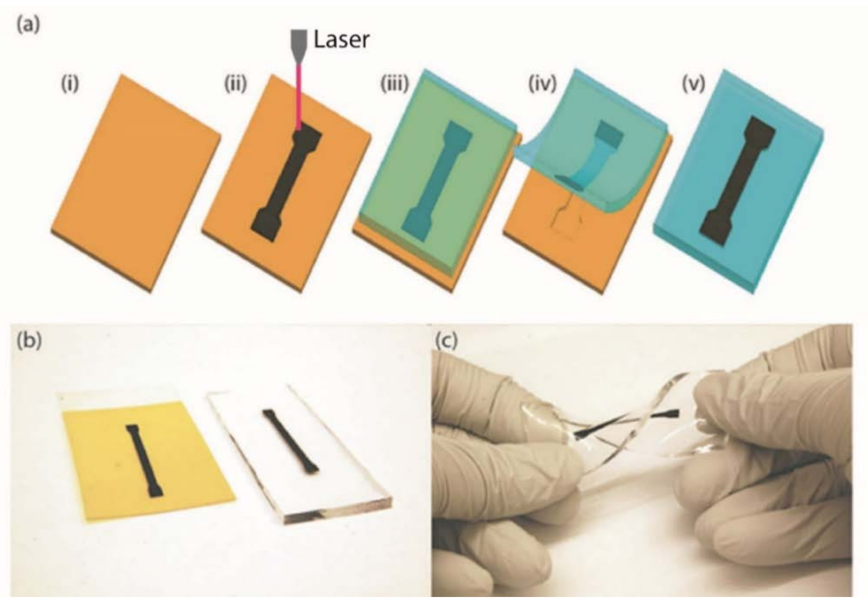
EDX spectra

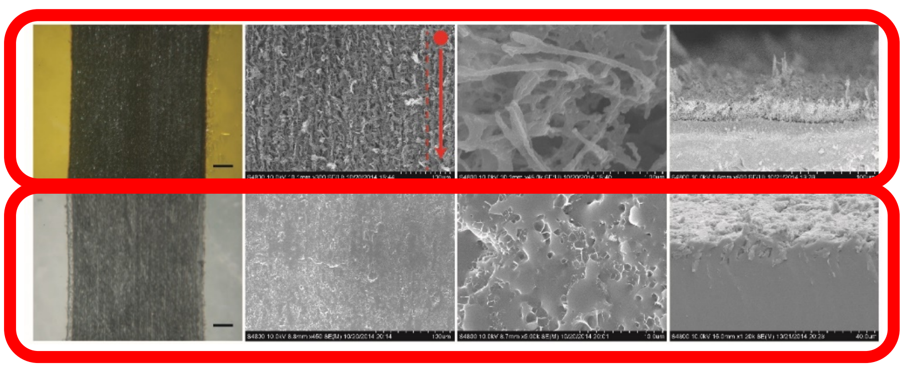


Raman spectra

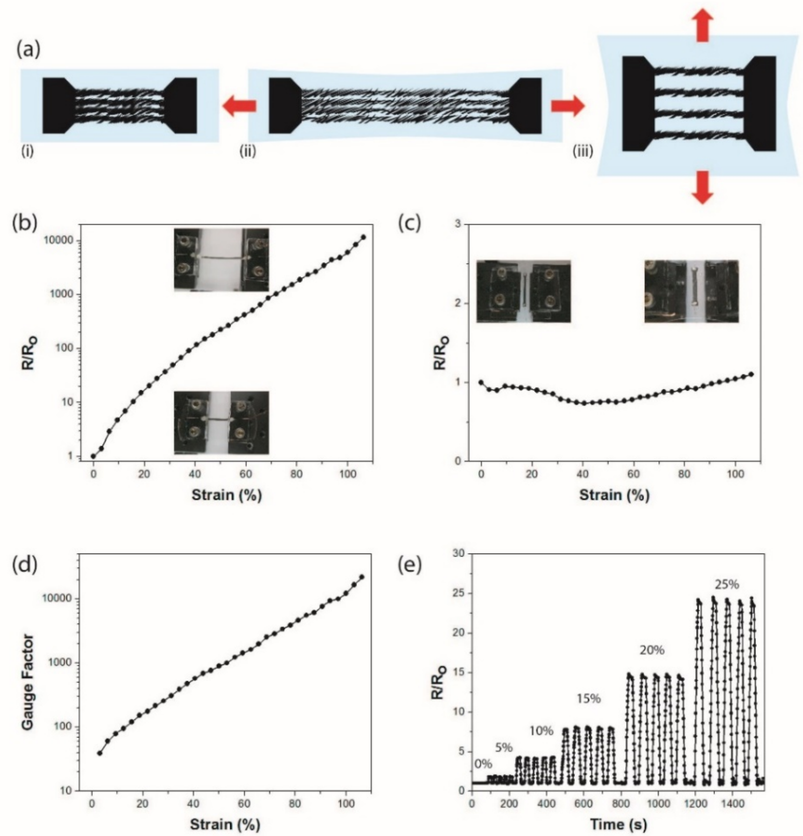
R. Rahimi, et al. MEMS (2015)

Piezoresistive strain sensor





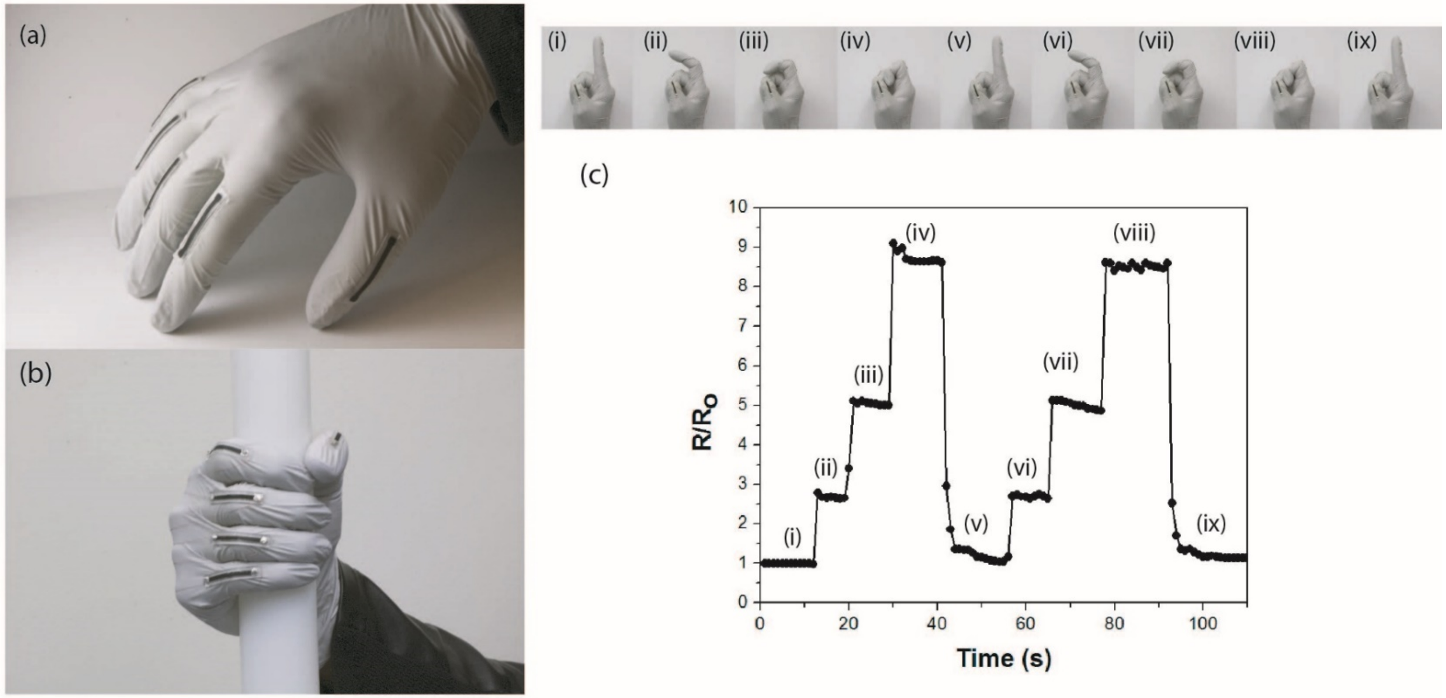
Transfer to PDMS



- Anisotropic orientation
- Unidirectional sensitivity
- (>20 MΩ) 100% longitudinal strain
- Gauge factor of 20,000 at 100% strain

R. Rahimi, et al. ACS applied materials (2015)

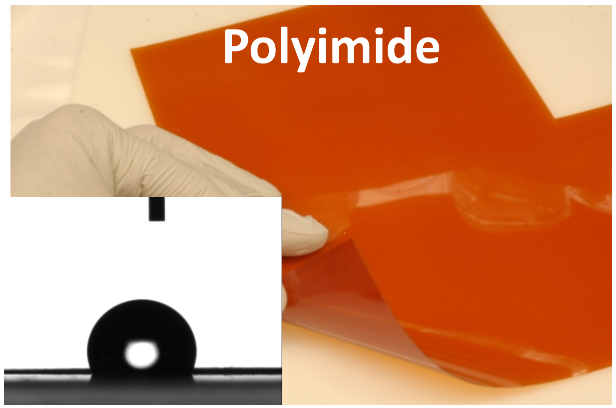
Finger motion detection



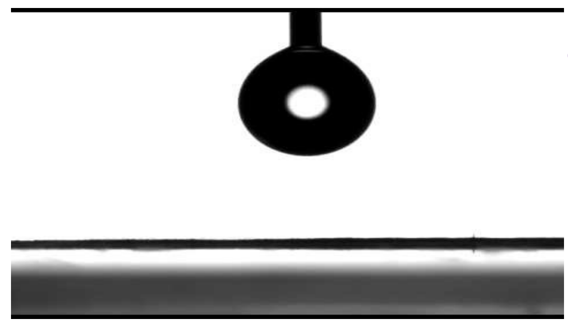
- Sensors where attached to a latex glove using a cyanoacrylate adhesive (Loctite 420)
  - The bending angle of middle phalangeal joint was motion detection with stretchable carbon traces
  - R/Ro ≈ 9 for a completely bent joint

R. Rahimi, et al. ACS applied materials (2015)

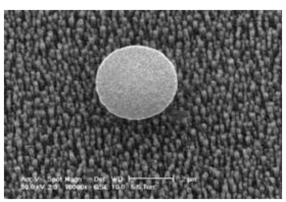
Surface wettability



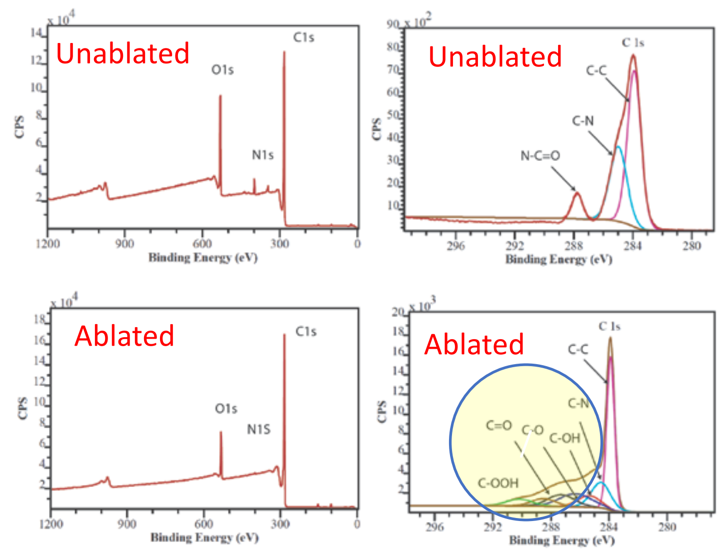
Laser carbonized Polyimide



Superhydrophilic



Lau, et al., *Nano Letters*, 2003

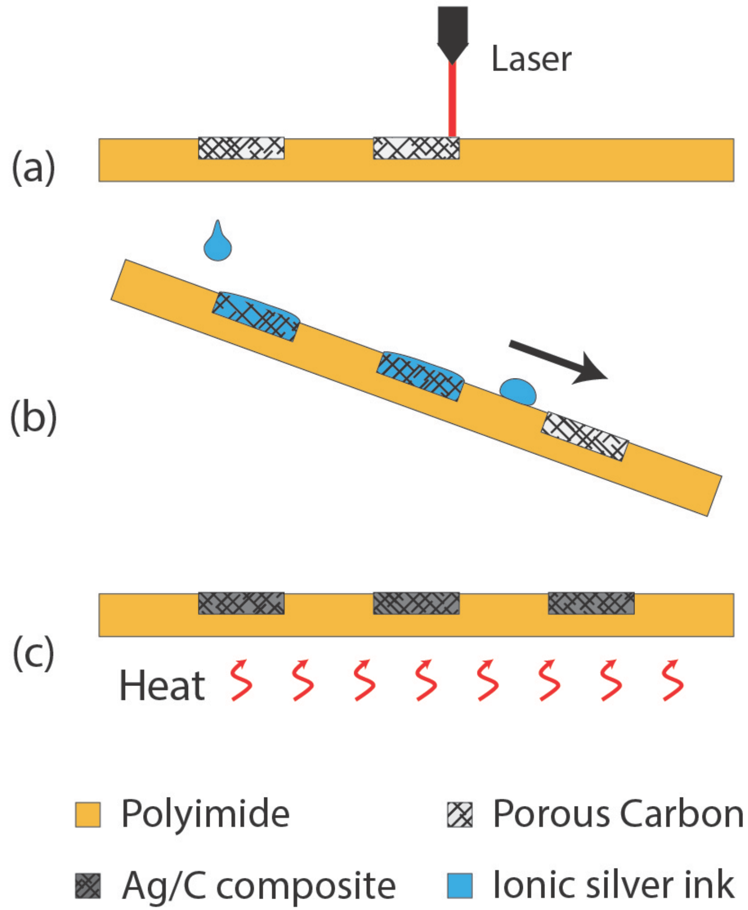


	Unablated area	Ablated area
O/C	0.29	0.09
N/C	0.11	0.02

Decrease in O/C and N/C after ablation

R. Rahimi, et al. ACS applied materials (2016)

Carbon and Silver composite



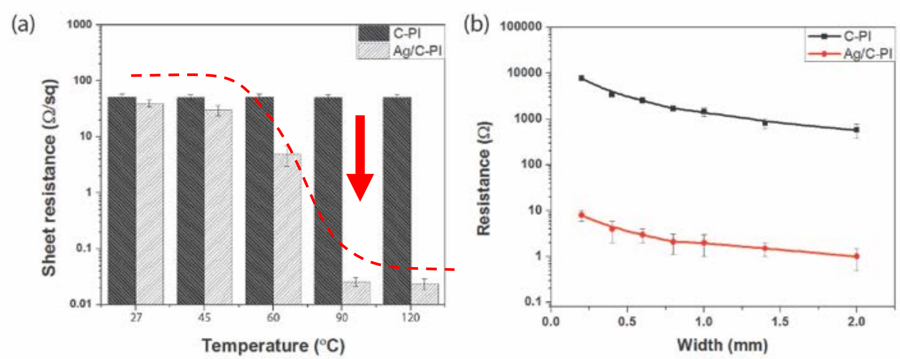
Particle-free
Ionic silver ink
30 wt % silver

Ammonium hydroxide NH_4OH/H_2O
+
Silver acetate $AgC_2H_3O_2$
+
Formic acid CH_2O_2

$$NH_4OH/H_2O + AgC_2H_3O_2 + CH_2O_2 \longrightarrow [Ag(NH_3)_2]^+[C_2H_3O_2]^- \longrightarrow Ag$$

Modified Tollens' process

* Walker, et al. JACS (2012)

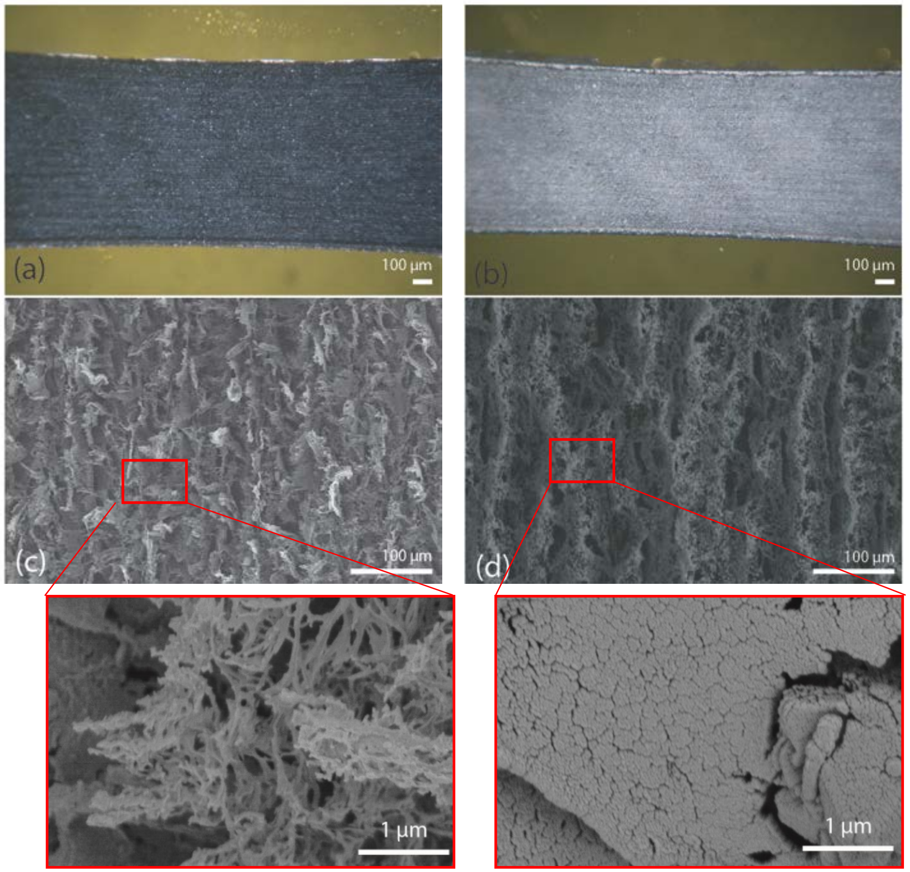


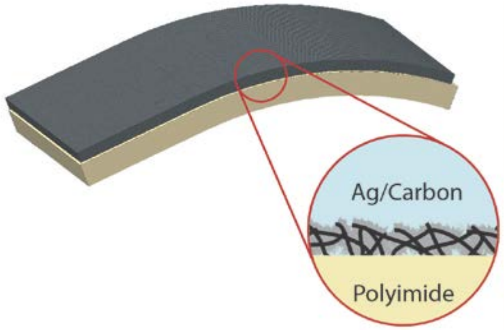
52 Ω/sq → 0.02 Ω/sq

R. Rahimi, et al. ACS applied materials (2016)

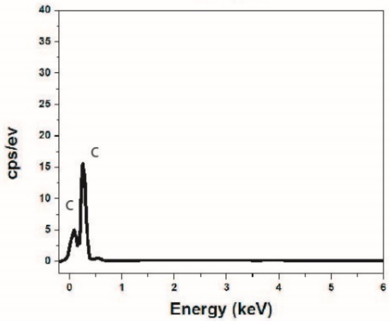
EDX mapping of silver and carbon

Laser Carbonized Polyimide | **Ag/Carbonized Polyimide**



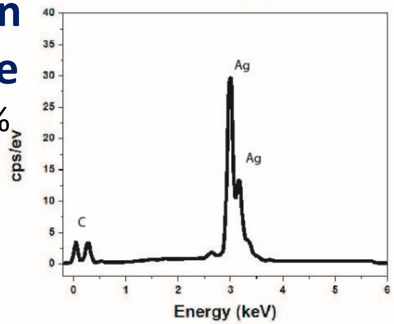


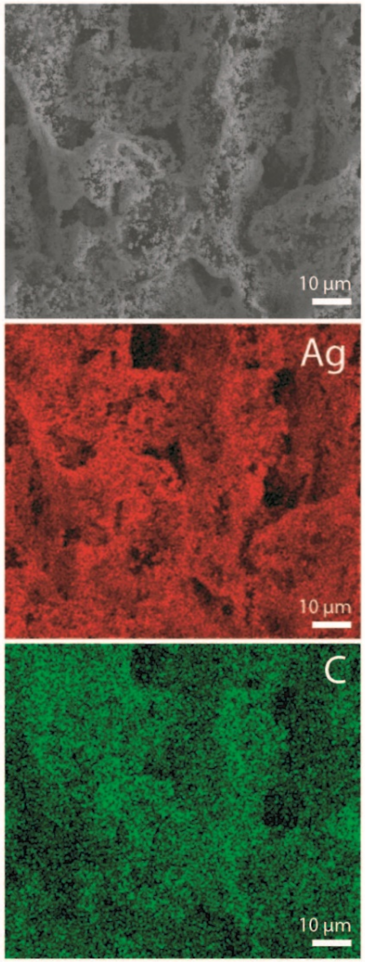
Porous carbon



Ag/carbon composite

Carbon ~17 %
Silver ~82 %

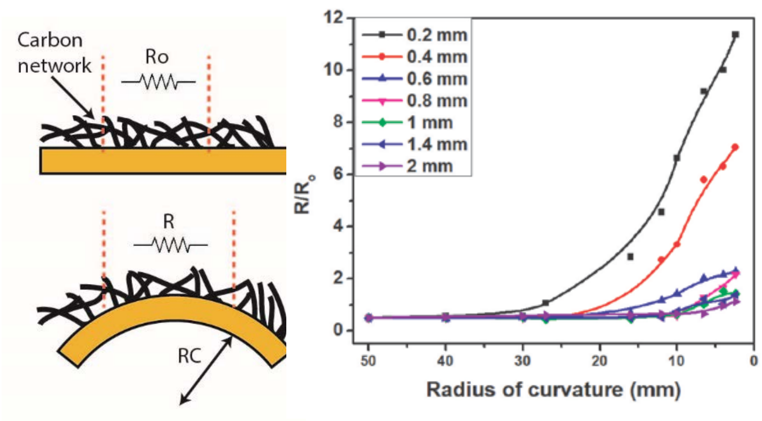




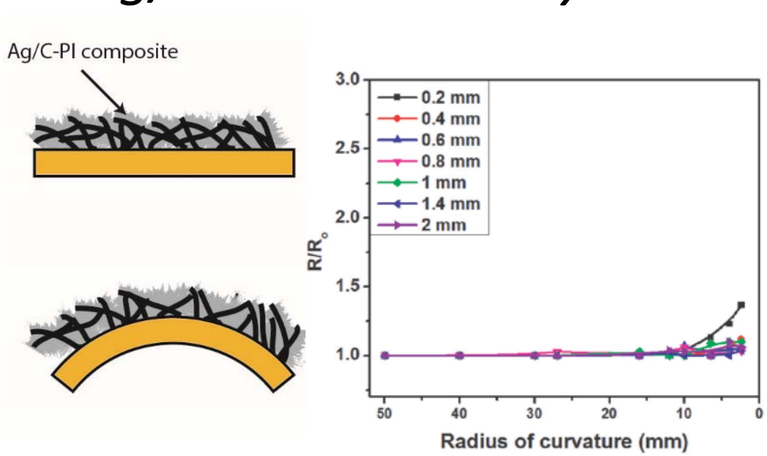
R. Rahimi, et al. ACS applied materials (2016)

Electromechanical properties

Laser Carbonized Polyimide



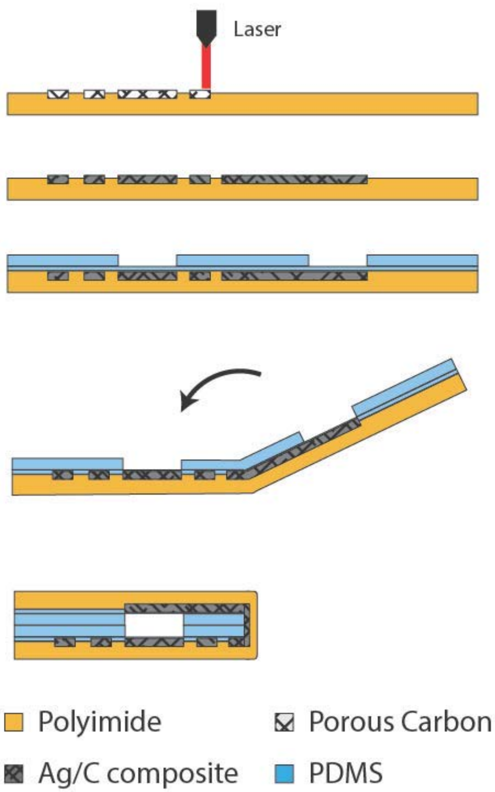
Ag/Carbonized Polyimide



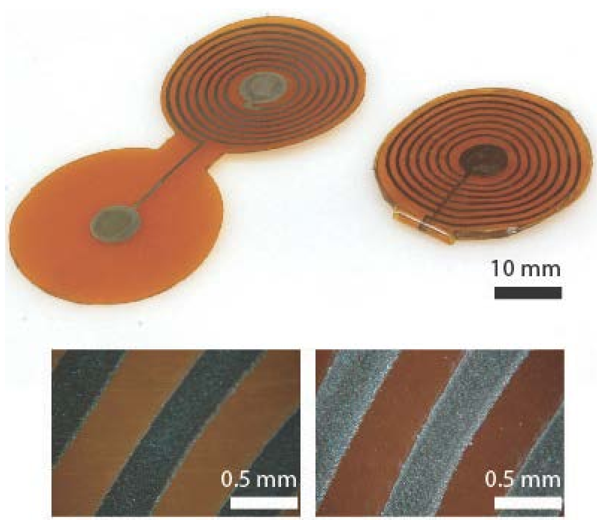
8.7 folds decrease in sensitivity

Wireless pressure sensor (C/Ag composite)

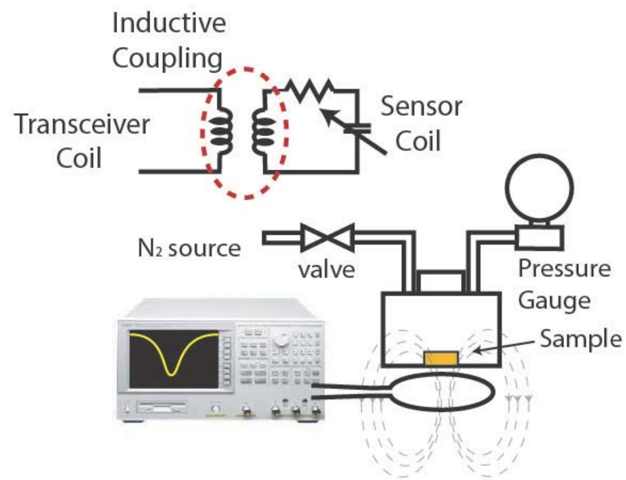
Fabrication process



Wireless LC passive pressure sensor

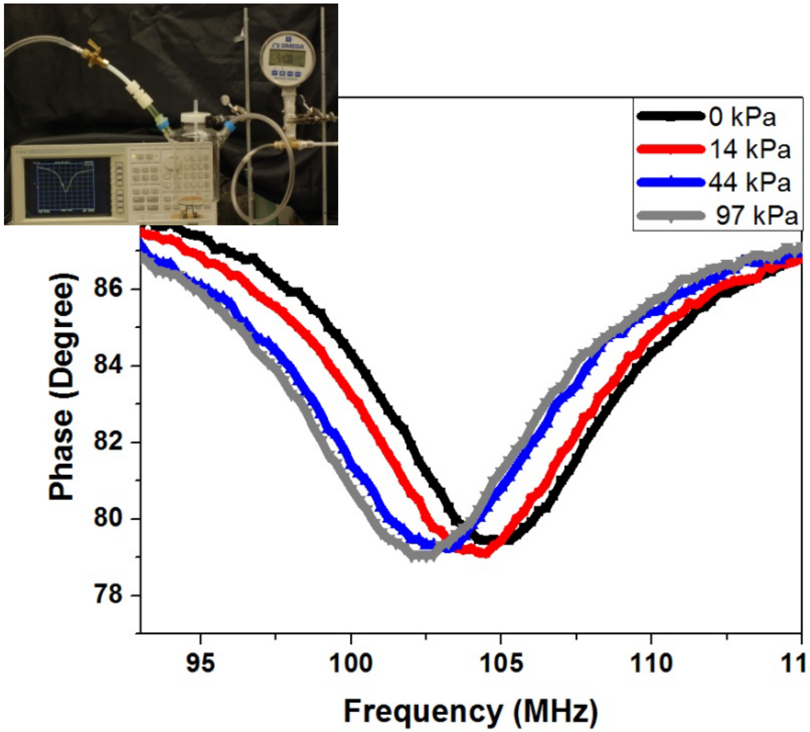


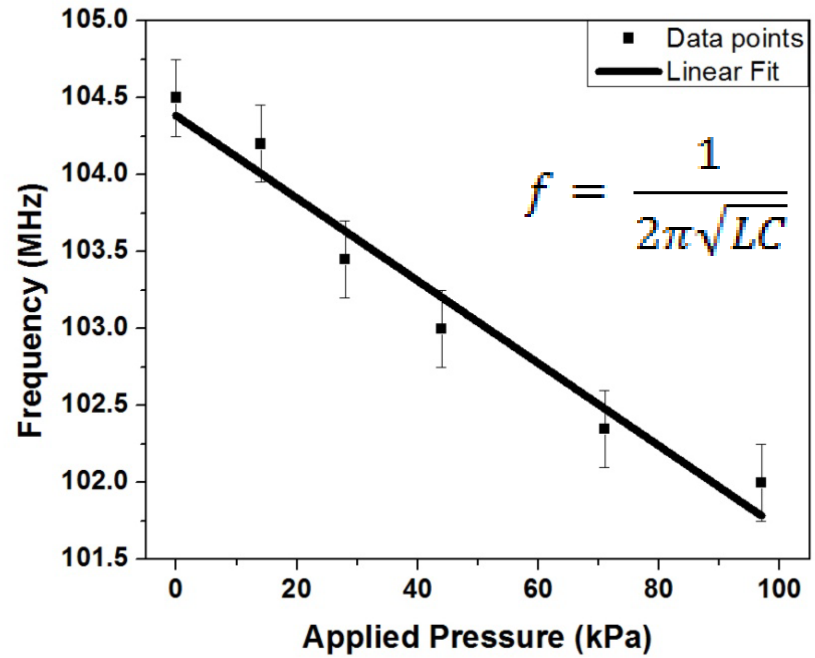
Experimental and readout system



$$f = \frac{1}{2\pi\sqrt{LC}}$$

Wireless pressure sensor

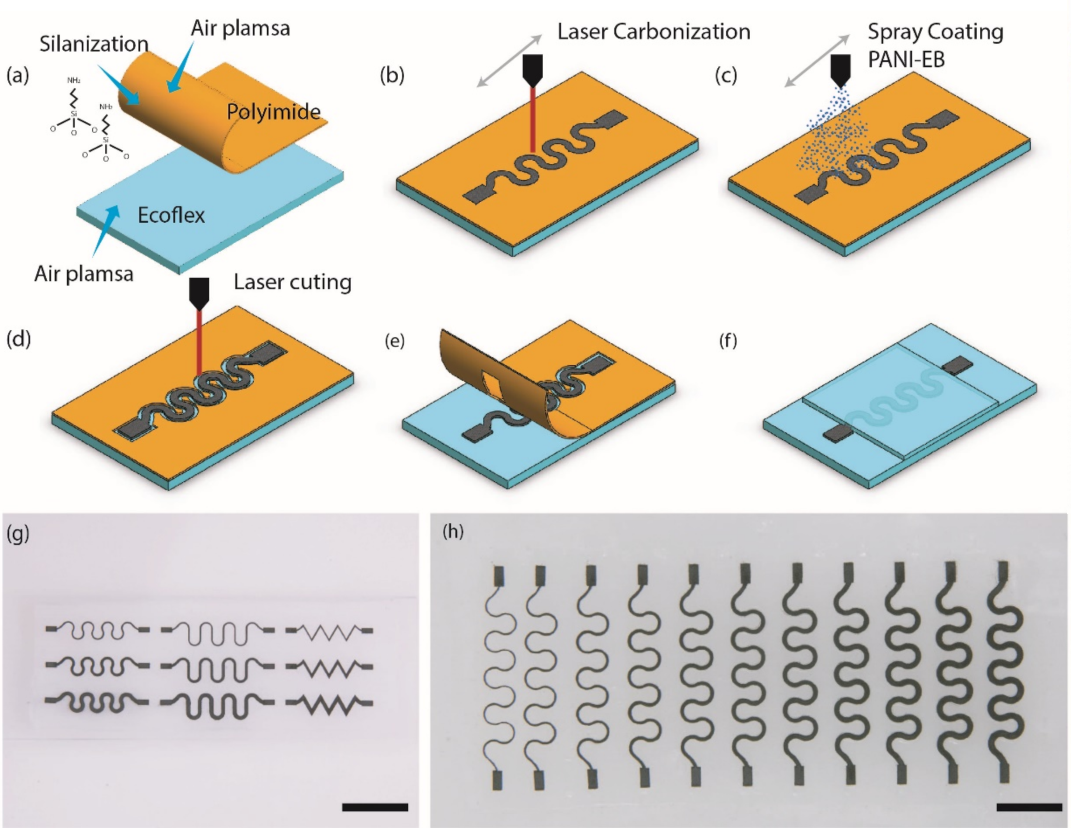


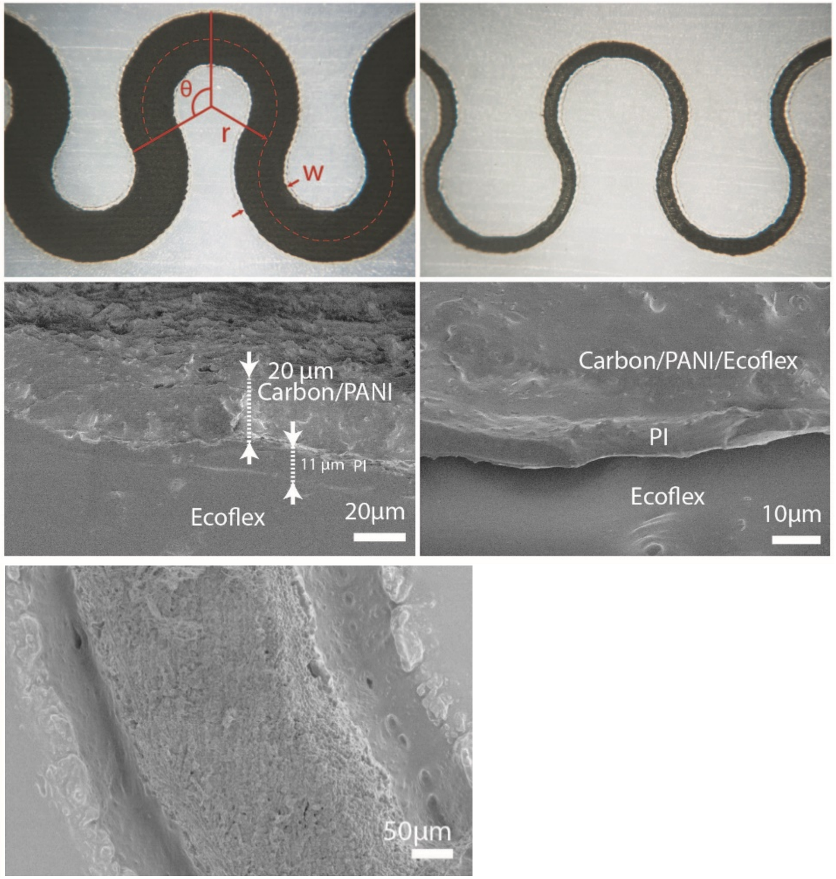


Dip in phase for pressures ranging from 0 to 97 kPa.

Frequency decreases linearly with pressures up to 97 kPa with an average sensitivity of -26 kHz/kPa.

Stretchable carbon–polyaniline composite





500 mg Polyaniline Emeraldine base dissolved in 5 mL of DMF

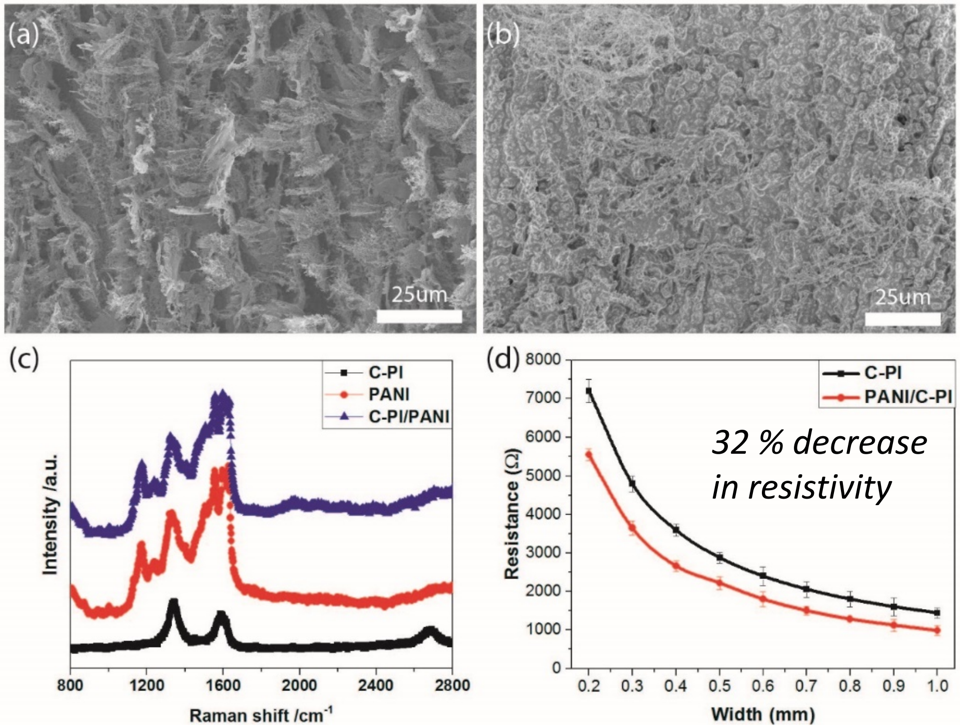
Structural parameters

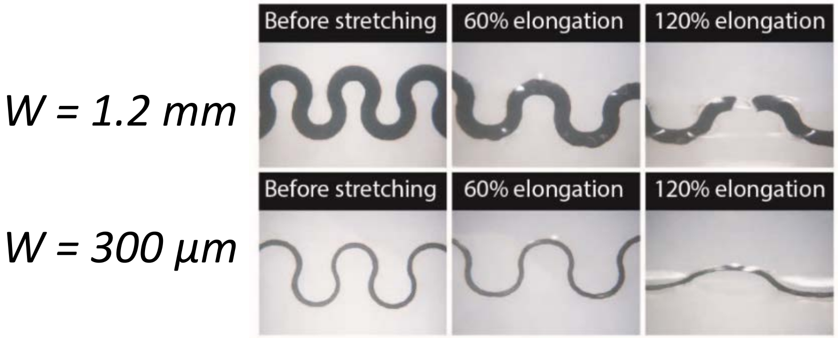
r = 1 mm, θ = 120°

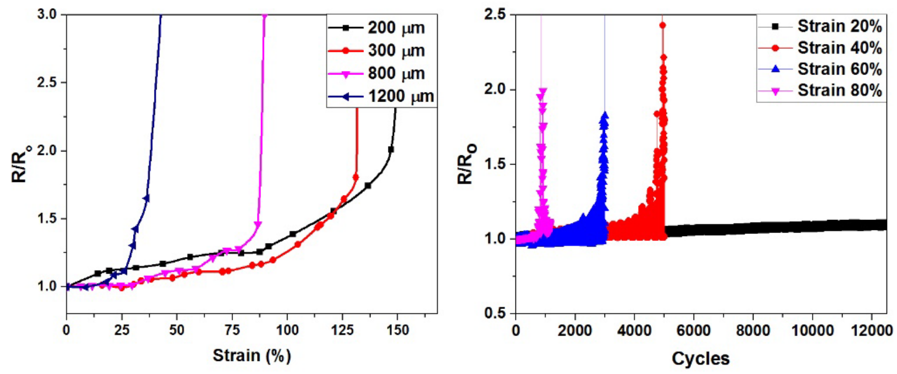
W = 300 μm to 1.2 mm

60 μm trench around the perimeter

Electromechanical characterization



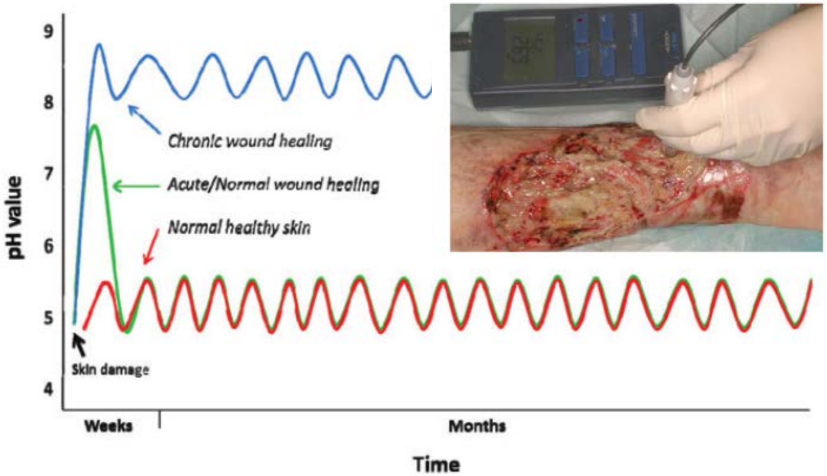


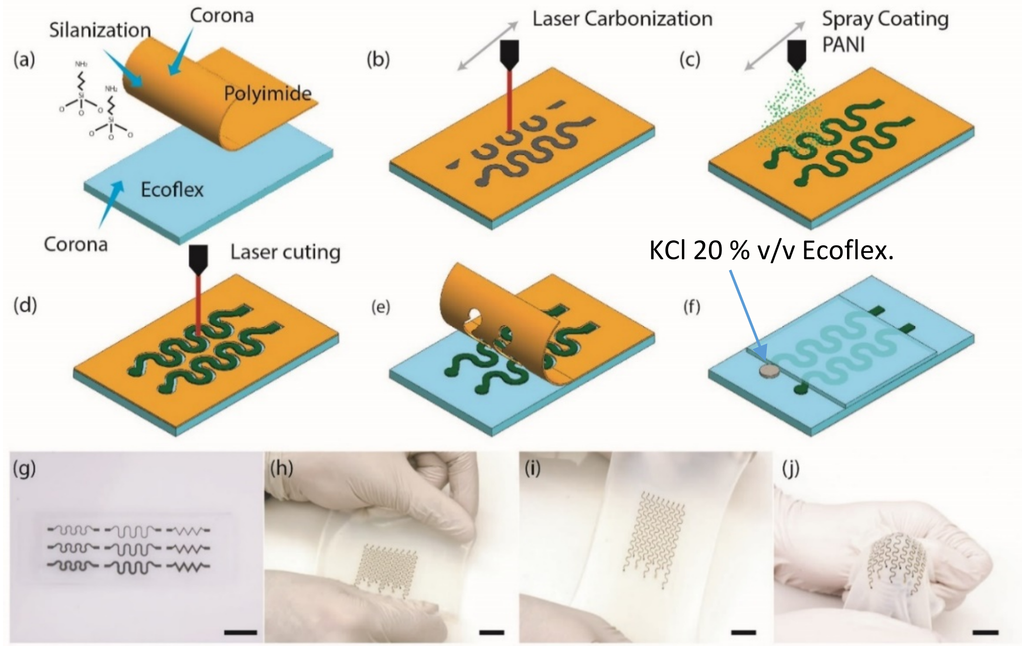


- Raman spectra before and after deposition of PANI
- PANI/C-PI composite after the protonation has an approximately 32 % lower resistivity (0.065 Ω.cm)

- Periodic out-of-plane deformation at the crests
- Micro-cracks proliferate at higher strains
- 300 µm serpentine traces:
  - Stable electrical resistance for elongation up to 100 % (less than 20% change in resistance)
  - 135 % Ultimate elongation

Stretchable pH sensor (C/PANI)





- Chronic wounds pH 7.15 to 8.9
- Susceptible to different infections such as staphylococcus

- Potentiometric pH sensor
  - PANI/C working
  - Ag/AgCl reference electrode
- PANI is the conductive filler, binding material, and pH-sensitive membrane
- Serpentine C/PANI traces serve as both the stretchable interconnect and the pH-sensitive electrodes.
- Solid electrolyte (KCL+Ecoflex)

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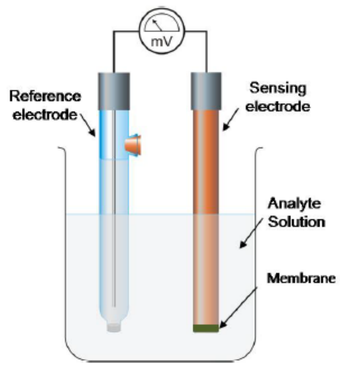
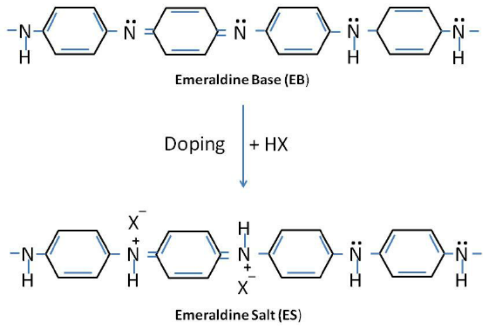
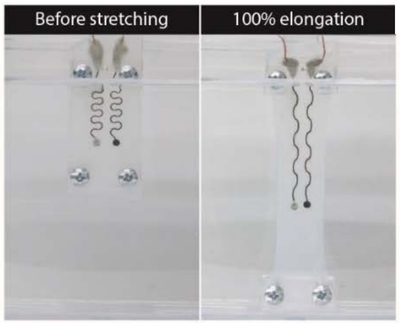
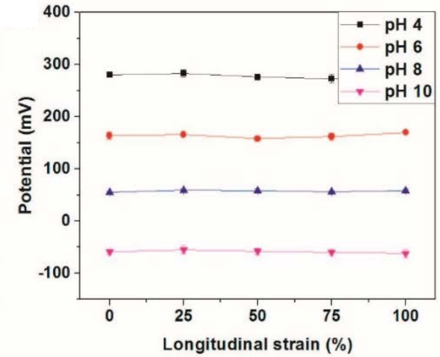
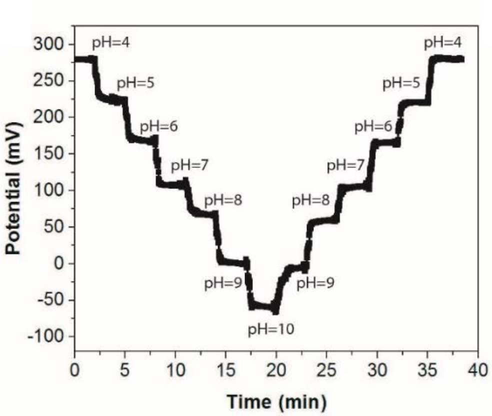
Stretchable Potentiometric pH sensor

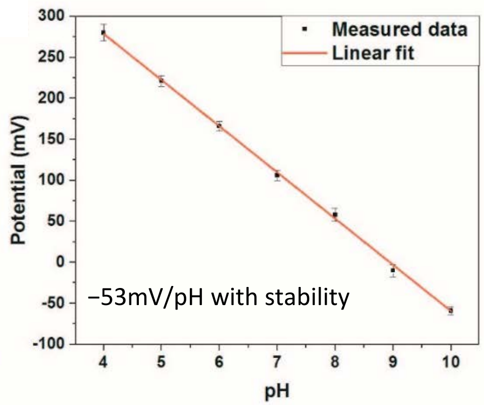


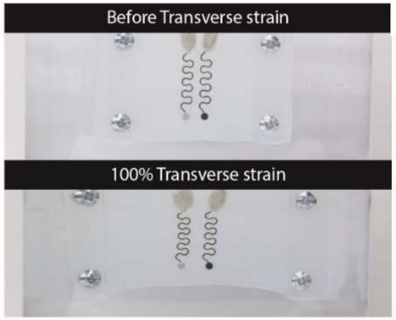


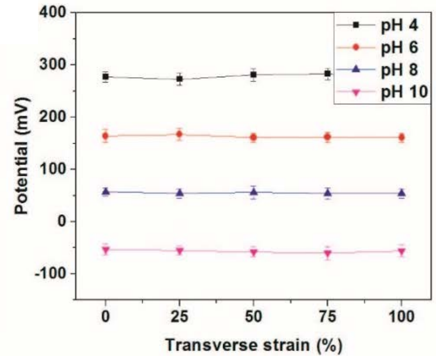








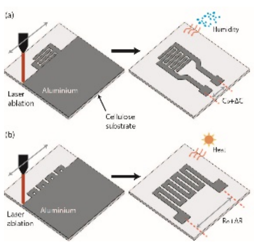


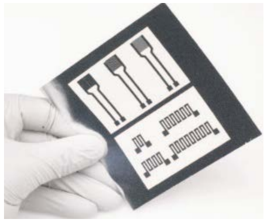


- Potentiometric measurement
- Protonation and de-protonation of PANI
- Linear sensitivity of −53mV/pH with stability

Outline

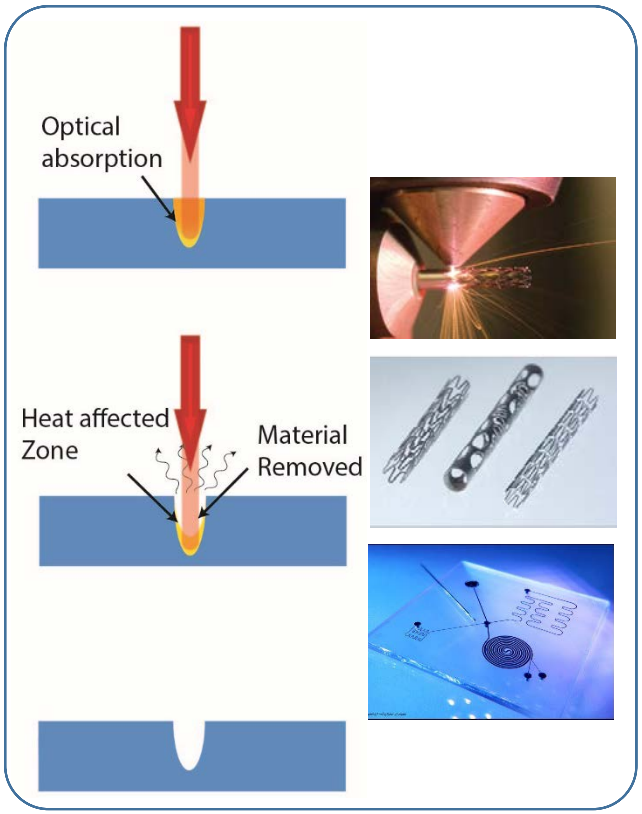
- Introduction
- Laser carbonization
  - Laser-induced porous carbon
  - Functionalization
- **Laser ablation**
  - Selective etching of multilayer films
  - CO_2 vs Nd:YAG
- Printed-electronics
  - Health-care
  - Precision agriculture
- Future work



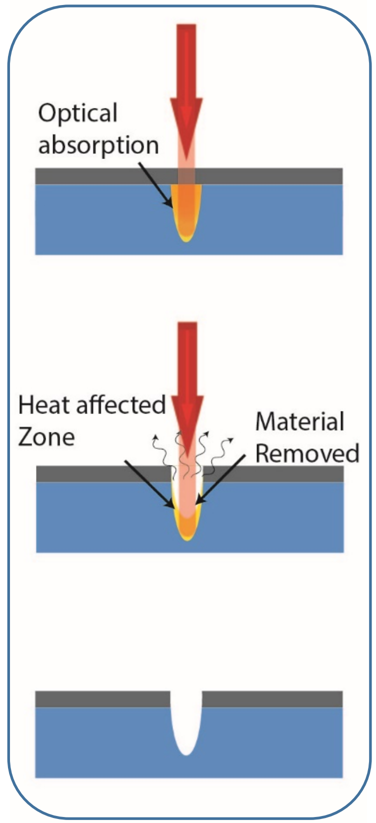



Laser ablation and selective etching

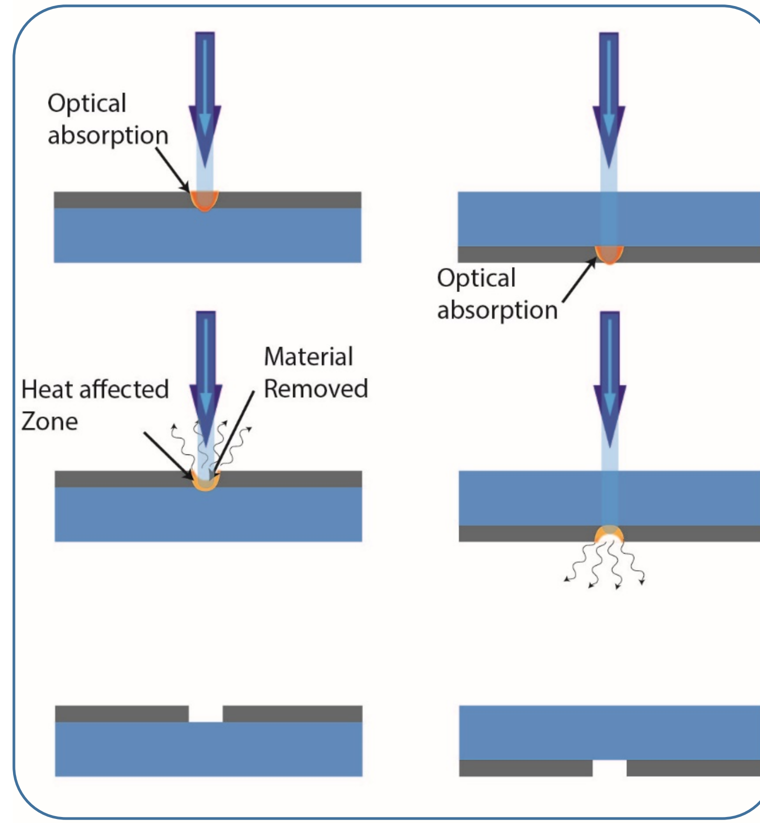
Laser ablation



Indirect ablation



Direct ablation



Removing material from

Similar material

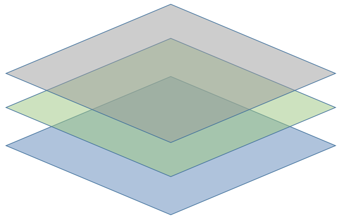
Laser etching from dissimilar materials

Multilayer film selective laser ablation

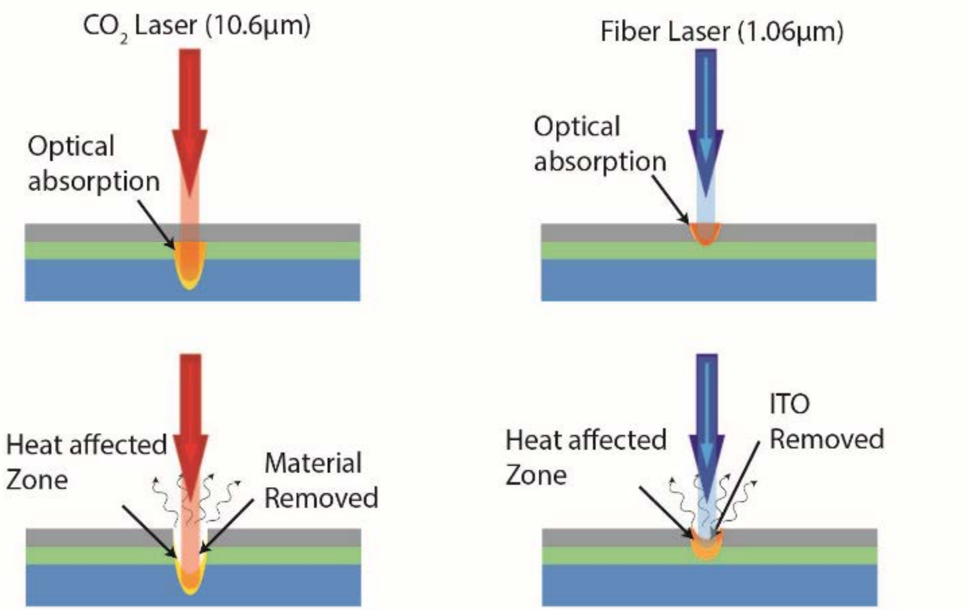
- Commercially available low-cost multilayer films
- Reduced cost of production by using readily available films
  - ITO-coated PET
  - Metalized paper
    - Vacuum deposited
    - Laminated

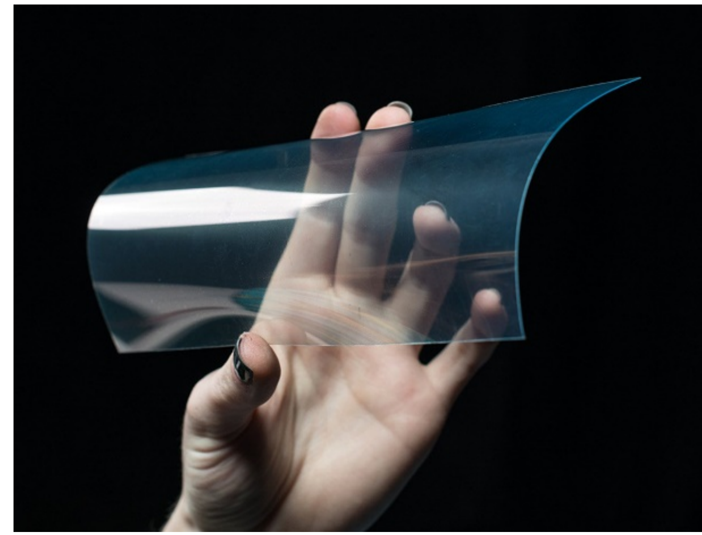
Laser patterning ITO-coated PET

ITO (72nm)
Hard coating (Si_2O)
PET film (127µm)



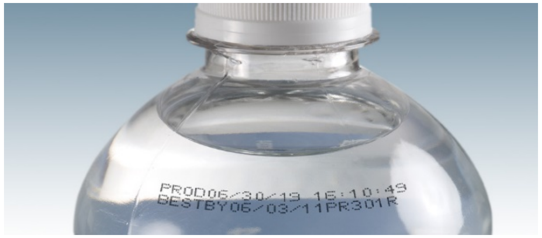
Indirect ablation **Direct ablation**

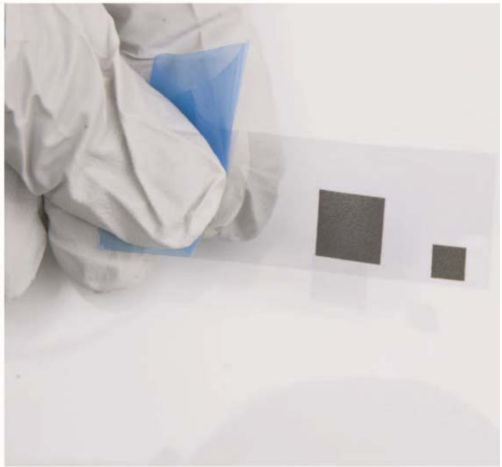


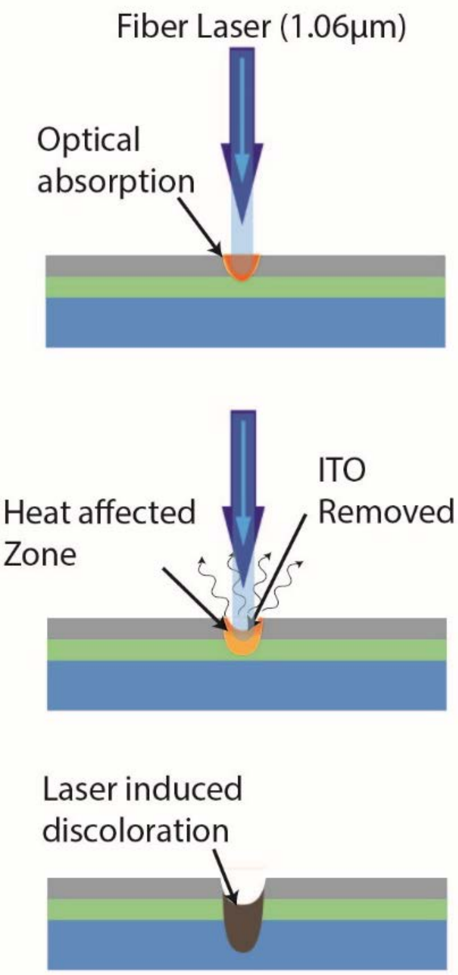


Direct ablation of ITO film

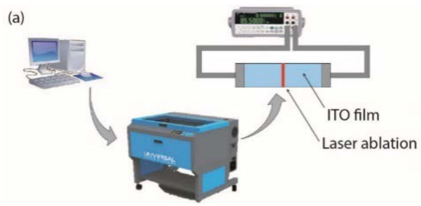
- ITO material absorbs the fiber laser energy (1.06µm) ~103 times higher than PET polymer.
- Absorbed laser energy vaporizes the ITO.
- Significant concern was the color change of the substrate
- Chemical decomposition of the polymer substrate.
- Used for marking PET in industry

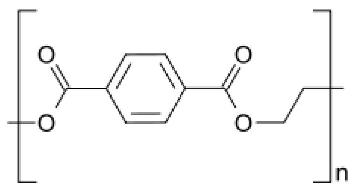




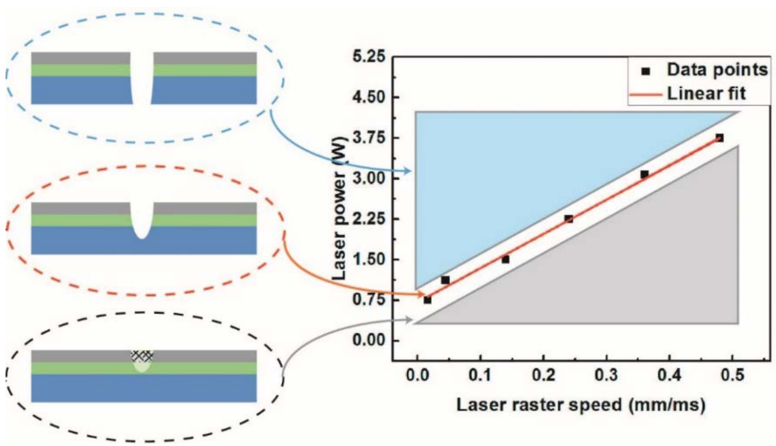


Indirect CO_2 laser patterning

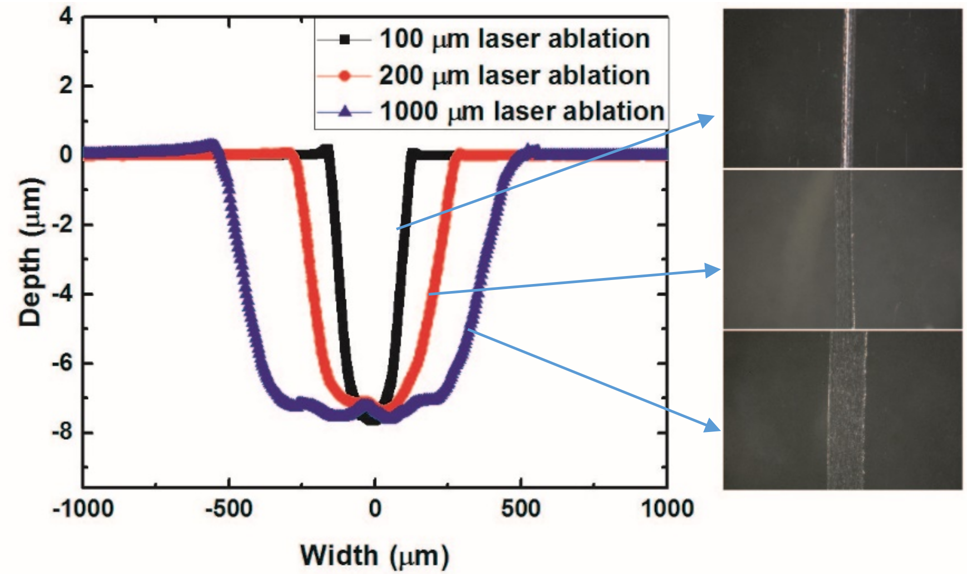


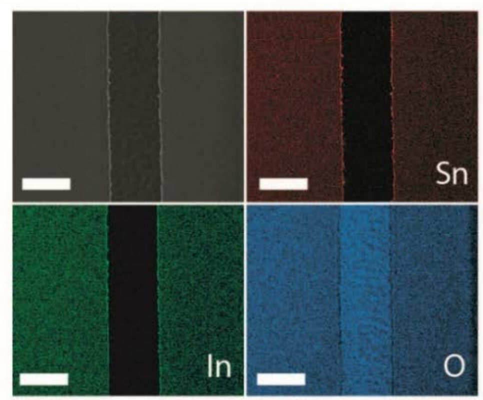


Polyethylene teraphthalate

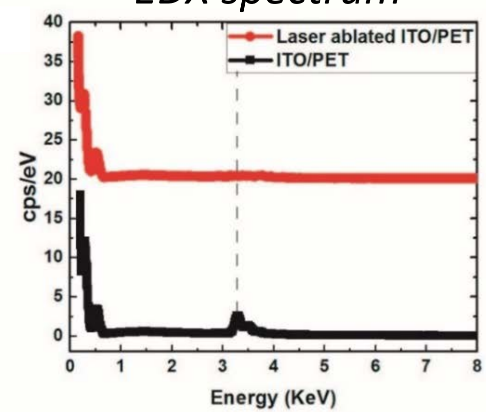


Laser ablated area



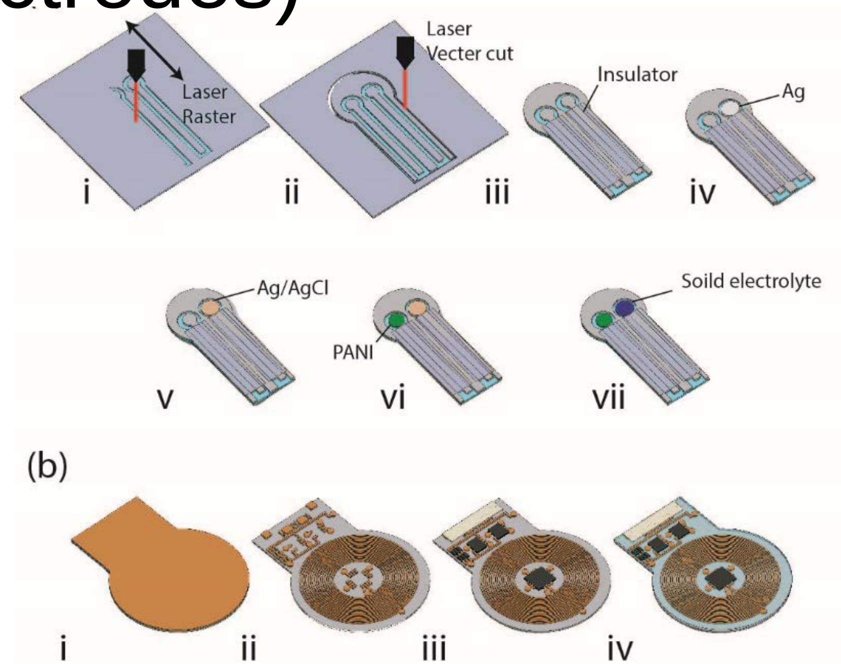


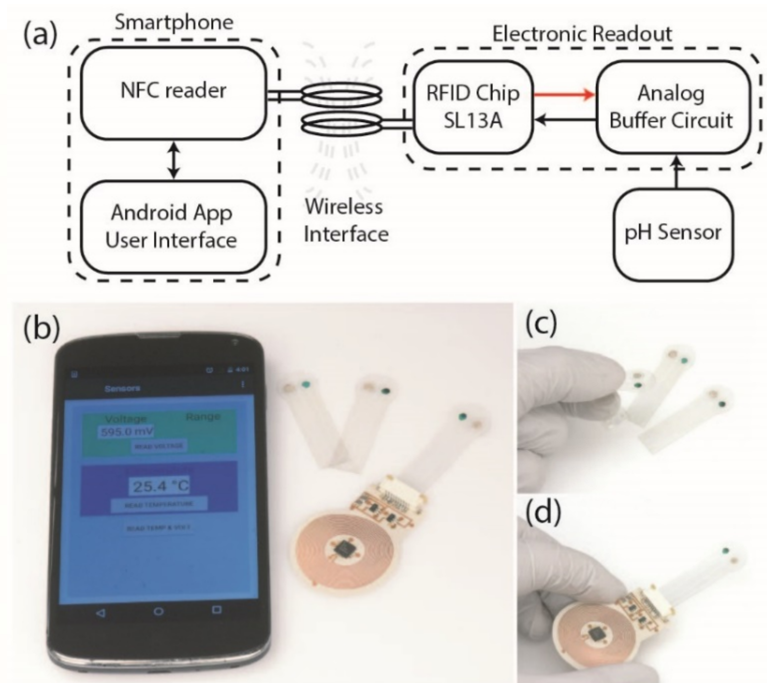
EDX spectrum



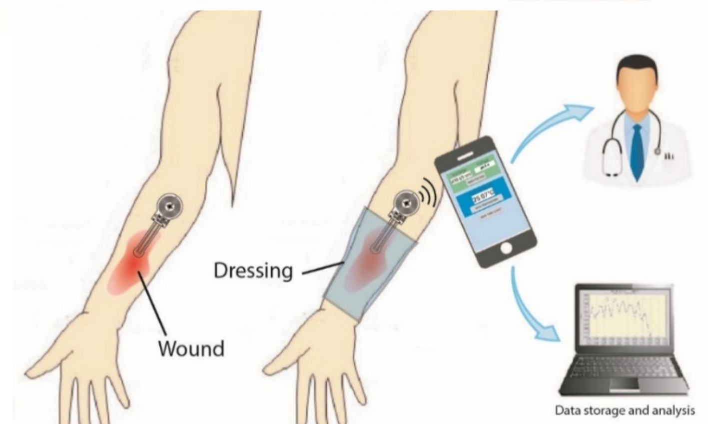
- Energy density of **0.6 J/cm²** required for electrical isolated ITO electrodes
- Average width of 90 µm
- Trench depth of 7.5µm

Transparent pH monitoring system (ITO electrodes)





- Laser-scrubbed using a CO_2 laser engraver to create isolated transparent electrodes
- Working electrode is prepared by electro-polymerization of aniline
  - 0.1M aniline in 1M HCl
- NFC substrate containing the coil/antenna and interconnects
  - Double sided copper PCB



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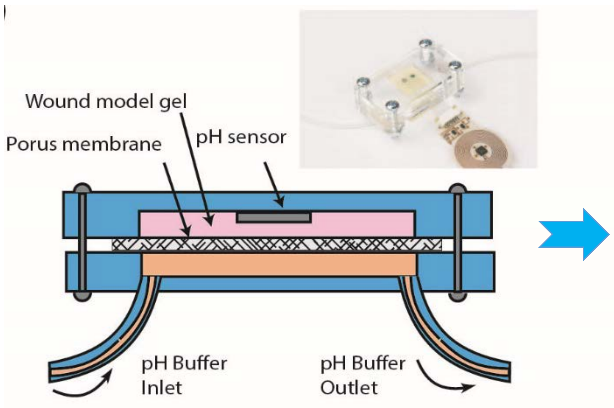
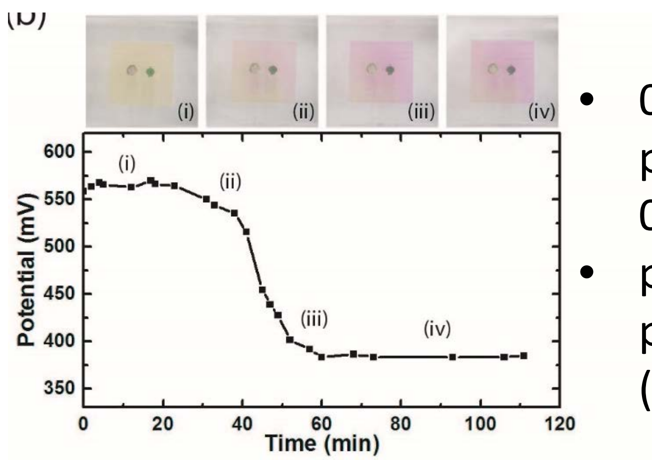
pH monitoring on wound models

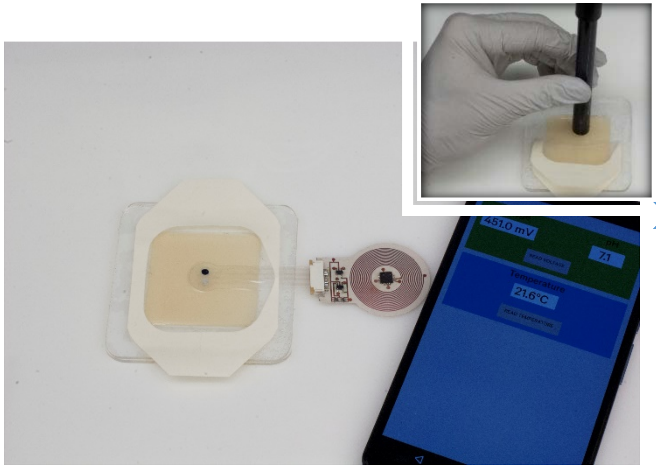
Microfluidic test setup

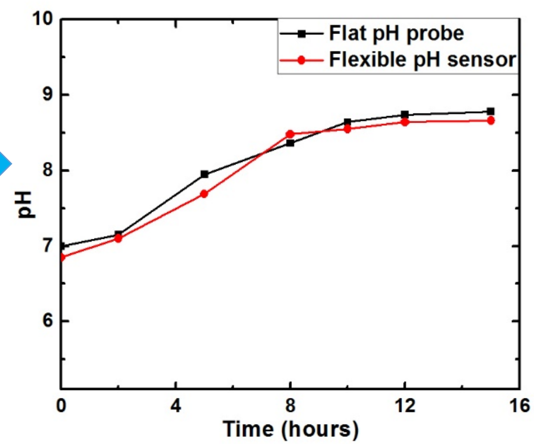




- 0.5 %w/v agarose gel prepared with pH 5 and 0.01%w/v phenol red
- pH 8 buffer solution was pump at constant flow (0.4ml/min).

In vitro infected wound model





- *In-vitro* wound model with ***Staphylococcus epidermidis***
- Change in pH 6.9 to 8.7 over 10 hours

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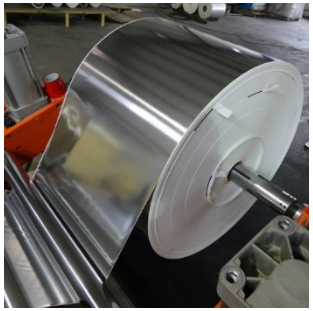
Metallized films

- Manufacturing process
  - *Physical vapor deposition* **(25 to 500nm Aluminum)**
  - *Lamination* **(5 to 20µm Aluminum)**
- Substrates
  - Plastic films (polypropylene, nylon, and PET)
  - Paper
- Cost of metal
  - **Aluminum 0.99 USD/lbs**
  - Copper 2.60U SD/lbs
  - Silver 1,203 USD/lbs
  - Gold 90,290 USD/lbs

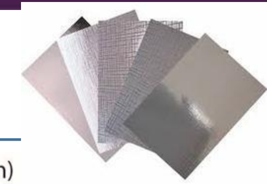
Comparison of Metallised PET and aluminium foil			
	Moisture (g/m².day)	Oxygen (mL/m².day)	UV light (%transmittance)
PET film, 12.7µm	31	465	91
Metallized PET	0.8	1.2	5
Aluminium foil 6µm	0	0	0

Physical vapor deposition

Lamination

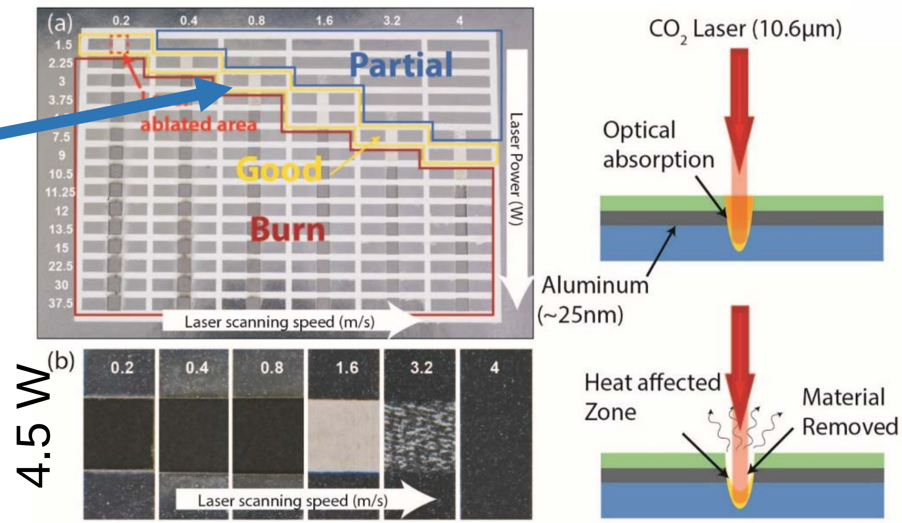


Metallized paper-Laser ablation



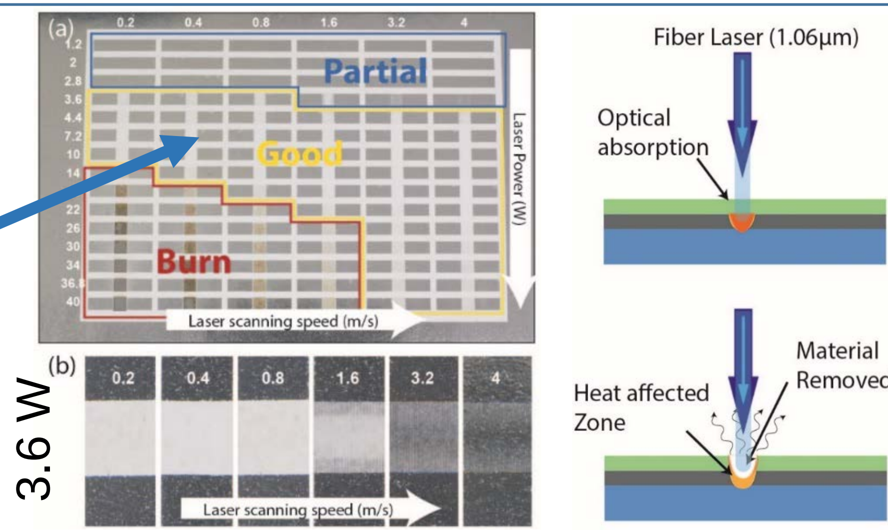
Indirect - CO_2 Laser ablation

- CW wave
- Minimal selectivity
- Color change
- 174mJ/cm^2 threshold energy for electrical isolation.
- Average decrease of 3.9 mg (~44.3%) in mass

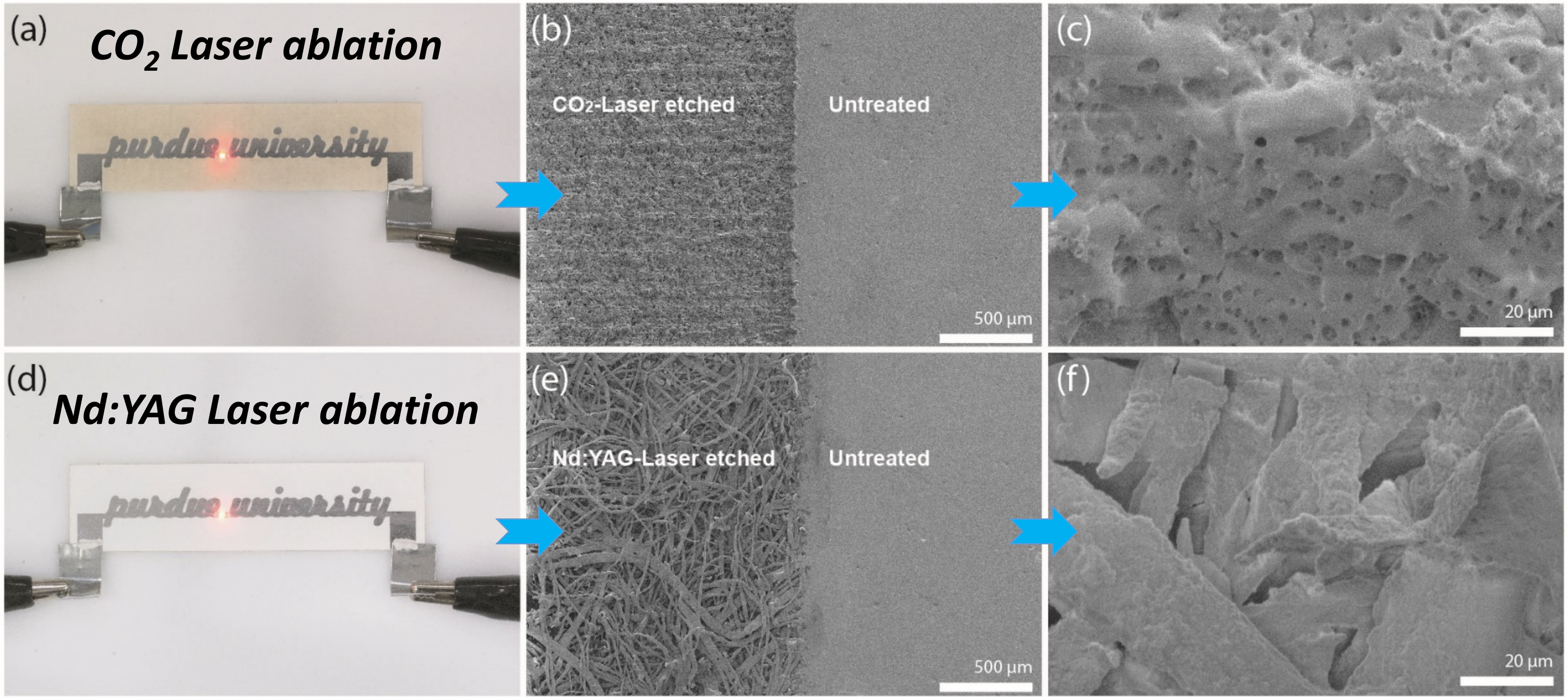


Direct - Nd:YAG Laser ablation

- Pulsed mode
- High selectivity
- Wider optimal setting of laser power and speed
- Minimal weight loss of less than 0.1mg (1.15% of original weight)



Surface analysis

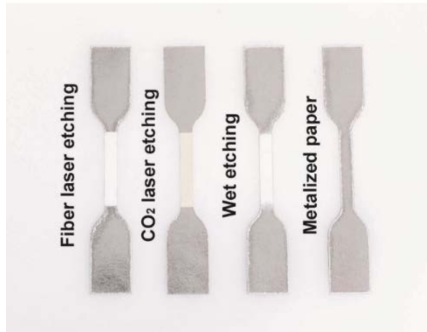


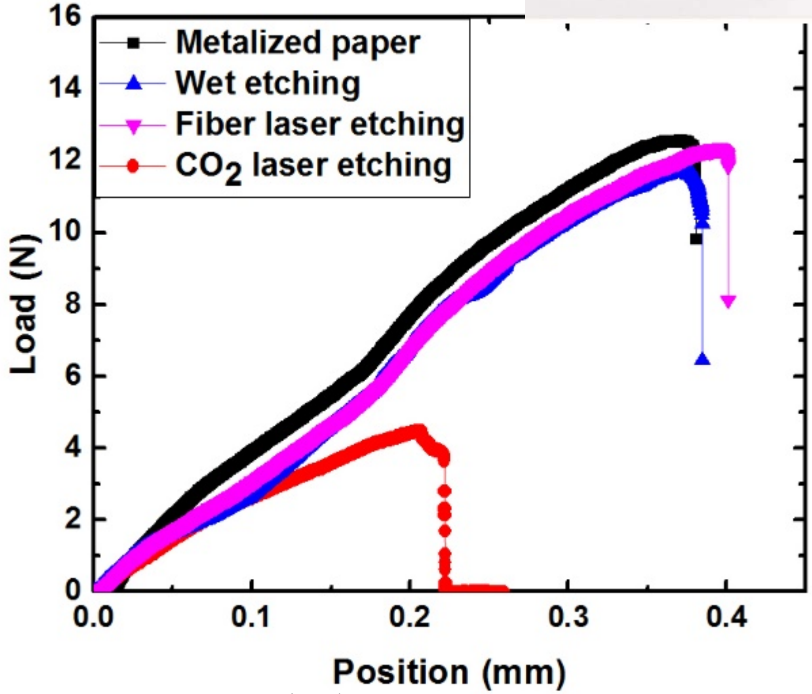
- CO_2 laser ablated samples
  - Destruction within natural microstructure of the paper.
- Nd:YAG laser ablated samples
  - Retention of highly porous fibrillary structure in the paper substrate

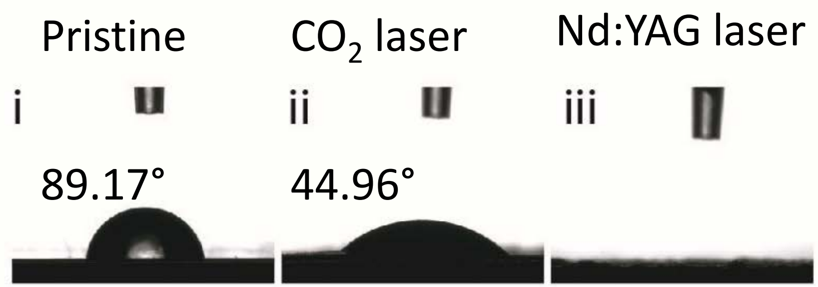
Mechanical and Surface wetting analysis

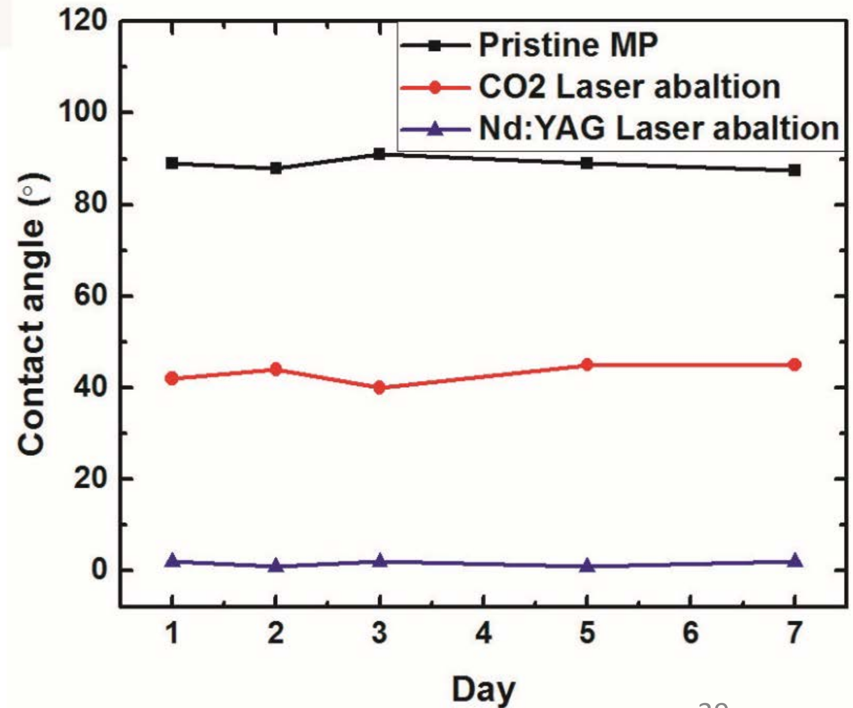
Decrease in tensile strength

- CO_2 laser → 64%
- Nd:YAG laser → 2.93%
- Wet etched → 6.74%

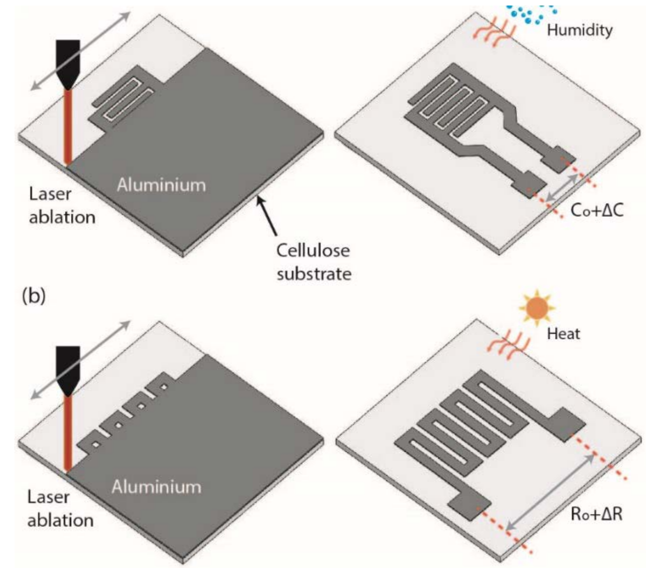








Paper-based humidity and temperature sensor



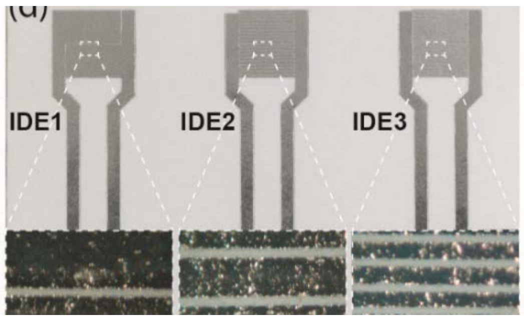
- Food waste in United States is **30 to 40% of the food supply.**
- Moisture in inappropriate amounts can reduce the shelf life of many foods and drugs.
- Moisture balance is important in achieving optimum wound healing conditions
- Laser ablated metalized paper

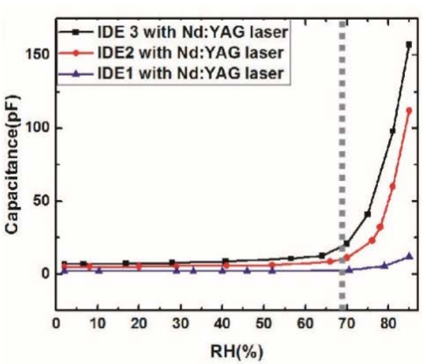
Paper-based sensors

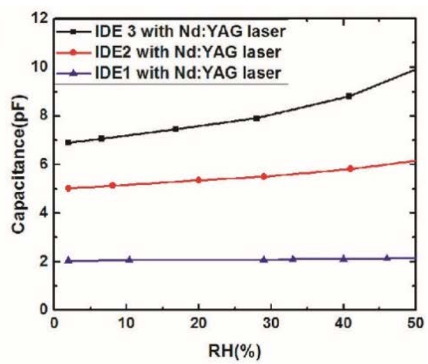
Humidity sensors

$$C = \varepsilon_r \varepsilon_o A/d$$

dielectric constant of the material







Region II (68-85 %RH)

- Capillary condensation effect
- Maximum change at 85% RH
  - IDE1 → 471%
  - IDE2 → 1740%
  - IDE3 → 1804%

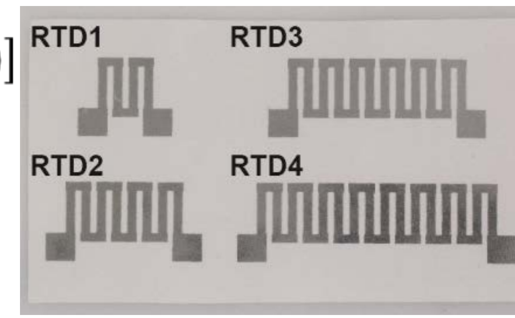
Region I (2-68 %RH)

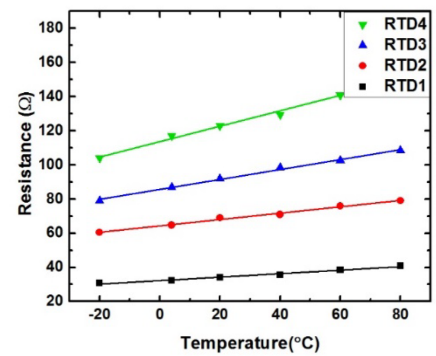
- IDE1 → 2.5 fF/%RH
- IDE2 → 45.7fF/%RH
- IDE3 → 83.2 fF/%RH

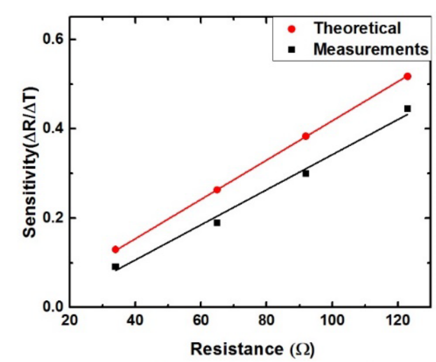
Temperature sensors

$$R = R_{ref}\left[1 + \alpha\left(T - T_{ref}\right)\right]$$

Temperature coefficient of the material







Range -20 to 80 °C

- RTD1 → 0.102 Ω/°C
- RTD2 → 0.186 Ω/°C
- RTD3 → 0.29 Ω/°C
- RTD4 → 0.451 Ω/°C

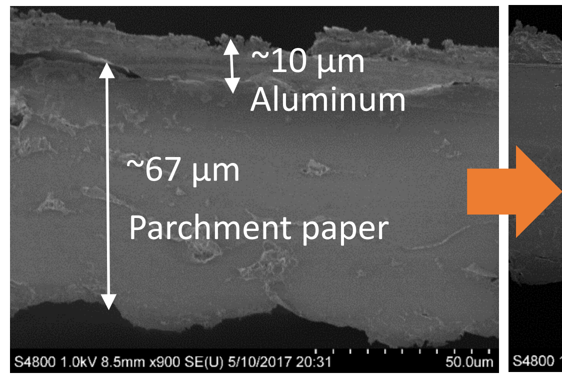
$$S = \Delta R/\Delta T = \alpha R_{ref}$$

R. Rahimi, et al. ACS applied materials (2018)

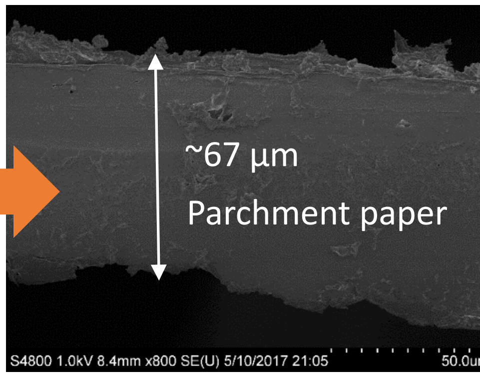
Laser ablating laminated Al foil

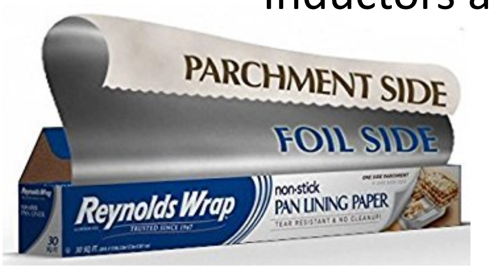
- Aluminum foil
  - Thickness → 10 µm
  - Nd:YAG laser abation
- Parchment paper substrate
  - Thickness → 67 µm
- High electrical conductivity
  - – Inductors and Antennas

Before

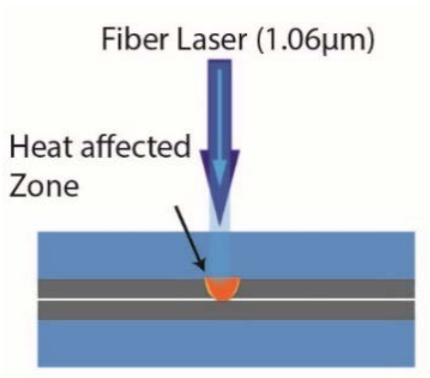


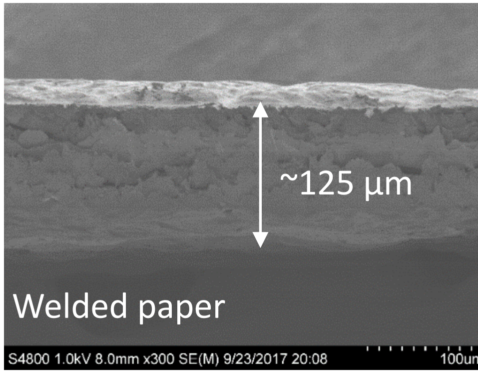
After laser ablation





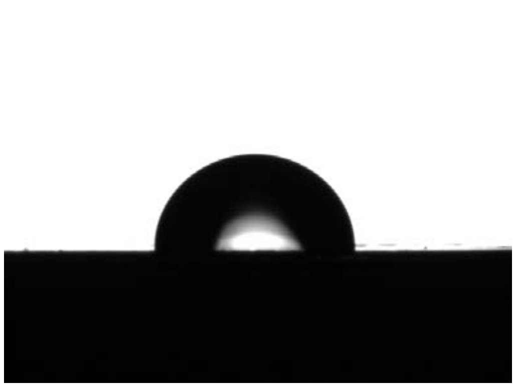
Laser welding conductive layers



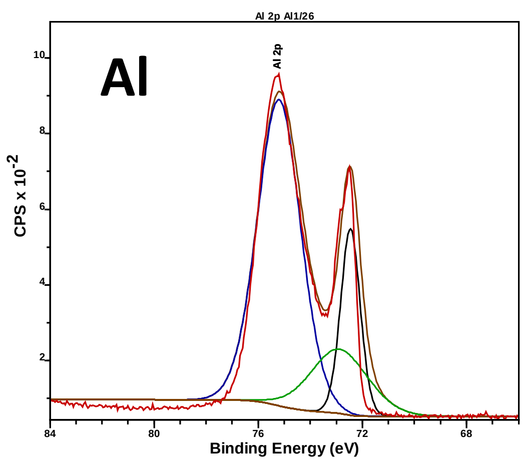


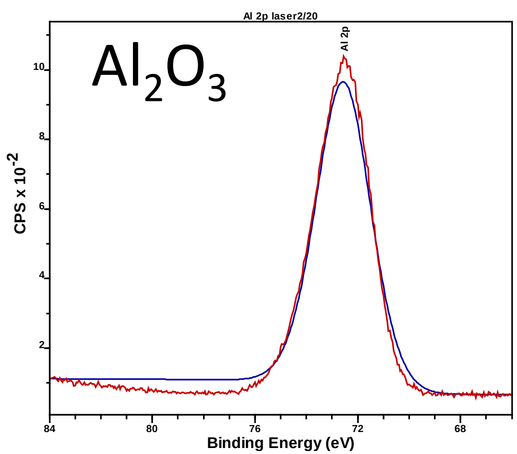
XPS and SEM Surface analysis

Before

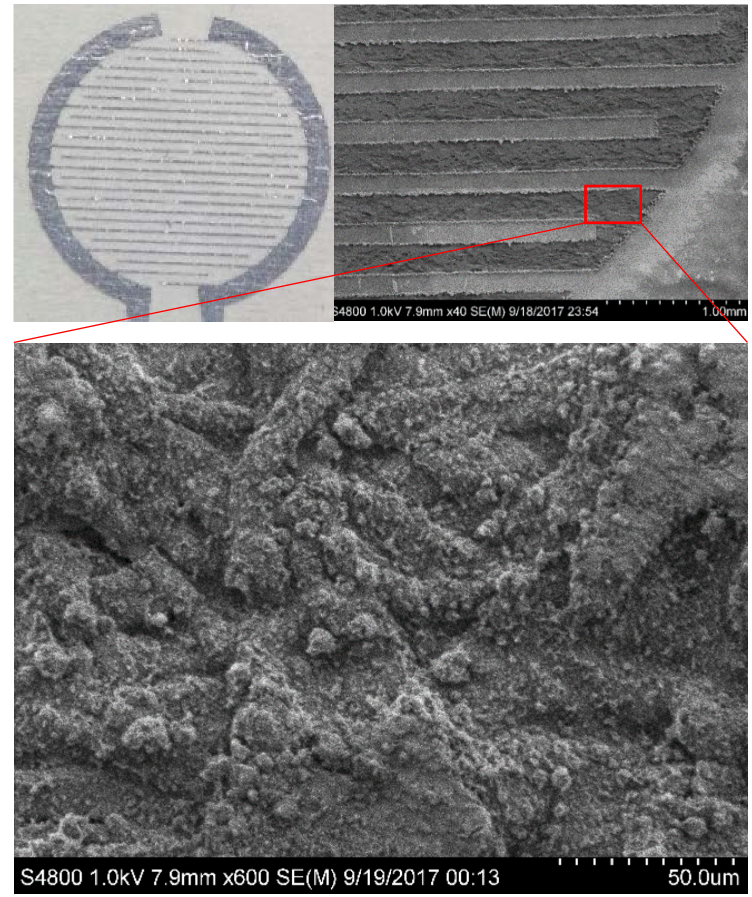


After laser ablation





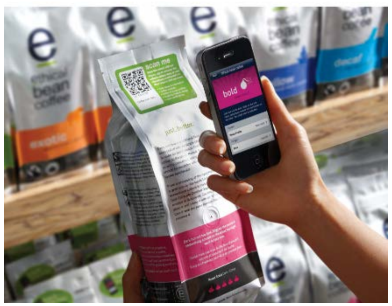
- Complete removal of conductive Al metal
- Al_2O_3 NP on laser ablated surface

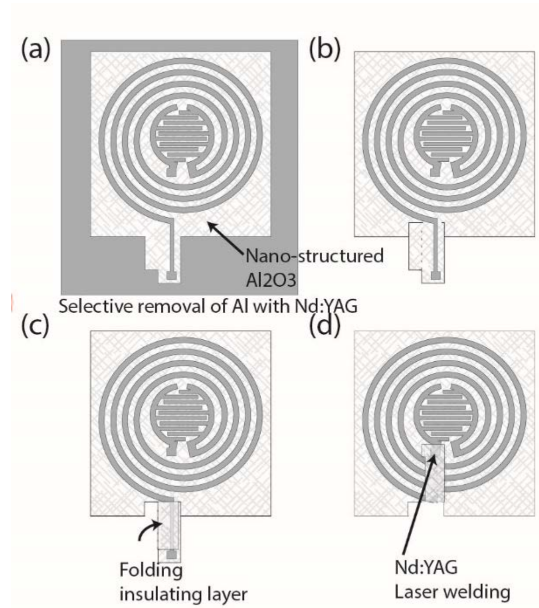


Interdigitated electrode

- 140 µm electrode width
- 180 µm spacing

Wireless humidity sensor



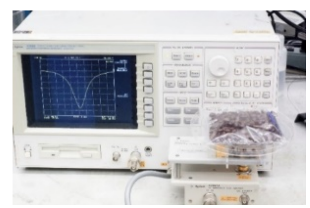


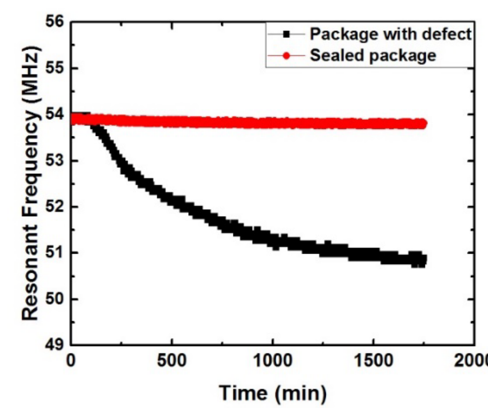
Intelligent packaging

- Ultra low-cost of manufacturing
- Chipless wireless monitoring

Coffee package filled with N_2 gas

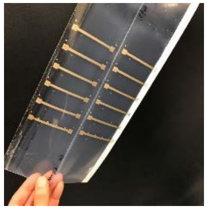
- Laminated polyethylene bag
- 3MHz drift with defected package
- Less than 0.2MHz change with well sealed package





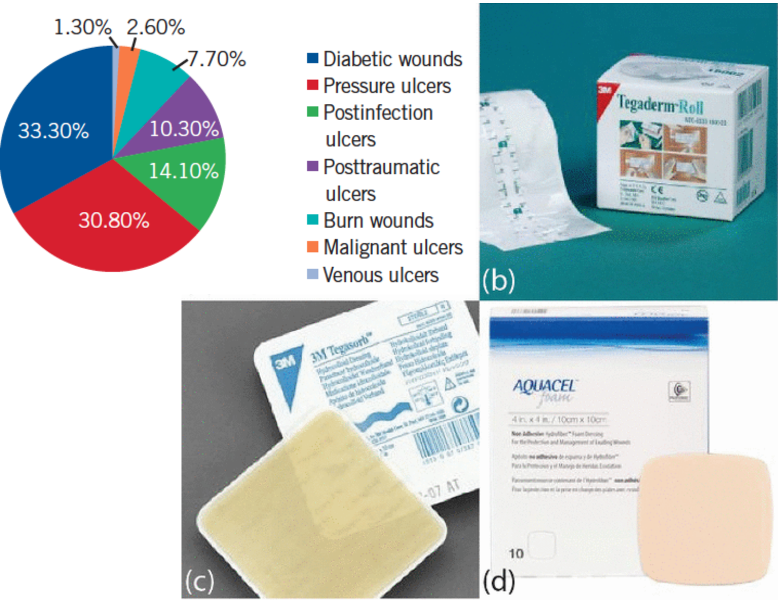
Outline

- Introduction
- Laser carbonization
  - Laser-induced porous carbon
  - Functionalization
- Laser ablation
  - Selective etching of multilayer films
  - CO_2 vs Nd:YAG
- **Printed-electronics**
  - Health-care
  - Precision agriculture
- Future work



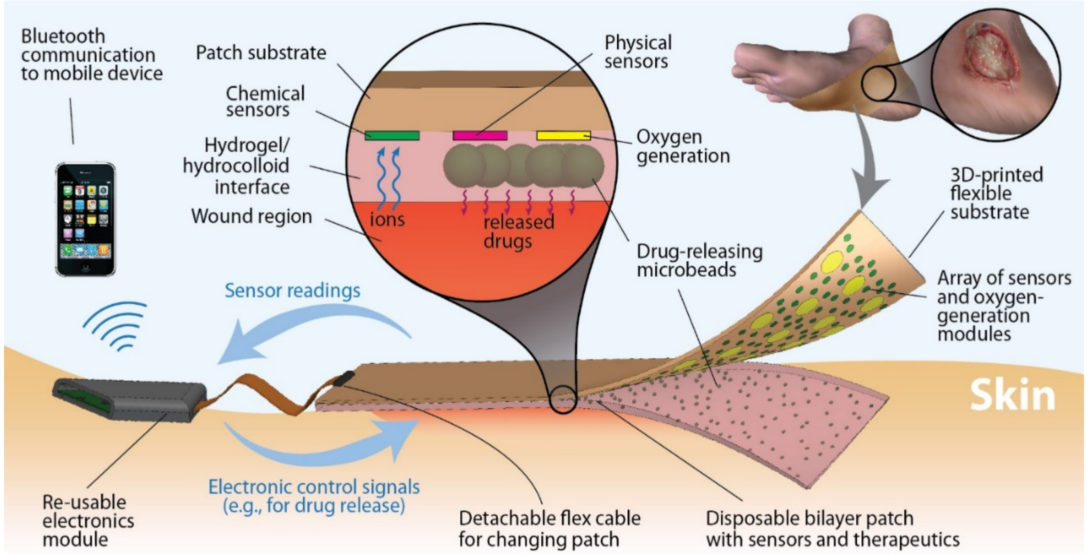
Chronic Wound Therapy

Current wound dressings



- Qualitative assessment of the wound with require extensive professional attention
- Treatments: moisture control and antibiotics.

Smart wound dressing approach



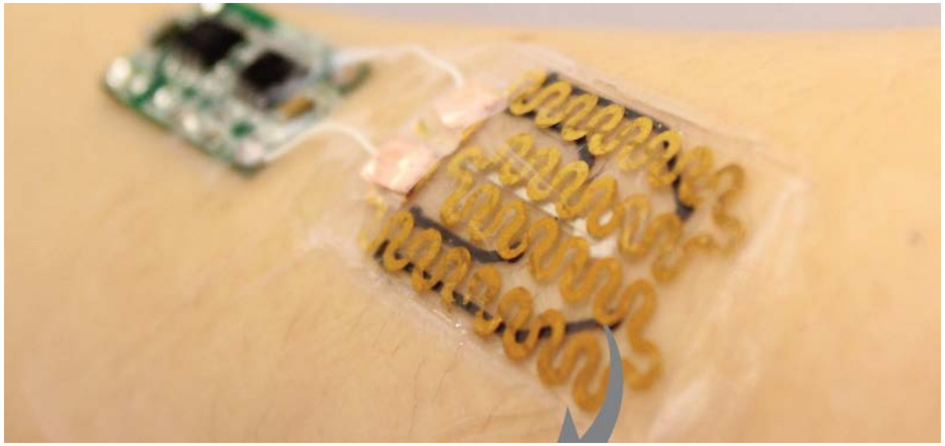
Sensing

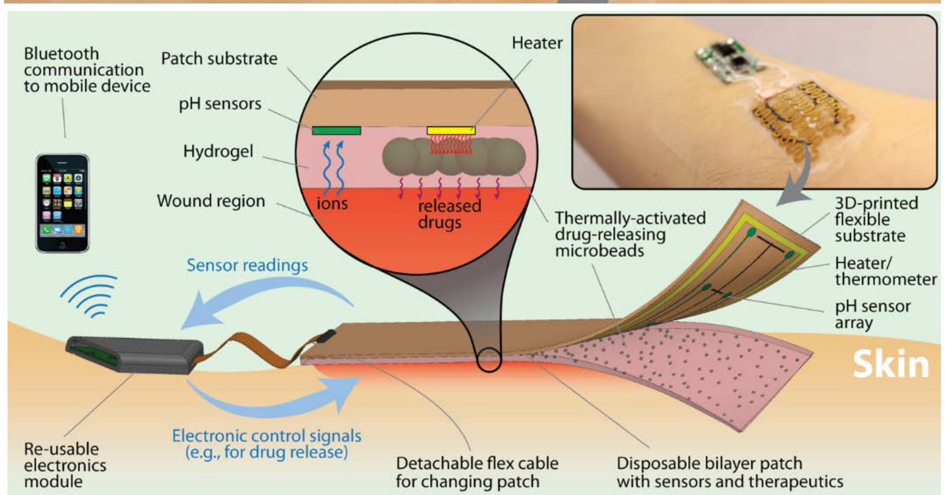
- Chemical (pH, O_2, biomarkers)
- Physical (moisture, temperature, strain, blood flow)

Delivery

- Oxygen
- Antibiotics
- Growth factor
- Electromechanical stimulation

Patch with pH sensing and drug delivery





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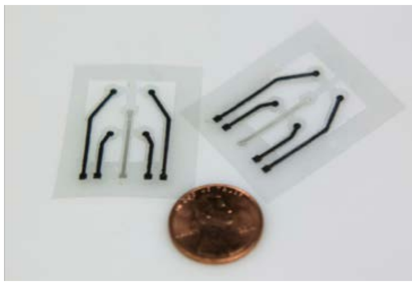
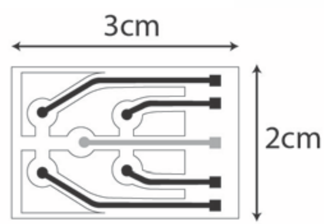
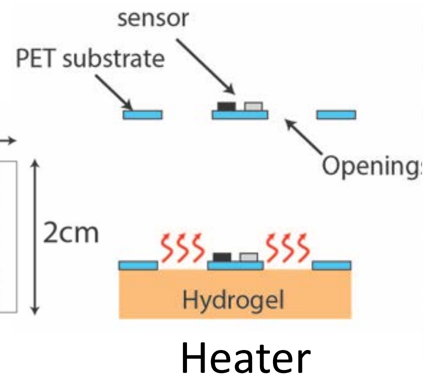
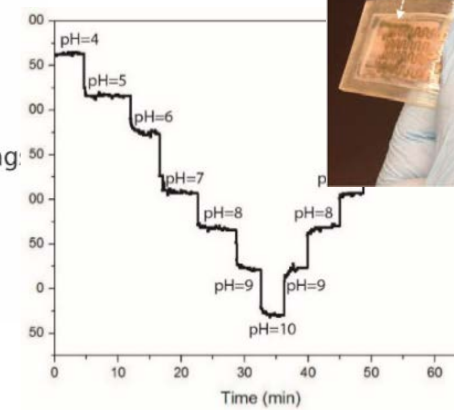
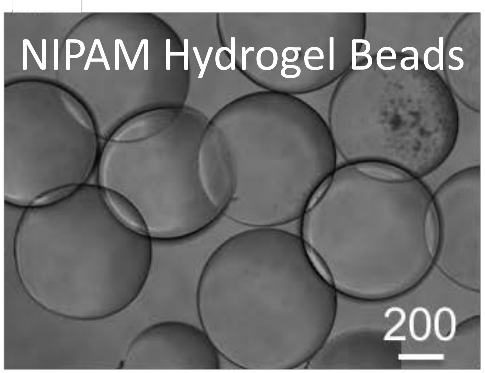
pH Sensor and Drug delivery

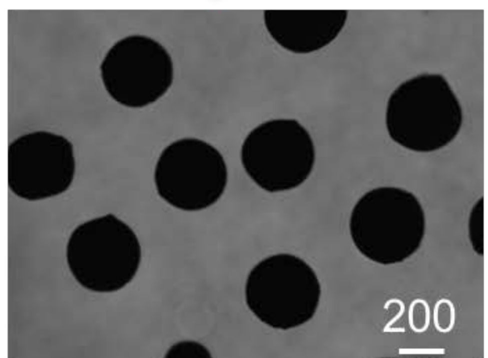


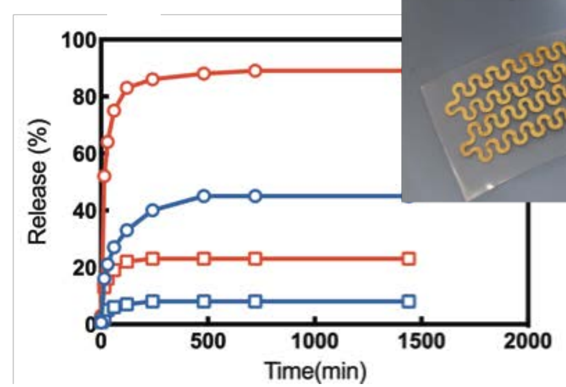


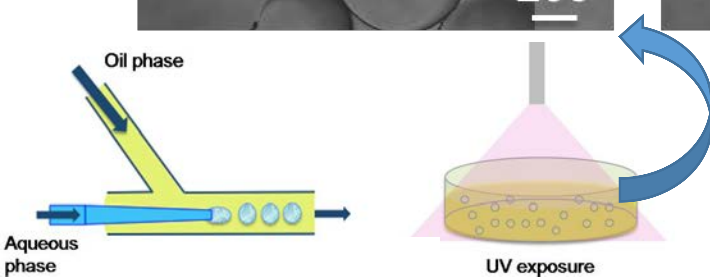












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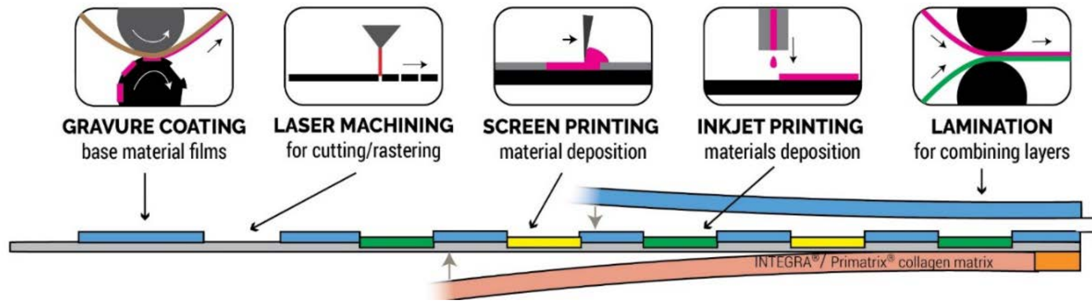
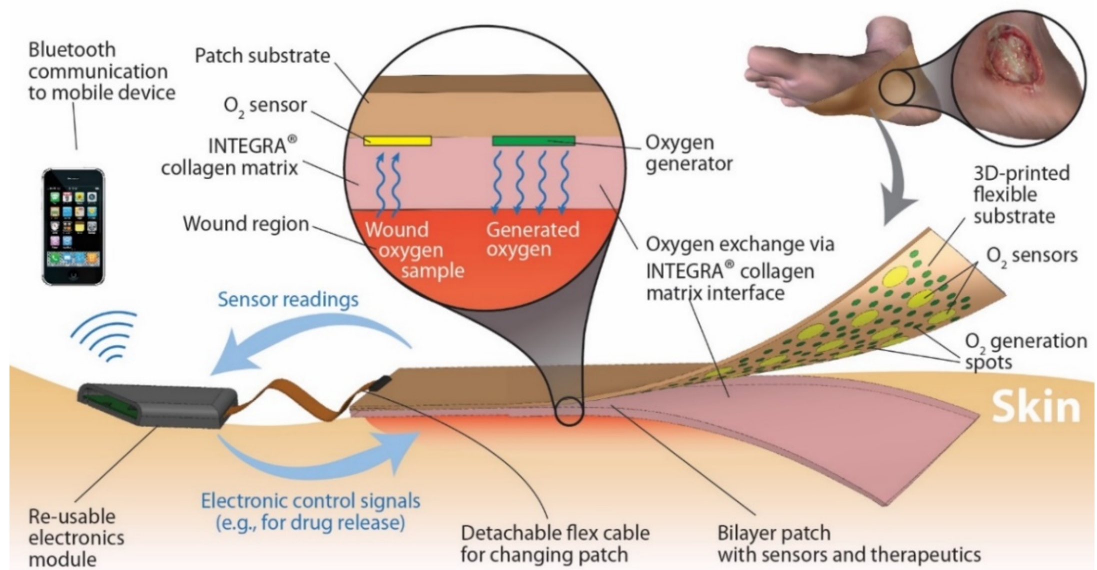
Oxygen in Wound Healing



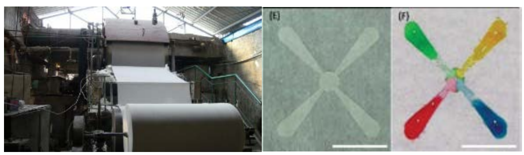


- Impaired vasculature susceptible to tissue hypoxia.
- 5 to 20 mm Hg in chronic wounds
- 30 to 50 mm Hg in normal tissue
- Oxygen is critical element for sustaining all phases of wound healing

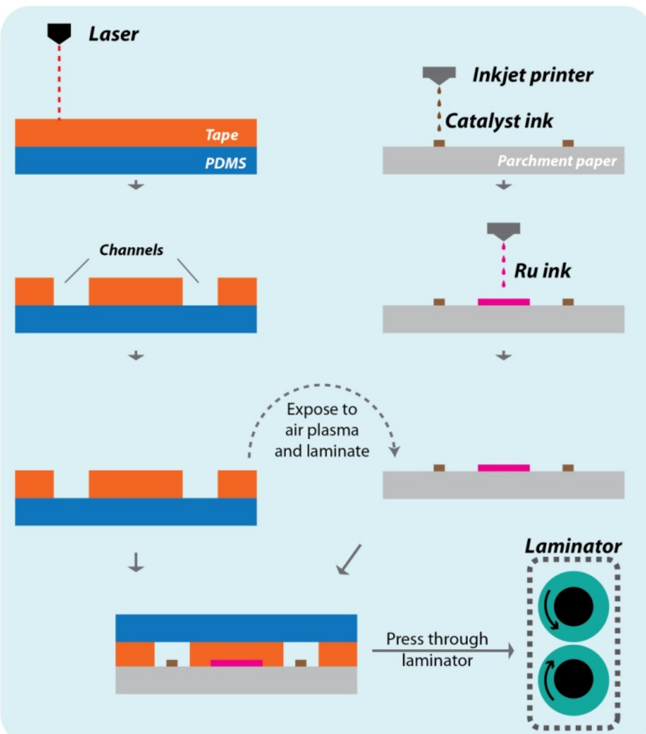
Substrate and interface films

Parchment paper substrate

- Flexible
- Available in rolls (for R2R)
- Inexpensive
- Gas permeable

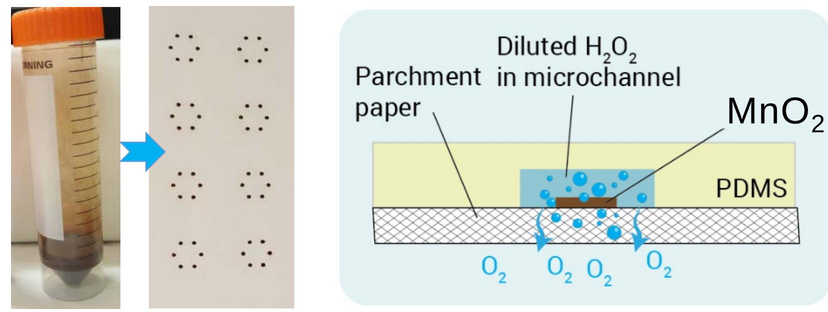


G. Chitnis et al. *Lab Chip*, 2011, 11, 61–5.



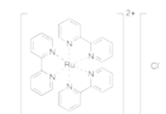
Generation via catalysis

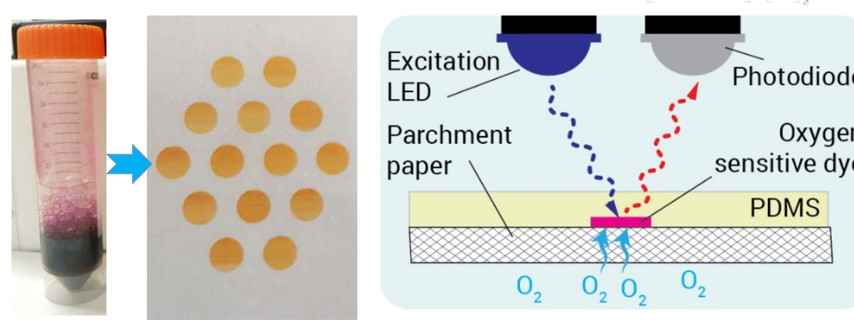
$$2H_2O_2 \xrightarrow{MnO_2} 2H_2O + O_2$$



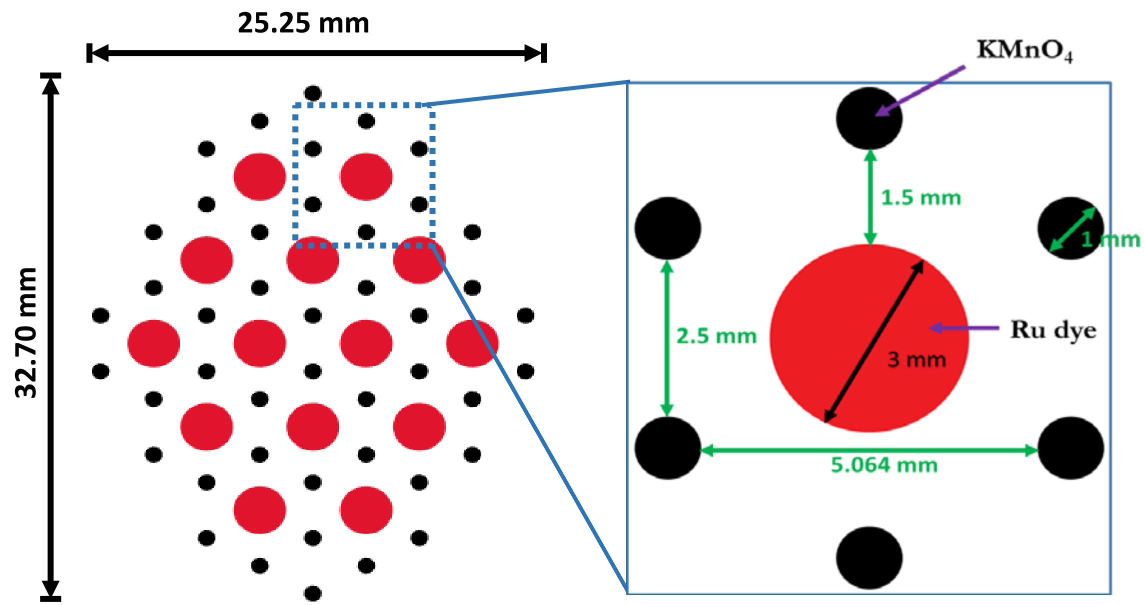
Sensing via phosphorescence

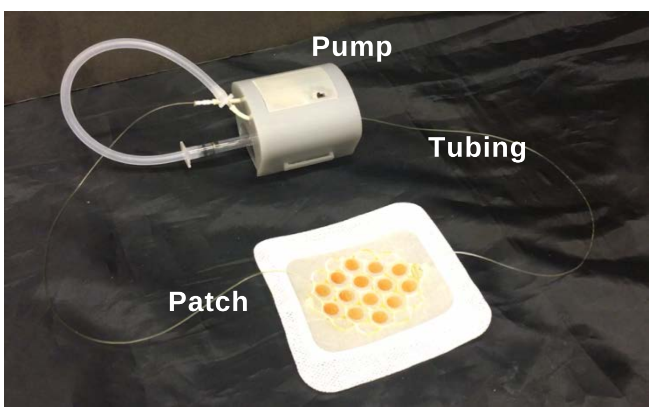
$Ru(dpp)_3Cl_2$

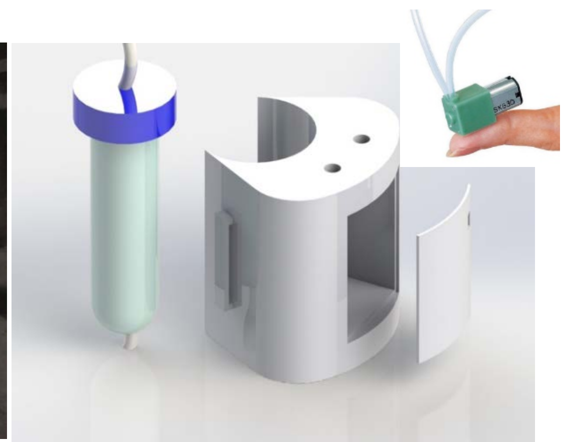




Design of honeycomb and unit cell patterns



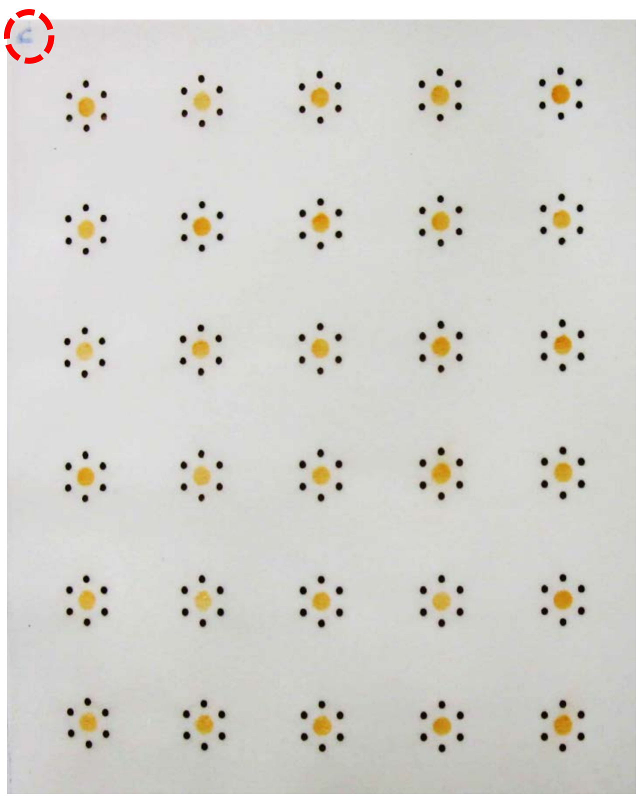




- PR Q1 Peristaltic pump
- 3.4 V DC voltage supply
- ATmega328P (Atmel) programmed to generate PWM signal
- ~50mA maximum current
- 5 - 100 µl/min flow rates
- 50 kPa pumping pressure

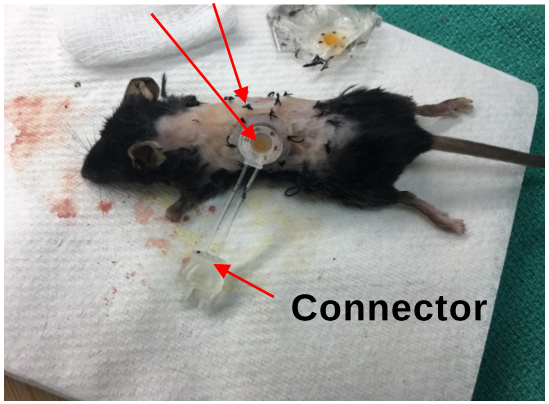
Unit cell and *in-vivo* studies

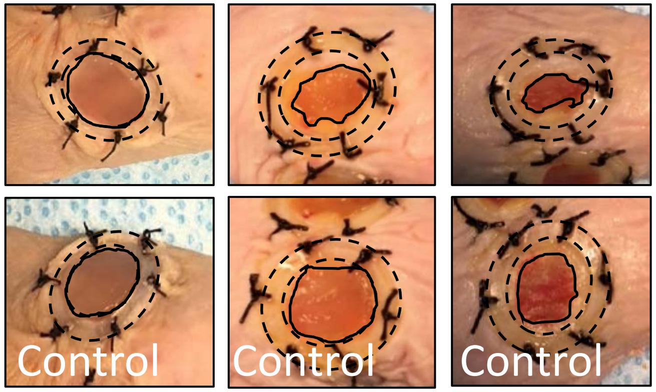
- Number of Ru layers = 1
- Number of $KMnO_4$ layers = 3
- Number of unit cell patches per sheet = 30



Printed unit cell array

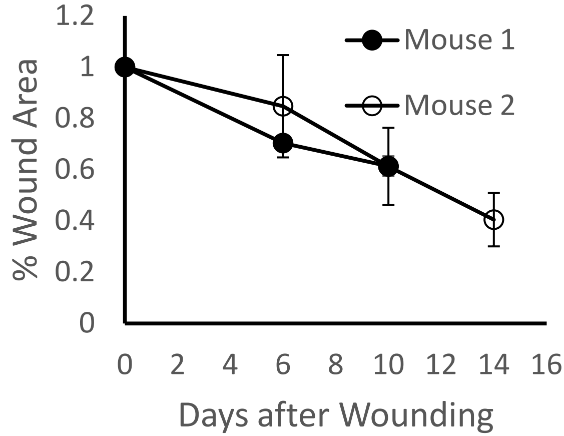
Patches on wounds



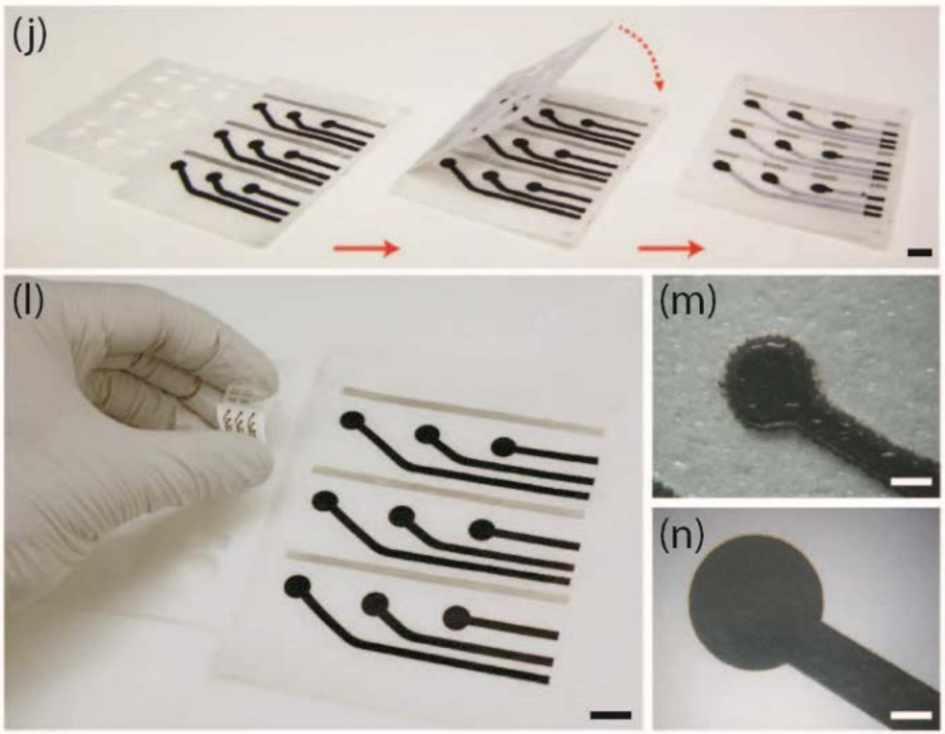


Mouse (diabetic) with patch and 14 day O_2 treatment vs. Integra alone

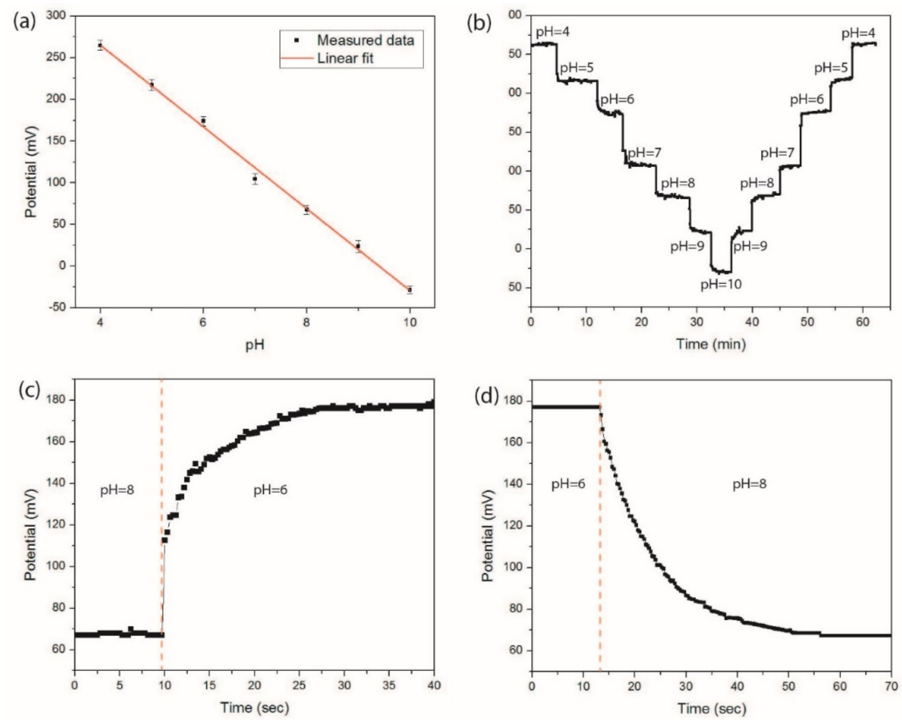
Wound area calculations vs. time



Screen printed pH sensor array on paper

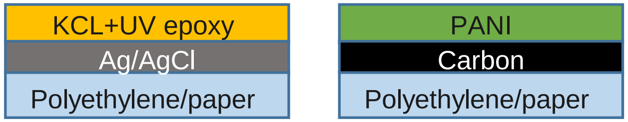


R. Rahimi, et al. Sensors and Actuators B (2016)



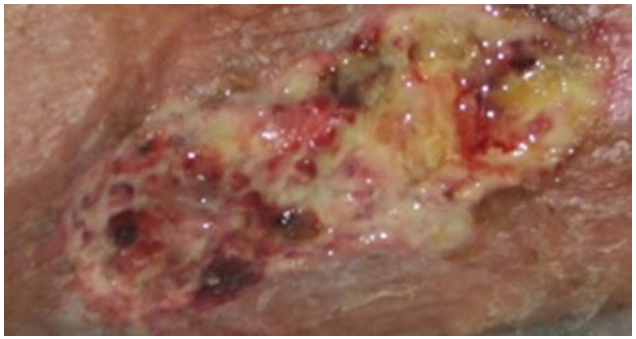
Potentiometric measurements:

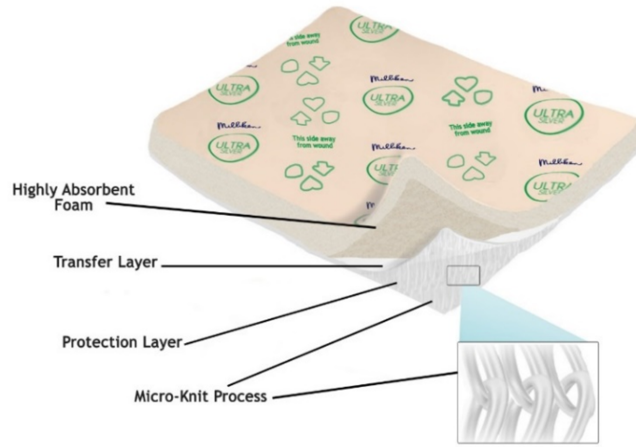
- 4-10 pH with sensitivity of −51 mV/pH
- Response time 24s for the for pH 6–8



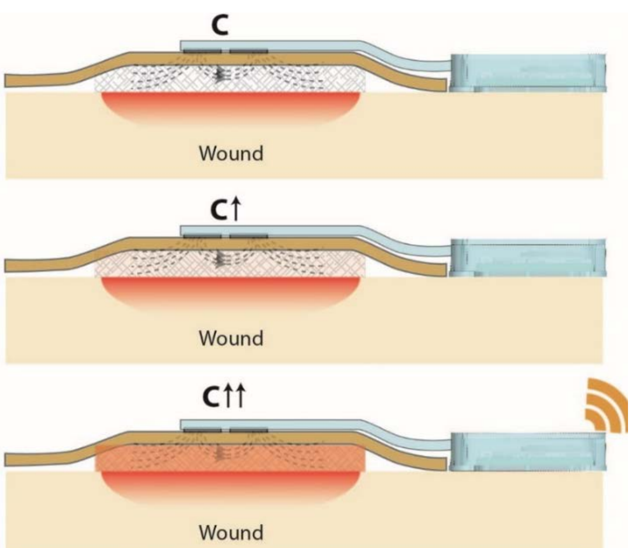
Purdue University · muRata · Cleveland Clinic

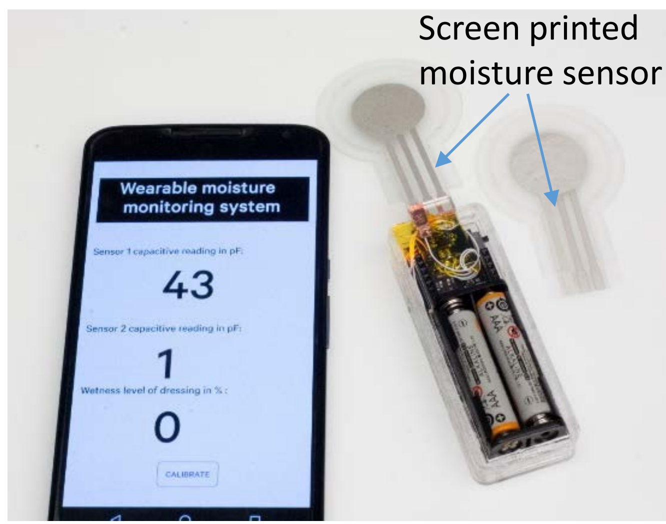
Moisture sensor for wound dressing





- Moist wounds **heal 2-3 times faster**
- Wounds that are too moist can become macerated, which can lead to further skin breakdown.





- Non-contact Capacitive moisture measurement
- Wireless low-power Bluetooth interface

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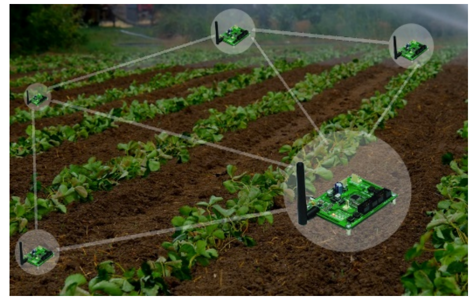
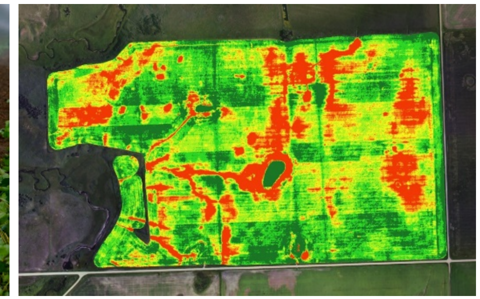
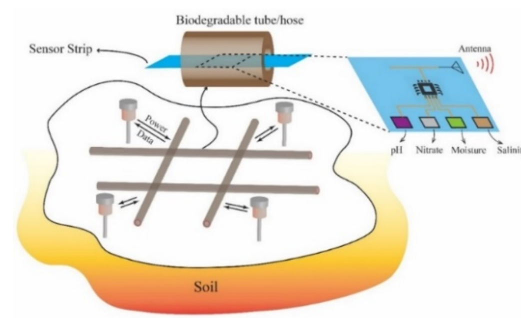
muRata

Smarter Agriculture

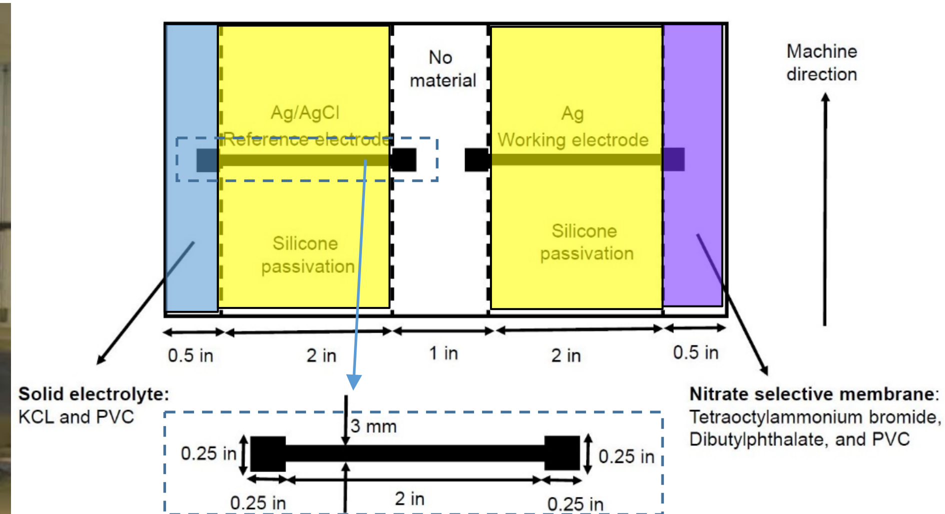
- Accurate measurement (such as N, P and K)
  - ➢ Adjust fertilizer application rates
  - ➢ Improve agricultural production
  - ➢ Excessive use of fertilizers causes contamination (groundwater)
- Real-time, in-field and non-destructive measurement
  - ➢ Reduce operational expense
  - ➢ Increase testing throughput





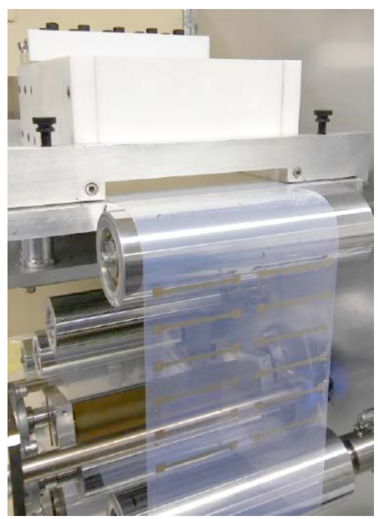


PRINTING SMART FILMS



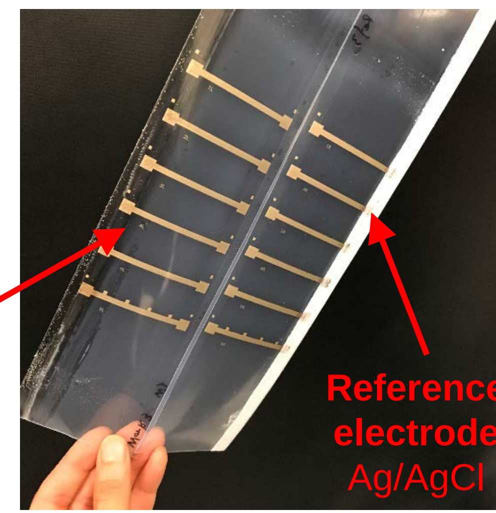
Printed silver electrode

Printed electrodes



Strip coating membranes

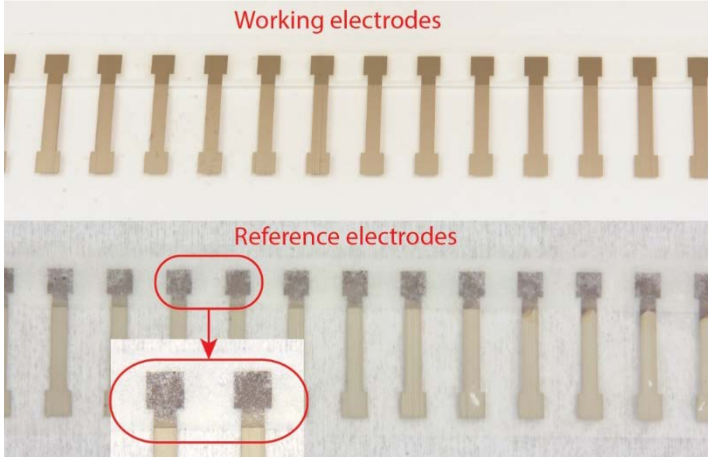
ISE Working electrode

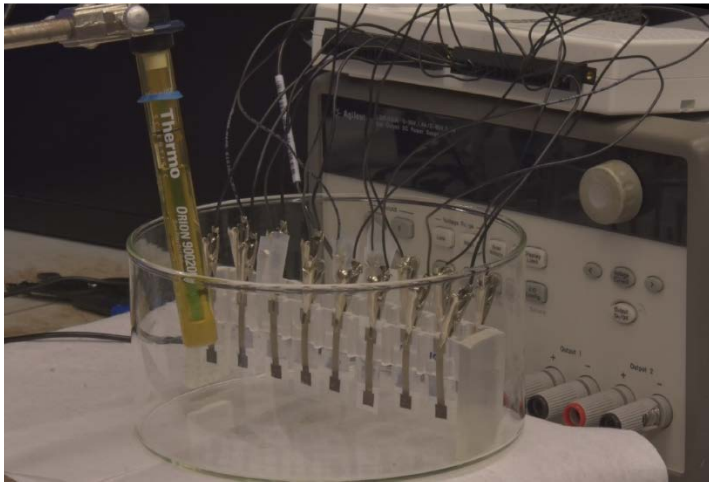


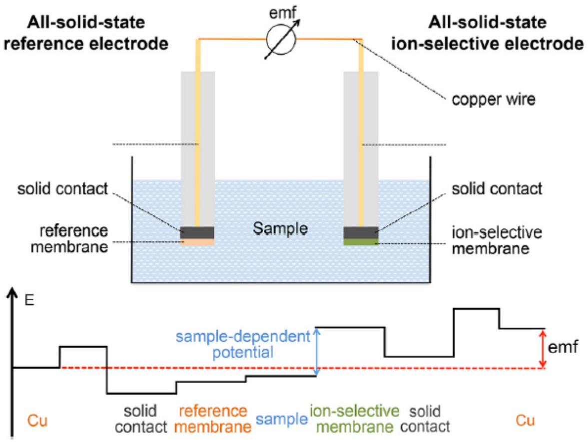
Reference electrode
Ag/AgCl

PRINTING SMART FILMS

Roll-to-roll fabricated Nitrate Sensors





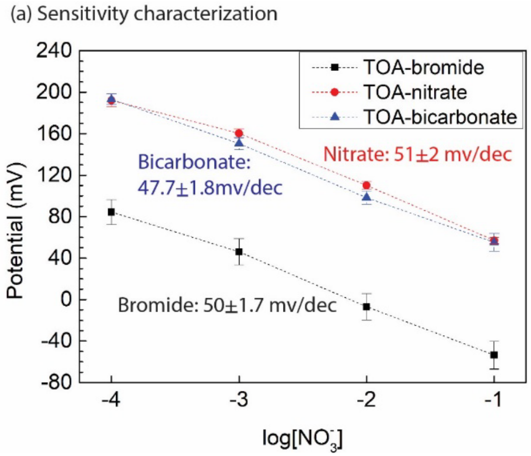


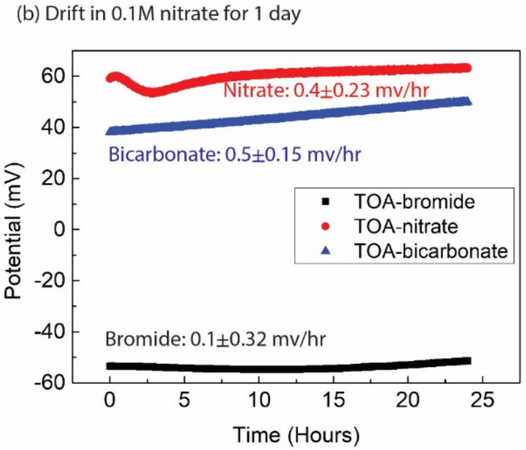
According to Nernst Equation:

$$E_{meas} = const + \frac{0.05916}{z} \log A_{unk}$$

Charge of ion

Ion activity/concentration



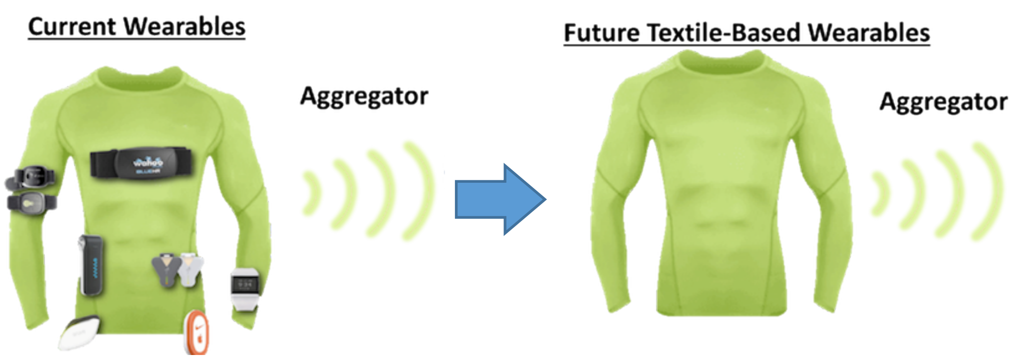


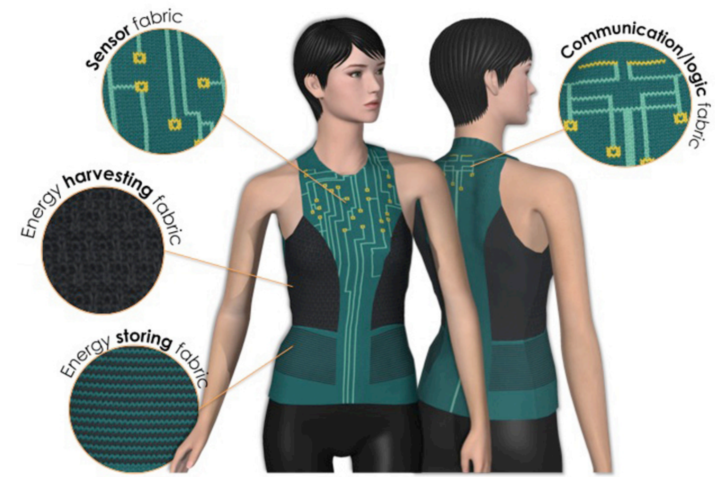
All the sensors show linear response vs concentration

Outline

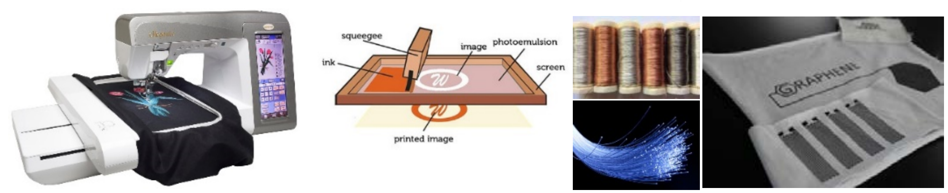
- Introduction
- Laser carbonization
  - Laser-induced porous carbon
  - Functionalization
- Laser ablation
  - Selective etching of multilayer films
  - CO_2 vs Nd:YAG
- Printed-electronics
  - Health-care
  - Precision agriculture
- **Future work**
  1) Textile-Based Wearable Electronics
  2) Smart Functional and Biodegradable Films
  3) Scalable manufacturing of hybrid systems

①Textile-Based Wearable Electronics

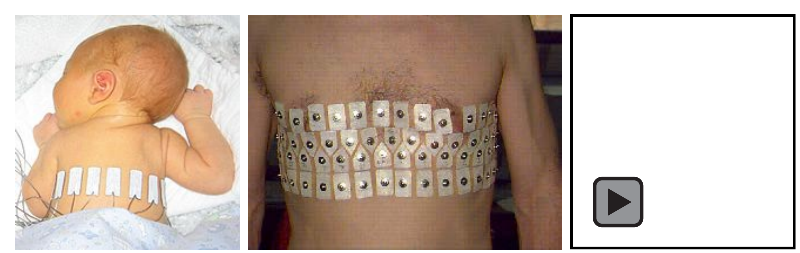




- Natural feeling and Breathable
- Functional materials:
  - Threads, Micro-tubes, fiber optics, inks and therapeutics.
- Screen printing and Embroidery
- Monitoring
  - EKG, Pressure ulcers, Gesture recognition
  - Aortic waveform, Tissue oxygen
  - Cystic fibrosis, Pneumothorax, Pulmonary blood flow (Perfusion)



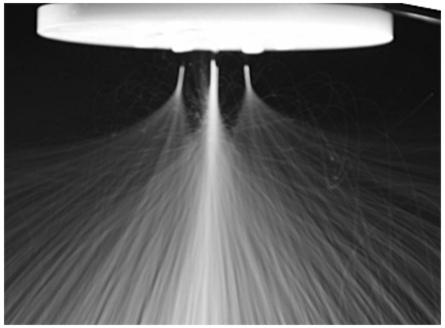
Embroidery, weaving and screen printing



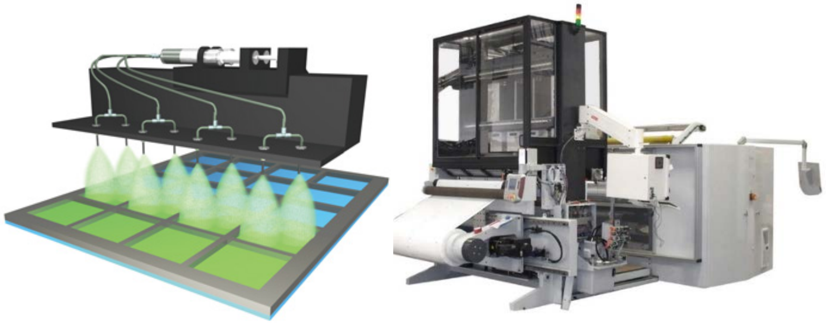
Electrical impedance tomography

NEXTFLEX

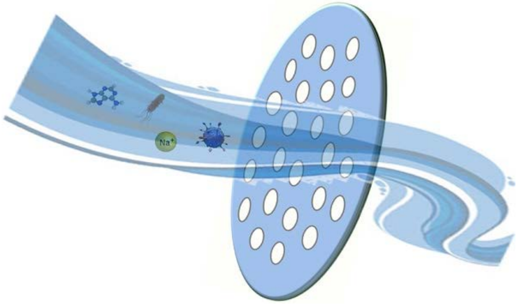
②Smart Functional and Biodegradable Films



Electro-spray nanofibers



Scale-up Laser processing



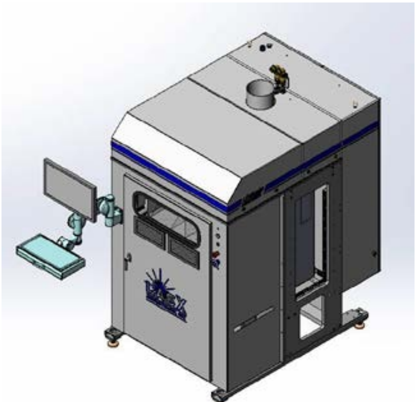
Filters/Energy storage

- Water purification
- Energy storage (e.g. Super capacitors, batteries)
- Food packaging with Nano materials
- Biodegradable films and Sensors
- Physiologically relevant films for tissue engineering and drug discovery
- Non-woven dressing with functional nano materials and hydrogels (e.g. AgNP, ZnO)

Hydrogel Electronics

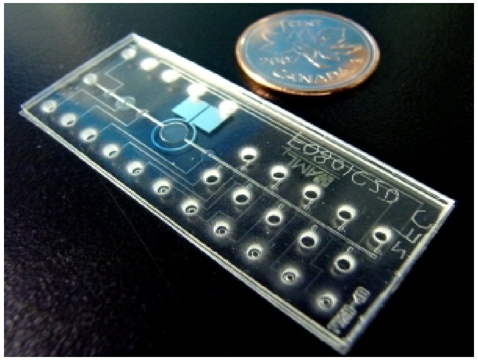
Biodegradable Electronics!

③Scalable manufacturing of hybrid systems



Scale-up Laser processing (LasX)

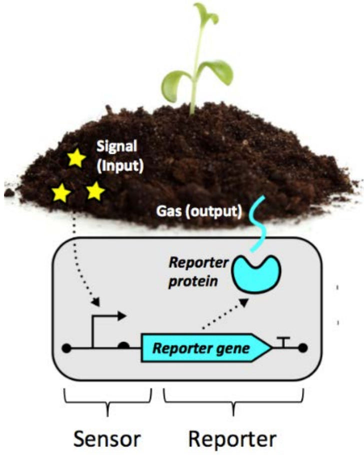
Drug delivery and pharm



Micro-fluidics /lab-on-chip

- Scale-up processing techniques with roll-to-roll laser system (LasX)
- Identifying Scale-up challenges
- Inexpensive Nano carbon-based Biosensors
- Hybrid electronics for food/therapeutics packaging
- Combat the spreading of the counterfeiting of drugs

Smart food/drug packaging



Soil microbial activities

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Prof. Alina Alexeenko
Prof. Lia Stanciu
Dr. Pooria Mostafalu
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Dr. Girish Chitnis
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Dr. Seung Huyn Song
Dr. Jun Hyeong Park
Dr. Albert Kim
Mr. Hongjie Jiang
Dr. Charilaos Mousoulis
Dr. Mohammad Ali Shirazi
Dr. Sultan Helmi
Dr. Hossein Pajouhi
Dr. Pankaj Jha
Dr. Shirisha Chittiboyina
Ms. Farzaneh Atrian
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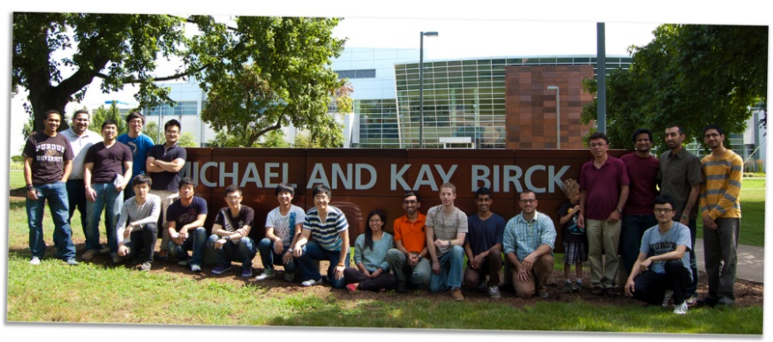

Thank you for your attention!

Questions?