Introduction to Nanotechnology and Nanoscience – Class#18

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Outline

- □ Review
- □ Conventional Electrospinning
- □ HW#6
- □ Paper 7
- □ Quiz I
- □ Small Project Presentations

Langmuir Blodgett Coating

Schottky Contact

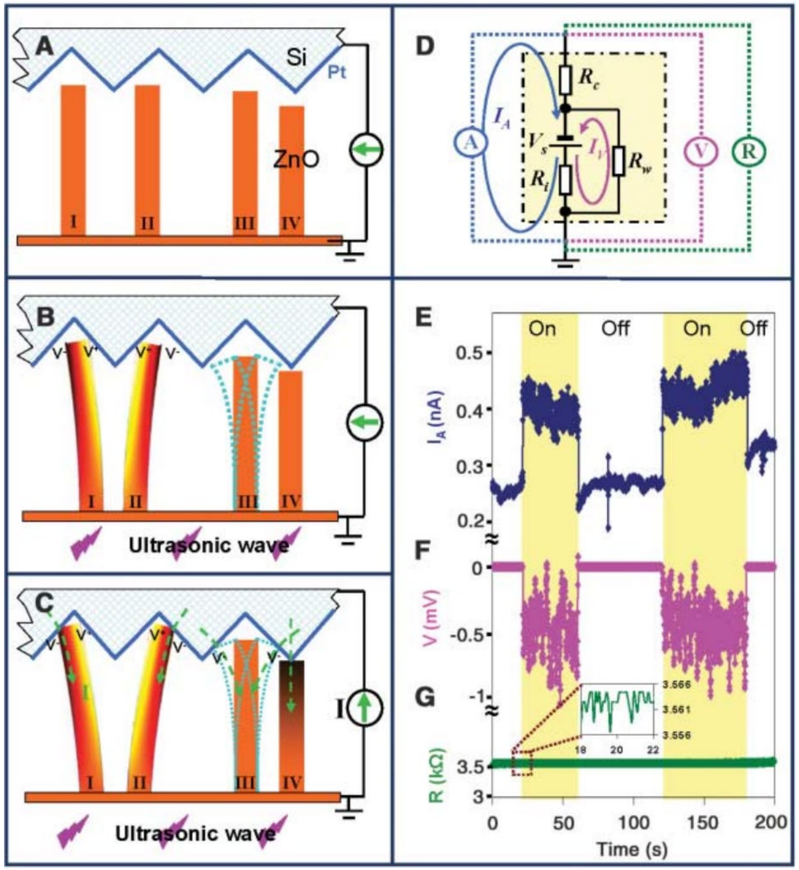
Schottky barriers have rectifying characteristics, suitable for use as a diode.

Not all metal–semiconductor junctions form a rectifying Schottky barrier; a metal–semiconductor junction that conducts current in both directions without rectification, perhaps due to its Schottky barrier being too low, is called an ohmic contact.

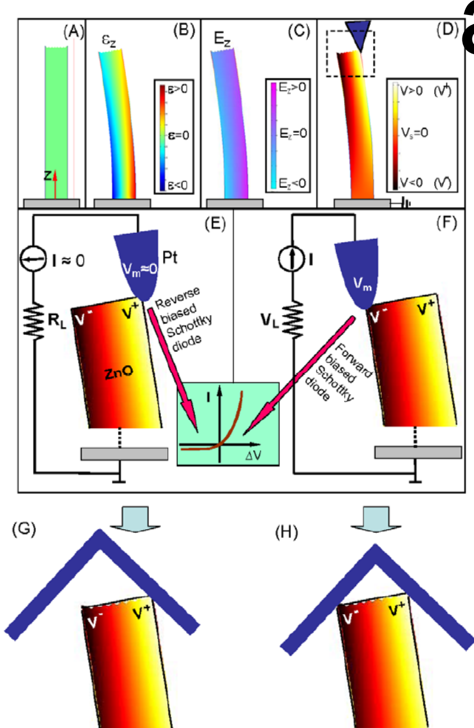
Schottky contact happens both when the semiconductor is n-type and its work function is smaller than the work function of the metal, and when the semiconductor is p-type and the opposite relation between work functions holds

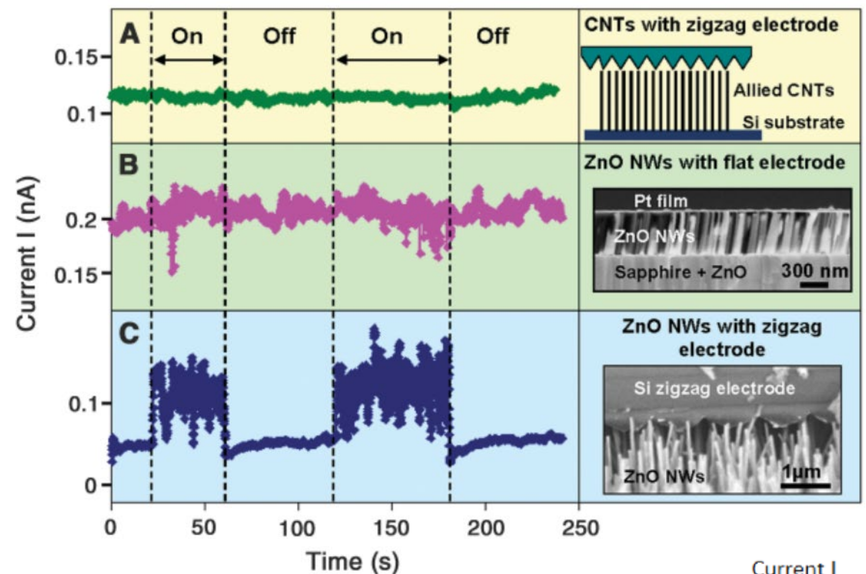
Ultrasonic Waves

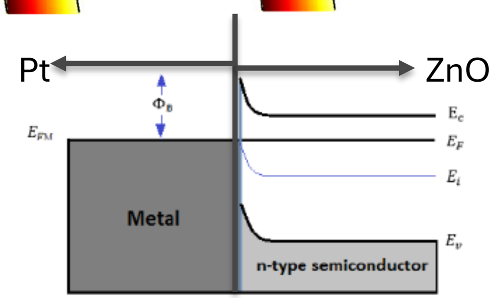
- 2 processes for creating, separating, preserving accumulating, and outputting charges
  - Asymmetric piezoelectric potential
  - Schottky contact
- Top electrode replaces the role of AFM tip
  - Zig zag trenches = array of aligned AFM tips
- **Discharge Process**
  1. Ultrasonic wave excitation
  2. Electrode moves down and pushes NW
  3. Lateral deflection of NW1
  4. Strain field created across width of NW1
  5. Inversion of piezoelectric field (V- to V+)
  6. Electrode contacts NW surface = little current across interface
  7. More pushing = NW reaches other side of adjacent tooth
  8. If electrode is in contact with compressed side of NW = sudden increase in output electric current



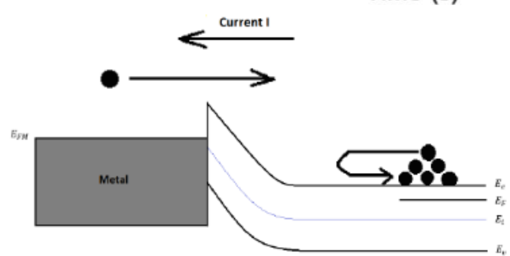
Mechanism of ZnO Generator and Control study (Page 4)



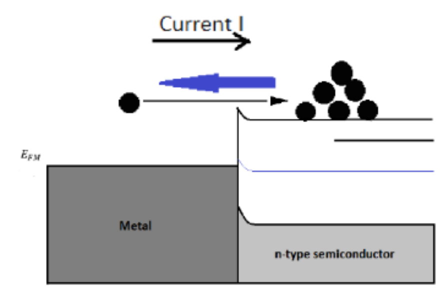




No strain in ZnO NW



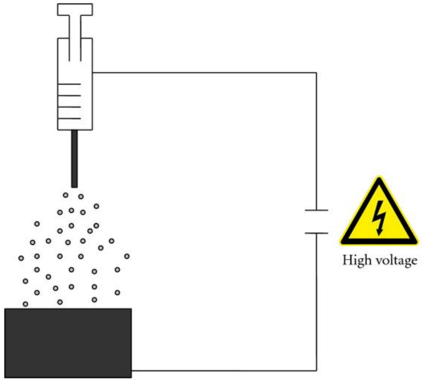
Corresponding to (G) Reverse Bias



Corresponding to (H) Forward Bias

Electrospinning history: *pre-1900*

- **Mathias Bose, 1735**
- Electrospraying of alcohol
- Early aerosol spray



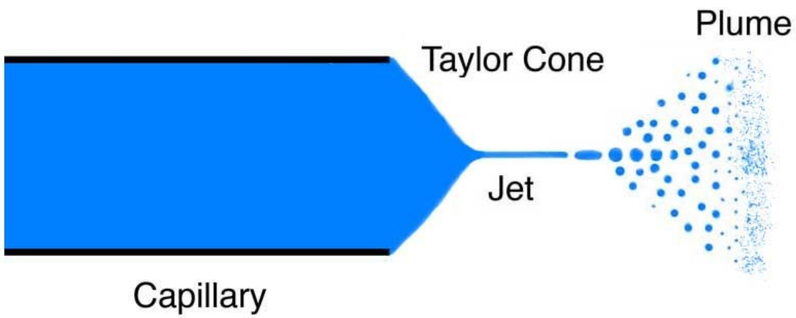
Cavalli, et. al. Poly(amidoamine)-Cholesterol Conjugate Nanoparticles Obtained by Electrospraying as Novel Tamoxifen Delivery System. 2011, *Journal of Drug Delivery*.

- **Lord Rayleigh, 1882**
- Calculated max amount of charge a drop can hold
- Electrical repulsion vs surface tension

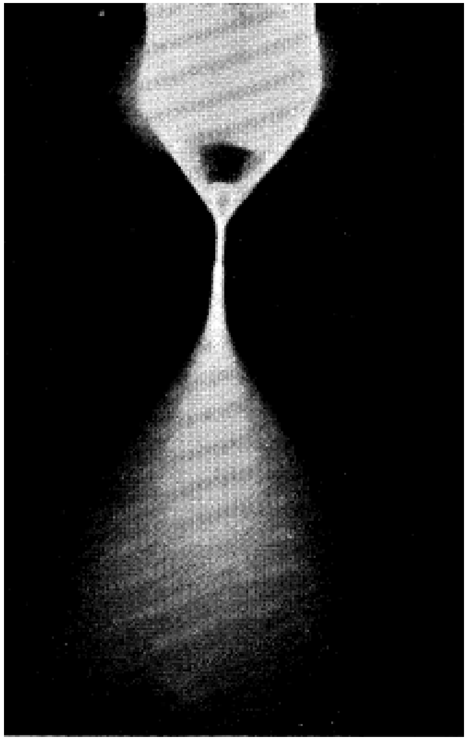
From *Wikipedia* article on Lord Rayleigh

Electrospinning history: *1900-1970*

- ☐ Zeleny 1917: first to record pictures of electrospinning
- ☐ Taylor: Taylor cone analysis (49.3° semi-angle)



From *Wikipedia* article on Taylor cone



Zeleny, J. Instability of electrified liquid surfaces. 1917 *Phys. Rev.*

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ME118/218N, Spring 2024 **Liwei Lin**

Problem Set #6
Due March 21 (Thursday)

Problem 1 (Nanowire Applications)

Draw a schematic diagram of a nanowire-based MOSFET (there are different ways to answer this question and you only need to come up with one way).

(a) If the nanowire is used as the "gate" – draw a process flow to make this MOSFET

(b) If the nanowire is used as the "channel" – draw a process flow to make this MOSFET

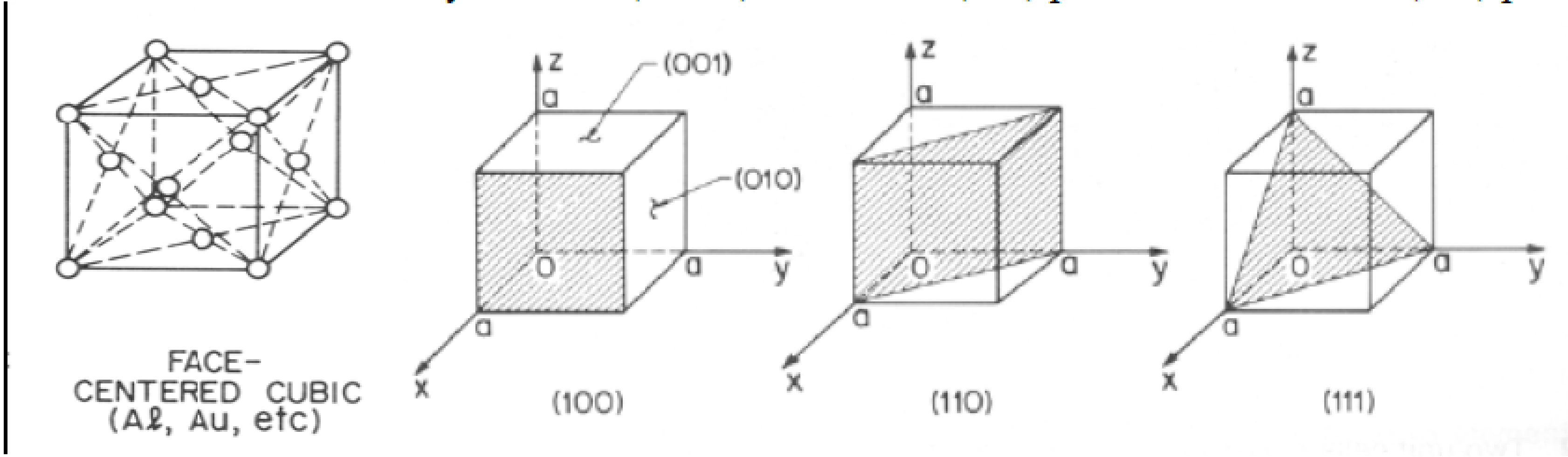
Problem 2 (Nanowire Basics - Crystallography)

Conventional (cubic) unit cell for a face-centered cubic crystal is shown below. There is an atom at each corner of the cube, and one atom at the center of each facet.

(a) Calculate the density of atoms ($\#.cm^{-3}$) in a face-centered cubic (f.c.c.) crystal as a function of the lattice constant **a**.

(b) Calculate the density of atoms in silicon. Crystalline silicon has a diamond structure (***not f.c.c.***) with lattice constant **a=5.43Å**

(c) Calculate the density of atoms ($\#.cm^{-2}$) in a silicon (100) plane and in a silicon (111) plane



Problem 3 (Conventional Electrospinning)
Please find FIVE different polymeric materials that have been successfully demonstrated in the literature by means of electrospinning.

a) Material or material compositions?
b) Their specific applications in the particular article you have found?
c) Please write down the author, title, journal, page numbers, year of the article similar to one would write as a reference in a research paper.

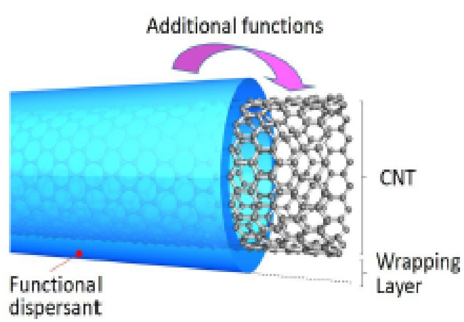
Small Projects

Carbon Nanotubes for Spacecraft Shielding

Drake Lin

Problems in Space

- Constant exposure to cosmic radiation damages and eventually destroys electronics
- Current material is too reflective
- Spacecraft relies a lot on weight



CNT Proposal

- Polymer nanocomposites incorporating CNTs have emerged as an alternative to traditional materials for EMI shielding
- CNT forests absorb light and converts to heat, resulting in ultrablack material

Thus, reinforce polymer with MWCNTs and utilize CVD to grow CNT forest

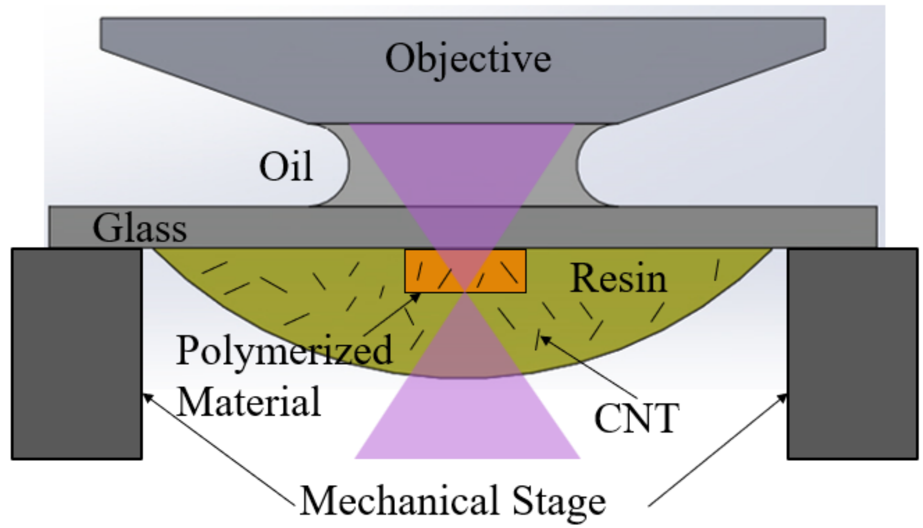
The resulting material will be highly effective and structurally sound for spaceflight

1. *Carbon Nanotubes: Applications in Satellites*, Prasad, Godwin
2. *Formation of Carbon Nanotubes in a Microgravity Environment*, Alford et a
3. *Radiation Shielding System Using a Composite of Carbon Nanotubes Loaded With Electropolymers*, Ames Research Center

CNTs in 2PP Printing

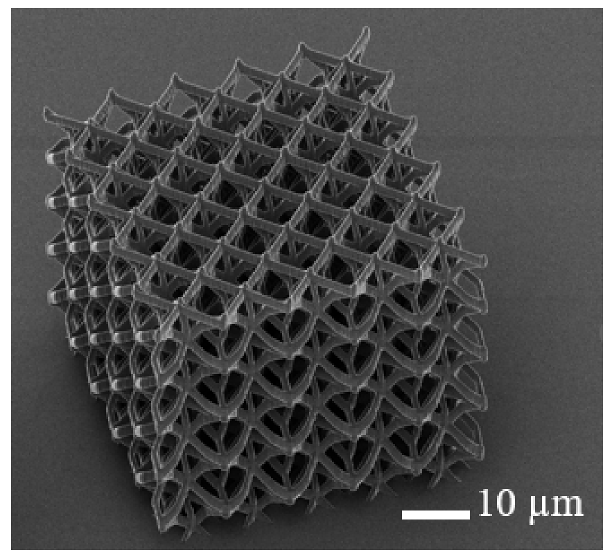
- 2-photon-polymerization printing
- High resolution additive manufacturing with nanoscale features

→ Adding CNTs in liquid polymer resin to enhance mechanical, electrical, and thermal properties



Example: Metamaterial Scaffold

- Deformation controlled by structural design (e.g. poisson ratio)
- Stiffness, buckling and thermal properties determined by Polymer/CNT nanocomposite



Facile Fabrication of Multilayer Stretchable Electronics via a Two-mode Mechanical Cutting Process

Renxiao Xu, He , G. Lan, K. Behrouzi, Y. Peng, D. Wang, T. Jiang, A. Lee, Y.Long, and L. Lin,

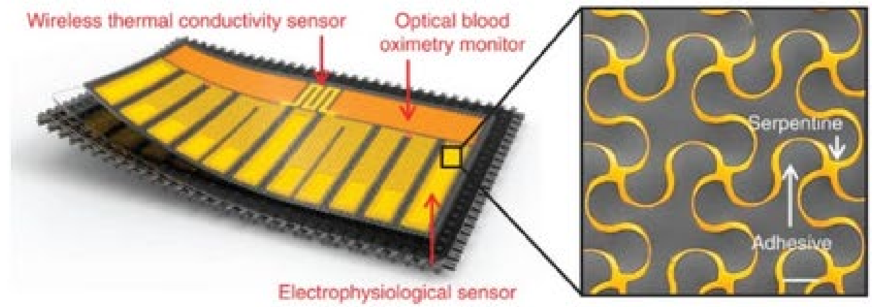
ACS Nano 2022

ME 118/218 Paper 7: Yichen Liu

Background

- Stretchable electronics are electrical system capable of mechanical deformations consisting of two types:
  - **Intrinsic** soft functional electrical materials
  - Rigid electrical **island** connected by soft **bridges**

- The mechanical capabilities fit curvilinear surface of skin and organs in bio-application



[1]

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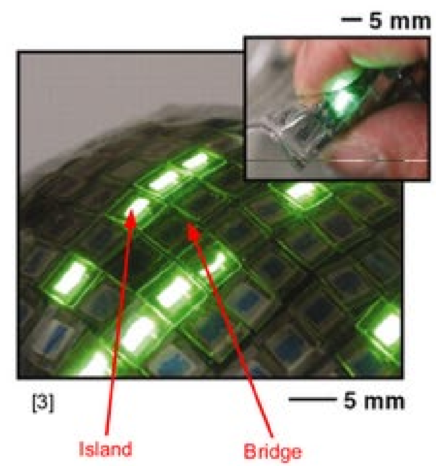


[3]

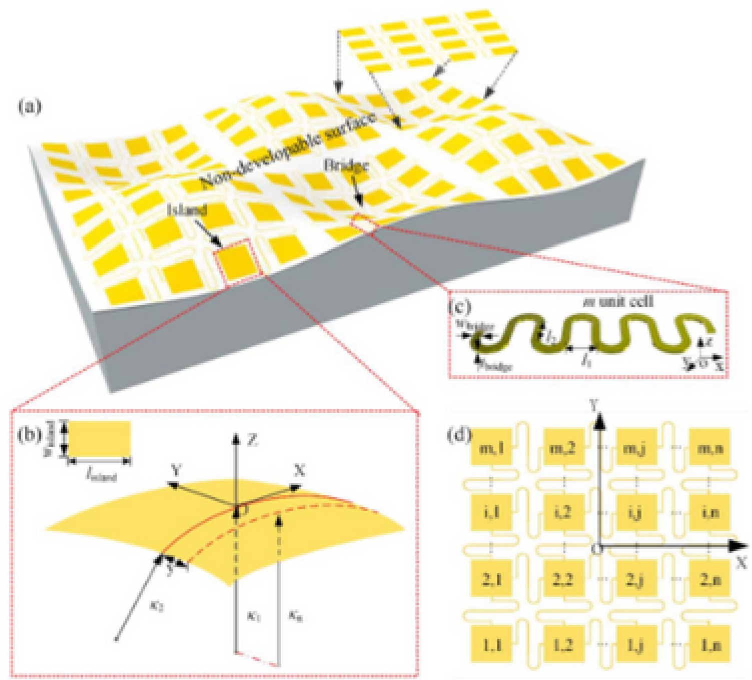
[1] Jang, K.-I.; Han, S. Y.; Xu, S.; Mathewson, K. E.; Zhang, Y.; Jeong, J.-W.; Kim, G.-T.; Webb, R. C.; Lee, J. W.; Dawidczyk, T. J.; Kim, R. H.; Song, Y. M.; Yeo, W.-H.; Kim, S.; Cheng, H.; Rhee, S. I.; Chung, J.; Kim, B.; Chung, H. U.; Lee, D.; et al. Rugged and Breathable Forms of Stretchable Electronics with Adherent Composite Substrates for Transcutaneous Monitoring. Nat. Commun. 2014, 5, 4779

[2] Shaolei Wang et al. ,Intrinsically stretchable electronics with ultrahigh deformability to monitor dynamically moving organs.Sci. Adv.8,eabl5511(2022).DOI:10.1126/sciadv.abl5511

[3] Sekitani T., et al., Stretchable active-matrix organic light-emitting diode display using printable elastic conductors. Nat. Mater. 8, 494 (2009).

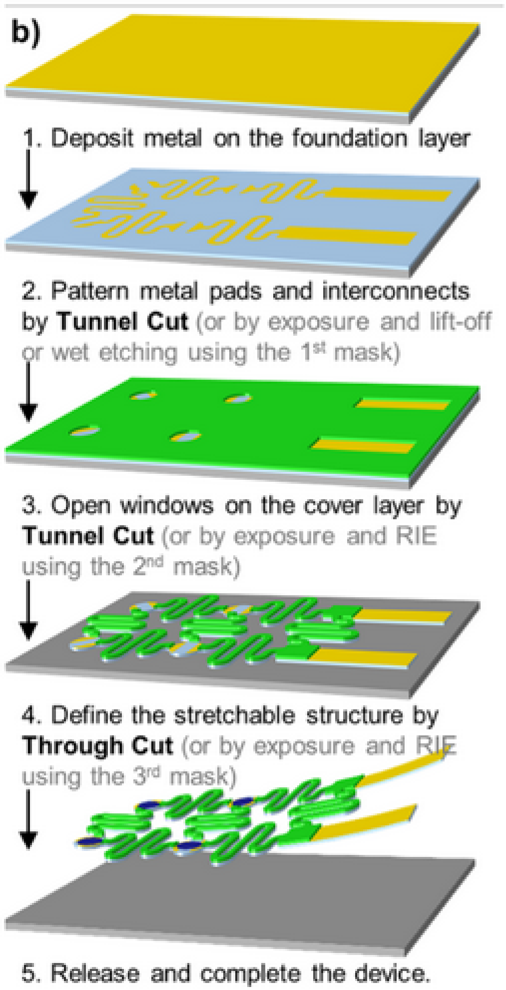
Island-Bridge Stretchable Device

- Island of traditional non-stretchable electronic material
  - Low strain
- Bridge of serpentine-shaped interconnect
  - Compliant material
- Wider range of application with more material selection



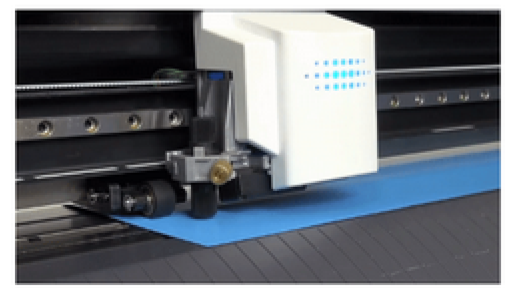
Traditional Fabrication Process

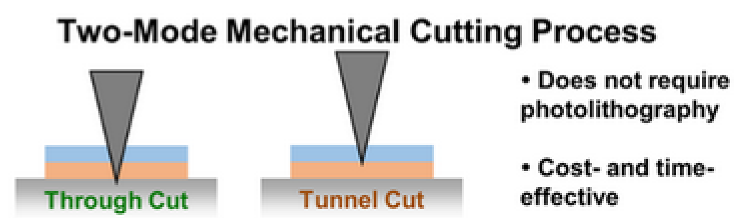
- Advantage:
  - High resolution ~10um
  - Scalable for large scale production
- Disadvantage:
  - At least three photomasks
  - Requires Reactive Ion Etch - Time and Cost
- Does not fit research and prototype needs



Two-Mode Mechanical Cutting Process

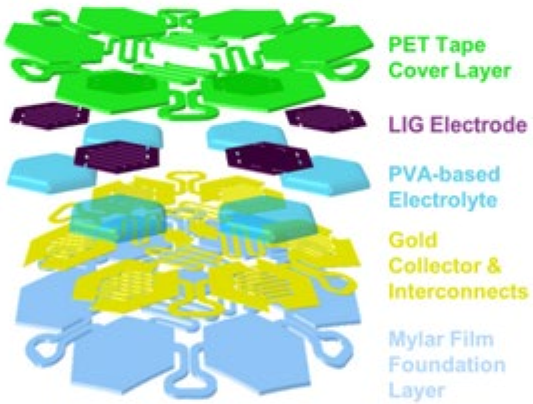
- Vinyl cutter is used to define pattern
  - Mechanical shear
  - Previous work shows 100-400um resolution
  - No heated added like laser cutter



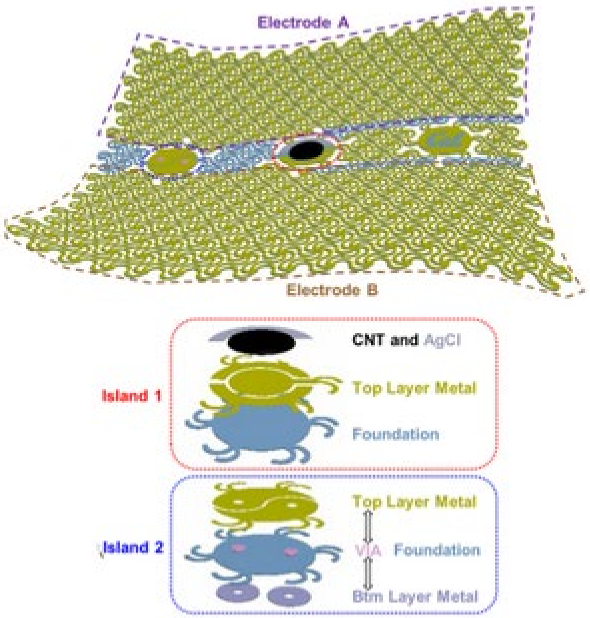


Sensor Application

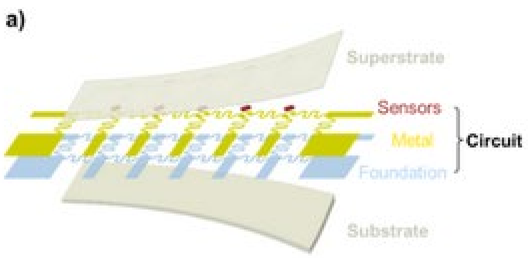
water-resistant stretchable supercapacitor patch



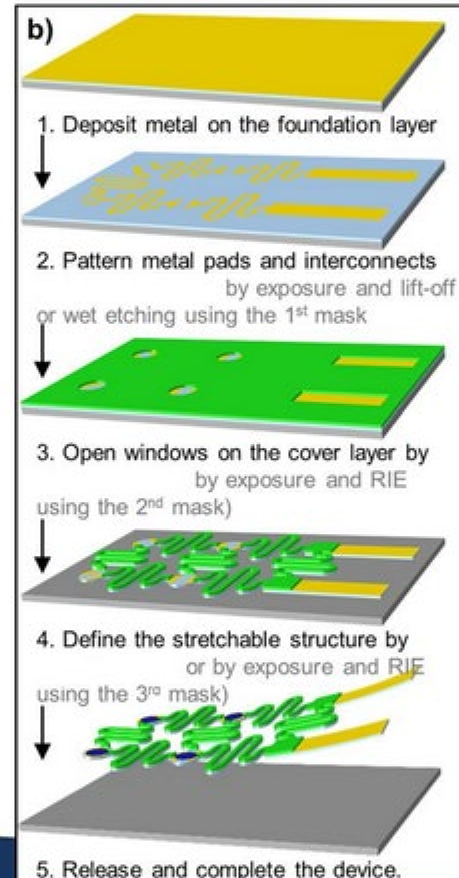
Stretchable "Smart Mesh"



Skin-mounted Human Breathing Monitoring Module



Photolithographic Fabrication



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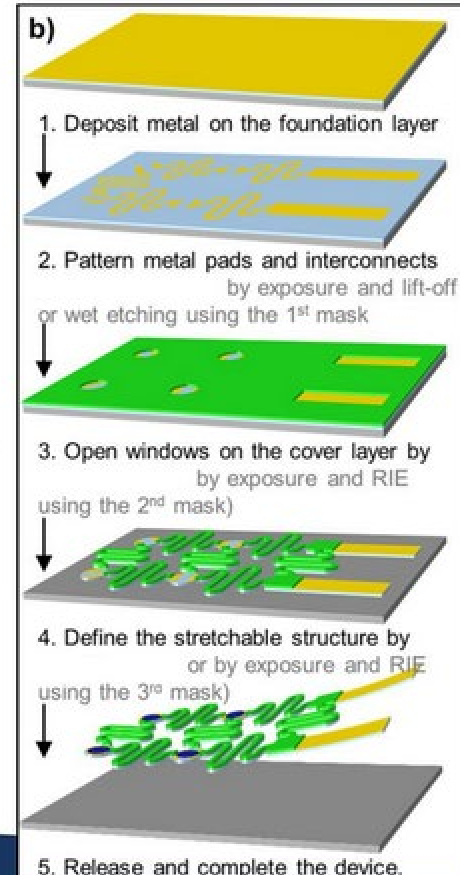
Photolithographic Fabrication

Downsides with Stretchable Electronics:

- Unsuitable for prototyping/small scale production (mask creation)
- Expensive Equipment
- Time consuming (especially drying)
- Fine resolution is unnecessary for many stretchable electronic systems (~10 cm²)



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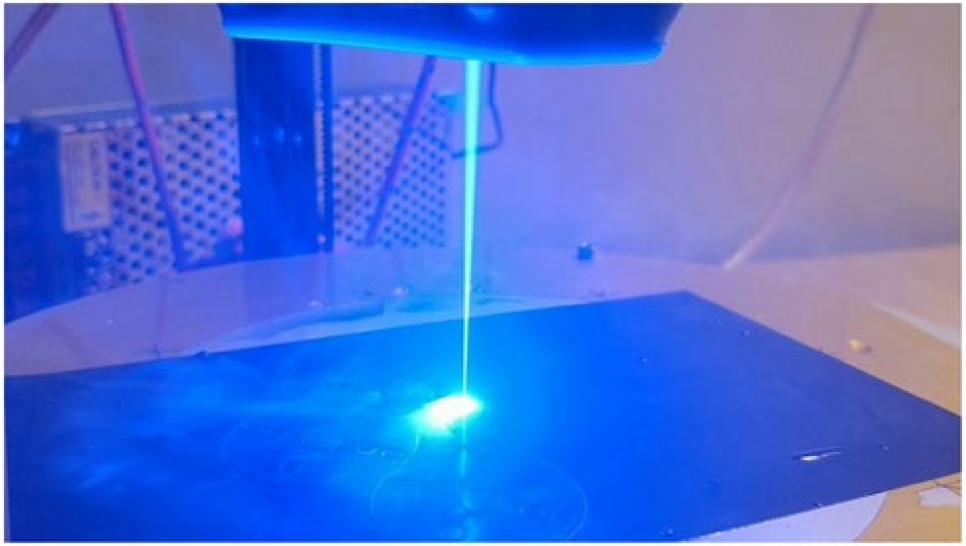
Laser Cutter Fabrication

Laser strength (usually ~9.6W) determines how much polyimide film is converted to graphene, changing electrical characteristics:

Low power -> High Resistance

High power -> Low Mechanical Stability

Can overheat nearby structures, affecting conductivity/nonconductivity



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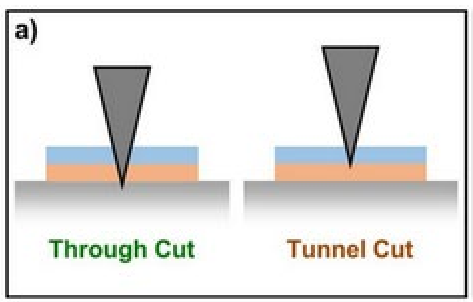
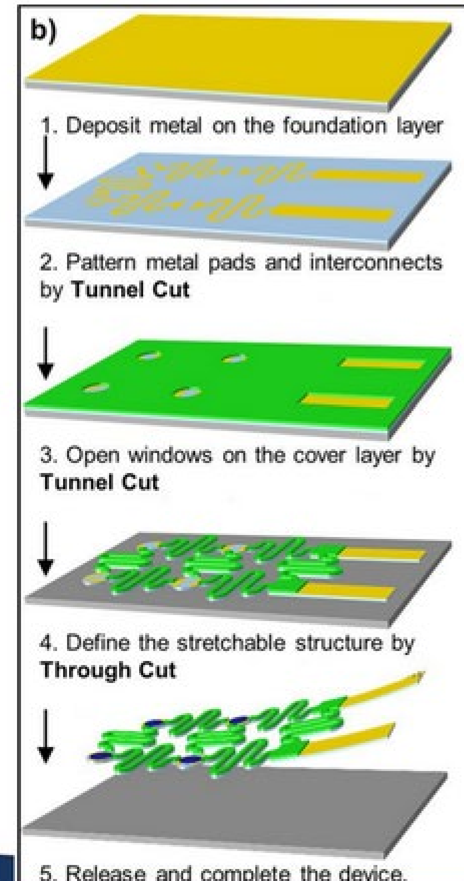
Proposed Method: Vinyl Cutter Fabrication





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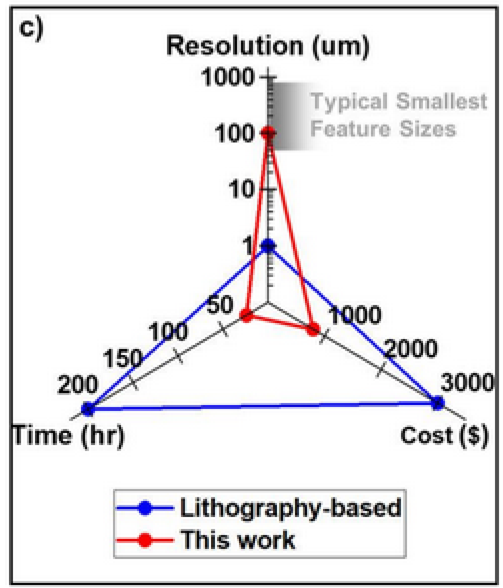
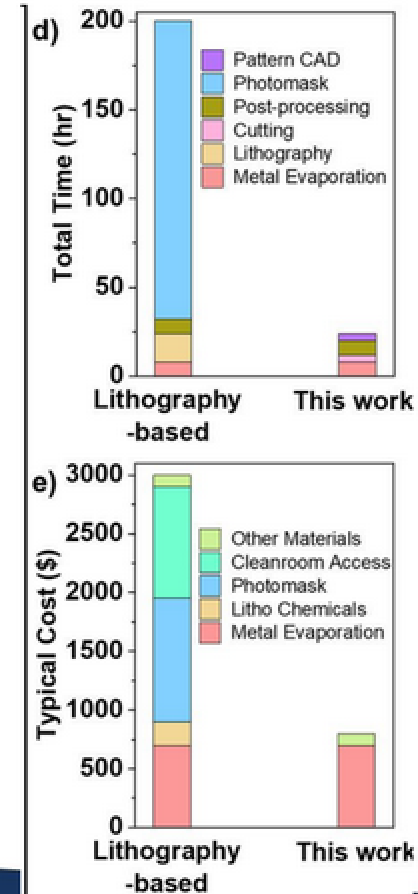
Proposed Method: Vinyl Cutter Fabrication

Advantages:

- No heat generation
  → No chemical alteration
- Inexpensive
- Fast





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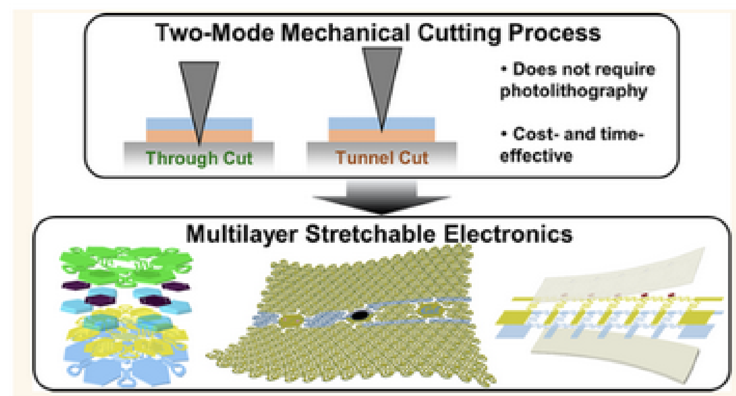
Modes of Mechanical Cutting and Innovative Applications

- Utilization of a desktop-sized commercial vinyl cutter (CAMEO 3, Silhouette Inc.) equipped with a cutting blade for defining and patterning material layers.
- Samples adhered through a thermal release sheet (TRS) to the cutting mat or directly to the mat's top surface during the cutting process.
- Temporary adhesive layer on TRS or cutting mat is heat-releasable or water-soluble (at 90 °C), allowing easy post-fabrication sample release.
- Flexible bilayer film setup achieves two mechanical cutting modes: **"through cut"** and **"tunnel cut"**
  - **"Through cut"** mode: high force and sufficient cutting depth to penetrate both material layers, defining outlines of deformable structures
  - **"Tunnel cut"** mode: lower force and adjusted blade depth, creates a tunnel in the upper layer while keeping the lower layer structurally intact
    - "Tunnel cut" serves as the foundation for patterning metallization and insulating cover layers *without* the need for photomasks or etching steps



Review of Cutting Modes

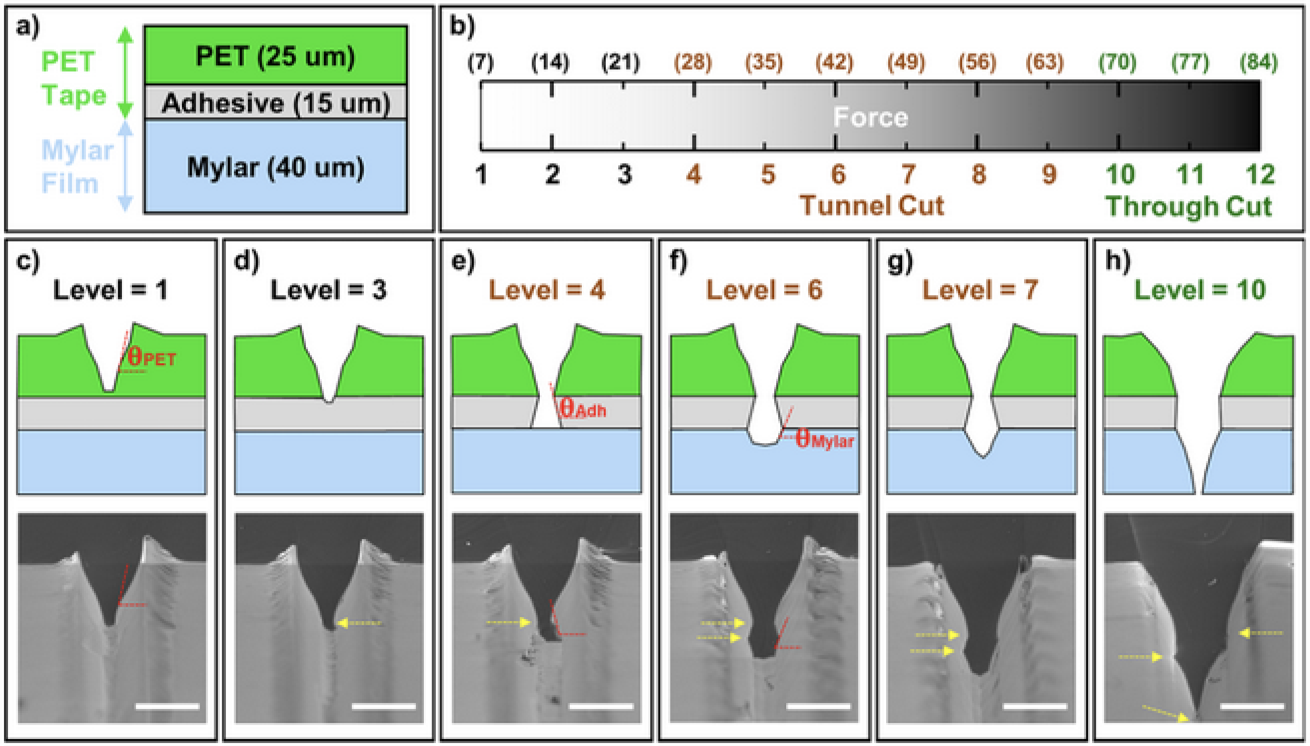
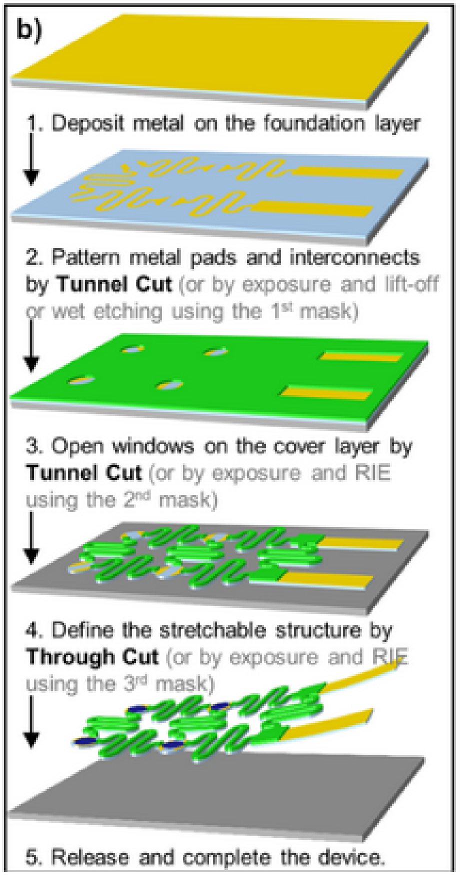


Figure 2. (a) Cross-sectional profile of a PET/adhesive/Mylar film. (b) Force level (force amount in gram-force) *vs* the mode of cutting for the film in (a). (c−h) Schematic illustrations (top row) and SEM images (bottom row) showing the effect of mechanical cutting at different force levels. Scale bars: 50 μm. Yellow arrows in SEM images correspond to interfaces between two materials, with the drastic changes in the slot angle.

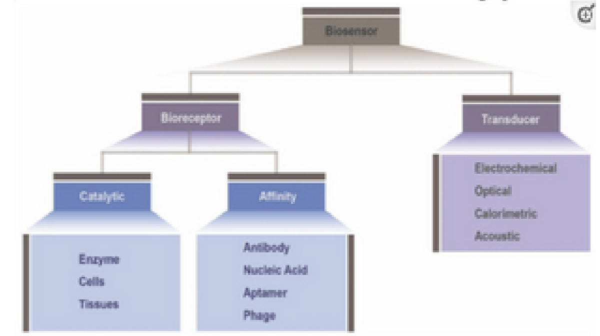
Fabrication Process

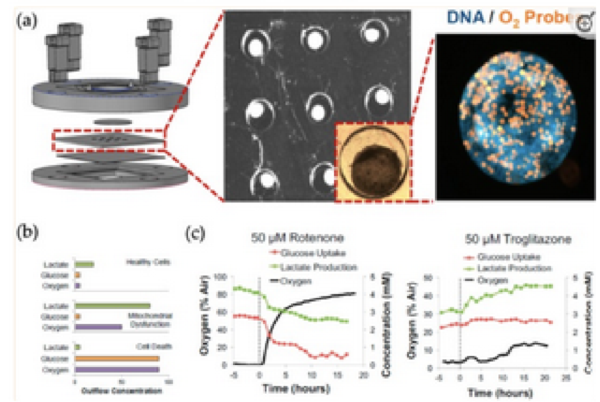
- Bilayer film setup with insulating, single-sided flexible tape as the upper layer adhered to a non-sticky flexible sheet as the lower layer.
- Steps of fabrication of the metal layer:
  - 1. Using "tunnel cut" mode to define patterns
  - 2. Removing selected regions by peeling
  - 3. Using remaining features as a physical mask during metal evaporation
  - 4. Completing the process by peeling off the upper layer
- This approach is termed the "mechanical lift-off" process, resembling traditional micromachining lift-off
- This process essentially allows you to “cut out” the expensive and intensive lithography process
- Steps of Fabrication of the Stretchable Area:
  - 1. Opening areas in stretchable electronics fabricated by using the "tunnel cut" mode along contour lines and separating them from the main portions of the upper layer
  - 2. peeling off the main structure
  - 3. transfer-pasting the upper layer with openings onto an insulating foundation film.
- For devices with multilayer cutting/patterning steps, inclusion of geometric alignment marks in each layer's patterns, akin to traditional multimask lithography, ensures layer-to-layer alignment error within an acceptable range of ~30 μm.

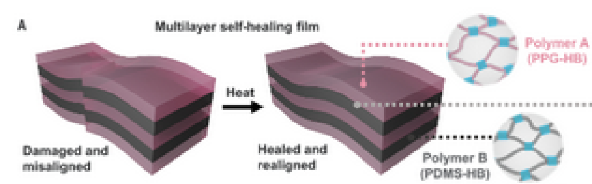


Cost and Time Savings through Two-Mode Mechanical Cutting

- The cutting process achieves small features **down to 100 µm,** suitable for typical stretchable electronics devices with **smallest feature sizes between 50 and 800 µm**.
- Key reductions in time (~82%) and cost (~35%) attributed to the *elimination of photomasks,* avoiding long fabrication/shipping cycles and associated costs.
  - Cutting-based fabrication does not require access to lithography-related specialty tools or a cleanroom environment, further contributing to overall cost savings.
  - The significantly shortened cycles make the cutting-based process **ideal for fast and rapid prototyping** of skin-mountable or implantable stretchable electronics systems.
- **Why do we care about this?**
  - Flexible, implantable or skin-wearable biosensors are a hot topic in research right now
    - (1) Organs on Chips
    - (2) Chemical + Electrical Sensors
    - (3) Close + accurate monitoring of various health conditions
    - (4) Self-healing electronic skin



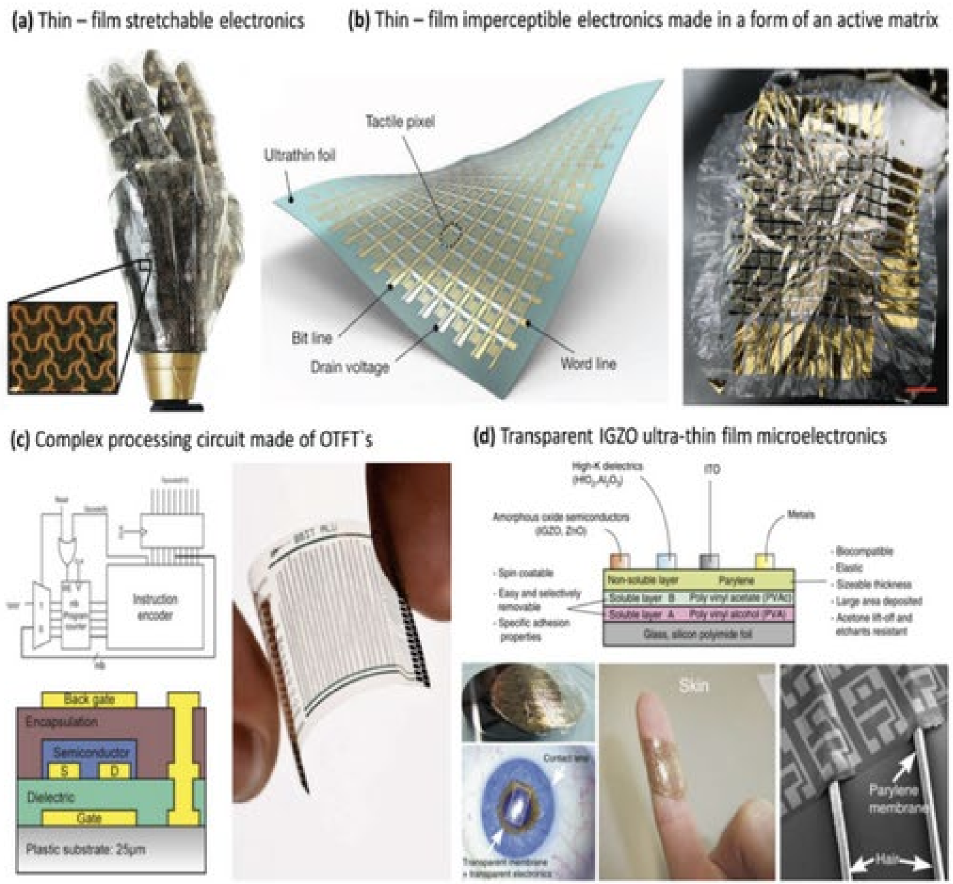




1-Kratz, Sebastian Rudi Adam et al. "Latest Trends in Biosensing for Microphysiological Organs-on-a-Chip and Body-on-a-Chip Systems." *Biosensors* vol. 9,3 110. 19 Sep. 2019, doi:10.3390/bios9030110
2- Kozai, Takashi D Yoshida et al. "Ultrasmall implantable composite microelectrodes with bioactive surfaces for chronic neural interfaces." *Nature materials* vol. 11,12 (2012): 1065-73. doi:10.1038/nmat3468
3- Kim, Dae-Hyeong et al. "Epidermal electronics." *Science (New York, N.Y.)* vol. 333,6044 (2011): 838-43. doi:10.1126/science.1206157
4- Christopher B. Cooper *et al.*,Autonomous alignment and healing in multilayer soft electronics using immiscible dynamic polymers.*Science*380,935-941(2023).DOI:10.1126/science.adh0619

Fine-tuning of this system for further applications

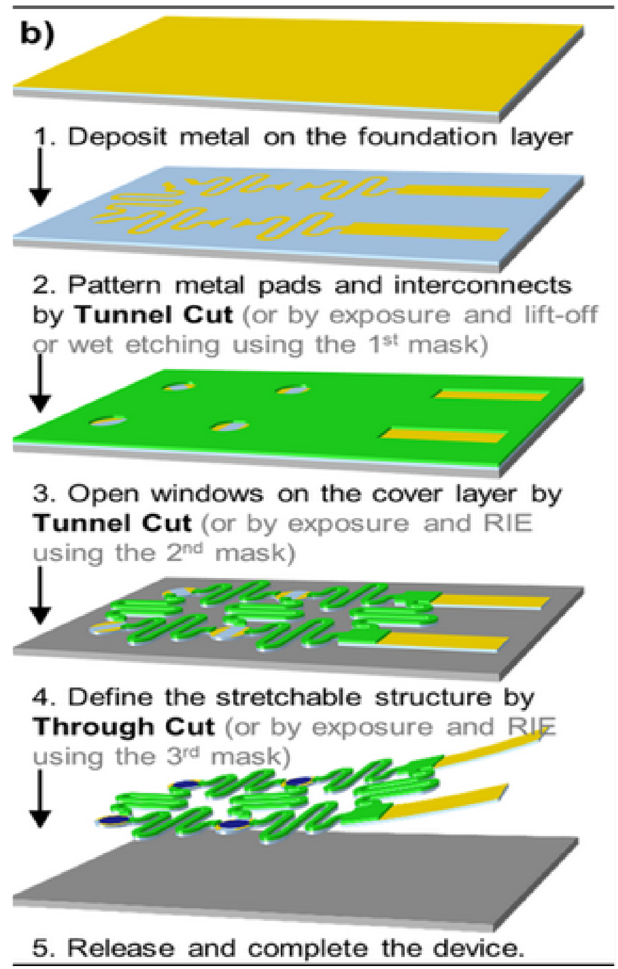
- This process can be relatively finely controlled, meaning that it is possible to create fine structures within the realm of 10's of **µm**
- **Can be combined with etching process to quickly prototype and test new small-scale electronics**
- As seen further on in this paper, this method can be used to create a variety of different devices, and the structures of these can be easily tuned via this cutting method
- Allows for future devices to be created, tested, and implemented more quickly
- More complex structures are now cheaper and easier to build



Karnaushenko et. al. (2019). 3D Self-Assembled Microelectronic Devices: Concepts, Materials, Applications. Advanced Materials. 32. 10.1002/adma.201902994

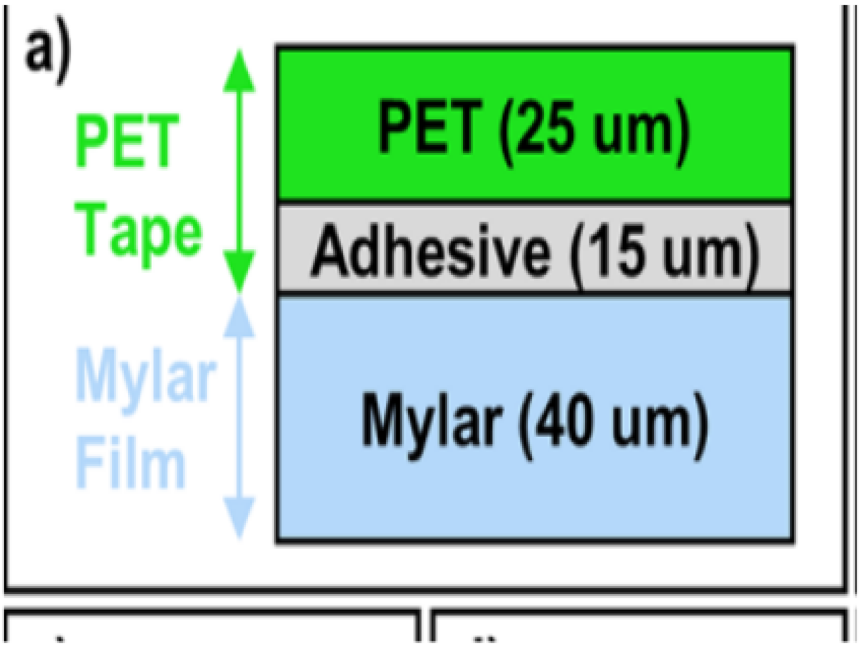
Two-Modes Manufacturing

- Two modes are the tunnel and through cut.
- Five stage fabrication process.
- Save up to around 88% processing time and 73% on costs for small batches.
- Up to 100 micron features.
- Does not need to go through specific lithography rooms and / or channels.



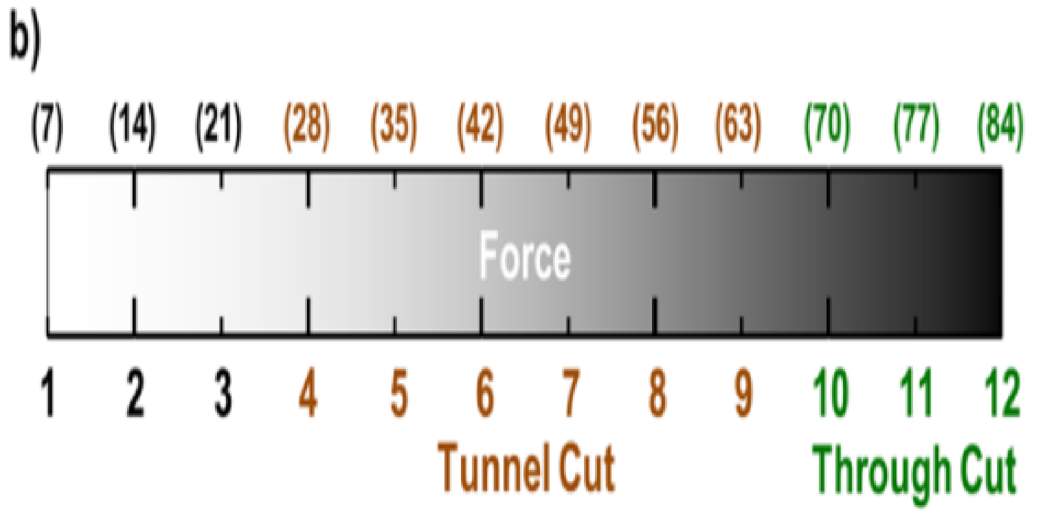
The Layers

- Cutting process involves a base of PET liner / adhesive / Mylar film in that order.
- Thickness varies at 25 / 15 / 40 microns respectively.
- Blade can be set at 10 locations.
- 33 levels of applied force for the cutter available.



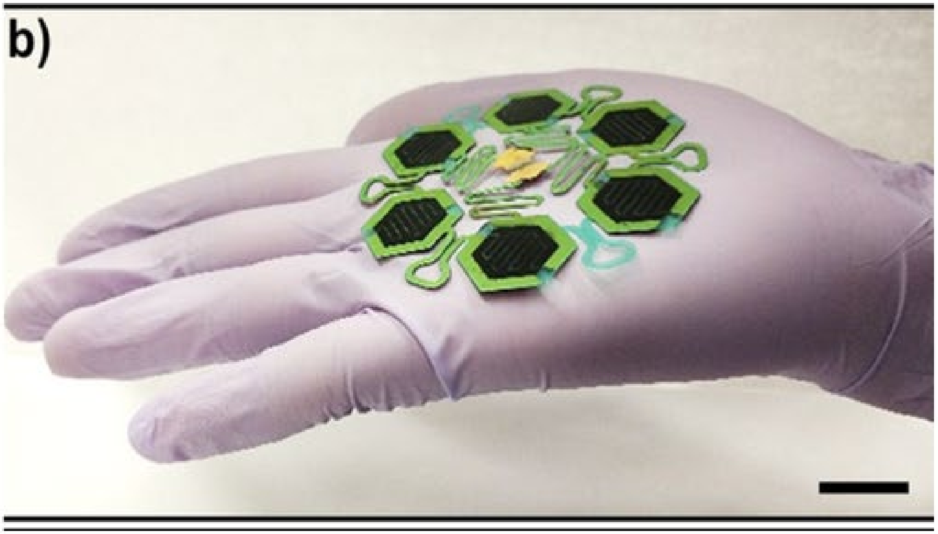
Tunnel and Through Cuts

- Tunnel cuts and through cuts depend on the force applied within that range.
- Through cuts cut all the way through the Mylar layer.
- Really challenging after the cutting is done to do more.



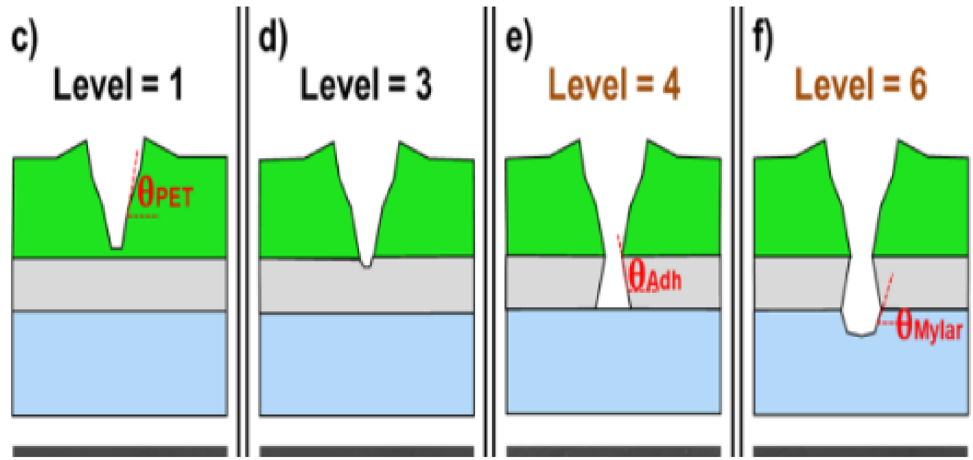
After Cutting

- Really hard to etch further detail after cutting.
- Cracks form easily from the cuts.
- A commercial elastomer (PDMS, Slygard 184, Dow Corning) is used to avoid this issue.
- Elastomer used as a soft adhesive and bonding agent.



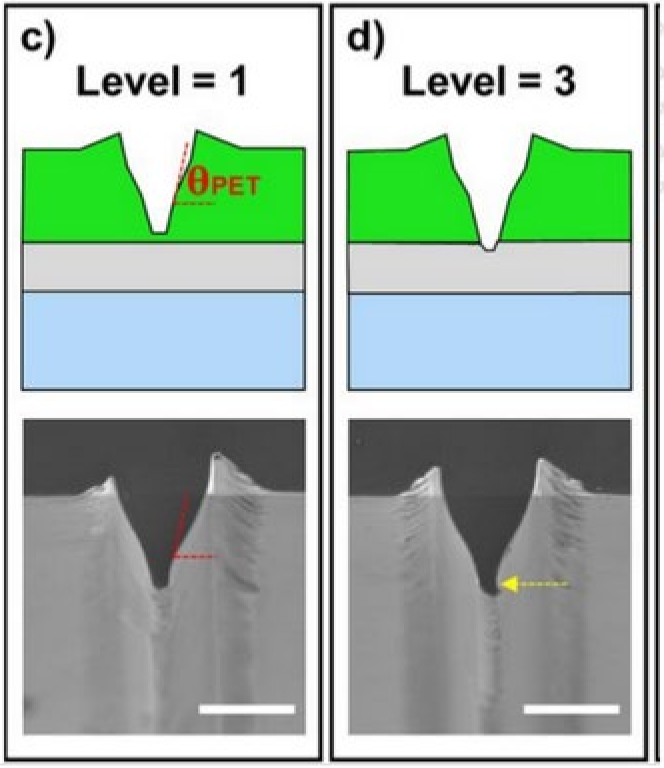
Precision of the Cuts

- Slot angle, point between the sidewall cut and horizontal line in the material
- Slot angles varies per layer of the process and per the material.
- Softer materials are more obtuse while harder ones are more acute.



Force Levels 1 and 3

- Force Level 1 (c)
  - Blade remains in the PET portion of the tape
- Force Level 3 (d)
  - Blade digs into the adhesive part



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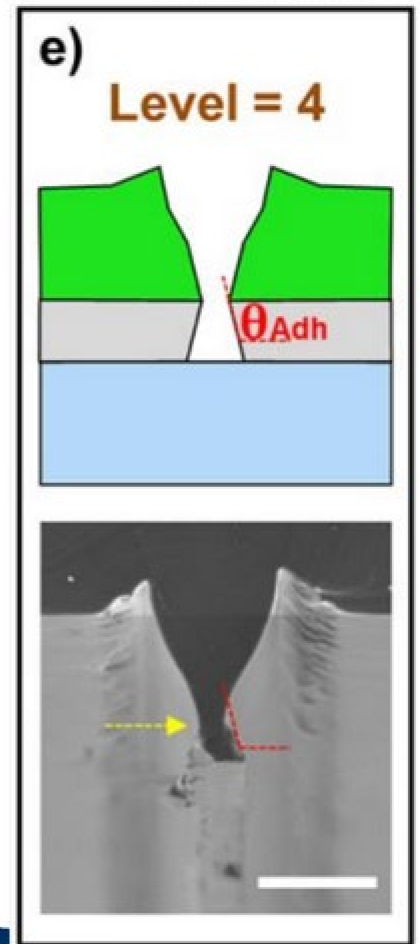
Force Level 4

- Force Level 4 (e)
  - Penetrates through adhesive to marginally reach the Mylar film at level 4
  - Desirable force setting for the "tunnel cut"
    - Provides consistent cuts through the upper layer (PET tape) without leaving significant marks or scratches in the lower layer



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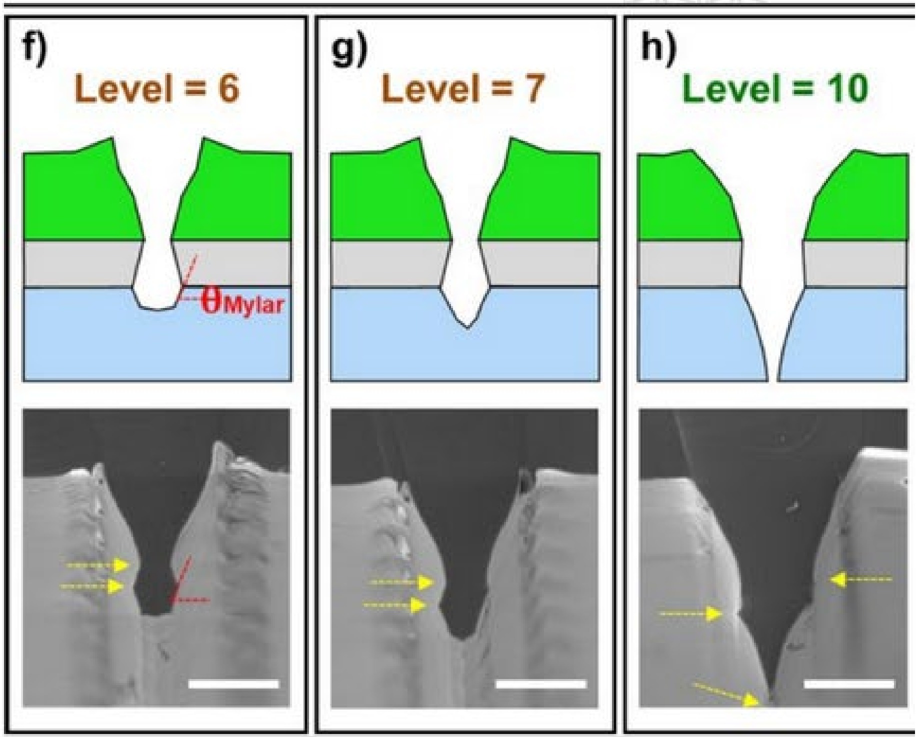
Force Level 10

- Higher force levels cut farther into Mylar film
- Level 10 as lowest setting for clean through cut



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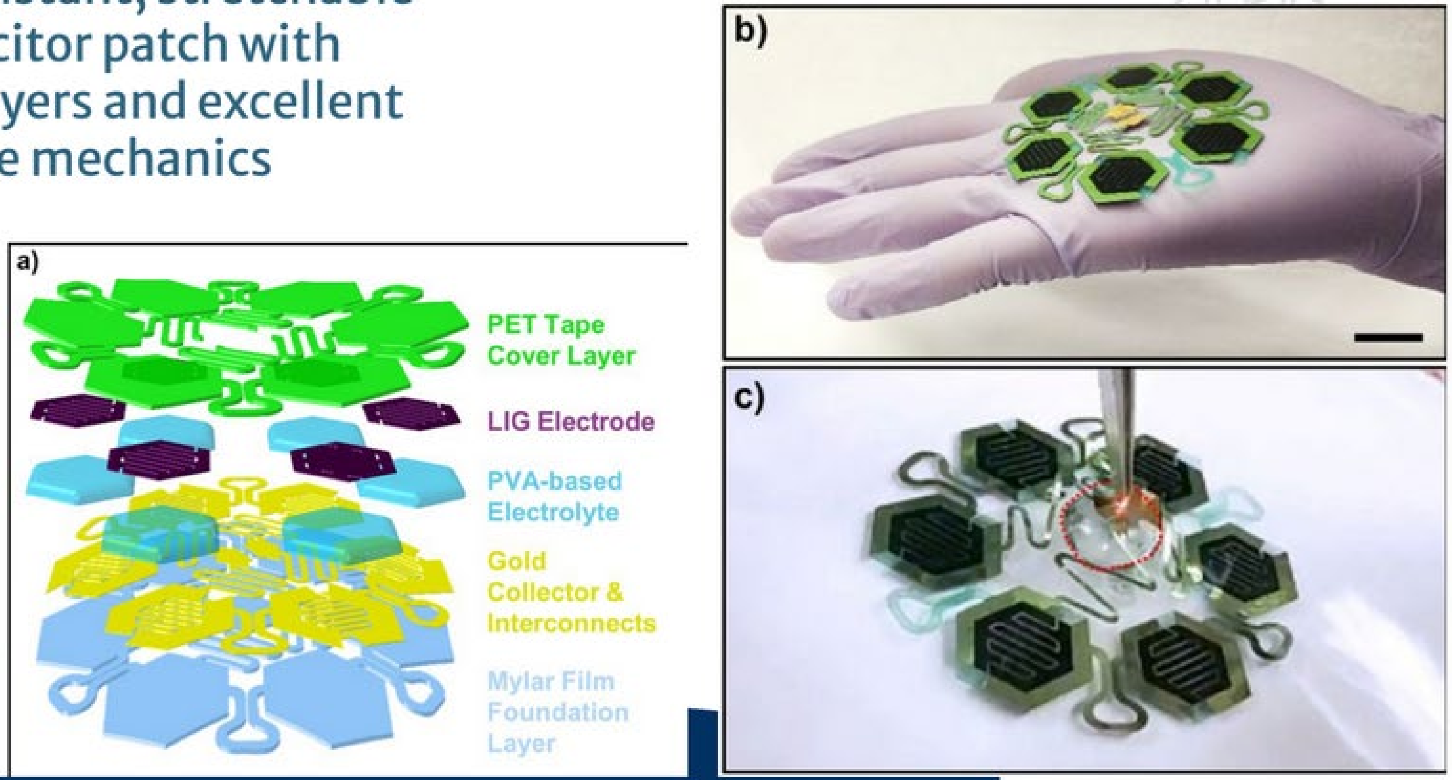
Application Examples

- Water-resistant, stretchable supercapacitor patch with multiple layers and excellent deformable mechanics

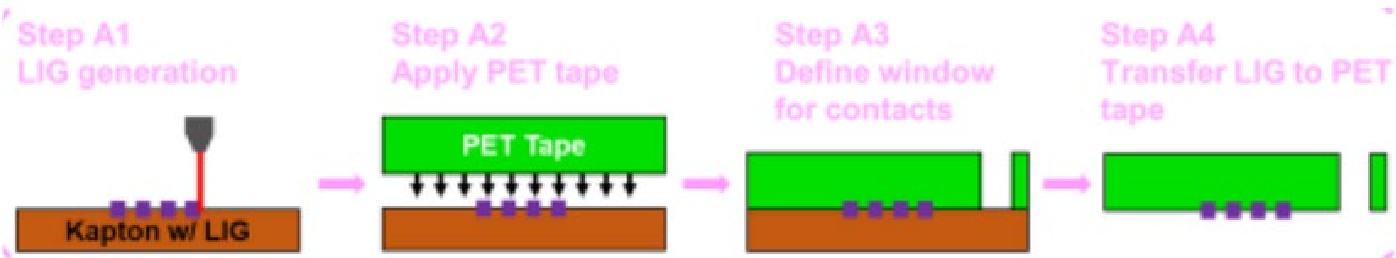


Additional Application Examples

- Stretchable mesh with sweat extraction and sensing functionalities
    - Showcases approach can easily adapt to nanomaterials, generate high resolution, complex geometric features, and fabricate electronics devices with double-sided circuit layers
- Skin-mountable breathing monitoring module for biomedical applications, with the integration of commercial electronic components

Water-resistant Stretchable SuperCapacitor patch (WSSC) Fabrication

Part 1:



Step A1:
Kapton film + CO2 laser cutter = Laser-Induced Graphene (LIG) electrode pattern

Step A2:
Polyethylene terephthalate (PET) tape is applied.

Step A3:
Vinyl cutter on "tunnel cut" mode to open windows in PET

Step A4:
Peel off PET tape which takes the patterned LIG with it due to the stronger bond

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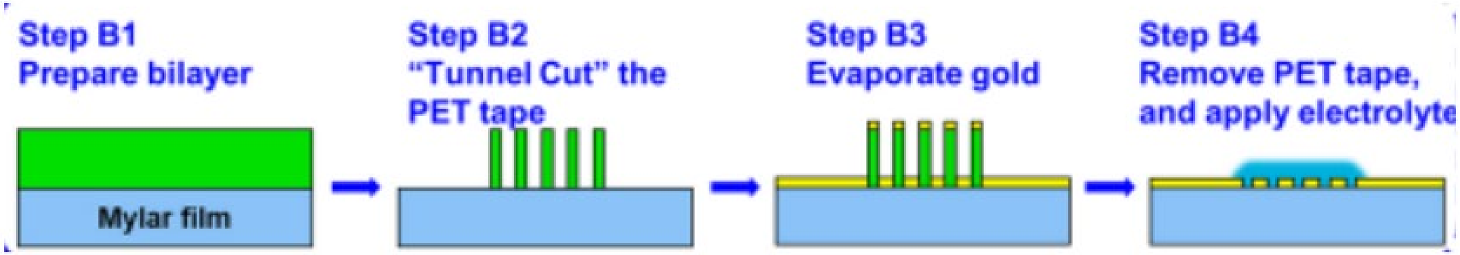
Water-resistant Stretchable SuperCapacitor patch (WSSC) Fabrication cont.

Part 2:



Step B1:
PET tape + Mylar film = Prepared bilayer

Step B2:
Vinyl cutter on "tunnel cut" mode to cut gold pattern in PET tape and removed

Step B3:
Evaporate gold onto the surface

Step B4:
Remove remaining PET tape and apply electrolyte (Polyvinyl alcohol +Lithium chloride +Deionized water)

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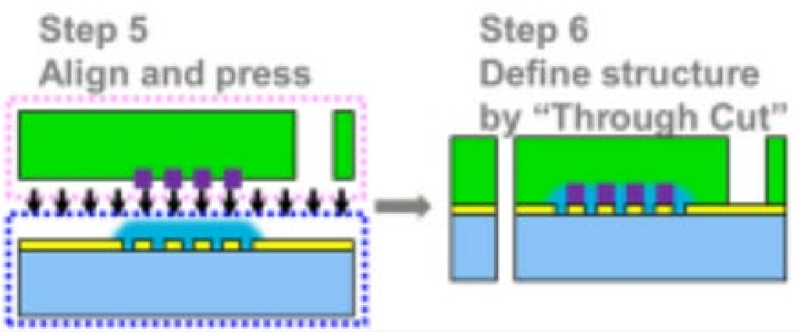
WSSC Combine and Benefits

Part 3:



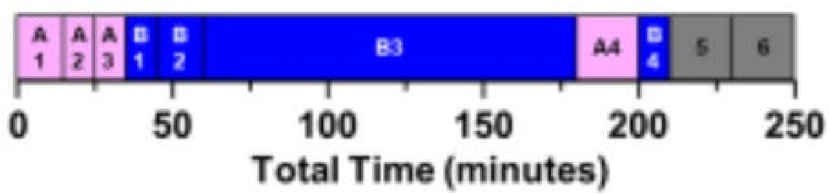
Step 5:

Step A4 and B4 are combined using alignment marks, PET tape sticks to gold and Mylar

Step 6:

Vinyl cutter on "through-cut" mode to cut out the outline of the entire device

Benefits:



- Rapid fabrication of multilayer device with several patterned layers ~ 250 minutes
  - can be reduced
- Low cost – as compared to small-batch photolithography
- No cleanroom needed

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WSSC Versus LIG Supercapacitor

Electrochemical Properties

Determined by using
- Galvanostatic charge-discharge (GCD)
- Electrochemical impedance spectroscopy (EIS)

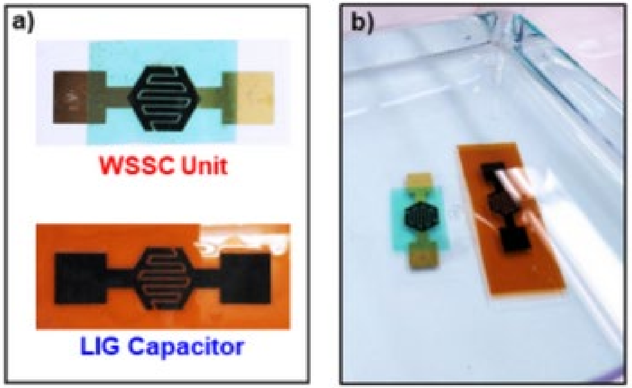
WSSC Unit:

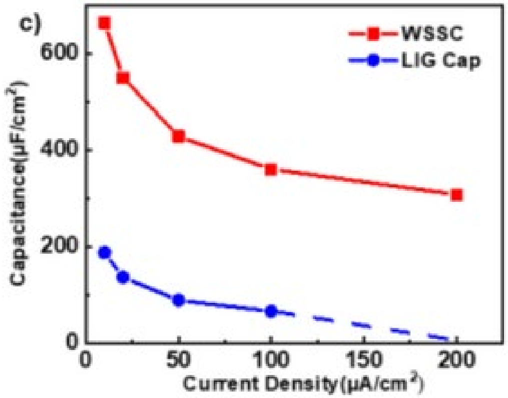
- Specific capacitance = 427μF/cm^2
- Discharge current density = 50μA/cm^2

LIG Capacitor:

- Specific capacitance = 88μF/cm^2
- Discharge current density = 50μA/cm^2

WSSC has a 5 times greater specific capacitance than a LIG capacitor!!!





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WSSC Vs LIG Supercapacitor Cyclic Voltammetry (CV)

Cyclic Voltammetry Scan

- 100 mV/s

WSSC Unit:

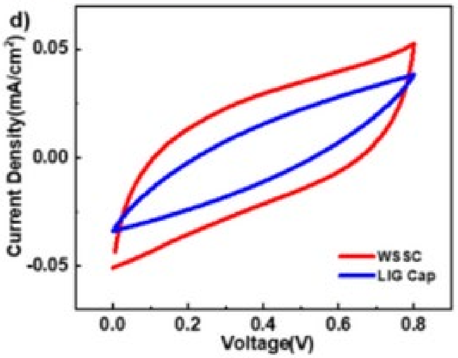
- Larger enclosed area rectangle-shaped CV curve
- Lower equivalent series resistance (~60Ω)

LIG Capacitor:

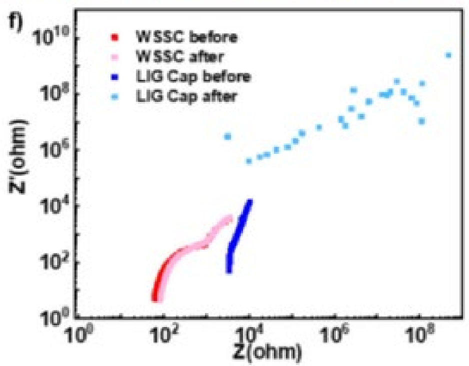
- Smaller enclosed area spindle-shaped CV curve
- Higher equivalent series resistance (~2000Ω)

Gold layer causes a much lower internal resistance which increases charge transport in WSSCs

Cyclic Voltammetry Scan



Nyquist Plot – equivalent series resistance



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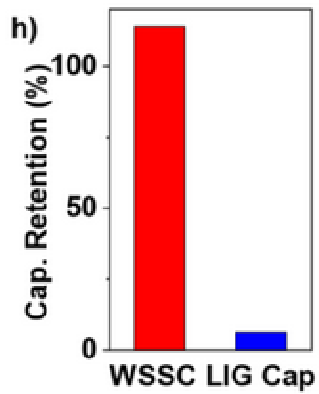
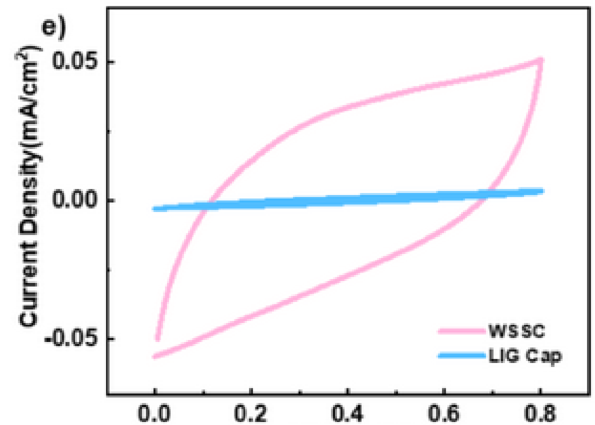
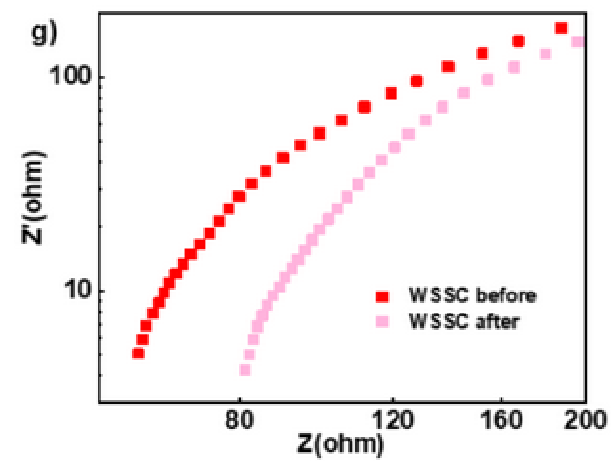
After Immersion in Water

- 16 Hours DI water
- LIG Capacitor loses most of its capacitance
- WSSC Capacitor improves
    - Likely due to improved contact between electrolyte and electrode surfaces with increased time

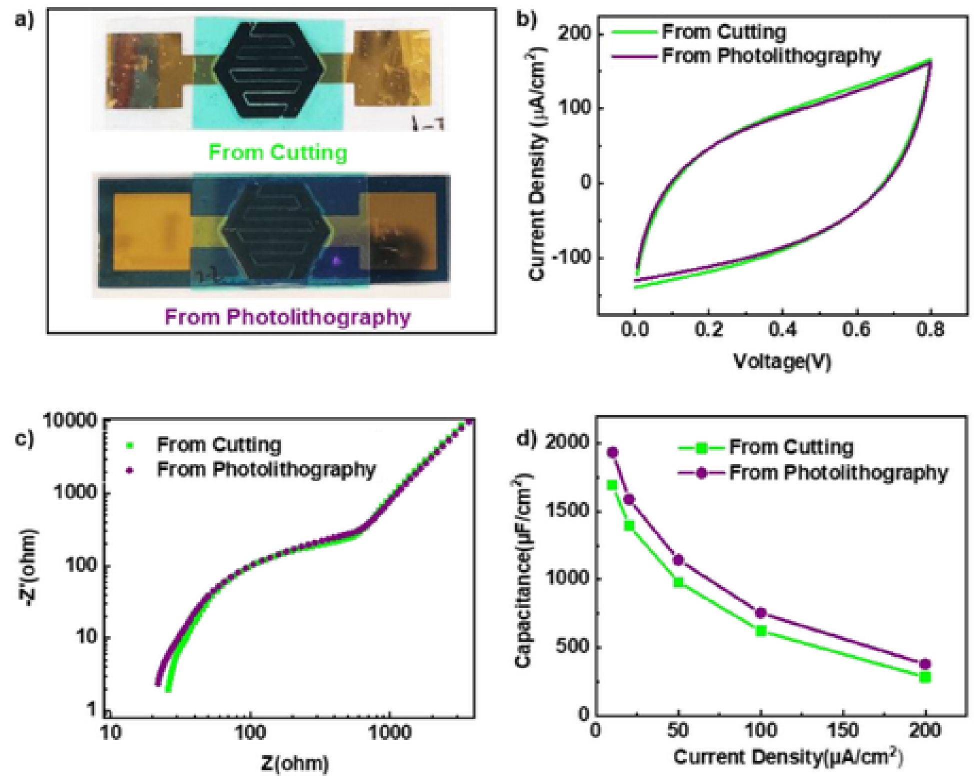






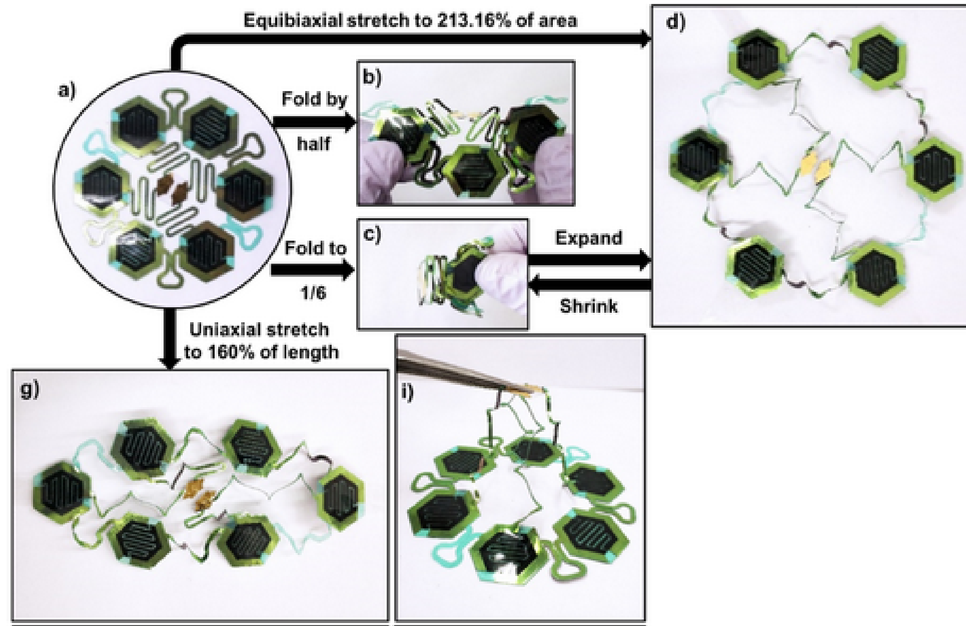
Electrical Comparison to Traditional Photolithography

- WSSC is compared to device using photolithography for patterning of gold layer
- Both devices performed almost identically
  - Suggests no loss in performance with new methodology



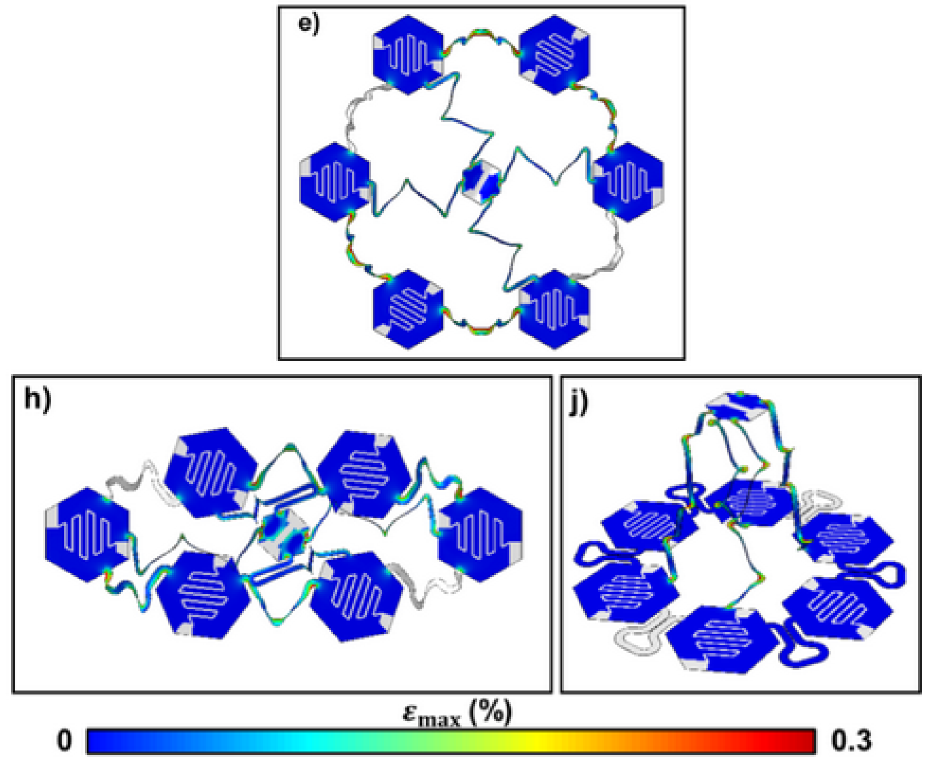
Mechanical Compliance of the WSSC

- 90µm thickness and geometric design allow for large deformations
- Can be folded to 1/6 its original area and stretched to ~2.1 times its original area
  - More than a 10x increase in size from smallest to largest configuration
- Also allows for out-of-plane elongation
  - 90µm to 35.5mm!



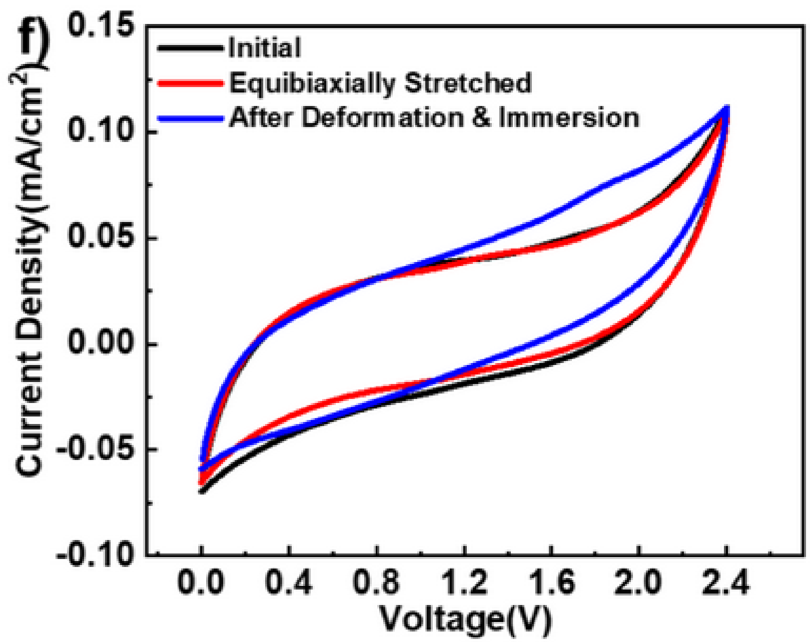
FEA Simulation of WSSC

- FEA indicates that the maximum strain for gold interconnects remains in elastic region
  - Indicates that previous stretching and folding is entirely recoverable



Electrochemical Performance after Stress Testing

- 30 cycles of uniaxial stretching, 15 cycles of biaxial stretching, 30 cycles of lifting, and 16 hours in DI water
- Once again electrochemical performance remains the same (if not improved as before)
- Results also independent of current deformation



Quiz I

Please answer the questions as concise as possible (less than 50 words) and use illustrations as much as possible to help your answers

a. What are the advantages to shrink the device size further down following Moore's Law – please write down three advantages. For example, the current state-of-art technology is 3 nm and researchers are working to make smaller ones such as 2 nm this year. (6%)

43/46

1. Lower power consumption. With smaller length, ther R decreases.

2. Lower manufacturing cost, since more chips on 1 wafer.

3. Signal transmit faster due to shorter length.

6/6

b. State two reasons/specialties/advantages that one may use TEM instead of SEM to examine nanostructures? (6%)

1. High resolution

6/6

2. Diffraction mode of TEM for crystal structure characterization.

c. What are the three major elements/conditions to make CNT during the CVD (Chemical Vapor Deposition) process and state the purpose/reason for each element/condition? (6%) What are the two types of growth mechanisms of CNTs?- (4%)

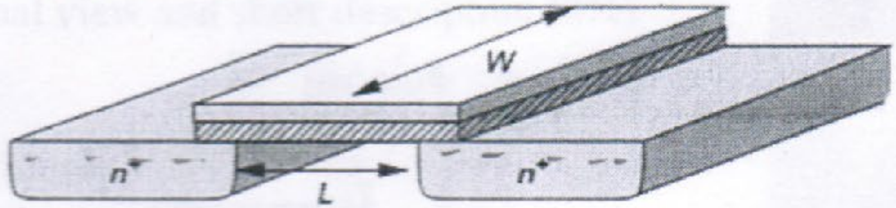
10/10

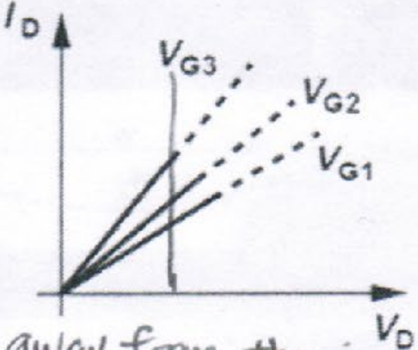
1. ① Gas : act as carbon source
   ② catalyst : facilate the directional growth and determine the diameter of CNTs
   ③ High temperature : provide energy for growth.
2. root - growth

This is determined by catalyst substrate adhesion force.

tip- growth

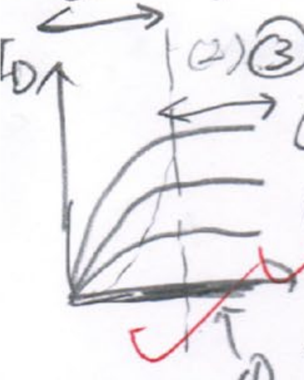
d. For an n-channel MOSFET as drawn in the figure: (1) explain the principal operation of the n-channel MOSFET and if the charge through the channel transported by holes or electrons? (3%) Explain modes of operation of a MOSFET including graphic illustration. (3%) For the I_D vs V_D curve as shown, should $V_{G3} > V_{G2} > V_{G1}$ or $V_{G1} < V_{G2} > V_{G3}$ and please explain the reason? (4%)





1. After the V_G increased, holes are repelled away from the substrate surface. The surface is depleted of mobile carriers. After $V_G > V_{TH}$, conduction layer forms. Thus, the e^- (electrons) at the inversion layer can flow, so there is current between drain and source.

form a resistive path so they can flow if $V_{DS} > 0$.



(2) ③ ① Subthreshold mode if $V_{GS} < V_{th}$ (OFF).

② Linear region, triode mode $V_{GS} > V_{th}$ & $V_{DS} < (V_{GS} - V_{th})$, inversion layer form (ON).

③ Saturation mode, active mode $V_{GS} > V_{th}$ & $V_{DS} > (V_{DS} - V_{th})$. Pinch off when V_{DS} increased to be equal to $V_{GS} - V_{th}$

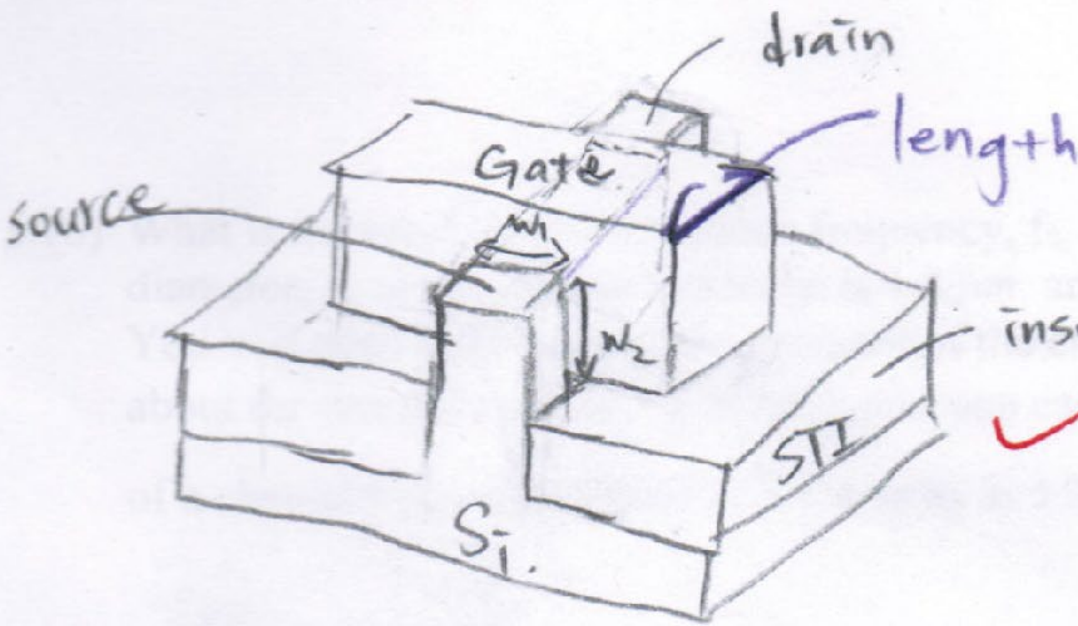
10/10

e. The current state-of-art transistor is based on the "FINFET" structure, please draw a 3D view and label the gate "length" and "width" in the figure (thickness is controlled by gate

2, Under the same V, $I_{D3} > I_{D2} > I_{D1}$, so $R_1 > R_2 > R_3$.

As $V_G \uparrow$, $R \downarrow \Rightarrow V_{G3} > V_{G2} > V_{G1}$ ✓

e. The current state-of-art transistor is based on the "FINFET" structure, please draw a 3D view and label the gate "length" and "width" in the figure (thickness is controlled by gate voltage). (6%)

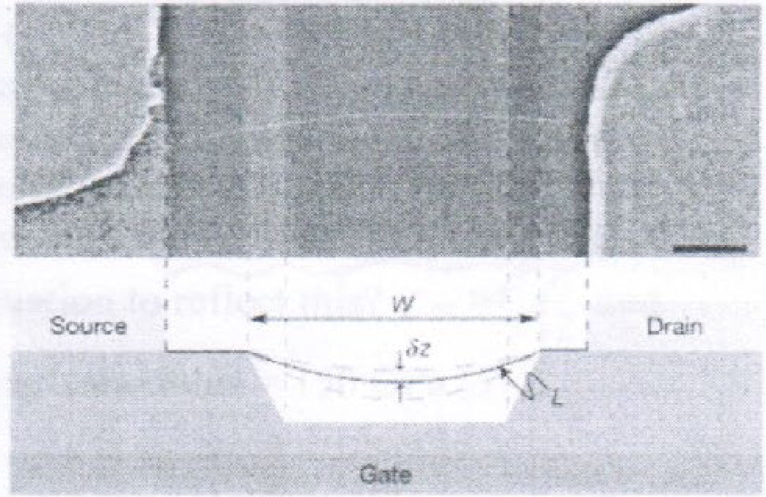


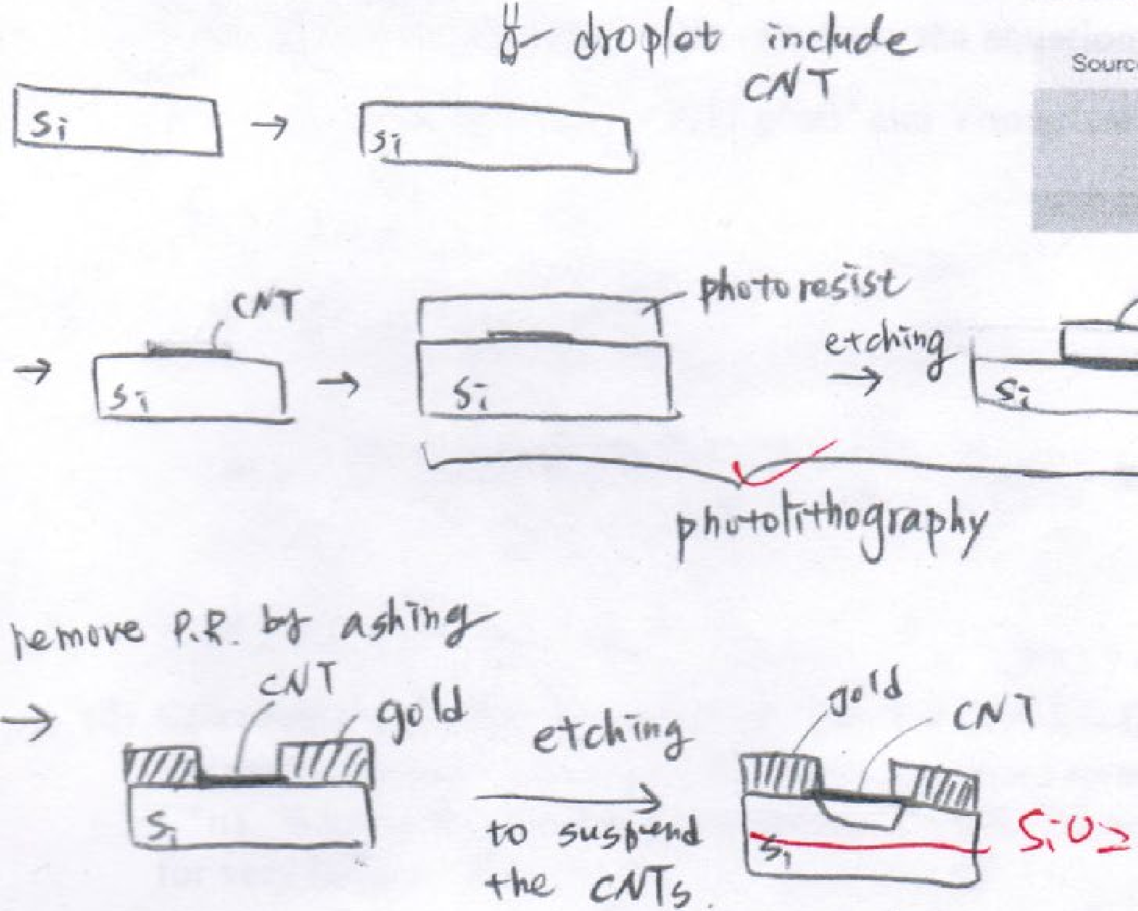
$W = W_1 + 2W_2$

Problem 2, CNT Application (34 points)

A carbon nanotube is suspended between two contacts as shown below (W in the figure is 1.0 μm. Figure is from Sazonova et al., *Nature* **431**, 284 - 287 2004)

(a) design a process flow to make this with cross-sectional view and short description (8%)





31/34

6/8

(b) What is the mechanical resonance frequency, f_0, of the nanotube? Consider that the diameter, d, of the carbon nanotube is 1.3 nm, and the Young's Modulus, E, is 1.2 TPa. You will need to know that the moment of the cross-sectional area of the carbon nanotube about the neutral axis is $I = (\pi d^4/64)$, and you can use $k = {192EI}/{L^3}$ where L is the length of a clamped-clamped beam. CNT density is 1.34 g/cm³(5%)

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}.$$

5/5

$$I = \frac{\pi \times (1.3\times10^{-9})^4}{64} = 1.402\times10^{-37}$$

$$k = \frac{192 \times 1.2\times10^{12} \times 1.402\times10^{-37}}{(1\times10^{-6})^3} = 3.23\times10^{-5}$$

$$m = \rho \times V = 1.34\times10^3\ \mathrm{kg/m^3} \times \pi \times r^2 \times L = 1.34\times10^3 \times \pi \times \left(\frac{1.3\times10^{-9}}{2}\right)^2 \times 1\times10^{-6}$$

$$= 1.7786\times10^{-21}$$

$$\Rightarrow f_0 = \frac{1}{2\pi}\sqrt{\frac{3.23\times10^{-5}}{1.7786\times10^{-21}}} = 21.447\ \mathrm{MHz}$$

(c) A student has a different resonator design using ultra-thin silicon nanowire in the cantilever setup with length (L) = 3.6μm, width (w) = 1.7μm and thickness (t) = 30nm. This student uses chemistry techniques to enable the binding of an analyte (i.e. the biological molecule he wants to detect) to the nanowire. The sensing method is based on the resonant frequency shift of the nanowire when the analyte binds to the nanowire. If m_a (9×10^{-20} Kg) is the mass of a single analyte, how does the resonant frequency depend on n, the number of analytes – you can show the equation to reflect this? $I = \frac{wt^3}{12}$ and $k = \frac{3EI}{L^3}$ silicon density = 2.33 g/cm³ and Young's modulus = 150 GPa (5%)

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}.$$

$$I = \frac{1.7\times10^{-6}\times(30\times10^{-9})^3}{12} = 3.825\times10^{-30}$$

$$k = \frac{3\times150\times10^{9}\times3.825\times10^{-30}}{(3.6\times10^{-6})^3} = 3.69\times10^{-2}$$

$$m = \rho\times V + n\times m_a = 2.33\times10^{3}\times3.6\times1.7\times30\times10^{-21} + n\times9\times10^{-20} = 4.278\times10^{-16} + n\times9\ldots$$

$$\Rightarrow f_0 = \frac{1}{2\pi}\sqrt{\frac{3.69\times10^{-2}}{4.278\times10^{-16} + n\times9\times10^{-20}}}$$

5/5

(d) Calculate the shift in resonant frequency for $\Delta f = f_0 - f_n$, n = 1, 5, 10, 40 analytes bound to the nanowire. Show on a plot that there is a linear relationship between Δf and n (i.e. $\Delta f = C*n$). What is the value of the constant C? (8%) Do you expect this curve to be still linear for very large n? Why? (2%)

① f_0 = $f_0 \doteq 1.478130$ MHz

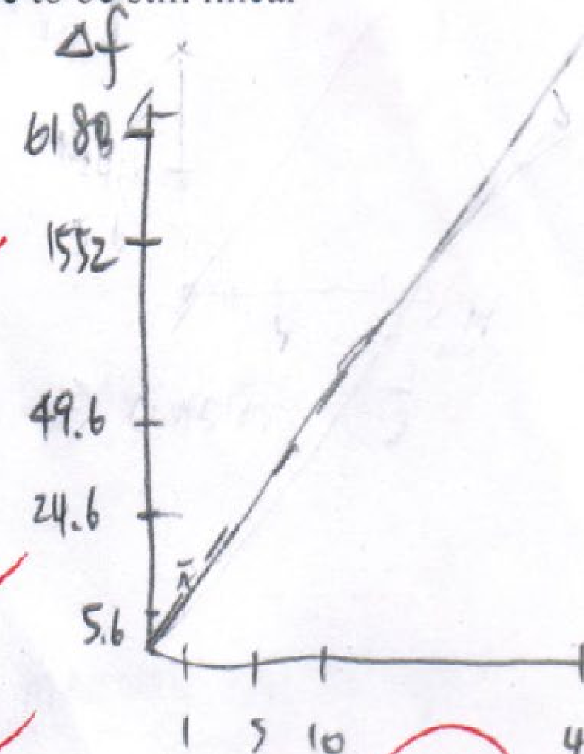
f_1 = $f_1 = 1.477975$ MHz — Δf: 150 Hz ≐ 1×150

f_5 = $f_5 = 1.477354$ MHz — 780 Hz ≐ 5×150

f_{10} = $f_{10} = 1.476578$ MHz — 1552 Hz ≐ 15×10

f_{40} = $f_{40} = 1.471950$ MHz — 6180 Hz ≐ 15×40

⇒ constant = 150



10/10

② No, , we can see as N gets larger, the mass portion of analytes i

(e) If the sensitivity of the system is 500 Hz (the limit is due to thermal energy), what is the minimum number of analytes, n, that the student is able to detect with this nanowire? (4%) Please suggest TWO different strategies to increase the sensitivity of the system. (2%)

$\Delta f = C \times n$. $C \hat{=} 154.41$

(1)

$Cn \geq 500$. $n \geq 3.21$ ⇒ The minimum # of analyt[e]
is 4 ok

(2) ① We can tune the dimension of the CNT s.t. C [i]s
$\Delta f = nC$ is larger. e.g. make it thinner.
② Improve the thermal control of the system
e.g. freezing.

10/10

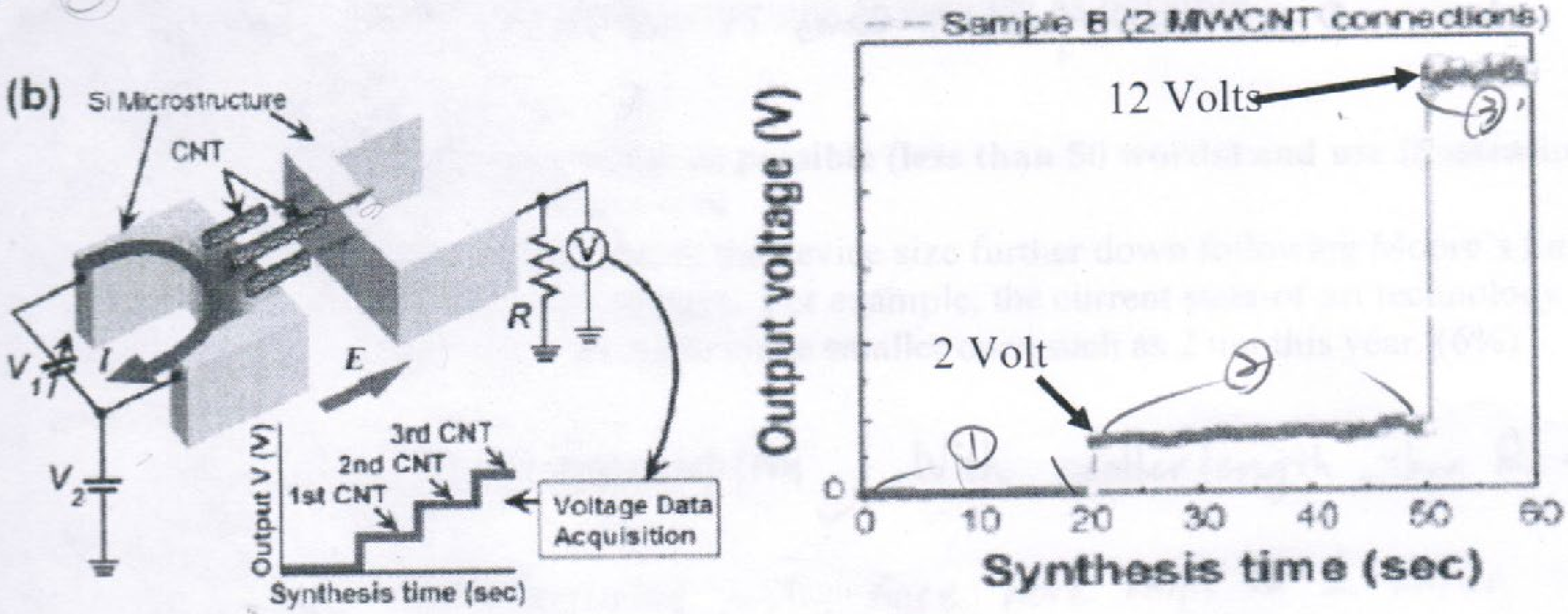
6/6

Problem 4, Local CNT Growth & Control Paper (20 points)

The figures show the setup and results to locally grow CNTs in paper #3. R = 20MΩ; V_1 = 10 Volts and V_2 = 4 Volts.

a. Explain the role/purpose/function of V_1, V_2, R and the voltage-meter used in the figure and explain the results shown on the right-hand side figure (10%)

b. Assumptions: the silicon micro-bridge resistance is much smaller compared to R; the contact resistance of CNT can be ignored; both 2- & 12-volt signals are from CNTs around the center of the micro-bridge; you are asked to estimate the resistance of the CNTs that are generating the 2-volt and 12-volt signals in the result figure, respectively. (10%)



①

a. V_1 : heating the Si structure.

V_2 : provide electric static field. After CNTs contact to the other electrode, there is a current.

R : have voltage difference from ground, so we can measure the voltage change to know how many CNTs developes.

Voltage meter: help to measure the Voltage change across R. to monitor how many CNTs growth and if it is good qualiry.

②

In ① stage, there is no CNT connect 2 side of Si, so V=0.

In ② stage, one CNT connetted Si from one side to the other side, be the qualiry is not that well (high R).

In ③ stage, there is another CNT connected, and this had good quality.

b. $V = \frac{R}{R+R_{CNT}} \times V_{in}$ ⇒ (1) $2 = \frac{20M}{20M+R_{CNT}} \times 9$ ⇒ $R_{CNT} = \frac{9}{2} 20\times10^6 - 20\times10^6 = 70\times$

$= 70$ M

$V_{in} = V_2 + \frac{V_1}{2} = 4+5=9$ (2) But for the 12 volt, the V_{in} is only 9 V,

the [illegible]