Center for Wearable Sensors

UC San Diego Jacobs School of Engineering

Additive Printing of Flexible Electronics for Sensing

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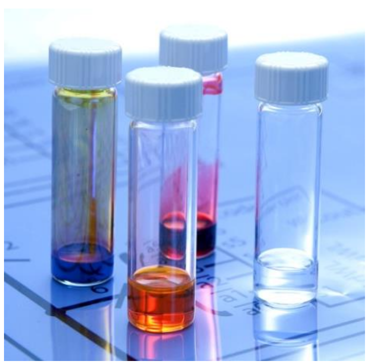
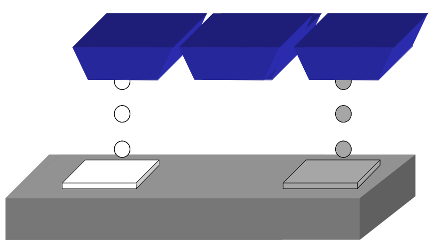
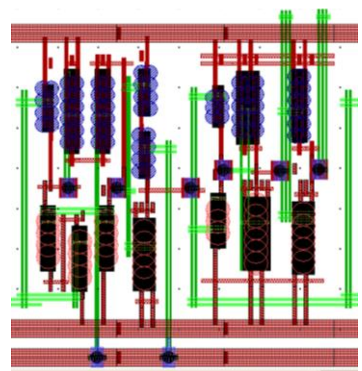
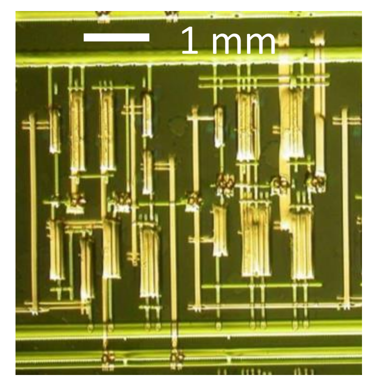


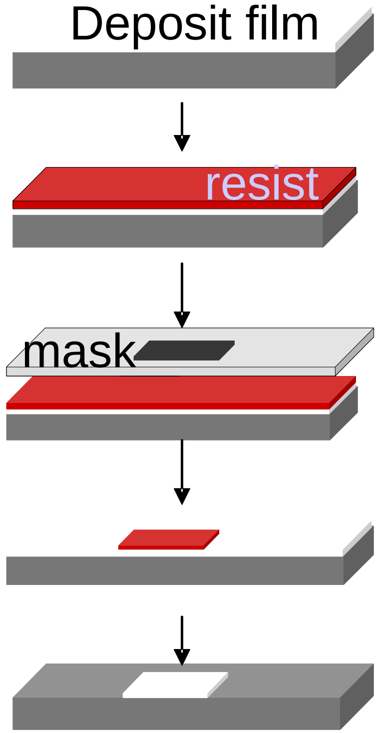




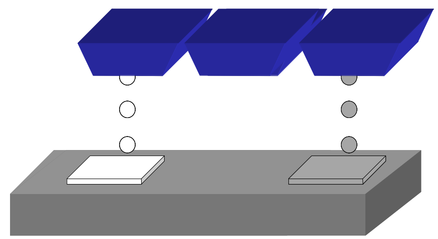


Advantages and limitations of printing

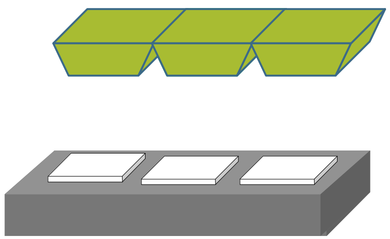
Photolithography



Digital Inkjet



Stamp printing



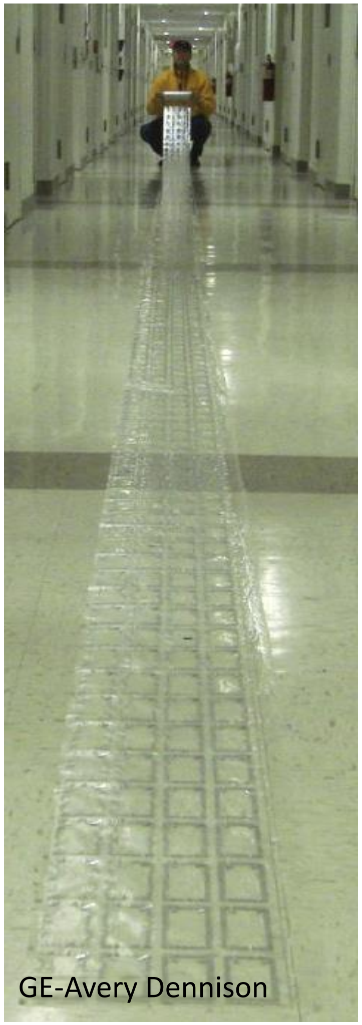
- Low-temperature process, low ink consumption (<10μL to cover a 4"wafer)
- Trade-off in resolution and printing speed

inkjet: ~35 micron resolution, web speed ~5miles/hr;
Imprint ~nm resolution, 20 eight-inch wafers/hr

Vacuum deposition

Solution printing in air

Applications for printed sensors

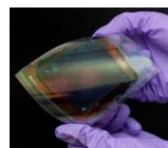

GE-Avery Dennison

- Scalable to large-area, flexible, tunable materials

  Human-computer interface (touch, imager, etc.)

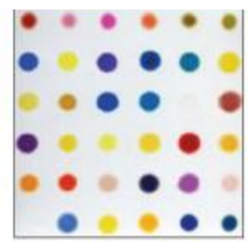
- Multi-component arrays that increase selectivity

  Low-cost, high-volume for distributed sensing

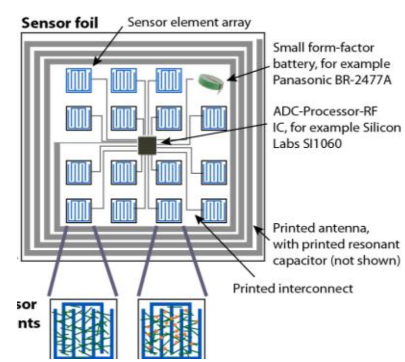



APL 92 (2008) 213303


Someya, U Tokyo

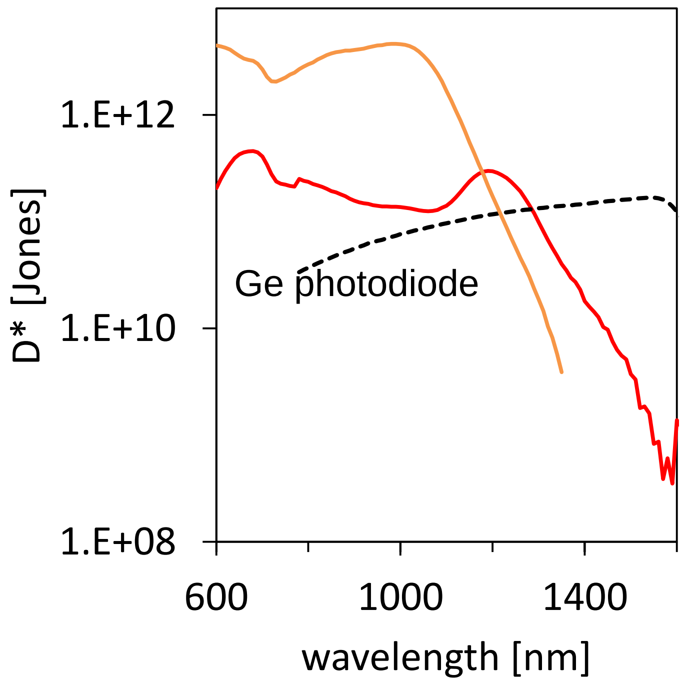

Suslick, et al., *Nature Chemistry*, 2009

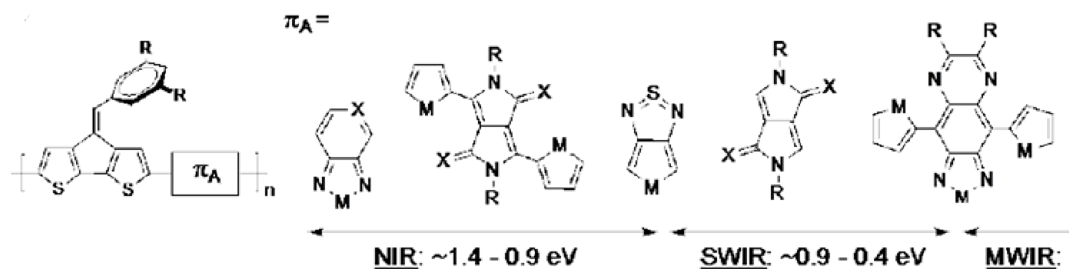
PARC ARPA-E MONITOR



Solution processed sensors comparable to conventional Ge

Tunable organic materials with infrared detectivity comparable to commercial Newport Ge diode

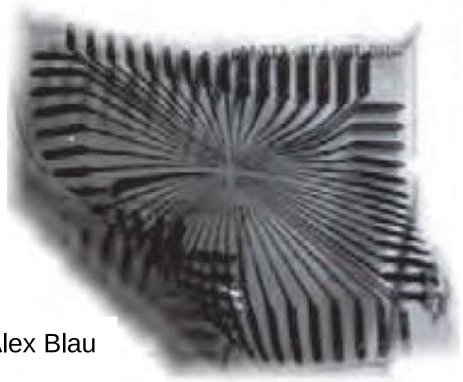




ACS Appl. Mater. Interface 9 (2017) 1654.
Polymer Science, DOI: 10.1039/c7py00241f

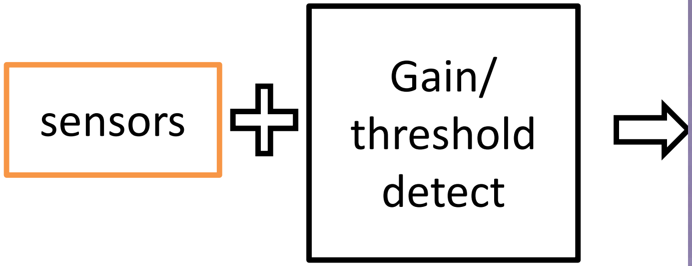
Printed TFTs for local sensor control

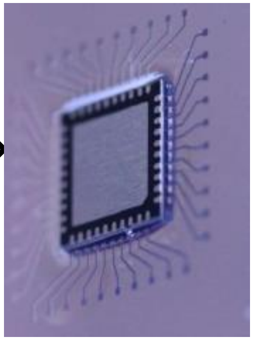
M x N lines, interconnect takes more space than sensors



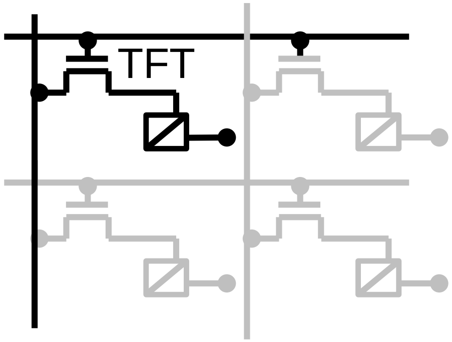
Alex Blau

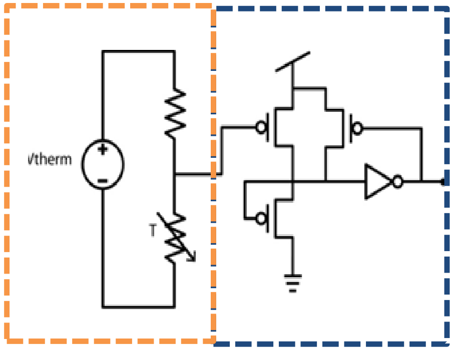
Simple signal conditioning/processing





With TFTs, M + N lines only

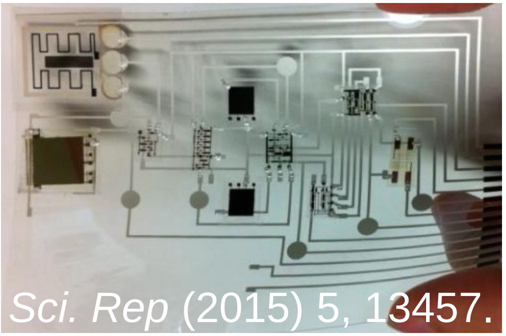




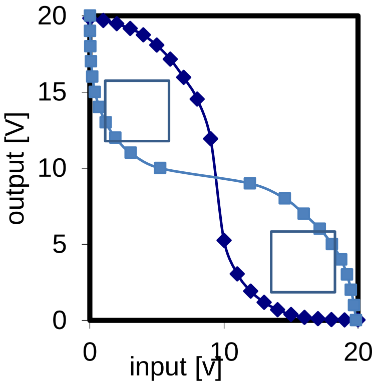
TFT integrated circuits provides signal conditioning before Si chip

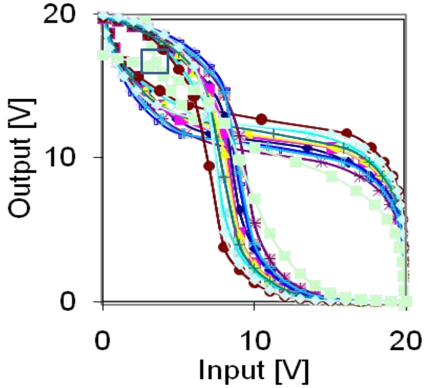
Key challenge for integrated TFT circuits

Challenge for implementation: Designs that tolerate variations in OTFTs



Proc. IEEE (2015) 103, 607



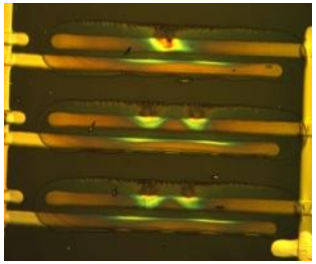


- Variation leads to circuit error
- Controlling variation is key to practical yield

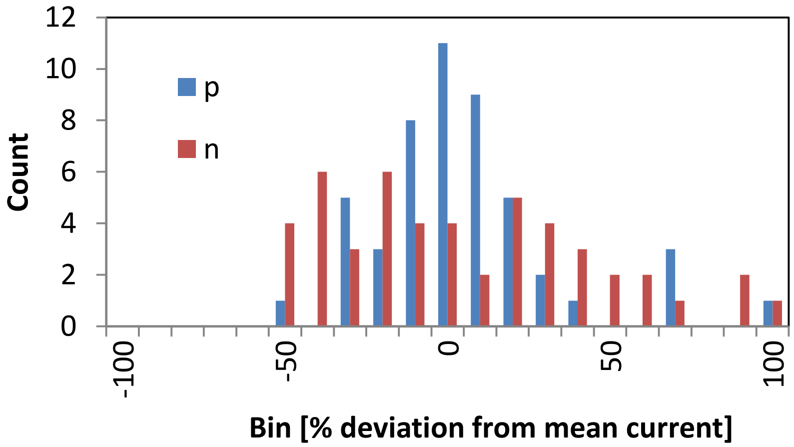
TFT variation (1s std dev)	Yield
25%	50%
10%	80%
5%	98%

Monte Carlo Simulation for 100 samples
-for a gain + latch circuit with 7 TFTs

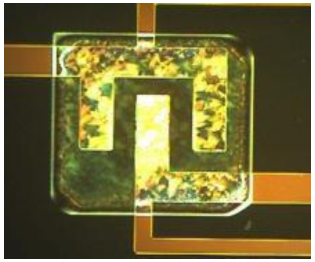
Printed vs photolithographic OTFTs



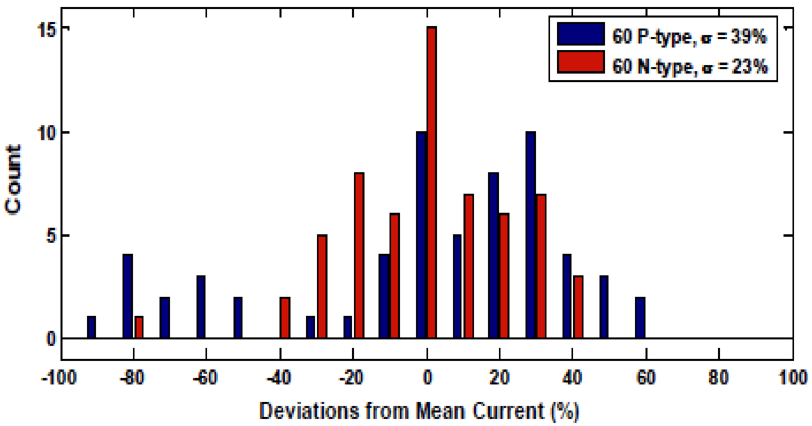
All-printed OTFTs



Sci. Rep (2012) 2, 585.



Photolithographically patterned OTFTs

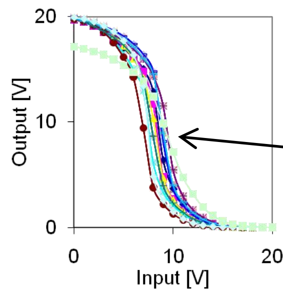


Courtesy of Murmann group at Stanford

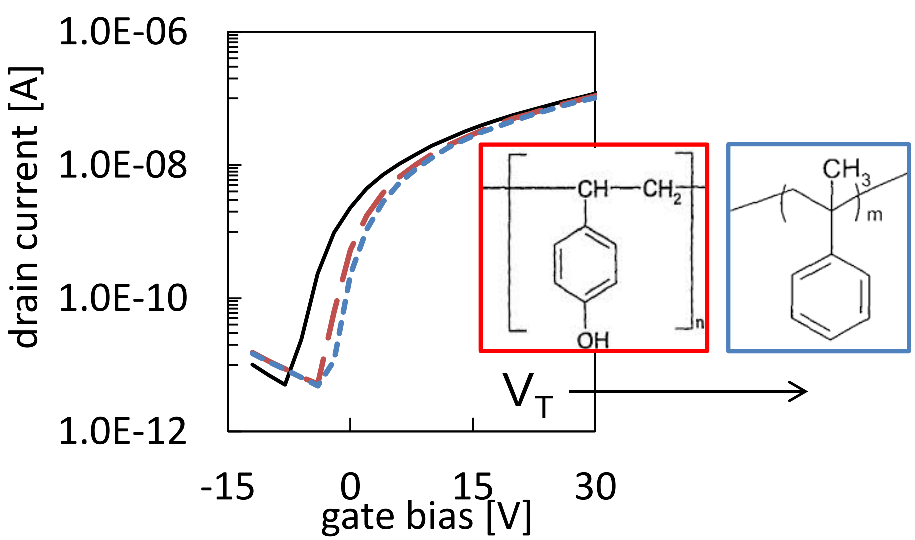
Similar level of variations: main source of variation is semiconductor, less impact from channel W/L

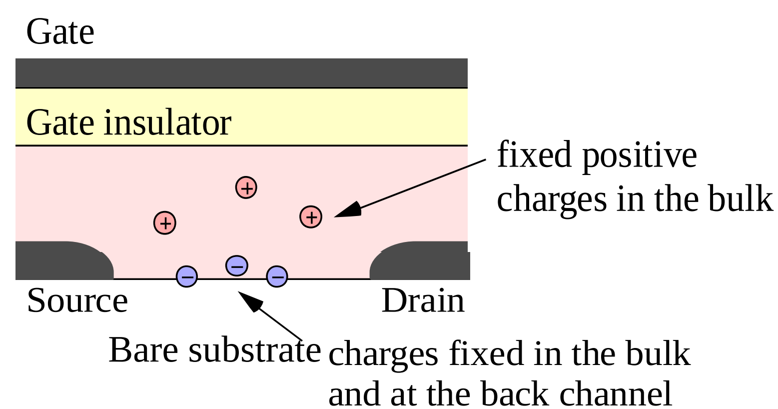
Modify channel surface to adjust V_T

- Important to control threshold voltage V_T
- Back-channel interface affects V_T: electronic dipole, film morphology, etc.



$$V_{inv} = \frac{V_{DD} + V_T^{\,p} + V_T^{\,n}\sqrt{\beta^n / \beta^p}}{1 + \sqrt{\beta^n / \beta^p}}, \beta = \frac{W}{L}\mu$$

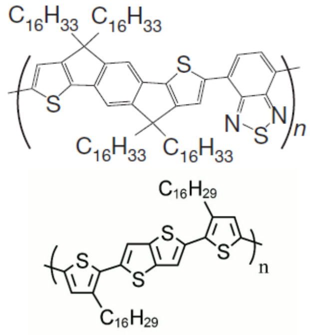


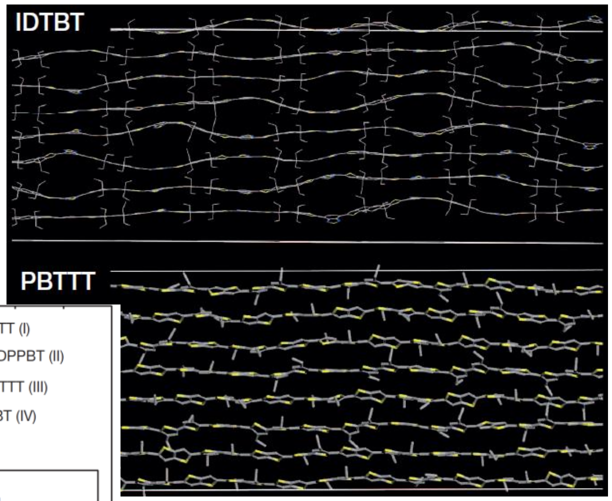


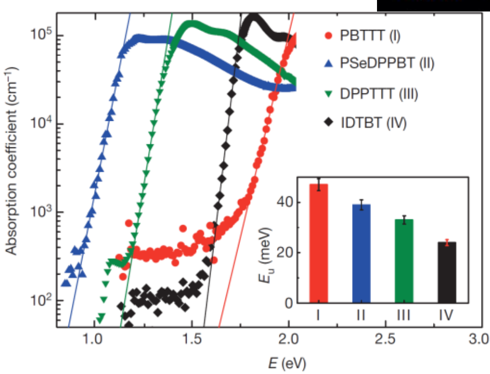
J. Appl. Phys. **113** (2013) 094506

Material structures that reduce disorder

Polymers:
Reduce tail states by rigid backbone that reduces torsion

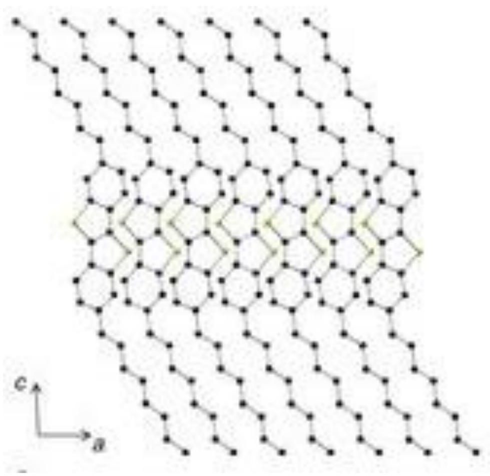


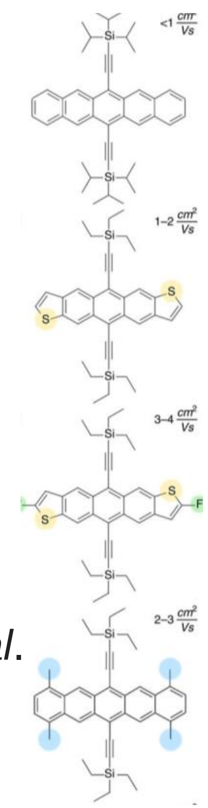




McCoullouch, *et al.*
Nature **515**, (2014) 384–388

Small molecules:
Suppressing thermal disorder by side chain location





J. Anthony, Sirringhaus, *et al*.
Nature Communications **7**, 10736 (2016)

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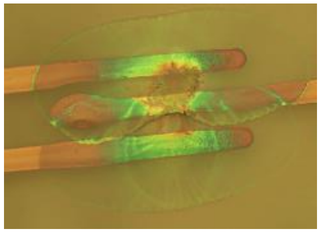
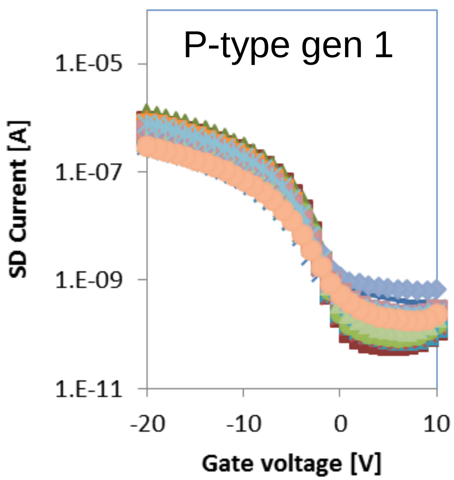
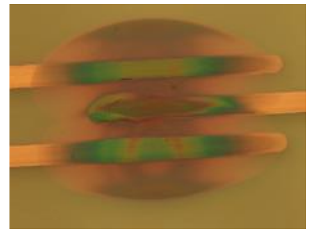
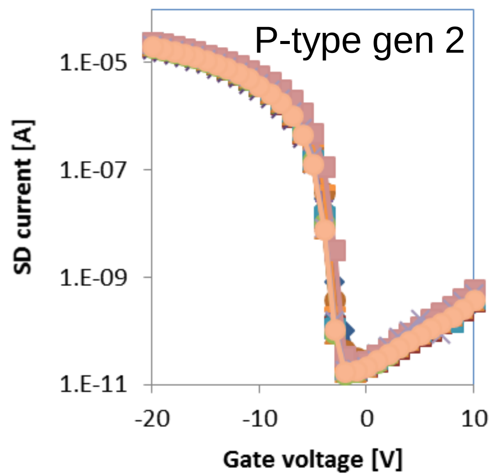
Reduced variations in printed OTFTs



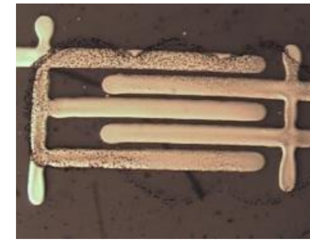


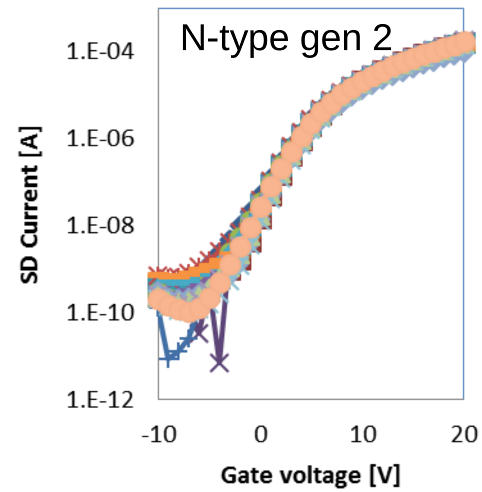
1σ =40%
Mobility =0.12cm^2/Vs





1σ =8-10%
Mobility =0.6cm^2/Vs



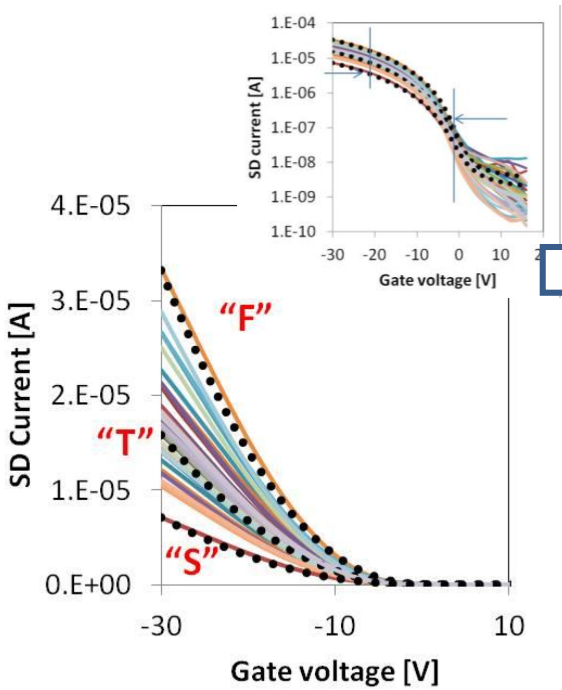


1σ =12%
Mobility =0.7cm^2/Vs

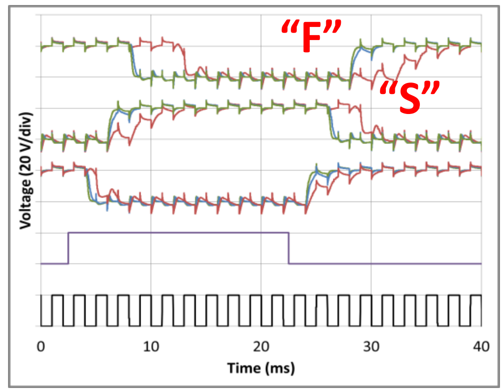
Uniformity can be improved in both polymer and small molecules

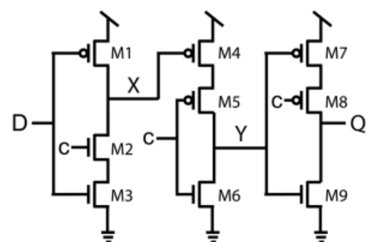
From materials to circuit fabrication

Develop ink & devices
→ Build device models

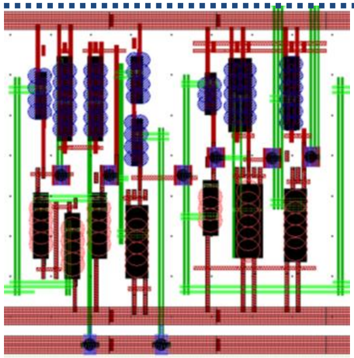


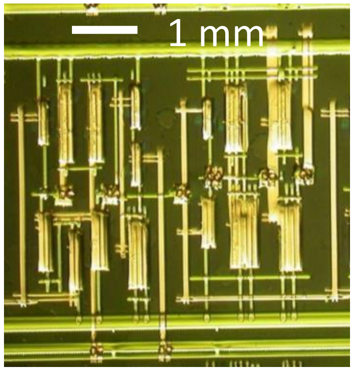
Design, simulate circuits





Print and test

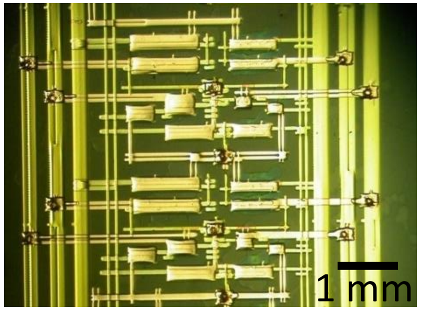


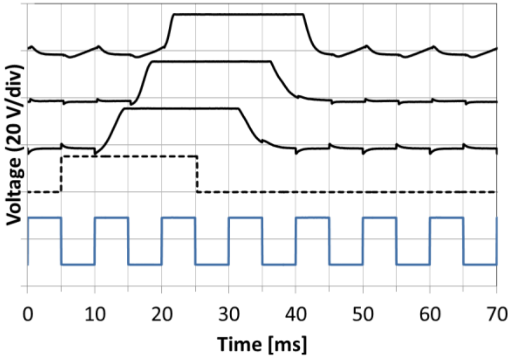


IEEE Elec. Dev. Lett. (2013) 34, 271.

Other examples of printed circuits

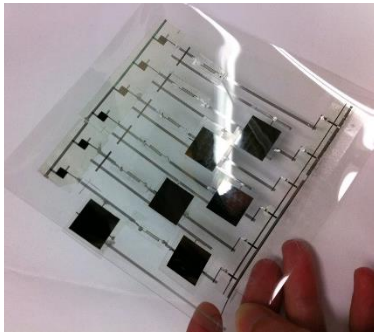
Shift register

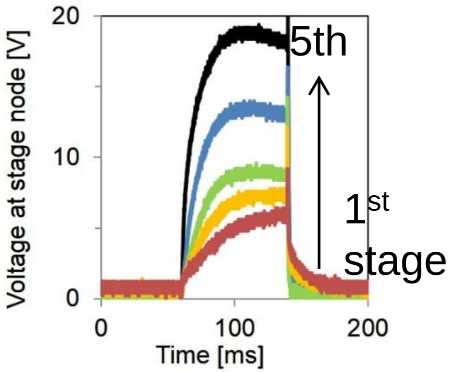




IEEE Elec. Dev. Lett., **34** (2013) 271.

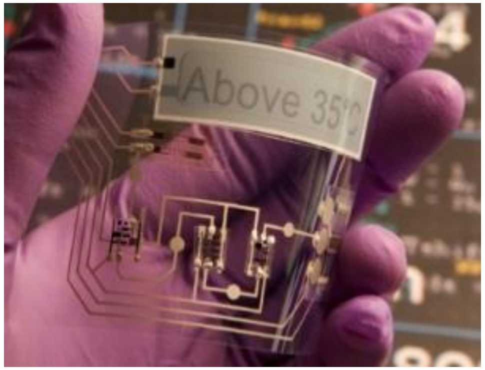
Voltage multiplier

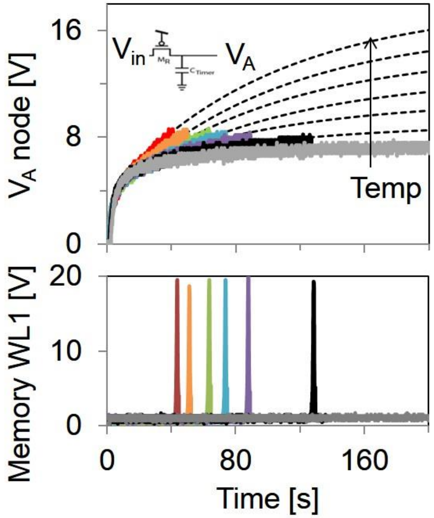




Flexible Printed Electronics (2016) 1, 015002.

Temperature dose tag



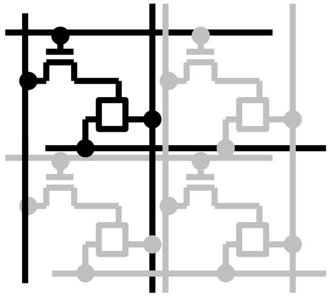


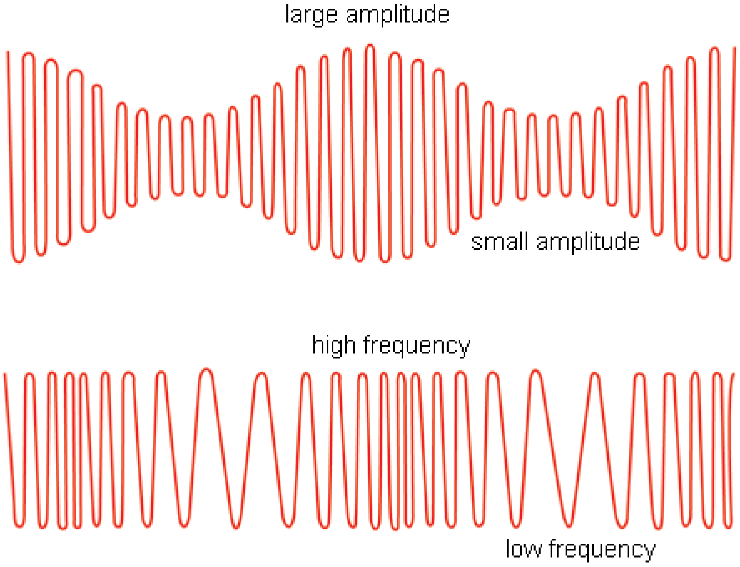
Sci Rep (2015), 5, 13457.

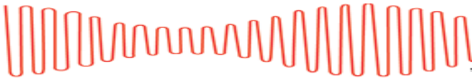
Desirable to digitize signal near sensor

Amplitude signal prone to attenuation error; frequency signal more reliable

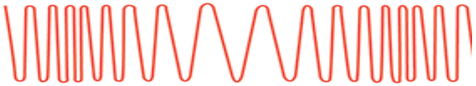
Need to add digitizing circuit near sensor





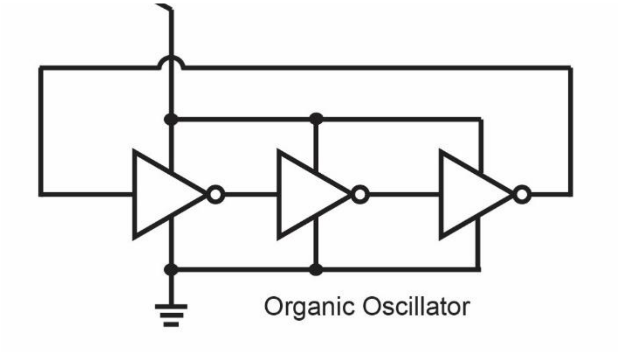


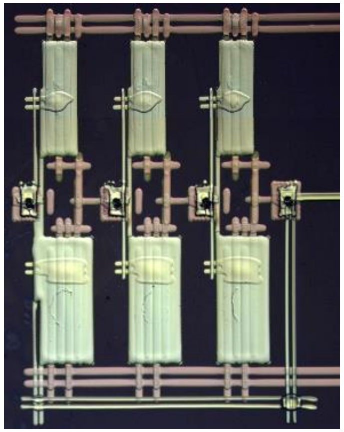
Attenuation affects amplitude measurement

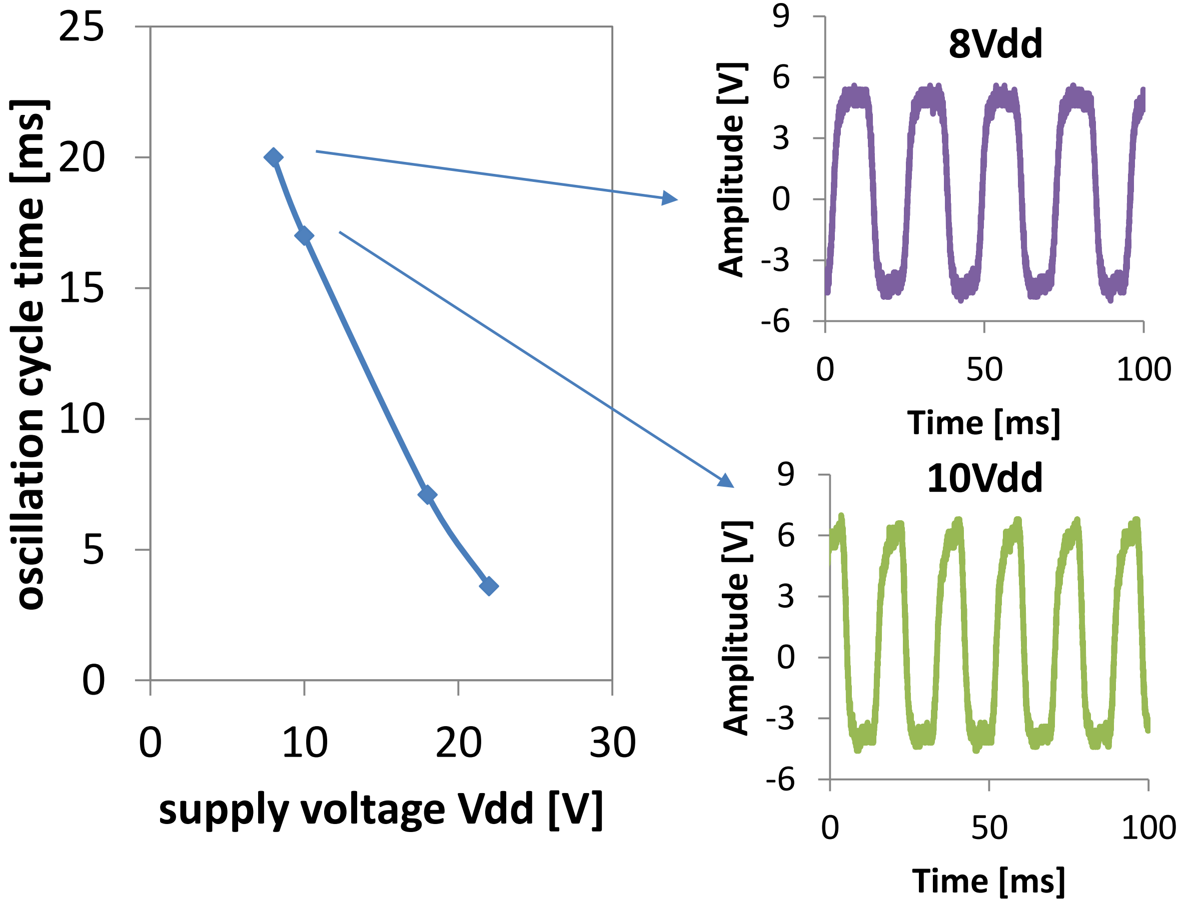


Same freq as before, will get same readout

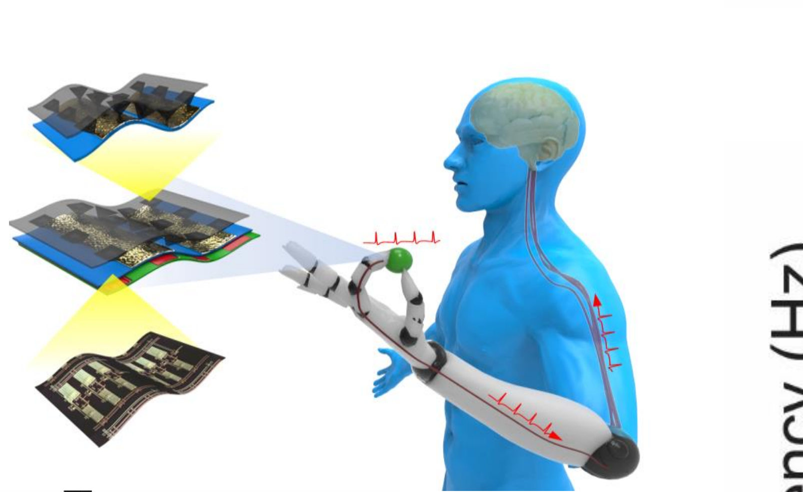
Voltage-controlled oscillator

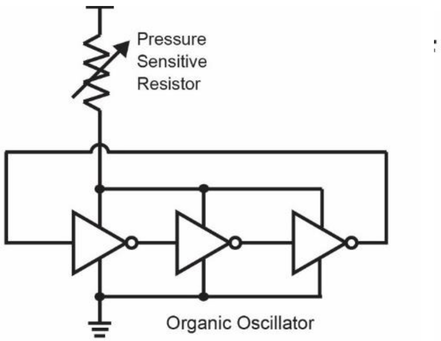


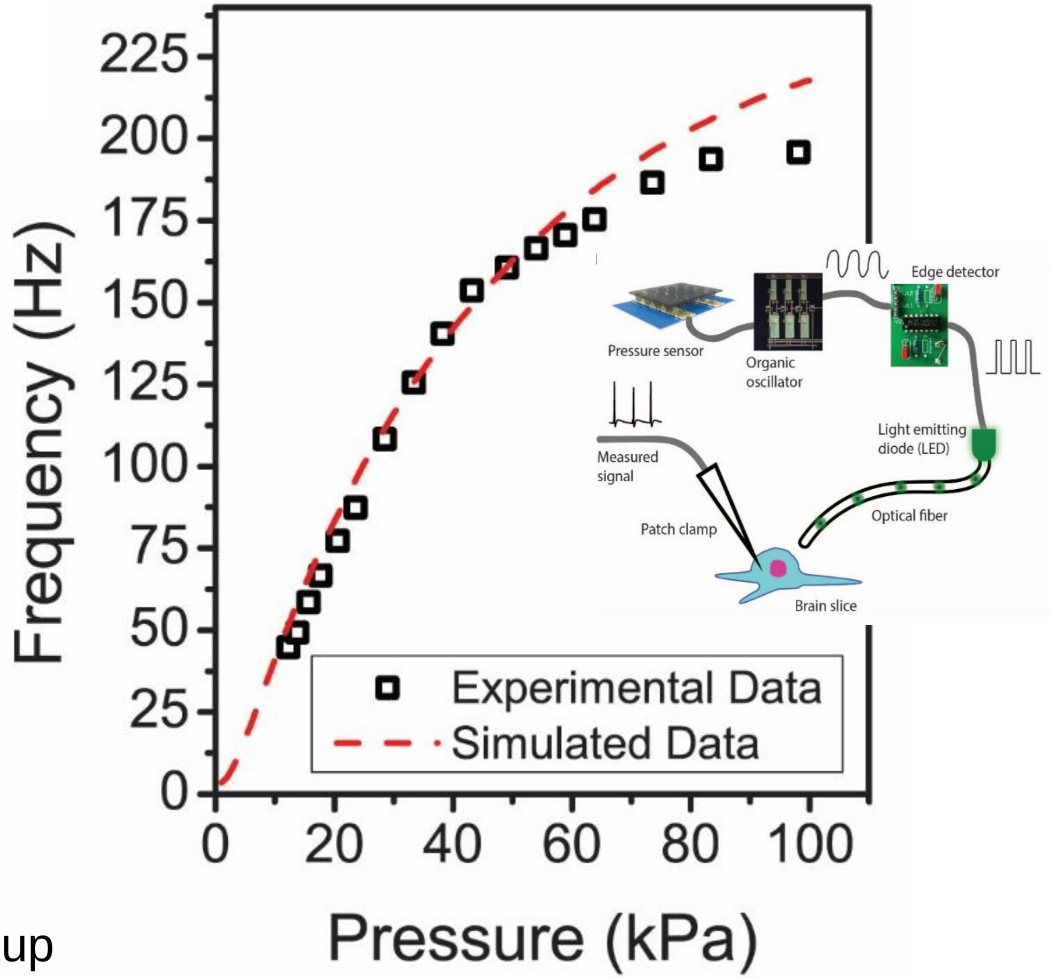




Using printed components to mimic skin mechanoreceptor







Science (2015) 350, 313.
In collaboration with Zhenan Bao group

Need to augment spasticity diagnosis

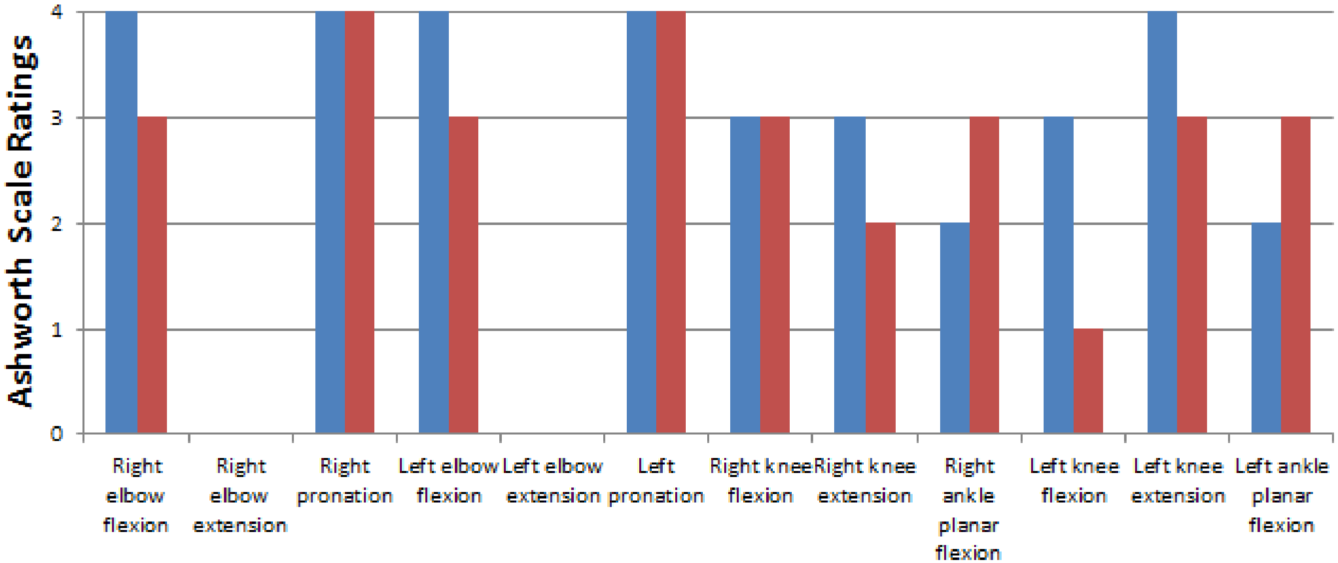
Score	Modified Ashworth Scale (MAS)
0	No increase in muscle tone
1	Slight increase in muscle tone, with a catch and release at the end of the range of motion (ROM)
1+	Slight increase in muscle tone, followed by minimal resistance throughout the remainder of ROM
2	More marked increase in muscle tone through most of the ROM, but affected parts easily moved
3	Considerable increase in muscle tone, passive movement difficult
4	Affected part is rigid in both flexion and extension

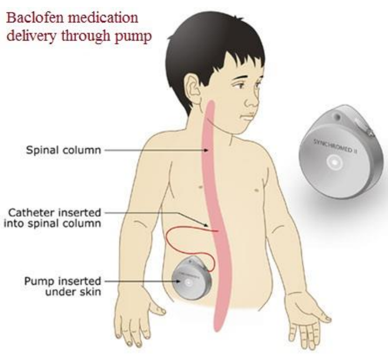
Spatiscity -involuntary activation of muscle, very common in patient with neurological disorders such as stroke, traumatic brain injury, cerebral palsy, etc. affect 764K in US; 17M world wide

Issue with reliability in MAS ratings

- 5 patients and 12 tasks: each doctor gave 60 MAS ratings
- Only 27% of the ratings were the same; poor inter-rating reliability, yet dosage is based on this rating

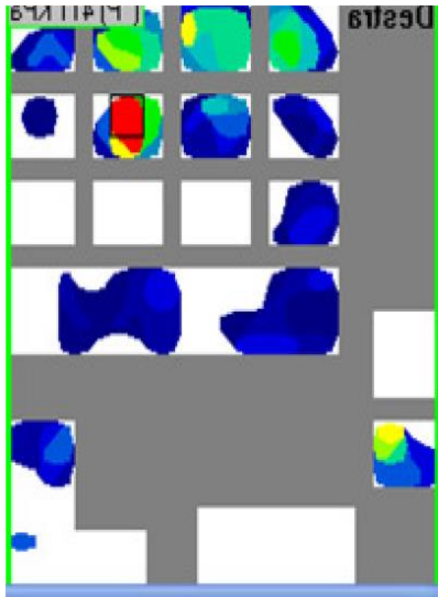
Two doctors' MAS ratings on the same patients

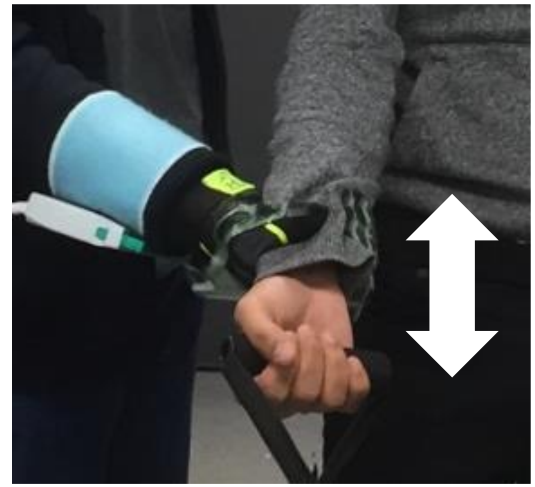


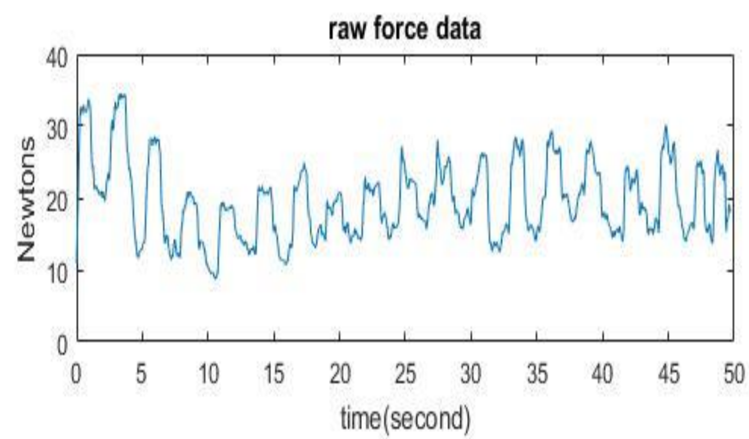


In collaboration with Dr. Garudadri (Calit2) and Dr. Skalsky at UCSD School of Medicine

Prototype glove to quantify spasticity

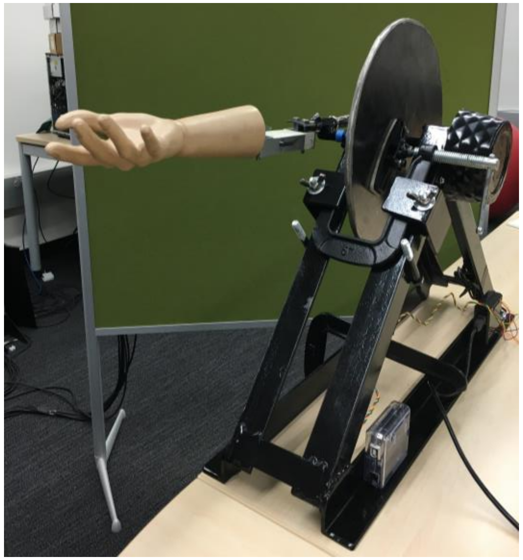


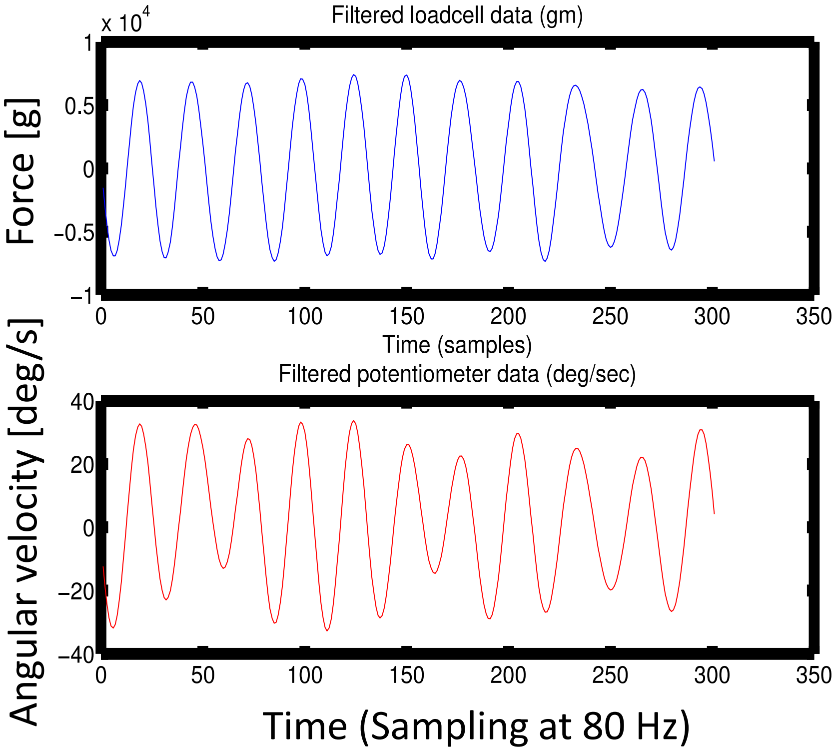




Glove worn by the doctor during assessment:
-measure force (printed pressure sensor by Tekscan) and angular velocity (gyroscope)
-Power to move a limb P=F*v

Mock patient to calibrate sensor glove

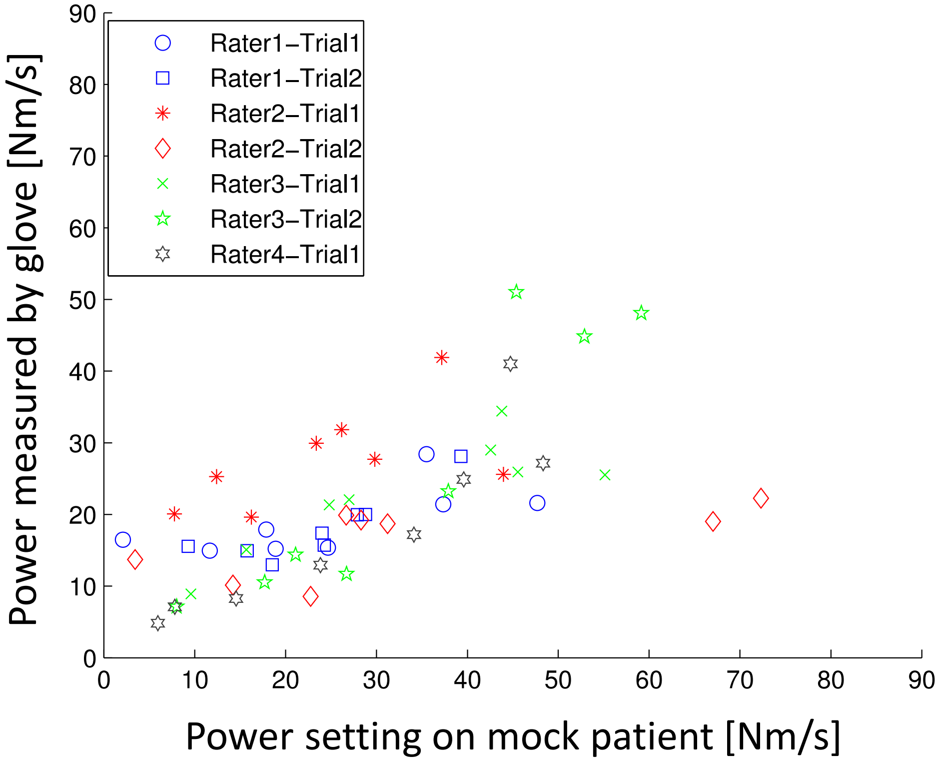


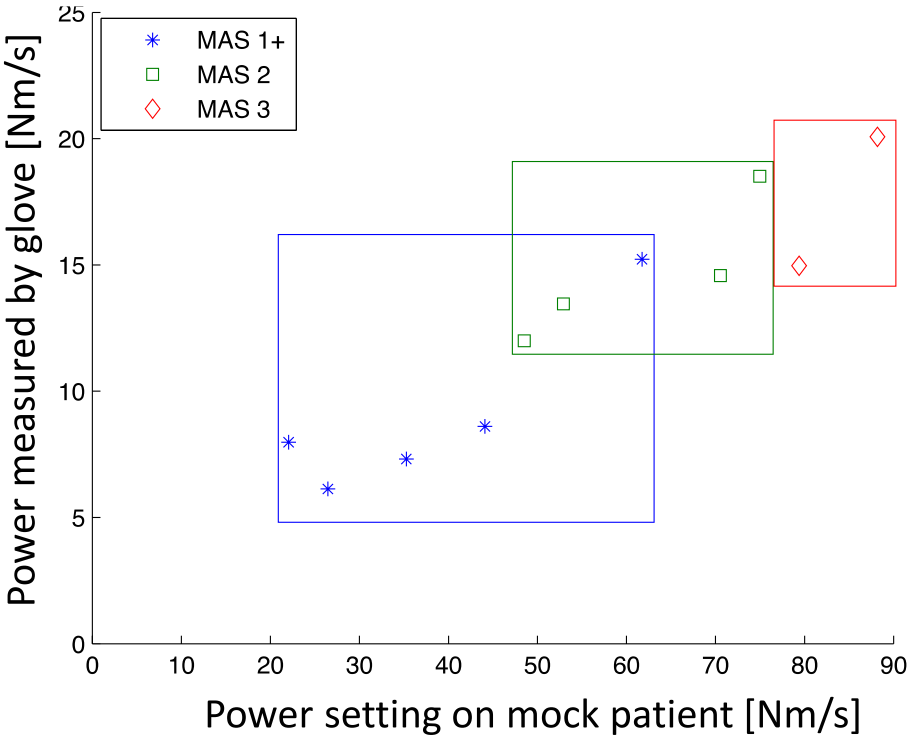


-calibrate sensor glove with a mock patient with changeable resistance (2-20kg)

- load cell to measure force
- potentiometer to measure angular velocity
- the power P=F*v to move the mock limb is recorded

Better resolution than MAS scale





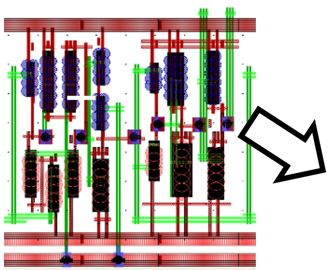
In press, IEEE-NIH 2016 HI-POCT Proceeding

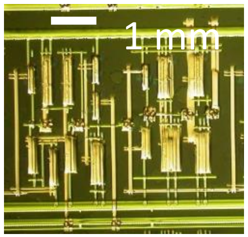
- Quantitative glove measurement allows comparison between rating trials, less dependence on rater perception
- Glove sensor improves the resolution of the spasticity assessment

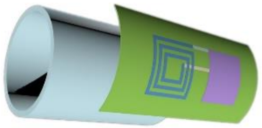
Summary

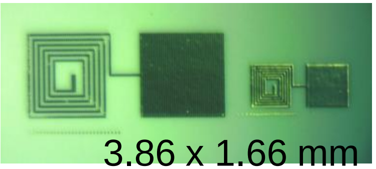
- Apply additive printing to demonstrate organic TFT circuits
    1. increase tolerance to device variation issues
    2. integrated local digitizing circuits near sensors

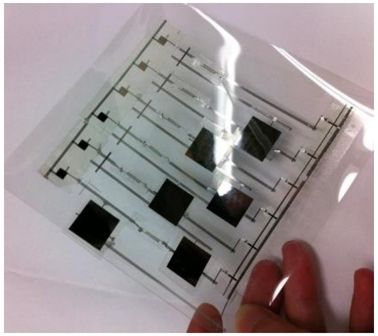
- Example application of printed pressure sensor to achieve quantitative assessment in spasticity diagnosis











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