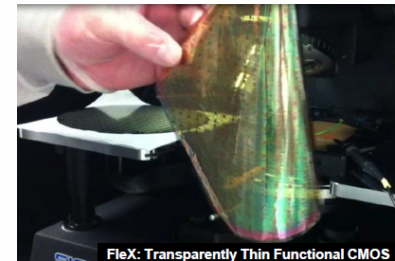
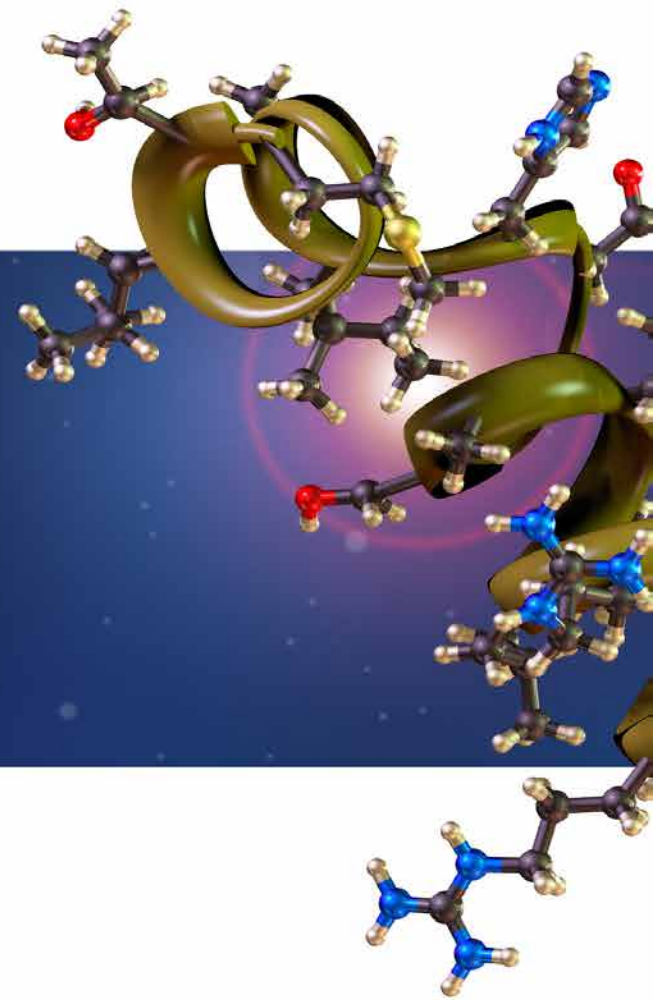


Developments in Flexible Electronics

Malcolm J Thompson PhD
CEO

Nano Bio Manufacturing Consortium



Flex: Transparently Thin Functional CMOS

Agenda

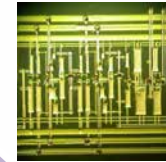


- Introduction to Flexible Hybrid Electronics
- NBMC Background
- Flexible Electronics Technology
- Next Generation Human Performance and Health Monitoring

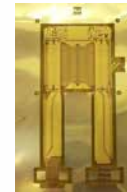
Flexible Hybrid Electronics



**More product flexibility,
lower costs, shorter time to
bring products to market,
and overall innovation and
new business
opportunities.**



**Rapid Fielding and
Distributed
Manufacturing**

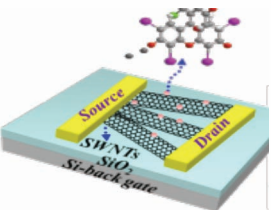
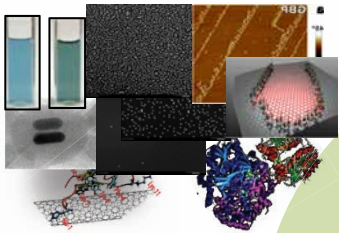
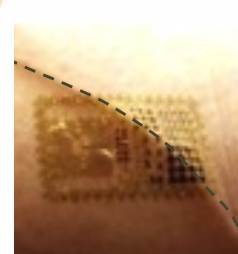


**Flexible Hybrid
Electronics**

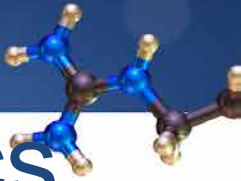
Flexible
substrates
Nanomaterials
sensors, batteries
interconnect etc
Low cost
manufacturing
e.g., R2R, printing

Flexible thin
high
performance
chips
Processors,
wireless
communication

Low cost
hybrid
integration
and
assembly



NBMC Background



AFRL Flexible Hybrid Electronics in Aerospace

Challenges and Opportunities

February 2013 AFRL awarded FlexTech with a contract to set up the Nano-Bio Manufacturing Consortium

NBMC Goal

Integration of Materials and Manufacturing within a common platform to address various flexible device applications



nbmc
Nano-Bio Manufacturing Consortium

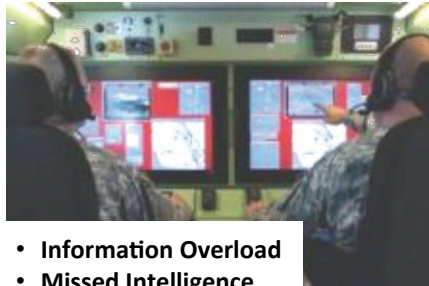
Program Supported By:



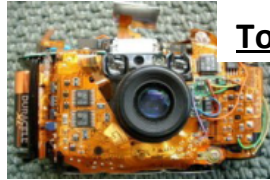
Flexible Hybrid Electronics

Human System and Cognition

Human Performance limits capability in MANY Military Missionsand New Technologies are Needed to Sense, Assess and Augment the “Man-in-the-Loop”



- Information Overload
- Missed Intelligence
- Threat/Danger Missed



Today



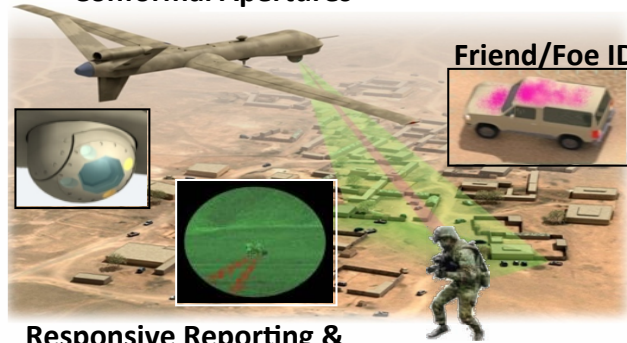
Future



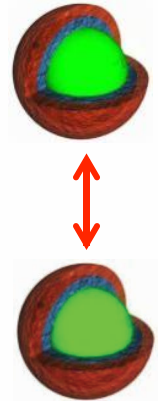
ISR and EW Integrated Capabilities

Information and tracking in contested environments (A2/AD) is foundational to decision making and force projection

Conformal Apertures



Responsive Reporting & Threat Detection



Energy Autonomous 24/7 Operations

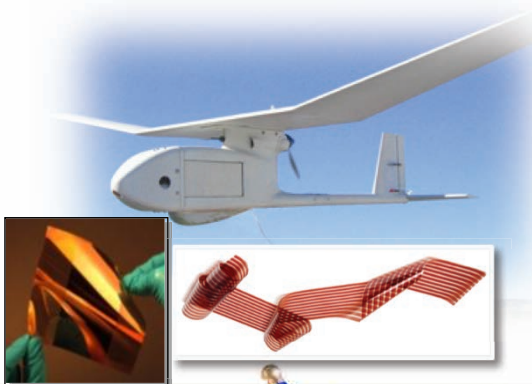
Energy limit operational capabilities and mission impact for large time and distances scenarios

Issues:

- Cost & Weight
- Scale-up
- Durability

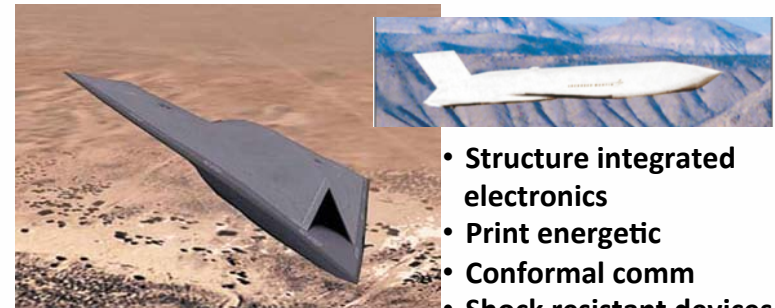
Integrated Power harvesting, storage, and management

Expected 1.5X – 3X increase in flight endurance.



Low Profile, Robust Munitions

Precision effects with smaller, low profile munitions pressing requirement for current and future platform effectiveness

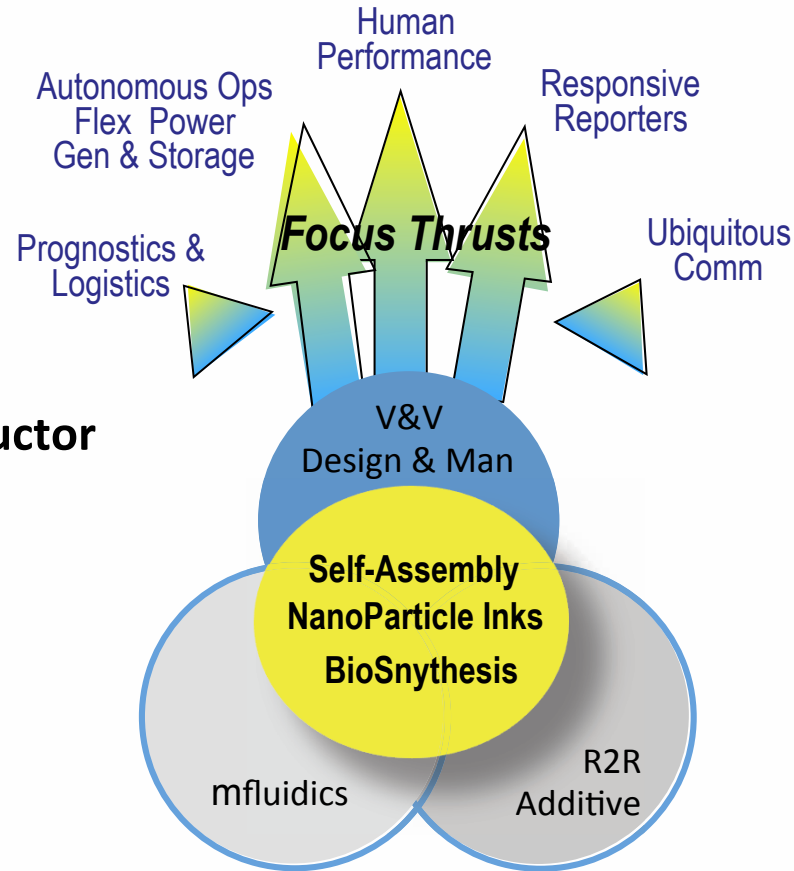


- Structure integrated electronics
- Print energetic
- Conformal comm
- Shock resistant devices



Nano-Bio Manufacturing Consortium

GE
DuPont
DuPont Teijin
PARC
Brewer Science
Soligie
American Semiconductor
MC10
Lockheed Martin
UES
I3 Electronics



UMASS
University of Arizona
Univ of Cincinnati
UC San Diego
Cornell University
Univ of Binghamton
North Eastern University
John Hopkins University
Arizona Center of
Integrated Medicine
UC Berkeley

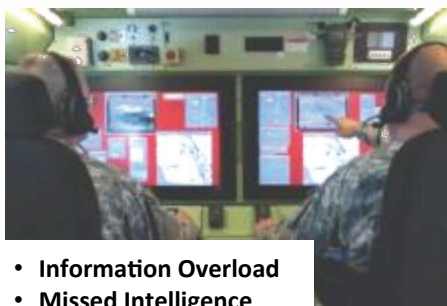
Human Performance Monitoring

Current State of the Art in Commercial Performance Monitoring – Biometrics

- Heart Rate
- Blood Pressure
- Skin Temperature
- ECG

Human System and Cognition

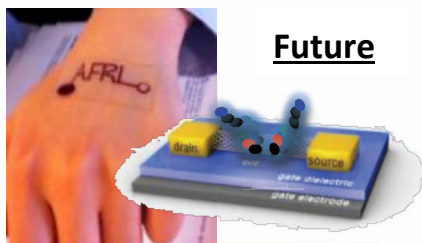
Human Performance limits capability in MANY Military Missions
....and New Technologies are Needed to Sense, Assess and Augment the “Man-in-the-Loop”



- Information Overload
- Missed Intelligence
- Threat/Danger Missed



Today



Future

Future Performance Monitoring: Real time Biomarker analysis

- Cognitive Effectiveness
- Levels of Stress PTSM Markers
- Fatigue/Vigilance
- Exposure to Chemical/Biological Agents





Samsung Galaxy Gear



Image from iagua.com



Image from bgr.com

Artistic Concepts

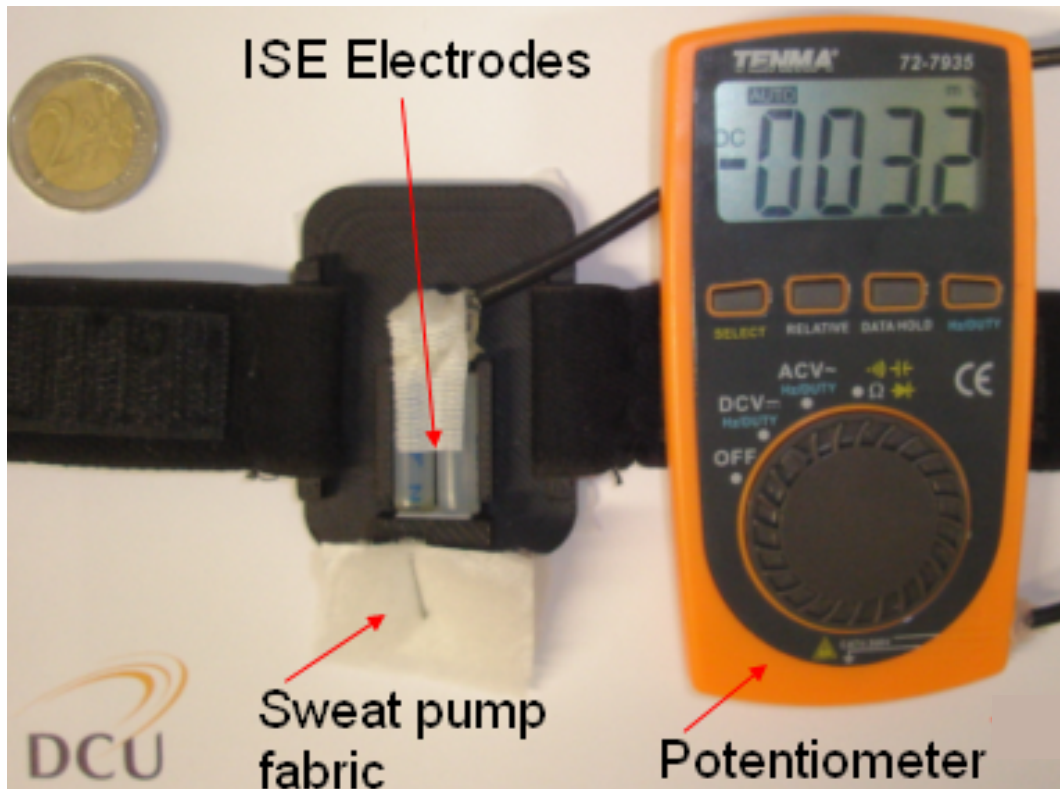


Pebble



Image credit: Todd Hamilton

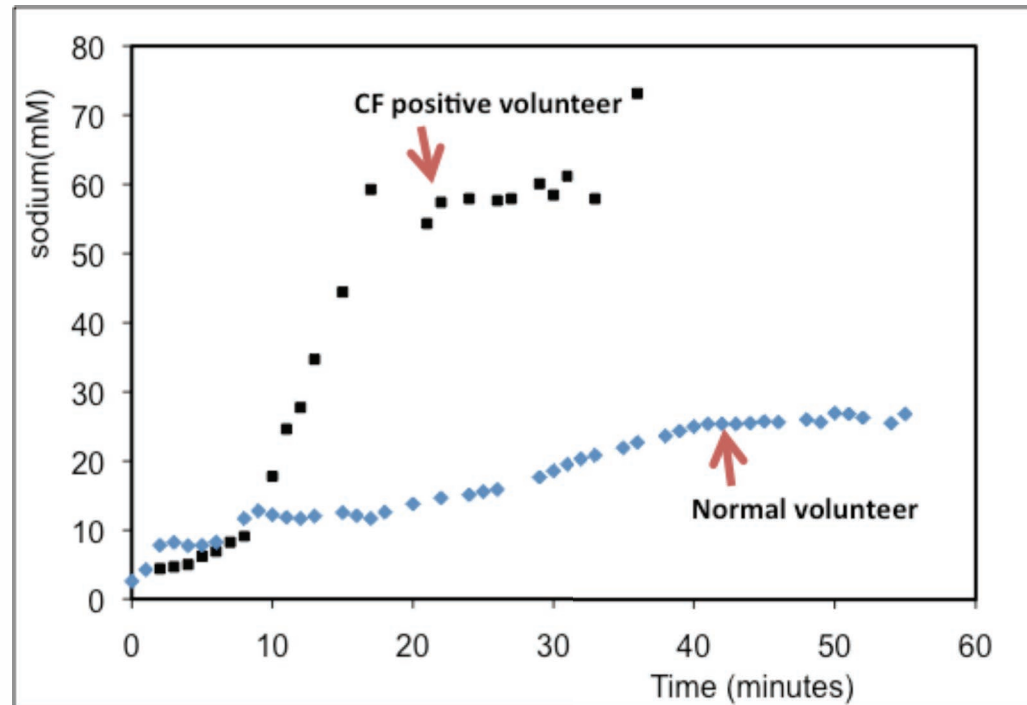
Na⁺ sensor: Sodium Sensor Belt (SSB)



Schazmann, B., et al., Analytical Methods, 2010, 2(4): p. 342-348.

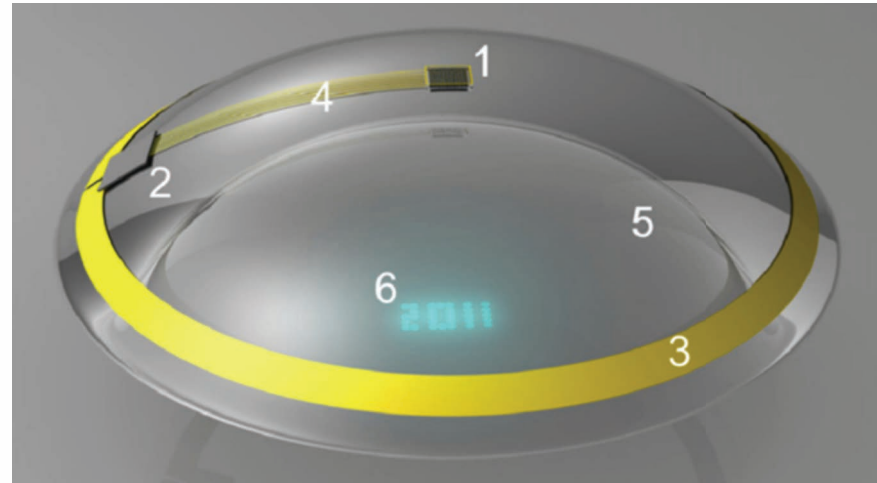
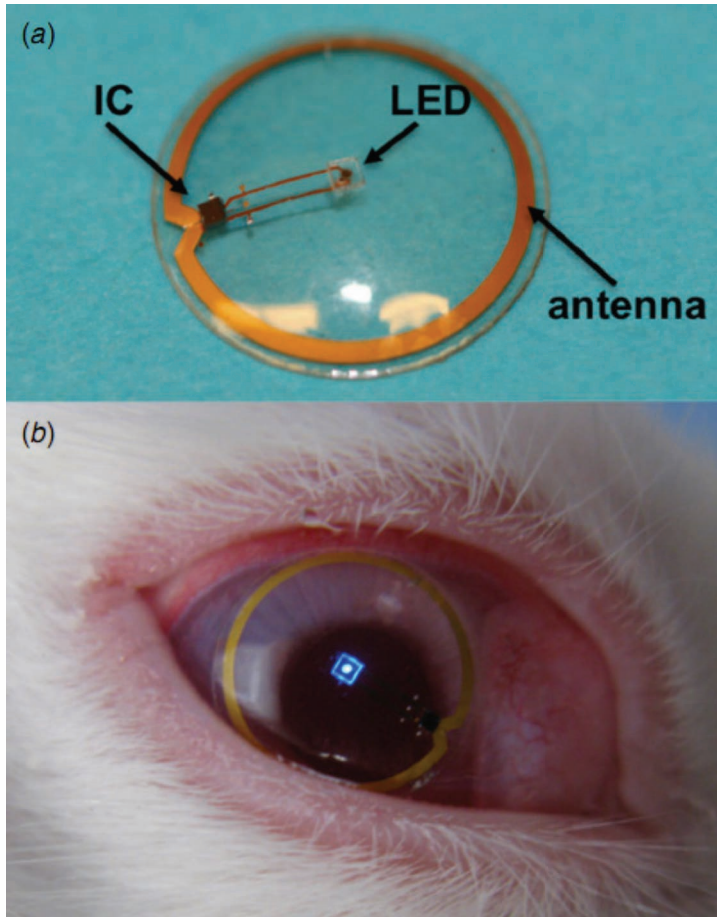
Na⁺ monitoring in sweat using wearable sensor

- Measurements successfully made with CF-positive and normal volunteers
 - clear difference between CF+ and normal levels
- Elevated levels of Na⁺ found in sweat of CF+ volunteers as expected
- Enables electrolyte loss to be estimated when combined with sweat rate/volume data
- Important for rehydration
- Interesting observations
 - elevated viscosity of sweat of CF+ volunteers
 - sweat rate much lower – in some cases no sweating occurred
 - could not exercise as long as normal volunteers



- Diagnostic CF threshold >60mM [Na⁺] reached
- Issue with initial delay
 - arises from inherent delay in onset of sweating
 - contribution from device 'dead-volume'

Babak Parviz: LED implanted on a contact lens

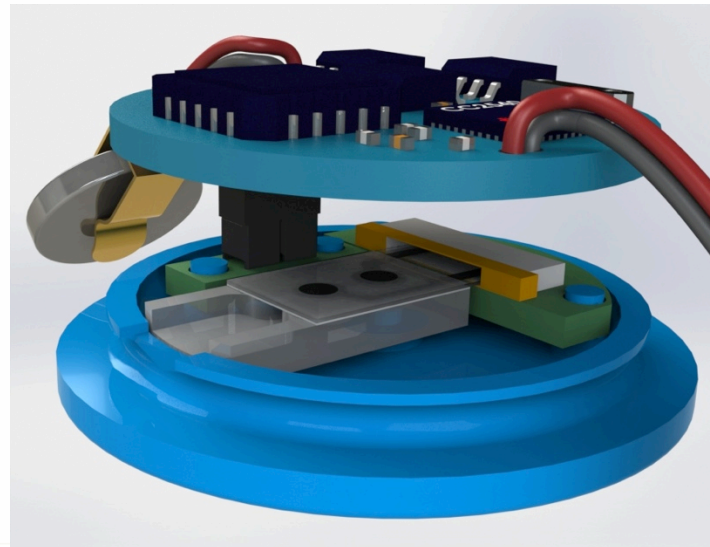
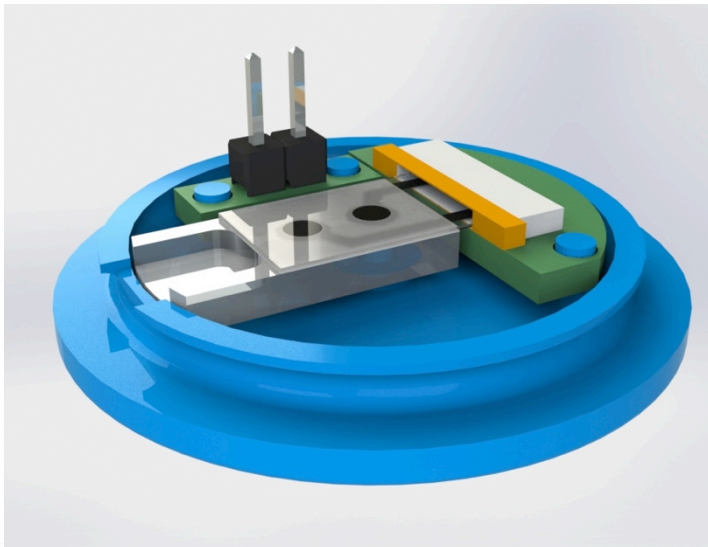


“There’s basically just two components, sandwiched between two layers of contact lens material: An antenna and rectifier, and a small glucose sensor. The problem with smart contact lenses, though, is the power source.”

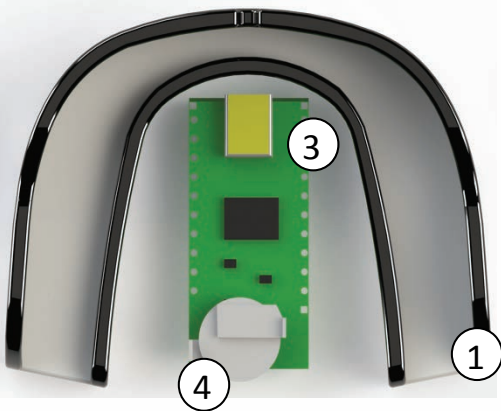
“The team, led by Babak Parviz, (University of Washington -> Google) has successfully displayed a single, remotely-controlled pixel onto a contact lens worn by a rabbit. Power from an external battery is transmitted via RF to an antenna that runs around the edge of the contact lens (the gold ring that you see in the image below), so that the wearer’s vision isn’t obstructed.”

<http://www.extremetech.com/extreme/174979-the-next-step-in-googles-cyborg-plans-smart-contact-lenses-for-those-with-diabetes>

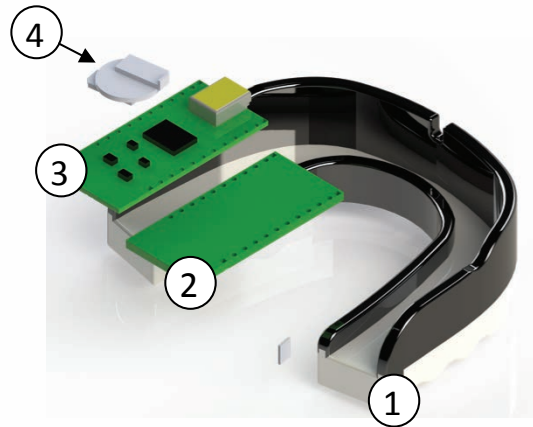
Next Generation: Watch Fluidic Sensor Concept



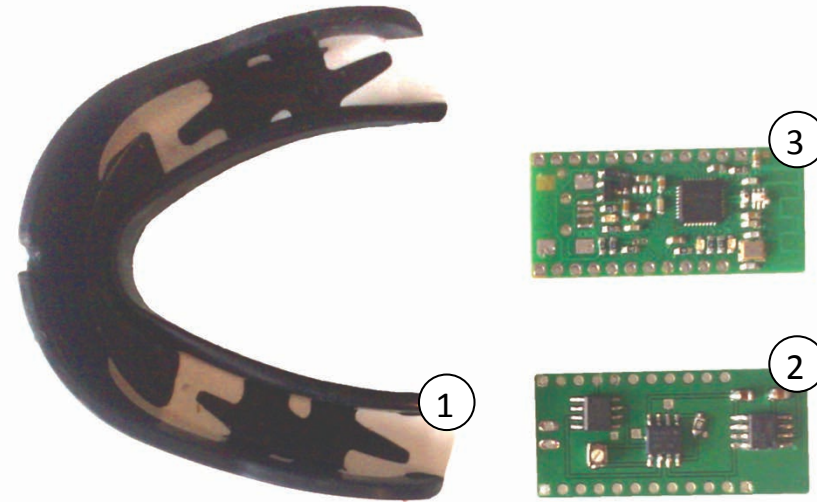
Smart Gumshield



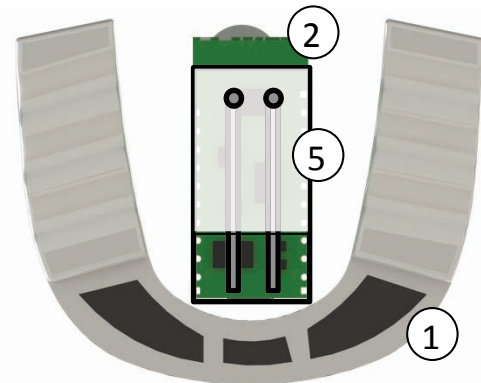
(a) Top View



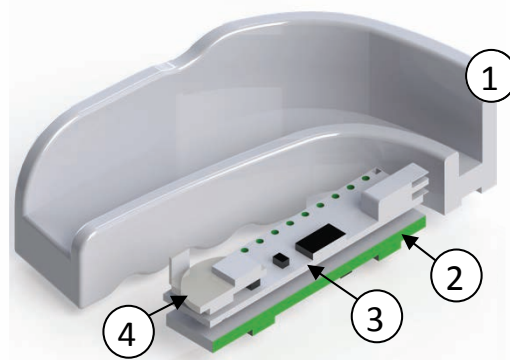
(b) Exploded View



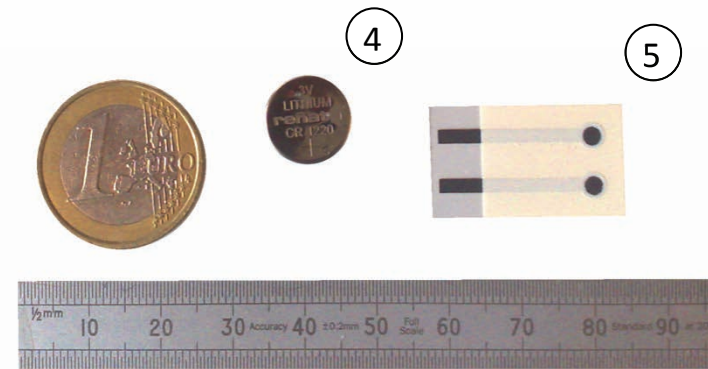
(e) Photo of components laid out



(c) Bottom View

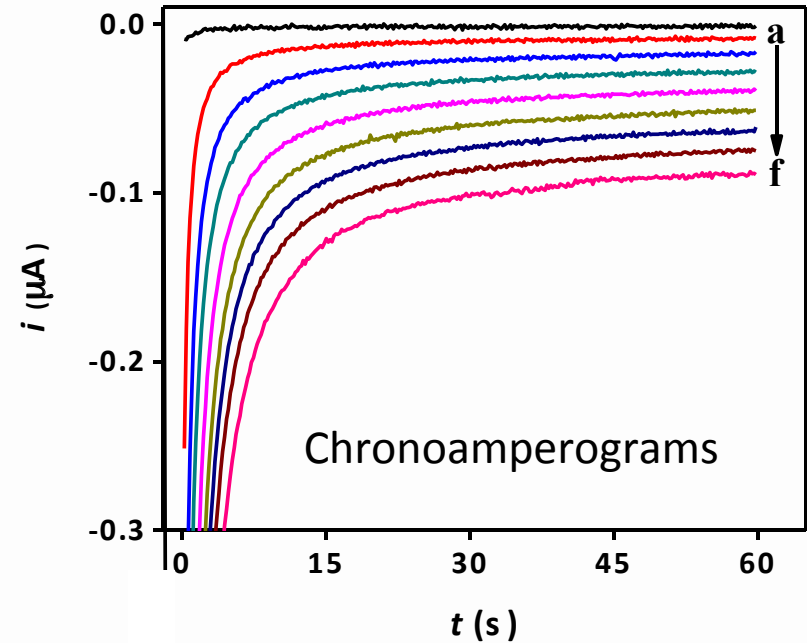
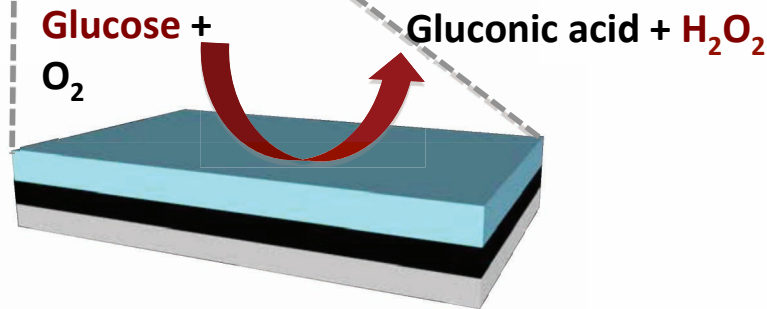


(d) Assembled Sectional View



NBMC Project

- PARC/UCSD Collaboration
- Develop biocompatible mouthguard for biomarker sensing



Flexible Electronics Status

Flexible Printed Electronics

Flexible Hybrid Electronics

Printed Electronics

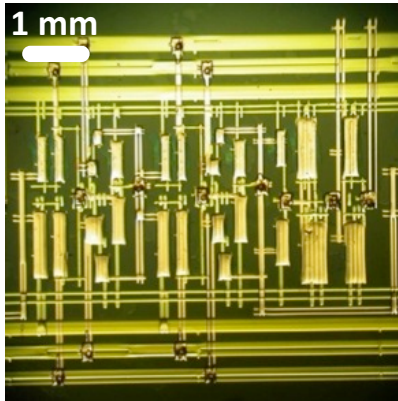
Flexible Si ICs

Packaging

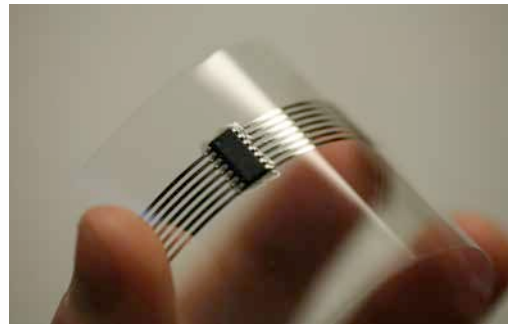


Approaches to Printed Electronics

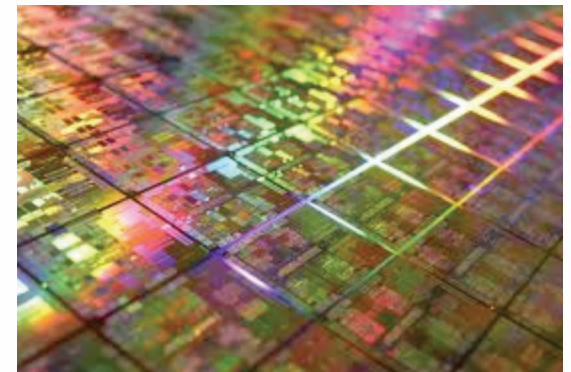
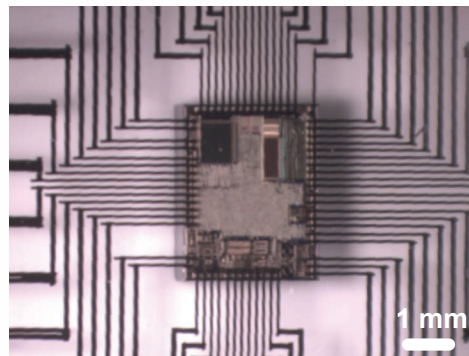
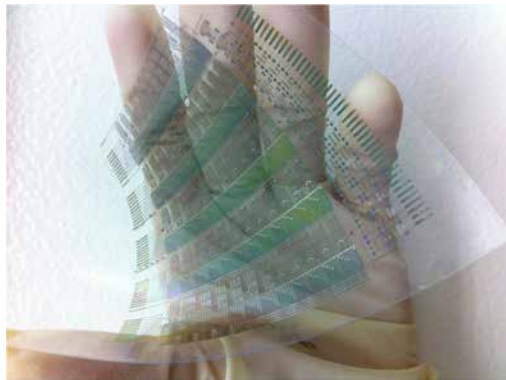
all-printed: all components printed from simple inks



hybrid: include some pre-fabricated components if needed



assembly: large scale assembly of electronic components



Flexible Electronics Status

Flexible Printed Electronics

Flexible Hybrid Electronics

Printed Electronics

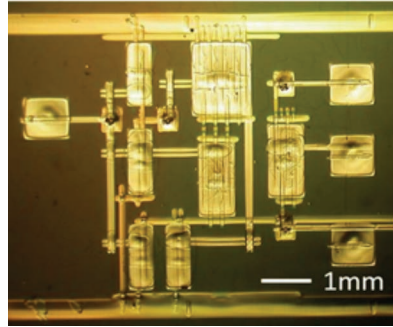
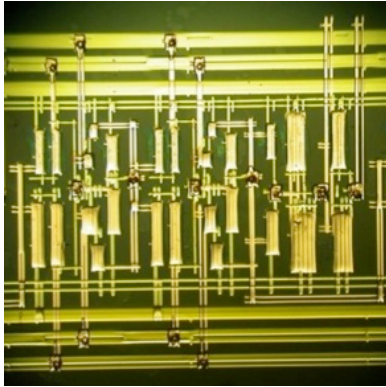
Flexible Si ICs

Packaging

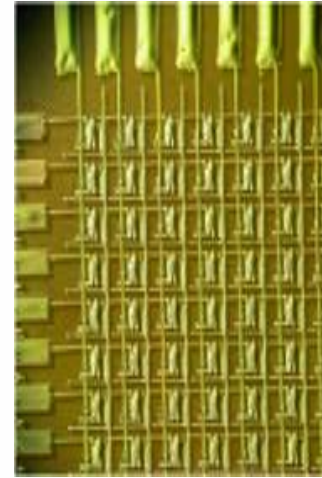


All-Printed Devices

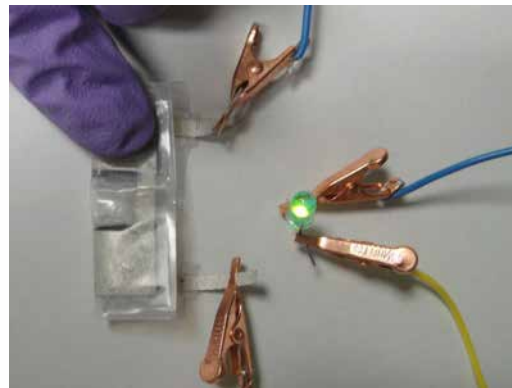
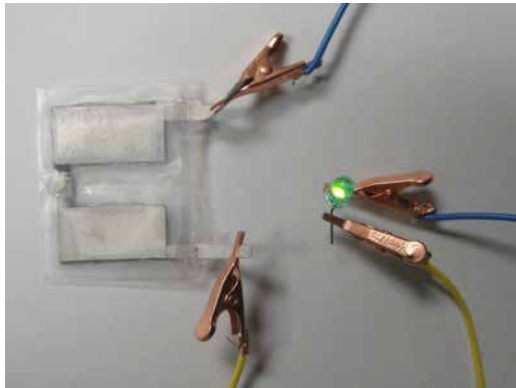
Many device types can be printed from simple inks



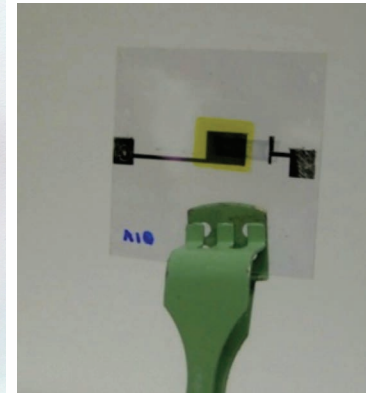
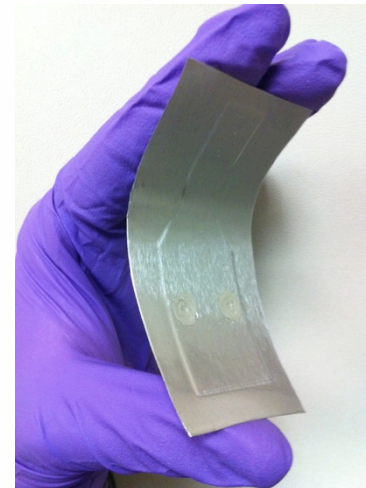
TFTs & complementary circuits^{1,2}



memory^{3,4}



electrochemical storage^{5,6}

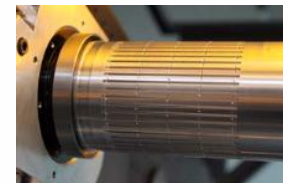
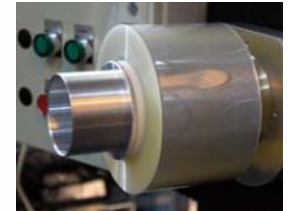
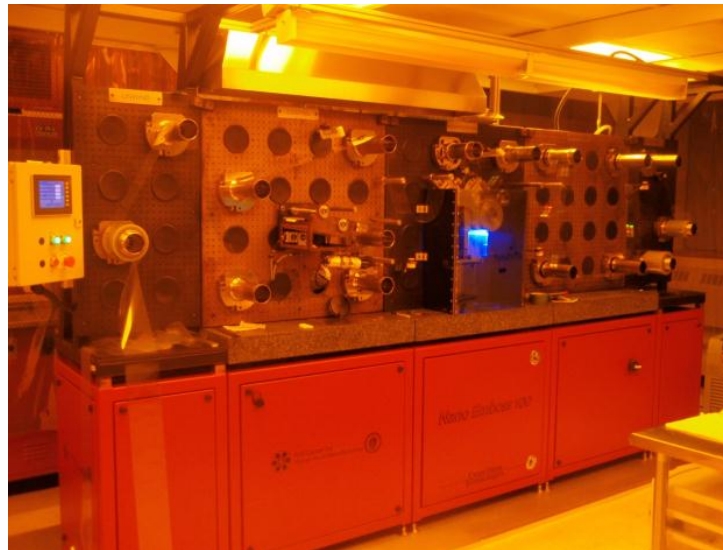


sensors^{7,8}

Printing

- Printed electronics will use platform/combo style machines
 - Inkjet
 - Flexography
 - Gravure
 - Screen
 - Litho

UMass / CHM R2R NIL Tool



Low cost
hybrid
integration
and
assembly

Printed sensor platform

FlexTech funded project (PARC/ThinFilm/UCB)

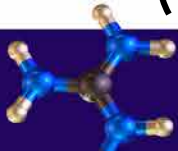
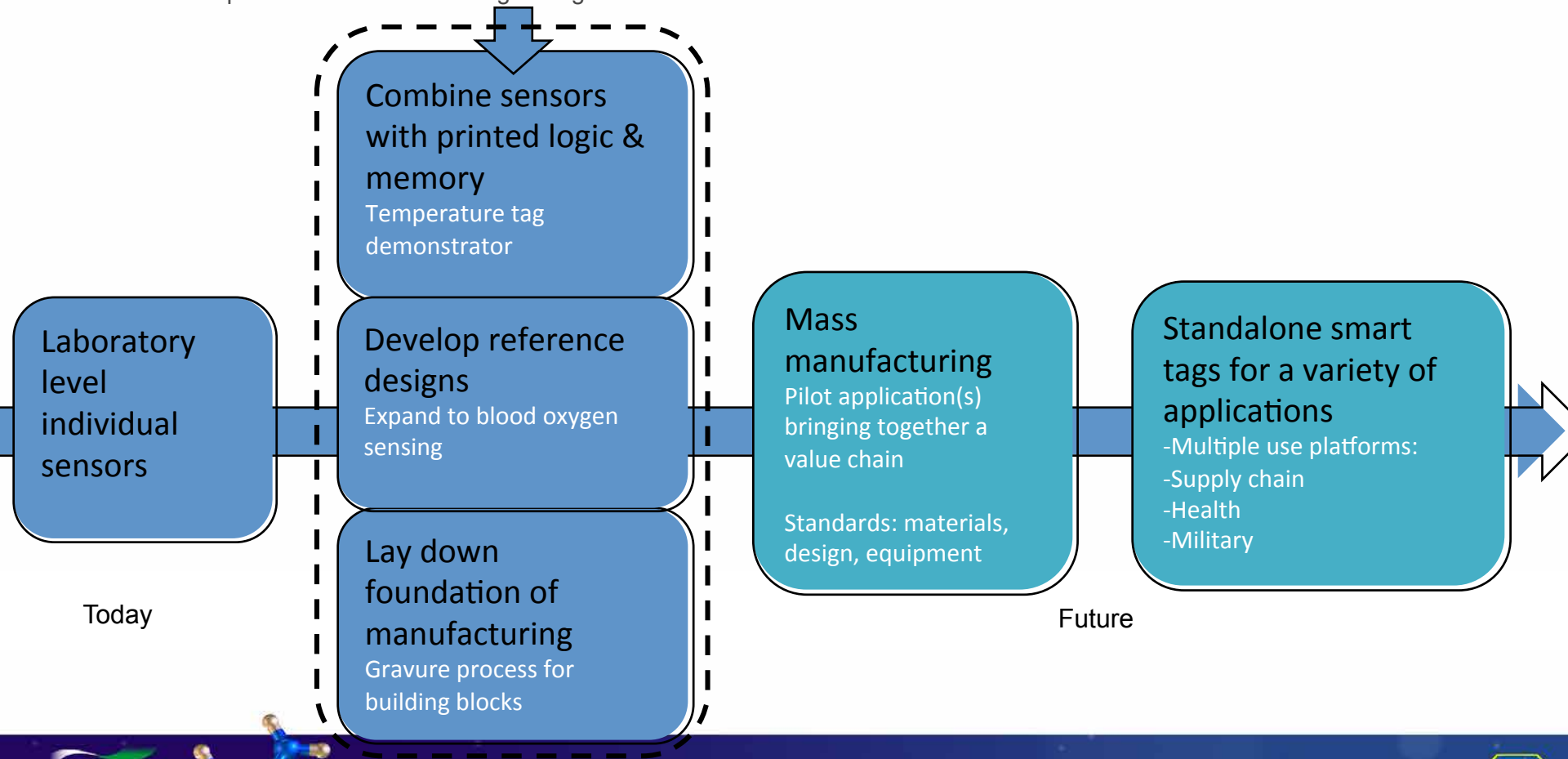
Printed sensors are a real opportunity for printed electronics.

There is a need for application driven explorations (temperature, blood oxygen):

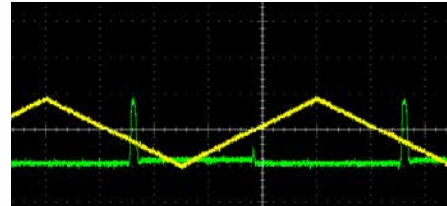
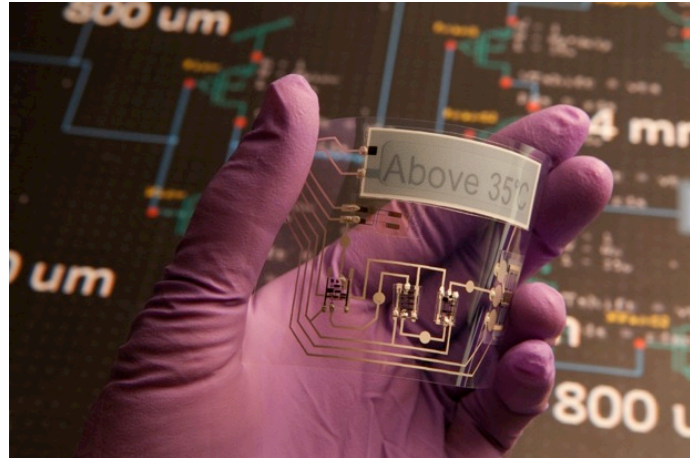
Step up complexity (add memory & logic, making tags standalone).

Lay the basis for manufacturing processes

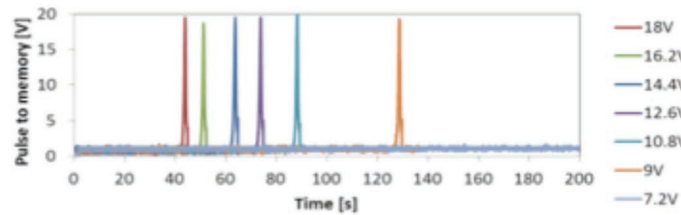
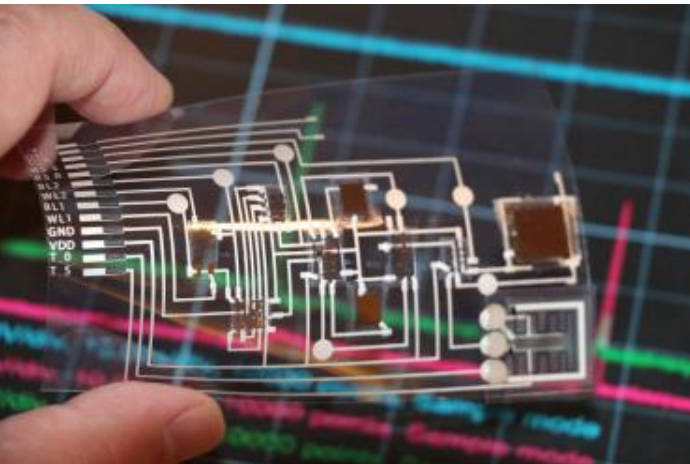
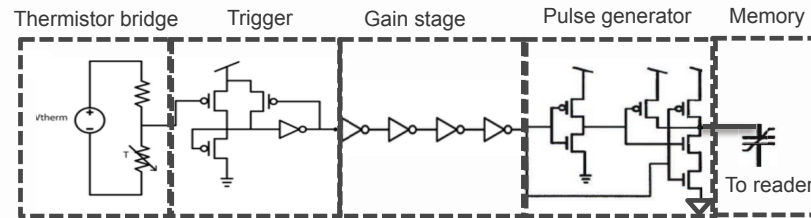
Provide platforms of understanding throughout the value chain



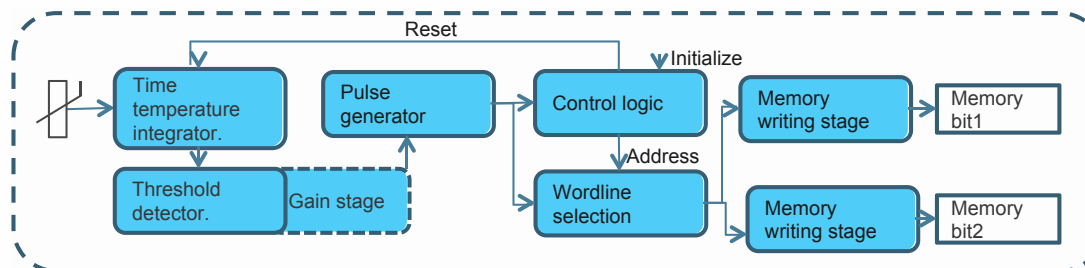
Sensor Systems



threshold temperature measurement
developed in collaboration with Thin Film Electronics



temperature dose tag
developed in collaboration with Thin Film Electronics, UCB and Flextech



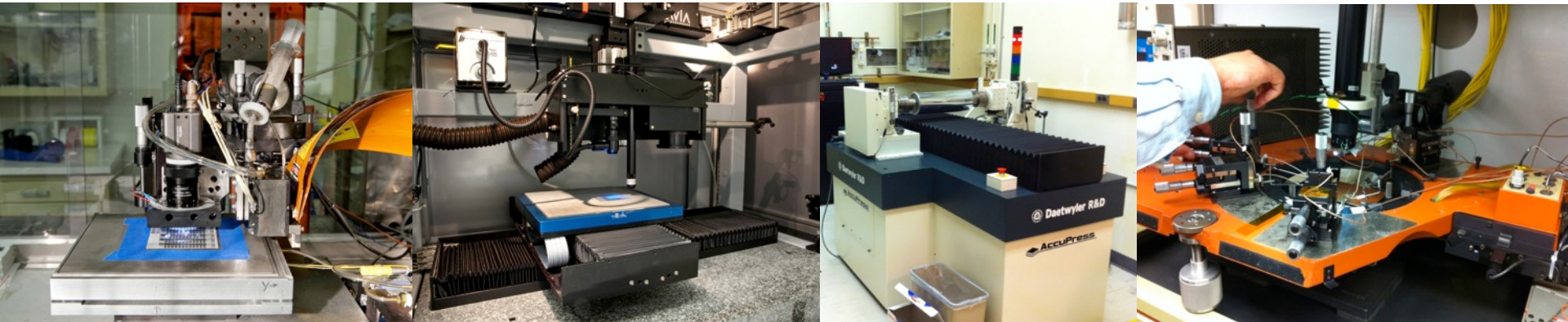
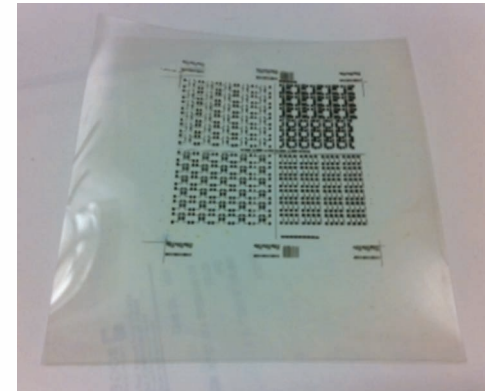
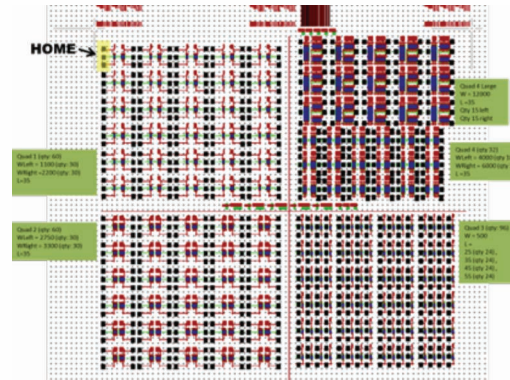
Printed systems and devices platform

Patterning: inkjet, laser, gravure, screen, lithography

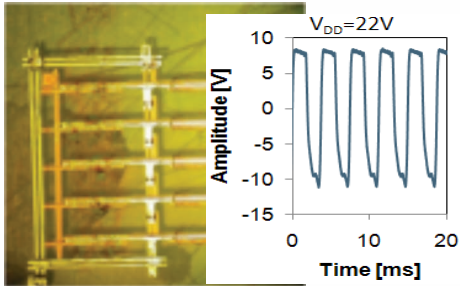
Metrology, automated testing

Circuit design and simulation

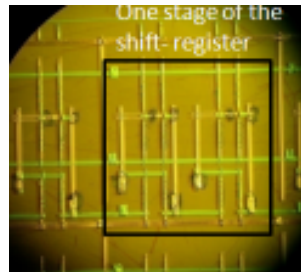
Device modeling, molecular modeling



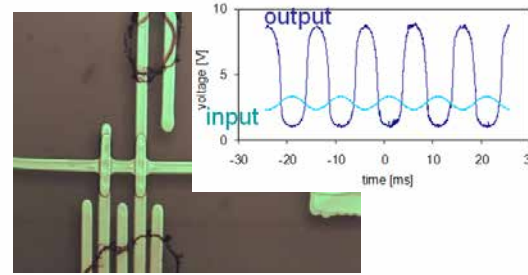
An expanding library of printed electronics building blocks



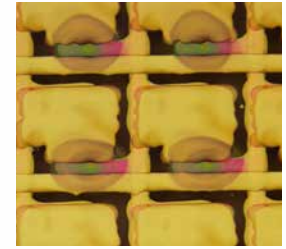
Ring oscillator



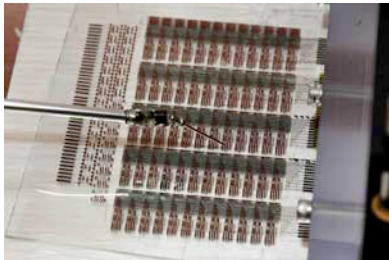
Shift Register



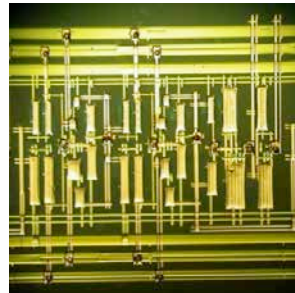
Amplifier



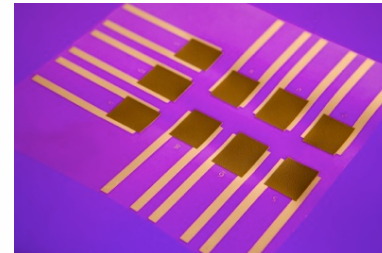
Active matrix TFT



Decoder



Complementary logic



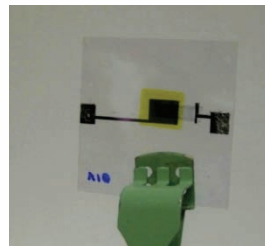
Temperature sensor



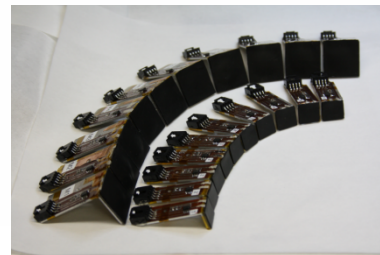
Flex battery



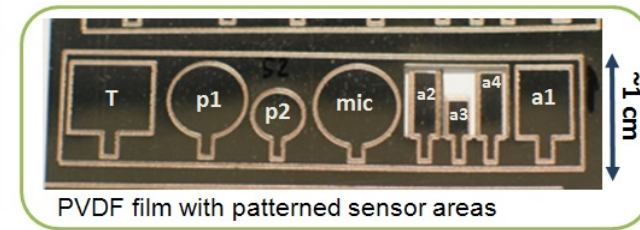
Image sensor



Light sensor



Pressure sensor



PVDF film with patterned sensor areas

MEMS

Flexible Electronics Status

Flexible Printed Electronics

Flexible Hybrid Electronics

Printed Electronics

Flexible Si ICs

Packaging



Example Hybrid System Design

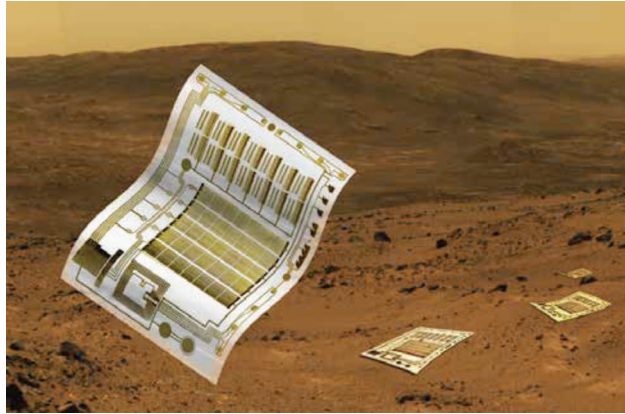
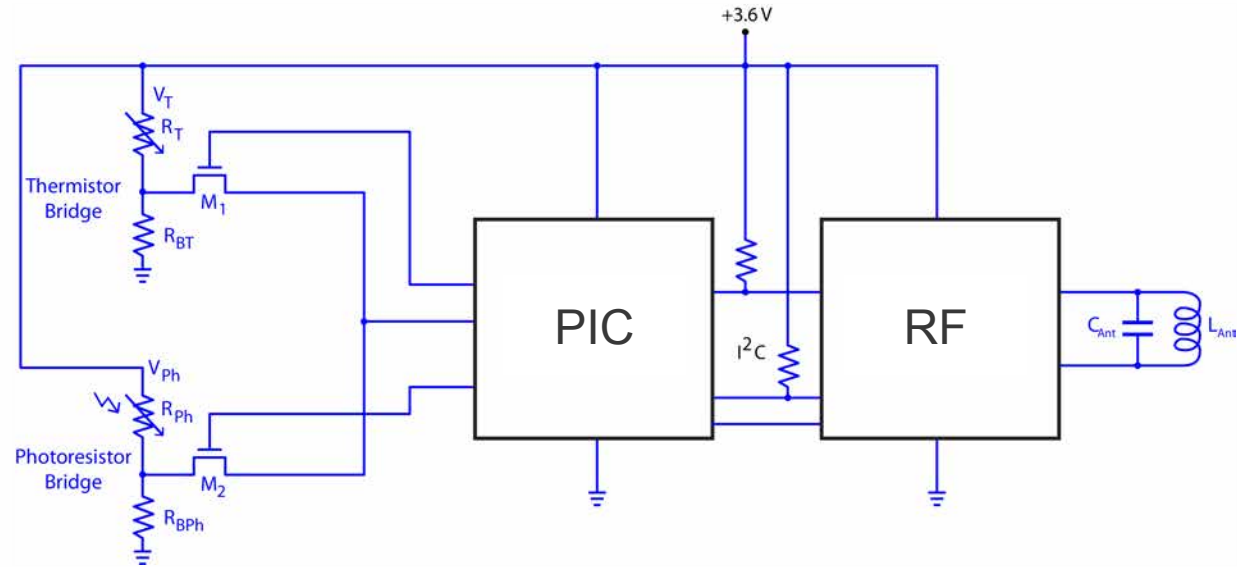
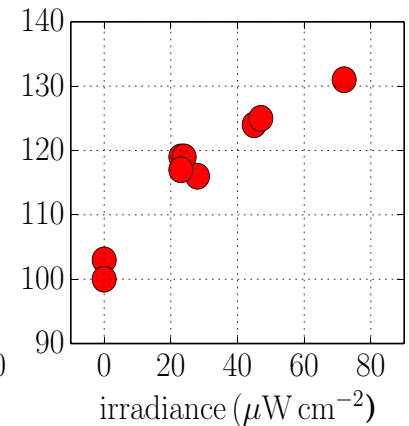
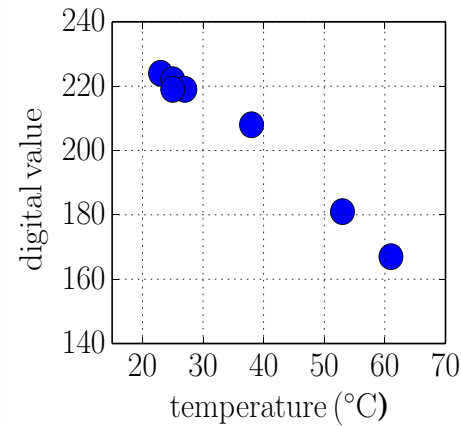
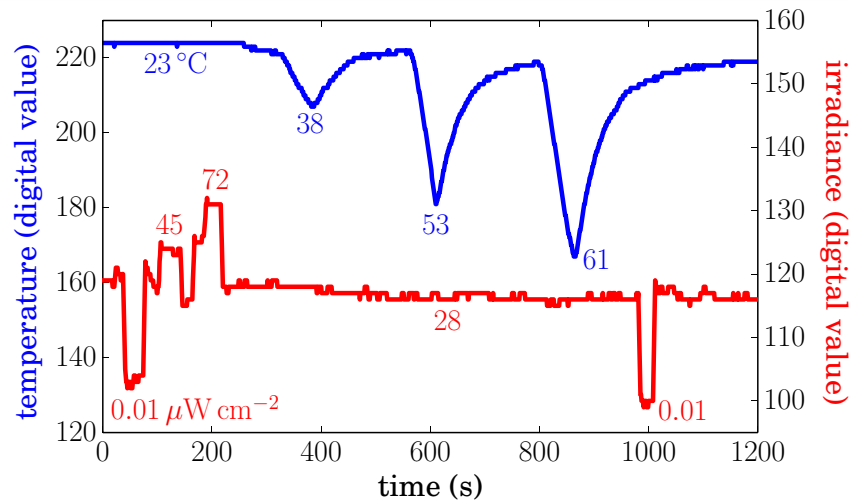
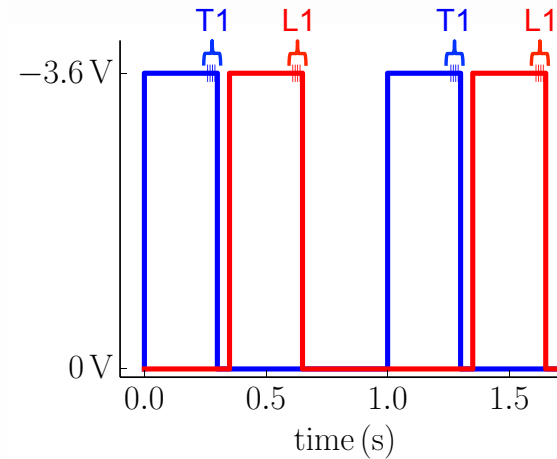
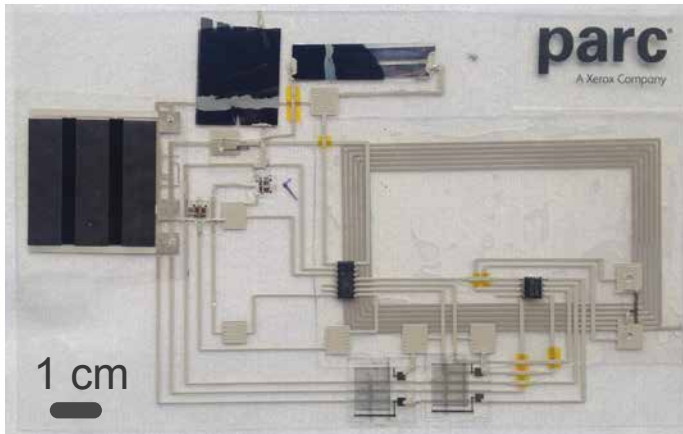


image courtesy of JPL



- Specific example for measuring temperature and light intensity
- Can be used generally for other sensor types
- Printed device, CMOS integration issues critical

Complete System





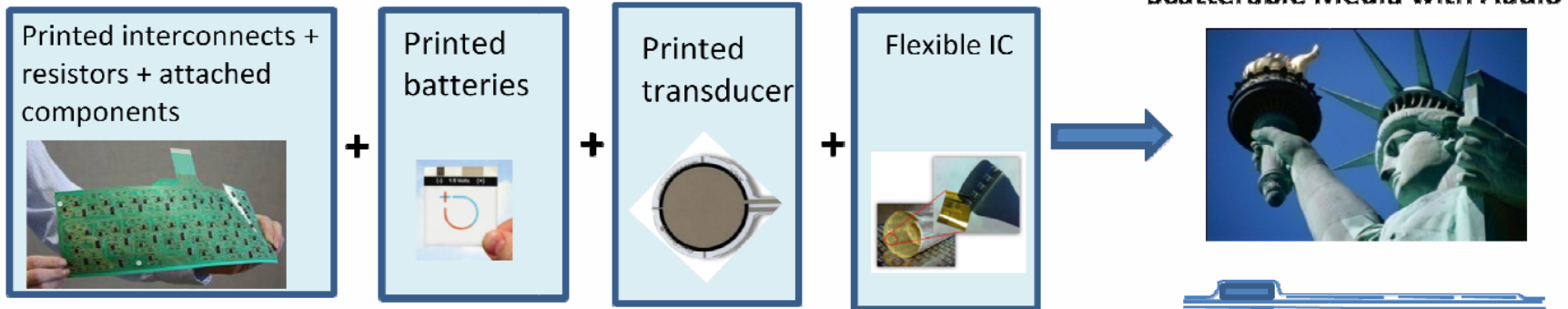
SOCOM Scatterable Media Project

Printed piezoelectric material

- Printable polymer with piezoelectric characteristics available from Solvay Solexis
- Enables direct integration of transducer on flexible substrate
- Enables use of large area for transducer
- Reduces complexity of assembly and enables thin form factor

FleX Silicon-on-Polymer CMOS

- American Semiconductor has developed the capability to create 130 nm CMOS devices in a flexible form factor
- Enables complex logic and data storage needed for audio applications
- Application specific IC needed for audio application (beyond the scope of this program)



Leverage some of this technology for other Army programs, e.g., Electronic Ground Reference Guide (GRG)

Flexible Electronics Status

Flexible Printed Electronics

Flexible Hybrid Electronics
Printed Electronics

Flexible Si ICs
Packaging



Flexible Chips

Flexible thin
high
performance
chips

Processors,
wireless
communication

FleX™ Properties & Benefits

Flexibility.

For integration into flexible systems or conformal on mounting of non-flat surfaces.

Durability.

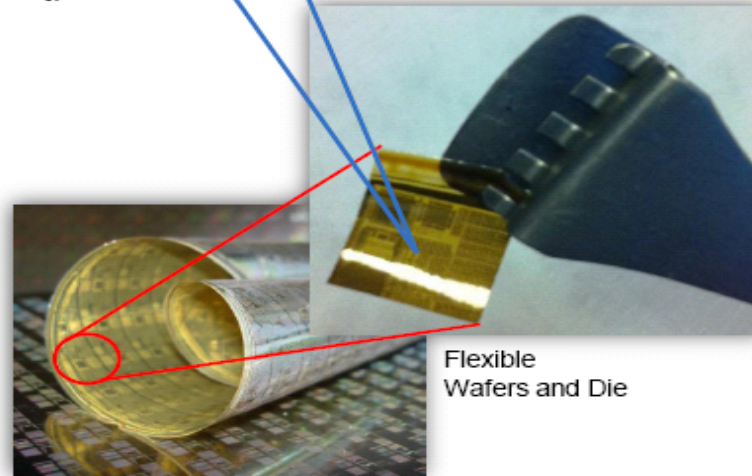
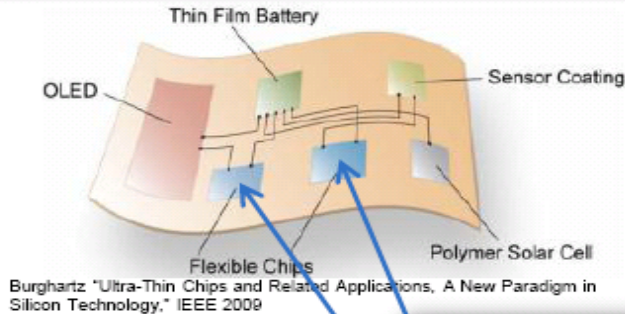
No silicon substrate improves tolerance to both mechanical and thermal shock.

Size.

Ultra thin form factor is useful in multi-chip packages and 3DIC.

Performance.

Transistors run 50%-100% faster on FleX wafers than on full thickness wafers.



Flexible Electronics Status

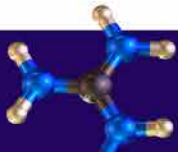
Flexible Printed Electronics

Flexible Hybrid Electronics

Printed Electronics

Flexible Si ICs

Packaging



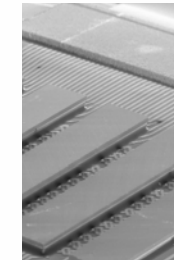
Advanced Novel Packaging



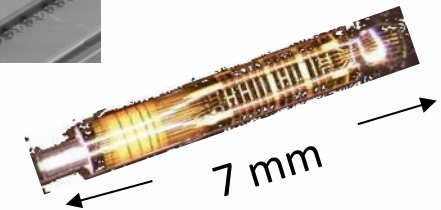
MC10



Intravascular Ultrasound (IVUS) is a catheter-based system that allows physicians to acquire images of diseased vessels from inside the artery.



Endicott Interconnect & CAMM



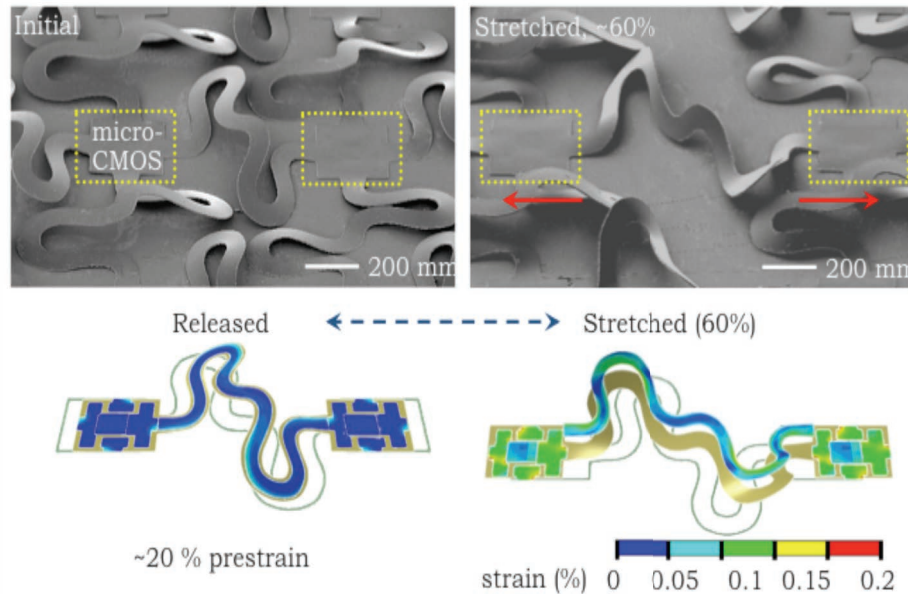
Part Description

Description: Flexible polyimide substrate with transducer (receiver / transmitter)

Dielectric: Polyimide, 12.5 μm

LW/LS: 14 μm / 14 μm

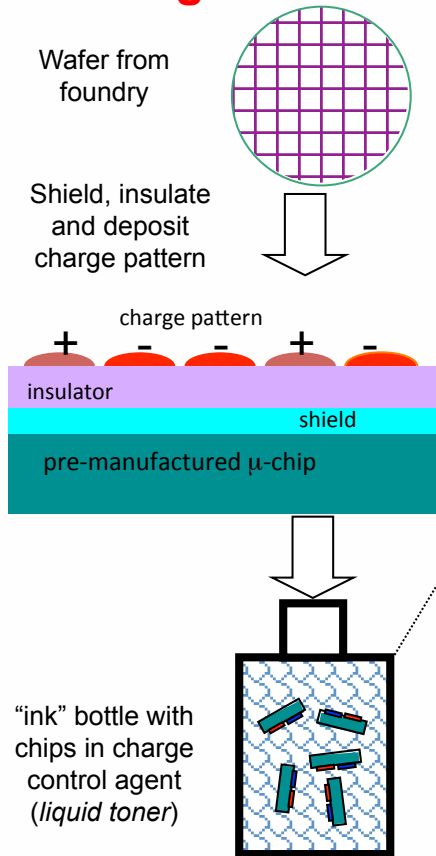
Flip Chip: 22 μm bumps, 70 μm pitch



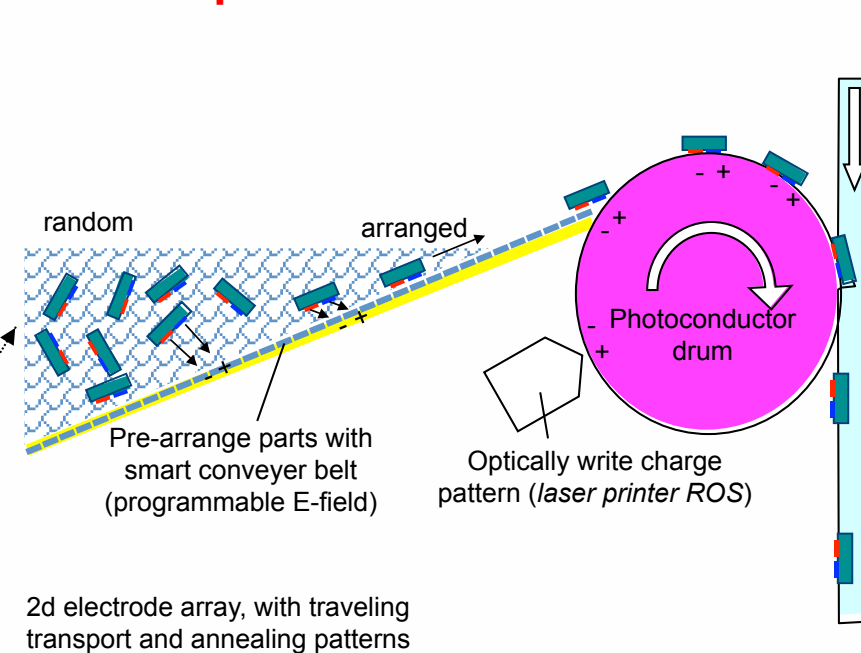
Digital Fluidic Microassembly

Use dynamic electric fields to transport, orient, and fix chips

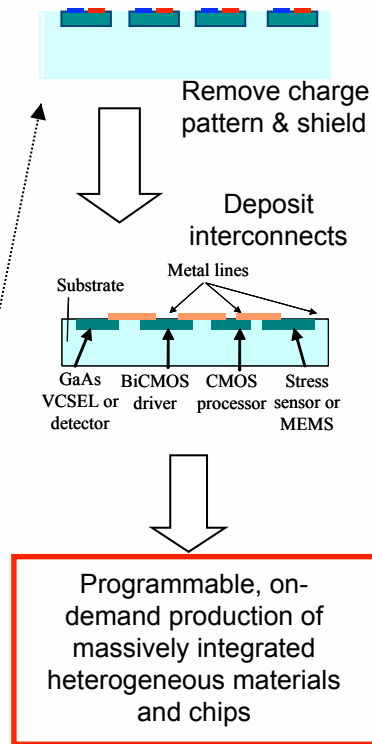
1) Encode & Singulate



2) Sort, Orient & Transport



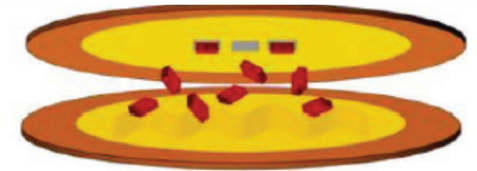
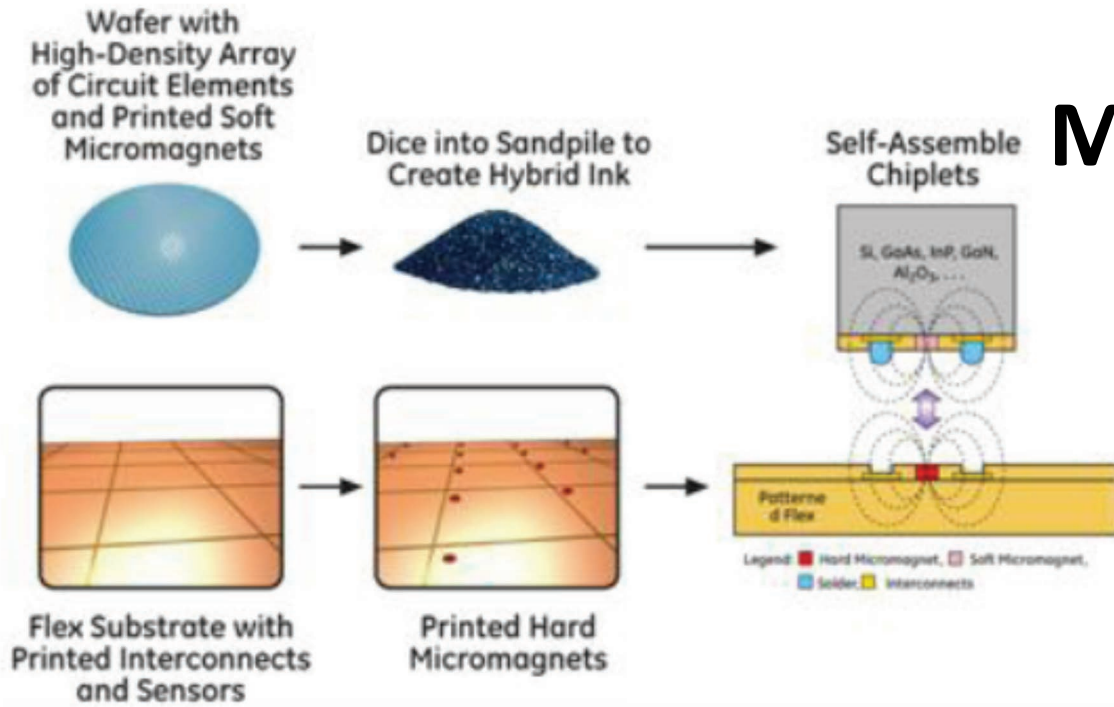
4) Clean & Connect



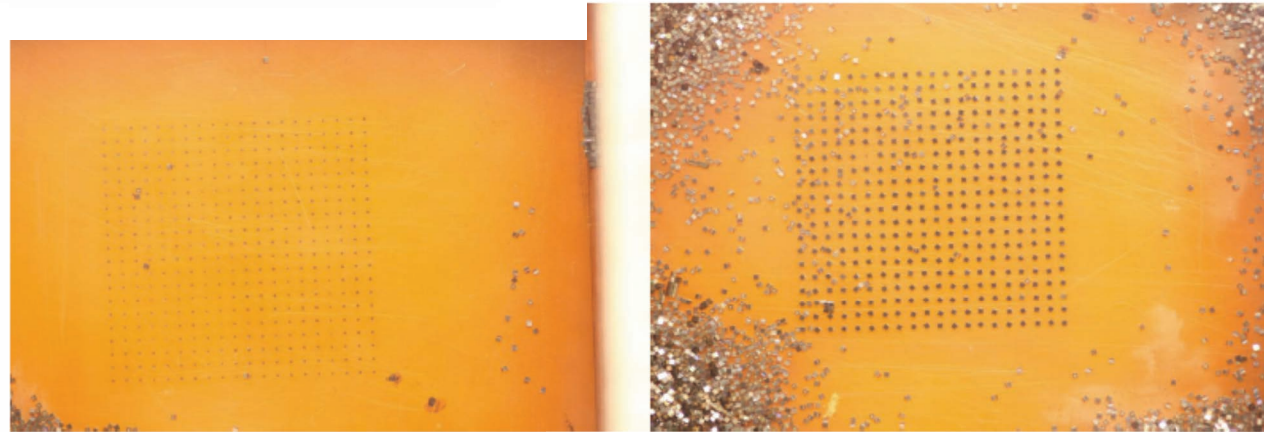
one chip per location, orientation control



Magnetically Directed Assembly



GE

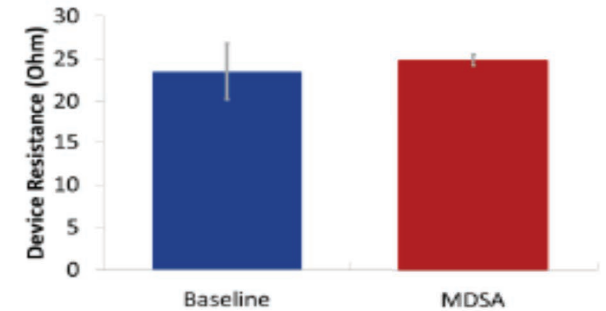
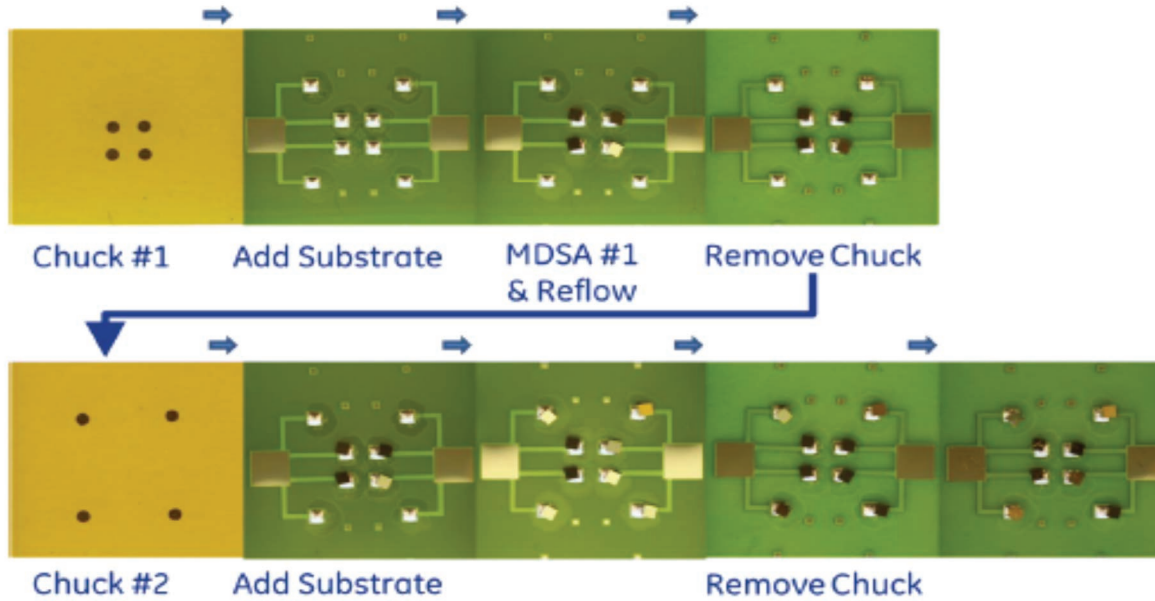
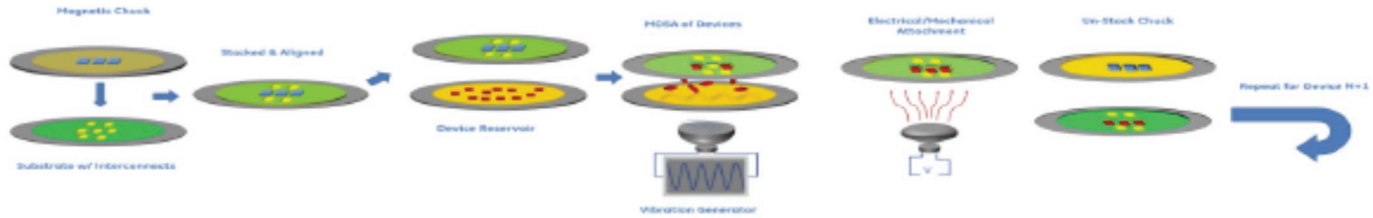


Unpopulated Substrate

After Attraction



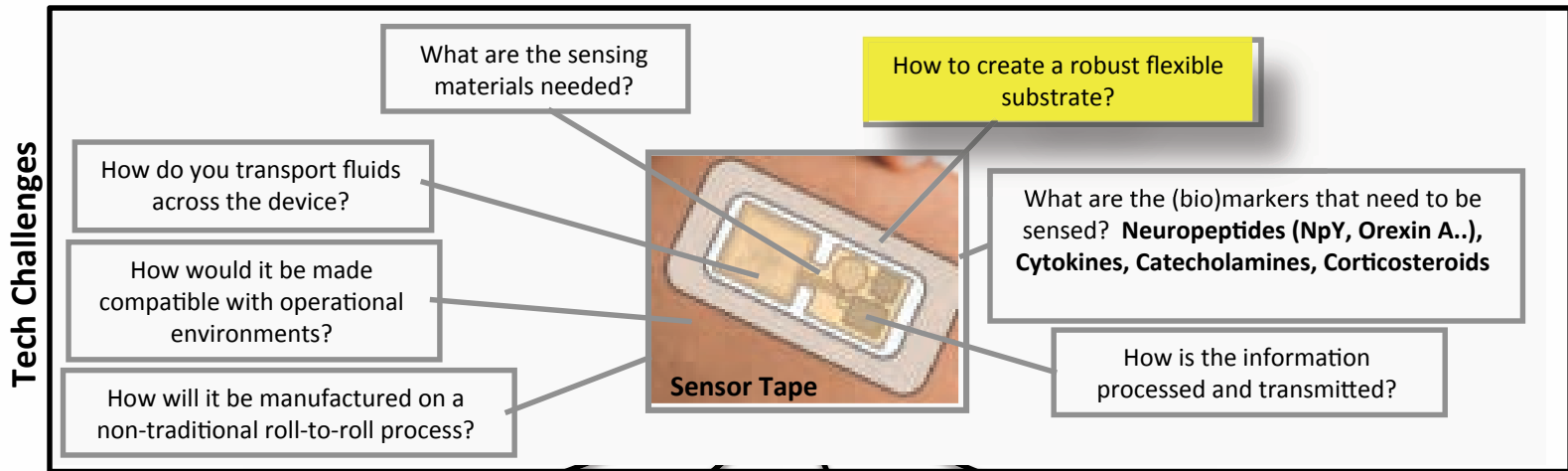
Magnetically Directed Self-Assembly: Process Flow



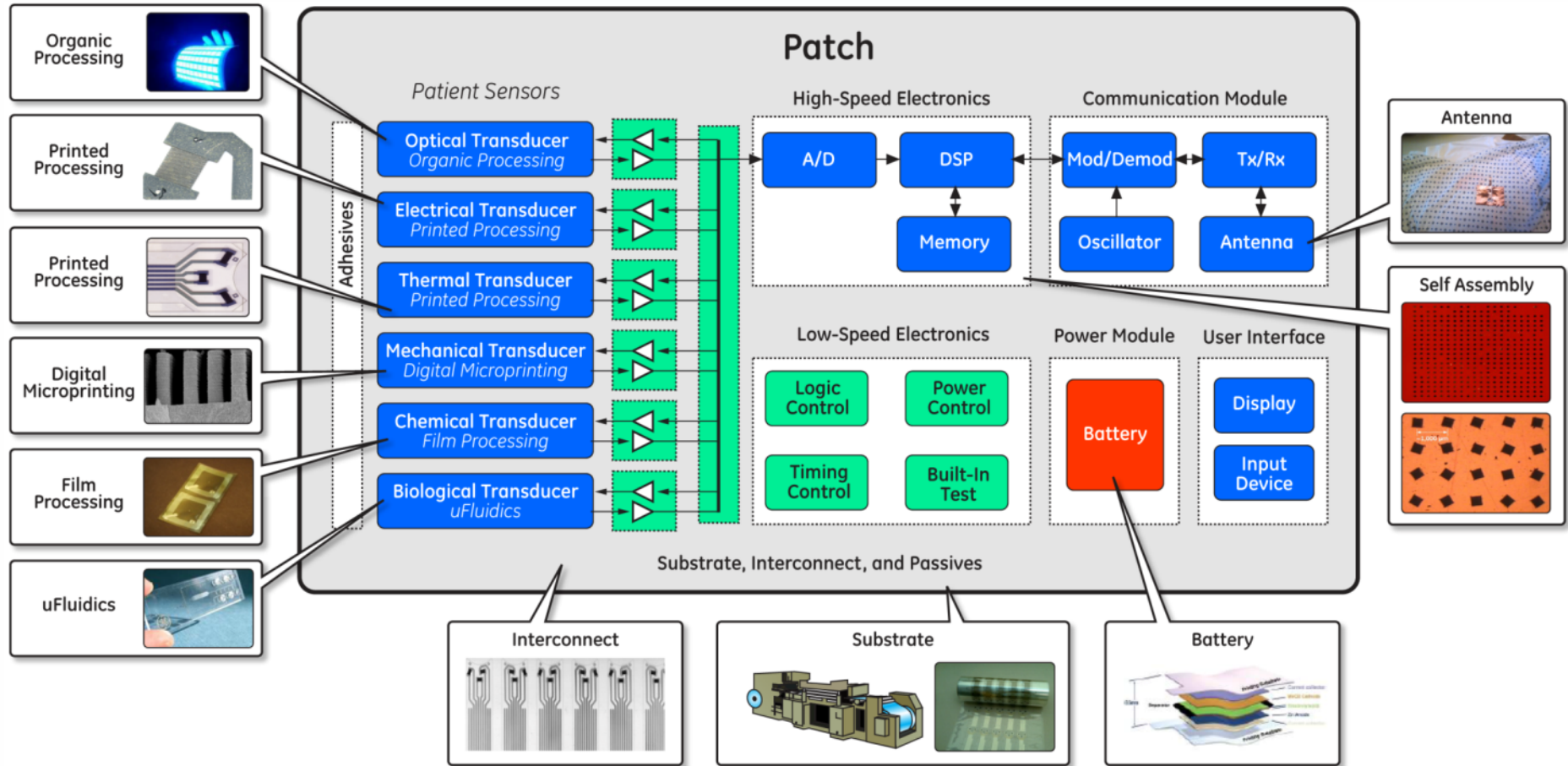
Hybrid integration and full electrical connection of semiconductor devices on flexible substrate using magnetically directed assembly is shown.

Materials and Manufacturing for Human System Platforms

Goal: <\$2, 24-72 hr, non-invasive, tailorable, common mfg platform, integrated with local network



Flexible Nano-Bio Sensor Platform



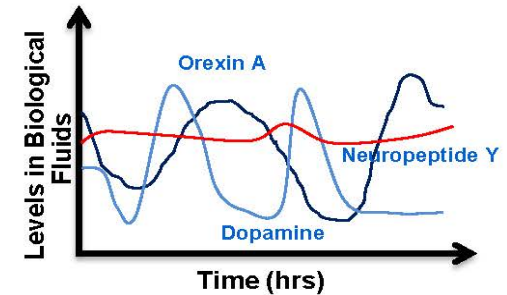
GE System Patch concept



Biomolecular Markers for Human Performance



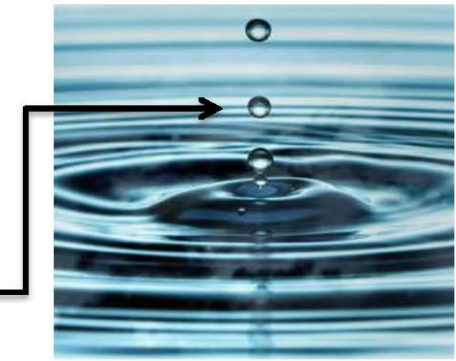
- Levels of biomarkers (10^{-12} - 10^{-6} M)
- Sweat > Plasma > Saliva (*in some cases*)
- Dynamic
- Profile specific to individual and task



Biomarker	Condition
Cortisol	<i>Stress, Cognition</i>
Dopamine	<i>Cognition</i>
Orexin A	<i>Cognition</i>
Neuropeptide Y	<i>Stress, Cognition, PTSD</i>
IL-6	<i>Stress, Multiple indicators</i>
TNF α	<i>Stress, Multiple indicators</i>
Oxytocin	<i>Behavioral</i>
Troponin	<i>Exercise, cardiac function</i>
Glucose	<i>Exercise, Stress</i>
Lactic Acid	<i>Exercise</i>

Table 2. Concentrations of Plasma and Sweat Patch Cytokines and Neuropeptides in Patients with MDD and in Healthy Control Subjects

Analytes	Plasma		Sweat	
	MDD	Healthy Control Subjects	MDD	Healthy Control Subjects
IL-1 α	52.6	5.9	57.5	7.6
	30.5-85.9	2.5-9.8	39.8-85.2	3.7-13.6
IL-1 β	139.9	10.5	160.5	10.9
	33.2-305.9	4.9-16.4	50.5-292.7	6.9-18.4
IL-6	101.8	7.8	133.8	10.4
	66.7-223.7	5.1-13.5	66.3-246.5	6.9-15.5
TNF α	158.8	11.1	177.9	12.8
	55.5-320.8	5.9-16.5	66.5-361.3	9.3-21.1
IL-8	50.7	2.7	63.2	2.9
	10.5-160.4	.6-5.5	16.5-153.8	1.5-6.1
VIP	5.3	17.2	6.2	22.5
	1.7-22.7	9.5-32.6	2.9-28.4	20.5-36.1
NPY	46.7	1.1	50.8	1.9
	5.4-69.8	.6-2.6	14.2-73.2	1.0-2.9
SP	77.2	3.3	88.6	3.8
	24.1-163.5	1.3-6.8	66.2-180.7	1.6-7.2v
CGRP	55.6	1.65	60.5	2.1
	13.5-101.8	.7-4.6	18.9-125.2	1.1-3.8



10^{-12} M ~ a drop in 2.5Mil gallons

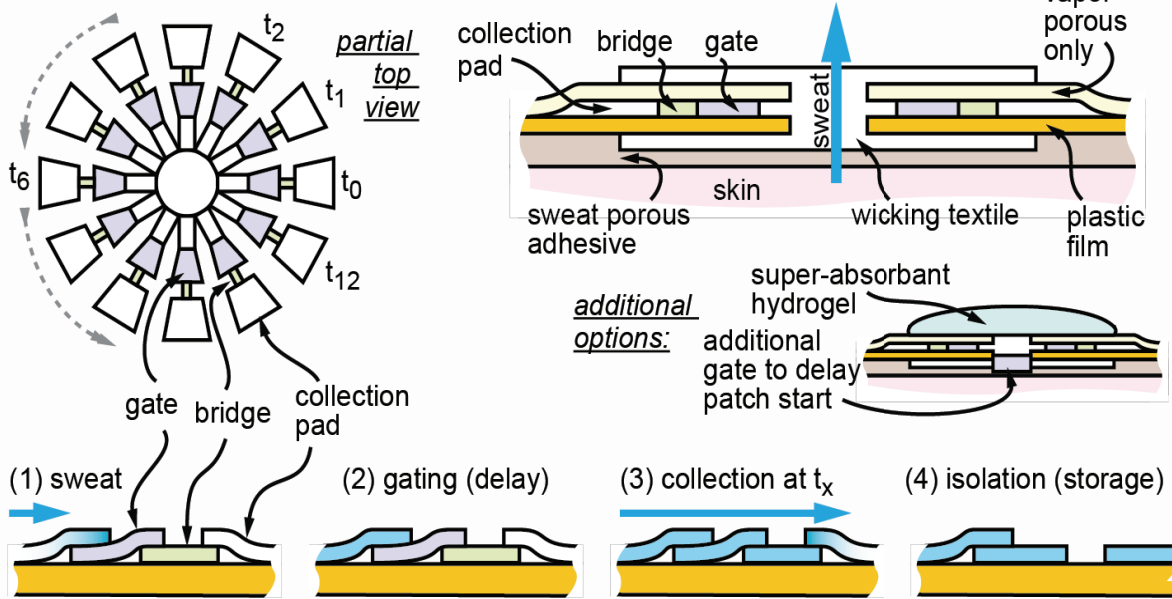
Biological Psychiatry, 2008. 64(10): p. 907-911

Distribution A. Approved for public release. Distribution unlimited

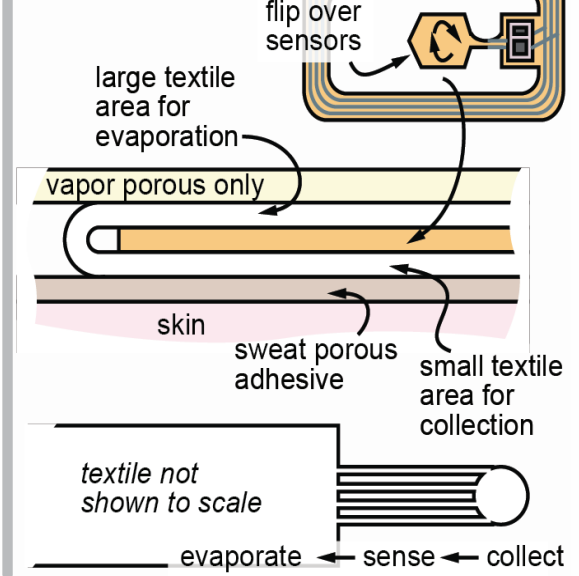


Challenges of analyzing sweat in real time – contamination of old sweat

(a) 'sweat record' device



(b) for 'sweat monitor' device



Univ. of Cincinnati



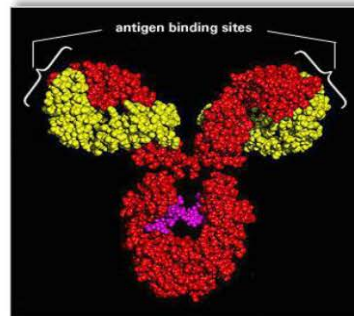
Biological Recognition Elements (BRE)



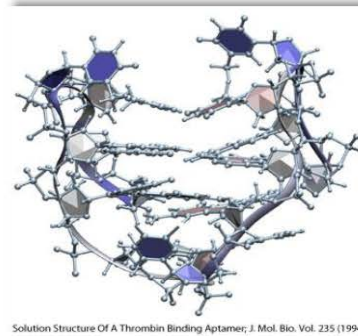
Needs:

- Sensitivity and selectivity
- Stability (shelf-life)
- Functionalization

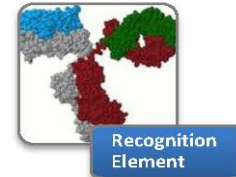
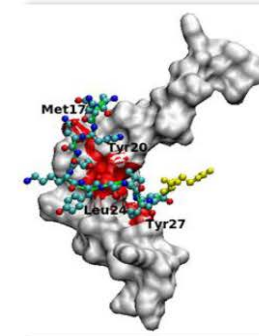
Antibodies



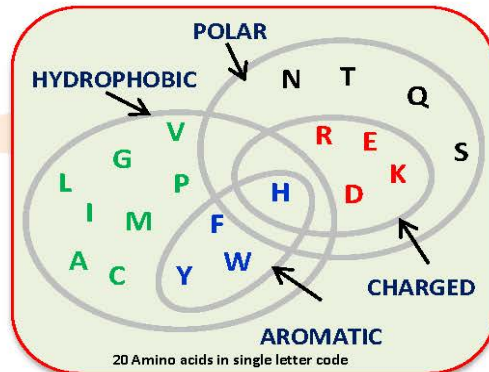
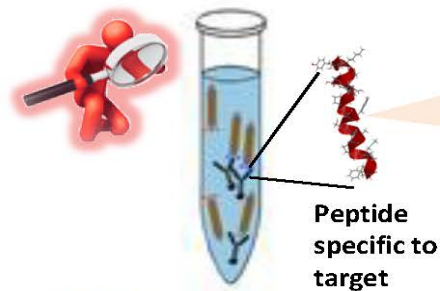
Aptamers



Peptides



Evolved Recognition Elements Using Combinatorial Libraries: Exploiting the chemical diversity of amino acids to identify selective binders!



Materials Specific BREs

SiO₂: **MSPHPHRRHHT**

Graphene/CNT: **HSSYWYAFNNKT**

Au: **AYSSGAPPMPFF**

Kim *et al.* (2012). *JACS* 133, 14480; Slocik *et al.* (2008) *Small* 4, 548;
Naik *et al.* (2002) *Nature Materials* 1, 169-172

Biomarker Specific BREs

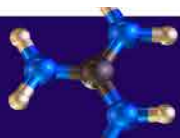
NPY: **YHPNGMNPYTK**

TNF α : **NNNKPNHELHR**

Orexin A: **DQSNKIISLQRL**

Hagen *et al.* (2012). *ACS Chem. Neurosci.* 4, 444;
Naik *et al.* (2012) *Lab Chip*, 12, 562.

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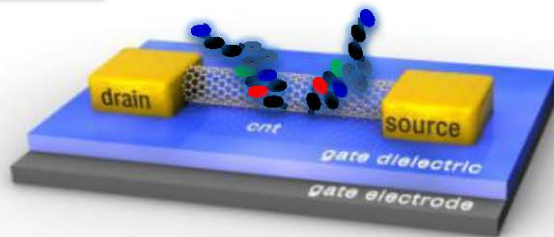
Bio-Functionalized Transducers



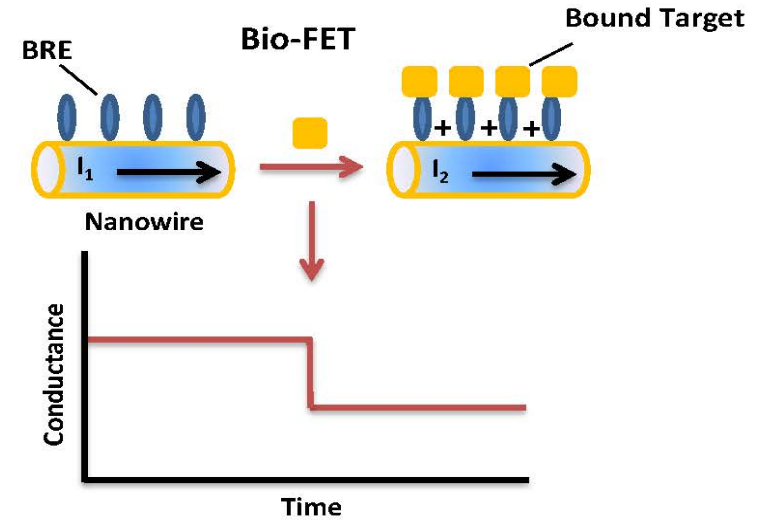
- Needs:**
- Label free
 - Real time
 - Sensitive
 - Reproducible*

Types of Transducers

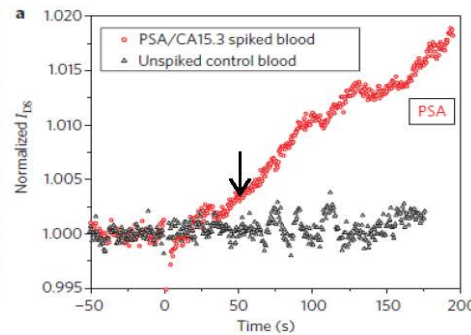
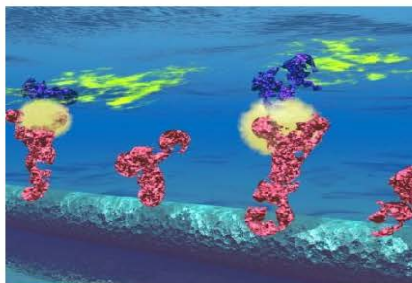
Electrical – Zinc Oxide, Carbon nanotubes, Graphene, Silicon
 Optical - Gold nanoparticles



Biofunctionalized Field Effect Transistor (Bio-FET)



SiNW-FET – Mark Reed (Yale)



Reed et al. Nature Nanotech (2010), 5, 138

***FY14 SBIR and STTR Topics – FETs and OFETs device fab, reproducibility and scale-up**

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