ADDITIVE ELECTRONICS FOR NOVEL WEARABLE DEVICES

DR. PATRICIA BECK, DR. ROBERT MALAKHOV, JEFF BERGMAN

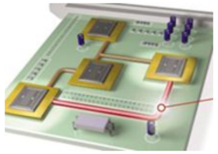
Outline

I. NextFlex Overview
II. Flexible Hybrid Electronics
III. Rigid to Flex Conversion
   a. Phase I: Thin Die Attach
   b. Phase II: Design and Manufacturing an FHE Prototype
   c. Phase III: Transition to Volume Manufacturing
IV. Process Improvements and Wearable Applications
V. Summary

Where Nextflex (a Public/Private Partnership) Fits

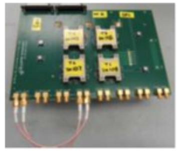
NEXTFLEX

Breadboard



Focus Examples:
- Technology and Industrial Base
- Materials
- Cost and Funding

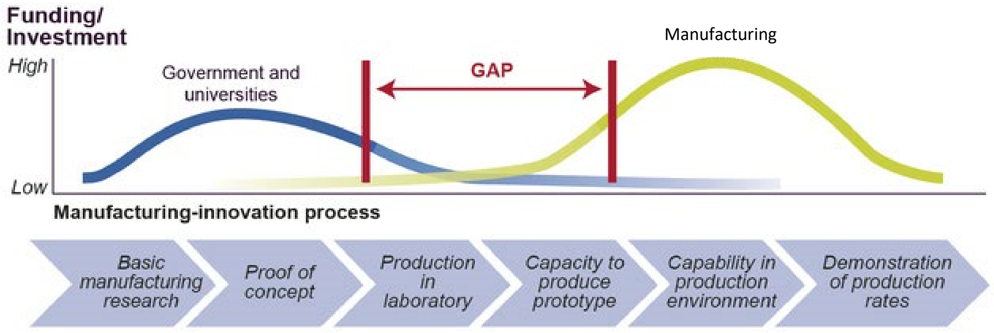
Brassboard



Focus Examples:
- Design
- Process Capability and Control
- Quality Management

Production

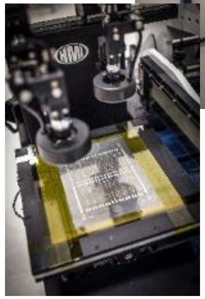
Focus Examples:
- Manufacturing Workforce
- Facilities
- Manufacturing Management



Source: GAO adapted from Executive Office of the President.

Pre Material Solution Analysis			Materiel Solution Analysis	Technology Maturation and Risk Reduction		Engineering & Manufacturing Development		Production & Deployment	
MRL 1 Basic Mfg Implications Identified	**MRL 2** Mfg Concepts Identified	**MRL 3** Mfg Proof of Concept Developed	**MRL 4** Manufacturing Processes In Lab Env't	**MRL 5** Components In Production Relevant Env't	**MRL 6** System or Subsystem In Production Relevant Env't	**MRL 7** System or Subsystem In Production Representative Environment	**MRL 8** Pilot Line Demonstrated Ready for LRIP	**MRL 9** LRIP Demonstrated Ready for FRP	**MRL 10** FRP Demo'd Lean Production Practices in Place
TRL 1 Basic Principles Observed	**TRL 2** Concept Formulation	**TRL 3** Proof of Concept	**TRL 4** Breadboard in Lab	**TRL 5** Breadboard in Representative Environment	**TRL 6** Prototype in Representative Environment	**TRL 7** Prototype in Operational Environment		**TRL 8** System Qual	**TRL 9** Mission Proven

Printing and Processing, Thin Die Integration & Testing Services for Commercial and Agency Projects



Meyer Burger
inkjet dielectric dep

HMI screen print

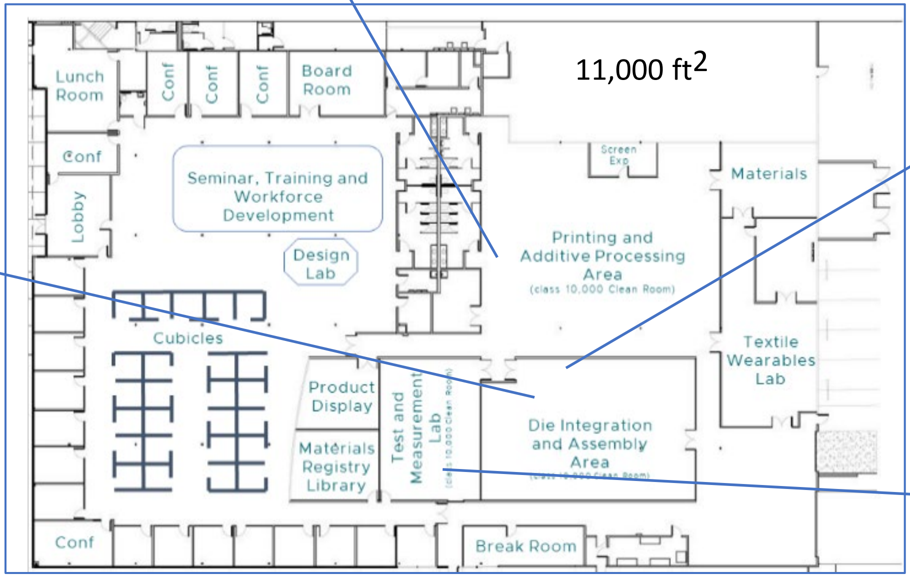
Komori gravure print

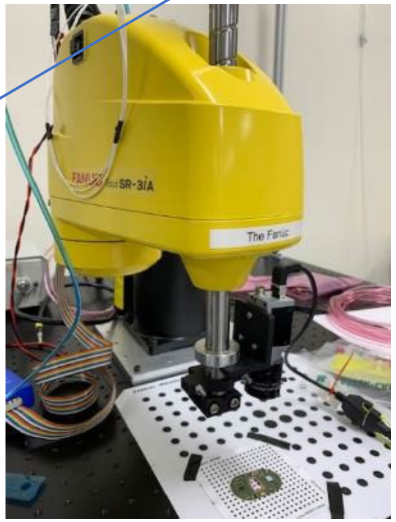
Besi Datacon (placement and dispense)

Universal Instruments Pick and place (+ wafer feeder for die attach)

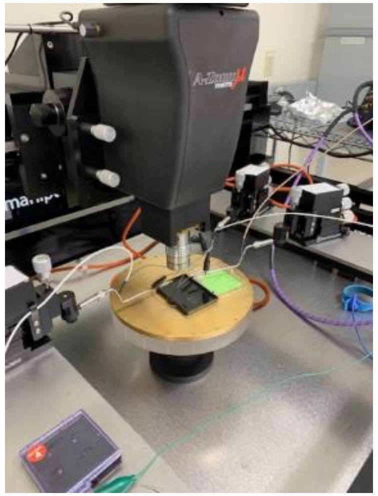
Nordson Asymtek (dep and epoxy encapsulation for LEDs)

ATP Bonder

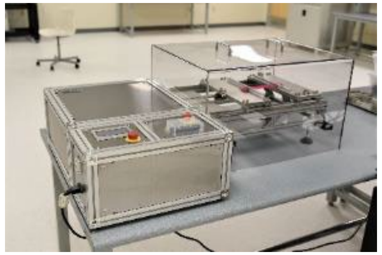




Fanuc Robot (test, component placement, epoxy dep)



Micromanipulator Probe station

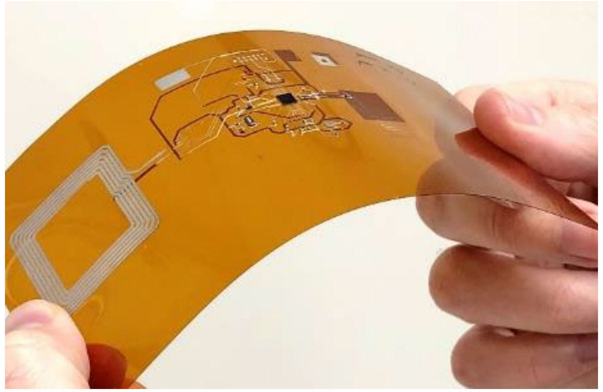


Yuasa 1

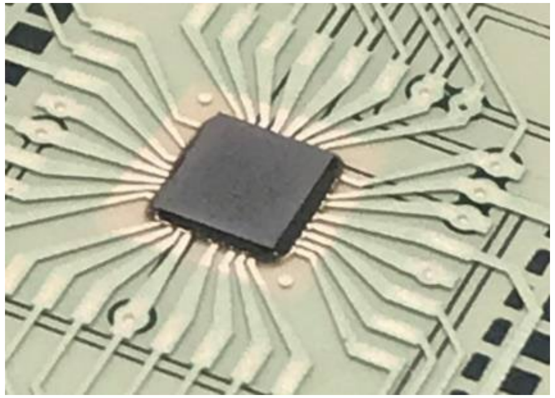
Yuasa 2

Unique Advantages of Flexible Hybrid Electronics

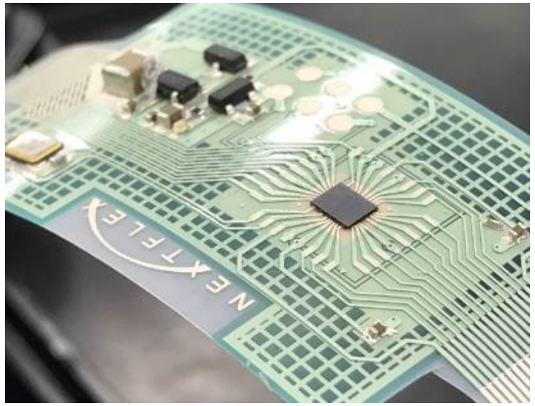
FHE combines the flexibility and low cost of printed plastic film substrates with the performance of semiconductor devices to create a new category of electronics (form factor, function, improved size, weight, power).



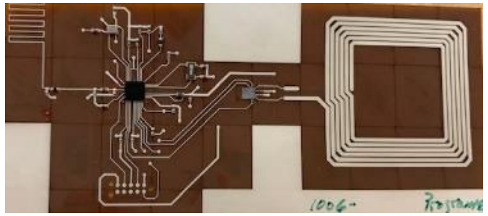
Thin, Lightweight, Flexible, Conformable

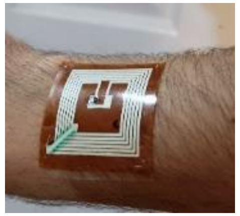


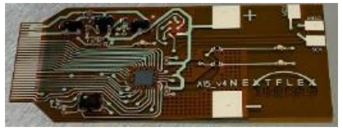
Semiconductors



BLE-Enabled Arduino Mini Clone

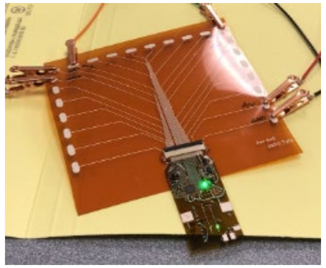




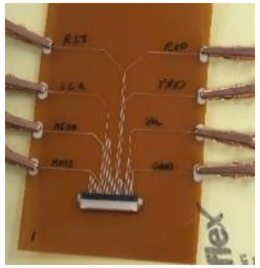


High-Mix Low-Volume Digital Manufacturing

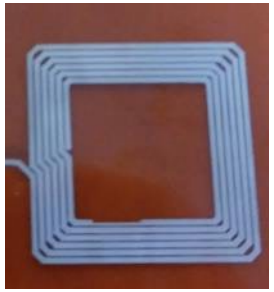
Day 1 Design



Day 2 Design



Rapid Prototyping and Design Customization



Wireless Communications for Data Transfer

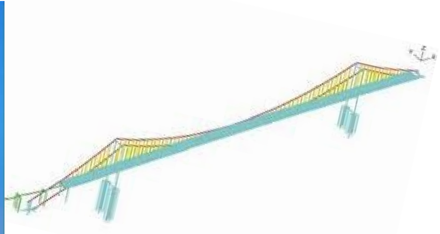
Power Harvesting Options (Qi, solar, etc.)

Structural Health Monitoring, Asset Management & System Level Integration

Acoustic US meas. pipe wall thickness vs. time

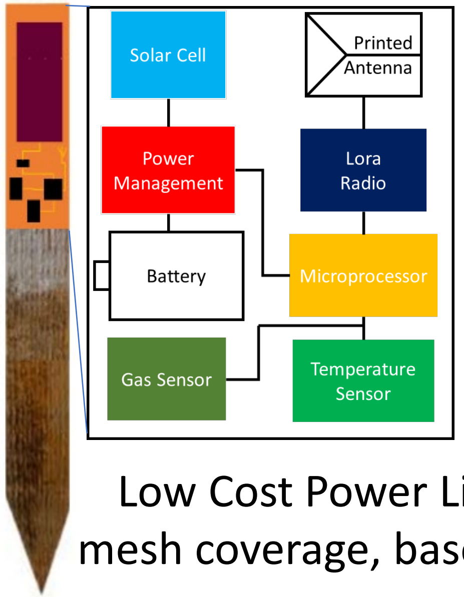
Crack Gauges

Cable Tension Monitoring



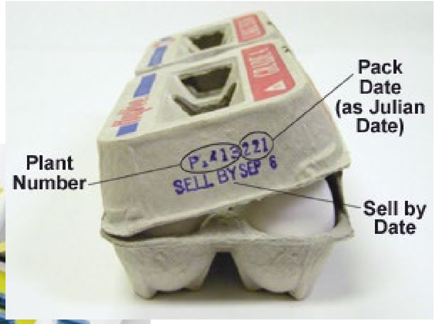
Vibration Analysis for Model Updating

Fatigue and Load Monitors



Low Cost Power Line Fire Monitoring (solar, mesh coverage, base stations on infrastructure)

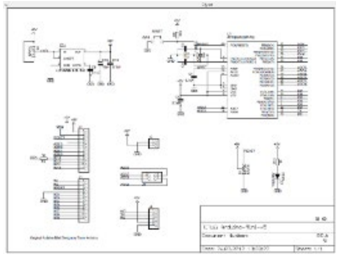
Secure Authentication



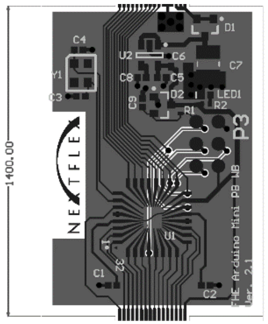
Asset Tracking

Rigid to Flex Conversion of an Arduino® Microcontroller

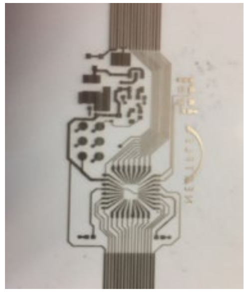
System Design → Layout → Print → Die Bond → SMT Assembly → Encapsulation → Test & Characterization



Single layer interconnect



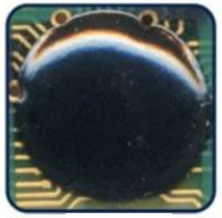
System Layout



Ink Jet
Aerosol Jet
Screen Print

Flip Chip Attach

Pick & Place



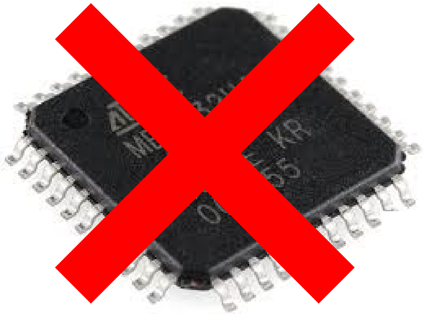
Apply Bead of UV Epoxy then Insert-Molding or Adhesive Glob Top

Electrical
Physical
Environmental

Greater than 50% reduction in the number of process steps (7 FHE) vs. rigid PCB manufacturing (19)

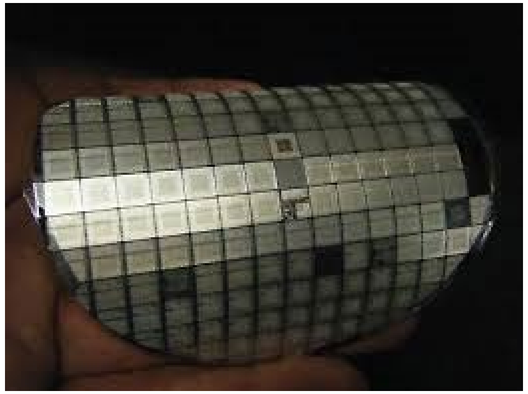
Commercial Off-The-Shelf IC's Are Not Made for FHE

Packaged IC's are large and do not bend or flex.

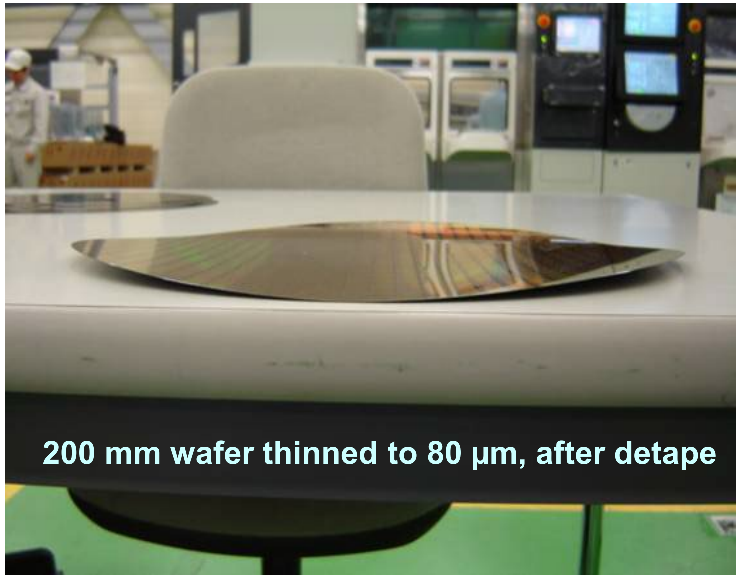


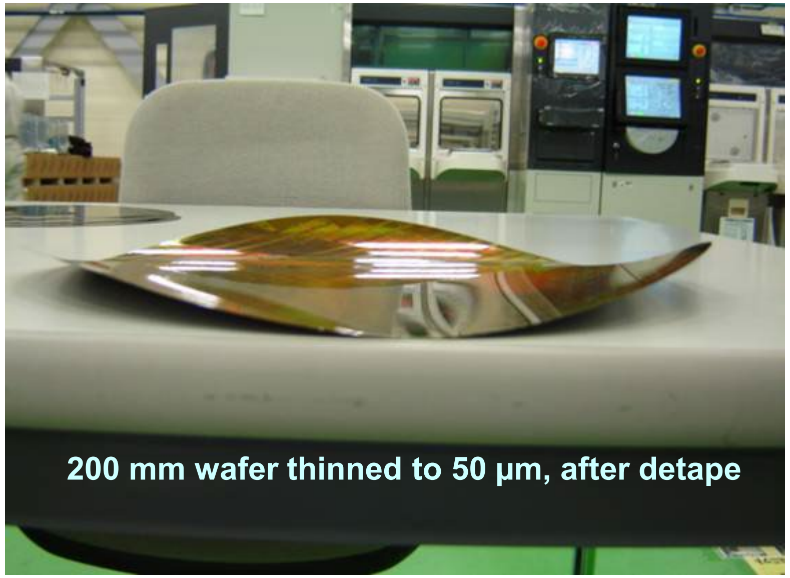
Advanced packaging wafer-level based technologies like Wafer Large Scale Chip Package (WLCSP) have large Ball Grid Arrays (BGA) which prevent thinning to our target of 50 microns or less. Solder balls of 350-micron diameter on a 50-micron die will not help reliability.

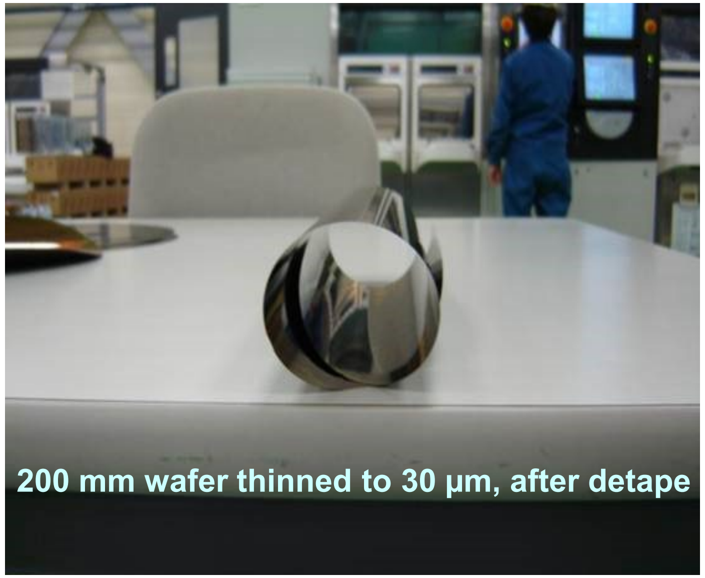
Our goal is to use wafers – thinned and diced – for direct integration into FHE devices.



Challenge: Thinning and Dicing To <50 Microns





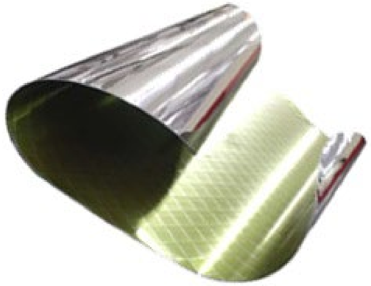


After thinning, there is the further challenge of pick and place of these ultra thin die
Requires ejection tool using multiple ejection pins per die and small distances between tape and pickup tool

Creating a Process Platform for Integration

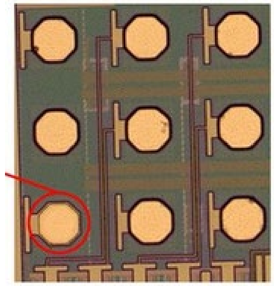
Instead of attempting to narrow down the selection of devices to integrate into an FHE system, we created a process flow where any type of device available in wafer form can be integrated:

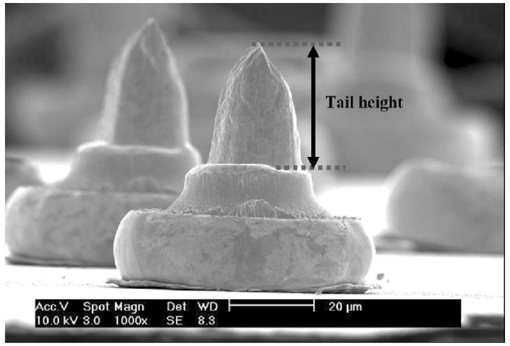
Thinning
Dicing/Singulation
Attach

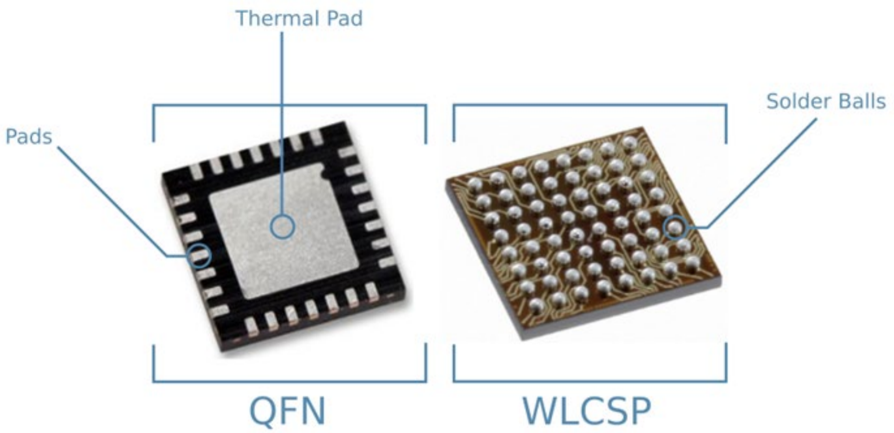


Bare die from Wafer Level Chip Scale Package (WLCSP) – bumped or unbumped

Die preparation for integration on FHE board
ENIG (Electroless Nickel Immersion Gold) bumping of contact pads
Au stud bumping of contact pads

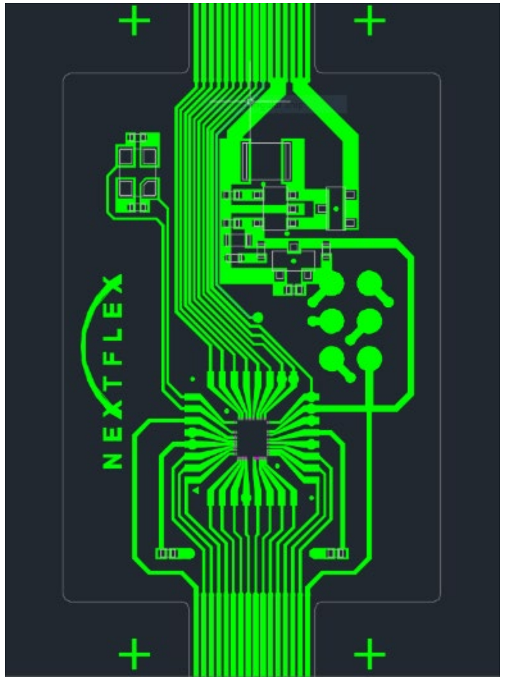




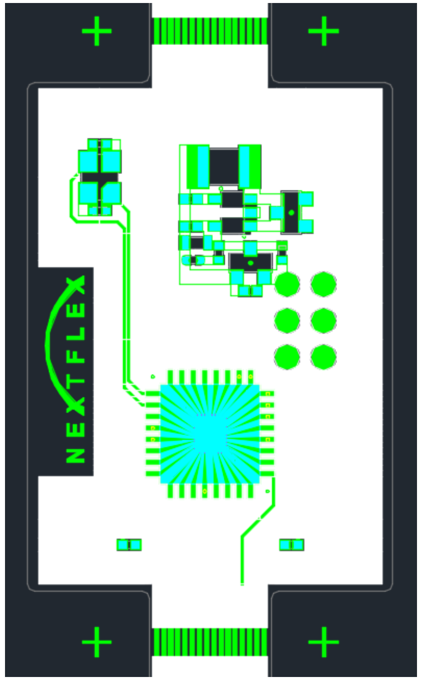


(Quad Flat No Lead)

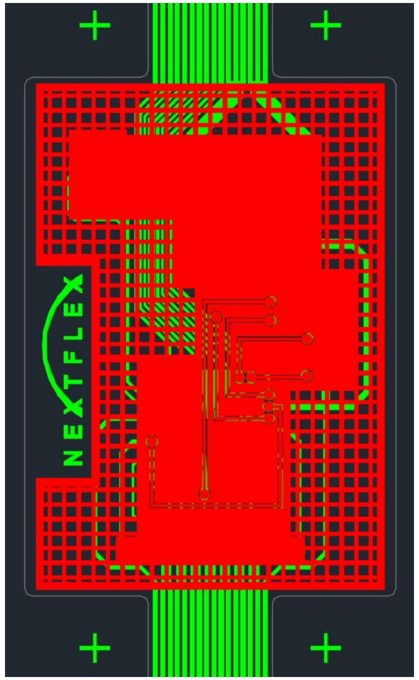
Phase II - FHE Design and Prototype



Front Side Metal



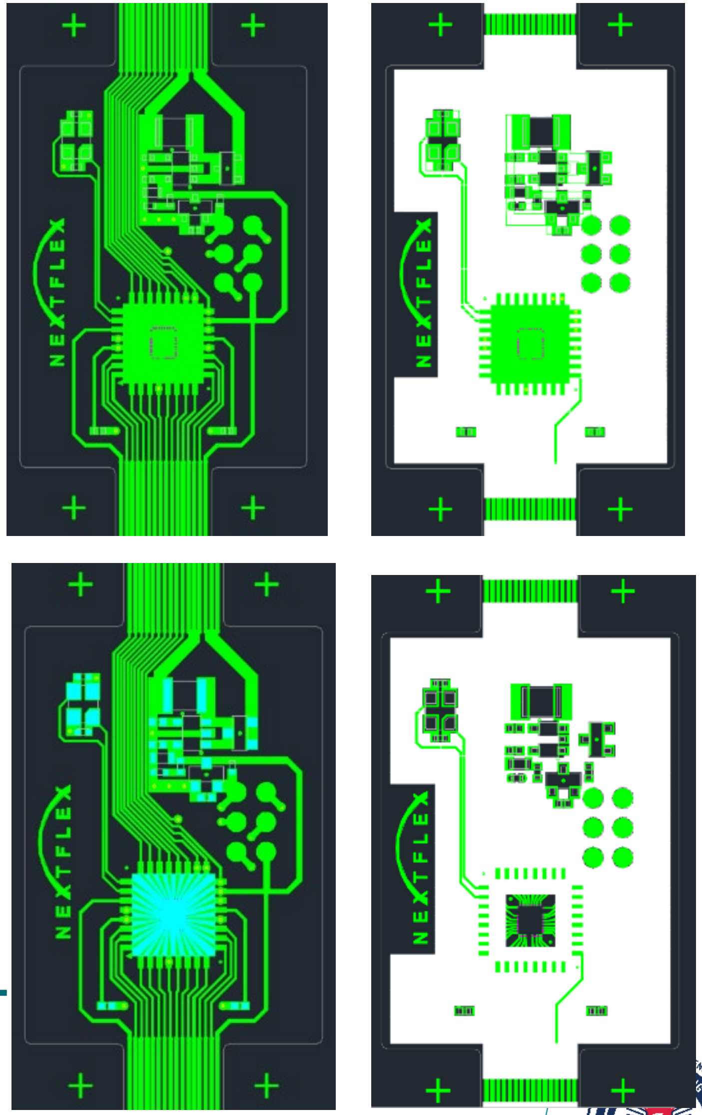
Dielectric Front



Backside Metal

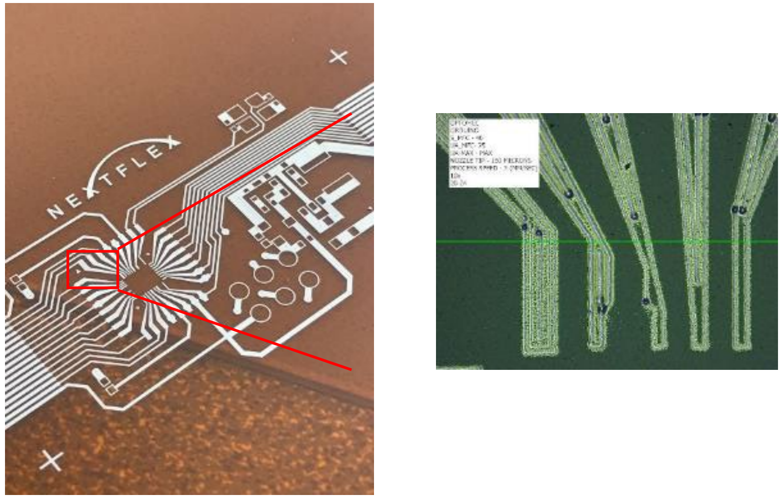
Print Files

- Design of the boards for two layers per side, one metal and one dielectric
- Laser cutting of vias in substrate prior to printing
- Laser ablation after printing for tuning of fine features and details
- Design was created to be manufactured on an 8-inch x 12-inch sheet

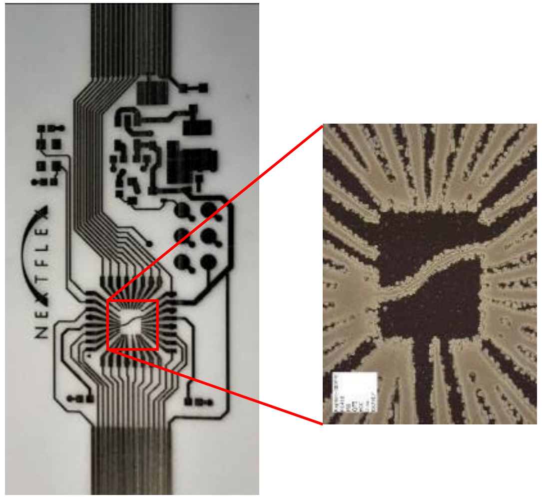


Laser Ablation

Down Selection of Printing Process

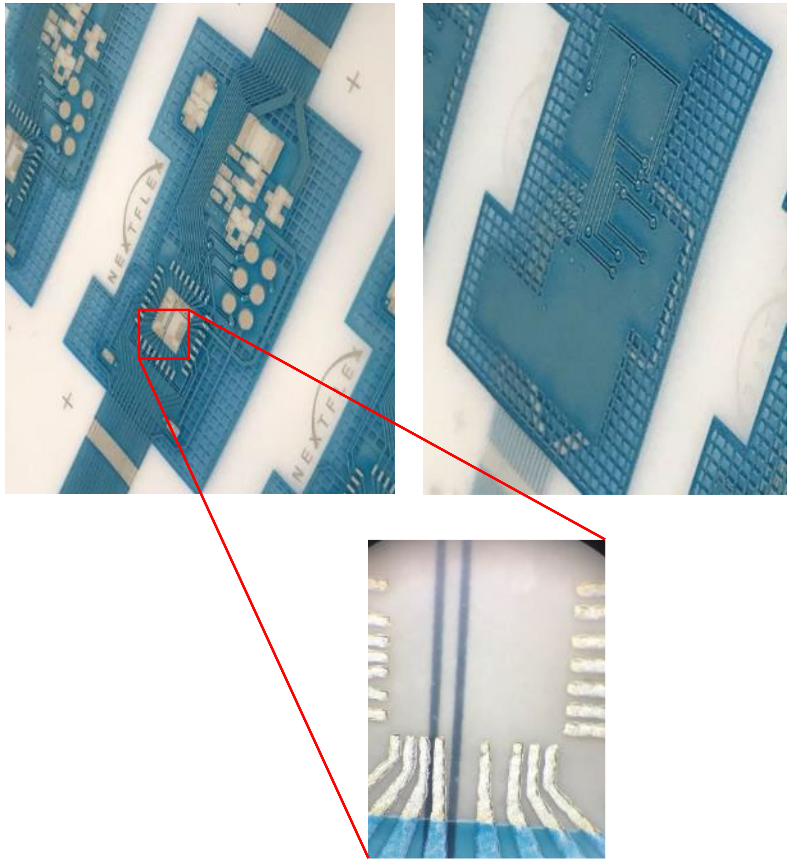


Aerosol Jet



Inkjet

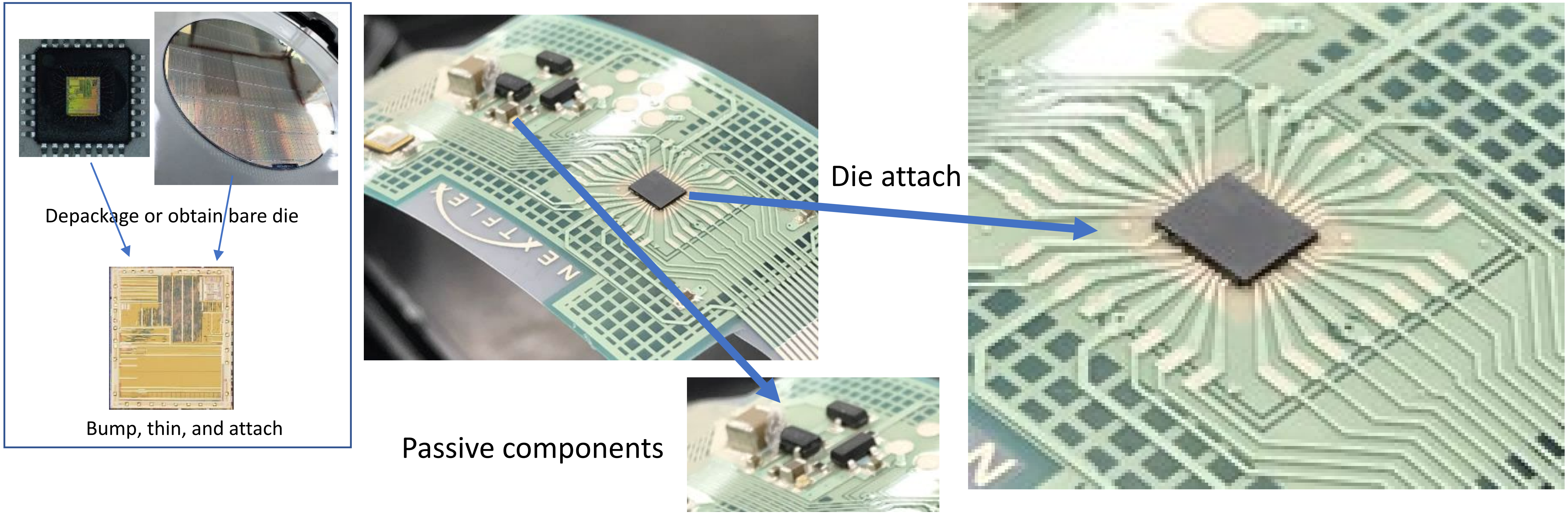
- Multiple printing processes were evaluated for the print
  - primary candidates: Aerosol Jet, Ink Jet and Screen Printing
- Screen printing was chosen as preferred fabrication method
  - Fast print time
  - Good ink thickness
  - Acceptable resolution



Screen Print front and back of FHE Arduino-compatible microcontroller

Flexible Arduino®-Compatible Microcontroller Before Encapsulation

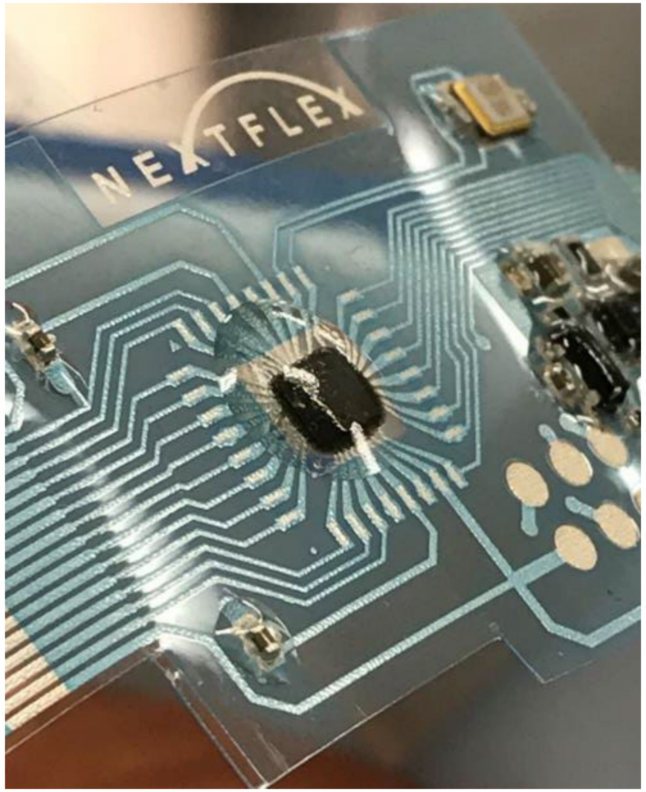
NEXTFLEX

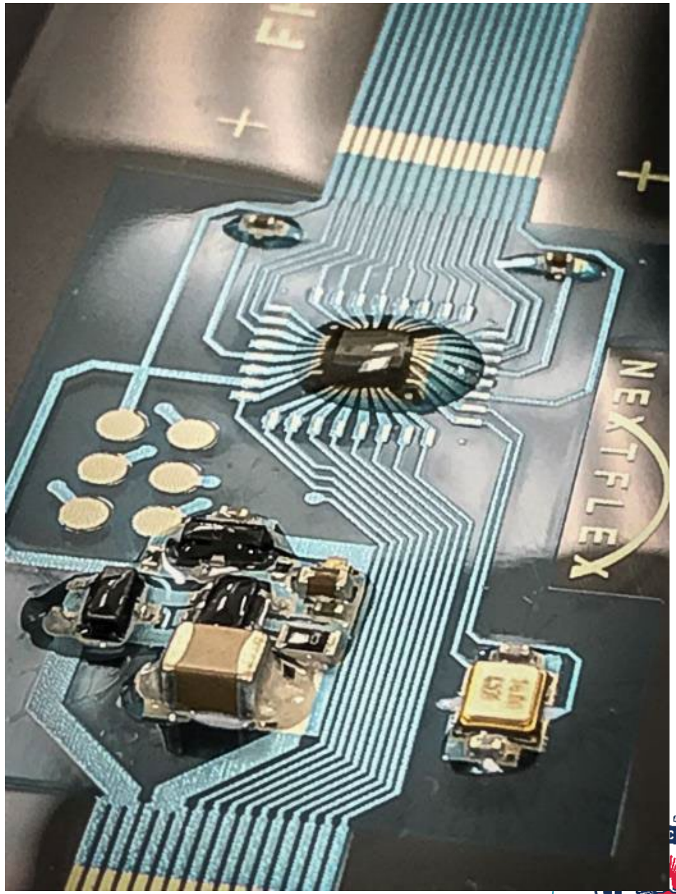


- To develop the flexible-design bare Microchip ATmega328 (microcontroller used in all Arduino minis) die were obtained through package removal of commercially sourced IC’s before being able to obtain bare die
- Both passive components and bare die were attached to the printed traces on the substrate to assemble the full device
- Once the assembly was complete the device build was finalized via encapsulation of the IC

Encapsulation

- IC's on the device were encapsulated using a syringe-deposited silicone
- Each IC was separately encapsulated to maximize the flex of the IC
- Once the silicone was deposited it was cured at room temperature
- A dielectric was screen-printed
- Later encapsulation would be by pouring and insert-molding



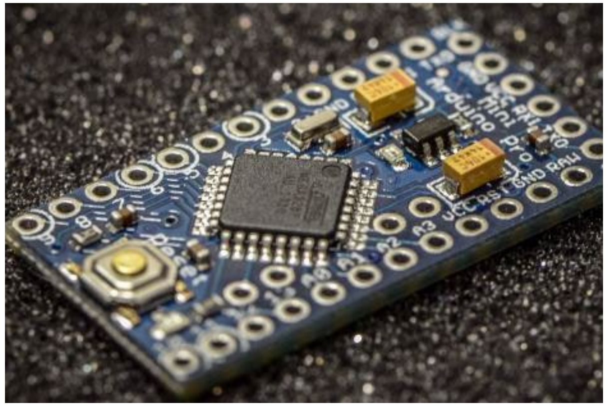


Transition to Manufacturing: Concept

Goal: Develop a mass-produced flexible copy of the Arduino®-compatible Mini Microcontroller board to:

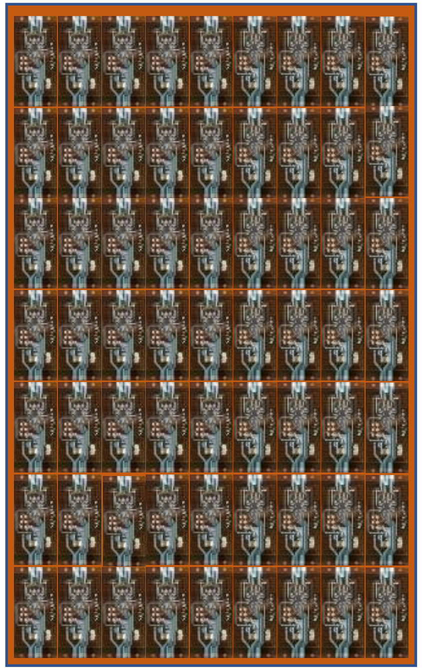
- Validate ability to mass produce printed hybrid electronics
- Minimize the cost of the device
- Create and validate an 8-bit microcontroller platform for potential future applications

Rigid Arduino Mini Board



Flexible Prototype

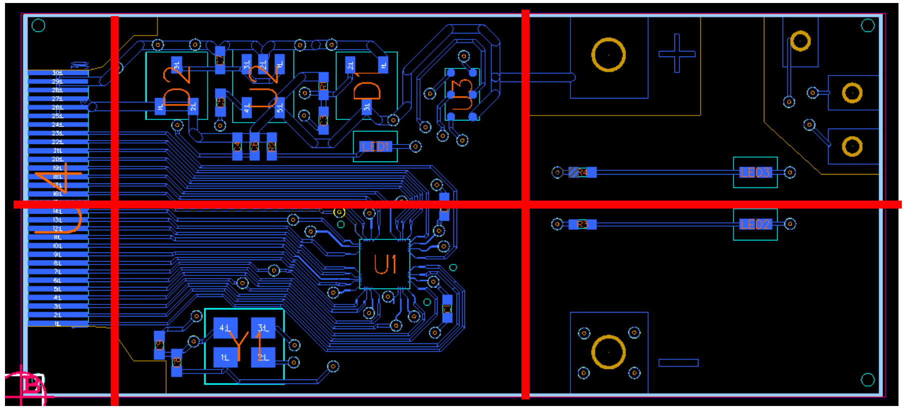
Mass Produced

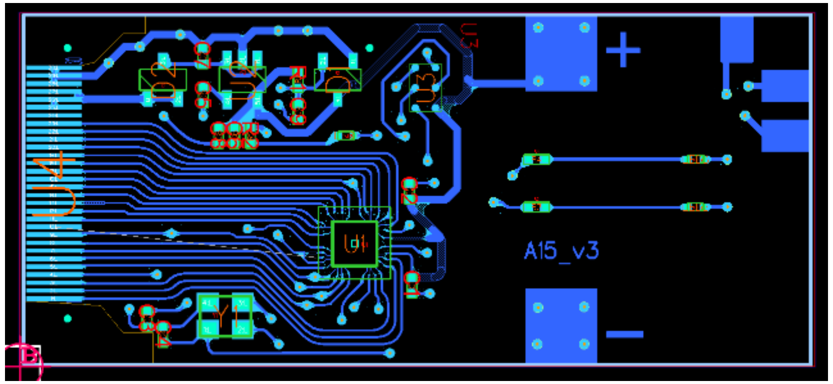


Case Study: Design Process & Application of Design Rules

Schematic and layout were performed in Mentor Graphics design software

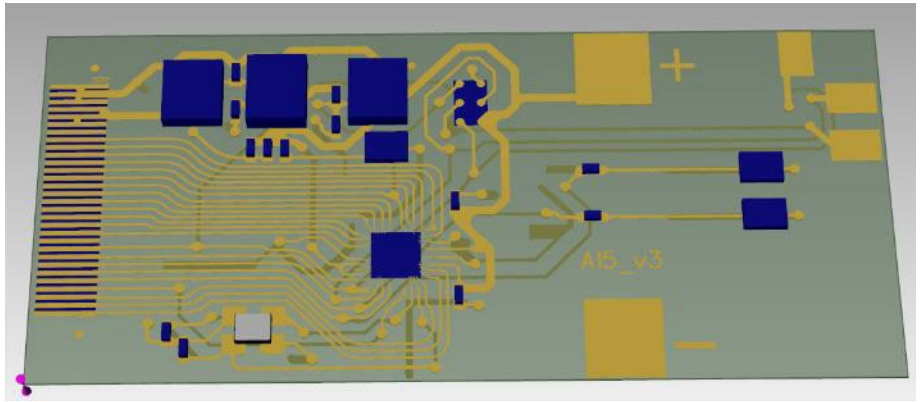
Desired bend locations were determined and components placed accordingly





Graphical files for printer were generated in Fab3000

3D Models were generated

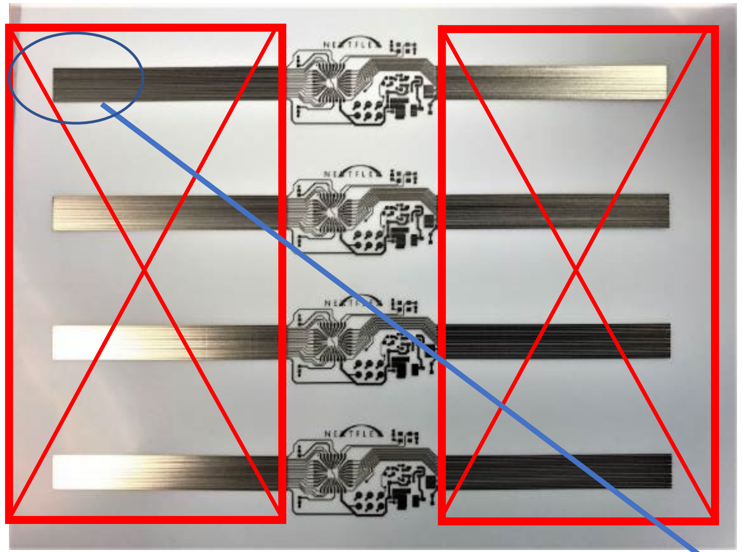


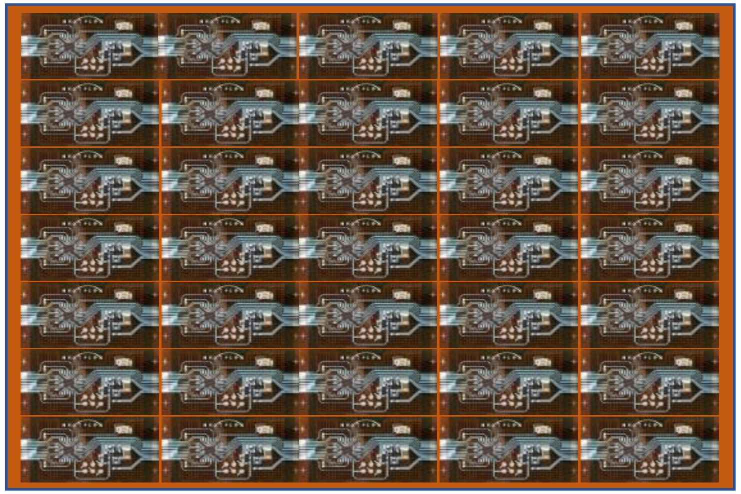
Applied design rules include:

- Minimum trace l/s of 150 um/150 um
- Minimum via (80 um)
- Minimum pad size (250 um)
- Mechanical layout based on desired bend locations

Case Study: Redesign for Volume Fabrication

Removal of extraneous ears of “wristband” circuitry



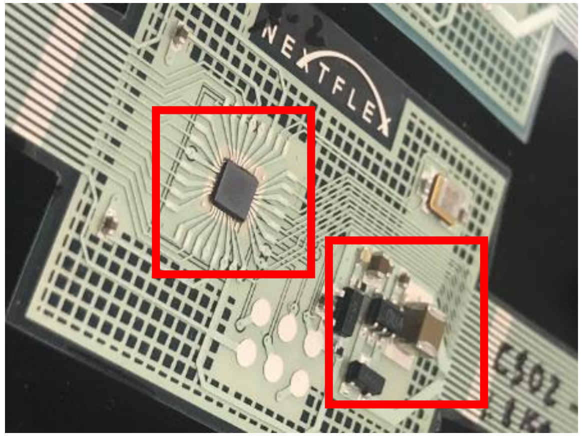


High device density per sheet to minimize waste

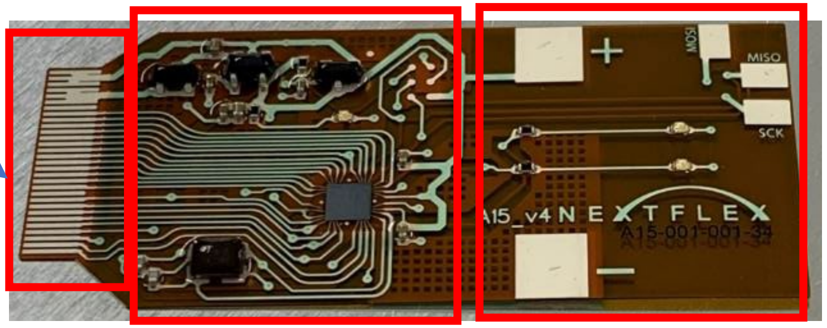
Move all ZIF pins to one side to simplify connections

Addition of LEDs and interface pads [power and SPI (serial peripheral interface) for testing and prototyping]

Removal of backup QFN pads to shrink die attach area



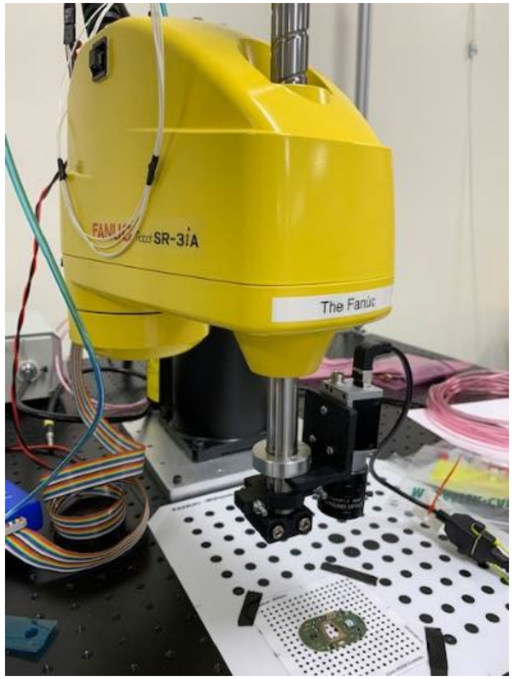
Standardization of passives to 0402 (4 mil x 2 mil US standard) size to maximize bend

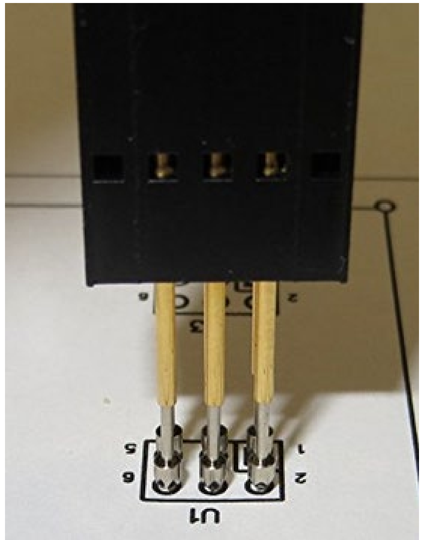


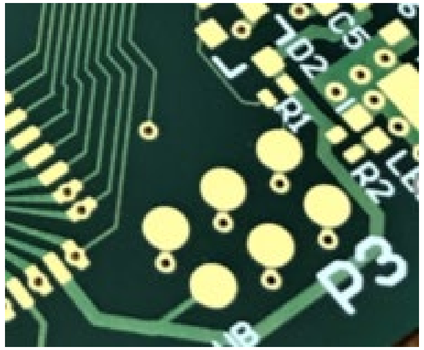
Packing of components into smaller area

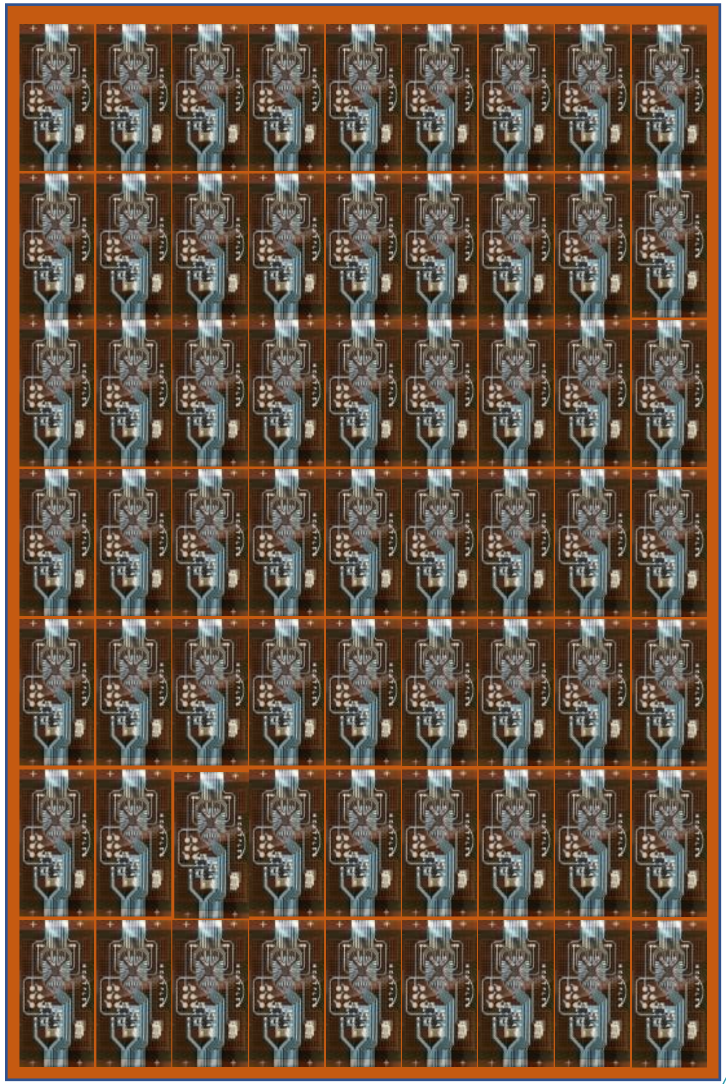
Automated Programming

- Programming was automated using a FANUC® robot
- Robot would automatically detect, properly place pogo pin connector on pads, program and test each device on the sheet using computer vision

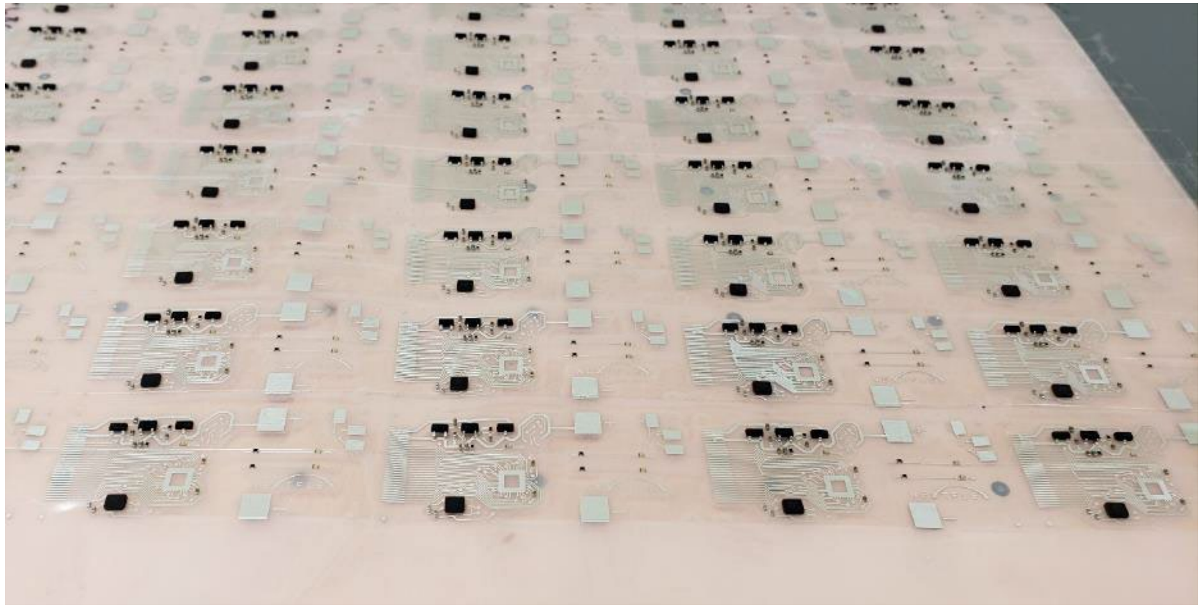


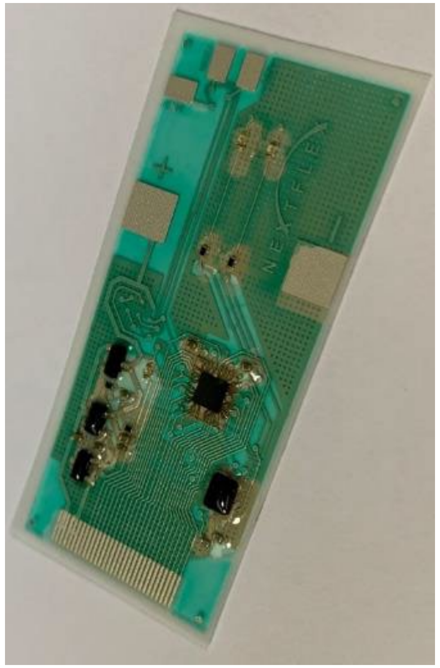






Singulation





- Up to 35 devices are produced on a single 8”x12” sheet
- Once fabrication of an entire sheet had been completed and the devices are tested, the devices are singulated and prepared for distribution

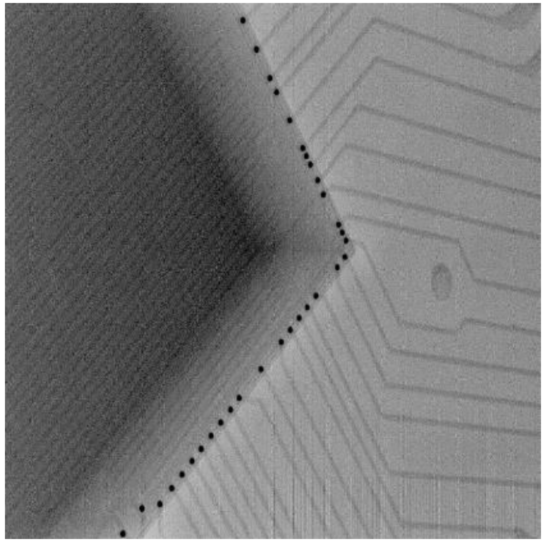
IMPROVEMENTS AND APPLICATIONS

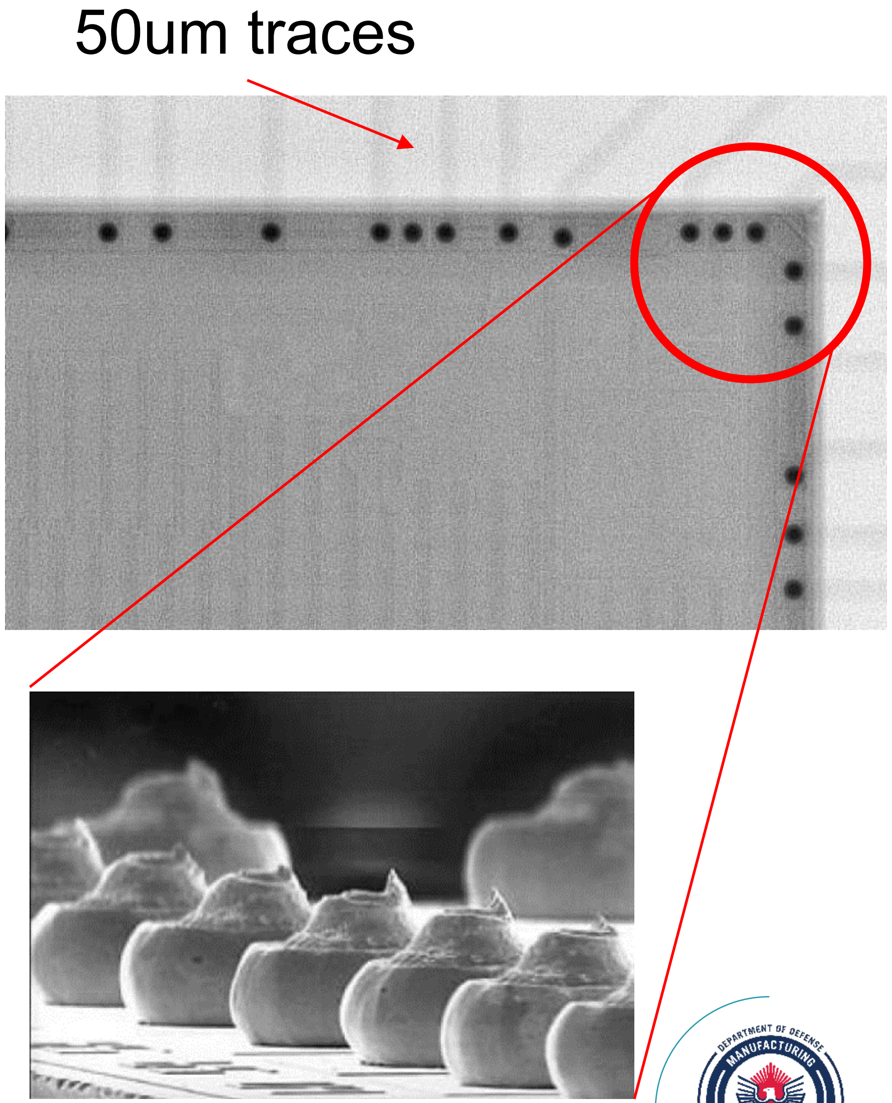
Stud Bumping for Fine Pitch Integration

- Starting with unpackaged die
- Pads are inset below the passivation layer requiring bumps to allow for flip-chip attach
- Gold pads also remove issues with oxide layers on aluminum pads

Two Options

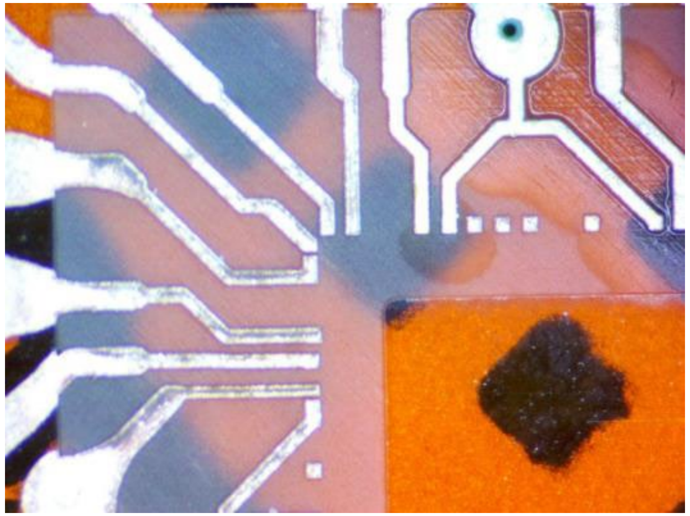
- ENIG (Electroless Nickle Immersion Gold)
  - Low Cost
  - Scalable
  - Limited pitch due to mushrooming
  - Limited control over where plating occur
- Stud Bumping
  - Higher Cost
  - Scalable
  - Ability to do fine pitch bumping (8 um gaps)
  - No plating in undesired areas
  - Spikes easily into silver traces





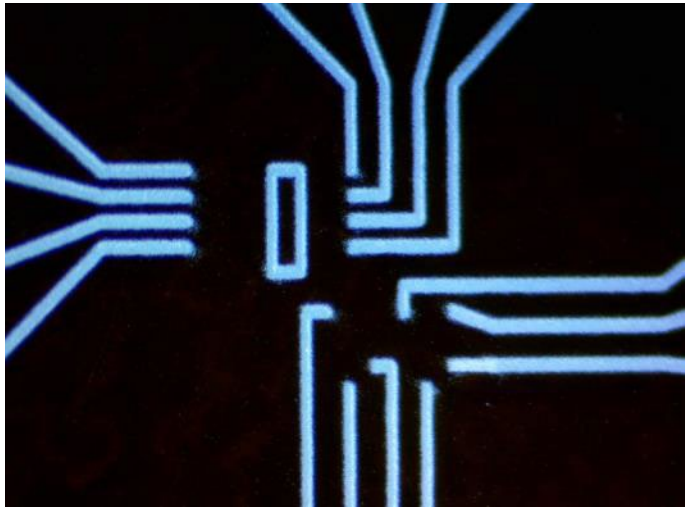
Die Interconnect Methods

Laser ablation



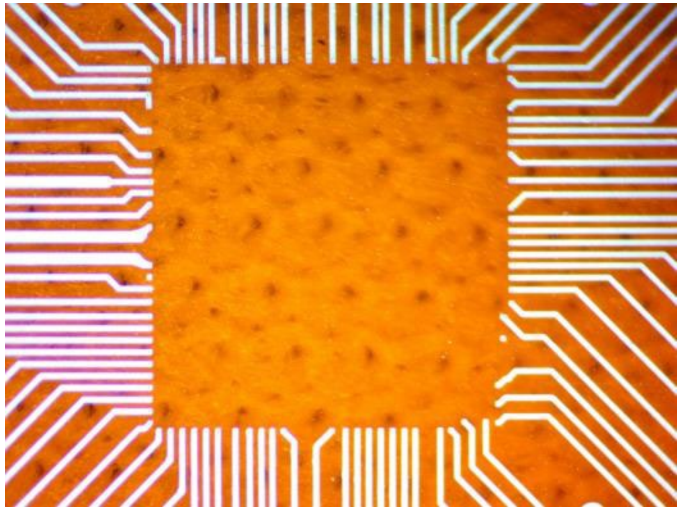
- **ESI 5200 femtosec green laser**
- Widest material set
- Thickest trace height
- Spot size ~10um

Aerosol jet



- **Optomec AJ5X**
- Great for prototyping
- Multi-axis printing
- Wide material set

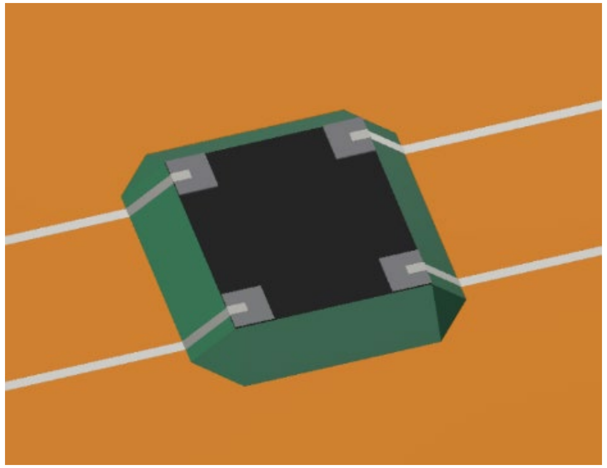
Gravure offset



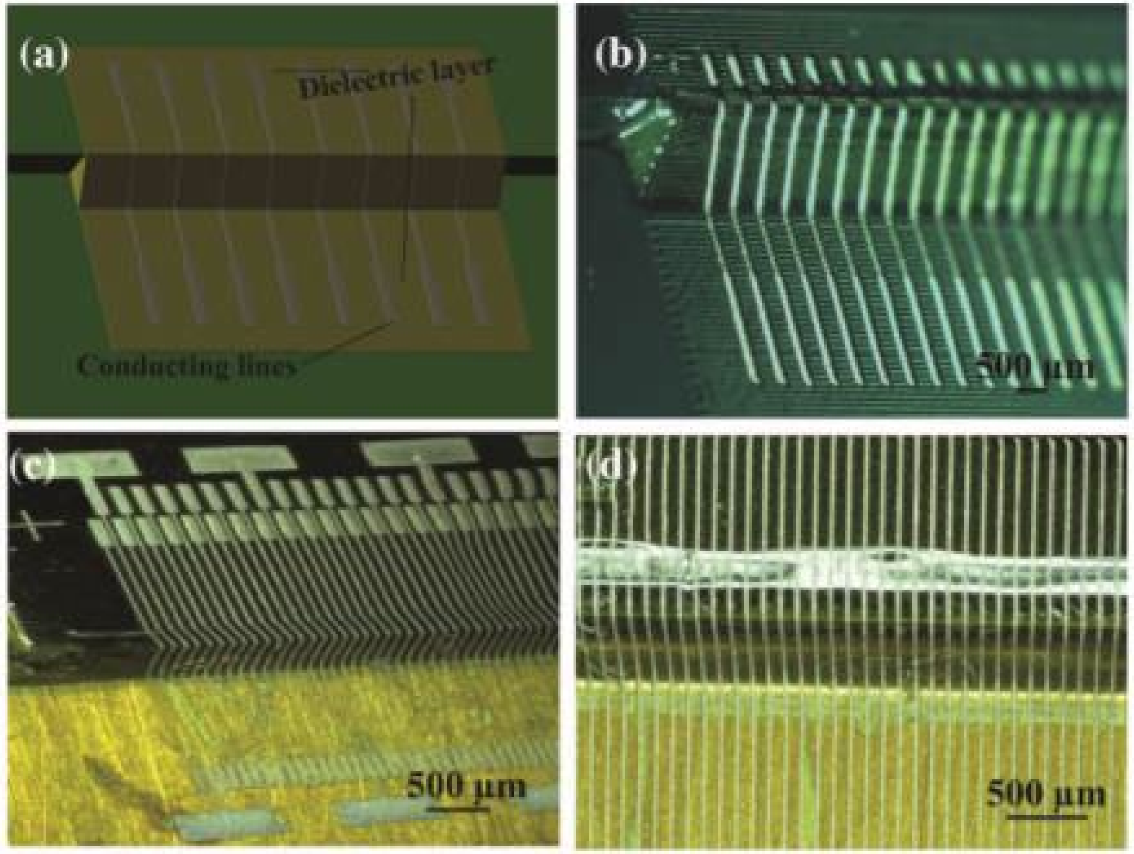
- **Komori sheet-fed**
- Fastest process by sheet
- Excellent edge definition
- Thin trace height ~2um

Pads-Up Die Attach

- Die attach alternate methods
  - Pads up & Print to pads
    - Print ramp for interconnect (aerosol jet or extrusion)



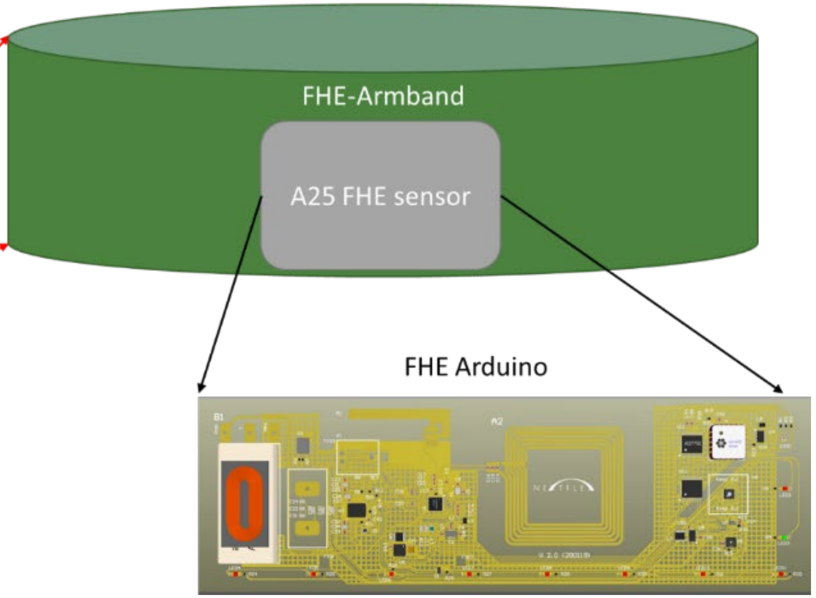
- Others
  - Flip chip w/ **magnetic field-oriented particles**
  - Stencil print bumps on substrate / attach with non-conductive underfill



Wearable Chemical and Environmental Sensor

NEXTFLEX

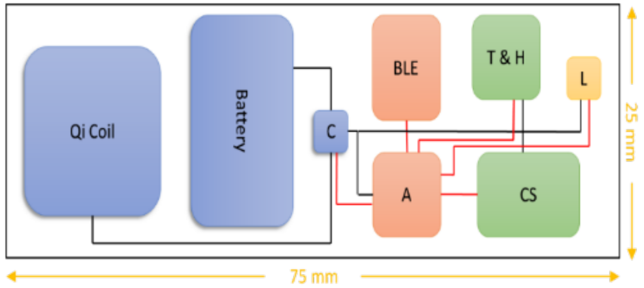
Confined Space Monitoring



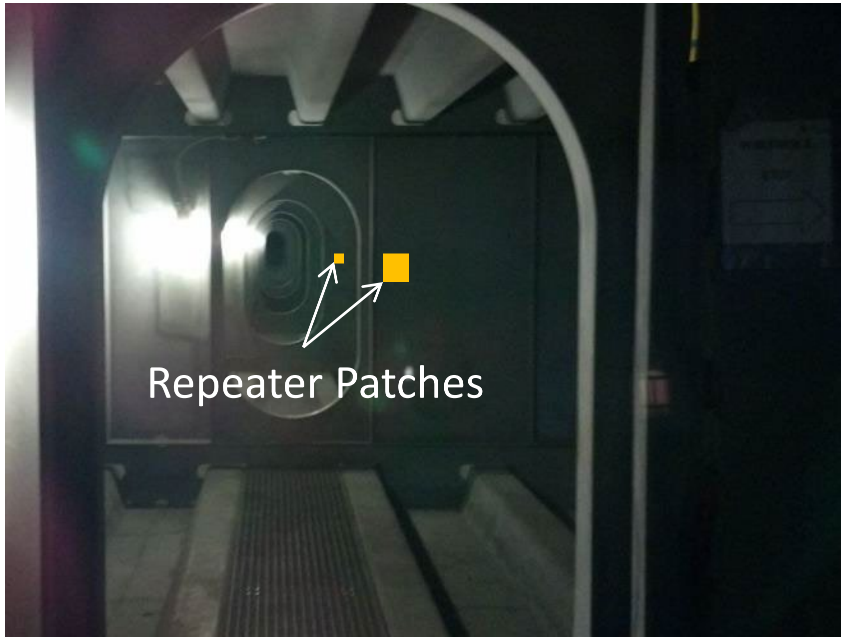
Low cost repeaters can be placed at intervals to rebroadcast message to personnel outside the immediate area

Microcontrollers are capable of mesh networking

C: charging chip
A: nRF52840
BLE: BT antenna
T&H: Temp and Humidity sensor
CS: chemical sensor (N5)
L: LED/sound indicator



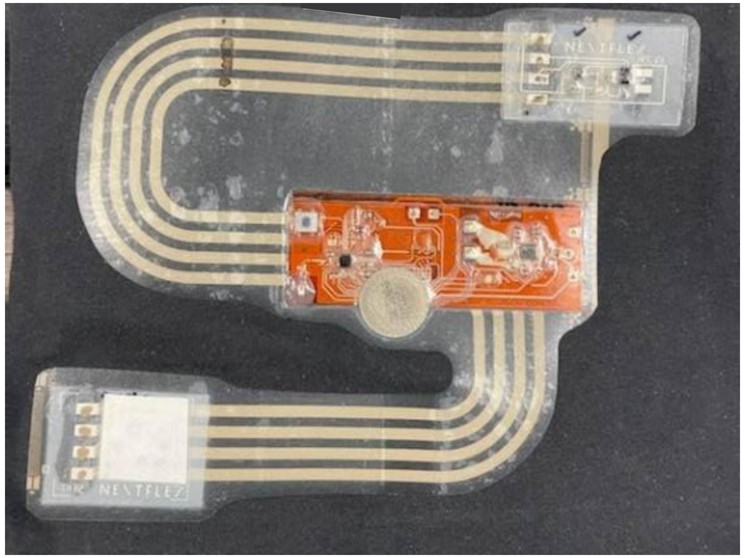
Block Diagram



Sensing built into clothing can monitor for health and safety issues and send warnings when safety issues are detected

Multi-Domain Operations Wearable Sensor System

- Wearable Sensor System
- Unobtrusive monitoring of soldiers
- Provides real-time data
  - Vital signs
  - Stress
  - Heat/cold injuries
  - Local environmental data
  - Signs of fatigue
- Flexible electronics laminated onto a regular shirt
- RF communications interface with wearable/embedded sensors

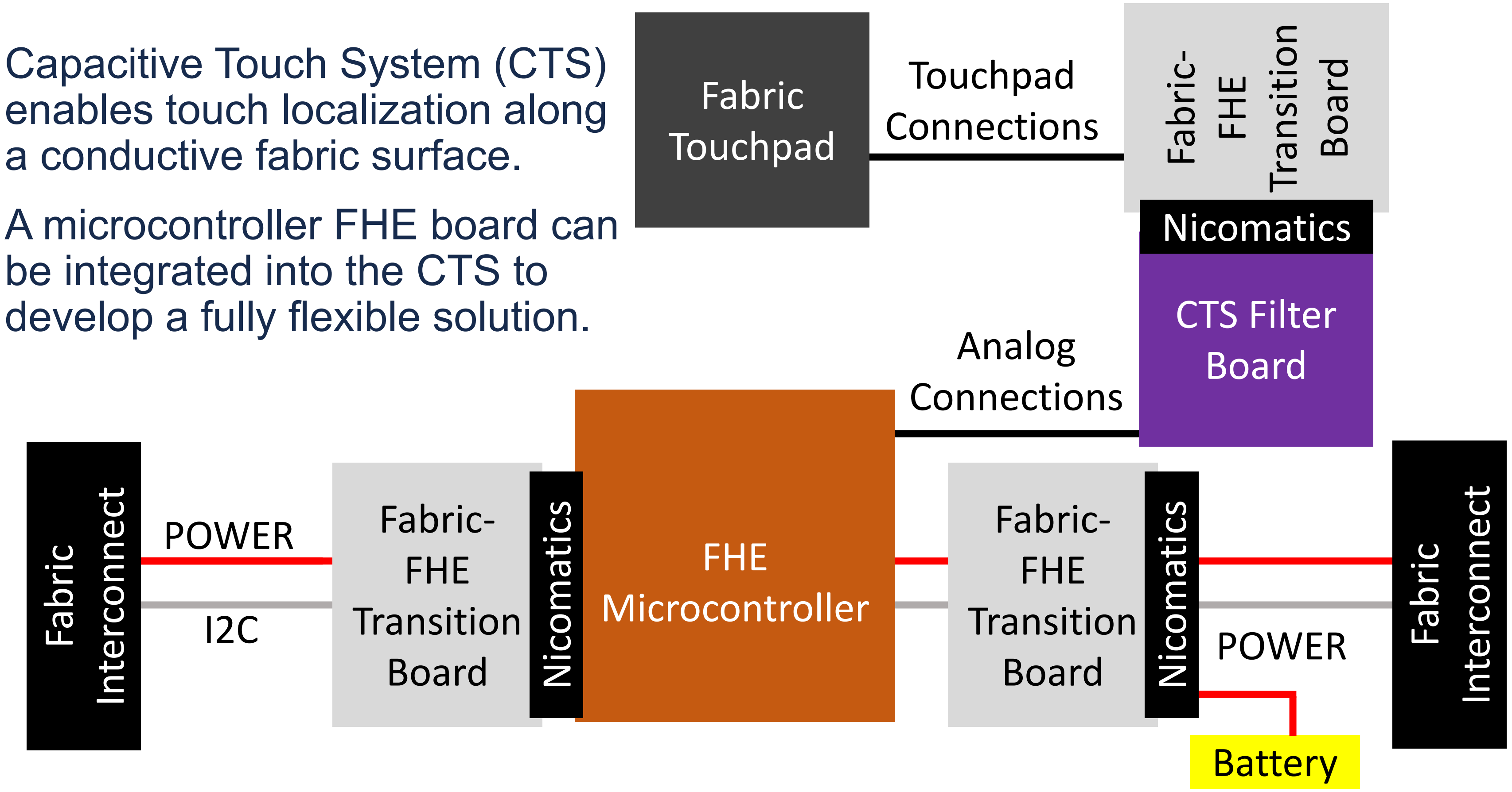


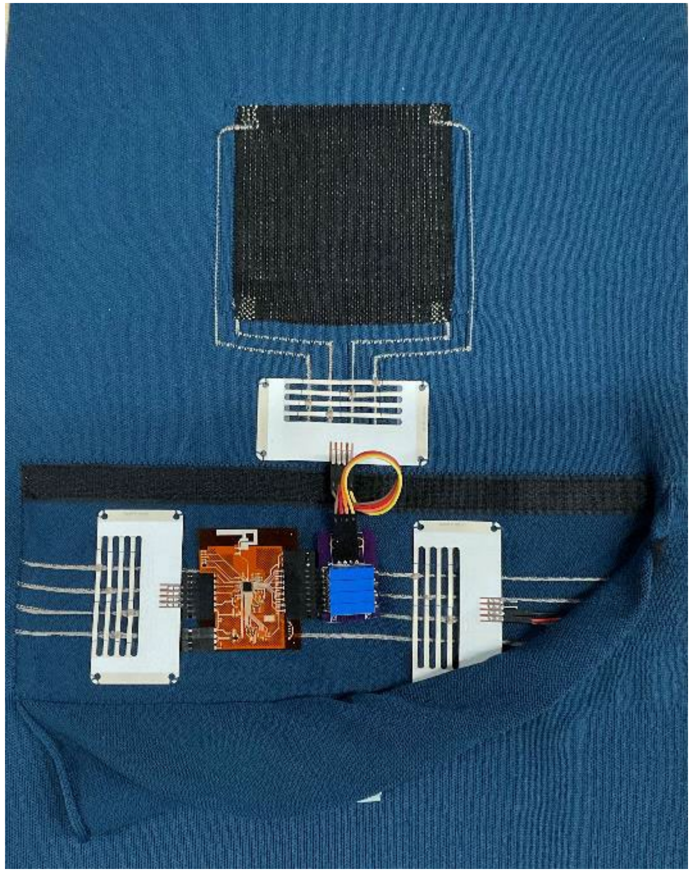
Microcontroller with Textile Integration

NEXTFLEX

Capacitive Touch System (CTS) enables touch localization along a conductive fabric surface.

A microcontroller FHE board can be integrated into the CTS to develop a fully flexible solution.





Sensing built into clothing requires leads in fabric – conductive threads, switches, touch sensors – but processing will be in additive components. Interfaces are important. Are they rigid or flexible? Electrical? Electro-optic?

Summary – A US Electronics Manufacturing Opportunity

NEXTFLEX

Sensor Integration	Microcontroller and Communications	Power
• MEMS pressure & inertial • CMOS chemical & optical • Printed sensors • Microfluidics	• Low power microcontrollers • BLE, NFC, LoRa, Zigbee, etc. • Printed antennas	• Primary / secondary battery • Wireless charging • Energy harvesting

Fully customizable

- Shape & size
- Materials & environmental capability
- Expected lifetime & life cycle (reusable/disposable)
- Cost target

Flexible Hybrid Electronics enables unique products

- Wearables, medical devices, machinery monitoring, secure authentication, IOT sensor nodes
- Structurally integrated sensors
- Conformal antenna arrays on aircraft

Printing and additive processes allow for new form factors, high mix, digital manufacturing

The FHE toolkit enables tighter integration of circuits and novel packaging

- Bare die integration, eliminating discretes, new design freedom
- Structural & system level integration

It takes a multidisciplinary effort to build FHE:

- Electronics, printing, robotics, material science, plastics processing, software

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