HETEROGENEOUS INTEGRATION ROADMAP

Heterogeneous Integration Roadmap

Integrated Power Electronics (IPE) Technical Working Group: Chapter 10

Doug Hopkins
North Carolina State University
DCHopkins@ncsu.edu

Presenter: Francesco Carobolante

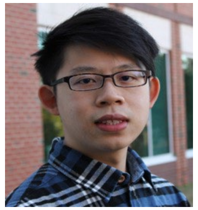
3D-PEIM
INTERNATIONAL SYMPOSIUM ON 3D POWER ELECTRONICS INTEGRATION AND MANUFACTURING

Patrick McCluskey
University of Maryland
mcclupa@umd.edu

This presentation contains only information that has previously been published in the open literature as the IEEE EPS Heterogeneous Integration Roadmap available at: https://eps.ieee.org/technology/heterogeneous-integration-roadmap.html

Chapter 10 Contributors

Co-Chairs



Doug Hopkins
North Carolina State University
DCHopkins@ncsu.edu

Patrick McClusky
University of Maryland
mcclupa@umd.edu

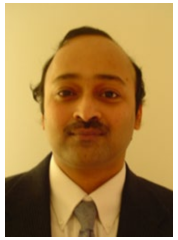
Thomas Becker
Thobecore Consulting & Research
dr.thomas.becker@outlook.de

Francesco Carobolante
IoTissimo
francesco@iotissimo.com

Tzu Hsuan Cheng
North Carolina State University
tcheng8@ncsu.edu

Bob Conner
X-Celeprint
bconner@finwavesemi.com

Daniela Iacopino
Tyndall National Institute
daniela.iacopino@tyndall.ie



Maeve Duffy
National University of Ireland, Galway
maeve.duffy@nuigalway.ie

Ray Fillion
Fillion Consulting
fillion.consulting@gmail.com

Michael Hayes
Tyndall National Institute
michael.hayes@tyndall.ie

Cian Ó Mathúna
Tyndall National Institute
cian.omathuna@tyndall.ie

PM Raj
Florida International University
mpulugur@fiu.edu

Brian Zahnstecher
PowerRox
bz@powerrox.com

Graphic Description of Chapter Contents

PART-I Inside SiP

Type C) In substrate
- On top side
- On land side

Type B) In interposer
- On top side
- Integrated in active interposer
- Embedded in organic interposer

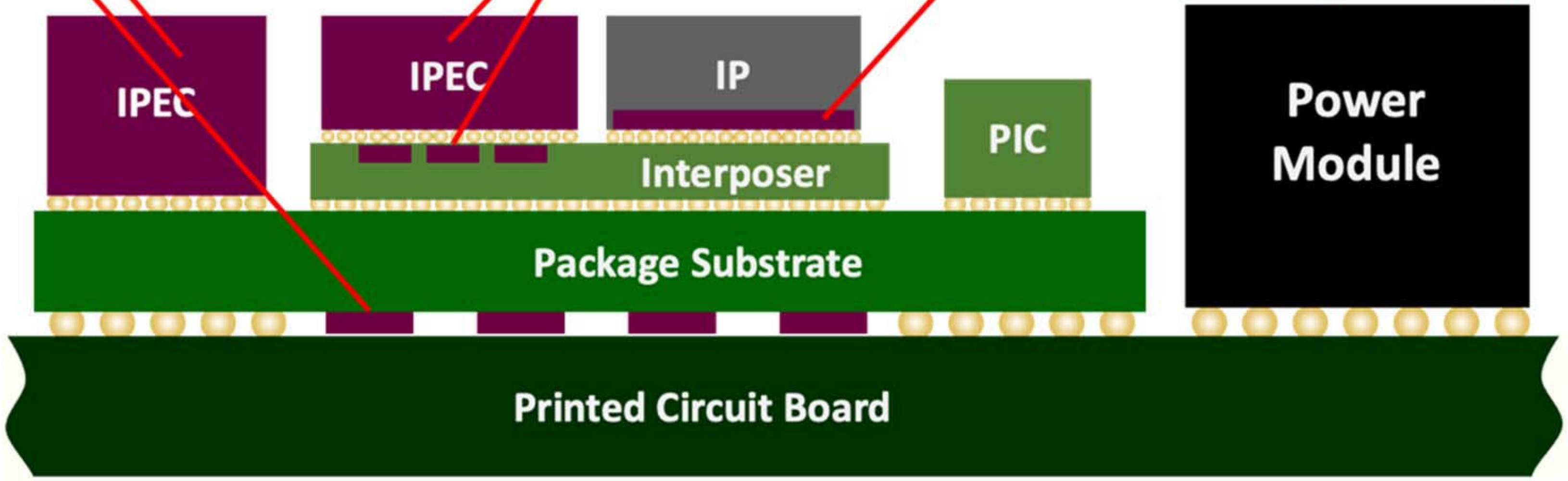
Type A) In load
- *(Ex. IP, HBM, PIC)*
- Monolithic integration
- Hybrid bonding

PART-II & -IV Board-Mount & Standalone

(Incl. Energy Harvesting)

PART-III Higher Power Modules

(Ex. Integrated Power Modules)



HIR Chapter 10 - Integrated Power Electronics (IPE), 2021

Addition for 2024: expanded Section IV – Energy Harvesting

- Content:
- Introduction
- Energy Harvesting (EH) methods and integration challenges
- Heterogeneous Integration of Storage for Energy Harvesting
- Heterogeneous Integration of Electronics

Introduction….. The Power IoT Challenge

- We already have many billions of sensors in the world, expecting to reach 1 trillion in the next few years
- >50% of these will be wireless IoT edge devices
  -> Cost effective, easy to retrofit & monitor on, in or near existing equipment, environment, infrastructure, people

BUT

Typical battery life is less than 2 years Vs

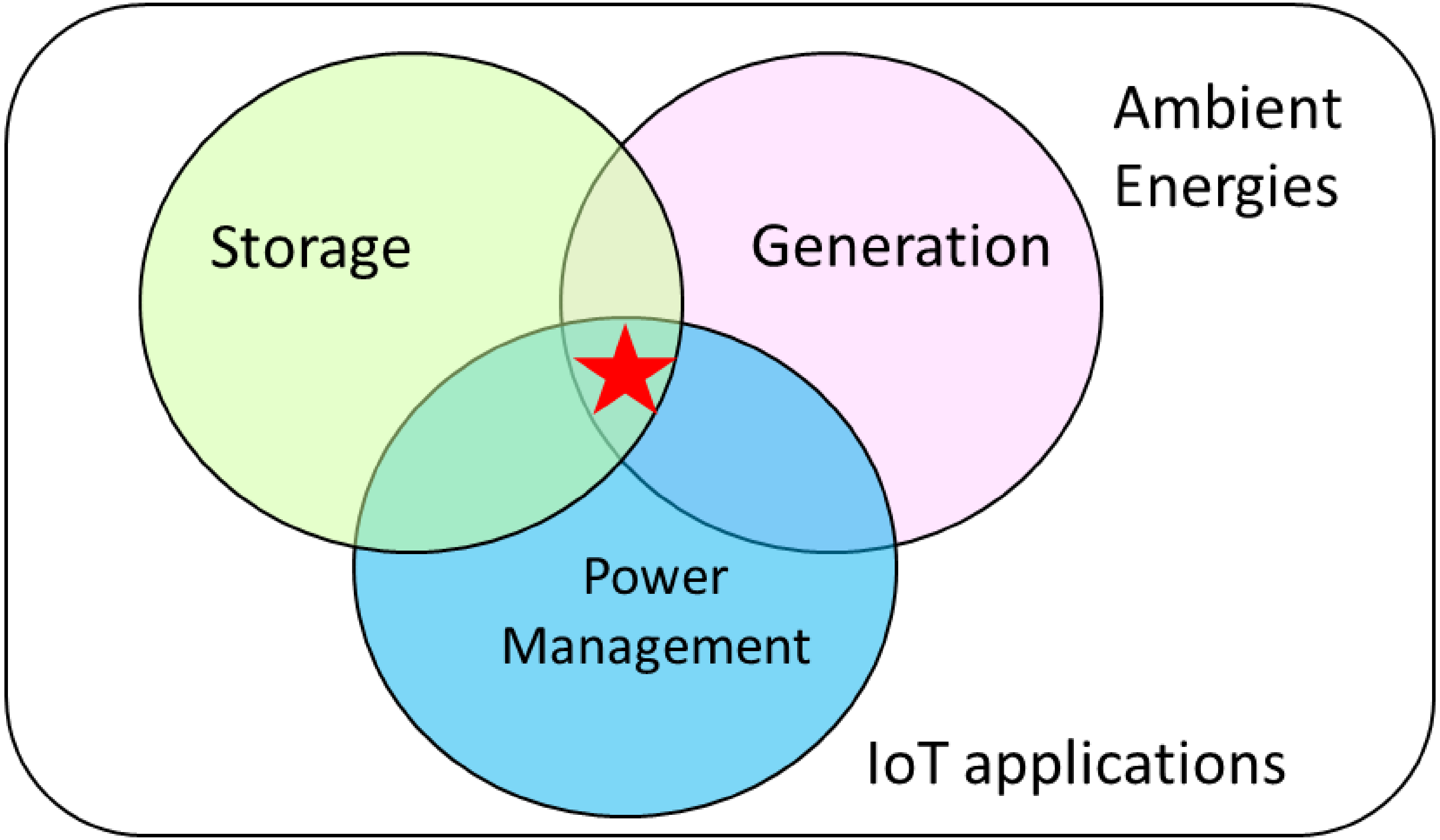
Most IoT devices need > 10 years.

-> Multiple battery replacements.
-> Device downtime and maintenance
-> Major environmental issues

130M/day

UNLESS WE IMPROVE, by 2025 we will manufacture and dispose of >130M batteries every single day just from IoT usage!

The Power IoT Challenge



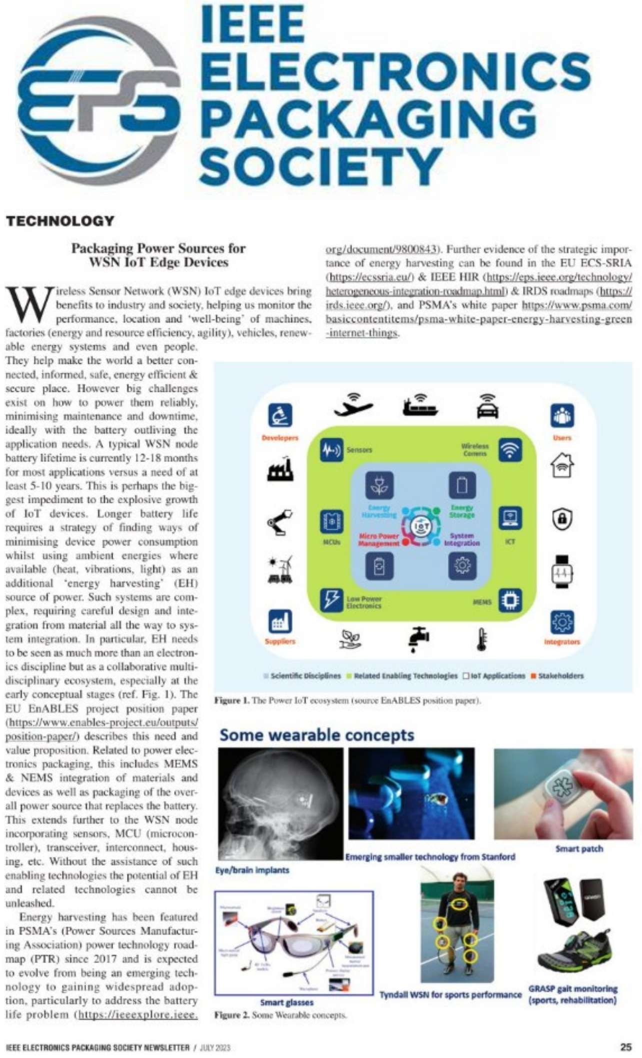
Storage

Generation

Ambient Energies

Power Management

IoT applications



TECHNOLOGY

Packaging Power Sources for WSN IoT Edge Devices

Wireless Sensor Network (WSN) IoT edge devices bring benefits to industry and society, helping us monitor the performance, location and 'well-being' of machines, factories (energy and resource efficiency, agility), vehicles, renewable energy systems and even people. They help make the world a better connected, informed, safe, energy efficient & secure place. However big challenges exist on how to power them reliably, minimising maintenance and downtime, ideally with the battery outliving the application needs. A typical WSN node battery lifetime is currently 12-18 months for most applications versus a need of at least 5-10 years. This is perhaps the biggest impediment to the explosive growth of IoT devices. Longer battery life requires a strategy of finding ways of minimising device power consumption whilst using ambient energies where available (heat, vibrations, light) as an additional 'energy harvesting' (EH) source of power. Such systems are complex, requiring careful design and integration from material all the way to system integration. In particular, EH needs to be seen as much more than an electronics discipline but as a collaborative multi-disciplinary ecosystem, especially at the early conceptual stages (ref. Fig. 1). The EU EnABLES project position paper (https://www.enables-project.eu/outputs/position-paper/) describes this need and value proposition. Related to power electronics packaging, this includes MEMS & NEMS integration of materials and devices as well as packaging of the overall power source that replaces the battery. This extends further to the WSN node incorporating sensors, MCU (microcontroller), transceiver, interconnect, housing, etc. Without the assistance of such enabling technologies the potential of EH and related technologies cannot be unleashed.

Energy harvesting has been featured in PSMA's (Power Sources Manufacturing Association) power technology roadmap (PTR) since 2017 and is expected to evolve from being an emerging technology to gaining widespread adoption, particularly to address the battery life problem (https://ieeexplore.ieee.org/document/9800843). Further evidence of the strategic importance of energy harvesting can be found in the EU ECS-SRIA (https://ecssria.eu/) & IEEE HIR (https://eps.ieee.org/technology/heterogeneous-integration-roadmap.html) & IRDS roadmaps (https://irds.ieee.org/), and PSMA's white paper https://www.psma.com/basiccontentitems/psma-white-paper-energy-harvesting-green-internet-things.

Figure 1. The Power IoT ecosystem (source EnABLES position paper).

Some wearable concepts

Eye/brain implants

Emerging smaller technology from Stanford

Smart patch

Smart glasses

Tyndall WSN for sports performance

GRASP gait monitoring (sports, rehabilitation)

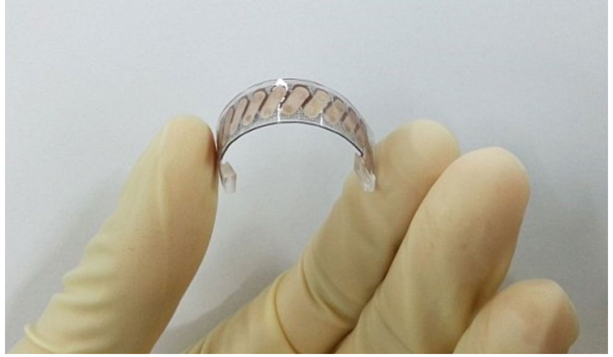
Figure 2. Some Wearable concepts.

IEEE ELECTRONICS PACKAGING SOCIETY NEWSLETTER / JULY 2023 25

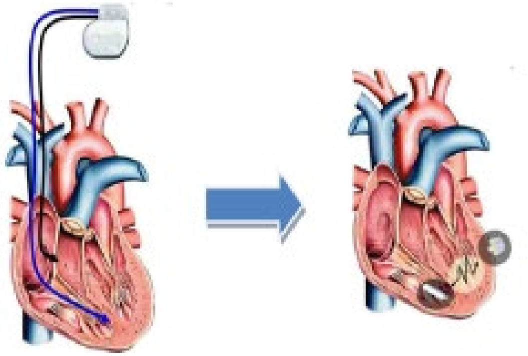
EH methods and integration challenges - I

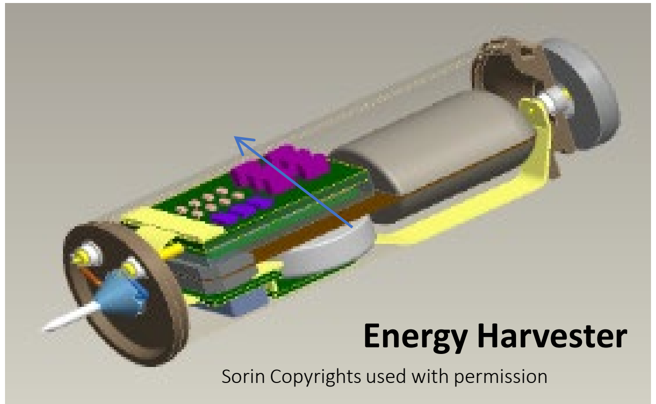
Smart wearables

Smart patch



Wearable TEG: KAIST,
40mW @ wristband size



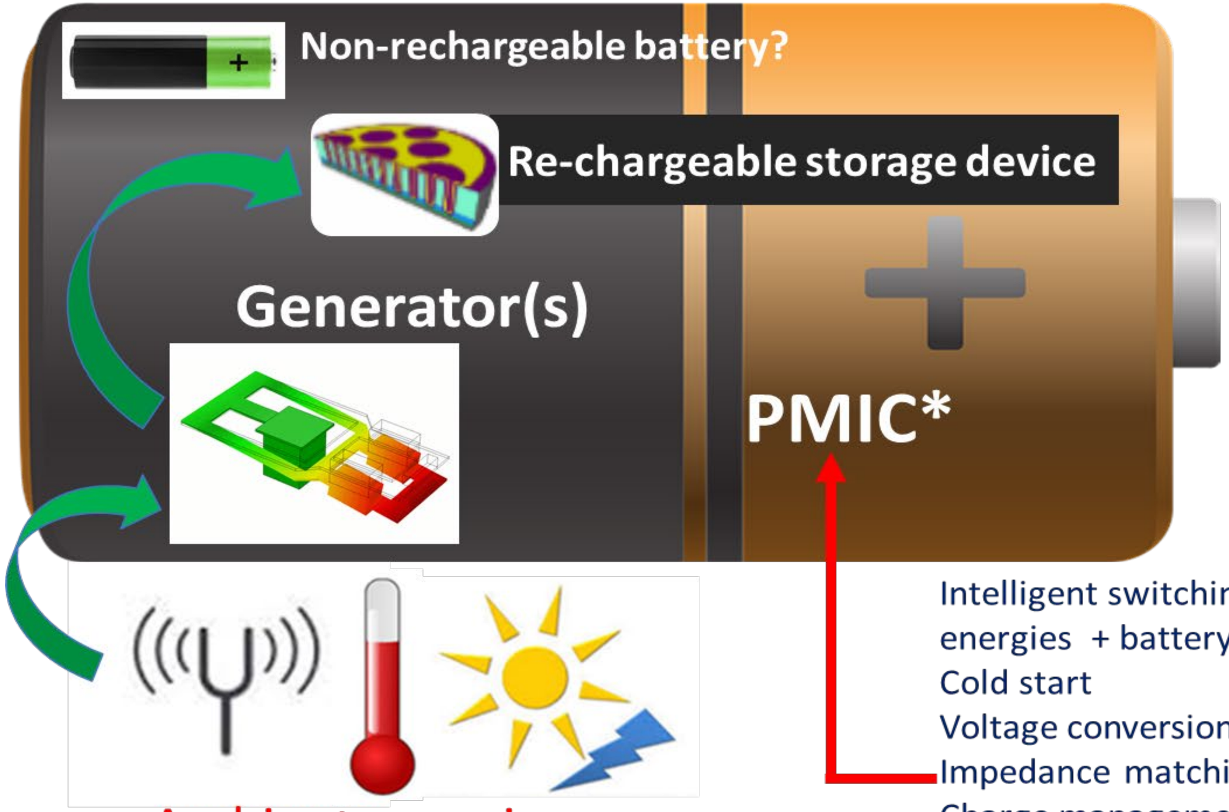


Energy Harvester

Sorin Copyrights used with permission

Implantable energy harvesting device to power pacemaker (Tyndall & EU Manpower project)

EH methods and integration challenges - II



Non-rechargeable battery?

Re-chargeable storage device

Generator(s)

PMIC*

Ambient energies
(sporadic, low power levels)

Load: Wireless Sensor Node

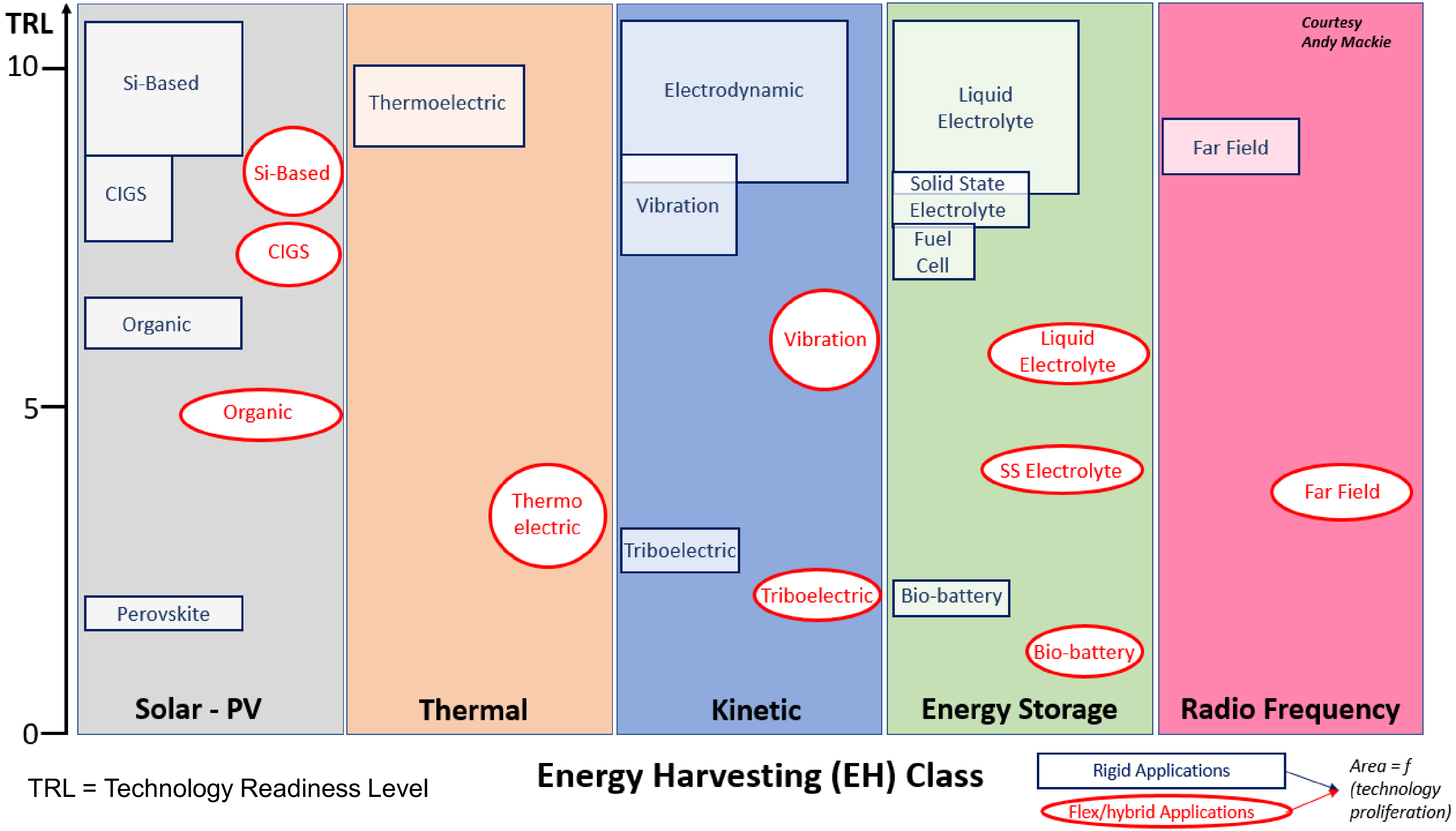
- Sensors + Interface
- Microcontroller
- RF

Intelligent switching between ambient energies + battery + storage devices
Cold start
Voltage conversion
Impedance matching
Charge management
Peaks, transients
Status monitoring

*Power Management IC

Replacing the function of a battery requires integration of a complex array of Technologies

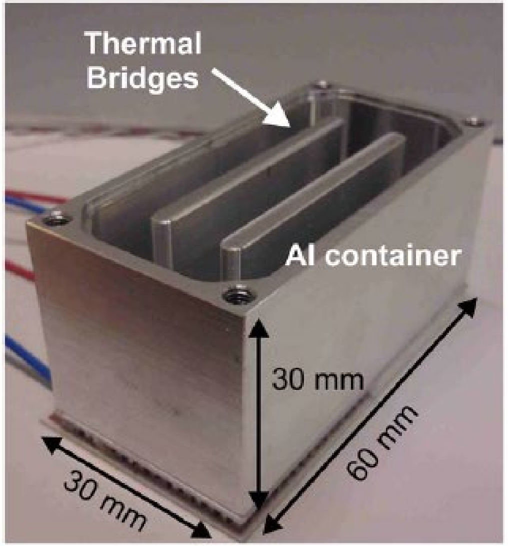
EH methods and integration challenges - III

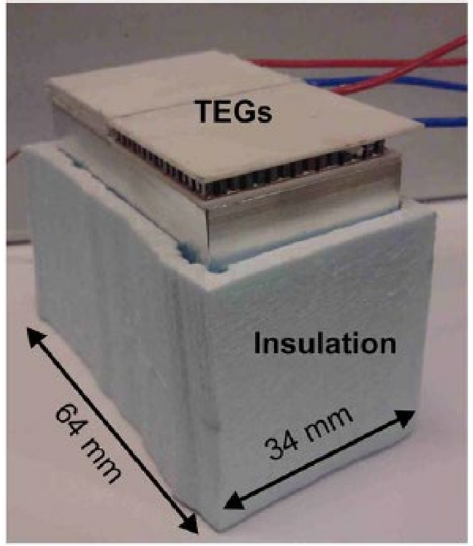


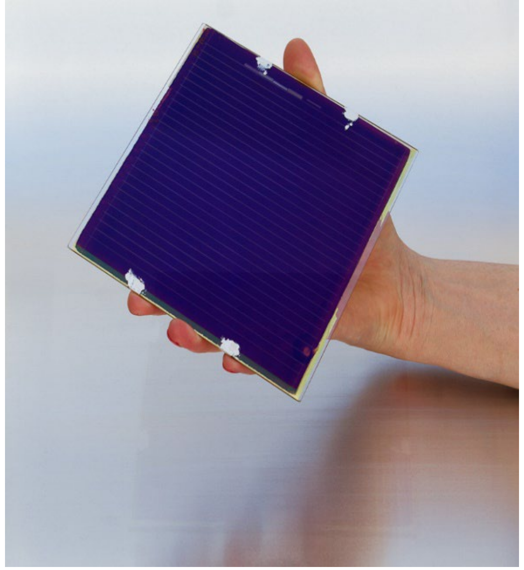
TRL = Technology Readiness Level

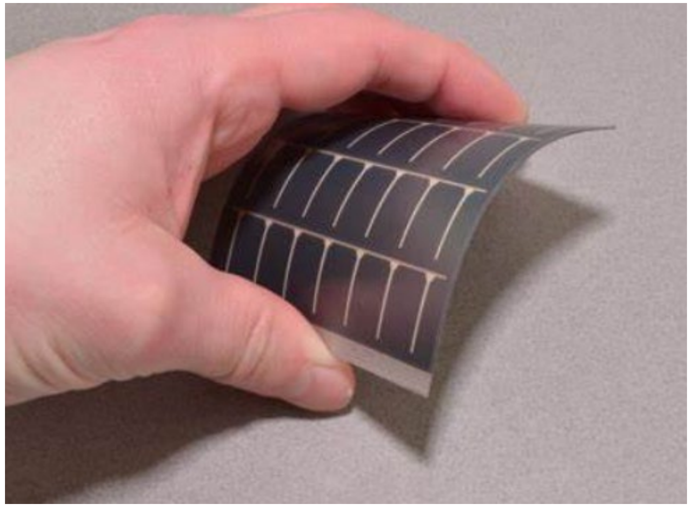
Many of the technologies at lower TRL – work required to package at device as well as system level

EH methods and integration challenges - III









Examples of integration considerations

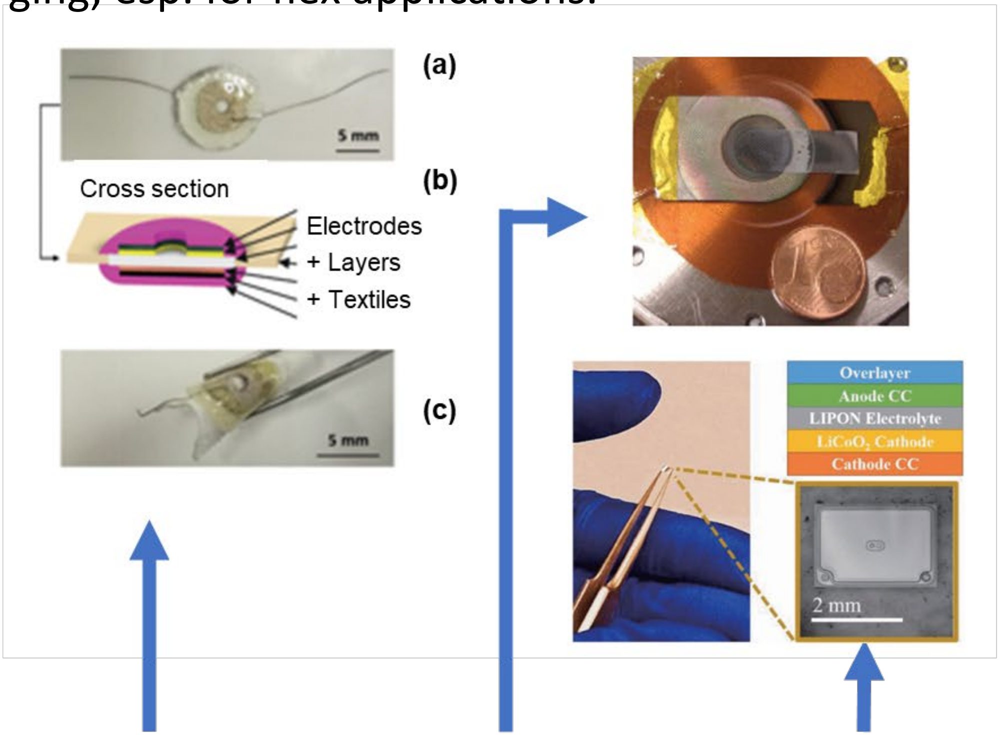
TEGs:- (ThermoElectric Generators)
Heat conduction, thermal insulation and heat storage capabilities need to be integrated into packaging to minimise losses

PV:- Material must be resilient to ingress and adsorption
Surface may be non-uniform or need to be flexible

Heterogeneous Integration of Storage for EH - I

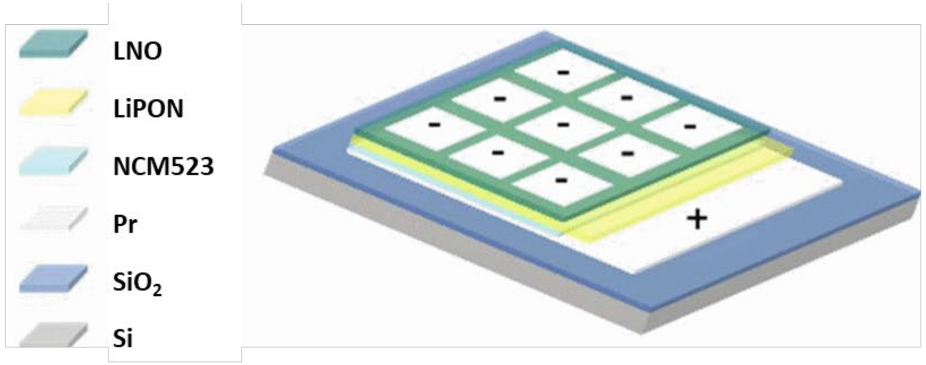
MEMS technologies developed for miniaturised batteries suitable for integration.

Due to safety concerns with liquid electrolytes, technologies suitable for integration of solid-state micro-batteries are emerging, esp. for flex applications.



(a) substrate release, (b) PVD, (c) 30 μm LIB (Lithium Ion Battery) produced by substrate thinning*

* Physical Vapour Deposition



(d) silicon compatible electrode build up

(e) gravure printed super capacitor

Heterogeneous Integration of Storage for EH - II

- Integration of PV and battery cells opens the possibility of reducing or eliminating power conversion stages required.
- Roll-to-roll manufacturing has facilitated integration of piezo sources with supercaps and some power conversion circuitry.
- High-Power solid state SMD micro-batteries create a new path to integrate energy storage elements within advanced packaging solutions and In-Mold electronics.
- 300µm micro-batteries can be integrated / stacked along with other electronic devices, weldable up to 260°C without risk of chemical and electrochemical degradation

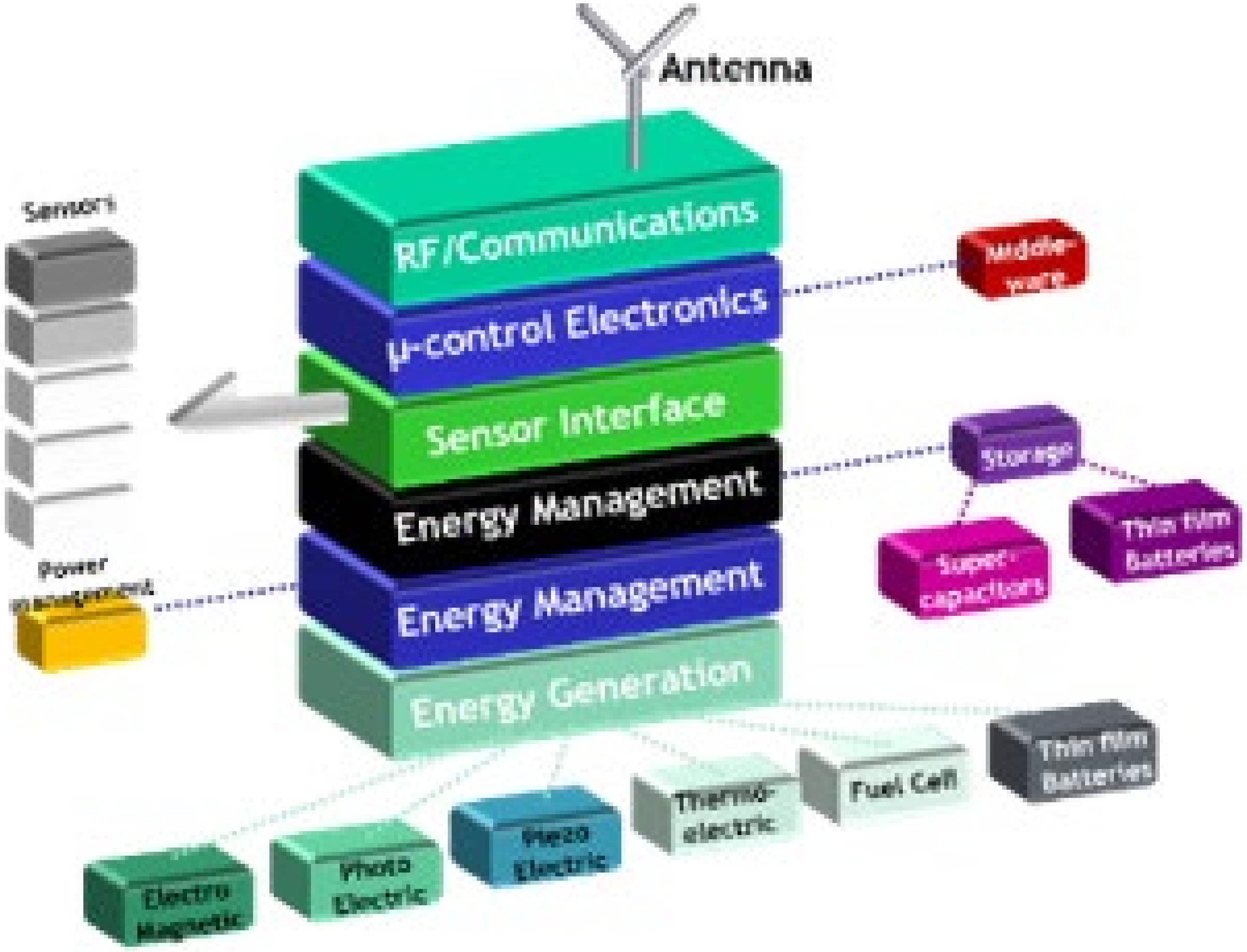
Revibe D cell shaped kinetic energy harvester

Iten solid state SMD micro-batteries

CSEM flexible PV cell

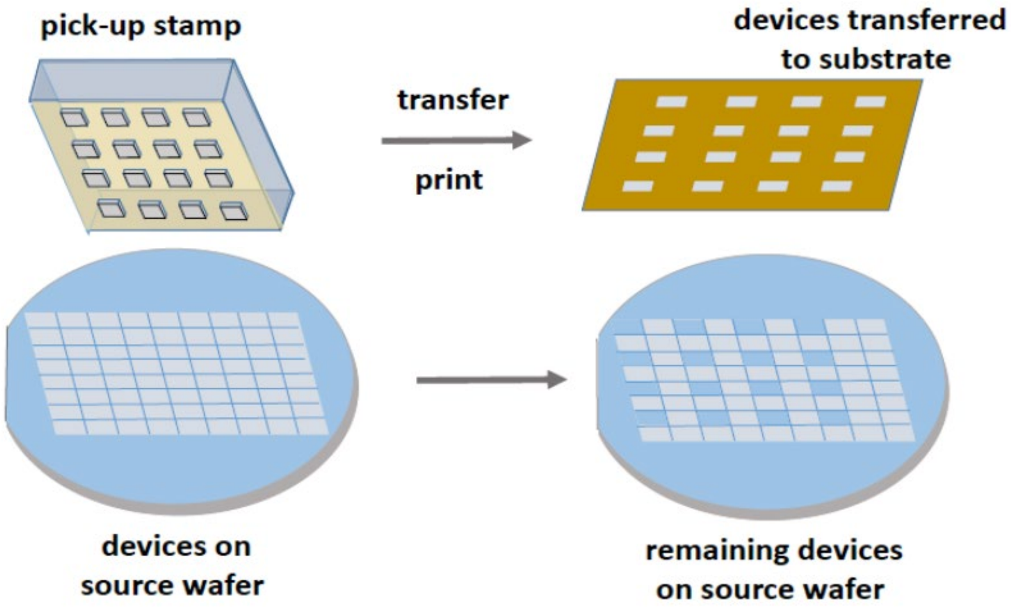
Heterogeneous Integration of Electronics

- (Multiple) Sensor interfaces
- EH (RF, Light, Motion, Chemical, etc.)
- MCU
- Memory
- Power Management
- RF/Communication
- Antenna



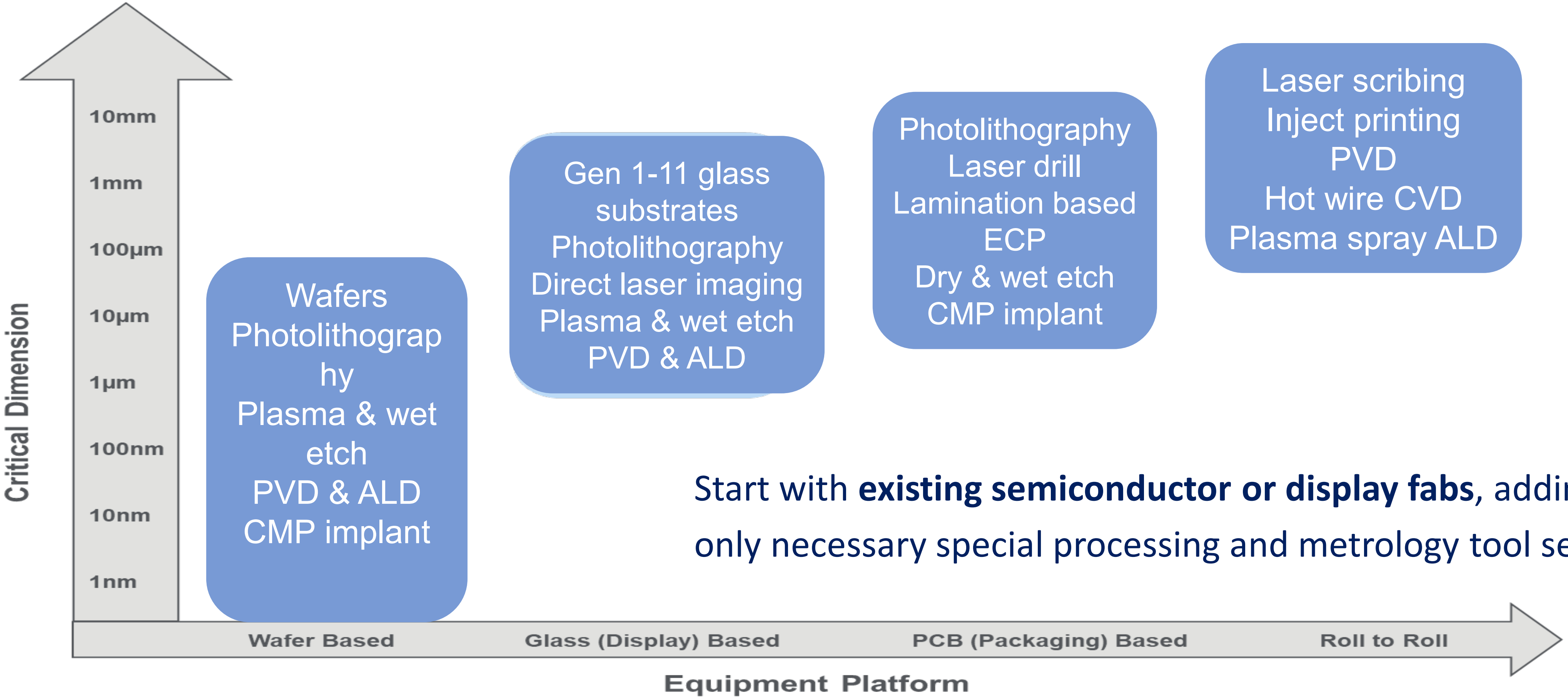
Enabling technologies

- **Printed Electronics (**screen printing, flexography, gravure, offset lithography, and inkjet)
- **Transfer & Micro Transfer Printing (MTP)**



MTP using a custom designed transfer stamp.
Courtesy Fillion Consulting

Miniaturization and integration: adopting appropriate platforms for HVM (High Volume Manufacturing)



Wafers
Photolithography
Plasma & wet etch
PVD & ALD
CMP implant

Gen 1-11 glass substrates
Photolithography
Direct laser imaging
Plasma & wet etch
PVD & ALD

Photolithography
Laser drill
Lamination based
ECP
Dry & wet etch
CMP implant

Laser scribing
Inject printing
PVD
Hot wire CVD
Plasma spray ALD

Start with **existing semiconductor or display fabs**, adding only necessary special processing and metrology tool sets

Integrated Power Electronics Technical Working Group

Many Thanks For Your Attention

If interested in joining our IPE-TWG please contact any of our members.

Other Considerations

- Sustainability challenge: need to consider FULL life-cycle footprint of WSN (wireless sensor node) devices (including disposal). The Sustainable IoT group in CONNECT is developing “green” sensors, supercaps and antennae: Biodegradable WSN, using abundant and renewable materials, with low environmental footprint fabrication methods.
- Flexible electronics have major processing limitations (temperatures and processing chemicals)
- Printed Conductive inks have ~ x2-3 lower conductivity than semiconductor or circuit board
- Flexible Organic photovoltaics (OPV) have relatively lower light conversion efficiencies but have lower cost and environmental impact in manufacturing.
- Many Condition-based monitoring applications need Flexible electronics with EH techniques esp. if there are difficulties in accessing equipment/infrastructure.
- Flexible & printed electronics important for healthcare industry, ideal for interacting with the human body.
  - e.g. help overcome the restrictions of Magnetic Resonance Imaging (MRI) on delicate patients