

PRINTED / FLEXIBLE /STRETCHABLE AND FUNCTIONAL FABRIC/ E-TEXTILE SENSORS AND SENSOR-BASED SYSTEMS: TECHNOLOGY LAUNCHPADS TO ENABLE EMERGING APPLICATIONS

PART 1: INTRODUCTION AND OVERVIEW

Sensors Converge Precon
Santa Clara California Convention Center
June 20, 2023
Roger H. Grace
President, Roger Grace Associates
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www.rgrace.com

SESSION OVERVIEW

- 10 Speakers (including me...providing introduction and summary))
- 20-minute presentations, two-25 minute keynotes
- Q and A to occur at the conclusion of the a.m. and p.m. sessions...using 3" x 5" notecards for questions from audience
- 15 minute mid-session breaks, one hour lunch break
- Kindly complete the questionnaire and it will be collected before the conclusion of the afternoon session...\$50 Amazon gift card to the lucky winner
- The most highly concentrated presentation of speakers on the topic of printed/flexible/stretchable and e-textile/smart fabric sensors to date
- For the first time we will address 3D printing...thanks to Doug Sparks
- Virtually all-new program from previous with small number of "return" speakers
- Copies of the presentations will be made available by Questex

A.M. SESSION

- 9:00-9:05 Welcome... Roger Grace, Roger Grace Associates, Workshop Organizer and Chairman
- 9:05-9:25 Roger Grace, Roger Grace Associates, Introduction and Overview of Printed, Flexible, Stretchable and Functional/E-Fabric Sensors and Sensor-Based Systems
- 9:25-9:50 Ravinder Dahiya Ph.D., Northeastern University, High-Performance Printed Electronics on Flexible Substrates (KEYNOTE)
- 9:50-10:10 Rob Podoloff, Tekscan, Design Considerations when Embedding Tactile Force Sensors-What OEMs Need to Know
- 10:10-10:30 Radislav Potyrailo Ph.D., GE Research, Conventional versus New Generation Gas Sensing: Meeting the Demanding Needs of Flexible Electronics and Emerging Markets
- 10:30-10:45 Morning Break
- 10:45-11:05 Doug Sparks Ph.D., Micro2Nano Technologies, 3D Printing Enables Complex Manufacturing Processes for Sensors
- 11:05-11:25 Robert Malakhov Ph.D., NextFlex, Additive Hybrid Electronics for Novel Wearable Devices
- 11:25-11:45 Maurizio "Mac" Macagno, Sensoria Health, A Gait Lab in a Textile Sensor-Infused Sock
- 11:45-12:00 Q and A
- 12:00-1:00 Lunch (Hosted)

P.M.SSESSION

- 1:00-1:10 Welcome... Roger Grace, Roger Grace Associates, Workshop Organizer and Chairman
- 1:10-1:35 Helena Alves Ph.D., INESC (Portugal), Self-Sustainable Textile Sensor Power Sources Based on Low-Cost Printing (KEYNOTE)
- 1:35 -1:55 Stephanie A.T. Brown, U.S. Army Combat Capabilities Development Command, Sensored Soldier at the Tactical Edge
- 1:55 -2:15 Sean Garbarino, DCS, E-Textile Based Systems for Damage Detection and Status Monitoring for Military and Other Applications
- 2:15-2:35 Roger Grace, Roger Grace Associates, Summary and Conclusions of Printed, Flexible, Stretchable and Functional/E-Fabric Sensors and Sensor-Based Systems
- 2:35-3:00 Q and A

MEA CULPA

- My colleagues have oft-times accused me of making “text-rich” presentations...and while I agree...the rationale for this is that I wish to provide the attendee with information that they can “take home” and use...rather than trying to remember my rambling comments or taking copious notes to collect the data points.
- I trust that you can appreciate my position on this...and thank you for your kind understanding.

PRESENTATION OUTLINE

- Definitions
- Why printable/flexible/stretchable and E-Textile/smart fabric sensors?
- Situational analysis
- Market analysis
- Technology status of printed/flexible system functionalities
- Manufacturing process
- Industry activities
 - Commercial
 - Research/Academic
- Critical Success Factors
- Monetizing
- Summary/Conclusions/Recommendations

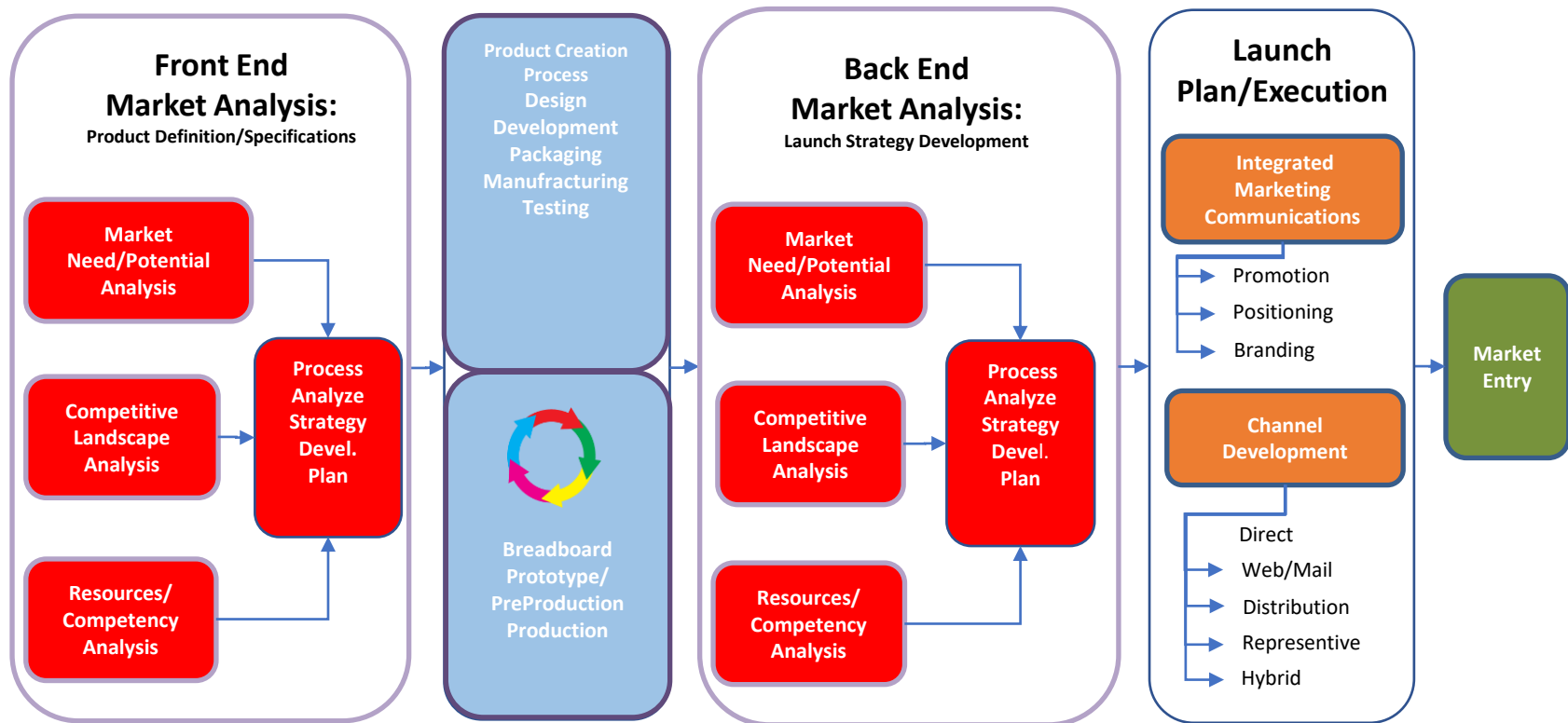
ROGER GRACE BACKGROUND

- Education: BSEE, MSEE (Raytheon Graduate Fellow) Northeastern University, Boston, MA; MBA Program, California Berkeley
- Design Engineer with specialty in microwave and RF, 13 years...Raytheon, Avco
- Applications Engineer, RF semiconductors, 3 years, Avantek/HP
- Marketing Manager, MEMS, 3 years, Foxboro ICT
- Marketing Consultant, MEMS, Sensors and Semiconductors, 40 years
- Guest Lecturer, University of California Berkeley, 1990-2003
- Alumni Engineer of the Year, 2004, Northeastern University
- Co-Founder ,Past President and Board member of Micro ,Nano and Emerging Technology Commercialization Education Foundation (MANCEF)
- Published over 70 papers and articles on MEMS/Sensors/Commercialization
- Organized and Chaired over 30 technical sessions worldwide on MEMS/Sensors
- Board membership...Florida MEP, University of Michigan WIMSS, Northeastern University High Rate Nanomanufacturing Center
- Organizing committee includes IEEE Transducers 2009,COMS, Smart Systems Integration (EU), Advanced Microsystems for Automotive Applications (EU), Bestowed Inaugural “Sensor Industry Impact Award” by Sensors Expo/Sensors Magazine 2016

ROGER GRACE ASSOCIATES OVERVIEW

- Founded in 1982, a pioneer in the MEMS/Sensors strategic marketing and analysis sector www.rgrace.com
- Clients include the “who’s who” of industrial and government organizations worldwide
- Headquartered in Bonita Springs, Florida / San Francisco, California
- Focus on MEMS/Sensors and Capital Equipment markets
- Capabilities include...refer to next PPT.
 - Custom market research...product definition, application opportunity assessment,
 - New product introductions
 - Market strategy development
 - Merger and Acquisition (M&A) due diligence
 - Sales and distribution channel development
 - Integrated marketing communications
 - Promotion
 - Public Relations
 - Positioning and Branding

TECHNOLOGY COMMERCIALIZATION* PROCESS MODEL



*Def: Process or cycle of introducing a new product or production method to the market

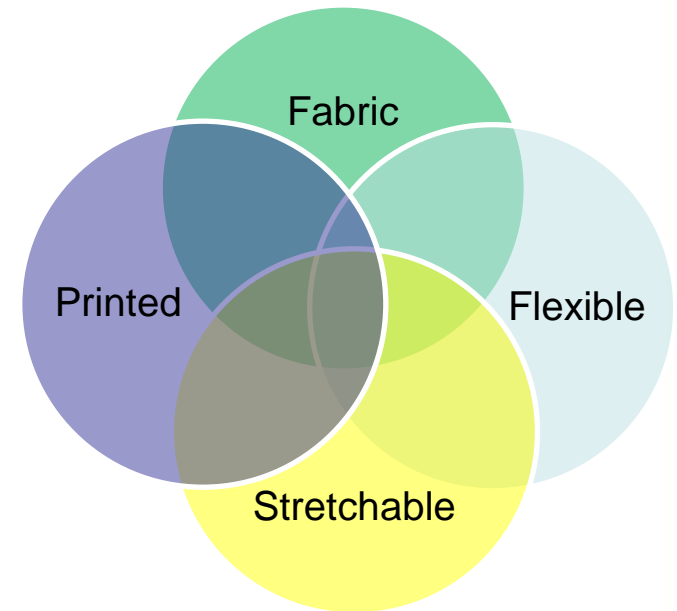
Roger Grace Associates supports its clients in front and back-end market analysis as well as in the product launch plan and execution

MARKET RESEARCH METHODOLOGY

- PRIMARY: OVER 120 in-person, in-lab and telephone in-depth interviews with technology participants beginning in early 2015...and continuing
- SECONDARY: Data mining vis-à-vis the web ...addressing the entire ecosystem of participants
- Attendance at several technical conferences and trade shows
- Participation in webinars

WHY PRINTED / FLEXIBLE / STRETCHABLE & E-TEXTILE / SMART FABRIC

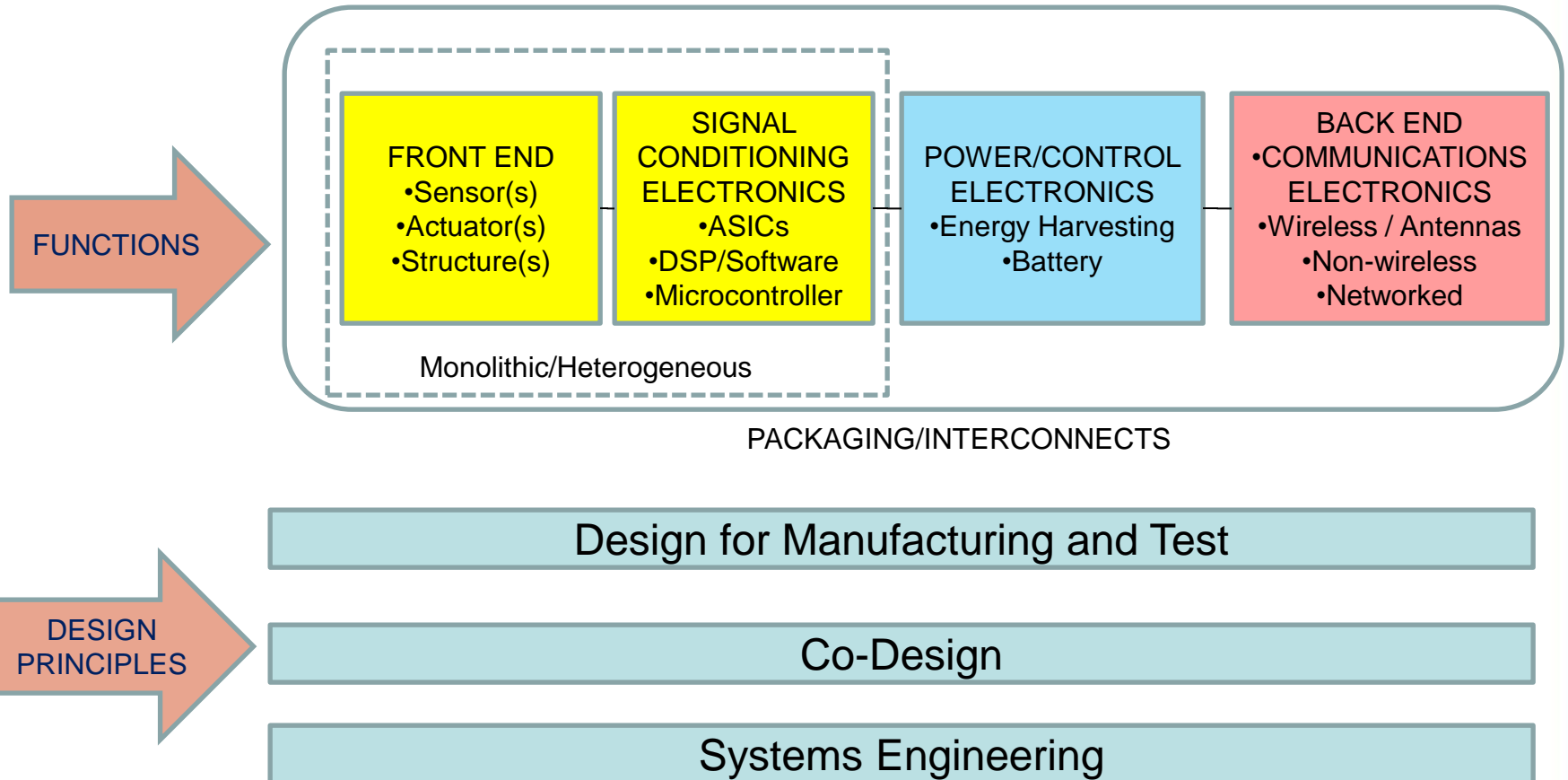
Attribute	Benefit	
	Cost	Functionality
Printed	<ul style="list-style-type: none"> • Low Infrastructure • Low Unit (R-2-R) 	<ul style="list-style-type: none"> • Large device size • Arraying capability • Low profile • Ease of hybrid integration • Reduced time to market
Flexible		<ul style="list-style-type: none"> • Application driven (especially human interface)
Stretchable		<ul style="list-style-type: none"> • Application driven (especially human interface)
E-Textile/ Smart Fabric	<ul style="list-style-type: none"> • Low Infrastructure • Low unit 	<ul style="list-style-type: none"> • Application driven (especially human interface) • Large device size • Arraying capability • Low profile



COMMERCIALIZATION DRIVING FUNCTIONS

- Small size / low profile / low weight
- Ability to conform to attaching surfaces...especially in bio applications
- Robust and highly reliable vis-à-vis judicious material selection
- Low manufacturing cost based on existing batch mode processing with the ability to be scaled to a uber- high volume / uber low cost roll-to-roll (R2R) or weaving manufacturing approach
- Enhanced performance over discrete 3-D solutions because of their size and geometry
- Device-to-device uniformity
- Low CAPEX requirements for manufacturing
- Ease for integration (including discrete) of other functionalities onto same or layered carriers...hybrid approaches
- Ability for arraying
- Large area coverage capability
- Expected to benefit from momentum of popularity of Flexible Hybrid Electronics (FHE) and associated manufacturing capabilities

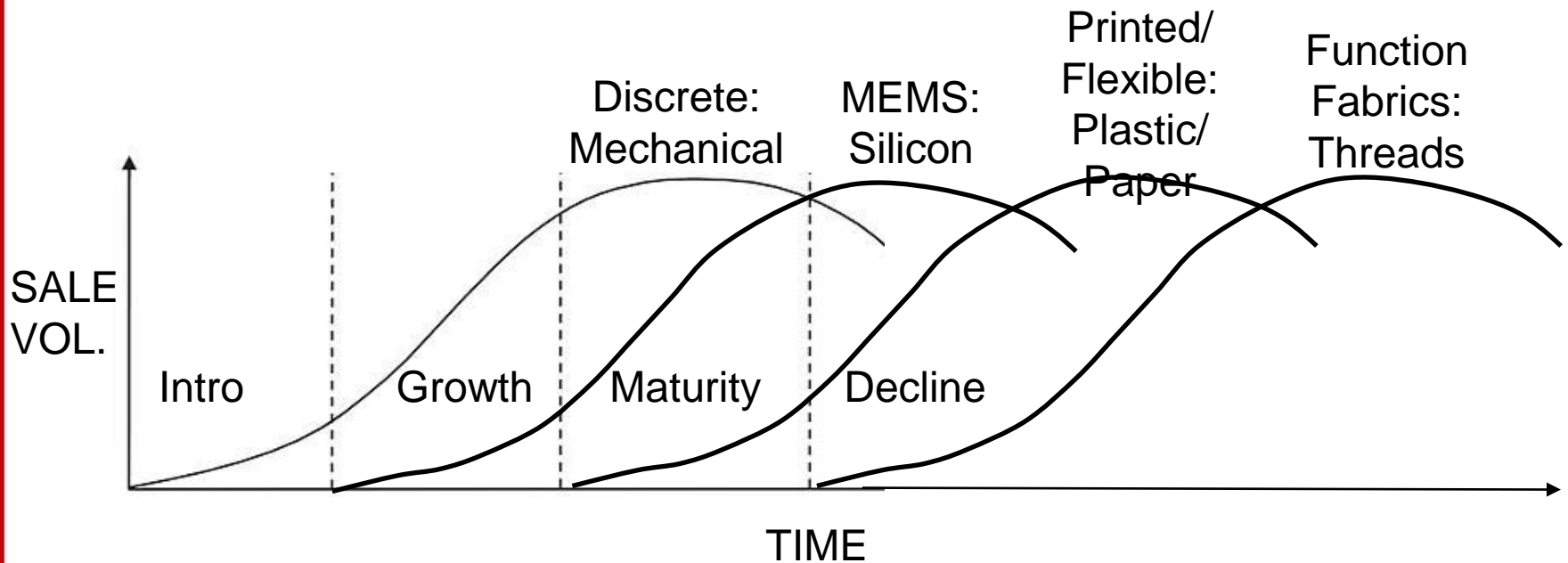
SENSOR-BASED SYSTEM SOLUTIONS



SITUATIONAL ANALYSIS

- Printed/flexible sensors are a logical extension of printed displays (OLED) and Flexible Hybrid Electronics (FHE) electronics...and are chemistry and materials (not electronically) driven and are truly a convergence of technologies
- First commercial success in 1985 by Interlink Electronics and followed by Tekscan ...Force Sensing Resistors (FSR)
- To be considered as a complement / not replacement to Silicon functionalities
- Use much the same infrastructure as printed electronics
- Sensors typically have simple structures and thus easy to manufacture
- Flexible / extensible manufacturing processes:
 - Batch mode for low-to-medium volume applications
 - Roll-to-Roll (R2R) for large volume applications
- Only a small number of companies currently in volume production
- Significant activity in agencies, research labs and universities worldwide
- Many possible application opportunities with a focus on major opportunities for wearables e.g. sports monitoring and home healthcare monitoring
- High volume application opportunities expected to fuel dramatic growth
- Adequate market research coverage to date...i.e. IDTechEx, Modor, Research and Markets
- Limited design and analysis tools currently available

SENSOR PRODUCT LIFE CYCLES





WHERE IT ALL BEGAN

Johannes Gutenberg; Mainz, Germany 1440

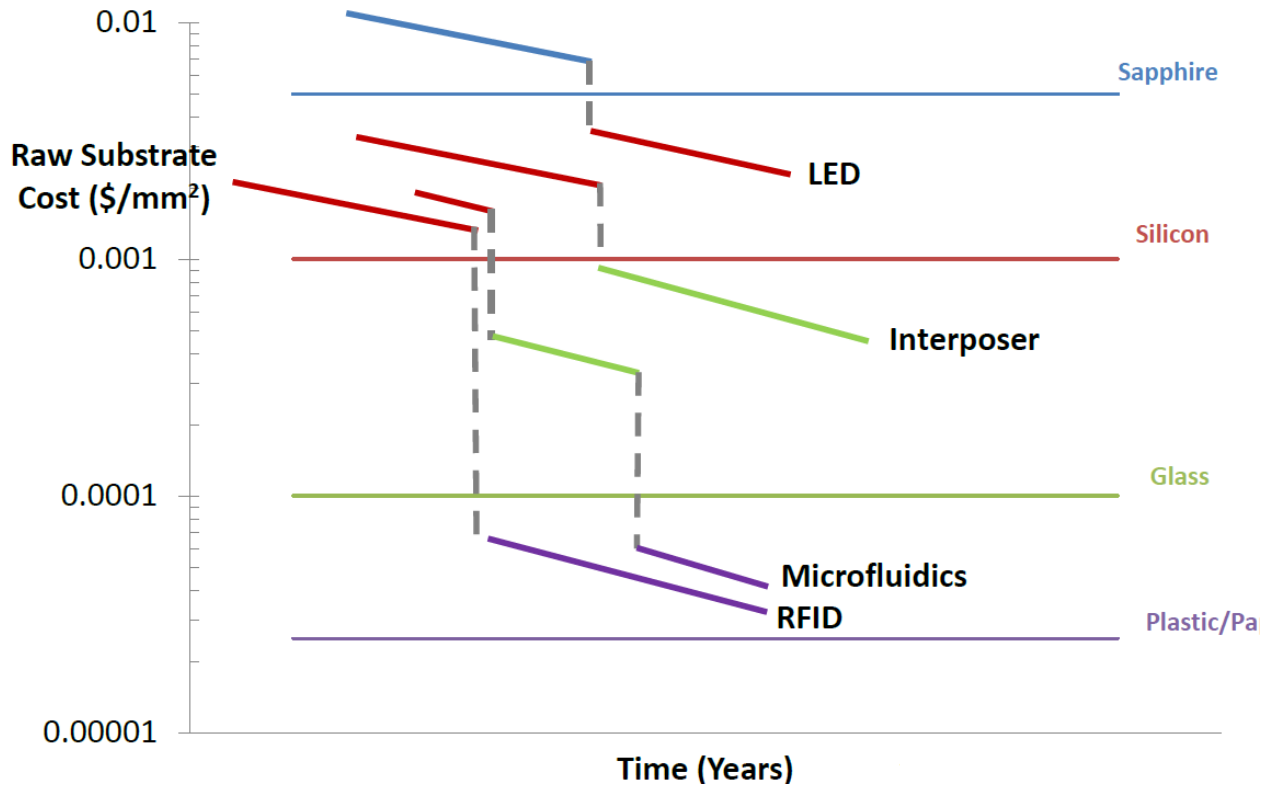
ECOSYSTEM

- Broad and in-depth (many suppliers for each) ecosystem in place in the value chain
- Suppliers include:
 - Materials, chemicals
 - Equipment
 - Sensors
 - Interconnects
 - Integration
 - Packaging
 - End product design
 - Manufacturing
 - Design, layout and analysis tools
 - Sales and distribution of final product
- Collaboration up and down the value chain will be critical for participants success...one cannot successfully go it alone

EMERGING HIGH VOLUME APPLICATION OPPORTUNITIES

- It is common knowledge that many high volume applications exists...however the big question is which are the most lucrative ones and when?
- Need to take into account the “Grace / Walsh 30 year development process for MEMS”
- Current acknowledged current application opportunities include:
 - Package tracking
 - International monitoring of the environment by chemical / gas sensors connected by mobile networks
 - Disposables....e.g. diapers
 - **Wearables ...Personal health / fitness monitoring e.g. “e-medical”/ military battlefield**
 - Food, beverage and drug status monitoring...e.g. UC Berkeley
 - Patient activity monitoring

DEVICE MATERIAL COST COMPARISON

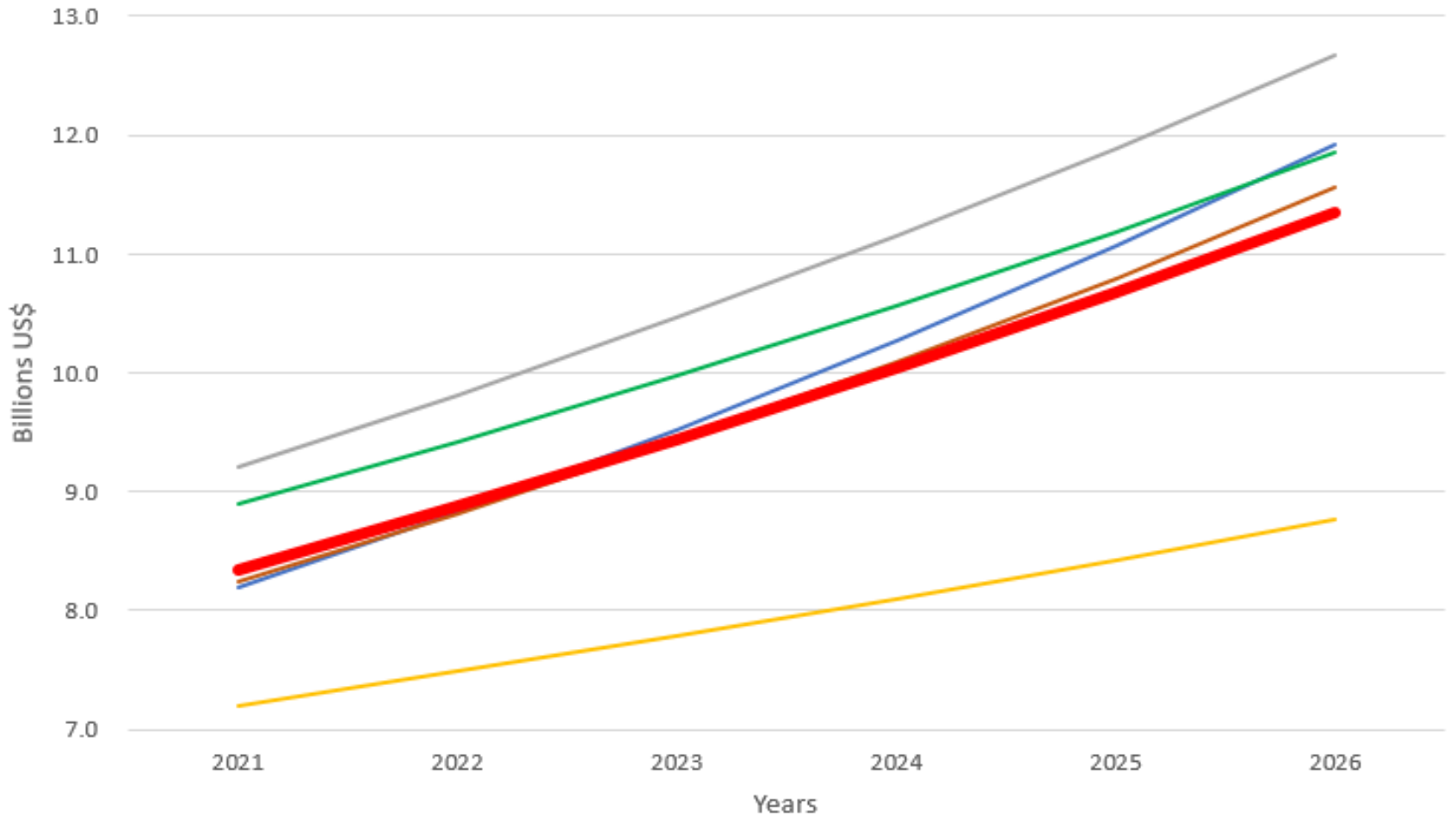


Source: AM Fitzgerald /adapted from P. Werbaneth

DESIGN & MANUFACTURING PROCESS

- Complex process flow...lots of “landmines” to avoid
- Critical to have design & manufacturing “kickoff” meeting to bring all aspects of the design & manufacturing involved and addressed from day 1
- Decision on printing process driven by several factors...Sheet fed or Roll-to-Roll
 - Volume
 - Specifications
- Scalability...start with sheet-fed for prototypes and low volumes...migrate to Roll-to-Roll for large volumes
- Selection of base materials and inks is critical to performance and manufacturability
- “Converters” or...packagers...integrate the sheets into the final products
 - Cutting
 - Lamination
 - Connection to the outside world

Printed Sensors Market Summary



— Precedence - No Date - 7.8 *

— Modor - 2021 - 6.6 *

— Report Linker- Jan 2022 - 7.0 *

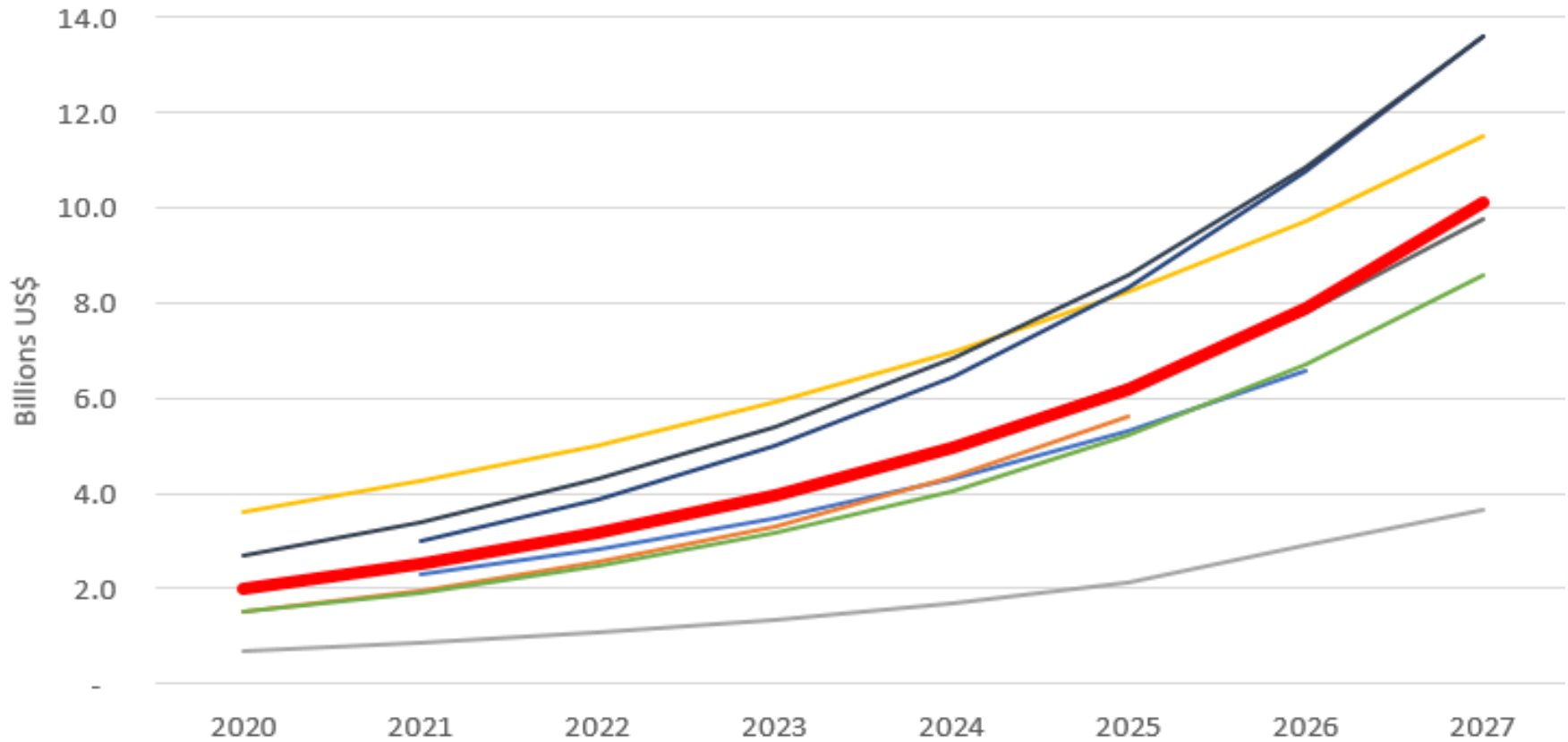
— Research and Markets - Apr 2021 - 5.9 *

— Market Watch - Apr 2022 - 4.0 *

— Average - 6.0 *

*CAGR – Compound Annual Growth Rate

E-Textile/Smart Fabrics Market Summary



— Markets and Markets/Sept. 2021 - 32.2 *

— Modor/2021 - 25.7 *

— IDTECHEX *

— IMARC/2021 - 29.1 *

— Transparency Market Research/Mar. 2022 - 25.0 *

Years

— Grand View Research/2018 - 30.4 *

— Research and Markets/Aug. 2021 - 18.0 *

— Reports and Data/Jan. 2022 - 28.3 *

— Insight Partners/Jan. 2020 - 26.1 *

— Average - 28.5 *

*CAGR – Compound Annual Growth Rate

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FUNCTIONAL FABRIC/ E-TEXTILE
SENSORS AND SENSOR-BASED SYSTEMS:
TECHNOLOGY LAUNCHPADS TO ENABLE
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PART 2: APPLICATIONS /
SUMMARY/CONCLUSIONS

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COMMERCIAL ACTIVITIES

CURRENT COMMERCIALIZATION PLAYERS

- Limited “reported” activity in sensors production
- No **apparent** large volume producers
- No **apparent** “big dogs” involved (yet)...e.g. Bosch, ST, ADI, Freescale ...however we believe that “big dogs” are funding efforts in P/F and FF vis-à-vis subcontracts with research institutes and universities
- Over 100 smaller players worldwide addressing individual parameters
- Virtually all current participants not “traditional” sensor companies but rather materials / chemical companies e.g. Brewer Science
- Sensor parameters currently being addressed include:
 - Chemical/gas
 - Touch/force/pressure
 - Temperature
 - Humidity
 - Bio
 - Air flow
 - Imaging
 - Conducting electrodes

SUPPLIER LANDSCAPE

Company	Force/Touch	Temperature	Humidity	Electrodes Gas	Bio-Chem	Imaging	Time of Flight Shock	Flow	Other
BodiTrack/Vista Medical (Canada)	•								
Brewer Science			•	•					
Drop Sense (Spain)					•				
Electrozyme						•			
Flexpoint	•			•					•
GSI Technologies					•				
Interlink Electronics	•								
ISORG (France)							•		
MC10						•			
Nikkoia (France)							•		
Peratech (UK)	•								
Piezotech (France)					•		•	•	
Plastic Electronics GmbH (Austria)	•								
PolyIC (Germany)	•								
PST (So. Africa)			•						
Sensitronics	•								
Spec Sensors					•				
Synkera					•				
Tactonic	•								
Tekscan	•								
Temptime			•						
T-Inc	•								

Not exhaustive
Alphabetical order

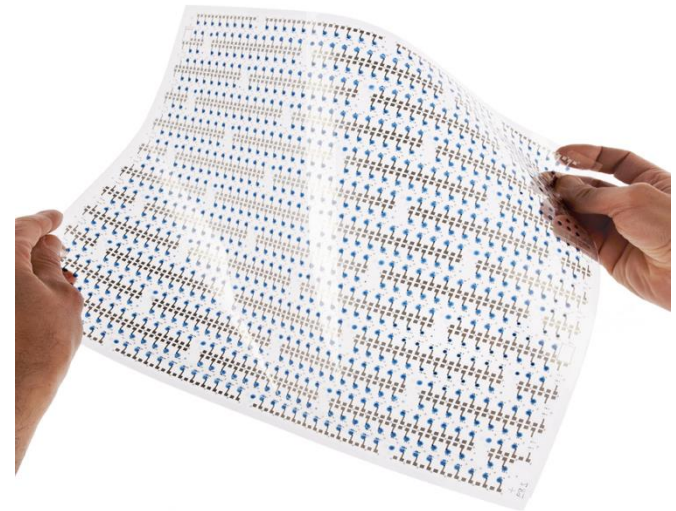
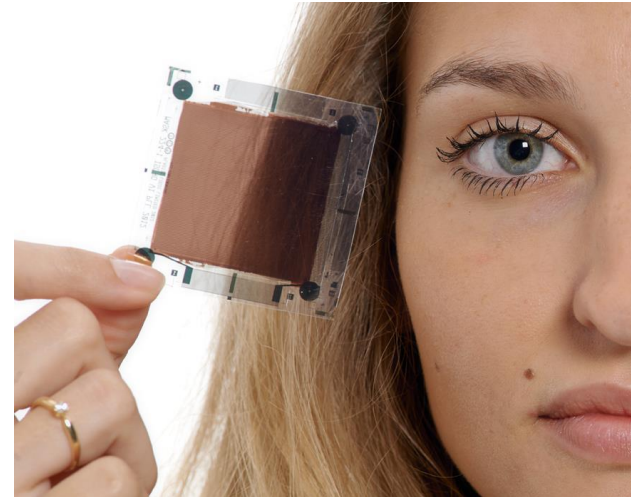
TEKSCAN

- Location: Norwood MA
- Introduced: Early 1990's
- Brand name: Flexiforce
- Parameter sensed: Force, rate of change of force, relative change in force, touch, contact
- Construction: Two layers of polyester substrates with printing of layer of conductive silver (connections) and layer of pressure sensitive ink attached by an adhesive bond
- Applications include sports/fitness consumer, medical devices, robotics, control and diagnostic



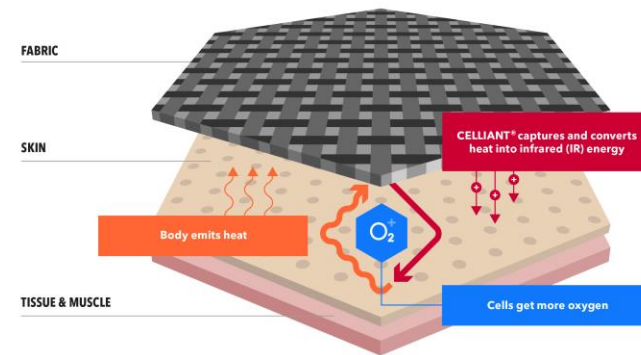
ISORG

- Location: Grenoble, France
- Parameter sensed: imaging sensor
- Visible/NIR up to 900 nm.
- Low dark current
- Large dynamic range
- PET plastic foil: 32 x 32 cm. moving to 60 x 60 cm.; 5 x 5 cm. device
- PET backplane
- Applications: whole -hand fingerprint analysis/biometrics, medical x-ray imaging ,IoT inventory analysis
- CEA-Leti spinoff in 2009
- Received 28M Euro infusion

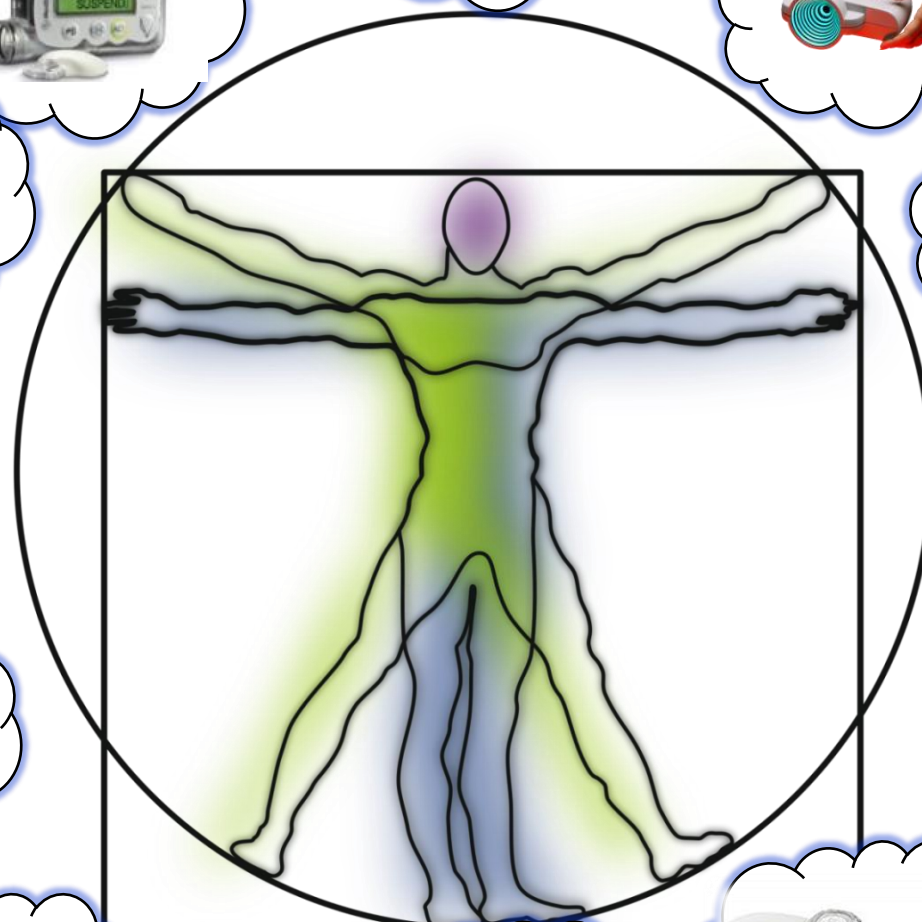


HOLOGENIX / CELLIANT

- Founded: 2017 in LA
- Works on principle of certain minerals plus 88 trace elements react to heat and emit full spectrum IR energy
- Proprietary minerals added to liquid phase of the polymeric thread extrusion process
- Currently EU Class 1 medical device
- FDA classified as medical device with no class determination
- Applications include apparel, medical/wound care, diabetes
- Products include T-shirts (UnderArmor), socks, sheets (Pure Care) Mattresses (Bear)



Applications



Electrical Brain Stimulation



Device Components

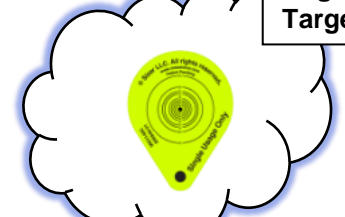


Eye Care

Electrocardiographic Mapping



Angioplasty Targets



Respiratory Monitoring



Cardiovascular Monitoring



In Vitro Diagnostics



Iontophoretic Patch



Heating Elements



Laboratory Testing



Gate Monitoring



WEARABLES:THE FUTURE OF MEDTECH*

- Definition:
 - On-body vs. off-body
 - Apple watch vs. Sensoria T-Shirt
- Objective: provide “transparent computing”...Davide Vigano/CEO Sensoria
- Forcing Factors
 - “the pandemic transformed healthcare”...Alfred Poor, Editor, Heath Tech Insider
 - Rate of adoption acerated by
 - Aging-in-place
 - Adoption of telemedicine/telehealth
 - Recent developments in AI
- Applications...remote and on-person monitoring
 - Post-procedure
 - Physical therapy
 - Chronic illness
- Technical Issues...Hardware
 - Hybrid/”pod” approach for sensing, computation, communication, power
 - Packaging/interfacesing sensor platforms to systems

*key take-aways from the WEAR Conference...June 7-9, 2022 Scottsdale, AZ

WEARABLES:THE FUTURE OFMEDTECH*(CONT.)

- Market Growth (Research and Markets Report: “Global Smart Wearables” Feb. 2023)
 - \$20.64 B(2022)
 - \$34.39B(2027)
 - CAGR=10.2%
- Technical Issues...Software/Data
 - What needs to be measured to impact decisions
 - How is it displayed to optimize efficacy
- Barriers to Commercialization
 - Data security
 - Regulation
 - CDC billing code approval
 - Broadband and smart phone access
- Companies to Watch
 - Butler Technologies...Smart T-Shirt
 - Hologenix...Smart power T-shirt (Under Armor)
 - Liquid Wire...sensors and connectivity solutions
 - Nextiles...smart fabric sensors
 - Sensoria...Smart socks, T-Shirts and bras

UNIVERSITIES / RESEARCH INSTITUTES ACTIVITIES

R&D LANDSCAPE OVERVIEW

- Considerable R&D activity in sensor development (and their integration) into systems a.k.a. products in many research institutes and universities:

Asia

- ITRI-Taiwan
- Sungkyonk wan University-Korea

- Europe

- CEA-Leti France
- CSEM Switzerland
- Fraunhofer Europe (67 with approx. 10 involved in P/F Electronics including Chemnitz/ENAS, Munich/EMFT, Dresden/IPMS and Berlin/IZM)))
- IMEC/ Holst Netherlands
- VTT Finland
- INESC Portugal

- US

- | | | |
|----------------------------|---------------|-----------------------------|
| – Arizona State University | GE Research | Western Michigan University |
| – Northeastern University | parc | Ohio State |
| – Stanford | UMASS Amherst | N.C. State |
| – UC Berkeley | UMASS Lowell | |
| – UC San Diego | UC Irvine | |

PRINTOCENT CLUSTER

- Location: Oulu, Finland
- Started: 2008 www.Printocent.fi
- Facilities (shared):
 - VTT
 - OUAS
 - University of Oulu
- Funding: 40M Euros (EU and Regional)
- Turnover of companies (2019): 25M Euros
- Total number of companies in cluster: 40
- Number of companies catalyzed: 30
- Number of jobs created: 300
- Purpose: Provide open access to companies for scale-up of manufacturing capabilities for the creation and manufacturing of “printed intelligence”
- Created a six-part series of webinars in mid-2020 on “Printed Intelligence”
- Offers free...”Handbook of Printed Intelligence” as pdf download



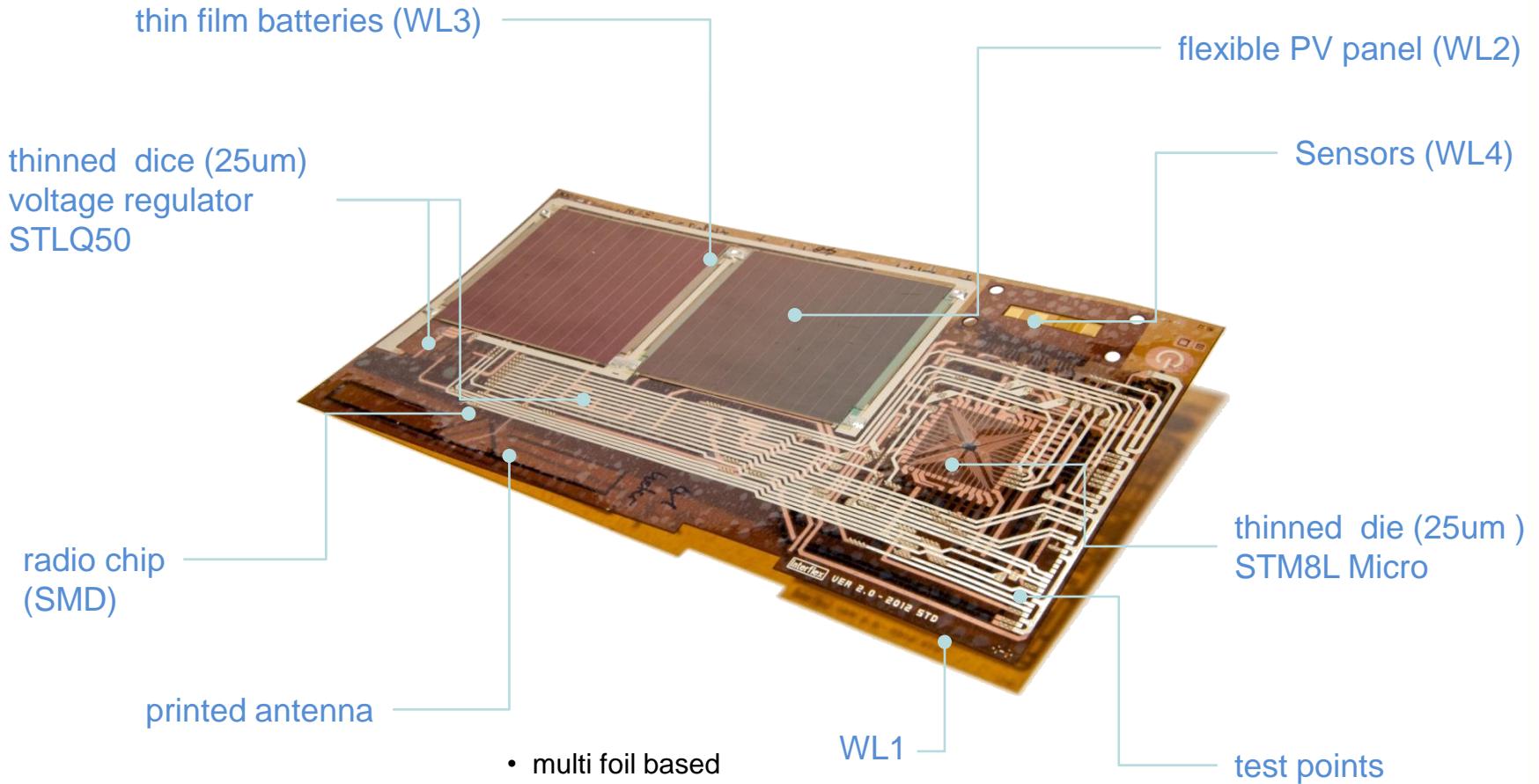
US PUBLIC / PRIVATE CONSORTIA

- AFFOA (Advanced Functional Fabrics of America) www.affoa.org.
 - Location: Cambridge, MA (MIT)
 - Founded in 2016
 - Funding: \$75M (US DOD) with grants from governments, industry and academia totaling approximately \$325M
 - Focus: Enabling manufacturing
- NEXT FLEX / SEMI www.nextflex.org.
 - Location: San Jose, CA
 - Founded in 2015
 - Funding: \$75M (US DOD) with grants from governments, industry and academia totaling approximately \$325M
 - Focus: Enabling manufacturing (flexible hybrid approach)

INTEGRATION CHALLENGES

- The future success will reside in the ability of suppliers to judiciously select the required functionalities of the individual circuit functions and determine the optimum format/platform for their realization in specific applications
- Monolithic vs. heterogeneous vs. hybrid integration strategies...TBD
- Connectivity of individual devices
- Packaging/encapsulation of total solution
- Reliability issues...especially with wearables continuous washing/drying
- Modelling challenges
- Determination of the manufacturing method to minimize cost, maximize functionality and maximize reliability e.g. Flextronics, Jabil
- Major efforts underway in EU to address this issue...also with NextFlex in the US

SYSTEM INTEGRATION



INFOTECH
automation



BOSCH
Invented for life



Fraunhofer
EMFT

ROGER GRACE ASSOCIATES
MARKETING COUNSEL

CRITICAL SUCCESS FACTORS

- Ability to demonstrate value- add to critical applications
- Ability of to demonstrate equal- to -better performance vs. competitive approaches...and my market research say “yes”
- Growth of the wearables market uncertainty
- Ability of non-flexible/non-organic functional solutions to accommodate application requirements
- Entry of additional players (with big R&D Budgets) to help commercialize the technology
- Adoption of standard processes based on the broad availability of materials
- Continuation of robust funding of research activities by governments ...e.g. Next Flex (US), AFFOA (US), PrintoCent (Finland)
- Ability of existing sensor companies to adopt a paradigm shift from a electromechanical technology mindset to that of a materials one
- Continuation of over-hyping of flexible electronics opportunities
- **BOTTOM LINE....I believe there is lots of uncertainty at this time...”as goes flexible hybrid electronics so goes its sensors”...R. Grace**

MONITIZING

- FACT...Its hard to make money just providing sensors (J. Bryzek)
- Need to add value...look for system solutions
- Actively seek partnerships/collaborations ... e.g. PST / ThinFilm (licensing)
- Possible acquisition strategy
- Ride the wave of the printed electronics (PE) growth
- Find and get designed into applications that can exploit the unique benefits of these sensor technologies and address unmet market needs especially in wearables

SUMMARY / CONCLUSIONS

- Limited:
 - number of success stories to date
 - number of commercial companies in volume production
 - number of parameters currently being measured:
 - Pressure / force / touch
 - Gas analyses
 - Temperature
 - Humidity
- Solid growth foreseen by several market research groups
 - Printed: CAGR (average) =6% (2021-2026)?
 - Functional Fabric: CAGR (average)= 28% (2020-2027)
- Growth forcing functions
 - Replacement of existing solutions...lower cost, enhanced functionality
 - Creation of new solutions based on enabling nature of P/F/S and FF
- Will require a significant marketing/applications pull vs. technology push
- A “systems solution” approach will be required...not just a sensor!
- Wearables for military, sport fitness, disposables, package tracking, e-healthcare and environmental monitoring expected to propel market
- Ability to scale to R-2-R for large volume/low cost application opportunities

SUMMARY / CONCLUSIONS (cont.)

- Low cost CAPEX makes commercialization by many organizations possible
- I believe that the success of Printed/Flexible/Stretchable and Functional Fabric/E-Textile sensors will weigh heavily on the success of flexible hybrid electronics (FHE) ...the future will be interesting

UPCOMING EVENTS OF NOTE

- IEEE Sensors Council-FLEPS (www.ieee-fleps.org)... Boston/Northeastern University...July 9-12, 2023...**connect with Prof. Ravinder Dahiya for details**
- Semicon West/NextFlex (www.nextflex.org)...San Francisco, CA...July 11-13, 2023
- WEAR (www.wear.com) San Diego...December 4-6, 2023

FURTHER READING

- Articles by Roger Grace on P/F/S and E-Textile/Smart Fabric sensors have appeared in:
 - Electronic Products-June, 2015 Electronic Products; July 2015
 - Sensors Magazine Newsletter-September 25, 2015
 - Sensor Magazin (Germany)-November 2015
 - Commercial Micromanufacturing Magazine (UK)-December 2015
 - Commercial Micromanufacturing Magazine (UK)-May/June 2018

...and all available on the Roger Grace Associates website
www.rgrace.com in the drop down tab... "Articles"

תודה
Dankie Gracias
Спасибо شكريا
Merci Takk
Köszönjök Terima kasih
Grazie Dziękujemy Děkojame
Ďakujeme Vielen Dank Paldies
Kiitos Tänname teid 谢谢
Thank You Tak
感謝您 Obrigado Teşekkür Ederiz
Σας ευχαριστούμε 감사합니다
ขอบคุณ
Bedankt Děkujeme vám
ありがとうございます
Tack

Since this was a shortened presentation due to time constraints...
the entire presentation will be available to attendees by kindly requesting it via email to me at
...rgrace@rgrace.com

**Please come by the Roger Grace Associates booth #324 and enter to win
a smart T-shirt and Smart socks courtesy of Hologenix**