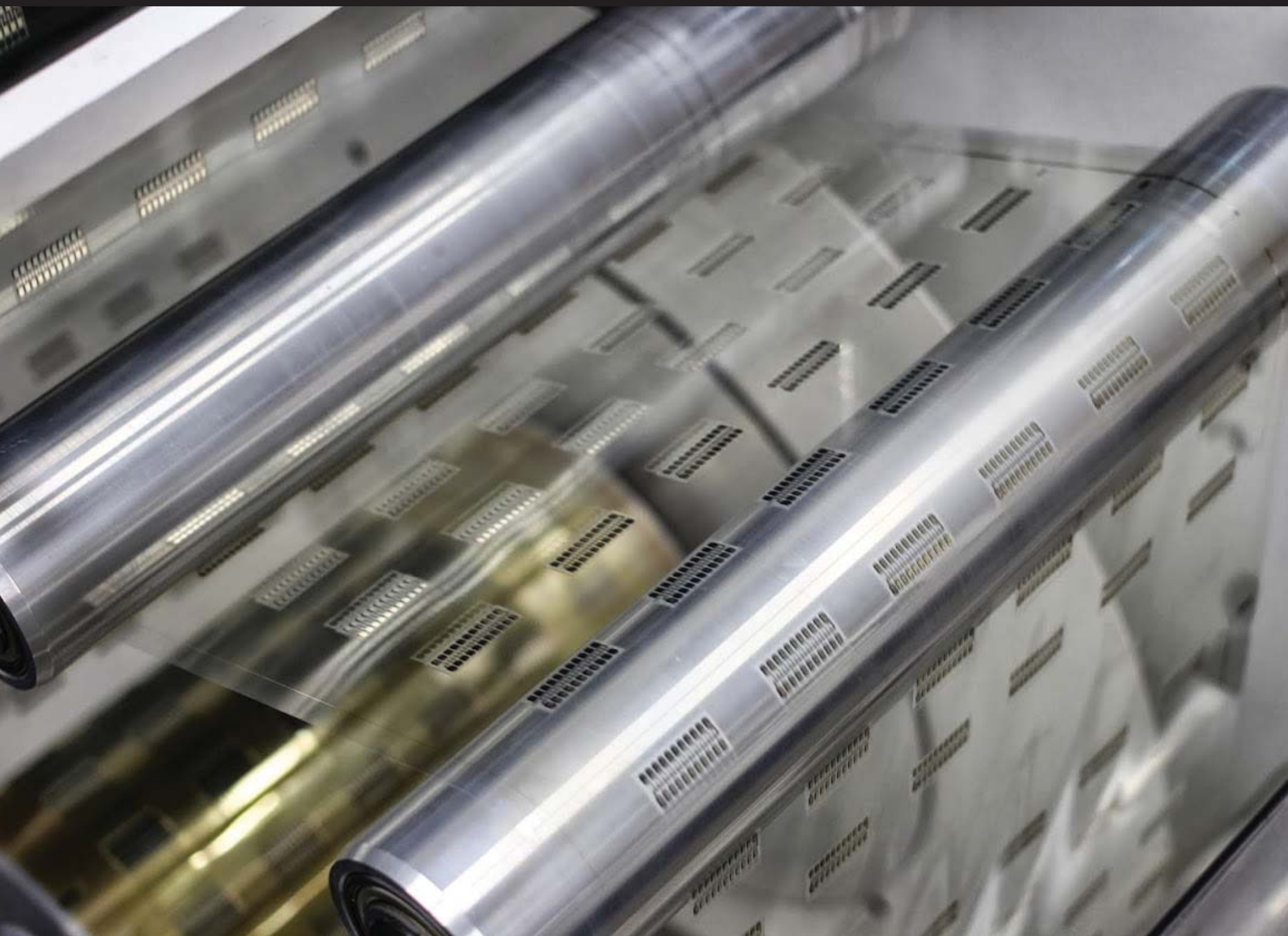
NSF Workshop on Advanced Manufacturing for Smart Goods



An NSF Workshop Report: Advanced Manufacturing for Smart Goods

May 14-15, 2015

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ONAMI OREGON NANOSCIENCE AND MICROTECHNOLOGIES INSTITUTE

NSF

Advanced Manufacturing for Smart Goods

An NSF Workshop Report – May 14-15, 2015

Sponsoring Organizations

U.S. National Science Foundation
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Oregon State University
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Host Organizations

Business Oregon and the Washington Department of Commerce

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Executive Summary

The promise of the Internet of Things (IoT) is dependent upon the ability of companies outside of the traditional information technology (IT) supply chain to assimilate wireless sensing capabilities within their products i.e. to develop "smart goods". Therefore, to accelerate the adoption of IoT technology, a national consortium is needed to bring together the needs of smart goods companies with the burgeoning capabilities of the electronics industry to address the common materials, design, manufacturing and educational challenges facing the emergence of an IoT industry.

Smart goods are the "things" in IoT consisting of everyday objects with the embedded computation, memory, sensing and wireless connection to cloud computing needed to enhance product performance. The growth in the number of smart goods over the next five years is expected to fuel a global economic impact of more than $9 trillion by 2020, driving massive expansion in the IT industry that will create millions of new jobs in personalized medicine, precision agriculture, smart grid and the industrial internet. However, the emergence of smart goods represents a seismic shift in the way IT is being designed, produced, distributed and marketed. Smart goods companies are typically not inside the traditional electronics supply chain. Consequently, while a great deal of potential exists for advancing IoT technologies into products, many potential smart goods manufacturers are unaware of how to capture the potential of IoT. Further, a gap exists between what is possible and what is needed.

In an effort to capture the state-of-the-practice in smart goods manufacturing and identify emerging research needs for companies producing smart goods, a National Science Foundation workshop on "Advanced Manufacturing for Smart Goods" was held on May 14 and 15, 2015, in Portland, Oregon. Key research needs and knowledge gaps identified by participants included:

- **Development of Smart Components and Interconnects.** Persistent themes included reduced power requirements, enhanced battery life, energy harvesting, smaller form factors and lower costs. Advances are needed in reducing the size, complexity and power consumption of interconnects. New digital printing and 3D printing methods offer opportunities to transcend existing board-level strategies for component integration.
- **Sustainable Design and Manufacturing of High-Performance Materials.** On one hand, higher performing structural, electrical and optical materials are key to meeting the needs of new smart components and interconnects. On the other hand, due to their ubiquitous nature, smart goods must be recyclable, compostable or biodegradable. Current biodegradable metals are difficult to handle offering higher electrical resistance. One promising area of research is the development of a digital material science that can predict the properties of gradient materials made possible by digital printing.
- **Scaling of High-Performance Functional Materials.** Scaling functional inks with desired ink-substrate interactions simultaneous with weak ink-print head interactions is extremely challenging. A major challenge includes the ability to characterize nanomaterials during high-rate synthesis to ensure proper size and shape distribution.
- **Conversion and Integration of Functional Inks.** Nanoparticle sintering methods that can create the traces at low temperature are of immense interest to the industry. Most current work focuses on single materials, and issues such as incompatible chemistries and interfacial bonding are rarely addressed. A related challenge involves the ability to integrate the nanomaterials into heterogeneous systems without losing their functional properties.
- **Low-cost, Large-area 3D Integration.** Efforts are needed to improve the resolution of conformal

printing onto curvilinear surfaces. Significant innovation is required to enable digital printing that is compatible with roll-to-roll, multi-head processing at an industrial scale.

- **Silicon and Hybrid Integration.** Research efforts are needed to learn how to better integrate sensing elements with CMOS-based devices. Research is needed to address the science and engineering of materials and methods directly compatible with integrated circuit metallization, reliability under thermomechanical stresses, and 3D-printed passive and active components over metallization.
- **Design Tools.** Smart goods design must consider multi-physics issues during electromechanical integration. New methods are needed for surrogate modeling as model sizes increase. Design rules are needed to capture the benefits of digital printing and design automation.
- **Data Volume Considerations in Large IoT Networks.** A network infrastructure will be needed to handle the massive data volumes that will be generated by smart goods. Standards for connectivity, communications and security will all be needed to drive the industry forward.
- **Education.** Electronics companies need to understand the requirements of emerging smart goods markets. Engineers and technicians within smart goods companies will need to learn new ways to design, manufacture and test products.

1 Introduction

In 2012, the U.S. information technology (IT) industry, consisting of semiconductors, computers, software, publishing, broadcasting, telecommunications, data processing, internet publishing, and other information services, contributed over $1.7 trillion to the United States gross domestic product.[1] By 2017, about one half of spending on IT equipment in the U.S. is projected to be in smart computing[2], much of which is driven by social networking and gaming through mobile and cloud computing platforms. By 2020, global IT is expected to become further distributed, growing from roughly 10 billion interconnected devices today[3,4] to as many as 200 billion[5] "smart goods", with computation embedded within everyday objects connected to cloud computing via wireless sensing i.e. the "Internet of Things" (IoT). These estimates include 30 billion interconnected autonomous systems that extend IoT beyond social networking and automated data collection[6] to include closed-loop actuation and teleoperation. The technology ecosystem surrounding these smart goods is estimated to be an $8.9 trillion global industry by 2020.[5]

For most of the prior 50 years, productivity in the IT industry has been driven by improvements in semiconductor manufacturing associated with Moore's Law, i.e., the doubling of transistors in an integrated circuit every two years. The emergence of smart goods represents a seismic shift in the way IT is being designed, produced, distributed and marketed. Computers are increasingly being sold as a subsystem within an existing product rather than as a stand-alone processor driving new requirements for form factors and component integration across sensing, computing and communication platforms. Further, mobile smart goods are driving new requirements for power management and energy harvesting, challenging conventional wisdom associated with semiconductor device design and integration. Like the IT revolution of the last 50 years, the IoT revolution of the next 50 years will be enabled in part by the development of manufacturing platforms capable of delivering higher performance at lower cost. In this way, these manufacturing platforms form part of the economic foundation necessary for advancing many significant IoT industries of the future including personalized medicine, precision agriculture, smart grid and the industrial internet among many others.

Many examples exist today of smart goods produced using conventional semiconductor and electronics assembly technology (e.g. mail trackers, thermostats, food freshness sensors, medication compliance monitors, lighting, power meters, diagnostic and therapeutic devices). While the near-term demand for smart goods will continue to leverage silicon complementary metal-oxide semiconductor (CMOS), microelectromechanical systems (MEMS) and surface mount technology (SMT) manufacturing platforms, it is anticipated that opportunities exist to reduce the cost of electromechanical integration within products through digital printing. Additional research and development is needed both to bring digital printing into the mainstream of manufacturing as well as to extend existing semiconductor processing platforms to meet future structural and functional requirements of smart goods. With this in mind, a two-day workshop sponsored by the National Science Foundation was organized to:

1) Examine and review the state-of-practice in manufacturing materials and process technologies for the emerging smart goods industry;
2) Gather the smart goods industry perspective regarding advanced manufacturing research needs, gaps and the associated challenges; and
3) Formulate recommendations for next steps, including follow-up workshops as needed, to advance manufacturing technologies for the emerging smart goods industry.

The workshop was held in Portland, Oregon on May 14 and 15, 2015. Also known as the Silicon Forest, the Portland, Oregon and Vancouver, Washington metropolitan area contains almost 900 semiconductor and electronics companies. The workshop drew a diverse group of participants from industry, academia and government including 20 industry speakers. A total of 120 people attended, including 38 (32%) from industry, 67 (56%) from academia and 15 (12 %) from state and federal government and non-governmental organizations. This total included participation from 19 states across the U.S. including Arizona, California, Georgia, Hawaii, Idaho, Kansas, Maryland, Massachusetts, Minnesota, Missouri, Nebraska, New York, Ohio, Oregon, Pennsylvania, Texas, Virginia, Washington and Wisconsin.

The purpose of this paper is to capture the state-of-practice and manufacturing research needs identified by workshop speakers and to make recommendations for advancing manufacturing research in support of this vital emerging industry. The remainder of this paper is organized as follows. Section 2 summarizes the workshop presentations from the five workshop sessions. In the first three sessions, smart goods needs were presented from both large and small company perspectives including specific manufacturing needs. The final two sessions covered the future research needs of both existing and emerging smart goods manufacturing platforms. Section 3 summarizes the industry needs to advance smart goods manufacturing and section 4 is a call to action to move this technology forward.

2 State-of-the-Practice

2.1 Smart Good Needs

Dr. Al Salour (Technical Fellow, Boeing) highlighted that cyberphysical system applications at Boeing are being driven by a 50% increase in the demand for airplanes. He emphasized that the advent of wireless sensing has enabled worker productivity gains and improvements in the quality of data available for a wide range of industrial internet applications. Manufacturing shop floor applications discussed included the use of RFID tags to provide real-time tracking of production assets like inventory and tools. He discussed efforts to implement condition-based maintenance of equipment, in place of scheduled maintenance, using wireless sensing platforms in combination with custom and off-the-shelf data analytics software to predict tool failure conditions before they happen. Specific examples included the use of smart phones for the collection of acoustic sensor data setup for equipment health monitoring by production mechanics. Advantages included the ability to simplify the calibration and training of mechanics as well as the ability for mechanics to use the data to identify failure modes before they occur to minimize safety risks and damage to products and equipment. Other cyberphysical applications discussed involved the use of wireless gauges to support statistical process control and quality assurance programs. Dr. Salour also discussed efforts at Boeing to implement structural health monitoring in composite sections of the airplane using fiber optic strain sensors. This application reflects only one of many needs that Boeing currently faces with regards to integrating sensor technology directly into the airplane as a smart good.

Dr. Roy Want (Research Scientist, Google) discussed the data management issues associated with the large and growing number of smart goods becoming available within society. Each smart good must be discovered and separately managed using a software application (app) which can become difficult to do on a mobile platform. Further, the large number of interactions can generate an overwhelming amount of data all the while posing an increased safety and security risk. Dr. Want proposed that each smart good have an embedded “UriBeacon” to broadcast a URL address referencing a web page with the specific data associated with the smart good. This is similar to Apple’s iBeacon concept except that in order to use the iBeacon, companies must develop their own apps. Further, connection of the device to a web page enables the devices to be found using current search engines. One example given for the use of UriBeacons was setting up a smart phone to search for temperature control points (e.g. thermostats, appliances, etc.) in an effort to influence the localized temperature within buildings. Advantages of the UriBeacon approach include easier use (i.e. lack of the need to develop apps) and the ability to monetize IoT through advertising. Current issues being worked on include privacy, power and search query processing. A review of current UriBeacon and iBeacon costs show a price of $50 per item (volume pricing available) which could be a barrier to the ubiquitous usage of these technologies to connect smart goods to the Internet.

Ned Lecky (Principal Engineer, Amazon) presented the challenges that all retailers face in tracking and monitoring the condition of retail goods being distributed worldwide. For Amazon, it requires tracking roughly 60,000 goods per hour per building through 200 distribution centers for a total of 12 million goods per hour. Tracking this volume of goods through a tightly coupled distribution system results in a very large real-time database of where everything is. This data is largely generated by barcode scanners which are expensive to build to meet the required throughput. Further, the problem is that barcodes must be visible to be scanned, so damaged, lost or stolen goods can be hard to track or find. Mr. Lecky indicated that even five cent radio frequency identification (RFID) tags would require $150 million per year in operating expenses which can be hard to justify when the "smarts" do nothing but track goods during distribution. Mr. Lecky emphasized that the reason RFID tags are not more ubiquitous is that they do not directly add value to the end use customer. On the other hand, many smart goods have the ability to track location, offering a chance to serve multiple purposes both for the distributor and retailer in merchandise tracking while directly adding value to the customer. In this manner, the costs of distribution could be reduced. Mr. Lecky proposed that as smart goods evolve, perhaps they could have tracking features built into them. Data of interest included monitoring of location, temperature, humidity, orientation and shock as a function of time. Concerns included privacy once the goods are passed on to the customer.

Dorota Shortell (President, Simplexity Product Development Inc.) highlighted two smart goods that her company recently developed and shared lessons from those experiences. Case studies included the Microsoft Band (Figure 1), a wearable device for the wrist, and smart dumbbells. Key challenges for the wearable device was its compact size, water resistance, safety and durability. Size and durability requirements drove designers away from the use of polymers toward materials with higher specific strength such as stainless steel. The need to drive metals into complex shapes with tight tolerances led to the use of metal injection molding and precision sheet metal forming techniques. Water/sweat resistance and safety drove designers towards low-cost space-saving integration strategies for the gasketing and sealing of components including insert molding onto flexible printed circuits and overmolding of thermoplastic elastomers onto structural elements to improve profile accuracy. Key challenges for the smart dumbbells included battery life and achieving the positional accuracy required for

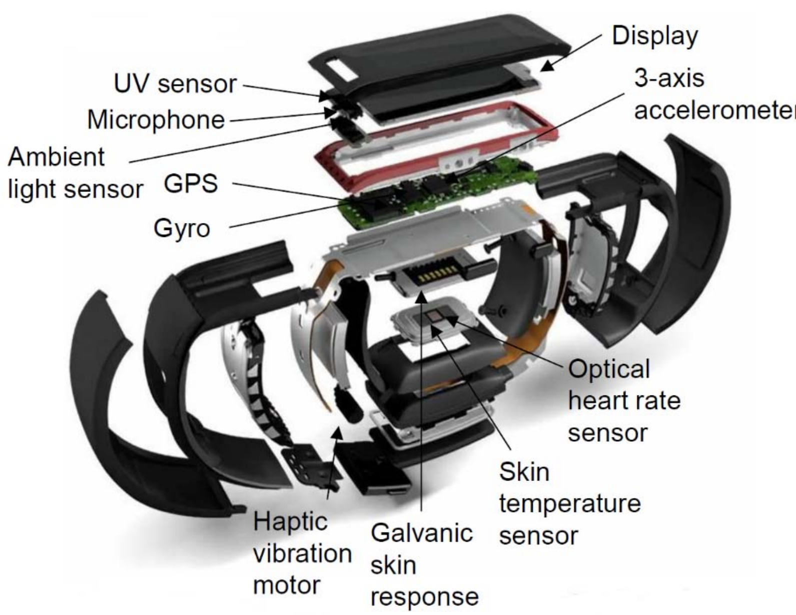

Figure 1. A case study in smart goods: The Microsoft Band. (Copyright 2015 Simplexity Product Development Inc.)

use. Power management solutions included the use of a low-power CPU and the development of software routines for minimizing sensor on-time. Common needs included the desire to further miniaturize common smart goods components (e.g. accelerometers, gyros, cameras and batteries), lower the power requirements of sensors, reduce the costs of positional measurement, reduce the amount of interconnect and increase the flexibility of interconnects. Ms. Shortell expected that future smart goods will move beyond sensing to manipulation of their environment which will bring needs for low cost, low power manipulators (e.g. motors, solenoids).

Brian Whiteside (President, VDOS Global) provided insights into the future of autonomous systems (Table 1). VDOS Global specializes in the use of drones for the inspection of on and off-shore petroleum refineries. Future needs included expanding bandwidth for communicating data wirelessly, increasing battery life and reducing the weight and cost of propulsion. Specific implications for manufacturing included the ability to use three-dimensional printing to not only “remove and replace” components but to build autonomous systems in a single printing cycle emphasizing the need for new platforms for electromechanical integration.

Table 1. A roadmap looking forward at the advancement of robotic systems over time.

	2008	2018	2028
Human Interaction	Requires Human Operator	Voice Commands	Multi-lingual
Swarm	Single Unit	Within Controlled Environments	Multi Domain Collaboration
Frequency	Restricted RF	Limited Frequency Agility	Multi Band Communications
Functionality	Single Mission Operator Directed	Programmed "Smart" Missions	Autonomous Behaviors
Operating Environment	Restricted Controlled Environments	Expanded Operating Limitations	All Weather Cross Domains
Payload	Single Mission Design	Integrated Sensors	Integrated Systems
Command and Control	Requires Human Operator	Operator Per Command Unit	Operator Per Region
Data Network	Limited by Technology Available	Smart Bandwidth Control	Bandwidth Independent
Endurance	Single Hour	Days	Years
Maintenance	Specialized Skill Maintenance	Remove and Replace	Self Repair
Artificial Intelligence	Sensor Data	Integrated Sensor and Mission Operation	Decision Making

Nikhil Deulkar (Director of Product Management, Impinj Inc.) discussed the opportunities and manufacturing needs of radio frequency identification (RFID) tags. Key new RFID markets include healthcare, pharmaceutical, automotive parts, food distribution and athletic competitions. One key challenge is the detuning of RFID tags within various environments. Another key challenge is the need for high speed manufacturing with Impinj shipping 5 billion RFID tags in 2015 alone. RFID inlays are produced by soldering an integrated circuit (e.g. a flip chip) to an antenna that has been previously printed, etched, stamped or vapor-deposited onto a paper or polyethylene terephthalate (PET) substrate. RFID inlays are then laminated between paper as labels or polymer films as cards or directly attached to items through the use of adhesives. Current bottlenecks in manufacturing production are the RFID printers used to encode the tag with data. Current efforts are being made in the industry to advance into graphene or silver-based antennae and to further simplify the interconnect. Future RFID platforms are moving toward enabling wireless sensing by attaching a front-end RFID tag to a back-end bus for connecting to sensors.

2.2 Smart Goods Manufacturing Needs

Bruce Angelis (Engineering Advisor, Itron) opened this session by discussing his insights on the needs of smart power meters. Itron designs, manufactures, markets, installs, and provides services systems and fixed communication networks for automatic and electronic meter reading. The company has been manufacturing smart meters, which collect, process, and transmit vital energy information, allowing utilities to leverage time-based rates, demand response, home networking and many other smart grid applications. However, key challenges facing the development of smart meters include the range of different communications technologies available (Optical probe, Wifi, Cellular), the possibility of outside interference (e.g. fraud, unauthorized/mass disconnection, energy diversion, behavior monitoring and denial of service) and the need for data security. Another challenge includes the need to extend battery life to twenty years requiring the integration of energy harvesting (Figure 2). Further, efforts are being made to leverage the use of additive manufacturing for fabricating sensors and devices. Of particular interest is the use of graphene for smart devices with primary interest in ultra-capacitors and low energy/high sensitivity sensors.

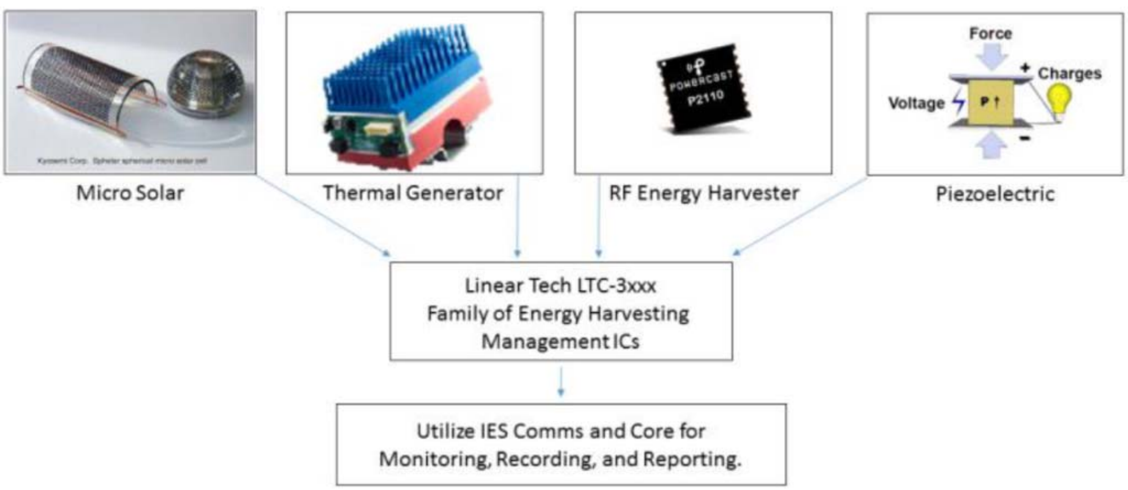

Figure 2. Energy harvesting research needs for smart meters (Itron).

Dr. Scott Johnston (Research Scientist, Boeing) talked primarily about the use of direct write (DW) technologies for use in structural health monitoring systems in aerospace applications. Specifically, the potential airplane applications of DW technologies included strain gauges, thermocouples, barcode tracking, data lines, power supply lines and antennae among others. At present, selected electronic components, such as switches, batteries and antennae are being printed on a wide variety of substrates using various DW technologies including ink jet, aerosol jet, screen printing, flexography, plasma-based thermal spray and fused filament. Integration of DW manufactured components into an aircraft is a very challenging process, which requires a long time (5 to 7 years) and a high caliber of testing and certification. However, DW applications are currently being applied and tested in many Boeing platforms. Areas of additional investigation or development include the need for:

1) conductor materials with performance close to current printed circuit board interconnects including the ability to sinter at low temperature with high adhesion;
2) substrate materials that are compatible with current aerospace materials and manufacturing environments;
3) DW equipment possessing higher levels of automation with minimal machine-to-machine variability; and
4) the ability to interconnect with traditional electronics.

Considerations for DW technologies within the aerospace industry include issues such as longevity, in-situ monitoring capabilities, nondestructive verification of viable traces and properties, and standard testing methodologies. Dr. Johnston also discussed material, electrical, and performance testing requirements of DW applications including the in-situ testing of thermal, adhesive, flexural, and fatigue requirements. The ability to implement DW applications on existing airplane materials without requiring new substrate materials is desired in order to minimize testing requirements.

Dr. Tolis Voutsas (Director of New Business Development, Sharp Labs of America) mainly talked about sensor technology development with an emphasis on manufacturing perspectives and needs. He acknowledged that we already use many sensors during our daily lives e.g. approximately 200 sensors per car, 100 sensors per smart home, 14 sensors per smart phone and 10 sensors per wearable device. Key sensors exist for motion, direction and heading, altitude, proximity and environment (pressure, temperature, etc.). New sensors are being advanced for biological sensing and user experience i.e. image, optical, microphone, etc. However, cost is a key constraint limiting the massive adoption of sensors as shown in Table 2. Three manufacturing options were discussed for sensor manufacturing including conventional Si-based, printed, and a hybrid of the two. Si-based technology currently is the platform for delivering low cost and high performance. Printed manufacturing cannot yet fabricate high performance circuits and systems. The combination of additive processes with the placement of Si chips (e.g. RFID tags) through hybrid manufacturing can be applied over larger areas with the advantage of Si performance where it is needed. Challenges in the use of three-dimensional printing include the need for higher performance materials. Other challenges discussed included battery life, applications designs, data management, and security.

Table 2. Cost dependency of manufacturing technologies for existing and potential sensor applications

Price point ($ per sensor)	Existing or potential applications for sensors	Manufacturing technology	
1.0	IoT applications fighting global hunger, pollution, healthcare and energy.	Conventional IC Hybrid	Exists/ Developing
0.1	Ultrahigh volume sensors applications for personal health, fitness and lifestyle.	Hybrid	Developing
0.01	Monitoring trillion shipped packages – UPS alone ships about 160 million/year.	Printing	Developing
0.001	Monitoring freshness and quantity of food in trillions of food packages sold every year.	Printing 3D printing	Developing/ Early stage
0.0001	Planting sensor arrays with plant seeds to monitor health and nutrient needs of every plant to optimize the crop yield.	3D printing	Early stage

Marco Micheletti (Senior Director of Operations, SNUPI Technologies) shared his views on smart goods manufacturing needs. SNUPI Technologies is a sensor and services company offering smart goods for home safety, security, and loss prevention. One example is the WallyHome^{TM} product which detects and alerts home owners of water leaks and high-levels of humidity within the home. The product offers a 10+ year battery life based on the use of an ultra-low power circuit and communications protocol. As a small company, key challenges discussed included the need to find investment for exploring advanced manufacturing capabilities and the ability to integrate many disparate engineering disciplines. For these reasons, the speaker advocated the need of a technology roadmap for smart goods which would help smaller companies, absent the marketing and product development capabilities of larger firms, understand the future direction of technology markets and investments. He also advocated for a consortium to help educate other industries about the capabilities available through IoT technology.

2.3 Digital Printing

Jim Stasiak (Distinguished Technologist, Hewlett-Packard) began by discussing the evolution of information technology from mainframes and personal computers to the World Wide Web and mobile computing to what HP now calls the Central Nervous System for the Earth, a highly intelligent network of sensors that can feel, taste, smell, see and hear. It is expected in the next decade that the number of sensors will grow to trillions per year or on average 150 new sensors per global citizen per year. Massive scaling in the production of sensors will be needed to meet this demand. The advantages of digital printing were lauded for being able to help meet this demand through embedding device and surface functionality. Digital printing strategies provide access to a broader array of materials likely needed to enable new approaches to sensing, energy storage and energy harvesting. The high materials utilization of digital printing will likely be important to minimize the cost of new materials development. Rates as high as 100 feet per minute are achievable in printing. Further, digital printing is programmable, enabling on-the-fly customization at high speed. Examples were given of companies developing a broad class of printable materials including organics, inorganics, nanomaterials and even biological materials. This broad class of films in printed format opens the opportunity for digital material science generating films and structures with gradient material properties. Graphene was singled out as an important material that is currently difficult to print. In general, much work is needed to improve the performance of printed functional materials.

Dave Tence (Jetting Development Manager, Xerox) discussed the wide variety of options for printing of electronics including gravure, flexography, inkjet and offset printing among many others. Inkjet printing methods include piezo, thermal, electrostatic and acoustic actuation. A key advantage touted for digital printing is the ability to replace six lithography steps with one inkjet step. The importance of the quality of inks was stressed in functional printing. Key factors include the stability and viscosity of the particle suspension as well as avoiding particle agglomeration. Challenges highlighted in jet-printing of electronic circuits included the substrate quality (e.g. hydrophilic, smooth), jetting reliability (e.g. drop-to-drop variation) and resolution. The control of Brownian motion and electrostatic forces was emphasized as crucial for improving resolution. Digital printing examples included patterning of selective emitters for solar cells, printed organic light emitting diode (OLED) displays and printed batteries among a variety of electronic components and circuits. Current efforts include work on combining 3D printing with the printing of electronic circuits to make functional electromechanical parts in one step.

Kurt Christenson (Research Physicist, Optomec) assessed the current state-of-the-art in IoT printing included gravure, offset, flexographic, screen and inkjet printing and traditional printed circuit board manufacturing techniques which have high throughput with limited material availability. Laser direct sintering (LPKF), needle dispense (Nordson), ultrasonic atomization (SonoTek) and aerosol jet printing were identified as 3D compatible but highly serial with low throughput. Aerosol jets, like piezo inkjets, can pattern a wider variety of inks, compared with thermal inkjets where the phase change can complicate printing. However, aerosol jets are continuous and can be focused down to a 10 µm diameter with a large depth of field (up to 5 mm) which is helpful for printing on contoured surfaces. A major part of the cost of a digital printing system is the motion control system. Electronics typically involve a two-axis system whereas 3D printing can involve 3, 4 or even 5 axis systems depending on the application. Yield problems can extend from poor uniformity of the ink. Research needs include standardized software tools to help implement electrical interconnection with printing platforms. Also, much research is needed in the development of new materials for improving performance at low cost. Near term focus will be on printed conductors, dielectrics and die attach materials, processes and requirements. Specific requirements included:

1) Conductors – curable at 80°C with the conductivity of silver; stability of ink
2) Dielectrics – high glass transition temperature that maintains stability when other materials are added
3) Die attach – absorb CTE mismatch with substrate; high thermal conductivity; cure on demand

Longer-term opportunities include materials development in support of strain, temperature, piezo, light, humidity, medical and chemical sensors as well as passive electrical components.

George Williams (President, Voxtel Inc.) discussed new additive manufacturing techniques for producing optical components. Optical technology is a $36 billion market including a wide variety of energy capture and information technology fields such as solar concentrators, photonics, cell phone cameras, microscopy and telecommunications to name a few. Optical components are typically the dominate cost within electro-optical systems such as cameras, high power laser assemblies and night vision goggles. The basis of optics (Snell's law) hasn't changed in hundreds of years. Advancing our thinking from a ray-tracing problem to a wave problem can lead to cheaper, more sophisticated optics based on materials with gradient optical properties. Efforts were discussed for using ink jet printing to embed high index of refraction (IR) nanomaterials within low IR polymers to produce gradient IR structures. Currently, a small research printer can take 25 hours to print a single one inch lens. However, the same technology could be setup to print 45,000 lens per hour using a commercial web printer. Further, opportunities to lower the cost of optical components include the ability to produce complex waveguides enabling the equivalent function of multiple optical components in one structure. Efforts are needed to develop the design tools based on wave propagation needed to optimize the design and manufacturing process.

The final presentation was offered by Dr. David Schut (General Manager, Shoei Electronic Materials, Inc.) who presented a new method for scaling up the production of colloidal nanomaterials, specifically quantum dots. A quantum dot (QD) is a semiconductor material typically below 10 nm in diameter whose excitons (electron-hole pairs of electrons that have jumped to a higher electron shell) are confined in all three spatial dimensions. Consequently, light emitted from a stimulated QD sees a blue-shift (photons decrease in wavelength) as the size of the nanoparticle decreases. Applications of QDs range from security taggants and biological probes to displays and lighting. Because the emission wavelength is tied to the size of the nanoparticle, it is critical to find ways to control the size of QDs at mass production scales. In continuous flow QD synthesis, convection heating can lead to thermal gradients between the wall and center of the tubing and a broadening of the QD particle size. Microwave heating can heat reagents and solvents from the "inside out" reducing the effect of the thermal gradient. Indium tin oxide and cerium oxide QDs were reported as being capable of being scaled to production volumes with standard deviations of 0.3 and 0.38 nm for 4.43 nm diameter and 2.94 nm diameter, respectively. This represents the state-of-the-art in scaling the production of nanomaterial colloidal chemistries that could be used in various digital printing applications.

In addition to the above presentations, Giovanni Nino (Composites R&D Director, Quest Integrated) discussed structural health monitoring of aircraft parts using direct write manufacturing. Sensors printed using aerosol jet technology was emphasized. One of the key requirements for such technologies is the low temperature sintering of the metallic traces. Such low temperature processing is necessary to make it compatible with composite aerospace structures. Reliability of the traces under thermomechanical loading is also highly important.

2.4 Electronic Design and Semiconductor Manufacturing

Serge Leef (Vice President of New Ventures and General Manager of the System-Level Engineering Division, Mentor Graphics) provided insights as to the directions and challenges of IoT technology. Examples of IoT applications included the use of wireless sensors on cows and smart lawn sprinklers. Measuring the vital signs of a cow enables the farmer to respond when the cow is sick or pregnant. Tracking the position of the cows over time enabled the farmer's to determine certain social behaviors which were linked to increased milk production. Design of these types of electronic systems is changing. Designs now include cloud-based infrastructure, web portals, mobile apps and even data analytics. In addition to electronics, controls and software, smart goods design must consider multi-physics, power and communications. Mr. Leef identified current limitations and challenges of IoT technologies including technology, monetization and security. The technology infrastructure is no longer a limiting factor as evidenced by the explosion of internet connectivity over the past ten years (Figure 3).[7] Building blocks are accessible. The cost of sensors continues to drop (Figure 4)[7] although there is still room for improvement in order to penetrate new markets. A huge opportunity exists to combine all these technologies in intelligent ways to create high-value, domain-specific user experiences. However, new business models are needed to figure out how to make money from the technology. Finally, IoT architectures offer many more places that hackers can invade our privacy. According to Cisco, the biggest concern with IoT technologies moving forward is security.

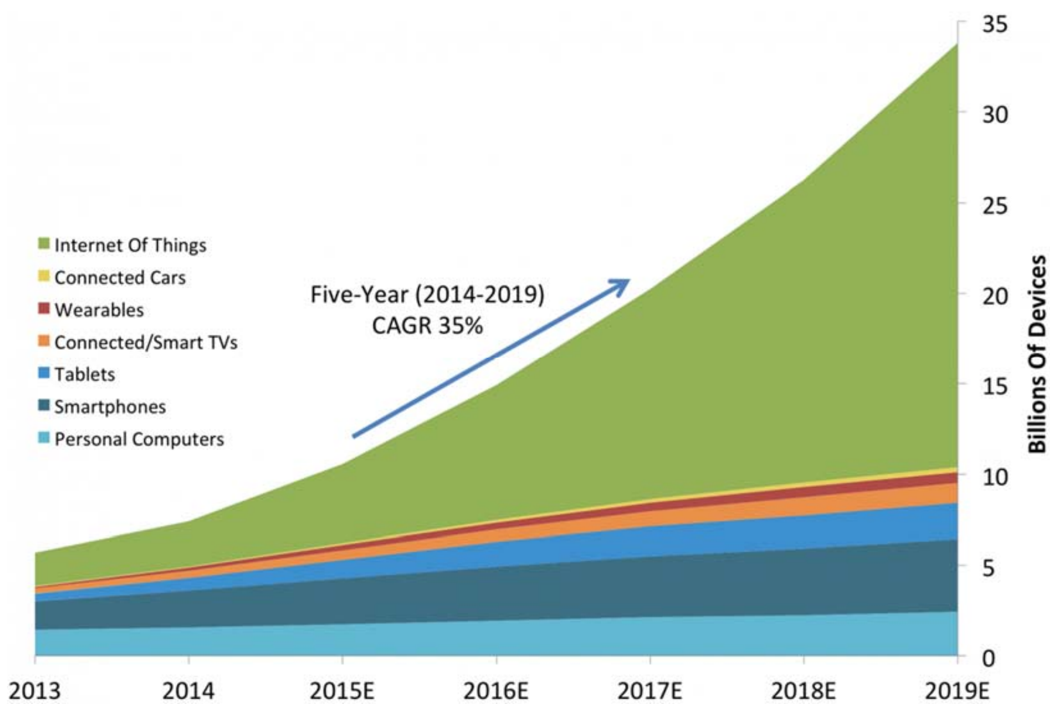

Figure 3. Number of devices connected to the internet as of 2014 (Source: Business Insider Intelligence Estimates).

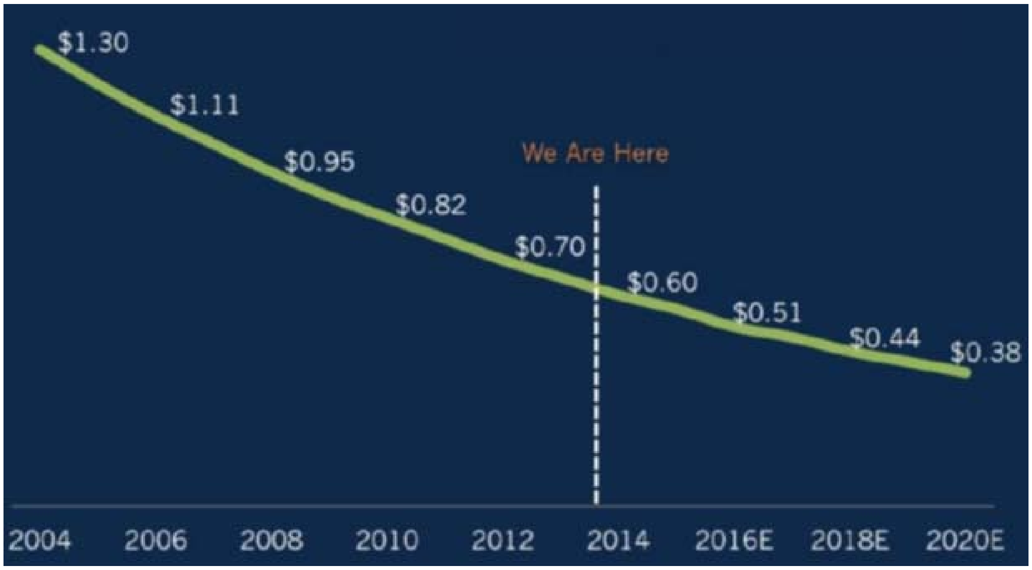

Figure 4. 2014 forecast for average sensor cost (Source: Goldman Sachs, Business Insider Intelligence Estimates).

Dr. Bill Cowell (Corporate Research and Development, ON Semiconductor) provided a summary of the Si-based technologies that are 'imperative' in making smart goods successful. Key growth drivers within ON Semiconductor are automotive image sensors and industrial image sensors. It was argued that the fastest way to dramatically reduce the cost of sensors (from several $/piece to a few cents/piece) is to integrate sensors on silicon. Figure 5 shows the perceived building blocks of the IoT

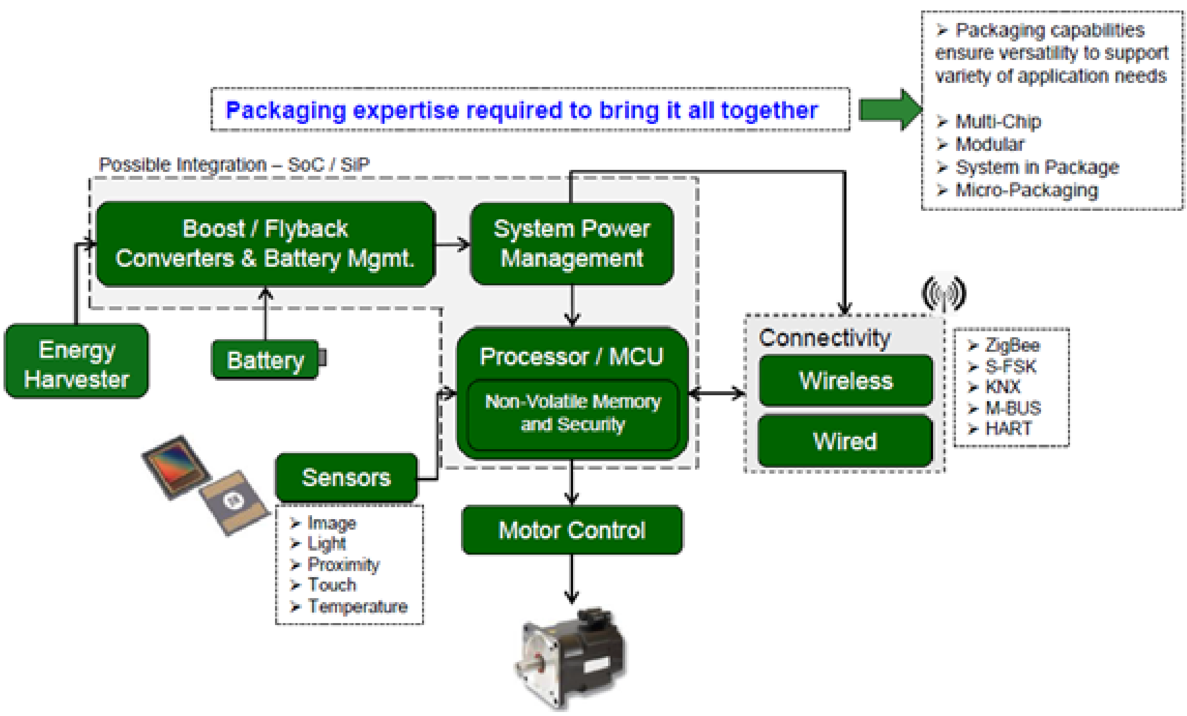

Figure 5. Si perspective of the building blocks for IoT (ON Semiconductor). The diagram identifies key research areas that can be addressed by academia to help industry address its critical problems.

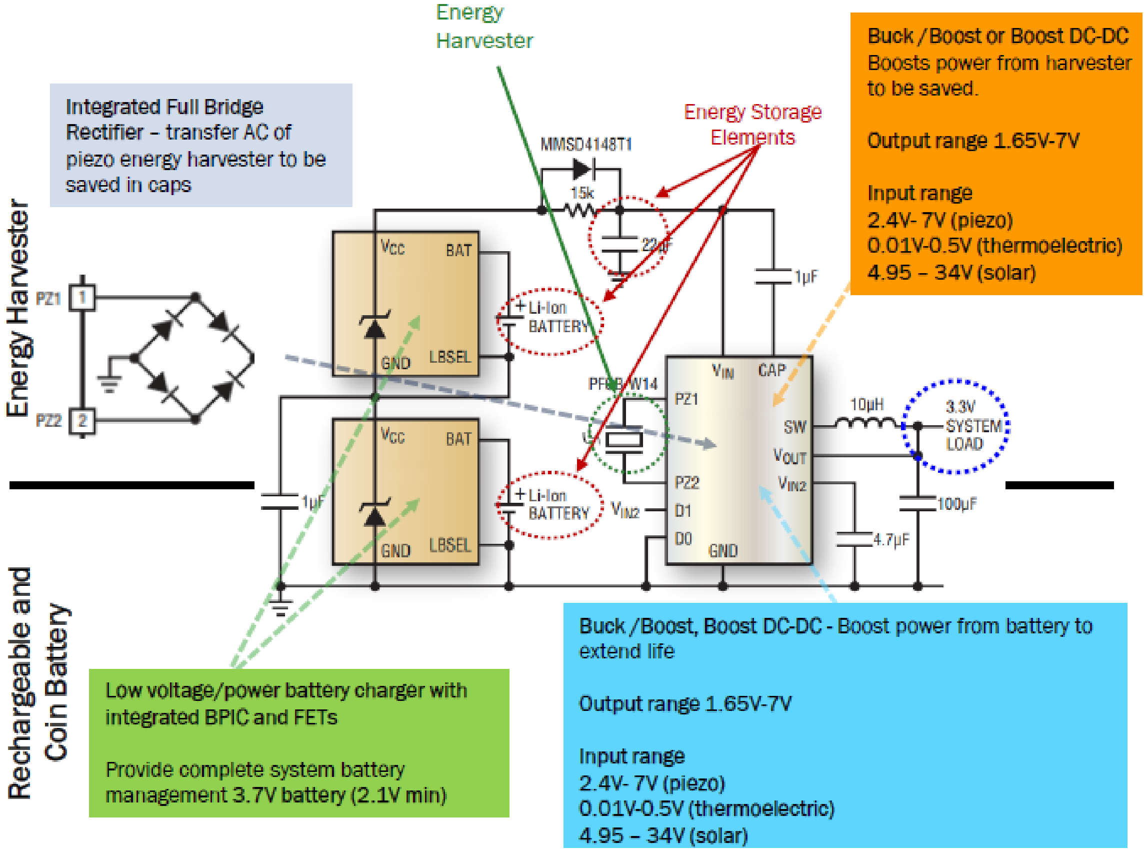

Figure 6. The Si-based power management areas for research (ON Semiconductor).

segment that will drive the future research needs in Si-based technologies. Research challenges in sensors include producing sensor elements compatible with CMOS. In automotive applications, the sensors with the corresponding electronics needs to bear high temperatures necessitating the use of high bandgap materials (to avoid leakage current at elevated temperature) such as SiC or GaN. Other challenges with sensors include scaling the infrastructure to handle the data volume generated by these sensors. Research challenges in power management stem from the electrical resistance heating of the circuit. Several Si-based logic/controller strategies can be used to implement power management strategies as shown in Figure 6 including the integration of energy harvesting and batteries. Challenges include managing multiple input and output levels/types. For example, the power from various harvesting devices can range from 0.01V (thermos-electrics) to >5V (solar). All of the power sources that operate at different voltages and time scales need to be manufactured such that the system power consumption is minimized. Also, research should include how to manage different storage devices operating at different voltages and time scales within a single smart device. Finally, several research challenges were discussed in the area of connectivity and controls with reference to the Si technology including power consumption, hardware integration, security and data volume. Standards are needed to help lower the cost of the smart goods.

James Hensel (CEO, Thermogen Technologies) discussed needs from an energy harvesting perspective. As pointed out, the IoT revolution will depend, among other things, upon the time between charging of the edge nodes i.e. smart goods, the “things” within IoT. As a result, the density of the energy storage device is highly important although battery energy density gains have been only incremental over the last 30 years. Consequently, in many mobile or remote applications, harvested energy is needed as a supplement to the batteries within the smart good. Although simple in concept, energy harvesting is challenging due to the 'quality' of energy (i.e. areal density and voltage) obtained as shown in Figure 7. While convenient, the harvesting of wireless radio frequency (RF) energy is highly inefficient providing low levels of harvested power. RF energy has restrictions on maximum intensity due to human health considerations. The use of solar energy as a source for energy harvesting is great due to the maturity of solar technology.

Energy Source	Harvested Power
Vibration/Motion	
Human	4 μW/cm^2
Industry	100 μW/cm^2
Temperature Difference	
Human	25 μW/cm^2
Industry	1–10 mW/cm^2
Light	
Indoor	10 μW/cm^2
Outdoor	10 mW/cm^2
RF	
GSM	0.1 μW/cm^2
WiFi	0.001 μW/cm^2

Figure 7. Surface power density from various harvested energy sources (Thermogen).

However, solar energy is highly time/space dependent. For example, the energy harvested by devices inside a building is about 1000x less than that outdoors. Further, the cyclical nature of solar power can be highly challenging to the electronic circuit. The research needs for solar are well documented involving efforts to increase photonic efficiency and are not specific to smart goods. Energy harvested by piezoelectric materials is an important emerging area. Such methods can be optimum for applications with continuous and consistent vibration frequency during operation such as found in athletic goods. The typical power obtained is in μW. Research challenges in these devices include integration into the device (e.g. need to capture the vibrational 'hotspots' to maximize the harvested energy) and increasing the energy density. The use of the Seebeck effect was discussed as a way to harvest energy using thermal gradients. Thermal gradients can be obtained from the human body itself. Several uses of thermoelectrics were discussed including medical monitoring, remote usage, fitness devices, and biosensors. Research innovations in thermoelectric manufacturing include the need to print high zT (thermoelectric figure of merit) particles on curved surfaces which could help move this technology from its infancy to large scale adoption.

Edoardo Gallizio (Product Marketing Manager, STMicroelectronics) discussed research needs in microelectromechanical systems (MEMS). The company has shipped over 9 billion MEMS-based sensors including light, noise, pressure, acceleration, and gyro. One of the key arguments regarding MEMs-based sensors was that the building blocks for this technology already exist. STMicroelectronics is building a STM32 Nucleo Ecosystem. This system is based on ST's 32-bit ARM Cortex-M based microprocessors. Development boards for all STM32 families are currently available to developers. STMicroelectronics has also developed boards with additional functionality including sensing, connectivity, power and analog. MEMS apps have also been made available by STMicroelectronics. Such innovations will make sensor technologies more available for smart goods applications and help expand the reach of the hardware in a manner similar to the way software proliferated through open source app development (Figure 8).

In the final session, Steve Brown (Innovation Strategist, Intel) provided a broad futuristic viewpoint

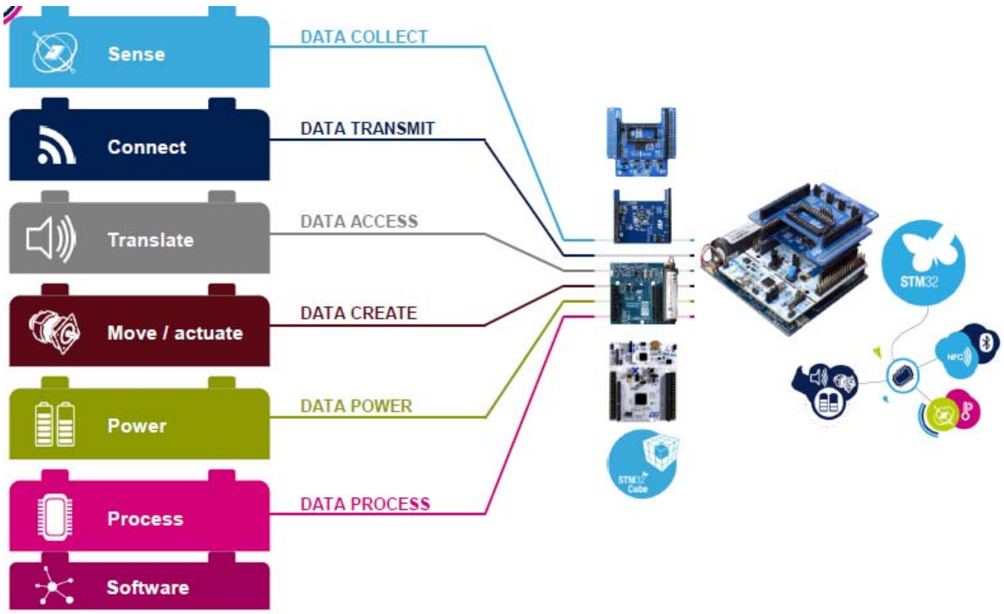

Figure 8. An open source 'modular' approach (STMicroelectronics). MEMS based sensors available to developers and consumers.

of the future of smart goods. First, "smart" is transformational and will require a different product perspective. For example, a product itself is only one part of the deliverable because it could be a service delivery mechanism with alternate ways to monetize it. In addition with improved development tools, everyone could become a developer, and non-technical creators may utilize other optimization metrics than efficiency. They may focus on experiences and may thrust human needs ahead of efficiency. Second, a computer should be able to see, hear, and interpret the world around it. With this capability, autonomous machines may be able to interface with humans safely. For example, if autonomous vehicles develop, transportation may be thought of as a service where people are packages that need to be moved from point A to B. This may lead to new sharing models moving from individual car ownership to municipal ownership where issues related to parking, licenses, insurance, etc. may disappear. Third, artificial intelligence and learning algorithms will be used in smart goods. Once devices are in the digital domain, we will all have the potential to be connected. 'Value' needs to be considered. For example, how much 'value' resides in the device verses the digital domain? How will scalability be addressed? Will smart lead to a more sustainable model because additional services may be readily added? Smart will be more than sensing; more than a product. Future users will be more accepting of letting robotics and smart systems do things for them, yet the majority of smart products today are centered on internet-connected sensors. The next wave of smart products need to be able to manipulate their environment based on their sensors thus resulting an increase in the blending of the human/machine world. Smart goods are evolving from simply pushing sensor data to the network to close-loop, autonomous control i.e. affecting another part of the device to take action.

3 Industry Needs

3.1 Development of Smart Components and Interconnects

Workshop participants consistently called for advancement of the components and interconnects required for developing smart goods. Persistent themes included reduced power, enhanced battery life, energy harvesting, smaller form factor and lower cost. Of particular interest was the desire to drive the costs of wireless sensing down in order to open up new markets for IoT. Key components of interest included sensors, batteries, ultracapacitors, energy harvestors, wireless antennae, passive electrical components, switches, optical components, motors and solenoids among others. Specific sensors mentioned included gyros, accelerometers, thermocouples, strain gauges and cameras as well as sensors for humidity and for detecting chemical and biological species and activity. Sensors and batteries need to further decrease in size to enable smart goods miniaturization. Current sensors consume significant power. Many of the components will have to operate in severely power-constrained environments, requiring improvements in energy efficiency and local energy harvesting.

Due to the relatively limited gains observed in battery technology over the past 25 years, industry is becoming more interested in harvested energy as an alternative source of power for smart goods. Energy harvesting platforms requiring advancement included radio frequency (RF), piezo and thermoelectric. Energy harvesting challenges requiring additional research included the inefficiency of RF energy harvesting, the need to match piezo to available vibrational frequencies and the need to develop high zT circuits on curvilinear surfaces using printing. The delivery of energy close to the sensor elements/IC chip can also reduce the inductive losses at high frequencies. The harvested power needs to reach mW/cm2 and beyond in order to have a practical impact for the smart goods.

Advances are also needed in reducing the complexity of and power consumption of interconnects. New form factors for circuits brought on by new smart goods applications will require flexibility and/or the need to print 3D interconnects. All of these developments must be advanced with key specifications in mind such as the durability and reliability of traces under thermomechanical loading. In-situ and nondestructive testing and monitoring of the thermal, adhesive, flexural and fatigue properties of circuits will be important for structural health monitoring applications. Standards development is needed to drive forward progress in the structural and electrical performance of materials used in smart circuits.

3.2 Sustainable Design and Manufacturing of High-Performance Materials

Workshop presenters consistently bemoaned the need for higher performance structural, electrical and optical materials. One promising area of research is the development of a digital material science that can predict the properties of gradient materials. Examples include the ability to optimize die attach materials capable of absorbing the thermal expansion between the die and substrate. Specific material needs for traces included higher electrical conductivity (e.g. silver) using low temperature (below 200°C) processes. Graphene was mentioned multiple times as a means for advancing antennae, ultra-capacitors and low-energy, high-sensitivity sensors. Efforts are needed to qualify substrate materials that conform to aerospace specifications (e.g. structural composites). Specific challenges with substrate materials include the need for smooth surfaces with good hydrophilicity. Challenges for dielectrics include higher glass transition temperatures and chemical stability in the presence of ink solvents. Due to the need to miniaturize many wearable applications, structural elements will require higher specific strengths moving structural elements away from polymers and towards metals. This highlights the need for higher precision metalworking including metal injection molding and advanced sheet metal forming techniques.

Several of the presenters agreed that a solution-based approach that avoided the need for vacuum deposition and lithography were key to low cost, energy efficient manufacturing. The ideal path from inks to functional materials, devices, and systems involves direct printing, patterning, and conversion with minimal energy input. Digital printing enhances materials utilization and, when combined with benign and sustainable functional material inks, addresses the grand challenge of environmental compatibility. Because smart goods are intended to be ubiquitous, they must be recyclable, compostable or biodegradable. This poses a challenge since available biodegradable metals (e.g. Mg) are difficult to handle and typically have higher electrical resistances.

An example of sustainable materials progress within the semiconductor industry has been the development of metal oxide resists as a means to advance extreme ultraviolet lithography.[8,9] For decades, silicon transistors have been patterned and processed by using polymer resists, but these materials have largely approached their fundamental resolution limits. By using new photosensitive, benign inorganic resists, patterning resolutions have been considerably extended to single-digit nm, materials utilization has been improved, and numerous processing steps have been eliminated. These materials and their chemistries have already been extended to digital printing.

3.3 Digital Printing

Digital printing technologies offer opportunities to transcend existing board-level strategies for component integration based on planar architectures reducing the cost and improving the performance of electronic assemblies. Robotically-manipulated printheads can enable the conformal printing of wireless sensors onto curvilinear surfaces, important for aerospace, trucking, and autonomous vehicle markets. Combined with the large evolving library of wet chemistries and post-processing techniques for producing functional films, digital printing can serve as an electromechanical integration platform for realizing a new generation of cheaper and smarter products.

Although inkjet and aerosol-jet methods are available to directly print materials on surfaces, key technical challenges remain in developing inks and processes that produce required functionalities at high resolution and high performance. Further, efforts are needed to demonstrate cost competitiveness and relax resolution limits compared with lithographic methods. Significant innovation is required in digital printing to enable unit processes that are fully compatible with roll-to-roll, multi-head processing at an industrial scale. Below are additional challenges that must be met in driving forward smart goods applications in digital printing.

3.3.1 Scaling of High-Performance Functional Materials

During the workshop, many promising examples were given of projects exploring the use of digital printing for smart goods. However, a current bottleneck is the need for the manufacture of specialty inks in sufficient volume for production. The point was stressed that opportunities exist to develop low cost, functional materials for digital printing applications in smart goods. The need for higher performing functional inks was emphasized by many of the speakers including the need for better colloidal stability. Graphene was singled out as an important material that is currently difficult to print.

Inks and wet chemistries are the central building blocks for cost-effective printing of the electrical components and circuits for smart goods. Inks are critical and developing inks with desired ink-substrate interactions simultaneous with weak ink-print head interactions is both critical and extremely challenging. The lack of specialty inks for printing of 3D objects with complex functionality was lamented. The need for inks that produce materials with desired electrical properties, either insulating, semiconducting, or metallic, with desired dielectric properties and proper adhesion between constituents was suggested as an area where significant research resources should be focused. The need to relieve stresses between constituents resulting from thermal processing is an additional challenge.

To address future markets in smart goods, significant developments are needed to scale functional materials capable of delivering the electronic, optical, and mechanical properties necessary to enable the required sensor, energy storage, and wireless functions. While nanoparticle materials for functional materials such as batteries and conductors[10,11,12,13,14,15] have been extensively studied, volume use of these materials requires scaling from milligram to kilogram quantities per day. Typical development scale synthesis is done in small batches where speed and efficiency is not important. However, for high volume production, continuous flow processes must be developed. Synthesis of nanomaterials using continuous flow microchannel reactors has attracted much attention in the past decade. [16,17,18,19,20,21] Advanced process control provided by microchannel reactors includes precise and rapid changes in reaction conditions, spatial separation of reagent introduction, and unparalleled temporal resolution. The reported microchannel reactors, however, are normally operated at relatively small flow rates (1-100 μL/min).

As highlighted at the workshop, one promising area of advancement is the use of continuous flow microchannel reactors to scale the solution-phase synthesis and functionalization of colloidal nanomaterials.[22] Microreactors have been used as a flexible and versatile platform for nanomaterials synthesis, assembly and deposition which will enable the integration of nanomaterials into heterogeneous systems.[23,24,25] Microreactors can also produce reactive fluxes of short-life, intermediate molecules for heterogeneous growth on a temperature-controlled substrate. A major challenge associated with the scale-up of functional materials includes the ability to characterize nanomaterials during high-rate synthesis to ensure proper size and shape distribution. The availability of high throughput, in-line diagnostic tools to monitor and control the process at kilogram quantities per day is difficult.

3.3.2 Conversion and Integration of Functional Inks

To produce these smart goods, it is critical that printable materials are available that are either directly useable or can be converted into functional forms without damaging the underlying product or surface. While direct printing of functional materials is the ideal path, conversion of the materials from some precursor form to a final functional material was often mentioned. Nanoparticle sintering methods that can create the traces at low temperature are of immense interest to the industry. For example, one of the key requirements for structural health monitoring in the aerospace industry is the need to print and sinter sensor elements and traces on these parts at low temperature (below 200°C) to avoid affecting the structural composite. Photonic sintering methods make use of the plasmonic resonance within many nanoparticles to allow sintering of nanoparticles at lower temperatures. The printing and photonic sintering of nanoparticle inks represents a low temperature path to form solid metallic conductors, antennae, passive electrical components and sensor elements among other components. Several companies highlighted the need to advance our understanding of photonic sintering as well as photonic curing, thermal sintering and plasma sintering.

An additional challenge highlighted at the workshop is the ability to integrate multiple functional materials e.g. combining energy harvesting piezoelectrics with conductive interconnects and battery materials all encapsulated for environmental protection. Most current work focuses on single materials, and issues such as incompatible chemistries and interfacial bonding are rarely addressed. A related challenge involves the ability to integrate the nanomaterials into heterogeneous systems without losing their functional properties. Efforts are needed to develop computationally-aided design, synthesis, and testing tools for functional inks to reduce the trial-and-error associated with integrating multiple materials and processes for smart goods.

3.3.3 Large-Area and Conformal Form Factors

The challenges of large area and non-planar, conformal form factors in the manufacturing of smart goods were highlighted in several presentations. Several applications required the integration of sensor elements, interconnects, antennae, power sources, and microprocessors within or onto complex 3D shapes (e.g. curvilinear surfaces). One example can be appreciated by considering the current development of the Google contact lens (Figure 9). Once developed, the contact lens will contain all of the components necessary to measure and transmit the glucose level in a tear drop to a smartphone or physician's office by using embedded wireless technology.

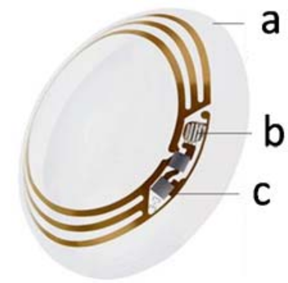

Figure 9. A Google smart device: a) contact lens that b) senses glucose levels and c) wirelessly transmits the reading to a smart phone.

At present, the integration of the sensing element with the radio-frequency antenna and ultra-low-power electronics involves conventional vapor deposition and lithography. Alternatives include fabricating a battery array on a flexible substrate[13], which enables conformal fitup to the 3D shape, but is limited to a restricted set of 3D geometries and possesses interfacial integrity issues that compromise reliability. Another way to integrate smart components onto 3D structures is to use existing 2D lithographic methods on a deformable substrate followed by mechanical folding to produce the desired 3D geometry. Batteries processed in 2D have been converted to 3D using origami principles.[26] Although several attempts have been made in academic research labs, fundamental technical issues, such as high stress and deformation in the areas of the folds have limited the function of the circuit. New solution-deposited materials and processes provide a means to pattern the circuit onto the contoured surface with less energy. Robotically-controlled digital printing can be used to directly print components on contoured surfaces, leading to 3D structures. Such a method is expected to provide considerable flexibility in adapting to geometric surfaces.

3.4 Silicon and Hybrid Integration

As pointed out in several presentations, the most immediate route to integrating low cost wireless sensing into everyday things will be through the use of silicon. High-performing digitally-printed materials do not yet exist in most applications. Solutions include the use of hybrid (silicon and printing) approaches to integration over large, conformal areas. Silicon will be used in the near future as the computing and sensing element for smart devices. Future manufacturing research needs to include the integration of the sensing elements with CMOS-based devices. Sensor manufacturing techniques will include MEMS-based and ink-based printing methods. Future research should address the science and engineering of materials and methods directly compatible with integrated circuit metallization, reliability under thermomechanical stresses, and 3D-printed passive and active components over metallization.

3.5 Design Tools

Several presenters mentioned the need to develop design tools to enable the development of smart goods. In many cases, the development of a smart good requires the simultaneous development of a cloud-based infrastructure with web portals, mobile apps and data analytics. As highlighted above, smart goods design must consider multi-physics such as thermomechanical stresses as a result of electromechanical integration. Power management and communications are becoming more important for designers. The need to develop optical components requires the ability to design based on wave propagation. Further, the use of digital printing and 3D printing technologies to develop interconnects requires the development of new algorithms for optimizing performance, energy efficiency and cost as well as the software drivers to run new digital printing and 3D printing platforms.

3.6 Data Volume Considerations in Large IoT Networks

A consistent concern expressed throughout the workshop was the need to develop a network environment that is able to handle the massive data volumes that will be generated by smart goods. The computing architecture will include diverse gateways, smart goods and protocols which must interconnect. Standards for connectivity, communications and security will all be needed to drive the industry forward. Data volumes will require network standards and improved reliability in data capture. Battery life will be extended based on system architectures and networking protocols. Multiple input and output voltages and timescales will require on-chip mixed signal processing. Of paramount importance is the issue of cybersecurity in the face of increased connectivity. Issues of privacy, fraud, disconnection, diversion, behavior monitoring and denial of service were all discussed. Data storage will need to evolve to minimize the computing overhead generated by the massive data (petabytes) collected through IoT networks. Improvements in visualization techniques will be necessary to extract accurate information and conclusions from the data captured by IoT networks. Finally, as software applications evolve, smart goods will need to be able to adjust and tune themselves to allow rapid deployment of new use cases and functionalities.

4 Recommendations

The emerging smart goods industry has a common set of research and educational challenges which must be overcome in order to advance a multi-trillion dollar IoT industry. A technology and business consortium process bringing smart goods companies together with the electronics industry is the most practical and impactful approach to solving smart goods problems and developing IoT networks for the future. Workshop attendees consistently acknowledged the need for consortia activity to pool resources in critical research areas and expressed the value of this consortia activity in different ways. Large companies expressed the value as coming together to better understand emerging smart goods markets and common areas for the development of standards. Small companies expressed the need for understanding future technology roadmaps indicating the direction of future markets and investments. Product and technology roadmaps can help to identify the technical challenges to realize the next generation of smart goods that meet consumer and industrial needs. Further, it was stated that an industry-university research consortium could help small companies access the talent and facilities needed to integrate emerging smart goods manufacturing platforms into their businesses. Small companies have a great need to integrate many different engineering disciplines in advancing smart goods. These capabilities can be provided within an ecosystem of university and industry partners working together to advance common causes. Such an ecosystem will help small companies to attract investment in manufacturing and further help educate other industries about the opportunities available through smart goods and IoT.

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