U.S. Department of Energy's Advanced Manufacturing Office Workshop on Integrated Sensor Systems for Manufacturing Applications

First in a series focusing on Semiconductor R&D

1. Introduction and Background

1.1 Workshop Purpose

On January 25th and 26th, the Department of Energy's Advanced Manufacturing Office will host the first in a series of workshops focused on different topics related to semiconductor R&D. The first workshop focuses on integrated sensor system R&D for manufacturing applications. As AMO is housed within the office of Energy Efficiency and Renewable Energy, the workshop will address not only industry needs and R&D opportunities, but also impacts that improvements in sensor systems can have on energy efficiency and greenhouse gas production. The first day of the workshop will feature industry perspectives and discussions on industry needs. The second day of the workshop will seek attendee input on current and emerging integrated sensor system technologies. The information gathered at this workshop will inform AMO's future portfolio of R&D investments, provide perspective on trends, drivers, and challenges for next-generation semiconductor sensor system applications, and help the stakeholder community understand the opportunities on the horizon.

The workshop will be focused on the development, manufacture, and integration of the semiconductor hardware that makes up integrated sensor systems for use in manufacturing applications. This includes a) sensing materials and platforms, b) integrated circuit devices and architectures for collecting, processing, and communicating the data from the transducer to manufacturing information systems, c) methods, materials, and devices that supply energy and condition power for sensor node operation, and d) hybrid and monolithic methods for integrating these technologies into a sensor module. Of particular interest are manufacturing innovations to make sensors more affordable, more reliable and more energy efficient. The focus of this workshop is on technology and approaches for manufacturing the integrated sensor systems rather than approaches for integration of sensors into application networks and control systems.

1.2 Background

The focus of this workshop—integrated sensor systems—supports AMO's goal to reduce all manufacturers' energy use. Low-power-consumption sensor systems are critical for both cutting manufacturer's energy use and for reducing the energy impact of integrated sensor systems over their product lifetime. AMO analysts estimate that deployment of smart manufacturing—for which sensors are a necessity—could reduce up to 15% of all manufacturer's energy use. Based on this strong alignment of the goals of sensor system users, manufacturers and AMO's mission, AMO believes that it could play an important role in integrated sensor system R&D for manufacturing.

Semiconductor devices, fabrication methods, and system integration approaches provide foundational technology for integrated sensor systems from sensing platform, signal- and power-conditioning, to communicating. The semiconductor industry itself is critically important to the US economy both directly and as a key enabler for many other industries. The continued growth and globalization of semiconductor production and use has made energy efficiency R&D a top priority for the semiconductor industry.

According to an October 2020 Congressional Research Service (CRS) report, the semiconductor industry in 2019 had $424 billion in sales with the U.S. accounting for roughly half. The CRS divides the industry into 4 segments with microprocessors and logic accounting for 42%, memory for 25%, analog electronics for 13% and sensors (grouped with optoelectronics and discretes — referred to as O-S-D) accounting for 20% or nearly $85 billion in sales. Thus, the sensor industry — so vital to manufacturing — is also a major component of the semiconductor industry. In subsequent workshops we will address other AMO-relevant components of the semiconductor industry including devices that underpin the microprocessor, memory, and analog electronics market segments.

The semiconductor industry's energy efficiency priority aligns with AMO's goal to reduce the lifecycle energy use of manufactured products. Furthermore, the end of the era of scaling and the increased diversification of application spaces has opened the semiconductor industry to a much wider range of materials and technologies with commercialization potential, providing many more topic areas for collaborative, public-private R&D. The SRC-SIA[1] R&D Decadal Plan has a sensor system efficiency-related goal as one of its top five priorities for government R&D. Just as with the Decadal Plan, we address sensing first.

2. Sensor Systems in Manufacturing

Today, sensor systems not only monitor processes but they can actively track process variables such that automatic, real-time adjustments can be made to greatly increase precision, reduce equipment down-times, and even enable a far greater degree of material and product customization.

For multiple reasons, sensors are necessary for manufacturers to stay internationally competitive. Sensors enable automated control systems used by manufacturers to achieve higher precision, lower costs, improved performance, and increased energy efficiency of existing operations. Sensors are also critical to obtaining the large amounts of data required by machine learning enabled analysis methods that continue to improve our understanding of materials and processes, and in turn our ability to control them.

As they improve in accuracy and range of capability, sensor systems are integrating more complex sensors and more sensor nodes. Therefore sensors themselves, as well as larger sensor platforms, need to become more energy efficient and be able to either store or harvest energy, in order to avoid the additional burden of integrating hard-wired connections to provide energy to each sensor. While the integrated sensor systems themselves use additional energy, with the ever-increasing energy efficiency of chips and advanced communication technologies this energy is a tiny fraction of that saved with ultra-reliable processes needed as the manufacturing environment becomes even more complex and competitive.

2.1 Types of Sensors

There are vastly different sensor devices to sense intrinsically analog phenomena and elements such as motion, sound, magnetic fields, light, liquid, gas, and materials. The type, use, and installation all depend

[1] SRC is the Semiconductor Research Corporation and SIA is the Semiconductor Industry Association.

on the specific application and environmental operating conditions the sensor will experience. Furthermore, sensitivity, selectivity, and stability are all carefully considered when choosing a sensor system. Generally, sensors commonly used in manufacturing systems can be broken down into four categories: light/motion, temperature, pressure and chemical/environmental as shown in Table 1.

Table 1: Summary of sensor type, application in manufacturing, and general strengths and weaknesses

Sensor Type	Sensor Technology	Uses and applications in Manufacturing	Strengths	Challenges
Light and motion	MEMS	Motion sensor in automated packaging	Small form factor	Low accuracy
	RADAR	Inspection of parts	Unimpeded by objects	Expensive
	CMOS	Imaging and inspection of parts	Mature manufacturing technology and supply chain	Low sensitivity, susceptibility to noise
Temperature	Thermo-electric	Temperature probe	Robust, simple construction	Low precision
	Resistive	Temperature probe	High accuracy	Limited temperature range
	Phase change	Energy storage	Auto-regulating	Limited temperature range
Pressure	Piezoresistive	Pressure gauge	Robust and stable	High power consumption
	Dielectric elastomer	Active vibration control	Lightweight	Electromechanical instability
	Optical	Harsh environments	Immunity to electromagnetic radiation	Susceptible to vibrational and acoustic interference
Chemical/ Environmental	Metal Oxide Nanowire	Gas sensors	High sensitivity	Reproducibility and reliability of MOX nanowire growth
	CNT/ Graphene	Biosensing	High sensitivity and selectivity	Reproducibility and reliability of CNT and graphene growth
	Electro-chemical	pH monitoring	Mature technology	Limited lifetime

The type, use, cost, and installation of integrated sensor systems all depend on the specific application and environmental operating conditions. Sensitivity, selectivity, and stability also must be carefully considered when choosing a sensor system.

2.2 Materials and Devices Used in Sensor Systems

All sensor technologies rely on specific transducer materials to respond to the external environment, and supporting semiconductor devices transform those responses into data to transmit it elsewhere. Environmental concerns –what is measured and what is withstood – often drive which materials are used in sensors. Silicon-based sensors are a versatile, cheap, and mature technology used in many sensor systems but cannot be used in most harsh environments. Other semiconductors such as SiC and other wide-bandgap materials are more robust and can be used in some harsh environments with proper coatings. Novel 'beyond CMOS' materials such as new carbon allotropes (carbon nanotubes-CNTs and few or mono-layer graphene) have been extensively researched but commercial adoption has been low, partially due to the difficulty in creating cost effective and scalable fabrication processes.

Challenges in materials development for advanced sensors include: precise understanding of the material growth process, scaling up to a manufacturing scale, and the stability of the sensor material. Table 2 summarizes a few example materials used in sensor systems and their sensitivity, selectivity, and stability.

Table 2: Comparison of sensitivity, selectivity, and stability of example sensor materials

Active Sensing Material	Applications in sensors	Sensitivity	Selectivity	Stability
Silicon	Optical imaging	Low	Fair	Fair
Platinum	Temperature probe	High	High	Fair
Phase change materials	Temperature probe and energy storage	High	High	Low
Dielectric elastomer	Vibration control	High	Low	Low
Quartz	Thickness gauge	High	High	Low
Functionalized CNTs	Chemical sensing	High	High	Fair
Metal Oxide Nanowire	Chemical sensing	High	Low	Fair

The supporting devices integrated with sensing materials to transform their input are equally as important and becoming increasingly complex. Given the ubiquitous nature of digital data computation and communication using CMOS-based devices, sensing materials are often chosen due to their compatibility with silicon. Innovations in advanced packaging and heterogeneous integration make these compatibility restrictions less important and provide increased options to transform the sensor data locally. Digital and analog hardware have reached capabilities where significant computational power can be located within the sensor module, which can greatly reduce the latency and increase the efficiency of the integrated sensor systems.

3. Stakeholder Needs for Sensor Developments

The workshop will feature panel discussions focusing on the needs of different types of stakeholders. We have chosen to separate the supply chain for integrated sensor systems into three major categories, each described here.

3.1 System Developer / Integrator Needs

This section focuses on needs of manufacturing operation control developers that use integrated sensor systems. This may include systems that integrate multiple types of sensor inputs, for example a chemical process monitoring system that uses temperature, pressure, and gas sensors. Needs related to hardware components that comprise individual sensor nodes are addressed in a later section. As noted in the introduction, the next generation of integrated sensor systems requires a true systems approach to design and fabrication. To quote Gordon Moore's celebrated 1965 paper "It may prove to be more economical to build large systems out of smaller functions, which are separately packaged and interconnected." Major integration issues for manufacturing applications include:

- Communication and cybersecurity standards for maintaining data integrity throughout the generation, transformation, and transmission process;
- Co-design of hardware and software, across sensor nodes and centralized analysis and operations infrastructures;
- New lower-cost sensor modules not currently possible with conventional manufacturing & assembly techniques;
- Self-configuring, and self-calibrating sensors that report uncertainty in addition to data value to enable future transactive controls;
- Incorporating methods to monitor sensor performance and maintain overall system performance as individual sensors degrade or fail; and
- Next generation sensing platforms that incorporate sensor components from the nano- to the meso-scale

The vision is to rapidly and efficiently manufacture and assemble integrated systems with orders of magnitude more heterogeneity, complexity, efficiency, and speed relative to current approaches. In achieving this future, a range of issues must be addressed, including achieving interconnection standards across sub-components, as well as achieving compatibility between new sensor modules on legacy technology or equipment.

3.2 Facility Owner/Operator Needs

Modern facilities are highly automated, running nearly 365 days per year, 24 hours per day. To meet these performance demands, sensor systems for manufacturing must be highly reliable and robust. Manufacturing enterprises continually face the challenge of balancing the pressure to operate uninterrupted and the need to further update and refine their manufacturing facilities/equipment to remain globally competitive.

Advances in sensor technology needed for facility owners/operators may include:

- Active monitoring and dynamic adjustment of material or product properties;
- Real-time reduction of defects through process variable changes;
- Monitoring and tracking film/ layers properties during additive manufacturing;

- Increased ability to withstand harsh environments such as high temperatures, high pressures, and corrosive conditions; and
- Predictive maintenance to prevent equipment degradation and/or failure.

With the rise of the IoT networking, the facility owner may also need to consider cybersecurity as well as costs, feasibility, and compatibility.

3.3 Sensor system equipment developer needs

Manufacturing processes for sensors are distinct from those for other electronic products as sensor system equipment developers must have knowledge of operational environment when selecting materials for advanced sensor systems. Integrating novel materials, designing energy efficient circuits, and constructing advanced sensor modules to retrofit onto older manufacturing equipment are just some items sensor system equipment developers must consider. Hence, the potential for advancement is highly dependent on application requirements especially for manufacturing where requirements are diverse and often extreme. It is similarly challenging to develop approaches to enable integration of the multiple diverse technologies required for an integrated sensor system.. Key performance requirements that differentiate what types of sensing or sensor technologies are best for a particular application include:

- Sensor specifications, such as sensing range, sensitivity, power consumption;
- Computational capability, driven by needs for timeliness of sensor data and availability of centralized computational capabilities, and bandwidth of sensor node communication;
- Environmental considerations such as operating temperature, noise, vibrations, and corrosivity;
- Data communication requirements, including environmental requirements to maintain signal integrity (e.g. RF and Sensor coupling effects, shielding); and
- Compatibility with adjacent manufacturing equipment.

Sensor equipment also must be cost effective and meet size, weight, and power (SWaP) requirements. These different conditions can dramatically impact system design. For example, an inertial MEMS sensor must be mounted on the moving element of the system, which is quite different than a gas sensor where packaging must have a physical opening for gas to interact with the sensing element.

4. Research Pathways to Address Industry Needs

The four research topics detailed below will serve as the four breakout sessions of the workshop. Facilitators will encourage discussion of challenges and open research questions to push integrated sensor system technology forward. Discussions in the breakout sessions should aim to address the needs of each of the stakeholder groups described in the previous section, as well as energy impacts.

4.1 Sensing Platforms and Materials

This breakout group will focus on novel materials, designs, and processes for new sensing platforms. Widespread acceptance of novel materials in sensor technology depends on how cost competitive they are to current technology. One of the outstanding challenges in novel sensing materials is the process variability in manufacturing them. Growth processes for many novel materials are still cost-prohibitive and have a propensity for high defect count, resulting in unstable sensor performance. Precise understanding of growth physics for many novel materials is not well understood, and current growth methods often have a high defect count, which results in unstable sensor performance.

Additionally, new sensor materials and platforms in harsh environments will require minimum standards of material stability and robustness to be met. In addition to materials development, a new suite of testing and measurement capabilities will be required to validate new sensors materials and platforms under harsh operating conditions.

Some guiding questions to consider before the workshop include:

- What are the main hurdles needed for wide-spread adoption of a new material in sensor technology?
- What transducer platforms and materials might operate effectively in manufacturing sensor environment (e.g. temperature, humidity, vibration, radiation, corrosive)?
- What sensor platforms might enable the transducer to be integrated with the sensor system monolithic or hybrid module) to enable expanded sensing capability and cost-effective sensor production?
- What are some promising sensor materials and structures that are not commonly used today? For each:
    - Why is it not commonly used? Manufacturing cost? Low-performance? Narrow application?
    - Would any of them provide advantages over widely used sensors today?
- How might embedded energy, operating energy, industrial emissions and lifecycle material use be improved for integrated sensor systems?
- What are integrated sensor system manufacturing challenges that could be addressed by new technologies or approaches?

4.2 Energy sources and power conditioning

This breakout group will focus on the energy sourcing and power conditioning needs and the challenges associated with novel sensor systems technology. As sensor systems are deployed in diverse contexts, the methods to provide their operating power can be quite complex. Self-powered wireless sensor systems are preferred in many applications, as it is often infeasible to provide utility power connections, to easily access sensors while in use, or to service batteries regularly.

Integrated sensor systems require electric power at appropriate voltage, current and quality levels to power logic, transceivers, sensors, actuators, and numerous other functions, and therefore power conditioning considerations become critical as sensor systems become more complex and heterogeneous. Sensor systems are likely to become more complex in their operations, as well as their hardware, and so considerations of power conditioning requirements for different modes of operation (e.g. sleep, low-power, high activity, etc.) are also important.

Enabling sensors to be self-powered requires them to harvest energy from their surrounding environment and in many cases store it for some period of time. Sources of energy for harvesting include of sun- or artificial light, waste and ambient heat, mechanical vibrations, and radio frequency sources.

Together, energy harvesting technologies, power conditioning circuits, and energy storage enable sensor systems with energy autonomy (requiring no connection to traditional energy infrastructure and possessing the ability to operate for long durations without any human intervention). Ongoing research in each domain strives to increase conversion efficiencies, identify suitable materials with low environmental impact, and to increase power densities and decrease device footprints.

Some guiding questions to consider before the workshop include:

- What are trade-offs between powering integrated sensor system through local energy harvesting, power delivery to sensor, and/or local energy storage (battery/capacitor)?
- What energy harvesting technologies are best suited for which manufacturing environments?
- What approaches might provide effective power delivery to various manufacturing sensing locations/environments?
- What discrete or integrated power electronics technologies might enable effective integration with transducer and communication technologies?
- What discrete or integrated power electronics technologies might operate effectively in manufacturing sensor environment (temperature, humidity, vibration, corrosive, etc.)?

4.3 Digital and analog circuits and communication

This breakout will focus on the computing and communication needs of sensor nodes, to enable their integration into larger systems for manufacturing applications. Advanced sensors today do far more than simply transmit the signal directly from the sensing component. It is vitally important for energy efficiency and industrial emissions reductions that the electronic control systems have appropriately high performance (fast, accurate). This ensures effective operation of the sensor system – including control of sensor platform functions, power conditioning control, and signal conditioning– . The likely increase of real-time sensing and control to further optimize industrial processes requires a corresponding increase in data computation and communication.

Some guiding questions to consider before the workshop include:

- What is the best balance between edge and cloud computing for optimal performance and stability, and is there a preferable balance in a manufacturing setting?
- What are the requirements for analog electronics and highly accurate analog to digital conversion systems at the interface between sensors and controllers?
- What integrated communication technologies are best to provide effective communication from the sensor location (RF, optical, wired, etc.)?
- What are trade-offs between higher performance local computing and higher bandwidth communication?
- What technologies and platforms might provide cost effective integration of analog and digital electronics and communications at the sensor location?
- What electronics and communication technologies might operate effectively in manufacturing sensor environment (e.g. temperature, humidity, vibration, corrosive, radiation)?

4.4 Monolithic and hybrid sensor system integration

This breakout will discuss emerging technologies and R&D opportunities around integrating individual sensor components with other supporting components to achieve the capabilities needed from a sensor node for a given application.

Appropriate sensor system integration is paramount for proper functioning of the sensor system. It is understood that advanced sensor systems will be embedded in new manufacturing equipment but it is crucial for advanced sensors to be able to retrofit on older equipment. Primary concerns with retrofitting older equipment with advanced sensor systems are compatibility and communication of the sensor and tool. Furthermore, a host of new sensing systems across a manufacturing facility will require component, architecture, and communication standards to be formalized to address compatibility concerns.

Some guiding questions to consider before the workshop include:

- What module and integration technologies and approaches would enable modules to be retrofitted onto existing manufacturing equipment/facilities?
- What are advanced approaches for integrating components into and integrated sensor system (on-chip or within hybrid module)?
- What integration technologies might operate most effectively in extreme manufacturing sensor environment (temperature, humidity, vibration, corrosive, etc.)?

What technologies and approaches might enable integrated sensor systems to address a wide range of applications to ensure economy of scale for sensor system productions?

5. Conclusion

As manufacturing industries become more digitized, sensor systems and the data they provide are critical enablers of productivity, efficiency, international competitiveness, and supply chain security. AMO recognizes that continued work is needed to ensure that advances in integrated sensor systems keep pace with the innovations in other aspects of advanced manufacturing. Smart manufacturing systems are only as good as the real-world data they have access to.

In order to appropriately address R&D opportunities, AMO must have accurate, timely understanding of the state of both research and industry. Tradeoffs between performance and cost must be clearly defined for a wide range of applications and solutions optimized. Integrated Sensor System research opportunities then need to be prioritized to maximize smart manufacturing competitiveness. This workshop is a key part of AMO's ongoing process of listening, understanding, and prioritizing. AMO will be drafting a summary report of the workshop in the coming weeks.

We invite you to bring your perspective on these and other questions, during the upcoming workshop.

6. References

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