Organic Electronics for a Better Tomorrow: Innovation, Accessibility, Sustainability

A White Paper from the Chemical Sciences and Society Summit (CS3)

San Francisco, California, United States

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ABOUT THE CHEMICAL SCIENCES AND SOCIETY SUMMIT (CS3)

The annual Chemical Sciences and Society Summit (CS3) brings together some of the best minds in chemical research from around the world and challenge them to propose innovative solutions to society's most pressing needs in health, food, energy, and the environment. This unique gathering boasts an innovative format, aiming to set the course of international science, and rotates each year among participating nations.

Organic Electronics for a Better Tomorrow: Innovation, Accessibility, Sustainability summarizes the outcomes of the fourth annual 2012 CS3, which focused on organic electronics. Thirty top chemists and other scientists from China, Germany, Japan, the United States, and the United Kingdom assembled in San Francisco to identify major scientific and technological research challenges that must be addressed to advance the field of organic electronics in a way that best meets societal needs. This white paper presents an international view on how the use of organic materials in electronic devices can contribute positively to creating a more innovative, accessible, and sustainable electronic world.

The CS3 initiative is a collaboration between the Chinese Chemical Society (CCS), German Chemical Society (GDCh), Chemical Society of Japan (CSJ), Royal Society of Chemistry (RSC), and American Chemical Society (ACS). The annual symposia are supported by the National Natural Science Foundation of China (NSFC), German Research Foundation (DFG), Japan Society for the Promotion of Science (JSPS), UK Engineering and Physical Sciences Research Council (EPSRC), and U.S. National Science Foundation (NSF).

This white paper was prepared by science writer Leslie A. Pray, PhD, in consultation with the American Chemical Society, and reviewed by 2012 CS3 participants.

FOREWORD: LETTER FROM THE 2012 CS3 DELEGATION CHAIRS

We live in an electronic world. Economic, health, and national security rely on and are positively impacted by electronic technology. However, the resources and methodologies used to manufacture electronic devices raise urgent questions about the negative environmental impacts of the manufacture, use, and disposal of electronic devices. The use of organic materials to build electronic devices may offer a more eco-friendly -- and affordable -- approach to growing our electronic world. Moreover, and some would say more importantly, organic small molecules, polymers, and other materials afford electronic structures unique properties impossible to obtain with silicon alone, creating untold potential for novel functionality.

However, the field of organic electronics is in its infancy with respect to devices on the market. Realizing the vision of organic electronics as a more innovative, accessible, and sustainable approach to growing our electronic world will require overcoming key research challenges.

Chemists, physicists, and other scientists and engineers engaged in organic electronics research representing China, Germany, Japan, the United Kingdom and the United States gathered in San Francisco in September of 2012 to discuss their visions for the future of organic electronics and to offer research recommendations for advancing the field in a way that will maximize its potential positive impact on society.

Our hope is that our research recommendations will be recognized and considered by science policy-makers worldwide – not just in the field of chemistry, but also in the broad range of other scientific and engineering disciplines that impact organic electronics research and development. While chemists play a vitally important role in synthesizing and transforming the organic “building block” materials that make organic electronics possible, our vision for the future will not be realized without the cooperation of physicists and other scientists and engineers from across academia and industry.

Xi Zhang
Chair, China Delegation

Peter Bäuerle
Chair, Germany Delegation

Takuzo Aida
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EXECUTIVE SUMMARY

Chemists, physicists, and other scientists and engineers are synthesizing and manipulating a wealth of new organic materials in ways that will change the way society interacts with technology. These new materials create novel properties impossible to replicate with silicon, expanding the world of electronics in ways unimaginable until now. *Organic Electronics for a Better Tomorrow: Innovation, Accessibility, Sustainability* examines where organic electronics are today, where chemical scientists envision the field is heading, and the scientific and engineering challenges that must be met in order to realize that vision.

Already, consumers are using organic electronic devices, such as smart phones built with organic light emitting diode (OLED) displays, often without even being aware of the organic nature of the electronic technology in hand. The Samsung Galaxy line of OLED-based smartphones occupies a major share of the global smartphone market.

Potential future applications are enormous and untold. Organic materials are being studied and developed for their potential to build devices with a flexibility, stretchability and softness ("soft electronics") not afforded by silicon or any other inorganic materials – that is, electronic devices that bend, twist, and conform to any surface. Imagine a smartphone that folds like a map. Devices made with organic materials also have the potential to interface with biological systems in ways not possible with inorganic materials. Imagine an artificial skin with a tactile sensitivity approximating real skin that can be used to treat burns or add functionality to prosthetic limbs. Potential applications of organic electronics span a broad range of fields, including medicine and biomedical research, environmental health, information and communications, and national security.

Because of the lower cost and higher throughput manufacture of organic-based electronic devices, compared to today's silicon-based devices, organic electronics also promise to expand the use of electronic technology in resource-limited areas of the world where supplies are limited or the necessary infrastructure is lacking. Already, organic solar cells are being installed on rooftops in African villages that lack access to standard on-grid electricity, providing rural populations with a safer and cheaper alternative to kerosene.

Not only do organic materials promise more innovative and accessible electronic technologies, they also promise more sustainable electronic technologies. The potential for greater sustainability extends across the entire life cycle of electronics, beginning with the use of materials that are synthesized, rather than mined from the earth, and ending with potentially biodegradable or recyclable devices. It is not just the devices themselves that promise to be more eco-friendly than silicon-based electronics, but also their manufacture.

Today, the major focus of research and development in organic electronic is on three main types of existing applications: displays and lighting, transistors, and solar cells. The vision for the future is to move beyond these already existing applications and explore new realms of electronic use. The intention is not that organic electronics, or any specific type of organic electronics, will replace silicon-based electronics. Indeed, organic molecules and materials are often used in combination with silicon materials. Rather, the vision for the future is one of an expanded electronic landscape – one filled with new materials that make electronics more functional, accessible, and sustainable.

The 2012 CS3 participants articulated three visions for the future of organic electronics:

1. ***Organic electronic devices will do things that silicon-based electronics cannot do, expanding the functionality and accessibility of electronics.***
2. ***Organic electronic devices will be more energy-efficient and otherwise "eco-friendly" than today's electronics, contributing to a more sustainable electronic world.***
3. ***Organic electronic devices will be manufactured using more resource-friendly and energy-efficient processes than today's methods, further contributing to a more sustainable electronic world.***

Arguably the greatest overarching challenge to realizing these visions is creating electronic structures at industry-level scale with high yield and uniformity. This is true regardless of type of material or application. While the electronics industry has already achieved enormous success with some organic electronic structures, such as those being used to build OLED-based smartphones, most organic electronic structures are being synthesized on only very small scales, with reproducibility in the formation of many materials being a major problem. Until wide-scale industry-level production is achieved, future visions for organic electronics will remain just that – visions.

CS3 participants identified four major scientific and technology research challenges that must be addressed in order to achieve high yield and uniformity.

1. ***Improve controlled self-assembly***. Chemists need to gain better control over the self-assembly of organic electronic molecules into ordered patterns to ensure that the structures being assembled are reproducible. Improved controlled self-assembly requires a better understanding of the electronic properties of organic materials, especially when those materials are in contact with other materials (i.e., their interfacial behavior). Only with that knowledge will researchers be able to predict how organic electronic materials actually perform when integrated into devices, and only with those predictions will engineers be able to develop industry-scale synthetic processes.

2. ***Develop better analytical tools***. Better analytical tools are needed to detect and measure what is happening with respect to structure and chemical composition when organic materials are assembled and integrated into electronic structures and devices, ideally at every step along the way. These

tools need to be non-destructive, non-invasive, and high-speed.

3. ***Improve three-dimensional (3D) processing technology***. Many organic electronic structures can be assembled on flexible substrates using existing printing technologies. However, fabrication of 3D organic electronic structures with the same precision achievable with two dimensional (2D) printing technology remains a major challenge to reliable high-throughput manufacturing of organic electronic devices.

4. ***Increase multi-functionality of organic electronic devices.*** As chemists gain better control over the synthesis of organic materials, they and their engineering collaborators will be able to build increasingly sophisticated optoelectronic[1] and other devices with multiple functions. However, in order to fully realize the multifunctional capacity of organic chemistry, chemists need to broaden their research focus beyond "charge-carrier" transport (i.e., electrons and holes, respectively) and gain a better understanding of optical, magnetic, thermal and other properties.

While chemical scientists have been critical drivers of organic electronics and will continue to serve an essential role in expanding the landscape of organic electronics, other areas of scientific and engineering research are equally essential. Chemists, physicists, material scientists and other scientists and engineers must combine their expertise and work together to realize the full potential of organic electronics. Multidisciplinary research and training programs that bring together scientists and engineers from different fields of knowledge, as well as from different sectors of activity (i.e., academia, industry, government), will facilitate the collaborative effort needed to meet these scientific and technological challenges

[1] An optoelectronic device is an electronic device that produces or interacts with light. Organic optoelectronic devices already in the marketplace include organic light-emitting diodes (OLEDs) and organic solar cells.

INTRODUCTION

We live in an increasingly electronic world, with computers occupying a central part of our lives. In 2012, there were an estimated 30-40 processors per person, on average, with some individuals surrounded by as many as 1000 processors on a daily basis. While silicon electronics has solved many of the challenges associated with our increased use of electronics, there are limits to what silicon can do. Chemists are synthesizing a wealth of new organic materials for use in electronic devices that create novel properties impossible to replicate with silicon. These materials hold tremendous promise to expand our electronic landscape in ways that will radically change the way society interacts with technology. *Organic Electronics for a Better Tomorrow: Innovation, Accessibility, Sustainability* examines where organic electronics are today, where chemical scientists envision the field is heading, and the scientific and engineering challenges that must be met in order to realize that vision.

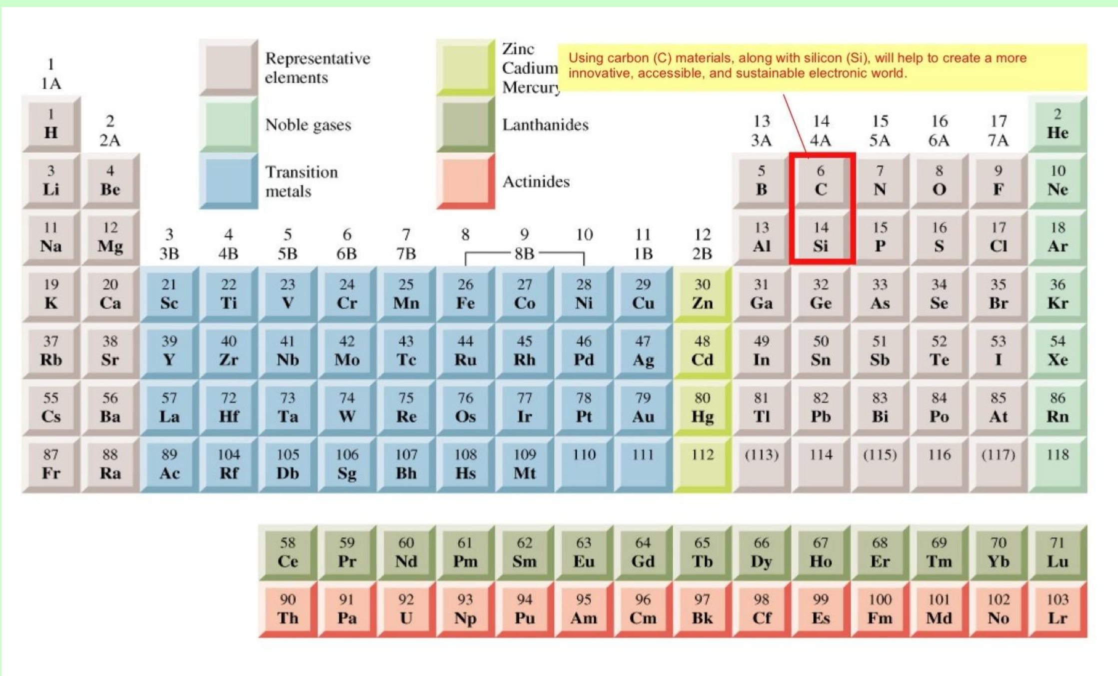


Figure 1. From silicon to carbon. Silicon (S) and carbon (C) may be in the same family on the periodic table, but the properties they confer on electronic structures are anything but similar. Source: Jin Zhang.

Our Electronic World

While Moore's prediction that the number of transistors per chip would double every 18 months has more or less borne true, many scientists and engineers speculate that such growth is not indefinite and that a limit will be reached. While the miniaturization of silicon-based electronic structures has created an electronic world full of affordable, high-performing devices, still there are things that silicon-based electronics cannot do and will never be able to do. Organic materials, whether used in combination with silicon or not, hold the potential to expand our electronic world in ways unimaginable when Moore made his prediction some forty years ago.

Organic Materials for Electronics: A Primer

Chemical scientists work with several different types of organic materials in their research on electronics. These materials include small molecules[2] and polymers; fullerenes, nanotubes, graphene, and other carbon-based molecular structures; ensembles of molecules and molecular structures; and hybrid materials. They use these materials to build electronic structures and then integrate those structures into electronic devices. Many of these devices are early-stage prototypes, with major scientific and engineering challenges still to be surmounted before the prototypes can become real-world products. But others are already commercial realities, some being used on a widespread basis. For example, both small molecules and polymers are being used in the manufacture of OLED displays (e.g., TV and cell phone displays), solar cells, and transistors.

Polymer electronic materials in particular are one of the most active areas of organic electronic research, so much so that polymer-based organic electronic devices (and device prototypes) have significantly improved in performance over the past decade. For example, power conversion efficiencies (PCEs) of organic photovoltaics (OPVs) have increased from 5 percent in 2005 to > 10 percent in 2012. This increased performance is being driven by newly developed polymers with improved solar light absorption properties and superior mobilities. For organic transistor devices, charge-carrier mobilities[3] have increased from less than 0.01 centimeter squared per Volt-second (cm^2/Vs) in 2000 to greater than 1.0-3.0 cm^2/Vs in 2010. Some high-performance polymers exhibit as great as 5.0-10.0 cm^2/Vs mobility. Increasing charge-carrier mobility and thereby improving device performance even further poses one of the greatest challenges to the field of polymer electronics. An additional concern is that most reported charge-

[2] "Small molecule" is used in this White Paper in reference to organic molecules that are smaller than polymers, that is, both monomers and oligomers.

[3] "Charge-carrier" mobilities characterize how quickly charged particles move through a semiconductor.

carrier mobility values are for isolated and optimized systems and that mobility decreases when such systems are integrated into actual devices.

Carbon-based materials hold tremendous promise for the field of organic electronics because carbon comes in so many different forms, with a wealth of chemistries associated with those different forms. Fullerenes were the first carbon nanostructures produced, in 1990. Carbon nanotubes were produced shortly thereafter and then, in 2004, graphene was isolated. Carbon-based materials are being researched and developed mostly to create bendable, or rollable, electronic displays, solar cells, and other flexible devices. But they are also being investigated for their charge storage potential, conducting ink capacity (e.g., graphene-based inks are being investigated for their use in security packaging such that tampering breaks the printed circuit, sounding an alarm), and other applications. Multi-walled carbon nanotubes are being produced on a large scale (e.g., Hyosung, Inc., South Korea, produces more than one ton daily) and being used as electrically conductive plastic parts in ATM machines and other devices. But single-walled carbon nanotube production has yet to be scaled up to an industrial level.

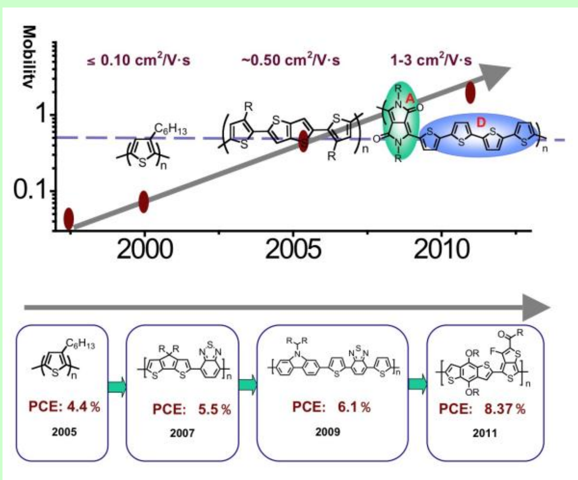


Figure 2. Improved electronic performance in devices made with organic polymer materials, 2000-present. Top: Continued research on polymer materials has led to a steady increase in charge-carrier mobilities in organic field effect transistors (OFETs) (top) and increased photoconversion efficiencies (PCEs) for organic solar cells (bottom). Source: Lixiang Wang.

Single Molecule Organic Electronics: Illusion or Insight?

The field of single molecule organic electronics has made great strides since the world's first single-molecule organic electric device, the molecular rectifier, was envisioned in the mid-1970s. Researchers have learned how to alter structures of single molecules in ways that change conductance and other electronic properties. However, they still face daunting challenges to integrating those structures into macroscopic circuitries and into actual usable devices. The field is still occupied largely by academic researchers, with some scientists speculating that the notion of single-molecule electronics is but an illusion. Or at least the notion of a single-molecule computer is but an illusion. There are other potential applications. Because single molecule devices involve constricting all electrical current to flow through a single molecule such that anything perturbing the molecule is sensed by the device, single molecule devices could make for fantastically sensitive sensors. At the very least, while no single molecule electronic device has yet become a commercial reality, research in the field has yielded a wealth of new knowledge about the chemistry of organic electronics. By shrinking electronic systems down to a single molecule, chemical scientists are learning about charge movement through molecules, molecule-electrode interfacial activity, and other phenomena that help to understand how organic molecules function as electronic device components.

ORGANIC ELECTRONICS TODAY

Organic electronics is not a new field. Electronic devices made with organic materials already have multiple applications and have been widely commercialized, mostly in display (e.g., smart phone displays), photovoltaic, and transistor technologies.

Organic Display Technology

Organic light-emitting diodes (OLEDs) are built from one or more layers of organic and hybrid material (either small molecules or polymers) sandwiched between two electrodes (e.g., indium tin oxide), all on a plastic or other substrate. Unlike other display technologies, which require a backlight in order for the display to show, OLEDs generate their own light via electroluminescence and therefore they do not require backlights. They require less power and are more energy-efficient than backlight-dependent display technology.

OLEDs are already widely commercialized in many Samsung and other smartphone models. The Samsung Galaxy line of OLED-based smartphones occupies a significant portion of the global smartphone market. Additionally, Samsung and LG Electronics have both announced forthcoming launches of large-screen OLED TVs. The new TVs are expected to not only be more spectacular than today's TV technology, with respect to crisper colors and sharper contrasts, but also lighter, thinner, and more energy-efficient.

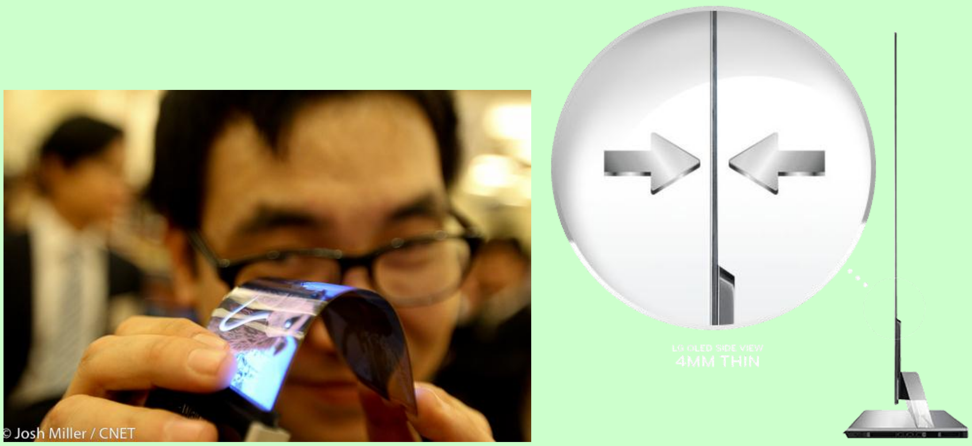


Figure 3. Building better OLED displays. Left: Samsung has announced the near-future release of a foldable smartphone built with a flexible plastic OLED display; the phone can be folded to an eighth of its size. Source: Josh Miller/CNET. Right: Both Samsung and LG Electronics have announced near-future releases of 55-inch, 4-mm thick OLED display TVs. Source: LG Electronics.

Organic Photovoltaics (OPVs)

Organic photovoltaics (OPVs), or organic solar cells, are generally viewed as one of most exciting near-future applications of organic electronics, not necessarily as a replacement for silicon-based PVs, rather because of unique ways that OPVs can be used due to their flexibility, large-area coverage, and low cost. However, a key challenge to expanding solar cell production is industry-scale reproducibility.

The harvesting of solar energy relies on chemical and physical interactions at the interfaces between materials that harvest the light and materials that transport electrical current. These interfaces can be either organic-organic or organic-inorganic. As chemical scientists gain a better understanding of the processes that occur at these various interfaces, engineers will be able to build interfacial structures that drive energy conversion even more efficiently than today's devices do. While current OPV technology boasts conversion efficiencies that exceed 10 percent, reaching even 12 percent, some researchers predict organic solar cells will reach 15-20 percent efficiency.

Transistor Technology

Transistors are considered a fundamental "building block" of modern electronic devices, either amplifying signals or operating as on-off switches. There are many different types of transistors. Most organic transistors are organic field-effect transistors (OFETs). OFETs have several unique properties not shared by silicon transistors, most notably their flexibility. Because OFETs can be manufactured at or near room temperature, they enable the manufacture of integrated circuits on plastic or other flexible substrates that would otherwise not withstand the high-temperature conditions of silicon-based device manufacture. OFETs are also highly sensitive to specific biological and chemical agents, making them excellent candidates for biomedical sensors and other devices that interface with biological systems.

With the synthesis of new organic materials, chemists have improved charge-carrier mobilities for small-molecule OFETs from < 1 cm^2/Vs in 2000 to 8-11 cm^2/Vs today. Initially, the improved mobilities were obtained only under very clean conditions in ultrahigh vacuum chambers. However, recent results suggest that high-performance OFETS can be fabricated using simple and relatively inexpensive techniques, such as solution processing. By 2020, with the synthesis of even more advanced materials, mobilities could increase to as much as 100 cm^2/Vs. As with small-molecule OFETs, polymer OFETs have also increased in performance, with typical mobilities increasing from about 0.01 cm^2/Vs in 2000 to greater than 1.0-3.0 cm^2/Vs in 2010.

Despite this progress, several challenges remain before OFETs will become a widespread commercial reality. For example, only recently have scientists demonstrated the fabrication of thermally stable flexible OFETs. High thermal stability is prerequisite to integrating OFETs into biomedical devices; otherwise they won't survive high-heat sterilization.

From Chemist to Consumer: OLED Displays

The touch-screen display on the Galaxy S series of smartphones manufactured by Samsung Electronics is testament to the tremendous progress already achieved in the field of organic electronics. Most other smartphones, as well as computers, tablets, high definition television sets and other similar devices, use liquid crystal display (LCD) technology, an organic-inorganic hybrid electronic technology that requires a backlight to produce the image displayed on the screen. But the Galaxy S uses a technology that doesn't require a backlight: organic light-emitting diode (OLED) display technology. OLEDs emit their own colored light to produce images. Because they do not need backlights, OLED displays are thinner and lighter than LCD displays. They have other potential advantages as well, including flexibility, with efforts underway to develop and commercialize foldable OLED display smartphones and other devices. Other similar devices are emerging in the marketplace. For example, the PlayStation (PS) Vita, a handheld game console, boasts a 5-inch touchscreen OLED display.

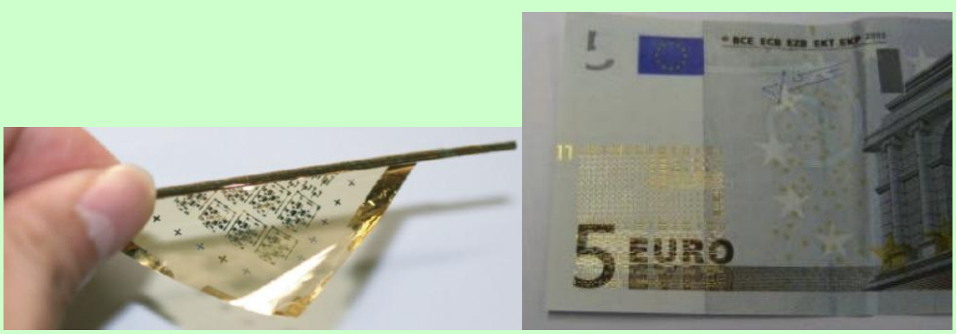
These and other future OLED devices exemplify how fundamental research in organic chemistry, including the chemical synthesis of new organic materials and the characterization of those materials, can evolve into mass production of a novel technology. To advance the technology even further, chemists, physicists, and other scientists are collaborating to develop yet more advanced organic materials with even better electronic and other properties. Researchers predict that OLED lighting technology, including large-area (white) lighting, will become a commercial reality within the next five years.

Organic Chemists Outsmart Counterfeiters

Organic thin-film transistors (OTFTs) create a wealth of innovative opportunities for electronic applications. For example, scientists are fabricating OTFTs on banknote surfaces as an anti-counterfeiting feature. Not only are OTFTs thinner than even the thinnest silicon-based transistors (less than 250 nanometers [nm], compared to 20 micrometers [µm]), making it possible to embed them into the banknote paper, they also operate at a low enough voltage (about 3 volts [V]) that they do not cause any damage to the paper. Most importantly, because they are made with organic materials, the OTFTs are flexible enough that they can withstand repeated crumpling, creasing, and sharp folding.

OTFTs on banknotes exemplify how research on organic materials, in this case with German and Japanese chemists collaborating on the use of very thin polymer substrates as the starting material for fabrication of the OTFTs, can eventually lead to development of a novel device otherwise impossible to build with silicon-based electronic structures. Flexible organic thin-film transistors are also being studied and developed for their potential applications in a wide range of other types of bendable devices, such as rollable solar cells.

Figure 4. OTFTs make for good anti-counterfeiting features in banknotes. Left: Polymer substrate with functional OTFTs wrapped around a cylinder with a radius of 300 µm. Source: Sekitani et al. 2010. Right: Banknote with OTFTs embedded as a counterfeiting feature. Source: Zschieschang et al. 2011.



ORGANIC ELECTRONICS: THE VISION FOR TOMORROW

As chemists continue to synthesize and functionalize new and improved organic materials for use in electronic structures and devices, the field of organic electronics will likely expand in ways not even imaginable today. Some applications have already been realized, like the OLED smartphones and the low-cost solar cells being installed on rooftops in rural off-grid communities in South Sudan. Some, like the ultra-thin OLED TVs and foldable smartphones, are expected to be launched in the near future. Others, like electronic skin that mimics human skin with its tactile sensitivity, will take longer. Still others cannot be foreseen. The potential future applications are many and varied, spanning across multiple fields: medicine and biomedical research, energy and the environment, national security, communications and entertainment, home and office furnishings, clothing and personal accessories, and more.

Not only will the field of organic electronics yield innovative applications not even imaginable today, it also has the potential to make electronics production, use, and disposal more environmentally sustainable. Chemists and their colleagues are seeking ways to make organic electronics – both the devices themselves and the manufacture of those devices – more resource-conservative and energy-efficient than today's silicon-based electronic world.

CS3 participants identified three overarching visions for the future of organic electronic materials:

Vision #1: Organic electronic devices will do things that silicon-based electronics cannot do, expanding the functionality and accessibility of electronics.

Organic materials give electronic devices unique properties impossible to achieve with silicon-based electronic structures, enabling a broad range of innovative "out-of-the-box" applications. These properties include sensing, biocompatibility, and flexibility.

Because of the unique structural and functional variation of organic materials, arguably one of the greatest areas for innovation in the field of organic electronics is in sensing -- that is, the use of electronic devices to sense chemical or biological substances in the environment, in or on the human body, in food and water, or elsewhere. For example, chemical scientists envision diagnostic sensors that detect changes in biomarker levels (e.g., changes in glucose levels in people with diabetes); environmental sensors that detect toxins in food or water; and national security sensors that detect trinitrotoluene (TNT) or other explosives. Biosensors are among the most exciting near-future applications of organic electronics. As just one example, chemical scientists envision biosensors that not only detect glucose levels in people with diabetes, but also actually dispense the appropriate dose of insulin at the right time.

Not only are organic electronic structures more chemically compatible with biological systems than silicon-based devices are, they also enable a flexibility, stretchability and mechanical "softness" not possible with silicon. Together, these properties create the potential for innovative bio-electronic sensors that can conform to the curvature and moving parts of the human body.

Flexible organic thin-film transistors (OTFTs) are being used to develop electronic skins with tactile sensitivity and other sensing capabilities. The hope is that this technology will be used to build artificial skin for burn patients, prosthetics with tactile capabilities, and other touch-sensitive devices impossible to build with silicon-based electronic structures. In the very distant future, some scientists wonder whether such "robotic skin" might even be capable of detecting emotional states.

The flexible ("soft") nature of carbon-based and other organic materials makes them mechanically compliant not just with biological systems, but also with a wide range of other types of curved surfaces and movable parts. Scientists envision flexible displays, solar cells, sensors, and batteries with applications in automobiles, clothes and other fabrics, and machinery. As just one example, the Smart Forvision Concept Car has been proposed as a futuristic car that would boast, among many other weight and energy-saving features, a transparent organic solar cell roof for fueling the car's climate control system and OLED lighting.

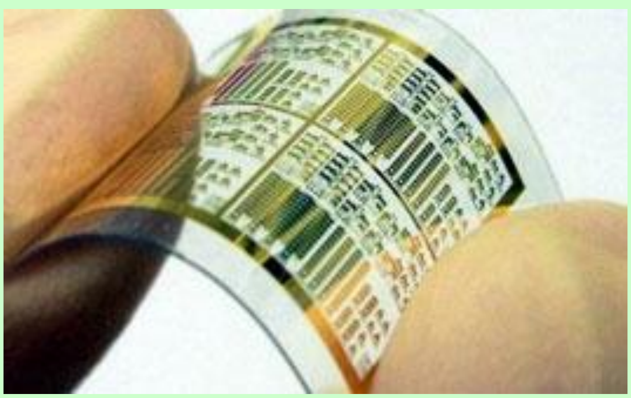


Figure 5. Flexible organic semiconductors. Circuits fabricated on a flexible and transparent organic substrate. Flexibility is an important advantage of organic materials. Source: Sun et al. 2011.

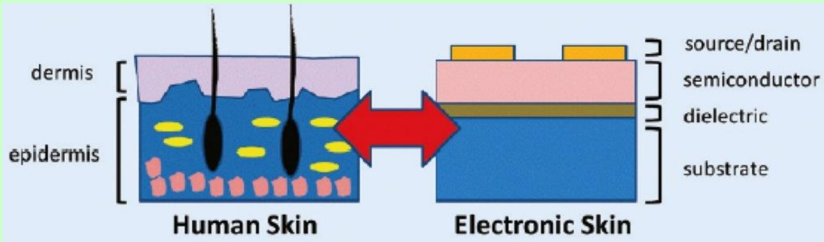


Figure 6. Using organic materials to create artificial skin. Scientists are using organic field-effect transistor (OFET) architecture to build electronic material that mimics human skin. The electronic skin is a stretchable two-dimensional (2D) array of tactile sensors that collect environmental signals and translate those signals into information. Source: Sokolov et al. 2012.

Vision #2: Organic electronic devices will be more energy-efficient and otherwise "eco-friendly" than today's electronics, contributing to a more sustainable electronic world.

As chemical scientists and engineers continue to improve the synthesis and characterization of organic materials for use in electronics, their hope is that the use of such materials will lead to more energy-efficient electronic displays and lights, solar cells, transistors, and other electronic devices. For example, while organic solar cells are already very energy efficient, with an energy "payback" time of less than six months, their energy efficiency needs to continue to improve in order to succeed as a widespread technology in places like Northern Europe where long spells of sunlight are but a dream.

As with organic solar cells, chemical scientists and engineers hope to improve the energy efficiency of organic transistors as well, in the case of OFETs by lowering their operating voltages. Lowering OFET operating voltages is more than an energy efficiency goal. It will also allow chemists to take advantage of the biocompatibility of OFETs; high-voltage FETs generate fatal levels of heat.

In addition to increasing energy efficiency, as chemists continue to study and improve their understanding of the electronic behavior of organic materials, engineers will be able to build devices that last longer and that are recyclable or perhaps even biodegradable.

Off-the-Grid Organic Electronics: Making Electronics More Accessible

While we live in an increasingly electronic world, access to that world is limited. An estimated 1.3 billion people have no access to electricity, with many people relying on kerosene, batteries, or diesel-fueled generators. Because of their cheaper manufacturing costs, organic electronics promise not only to change the way people use technology, but also to expand the use of technology to populations without access to on-grid electricity. For example, in 2011, Eight19, a Cambridge, UK-based company dedicated to the development and manufacture of organic solar cells, launched a program called Indigo to provide off-the-grid solar-powered energy to rural markets. The pay-as-you-go program eliminates the high initial purchase cost of solar power systems (customers pay for the system with scratch cards on a week-by-week basis until they own the product outright), costs less than kerosene (after the customer has paid for the product, usage is free), and is environmentally safer than kerosene (kerosene emits poisonous fumes). The technology being used in the Indigo program -- indeed all organic solar cell technologies -- would not be possible without ongoing work by organic chemists to synthesize and functionalize new materials.

Vision #3: Organic electronic devices will be manufactured using more resource-friendly and energy-efficient processes than today's methods, further contributing to a more sustainable electronic world.

The use of organic materials to build electronic devices holds the promise that future electronic manufacturing methods will rely on fewer, safer, and more abundant raw materials. The vision is for resource-efficient synthetic methodologies, whereby both the devices themselves and the manufacturing of those devices use less material than today's silicon-based electronic methodologies require. For example, materials can be saved by relying on less wasteful processes, such as printing, whereby materials are added to structures or devices layer by layer as they are built, in contrast to spin-coating which involves removing materials and disposing of those excess materials. In addition to using fewer materials, chemists are seeking ways to use safer materials. For example, many polymers require carcinogenic solvents, including some solvents not even allowed in the EU printing industry because of their toxicity. Chemists are hoping to design polymers that are soluble in non-toxic solvents and that rely on more benign methodologies in general. Finally, the resource-friendly vision is for reliance on more abundant starting materials, thereby conserving precious and endangered resources. For example, graphene is being investigated as a replacement for indium tin oxide (ITO), as indium is considered a limited resource.

In addition to becoming more resource-friendly, organic electronic manufacturing methods will also become more energy-efficient as materials and process engineers continue to learn and improve methodologies for synthesizing organic materials and assembling electronic structures. The vision is for manufacturing processes with fewer steps and with methods for recovering lost heat. Currently, both carbon nanotube and graphene synthesis methodologies are highly energy-intensive, with the scale of production being too small to invest in the infrastructure necessary for recovering lost heat. As the manufacture of carbon-based electronics expands in scale and the volume of material being processed increases, the hope is that process and materials engineers will develop ways to build the infrastructure needed to reclaim heat.

Figure 7. Accessible electronics. Pay-as-you-go organic solar cell technology is being distributed throughout rural areas of southern Africa and elsewhere, providing a low-cost and safe alternative to kerosene. Source: Eight19.

Sustainable Electronics

What is "sustainable electronics"? And how can organic electronics help to make electronics more sustainable? The meaning of sustainability is open to interpretation. The 2012 CS3 participants considered several different definitions of sustainable electronics.

Environmental sustainability. For most people, mention of "sustainable electronics" brings to mind images and concerns about energy efficiency, resource use, and waste disposal or recycling – that is, building an electronic world that enables sustainable management of natural resources. For example, how can electronic devices be built that operate more energy efficiently than today's silicon-based devices? Creating more sustainable electronic products is not just about building a more "eco-friendly" solar cell or other device, but also using more "eco-friendly" manufacturing methods to do so. In fact, sustainability cuts across the entire life cycle of an electronic product, from raw resources to disposal. Chemists and other scientists and engineers are using organic materials to steer electronics into the future in a more environmentally sustainable way than is possible in today's electronic world, for example by using carbon-based materials instead of precious earth-mined resources and by relying on safer and less energy-intensive manufacturing methods than silicon-based electronic processing methods.

Social sustainability. More broadly, "sustainable electronics" also implies building an electronic world that enables a more sustainable society – that is, as described in the United Nations 2012 report *Realizing the Future We Want for All*, one that ensures "inter-generational justice and a future world fit for children … in which children will be able to grow up healthy, well-nourished, resilient, well-educated, culturally sensitive and protected from violence and neglect …" Organic electronics is helping to steer electronics into the future in a way that ensures such justice and in a way not possible with today's silicon-based electronics. Specifically, organic electronics is making electronics in general more accessible to people worldwide. Chemists are using organic materials to develop "off-the-grid" solar cells, low-cost water sensors, and other devices for use in areas where people otherwise do not have the resources or infrastructure to light their homes or monitor water quality. Even in resource-rich areas where electronics are already pervasive, organic materials hold the potential to expand the use of electronic products in ways that will benefit society. One of the potential advantages of organic electronics is its more cost-effective large-scale manufacture, compared to silicon electronics, which creates opportunities for high-throughput production of item-level sensors and other devices that could be used to monitor and protect our environment, including our food supply, in ways not possible until now. For example, chemists envision item-level food spoilage sensors that would significantly reduce the amount of wasted food.

Technology sustainability. Finally, "sustainable electronics" implies that electronics itself is long lasting – not just the actual devices, but also organic electronic technology in general. Chemical, materials, and other scientists and engineers have only just begun to tap the vast potential for innovative functionality made possible through the use of organic materials in electronic devices. The way that organic electronic structures interact with biological systems opens up a vast world of possibility with respect to medical, sensing, and other human interface applications. The versatile nature of organic electronics, combined with the promise the field holds forth for environmental and social sustainability, point the way to a very long-lived set of technologies.

RESEARCH PATHWAY TO THE FUTURE

Realizing the visions articulated in the previous section will require overcoming several major scientific and engineering research challenges. Arguably the greatest overarching challenge to the field of organic electronics is to create electronic structures at industry-level scale with high yield and purity. This is true regardless of the type of material used or application. Until industry-level production of well-controlled structures is achieved, the visions for organic electronics will remain just that – visions. Only by addressing these challenges will the field of organic electronics expand the functionality, accessibility and sustainability of our electronic world:

(1) ***Improve controlled self-assembly***. Chemists need to gain better control over the self-assembly of organic electronic molecules into ordered patterns to ensure that the structures being assembled are reproducible. Today, a lack of reproducibility in the formation of many materials precludes industry-scale processing. To overcome this, chemists need to gain better control of the self-assembly of organic electronic molecules into ordered patterns. Improved controlled self-assembly requires a better understanding of the electronic properties of organic materials, especially when those materials are in contact with other materials (i.e., their interfacial behavior). Only with that knowledge will researchers be able to predict how organic electronic materials actually perform when integrated into devices, and only with those predictions will engineers be able to develop industry-scale synthetic processes.

(2) ***Develop better analytical tools***. Better analytical tools are needed to detect and measure what is happening with respect to structure and chemical composition when organic materials are assembled and integrated into electronic structures and devices, ideally at every step along the way. These tools need to be non-destructive, non-invasive, and high-speed. Additionally, highly sensitive analytical methods are necessary to detect degradation products of organic materials under operating conditions in order to better understand the break-down mechanism of such materials and eventually increase their lifetime in electronic devices.

(3) ***Improve three-dimensional (3D) processing technology***. Many organic electronic structures can be assembled on flexible substrates using existing printing technologies. However, fabrication of 3D organic electronic structures with the same precision achievable with two dimensional (2D) printing technology remains a major challenge to reliable high-throughput manufacturing of organic electronic devices.

(4) ***Increase multi-functionality of organic electronic devices.*** As chemists gain better control over the synthesis of organic materials, they and their engineering collaborators will be able to build increasingly sophisticated optoelectronic and other devices with multiple functions. However, in order to fully realize the multifunctional capacity of organic chemistry, chemists need to broaden their research focus beyond "charge-carrier" transport (i.e., electrons and holes, respectively) and gain a better understanding of optical, magnetic, thermal and other properties.

Organic Electronics: The Role of Chemistry

Chemistry research plays a critical role in the development and commercialization of organic electronics. After all, it is chemists who synthesize and functionalize the organic materials being used in the OLED smartphones, organic solar cells, and other devices either already on the market or in the development pipeline. Without those materials, these devices would not exist. Not only do chemists provide the raw starting materials, but they also play a key role in improving the performance of those materials over time. For example, charge-carrier mobilities of polymer-based OFETs have increased dramatically over past 10 years, from 0.01 cm^2/Vs in 2000 to greater than 1.0-3.0 cm^2/Vs in 2010, largely because scientists know a great deal more about the chemistry of the polymers than they did in the past. Still, there is a great deal more to learn. Many high-performance polymers being developed for use in organic electronics show non-textbook behavior, making it difficult to predict and control how polymeric structures will actually pack and perform once integrated into electronic systems. The reasoning behind this chemical behavior, and the possible uses of these polymers are still unknown. Continued research will help chemists to gain a better understanding of how these materials behave when they are integrated into electronic systems and hopefully point the way to even better-performing polymer-based OFETs.

Research Challenge #1*: *Improve Controlled Self-Assembly

Organic chemistry enables a vast array of complex structures and large-scale molecular assemblies to be built. However, the actual self-assembly[4] process is complex and still very poorly understood. Some design rules are beginning to emerge for small molecule self-assembly, but for the most part chemists are still operating on a largely trial-and-error basis. While it is known that small changes in microstructure can significantly impact self-assembly in the solid state, in most cases it is difficult or impossible to predict *how*. Without controlled self-assembly of organic electronic structures, the manufacture of devices built from those structures will be hindered and visions for the future of organic electronics thwarted.

For polymer materials in particular, improved control of morphology is arguably among the greatest challenges to moving the field forward. This is true even for P3HT [poly(3-hexylthiophene-2,5-diyl)], the well-studied of polymeric electronic materials, especially for OPVs. Even though the mechanism of P3HT polymerization is well understood, recent research has demonstrated how certain defects that significantly impact electronic performance emerge even with the most commonly used synthetic protocol. Even for commercial polymer materials already available for purchase, batch variation is significant. Thus, industrial scale-up of polymer-based electronics will require a more robust understanding of polymer self-assembly.

For *all* organic materials, chemists need to be able to model structure-property relationships at the molecular level so that they can design systems with more controlled self-assembly, regardless of whether that self-assembly occurs in solution (i.e., in ink) or on a surface. In other words, they must develop a more predictive science of organic electronics. Otherwise, synthesis will continue to yield decidedly non-uniform mixtures of structures that behave in unpredictable ways.

The issue of batch variation and reproducibility, or lack thereof, raises questions about whether some defects or impurities might be tolerable. It appears that most are not, with defects occurring at frequencies of less than one percent having significant impact on performance, especially for small molecule aggregate electronic devices. Whether defect-tolerant molecular architectures exist and, if so, under what conditions, remain a matter of investigation.

The challenge of reproducibility is especially acute for large-scale synthesis of carbon-based materials. Currently, only gram quantities of semi-conducting carbon nanostructures can be manufactured. Even then, defects are pervasive, with typical batches being heterogeneous mixtures of forms with varying electronic and other properties. A better understanding of self-assembly, including a better understanding of kinetic versus thermodynamic control during the self-assembly process, would help chemical engineers to develop the necessary selective synthesis tools for separating semi-conducting carbon

[4] In this White Paper, self-assembly is defined as the spontaneous ordering of patterned building blocks at a macroscopic scale.

nanostructures from other types of molecular structures.

The Importance of Understanding Interfacial Behavior

Improved self-assembly requires not only a greater understanding of the electronic properties of any given organic material, but also how those properties manifest when the material is in contact with another material. Chemical scientists need to gain a better understanding of interfacial chemistry and the impact of the interface on device performance. For example, graphene materials have charge-carrier mobilities on the order of 200,000 cm^2/Vs in a vacuum environment. But those mobilities drop orders of magnitude when the same materials are assembled on substrates. The mechanism and interfacial chemistry responsible for driving this drop in mobility is still unknown.

The need for a greater understanding of interfacial behavior, especially interfacial self-assembly, is true of all organic-organic interfaces (e.g., assemblages of multiple layers of organic materials, single molecules in contact with a carbon nanotube) and all organic-inorganic interfaces (e.g., single organic molecules in contact with an electrode). While molecule-electrode interfaces are key to increasing the energy efficiencies of many devices, any or all of these different points of contact can impact electronic behavior.

The significance of the interface is not limited to the electronic structures or devices themselves. Interfacial behavior also impacts manufacturing. Chemists need to gain a better understanding of the various molecule-solvent interactions that occur during solution processing (e.g., inkjet or screen printing).

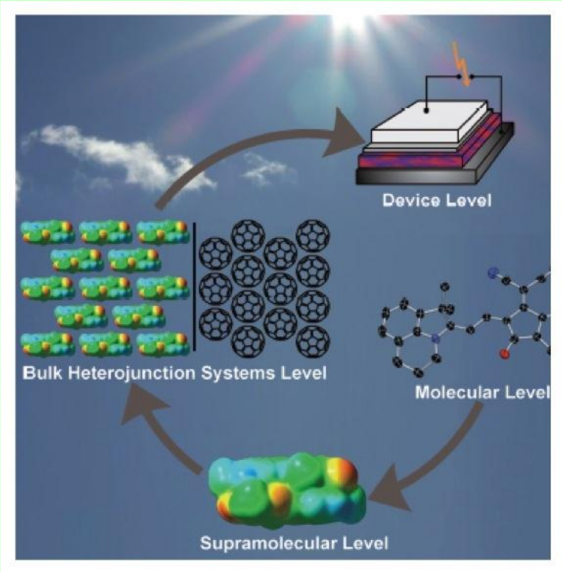


Figure 8. The complexity of self-assembly calls for a complexity science approach: The self-assembly of well-ordered patterns of organic electronic materials, whether those materials are molecules, polymers, carbon-based or not, is very difficult to predict and control. Until such self-assembly is better understood, such that well-controlled structures can be synthesized repeatedly and reliably, large-scale production of many of the envisioned applications for organic electronics will not be possible. Chemists need to gain a better understanding of self-assembly in order to achieve the prediction and control needed for industry-level production. Some chemists are calling for a systems-level approach to studying the complexity of self-assembly. Source: Würthner and Meerholz 2010.

Research Challenge #2: ***Develop Better Analytical Tools***

Reliable analytical tools are key to building a predictive science of organic electronics. Only when scientists are able to better characterize the electronic and other properties of their systems at the highest possible resolution will they be able to predict how molecular structure impacts performance. Currently, chemists have limited capabilities to characterize the local molecular environments of the structures they are building. Better tools are needed for analyzing the molecular composition, molecular organization, and local electronic and other properties of the organic electronic systems they are building.

A stronger fundamental measurement science would not only help with developing a more predictive science of organic electronics, it is also key to scaling organic electronic processing up to an industry level. In order to guarantee quality control, process engineers need to know what is happening at every point in the process. They need non-invasive, non-destructive, high-speed analytical tools.

Research Challenge #3*: *Improve Three-Dimensional (3D) Processing Technology

In order to scale organic electronic processing up to an industry-level standard, chemical scientists and engineers need improved three-dimensional (3D) fabrication technologies. An important advantage of many organic electronic structures and devices is that they can be assembled on plastic, paper and other flexible substrates using existing low-cost, high-throughput inkjet printing technologies. Printing also enables large-area fabrication of OLEDs, organic solar cells, OFETs and other organic electronic devices. Moreover, its additive approach makes for more sustainable production (i.e., necessary resources are added as needed rather than excess resources being subtracted and removed as waste). However, defect-free 3D processing of organic electronic structures remains a major challenge to industry-scale manufacture. Engineers need to build on what has already been done with 2D lithography so that they can fabricate uniform 3D structures in a controlled manner on a nano-level, not just micron-level, scale.

Research Challenge #4: Increase Multi-Functionality of Organic Electronic Devices

Organic electronic devices can do more than transport electronic information. They can also transport optical, magnetic, and thermal information. Indeed, many of the organic electronic devices already on the market are multi-functional. For example, organic light-emitting diodes (OLEDs) and organic solar cells are multi-functional optoelectronic devices, that is, electronic devices that use or produce light in addition to using or producing electrons. As chemists gain better control over the synthesis of organic materials, they and their engineering collaborators will be able to build increasingly sophisticated optoelectronic and other multi-tasking devices with multiple inputs and multiple outputs. For example, researchers envision multi-tasking window glazings that function as solar cells that generate electricity *and* as OLEDs that generate light. In order to fully realize the multifunctional capacity of organic electronics, chemists need to broaden their research focus beyond charge transport and gain a better understanding of how molecular structure and interfacial behavior impacts not just electronic but also optical, magnetic, thermal and other properties.

CONCLUSION

In 2004, it was predicted that chemists would soon synthesize organic semiconductors with charge-carrier mobilities greater than 10 cm^2/Vs and organic photovoltaic cells with 10 percent power conversion efficiencies. Those predictions have come true. More recently, it was predicted that organic electronics would become a US$30 billion industry by 2015. While this more recent prediction may have been overly optimistic, nonetheless the field of organic electronics clearly has made tremendous strides over the past few decades, with some devices already on the market and a multitude of device prototypes in development.

The field will continue to grow, changing the way society interacts with technology, as chemists, physicists, and other scientists and engineers address the research challenges identified by the 2012 CS3 symposium participants. Multidisciplinary research and training programs that bring together scientists and engineers from different fields of knowledge, as well as from different sectors of activity (i.e., academia, industry, government), will facilitate the collaborative effort needed to meet these challenges.

REFERENCES

Abidian MR, Ludwig KA, Marzullo TC, et al. 2009. Interfacing conducting polymer nanotubes with the central nervous system: chronic neural recording using poly(3,4-ethylenedioxythiophene) nanotubes. Advanced Materials 21(37):3764-3770.

Bachilo SM, Strano MS, Kittrell C, et al. 2002. Structure-assigned optical spectra of single-walled carbon nanotubes. Science 298: 2361-2366.

Berrouard P, Najari A, Pron A, et al. 2012. Synthesis of 5-Alkyl[3,4-c]thienopyrrole-4,6-dione-based polymers by direct heteroarylation. Angewandte Chemie International Edition 52:2068-2072.

Briseno AL, Aizenberg J, Han YJ, et al. 2005. Patterned growth of large oriented Organic semiconductor single crystals on self-assembled monolayer templates. Journal of the American Chemical Society 127:12164-12165,

Cai J, Ruffieux P, Jaafar R, et al. 2010. Atomically precise bottom-up fabrication of graphene nanoribbons. Nature 466(7305):470-473.

Chen W, Widawsky JR, Vazquez H, et al. 2011. Highly conducting □-conjugated molecular junctions covalently bonded to gold electrodes. Journal of the American Chemical Society 133:17160-17163.

Claussen JC, Franklin AD, ul Haque A, et al. 2009. Electrochemical biosensor of nanocube-augmented carbon nanotube networks. ACS Nano 3(1):37-44.

Diez-Perez I, Hihath J, Lee Y, et. al. 2009. Rectification and stability of a single molecular diode with controlled orientation. Nature Communications 1: 635-641.

Drain CM, Nifiatis F, Vasenko A, Batteas JD. Porphyrin tessellation by design: metal mediated self-assembly of large arrays and tapes. Angewandte Chemie International Edition 37:2344-2347.

Gabor NM, Zhong Z, Bosnick K, et al. 2009. Extremely efficient multiple electron-hole pair generation in carbon nanotube photodiodes. Science 325:1367-1371.

Gather MC, Köhnen A, Falcou A, et al. 2007. Solution-processed full-color polymer OLED display fabricated by direct photolithography. Advanced Functional Materials 17: 191-200

Gather MC, Meerholz K, Danz N, Leosson K. 2010. Net optical gain in a plasmonic waveguide embedded in a fluorescent polymer. Nature Photonics 4: 457-461.

Geim AK, Novoselov KS. 2007. The rise of graphene. Nature Materials 6:183-191.

Haigh SJ, Gholinia A, Jalil R, et al. 2012. Cross-sectional imaging of individual layers and buried interfaces of graphene-based heterostructures and superlattices. Nature Materials 11:764-767.

Hau, SK, Yip H-L, Acton O, et al. 2008. Interfacial modification to improve inverted polymer solar cells. Journal of Materials Chemistry 18:5113-5119.

He Z, Zhong C, Hunag X, et al. 2011. Simultaneous enhancement of open-circuit voltage, short-circuit current density, and fill factor in polymer solar cells. Advanced Materials 23:4636-4643.

Hodge SA, Bayazit MK, Coleman KS, Shaffer MS. 2012. Unweaving the rainbow: a review of the relationship between single-walled carbon nanotube molecular structures and their chemical reactivity. Chemical Society Reviews 41(12):4409-4429.

Hoeben FJM, Jonkheijm P, Meijer EW, Schenning APHJ. 2005. About supramolecular assemblies of π-conjugated systems. Chemical Reviews 105: 1491-1546

Ju S-Y, Doll J, Sharma I, Papadimitrakopoulos F. 2008. Selection of carbon nanotubes with specific chiralities using helical assemblies of flavin mononucleotide. Nature Nanotechnology 3:356-362.

Kagan CR, Breen, TL, Kosbar, LL. 2001. Patterning organic-inorganic thin-film transistors using microcontact printed templates. Applied Physics Letters 79:3536-3538.

Kaltenbrunner M, White MS, Glowacki ED, et al. 2012. Ultrathin and lightweight organic solar cells with high flexibility. Nature Communications 3:Article number 770.

Kanibolotsky AL, Perepichka IF, Skabara PJ. 2010. Star-shaped π-conjugated oligomers and their applications in organic electronics and photonics. Chemical Society Reviews 39:2695-2728.

Kim JB, Allen K, Oh SJ, et al. 2010. Small-molecule thiophene-C_{60} dyads as compatibilizers in inverted polymer solar cells. Chemistry of Materials 22:5762-5773.

Kim JB, Kim P, Pegard NC, et al. 2012. Wrinkles and deep folds as photonic structures in photovoltaics. Nature Photonics 6:327-332.

Klauk H, Zschieschang U, Pflaum J, Halik M. 2007. Ultralow-power organic complementary circuits. Nature 4455:745-748.

Kohn PP, Huettner SS, Komber HH et al. 2012. On the role of single regiodefects and polydispersity in regioregular poly(3-hexylthiophene): defect distribution, synthesis of defect-free chains, and a simple model for the determination of crystallinity. Journal of the American Chemical Society 134:4790-805.

Kuribara K, Wang H, Uchiyama N, et al. 2012. Organic transistors with high thermal stability for medical applications. Nature Communications 3:Article Number 723.

Levendorf MP, Kim C-J, Brown B, et al. 2012. Graphene and boron nitride lateral heterostructures for atomically thin circuitry. Nature 488:627-632.

Li G, Shrotriya V, Huang J, et al. 2005. High-efficiency solution processable polymer photovoltaic cells by self-organization of polymer blends. Nature Materials 4:864-868.

Li N, Z Chen, W Ren, F Li, H Cheng. 2012. Flexible graphene-based lithium ion batteries with ultrafast charge and discharge rates. Proceedings of the National Academy of Sciences 109(43):17360-17365.

Li Y, Sonar P, Singh SP, et al. 2011. Annealing-free high-mobility diketopyrrolopyrrole-quaterthiophene copolymer for solution-processed organic thin film transistors. Journal of the American Chemical Society 133: 2198-2204.

Lv W, Tang D-M, He Y-B, et al. 2009. Low-temperature exfoliated graphemes: vacuum-promoted exfoliation and electrochemical energy storage. ACS Nano 3(11): 3730-3736

McCulloch I, Heeney M, Bailey C, et al. 2006. Liquid-crystalline semiconducting polymers with high charge-carrier mobility. Nature Materials 5:328-333.

Müller CD, Falcou A, Reckefuss N, et al. 2003. Multi-color organic light-emitting displays by solution processing. Nature 421: 829-833.

Novoselov KS, Falko VI, Colombo PR. 2012. A roadmap for graphene. Nature 490:192-200.

Novoselov KS, Geim AK, Morozov SV, et al. 2004. Electric field effect in atomically thin carbon films. Science 306:666-669

Park SH, Roy A, Beaupre S, et al. 2009. Bulk heterojunction solar cells with internal quantum efficiency approaching 100 %. Nature Photonics 3:297-302.

Peet J, Kim JY, Coates E, et al. 2007. Efficiency enhancement in low-bandgap polymer solar cells by processing with alkane dithiols. Nature Materials 6:497-500.

Safont-Sempere MM, Fernández G, Würthner F 2011. Self-sorting phenomena in complex supramolecular systems. Chemical Reviews 111: 5784-5814.

Saudari SR, Frail PR, Kagan CR. Ambipolar transport in solution-deposited pentacene transistors enhanced by molecular engineering of device contacts. Applied Physics Letters 95:023301-023303.

Sekitani T, Noguchi Y, Hata K, et al. 2008. A rubberlike stretchable active matrix using elastic conductors. Science 321(5895):1468-1472.

Sekitani T, Zschieschang U, Klauk H, Someya T. 2010. Flexible organic transistors and circuits with extreme bending stability. Nature Materials 9:1015-1002.

Sirringhaus H, Brown PJ, Friend RH, et al. 1999. Two-dimensional charge transport in self-organized high-mobility conjugated polymers. Nature 401:685-688.

Sokolov AN, Tee BC, Bettinger CJ, et al. 2012. Chemical and engineering approaches to enable organic field-effect transistors for electronic skin applications. Accounts of Chemical Research 45(3):361-71.

Sun D, Timmermans MY, Tian Y, et al. 2011. Flexible high-performance carbon nanotube integrated circuits. Nature Nanotechnology 6:156-161.

Torrisi F, Hasan T, Wu W, et al. 2012. Inkjet-printed graphene electronics. ACS Nano 6:2992-3006.

United Nations [UN] System Task Team on the Post-2015 UN Development Agenda. *Realizing the Future We Want for All*. Report to the Secretary-General. https://docs.google.com/gview?url=http://sustainabledevelopment.un.org/content/documents/614Post_2015_UNTTreport.pdf&embedded=true.

Uwe H, Bunz F, Menning S, Martin N. 2012. Para-connected cyclophenylenes and hemispherical polyarenes: building blocks for single-walled carbon nanotubes? Angewandte Chemie, International Edition 51:2–10.

Wang QH, Hersam MC. 2009. Room-temperature molecular-resolution characterization of self-assembled organic monolayers on epitaxial graphene. Nature Chemistry 1: 206-211.

Woll A, Mukherjee MP, Levendorf EL, et al. 2011. Oriented 2D covalent organic framework thin films on single-layer graphene. Science 332:228-231

Würthner F, Meerholz K. 2010. Systems chemistry approach in organic photovoltaics. Chemistry: A European Journal. 16(31):9366-9373

Würthner F., Stolte M. 2011. Naphthalene and perylene diimides for organic transistors, Chemical Communications 2011, 47, 5109-5115.

Xu B, Tao NJ. 2003. Measurement of single-molecule resistance by repeated formation of molecular junctions. Science 301:1221-1223.

Yoo JE, Lee KS, Garcia A, et al. 2010. Directly patternable, highly conducting polymers for broad applications in organic electronics. Proceedings of the National Academy of Sciences 107:5712-5717.

Yoon M-H, Fachetti A, Marks TJ. 2005. □□□ molecular dielectric multilayers for low-voltage organic thin-film transistors. Proceedings of the National Academy of Sciences 102:4678-4682.

Zschieschang U, Yamamoto T, Takimiya K, et al. 2011. Organic electronics on banknotes. Advanced Materials 23(5):654-658.

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