

Flexible Electronics: The Next Ubiquitous Platform

This paper reviews thin-film materials and technologies for flexible electronics and considers future applications in healthcare, the automotive industry, human-machine interfaces, mobile devices, and other environments.

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ABSTRACT | Thin-film electronics in its myriad forms has underpinned much of the technological innovation in the fields of displays, sensors, and energy conversion over the past four decades. This technology also forms the basis of flexible elec-

tronics. Here we review the current status of flexible electronics and attempt to predict the future promise of these pervading technologies in healthcare, environmental monitoring, displays and human-machine interactivity, energy conversion, management and storage, and communication and wireless networks.

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I. INTRODUCTION

Ever evolving advances in thin-film materials and devices have fueled many of the developments in the field of flexible electronics. These advances have been complemented with the development of new integration processes, enabling wafer-scale processes to be combined with flexible substrates. This has resulted in a wealth of demonstrators in recent years. Following substantial development and optimization over many decades, thin-film materials can now offer a host of advantages such as low cost and large area compatibility, and high scalability in addition to seamless heterogeneous integration.

Diodes and transistors are two of the most common active thin-film devices used in a wide range of digital and analog circuits, as well as for detection and energy generation. While they have been successfully used in flexible platforms, their performance and applicability in systems is limited by a number of factors, inevitability requiring

use of exotic device architectures, consisting of highly optimized geometries combined with integration of novel materials. This has often facilitated tailoring of the electronic properties toward particular applications that demonstrate vast improvements in form factor, though typically at significant financial cost, which is unacceptable at the *en masse* scale. Though such “one-off” devices are of significant interest to the academic community, little has been achieved in the way of full-scale system integration. Indeed large-area simple devices, such as resistive and inductive networks, have been demonstrated. In order to achieve the goal of full-system integration in “next-generation flexible systems” a paradigm shift in design and fabrication is necessary. The ethos of the conventional integrated circuit (IC) manufacturer must be adjusted. Notwithstanding, improved understanding in the material growth/deposition, integration, and processing must certainly be advanced and such knowledge is often derived via the speculative academic. Reduced cost, large area, roll-to-roll, and flexible systems, such as low-cost flexible displays, require conformal, distributed, and integrated functionality, which is hitherto unavailable from more traditional brittle material and device platforms. Such functionality will certainly offer disruptive alternatives for more established technologies that cumulatively represent perhaps one of the world’s largest economic markets in human history, while also facilitating the development of distinctly niche markets that exploit these new capabilities in truly unexpected applications. Just as the IC replaced discrete circuit board electronics, flexible electronics will almost inevitably—by virtue of the ever-demanding end-user—supersede solid-state ICs, in particular, applications where form factors are important; though the materials, technologies and devices necessary to achieve this are still largely unclear to many.

This paper reviews the materials, design issues, and technologies for next-generation flexible electronics, and primarily considers future applications therein (Fig. 1). We summarize the potential of flexible thin-film devices, the limitations of particular materials with regard to manufacturability, deposition issues, and monitoring techniques that must be resolved and improved prior to their wide adoption, with particular reference to a new class of materials available to system designers—the nanomaterials. This paper is foremost organized from the standpoint of applications, with some of the more pertinent questions posing the materials engineer introduced to stimulate discussion. We present examples of potential applications of flexible electronics in various societal sectors, including: healthcare; the automotive industry; human-machine interfaces; mobile communications and computing platforms; embedded systems in both living and hostile environments; as well as market-specific applications, such as: human-machine interactivity, energy storage and generation, mobile communications and networking, while touching on the application of

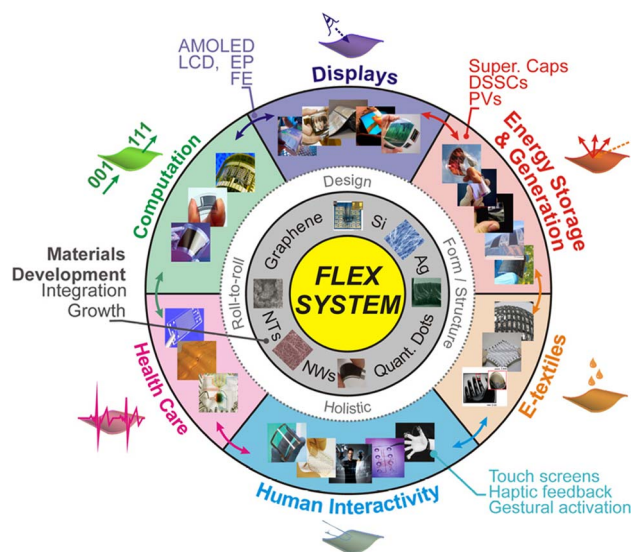


Fig. 1. Next-generation flexible electronics systems and the key relevant sectors, the underlying materials—such as the industry pervading, historically relevant and standard aluminium, silicon, germanium, and silver, as well as more exotic low-dimensional materials including nanowires, quantum dots, and nanotubes—all of which will be necessary to facilitate the development and the exploitation of disruptive applications in the fields of human interactivity, computation, displays, energy generation, and storage as well as electronic textiles.

flexible electronics on ubiquitous computing platforms throughout.

II. MATERIALS, TECHNOLOGIES, AND INTEGRATION PROCESSES

The fundamental properties of thin-film materials, as well as the quality of various device interfaces, give rise to inherent limitations in device performance. For instance, consider the ring oscillator. As one of the most essential building blocks in many systems, it is fundamental to many emerging technologies, such as radio-frequency identification (RFIDs) tagging. A large number of design parameters influence the oscillation frequency of ring oscillators. These include geometric attributes, parasitic capacitance, and the supply voltage. However, these adjustments are often dwarfed by the inherent performance limitations of the transistors. Considering the field-effect mobility as a key performance indicator, one can populate a stage delay V_s mobility map to illustrate the mobility dependency of operating speed of ring oscillators using common semiconductors, as shown in Fig. 2. The indicated values are from a variety of sources [1]–[21] and the observed scatter is indicative of typical variation in device layout, parasitic capacitance, and supply voltage. Despite this, an overall distinction can be made between different classes of materials.

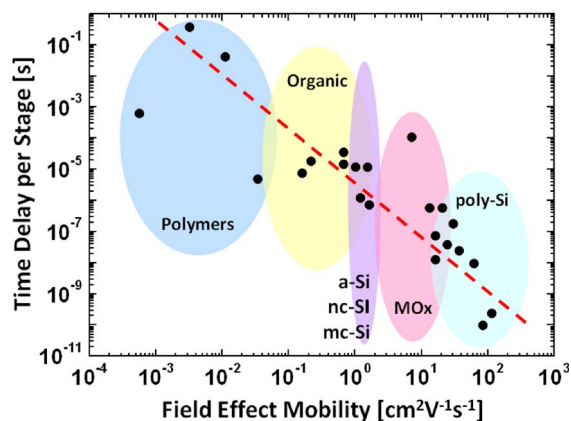


Fig. 2. Correlation in the field-effect mobility of TFTs and switching speed of inverter-based ring oscillators. A general trend can be observed across different classes of thin-film semiconductors despite the large scatter associated with variation in device attributes, parasitic capacitances, and supply voltages. Data taken from [1]–[21].

The field-effect mobility itself is a function of a number of parameters. As well as material's band mobility [22] and the quality of the dielectric/semiconductor interface, it is also influenced by the contact resistance [23], [24] and the dynamic characteristics of the thin-film transistor (TFT) [25].

Although it is desirable to use thin-film materials with the highest possible mobility, issues of cost and scalability play critical roles in material selection. For instance, the two highest mobility materials (Fig. 2) are polycrystalline silicon (poly-Si) and semiconducting metal oxides (MO_x). Currently, MO_x are costly due to the global localization and shortage of indium [26], [27]. Despite the availability of low-cost Si, the fabrication process of poly-Si is also rather costly, due to postdeposition processing requirements in large-area applications [28]–[30].

Incorporating nanowires (NWs), carbon nanotubes (CNTs), graphene or other nanomaterials within semiconducting thin films allow tailoring of their properties [31], [32]. Devices based on such composites typically exhibit enhanced electrical performance, such as higher field-effect mobility and subthreshold slope, leading to lower operating voltages—an important consideration in low-power circuit design. Moreover, the composite nature of the thin films affects their mechanical properties [33], [34], and the TFT durability when subjected to mechanical stress: an essential requirement for truly flexible electronics.

In addition to the aforementioned device performances and costs, their stability when subjected to prolonged electrical [35] or optical bias [36], [37] is critically important. For instance, although Fig. 2 depicts a marginal performance variation between microcrystalline (*mc*-Si), nanocrystalline (*nc*-Si), and amorphous silicon (*a*-Si) on the global scale, the stability of TFTs when subjected to electrical bias and/or illumination is considerably differ-

ent. Through engineering mixed-phased heterogeneous materials, it is possible to achieve higher degrees of stability compared with conventional *a*-Si [38].

Recently, novel fabrication techniques have allowed TFTs to harness the potential of 1-D semiconductors, such as CNT and NWs, as well as 2-D semiconductors and dielectrics such as graphene [39], [40] and molybdenum disulfide (MoS_2) [41] and hexagonal boron nitride (h-BN) monolayers [42]. These devices exhibit remarkable properties, though further progress is critical before they can be commercialized in flexible circuits and integrated systems.

Fabrication methods also have an important effect on the characteristics, cost, and stability. For example, instead of using a high mobility material to achieve high device transconductance, it is possible to adjust the architecture. Employing short channel lengths is one way to achieve this. In conventional planar TFTs, the channel length is ultimately limited by the diffraction limit in the photolithography process. Vertical transistors, where the channel length is set by the thickness of the semiconductor, have been demonstrated as to achieve submicrometer channel lengths, paving the way for high transconductance devices using conventional materials such as *a*-Si.[43].

Alternative approaches have also been developed to fabricate organic submicrometer TFTs uniformly over large areas [44]. One such approach is based on a novel edge effect that is induced by spin-coating a polymer onto a prepatterned structure, as shown in Fig. 3. Polymer TFTs, with channel widths as narrow as 400 nm, can be fabricated by this method, with a mobility of $5 \times 10^{-3} \text{ cm}^2/\text{V} \cdot \text{s}$ and ON/OFF current ratio of $\sim 10^6$ using poly (9, 9-dioctylfluorene-co-bithiophene) (F8T2) [44]. One key advantage of this method is it facilitates the use of low-resolution patterning techniques, such as shadow masking, to create highly reproducible submicrometer features thereby obviating more conventional, time-consuming lithographic processes. This, combined with inkjet printing, provides an exciting opportunity to apply on-demand material deposition and desktop programmable wiring of *ad hoc* patterns. The latter has already been demonstrated for CNT and graphene-based inks [45], [46]. Though rather exotic, such innovative fabrication techniques will facilitate the technologies' widespread usage for fabrication of TFT with high transconductance.

Few novel processes have been developed to fabricate solution processable TFTs with one-step self-aligned dimensions in all functional layers [47]. The TFT-channel, semiconducting materials, and effective gate dimension were controlled by a one-step imprint process and subsequent pattern transfer, without the need for multiple patterning and mask alignment, as shown in Fig. 4. Both *p*- and *n*-type organic TFTs have been demonstrated using this method. In the case of *n*-type TFTs, Li *et al.* [47] reported that 20 transistors were fabricated without process optimization, with a yield of 100% and a variation

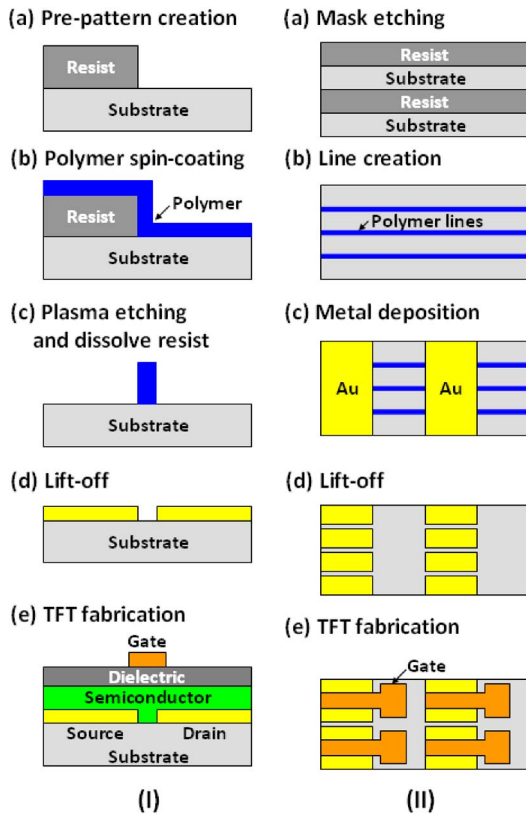


Fig. 3. Schematic illustrating the fabrication of short channel transistors using spin-coating-induced edge effect (I, side view) and the specific process used for TFT fabrication (II, top view). Adapted from [44].

in mobility and ON/OFF current ratio of a factor of 3 and 5, respectively. All the used techniques (i.e., imprinting, wet/dry etching, and inkjet printing) are already available in roll-to-roll processes. The demonstrated high-resolution features, mask-alignment-free process, and compatibility to roll-to-roll fabrication show that these, and similar techniques are commercially attractive, inexpensive, and ready to use. It is expected that these methods can be extended to the level of integrated complementary metal-oxide-semiconductor (CMOS) circuit fabrication.

Diodes constitute another important class of active electronic devices. Apart from their ubiquitous application in electronic circuits, they can be used as photodiodes or photovoltaic (PV) solar cells, depending on their mode of operation. They can also work as light-emitting diodes (LEDs) to generate illumination. Thin-film diodes can be incorporated within systems to enhance their functionality. For example, thin-film LEDs can be painted on the internal façades of building as an alternative to traditional single-point illumination, providing future architecture with additional means of lighting design.

With anticipated developments in alternative means of energy generation, such as fusion power, the role of PVs is

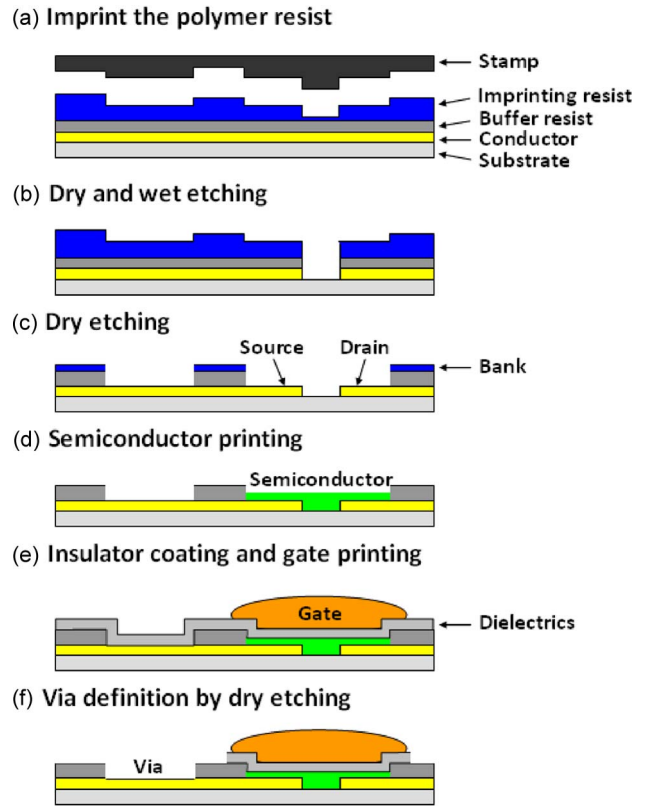


Fig. 4. Schematic illustration of a TFT fabrication process by a self-aligned, one-step, multilayered patterning. Adapted from [47].

likely to be targeted for niche applications. Solar cells can also be incorporated within mechanically flexible, field-deployable self-sustaining systems.

All real-world systems are based on devices with proven manufacturability, at low cost. This is a nontrivial achievement that normally is established in pilot product plants, rather than laboratories where the initial concepts were first demonstrated.

Any manufacturable device has four essential characteristics:

- superior and prespecified performance, with reproducibility, uniformity, and reliability;
- high yield to acceptable tolerance;
- simulations exist for both reverse engineering during development and right-first-time design;
- proven adequate in-service lifetime.

For electronics, optoelectronics, and sensing with nanoscale structures, all four characteristics are challenging to establish. Consider nanotubes or nanoscale wires more generally, or even quantum dots. Anything patterned in two dimensions on the nanometer scale experiences a limiting scale, set by the statistical variability of sets of small numbers ($\sigma_N \sim 1/\sqrt{N}$), below which six-sigma manufacture may be impossible, and is certainly ambitious. When etching or deposition is used to add or remove

individual atoms to, or from, structures, this limit appears at the 7-nm half-pitch. For arrays of nanometer half-pitch, $\sigma = 12\%$, highlighting a clearly intolerable variation for the electronic transport or optical properties of arrays made of elements with such intrinsic variability. Even if we could successfully fabricate such arrays by heroic processing, at very high cost, one must note—atom by atom with a force microscope of sorts—that there would never be such an array to write, store, or read information as the electrons and photons would leak extensively over extremely short timescales [48].

Consider quantum wires. Adequate control over the cross-section area from wire to wire is difficult, as it is for any regularity in the spacing of the wires across the substrate. Until these are achieved, any ideas based on anything other than their prevailing bulk properties is practically impossible. Computer models of these wires are primitive and certainly not adequate for producing a right-first-time design—the incorporation of detailed boundary conditions is inadequate, and interwire interactions are not treated with any suitable regard. The grand challenge is to produce an array, or even a single wire, that has precisely 15% variation in its properties across an array. Only small stresses during in-life operation are sufficient to have atoms move or conductivities change, so that 10^3 hours with less than 5% change in the device operation is harder to achieve, especially if high local powers are involved.

The same problems arise, but for different reasons, when considering the bottom-up or self-assembly process. Very few of the molecules used in self-assembly are available at the 5-nines (99.999%) purity level which is implied by a six-sigma manufacturing quality. It may also be that approximately spherical molecules will not be suitable for connected arrays—it is likely that the individual molecular elements of the arrays will need “handles” to assist in the subsequent wiring of an array for electronic addressing. In the 3–7-nm diameter range for these molecules, the ability to align such nonspherical arrays with a sufficiently small standard deviation in the in-plane orientation of the “handles” is also a challenge for future research.

The proof of manufacturability is intimately linked with the intrinsic physics and materials science at the nanoscale. Any establishment of device manufacturability must come from the science and engineering laboratory before moving into pilot production plant. This is a culture change which is not happening. Fewer than 1% of papers in nanotechnology literature contain the words “yield,” “reproducibility,” or “lifetime.” It seems timely for such a culture change so that the end-to-end efficiency, i.e., from device concept to real product, can be improved. Why persist with the science of something that is intrinsically unmanufacturable? However, such arguments apply only to applications where the individual nanostructures are acting as discrete elements of an array. Clearly, if one is using the average of a cluster of such structures, then

nanoscale electronics are clearly viable and the statistics of the average properties are perhaps more pertinent. Even in presence of such challenges, there is an increasing number of extremely promising applications, prototypes, and demonstrators based on nanomaterials, in electronics [49], photonics [50], [51], and optoelectronics [52]. Transferable and composite nanomaterials offer a range of desired electrical, physical, and (bio)chemical properties. However, the dimensions required to derive these properties often impose limitations on the tools used in their growth. A key challenge to exploit the full potential of such an approach is to understand the principles that guide the design and functionality of individual nanostructures, as well as the heterogeneous, interconnected networks based on nanostructures. A family of high-aspect ratio 1-D and layered 2-D nanomaterials, including metal and semiconducting and metallic nanowires, CNTs, graphene, h-BN, transition-metal chalcogenides and oxides, with a wide range of properties, have emerged as highly promising candidates for applications in flexible electronics. One of the most attractive aspects is that various nanostructures grow via mechanisms based on self-organization. No expensive lithography is required to access the nanoscale dimensions, hence the novel properties available at the scales. Though individual nanoscale devices, as discussed previously, are quite possibly nonmanufacturable, the thin-film “mean” characteristics are, and to derive some understanding of these mean properties requires some deeper understanding of the individual nanoscopic elements. Novel heterostructures can be grown at an atomistic level and the as-grown, high-quality materials can be used as building blocks for further self-assembly. It has been shown that these low-dimensional structures can be transferred to any arbitrary substrates via various wet chemical processing processes. It is possible to thereby tailor composite materials over many size scales, as well as to incorporate a wide range of materials such as inorganic and metal nanoparticles, organic molecules/nanostructures, and polymers. These assemblies will become pivotal architectural elements for future flexible electronics. The overall properties are defined not only by the properties of the individual nanostructures, but also, and often more importantly, by their interfaces and contacts. The properties of the nanostructures themselves closely relate to the detailed structure and interface/environment.

A central question therefore is how well the process of self-organization, assembly, and processing can be controlled at scalable production level to achieve reproducible material properties. Although most of these novel nanomaterials can be synthesized already, the fundamental mechanisms that govern the self-organization remain largely unknown. Hence, most processing in this field is guided by empirical, individual calibrations that often do not transfer. Historically, early examples of superior functions in composites, due to nanostructures, include ancient Damascus sabres and Hessian wares [53], [54]. The recipes

Table 1 Comparison of possible plastic substrate for thin-film deposition [65]. CTE Denotes the Coefficient of Thermal Expansion. T_{Max} denotes a maximum deposition temperature

| Max Dep. Temp. °C | Material | Properties |
|-------------------|----------------------------------|---|
| 250 | Polyimide (Kapton) | Orange color; high thermal expansion coefficient; good chemical resistance; expensive; high moisture absorption |
| 240 | Polyetheretherktone (PEEK) | Amber; good chemical resistance; expensive; low moisture absorption |
| 190 | Polyethersulphone (PES) | Clear; good dimensional stability; poor solvent resistance; expensive; moderate moisture absorption |
| 180 | Polyetherimide (PEI) | Strong; brittle; hazy colour; expensive |
| 160 | Polyethylene Naphthalate (PEN) | Clear; moderate CTE; good chemical resistance; inexpensive; moderate moisture absorption |
| 120 | Polyethylene terephthalate (PET) | Clear; moderate CTE; good chemical resistance; inexpensive; moderate moisture absorption |

to manufacture these materials were found by chance and only now, thousands of years later, we can characterize these materials with sufficient resolution to reveal that they contain nanostructures [55], [56]. However, even now we can often only resolve and adequately characterize nanomaterials at a postprocess stage and not under actual *in situ* reactor or device operation conditions. Hence, we are left to speculate what atomic mechanisms actually govern their growth or behavior in real devices. To unlock the full potential of nanomaterials, new experimental techniques are required that can reveal atomistic detail under realistic and operational conditions. Substantial progress has been made recently in developing such *in situ* metrology, in particular, for heterogeneous catalysis [57]. Such *in situ* probes range from environmental transmission and scanning electron microscopy [58]–[60], high-pressure X-ray photoelectron spectroscopy [61], [62], *in situ* X-ray scattering and diffraction techniques, and *in situ* scanning probes and optical spectroscopy techniques [57]. The recent advent of this *in situ* metrology has led to numerous breakthroughs in nanostructure catalysis and operation. Hence, further development, complementary combination, and wider availability are key to the future emergence of many, if not all, known nanomaterials.

The materials and technologies behind flexible substrates are an important consideration for flexible electronics. Perhaps two of the main flexible substrate candidates are plastic and stainless steel. Although stainless steel is compatible with standard deposition temperatures, it results in a substantially heavier system due to its higher mass density—a critical consideration for portable flexible technologies. Also, stainless steel is not particularly

deformable, and is thus unsuitable for many applications, in particular, wearable electronics [63], [64]. Plastic substrates are lighter and deformable alternatives. Substrates need to be solvent resistant, so that standard optical photolithography process can be used. Additional substrate requirements include low cost (allowing large area, mass production), and moisture resistance. Table 1 compares some of the more critical properties of some key plastic substrates [65].

One of the main challenges facing plastic as a next-generation substrate is the substantially reduced processing temperature window. The maximum fabrication temperature, shown in Table 1, is related to the glass transition temperature above which inelastic deformation takes place and the substrate no longer retains its original dimension, essential for photolithography. For example, polyethylene naphthalate (PEN) satisfies all requirements and tolerates temperatures as high as 160 °C. More recently, a number of electronic devices and circuits have been demonstrated, utilizing paper as a substrate and/or as a gate dielectric [13], [66]. Such approaches lead to electronic devices with the potential for *en masse* integration at low cost, which are also disposable and fully recyclable.

III. HOLISTIC SYSTEM DESIGN

Although research base provides the foundations of future flexible technologies, these advances can only transform into commercial products if technological innovation progresses from laboratory, with the explicit view of exploring potential applications and ultimately embody these in products. Often pioneering research has had an expectation

of future commercial application, albeit in the distant future. These expectations can only be satisfied if the needs of potential end-users and consumers of this technology are considered from early stages of research. In the case of flexible thin films such end-user requirements are clear and discussed earlier in the paper. However, the challenge lies in the successful integration of these technologies.

Throughout the 20th century, industrial designers have supported firms to ensure that new technologies, particularly disruptive technologies such as flexible electronics, are embodied in forms that can be commercialized. Earlier pioneers of industrial design, such as Peter Behrens, a German architect who worked closely with Allgemeine Elektrizitäts Gesellschaft in the early 1900s, have helped turn radical new technologies into products for mass consumption. In the mid-20th century, Dieter Rams formalized the design excellence principles, as outlined in Table 2, to guide the future generations of industrial designers.

We can see that designers play a critical role in turning technology into products, and the same approach cannot be absent from the future generation of products based on thin-film flexible electronics. There is substantial anecdotal [68] and empirical [69], [70] evidence of the value of industrial design in the development of new technology in industry. We all experience this first hand when we interact with products that combine the changes enabled by new technology with elegance, beauty, and simplicity (e.g. see Fig. 5). However, it is less common for designers to work with scientists who are creating tomorrow’s technologies. For example, in the United Kingdom, the 2005 Cox Review recognized that two key strengths of the United Kingdom are disjointed—the national design capability and the science base: “technology that is not carried through into improved systems or successful products is opportunity wasted” [71]. More recently, the 2007 Sainsbury Review highlighted how “the use of design helps scientists to develop commercial applications for their work while it is still at the research stage or at the outset of the technology transfer process” [72].



Fig. 5. Braun radio, Apple iPod, Apple iPhone, and Braun calculator.



Fig. 6. Philips “fluid” smartphone concept.

The challenge of commercializing breakthrough flexible-based electronic technologies is evident in the case of plastic LEDs. Pioneering research, at Cambridge University, resulted in a patent for P-LEDs in 1989. Some 20 years later, flexible plastic displays are only just beginning to gain low-to-medium-scale usage [73]. Following the initial scientific breakthrough, the technology was developed to enable improved performance, but also to enable robust manufacturing. Designers were quick to explore the potential of such deformable displays in conceiving a wide range of future product concepts (e.g., Philips “fluid” smartphone concept [74], Fig. 6), however few such devices have successfully made it to the market.

In addition to the expected contribution of designers in supporting, and even driving, the commercialization of novel technologies, there is significant scope for industrial

Table 2 The Design Principles of Dieter Rams From Braun. Adopted and expanded

| Good design is | Sins of bad design | Good vs. bad design |
|--|---|--|
| <ul style="list-style-type: none"> • Innovative • Renders utility as a product • Is aesthetic • Makes a product easy to understand: form follows function • Is unobtrusive • Is honest • Strives for longevity • Is consistent to the smallest detail • Protects our environment • Is as little design as possible | <ul style="list-style-type: none"> • Is a cynical exploitation of human weakness • Is dull and unexciting • Is more than is necessary • Promises but does not deliver | <ul style="list-style-type: none"> • Simple is better than complicated • Clear is better than confused • Quiet is better than loud • Unobtrusive is better than exciting • Small is better than large • Plain is better than coloured • Well balanced is better than exalted • Continuity is better than change • Sparse is better than profuse • Neutral is better than aggressive • The obvious is better than that which must be sought • Few elements are better than many • A system is better than single elements • Convergence is better than divergence |

design to have a direct impact on the underlying research. When involved early in the scientific research process, designers can challenge the research direction and support scientists in exploring, demonstrating, and communicating potential future applications. However, designers may support scientific research in a variety of other ways. These perhaps include the following.

- 1) *By assisting in the fabrication and development of models and prototypes:* The designer's skills in model making, prototyping, and computer-aided design (CAD), and their knowledge of materials and manufacturing processes can benefit scientists by allowing them to quickly evaluate ideas in reality, demonstrate the feasibility of concepts, and provide evidence to support funding applications.
- 2) *Bringing the perspective of users and the marketplace to research:* The designer's focus on the needs, motivations, and behaviors of users and consideration of market requirements can speed up the process of commercialization and help to focus research objectives.
- 3) *Communicating the potential of new technology to investors and other nonscientific stakeholders:* By visualizing "market ready" embodiments of potential future applications, industrial designers can help to communicate the key benefits of new technology in an engaging way that can be understood by a wider audience.
- 4) *Exploring and demonstrating applications for new technology:* Industrial designers can challenge what scientists believe the potential applications of their technology might be, and support the development of demonstrators. Designers are also able to embody the "unique selling points" of technology in applications.
- 5) *Identifying routes to commercialization:* Designers may be able to provide support for scientists struggling to gain investment in the development of new technology, by identifying new routes to market or lines of scientific enquiry.
- 6) *Providing early insight into practical issues:* By attempting to make objects, industrial designers can help to identify the practical capabilities and limitation of new materials, and highlight any potential issues which may arise in scaling up new technologies (both in terms of physical size and volume).
- 7) *Influencing the research direction:* By identifying practical challenges for technologies to overcome in order to achieve application, industrial designers can potentially influence the direction of research.

Designers, in discourse with engineers, have a powerful role to play in supporting scientists in taking breakthrough ideas from the laboratory into commercial

products. However, this important resource is often underutilized and the potential for design is frequently not recognized. It is rare for the scientist to involve such design expertise unless they have already progressed some way toward commercialization. In the following sections, we present examples of applications where flexible systems may offer enhanced functionality and that are likely to emerge as market-adjusting technologies.

IV. HEALTHCARE

Flexibility in electronic materials is very attractive for medical and bioengineering. Living organisms are intrinsically flexible and malleable. Thus, flexibility is a necessity for successful integration of electronics in biological systems. Furthermore, in order to carry out daily tasks, flexibility is less likely to hinder over stiffness [75]. Recently, some electronics have been integrated into human bodies [75]–[78]. One example is the bionic eye [79]. Here a vision-compromised patient requires an electrically active addressable matrix array, with each unit or pixel recording an image and transmitting this to the patient via the optic nerve [77]. Such technology is not restricted to vision, and is applicable to many other types of sensation.

The bionic ear, shown in Fig. 7, offers an ideal platform for flexible thin-film electronics. In auditory systems, in particular inside the cochlear, the basal membrane of the organ oscillation is key for listening and fine tuning. With a unique stiffness and geometry, a thin film coupled together with pressure sensing arrays acts as a biomimicking auditory system. At a specific frequency and sound pressure, the basal membrane vibrates at a specific location with predefined amplitude [80]. A microarray

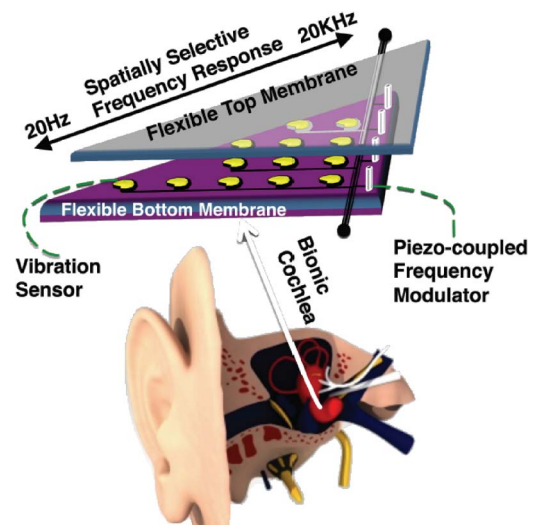


Fig. 7. A bionic ear. Ear diagram by Salvatore Vuono (permission obtained).

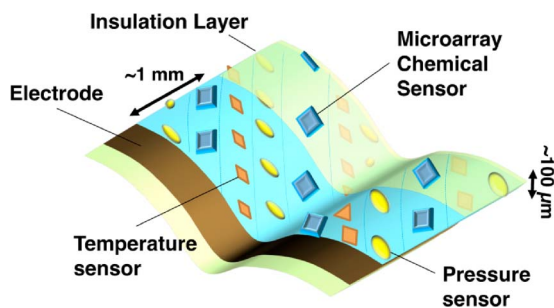


Fig. 8. Schematic diagram of the active sensor matrix thin film for the artificial nose and tongue.

pressure sensor can be activated for each specific location, emitting a signal of known pitch and loudness, mimicking the incident sound. Small piezoelectric structures ($\sim 2\text{--}5\ \mu\text{m}$ tall) can also be integrated, thereby forming an in-built feedback loop. Normally human ears can fine tune to cancel “noise” and isolate specific sounds of interest. Such feedback mechanisms can oscillate the membrane, so that it vibrates increasingly at a specific frequency, which can amplify the “signal” of interests, while canceling other “noise” with proximal frequency. In comparison to the current cochlea implant [78], [81], this mechanism allows much wider frequency and sound level to be sensed, much like a real ear.

Further applications of microarray systems based on such flexible thin-film technology is as a facilitator for artificial noses and tongues, as shown in Fig. 8. Sensory receptors in olfactory (nose) and gustatory (taste) systems have a range of chemical receptors. Many of these receptors sense particular chemical properties, including acidity, salt concentration, and enzyme affinity. The frequency of neurons firing is often sensed in proportion to the magnitude of the “taste” or “smell” [80]. Sourness, saltiness, as well as subtypes of sweetness are recognized as pH, alkaline metal, or calcium ions, respectively [82], where these parameters can be extracted by some state-of-the-art electrical impedance analyzer. Molecular compounds, such as sugar or “umami” precursors can also be converted by enzymes and transducers into measurable electrical signals [83], [84].

Subcutaneous implantation of such thin films, equipped with pH, temperature, pressure, or particular enzyme sensors would be a breakthrough in medicine in terms of real-time patient monitoring and quality of life improvement. If such systems were to be implemented they would be capable of monitoring the elemental content of the patients’ blood, thereby extracting valuable data noninvasively. If applied to the wounded on site, critical information on the recovery and survival rate as well as the treatment plan would be instantaneously available, while providing more traditional structural support by being integrated into a bandage, for example. Furthermore, these

thin films can also be integrated into bed linen and patient dormitories, and can operate in similar ways to monitor and identify abnormalities in body temperature, as well as sweat elemental analysis. As with the lab-on-a-chip (LOC) applications, these thin films will become a key component of our approach to next-generation healthcare. Heat distribution in the body, sweat content, and frequency or postural pressure on part of the body can all reveal vital information on pathological symptoms or recovering stages.

Also in terms of medical technology, flexible electronics can be installed outside the human body as a diagnostic and monitoring tool. For example, similar heat, humidity, salt, or pressure sensor arrays can be used as a bed sheet and monitor a patient in real time. The body heat distribution, sweat content, and frequency or postural pressure on part of the body can all reveal vital information on pathological symptoms or recovering stages.

Flexible thin films could also play a key role in deciphering the thought processes occurring in the brain. Understanding the underlying neural network and its impact on the physiology and actions of an individual have been the center of many neuroscientists’ research, with significant cultural and societal impact. Although different imaging techniques exist today, such as near infrared (NIR) spectroscopy, magnetic resonance imaging, and electroencephalograms, most of these commonly used cognitive tests have limited versatility. Using thin-film multifunctional pixel arrays composed of NIR diodes, detectors, inductors, heat sensors, and electrodes would allow high-resolution multipurpose imaging and stimulation. More importantly, the simultaneously acquired data will give increasing insights on neural signal propagation, processing, and storage mechanisms.

Novel materials are now available that are robust, optically transparent, flexible, and yet electrically active. These include: ZnO-based power generation [85]–[87], thin-film oscillators and wireless power transferring systems [14], [88], and thin-film energy storage and batteries [89], [90]. These examples hint at the possibility of a futuristic deformable film where health monitoring, data processing, data communications, and energy generation and storage can be achieved on a single polymeric platform. However, routes to the control and interaction of the liquid sensing environment with these flexible systems must still be addressed.

LOC is one of the most important microsystems for next-generation healthcare, with promising applications in microanalysis, drug development, diagnosis of illness, and disease [91]–[93]. It is envisaged that flexible LOCs may form *in situ*, plaster-like, wearable health diagnostics and drug delivery. LOCs typically consist of microfluidics, sensors and, in some cases, drive and analysis electronics. Integration of microfluidics and sensors on a single flexible platform can greatly enhance the efficiency of biochemical reactions and the sensitivity of detection, increase the

reaction/detection speed, and reduce the potential cross contamination, fabrication time, and cost. However, fabrication techniques of microfluidics and sensors are different, making the integration of the two main components complicated, thereby largely increasing the system cost, particularly on polymer-based substrates.

Micropumps and mixers employing surface acoustic waves (SAWs) as actuation mechanisms are attractive alternatives from an integration perspective [94]. They offer great potential for microfluidic applications, as they are based on low-cost ZnO piezoelectric thin films that can be deposited on commercially available Si and deformable substrates. SAW-based micropumps and micromixers are simple in structure and fabrication, are inexpensive, and function as active pumping and mixing devices without any moving parts. They have proven reliable and effective [94].

SAW devices have been reported on nanocrystalline ZnO thin films deposited on Si substrates using RF sputtering [95]. No direct integration on flexible polymeric substrates have yet to emerge, though this burgeoning field is certain to bloom in time following various technological advancements. When an alternating current (ac) signal at the intrinsic resonant frequency is applied to an interdigitated transducer, acoustic waves are generated, through the piezoelectric effect [95], and travel on the surface, as shown in Fig. 9. Coupling of acoustic waves into a liquid induces acoustic streaming and motion of a droplet if in contact with a suitably hydrophobic surface. When the surface energy of the SAW device is reduced, using a self-assembly monolayer perhaps, the acoustic wave can be effectively used to pump droplets. Higher order mode waves, e.g., the Sezawa wave [96], are more effective in streaming and transportation of microdroplets. A SAW device on a ZnO island has also been used in [96] to pump and mix liquids remotely, thus avoiding direct contact of the extremely reactive ZnO film with biochemical solutions.

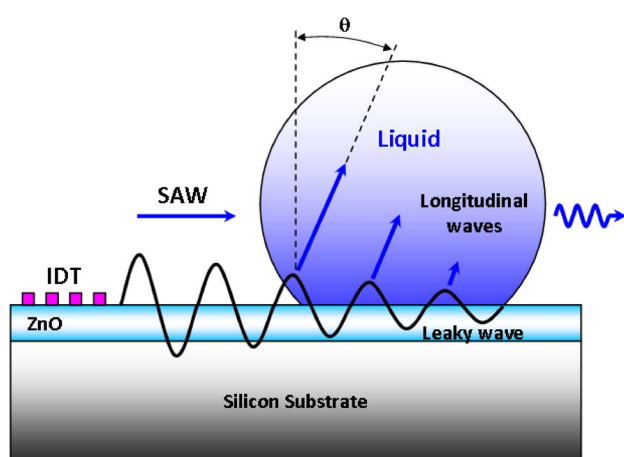


Fig. 9. Schematic diagram of interaction between surface acoustic wave and a liquid droplet and defining the Rayleigh angle (θ).

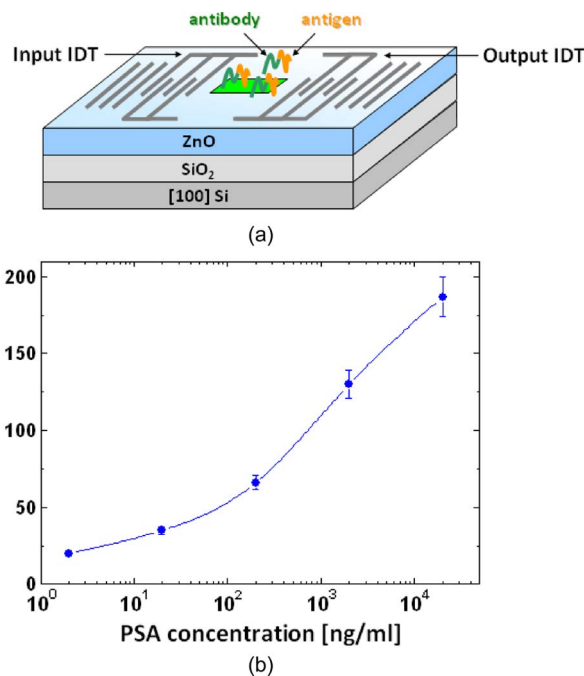


Fig. 10. (a) SAW sensor. (b) Frequency shift as a function of PSA concentration.

ZnO-based SAW devices have been utilized for biosensing [97]. Their well-defined resonant frequency decreases once additional mass is attached to the surface, where the sensitivity of the acoustic devices is proportional to the operating frequency. The high-frequency Sezawa wave of devices was used to detect reactions between prostate antigens and its antibodies. The shift of resonant frequency was found to increase as the concentration of the prostate antigens increases, indicating the potential for early stage prostate cancer detection, as shown in Fig. 10 [97]. However, SAW sensors are relatively large, which limits their resonant frequency and hence their sensitivity.

Increased sensitivity is offered by thin-film bulk acoustic resonator (FBAR) sensors [98]. These work similarly to quartz crystal microbalances (QCMs). FBARs consist of a piezoelectric film (e.g., ZnO and AlN) sandwiched between two metal electrodes to which a microwave signal is applied.

The acoustic waves generated by the microwave signals are used in a similar way as in QCMs [99]. However, in FBARs, resonant frequencies in the gigahertz range are utilized, whereas in QCMs, they are limited to a few megahertz. Hence, FBARs are potentially much more sensitive. They also have the added advantage that because of their much smaller size they can be used for array sensing, are relatively inexpensive to manufacture, and are compatible with traditional CMOS. A typical FBAR structure is shown in Fig. 11. The response of the FBARs mass-loading from bovine serum albumin (BSA), using

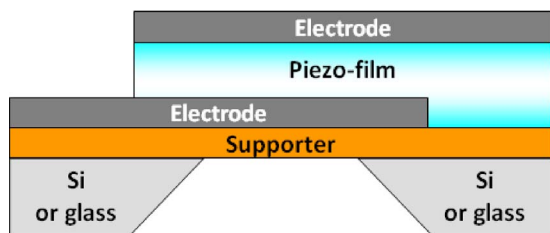


Fig. 11. Typical thin-film FBAR structure.

physically adsorbed protein coatings, has been investigated. The response is shown in Fig. 12. For a FBAR resonating at 1.5 GHz, a 3 orders of magnitude increase in response was observed compared with a QCM, for a given BSA concentration.

These results clearly demonstrate the feasibility of using a single actuation mechanism for both microfluidics and sensing. They also show the suitability of acoustic waves for LOC applications. This greatly simplifies the fabrication and operation of these microsystems, and enhances their sensitivity and performance.

Although various technologies have emerged as viable candidates for biologically compatible electronic interfaces and LOC structures, little has been achieved by way of full-scale interaction and the next challenge is to fabricate such structures on deformable plastic substrates. Preliminary work on this is currently ongoing [100], [101].

V. AUTOMOTIVE INDUSTRY

The combustion reaction has fueled the development of humanity since the discovery of fire. The main reasons for the ubiquity of combustion are twofold. The first one relates to its intrinsic mass and volume energy densities. For example, 1 kg of crude oil contains nearly 50 MJ of chemical potential energy. The second one relates to

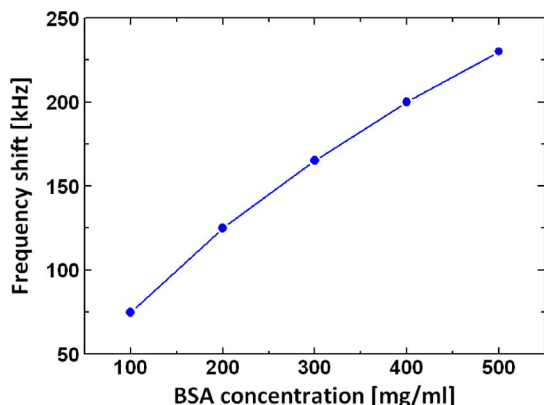


Fig. 12. Resonant frequency shift as a function of BSA concentration.

storage and portability. Crude oil happens to be liquid at surface conditions, making it easy to store, transport, and convert, which is fundamental for applications such as transportation. As a comparison, Li-ion batteries provide about 0.5 MJ/kg [102]. However, new battery chemistries, pressure for lower CO₂ emissions, and lightweight designs are contributing toward the electric alternative.

Although electric vehicles trace their invention to the mid-1800s [103], their widespread adoption has not yet materialized. This is partly due to the high energy density (J/kg) of fossil fuel compared to the batteries [104] with the implication that electric vehicles require unfeasibly heavy and large batteries to store equivalent energy as a tank of fuel. As well as low energy density, batteries suffer from low power density (W/kg) leading to electric vehicles with comparatively low performance when compared to equivalent fuel powered vehicles [105]. Despite these issues, increasingly scarce fossil fuel resources, as well as environmental incentives, have increased the adoption of electric vehicles [106], fueling research and development in this field.

Advances in thin-film battery technology through the use of nanostructures for enhanced energy density [107] and hybrid supercapacitor allowed increased energy and power densities [108]. Lightweight substrates, such as polyethylene terephthalate (PET) and paper, have led to a reduction in battery weight. Furthermore, recent developments in the structure of batteries [109]–[112] has resulted in their seamless integration within the carbon-fiber frames of electric vehicles, leading to significant overall weight and space savings. Flexible, thin-film technology is especially beneficial in this instance, as it allows batteries to be moulded into suitable shapes at relatively low costs. Fig. 13 shows a schematic of a flexible thin-film battery on a PET substrate.

Flexible thin-film technology may also find applications in road signs [113] and markings [114]. Intelligent roads will be engineered with the aim of improving road safety, lowering road congestion and energy consumption. The road and vehicle will be able to interact to dynamically adjust either party to energetically optimize their systems. The advantage of flexible thin-film technology is its mechanical durability and ease of inexpensive integration within the existing road networks.

VI. DISPLAYS AND HUMAN–MACHINE INTERACTIVITY

Improving user experiences with electronic devices requires a continuous technological development toward flexible, deformable architectures, including displays, processors, memories, and other vital electronic components. Such designs will enable wearable, interactive, portable devices. Possibly the key component here is the display. Several flexible prototypes have been presented by different commercial entities over the past few years [115],

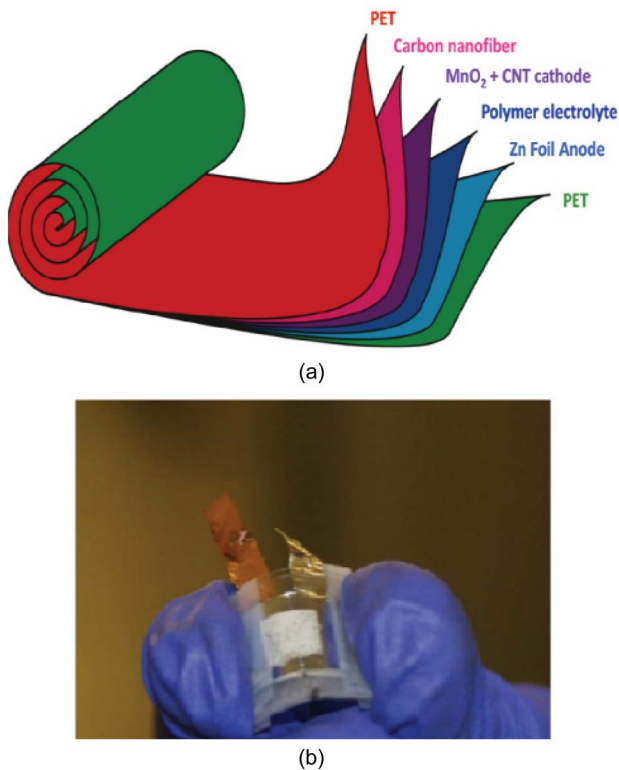


Fig. 13. (a) Battery structure. Each component must withstand flexing in order to get an overall flexible battery. (b) Optical micrograph of a flexible battery during flexing.

[116], most commonly using inkjet printing fabrication of functional polymer devices with metallic nanoparticle-based interconnects [116]–[120]. Advancement of printable polymers and devices for flexible architectures has also been explored using other nanostructures, such as NWs [121], CNTs [45], [122], and graphene [46].

The advent of touchscreen-enabled devices means further improvement in user-device interaction. An important aspect in the overall user experience now primarily revolves around the display itself. In this context, nonvisual interaction with displayed information is a vital element for next-generation display-centric devices. These are necessarily heading toward flexible form factors. New interaction technologies for touchscreens are continuously being developed and commercialized, for example, multi-touch gestures [123], [124]. However, these still fail to provide 100% satisfaction in terms of user experience, since they only give real-time visual feedback, requiring significant cognitive efforts. Current solutions for lower cognitive effort touch interfaces, in particular, vibration-enabled feedback, generate simple, monolithic vibrations (through vibramotors [125], [126], impact actuators [127], [128], or piezo-based [129] feedback systems) over the entire device, without conveying explicit interaction information to the user. In this context, flexible displays

with location-specific, real-time textural feedback that mimic the display itself can truly revolutionize the user interface ecosystem.

There have been several attempts at location-specific perception for general purpose electronic devices, most notably, using an array of electrodes through electrocutaneous stimulation (i.e., passing a small current from electrodes to the afferent nerve fibers in the user’s finger to generate perceptive stimulation [130], [131]). However, such an architecture is incompatible with the current generation of display-centric devices, which inherently dictates that the feedback must come from the display surface itself without visually obstructing it [129].

One simple way to achieve haptic feedback without obscuring the display itself is to use “electrovibration,” a phenomenon reported over 50 years ago [132], [133]. This was described as “producing a characteristic feeling when a metal, connected to an ac power line and covered by a thin insulator, is touched, which disappears when the power line is disconnected” [133]. This has later been explained through electrostatic interaction between touch surface and finger [134]. As users slide their fingers on the surface, the applied time-varying potential induces intermittent attractive and repulsive electrostatic forces between the buried conducting layer and the finger. This electrostatic attraction varies the normal contact force between user’s skin and surface and, in turn, modulates the dynamic friction and touch perception [132], [135]. Subsequent studies indicate correlations between the nature of the applied electrical signal to the buried conductor and the touch perception, promising a reasonably realistic programmable touch surface [134], [135]. Flexibility of such devices is strongly limited by conventional transparent conductors (TC), dominated by brittle metal–oxide–semiconductors [135], [136]. Graphene, being the ideal flexible TC, coated with a flexible polymer dielectric layer, such as parylene [137], can be used to fabricate fully transparent, location-specific feedback surfaces [52]. Such a device needs to be visually transparent so that it can be unobtrusively laid over existing flexible displays, enabling the generation of the location-specific, real-time programmable textures. A graphene-based programmable touch surface with flexible device architecture was recently demonstrated [138]. A generalized device schematic is shown in Fig. 14. It consists of a graphene-based TC integrated on a flexible display, a flexible, optically transparent polymer dielectric layer coated with a nanostructured touch surface. This prototype flexible electrotactile device accepts input signal patterns stored in audio files from a mobile phone, can operate with a wide range of applied electrical signals, and is capable of generating varying touch perceptions [138]. When integrated onto touchscreens, this could provide a completely new interaction experience for general users, as well as becoming one of the most essential communication media for the visually impaired.

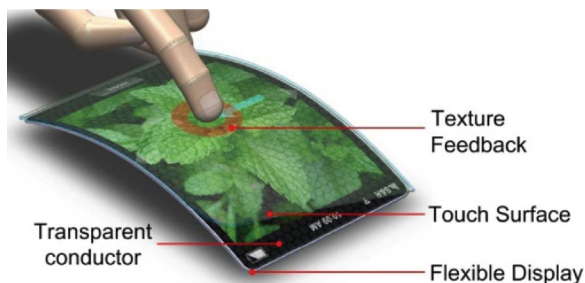


Fig. 14. Schematic of an electrotactile surface integrated on a flexible display. The ET surface consists of a TC, for example, based on graphene, and a transparent dielectric layer, which can also act as the touch surface. To improve the durability, an additional flexible transparent touch layer may also be incorporated.

VII. ENERGY MANAGEMENT AND MOBILE DEVICES

A large demand for portable, on-demand energy comes from consumer electronic devices like RFIDs, mobile phones, laptops, netbooks, tablets, and portable music players. In these situations, batteries, and more recently, electrochemical capacitors, have been the sole solution. Many advances have been made in battery technology in recent years, with research primarily directed in two streams. One aimed at: increasing energy and power densities via new chemistry; new materials or by the optimization of current systems; reducing the ratio of inactive to active components to improve energy density; increasing conversion efficiency and recharge ability; as well as enhancing safety and environmental characteristics. In particular,

- Nanomaterials play a big role in this development. The fine level of structural control they allow (e.g., higher surface area, direct electron transport, hybrid materials, and granular control of architecture) opens up possibilities for a greater control of charge transport and surface phenomena at the electrode interfaces. These developments have also allowed the use of materials and chemistries previously discarded, such as Si anodes [139] and Li-air batteries [140], paving the way for further enhanced energy and power densities. Some of the benefits include high surface areas with controlled porous structure for optimum ion penetration, permitting faster charge/discharge capabilities [141]. Fabrication of hybrid materials combines high conductivity and high storage capacity in an architected fashion [142].
- Use of entangled nanomaterials, which tolerate mechanical flexure without surface-occluding binders [143]. Nanomaterials, such as SiNWs, which make use of higher surface areas, but also allow mechanical tolerance for materials previously not

considered practical due to volume expansion and cracking [139].

- Prevention of polymer crystallization, to improve the ionic conductivity of polymer or ionic-liquid-based electrolytes provide greater mechanical rigidity and higher voltage tolerance [144].

On the other hand, much emphasis is placed on designing alternative form factors, departing from the solid bulk component toward thin, flexible [145], and even stretchable [146] and transparent [143] devices.

The advent of nanotechnology is boosting the development of energy conversion and storage. For example, graphene has already been exploited for a variety of energy applications such as batteries [147], [148], supercapacitors [149]–[152], water splitting [153], and PVs [154]. The large accessible surface-area-to-volume ratio of graphene makes it very attractive for such devices due to their high stability in electrochemical environments [149], mechanical flexibility [155], excellent electronic [40], and optical properties [52].

Although the use of graphene in energy applications has just started, the results up to date are promising. For instance, graphene-based supercapacitors outperform those based on activated carbon, with energy densities comparable with commercially available batteries [151].

Moreover, graphene could be used for a new generation of energy harvesting nanodevices, such as nanooptoelectromechanical systems (NOEMS). These could access energy sources arising at the nanoscale, converting energy from environmental sources, such as ambient noise or electromagnetic radiation, to mechanical vibrations.

This route opens up many possibilities, where device deformation allows for transformability and new paradigms of user interaction, such as in the Nokia Morph Concept (Fig. 15). These advances permit yet another form factor: textile integration. Textile-embedded electronics is becoming a reality, and textile-embedded sensors are likely to become ubiquitous. Hence, an energy source is essential. Conforming to textiles puts significant strain on

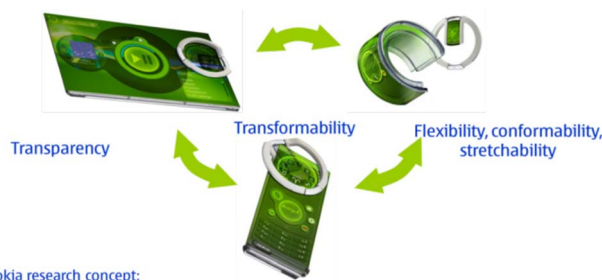


Fig. 15. The Morph mobile phone concept, where factors such as flexibility and transparency become important. Courtesy of Nokia Research.

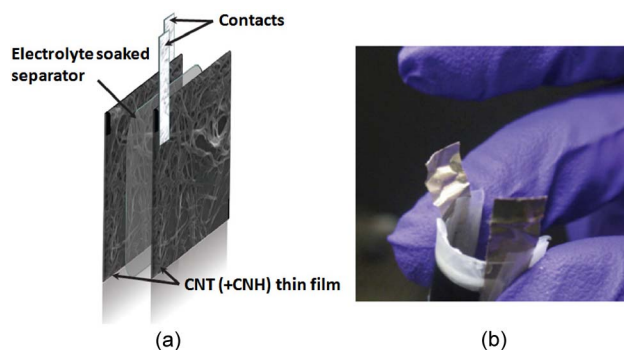


Fig. 16. (a) Schematic of the supercapacitor. (b) Flexible supercapacitor constructed on PE.

the energy storage device, requiring not only thin dimensions and flexibility, but also tolerance to stretch (10%–20% strain) for full conformability. Fibrous structures are well suited to high surface area electrodes [156]. Working strains of up to 100% have been demonstrated in packaged devices (Fig. 16) without any degradation in performance. Previously unreported stretchable electrochemical capacitors have been tested at 50% strain and have shown to offer impressive performance. These open the panorama for many new possibilities, including the integration of thin-film energy scavenging (e.g., PVs or thermoelectrics) and textile energy storage.

The growing number of miniaturized integrated devices has increased the total power consumption of current mobile phones, mainly due to processing power, displays, and RF interfaces [157]. Future devices may require an ever-increasing power and longer term standby times. Conventional batteries do not presently provide enough energy density to meet these requirements [157], as previously touched on in earlier sections. Moreover, the need for standalone devices, designed to work for long periods without a power supply, is rapidly increasing [157]. Thus, energy harvesting and storage is one of the challenges facing mobile device makers.

Today, lithium batteries are widely used. The need for ever slimmer devices is driving the transition toward supercapacitors (Fig. 16) [158], [159], with reduced size and weight, and with longer and more stable performance. More efficient energy harvesting methods could create completely autonomous mobile phones in the near future.

There are different ways to harvest, or scavenge, energy from the surrounding or ambient environment, such as the collection of low-frequency vibrations [160], heat (via temperature gradients) [161], biomechanical motion [162], and solar energy [163]. Among these, solar energy is perhaps the most promising and was demonstrated more than ten years ago by powering the Nokia 1611 mobile phone.

Si is by far the most widely used photon absorber and currently dominates the market of PV devices [164], with

an energy conversion efficiency (η) of up to 25% [165]. Despite significant development over the past decades [166], the high cost of Si-based solar cells is still a bottleneck for the implementation of solar electricity on a large scale (in the absence of government subsidies). The development of new materials and concepts for PV could be a way to reduce the overall production costs, as well as increase efficiency. The latter is crucial in view of applications in mobile devices that have a limited surface area.

Thin-film solar cells such as *a*-Si [167], cadmium telluride (CdTe) [168], copper indium gallium diselenide (CIGS) [169], and thin-film crystalline Si are termed “second-generation PVs.” The development of thin-film solar cells has been driven by the potential of manufacturing cost reduction. An even cheaper and versatile approach relies in the exploitation of organic photovoltaic (OPV) cells [170] and dye-sensitized solar cells (DSSCs) [171], [172]. They can be manufactured economically compared with Si cells, for example, by roll-to-roll processing [173], even though they have low η . An OPV relies on polymers for light absorption and charge transport [170]. It consists of a TC, a photoactive layer, and the electrode [170]. DSSCs use an electrolyte (liquid or solid) as a charge-transport medium [171]. They consist of a high-porosity nanocrystalline photo anode, comprising titanium dioxide (TiO₂) and dye molecules, both deposited on the TC. When illuminated, the dye molecules capture the incident photons, and generate electron–hole pairs. The electrons are injected into the TiO₂ conduction band, and are then transported to the counterelectrode. Dye molecules are regenerated by capturing electrons from the electrolyte.

Thanks to its exceptional electronic [40] and optical properties [52], graphene can fulfil multiple functions in PV devices: TC window, antireflective layer, photoactive material, channel for charge transport, and catalyst [52]. Graphene transparent conductive films (GTCFs) can be used as window electrodes in inorganic [174], organic [175], and DSSCs [154], as shown in Fig. 17. The best performance achieved to date is $\eta \approx 1.2\%$ using CVD graphene as the TC, with sheet resistance (R_S) 230 Ω/\square , and $T = 72\%$ (at 550 nm) [176]. However, further optimization is certainly possible, considering that GTCFs, with $R_S = 30 \Omega/\square$ and $T = 90\%$, have already been demonstrated [177]. Graphene-hybrid structures have also been produced with $R_S = 20 \Omega/\square$, $T = 90\%$ [178]. Graphene oxide (GO) dispersions were also used in bulk heterojunction PV devices, as electron acceptors achieving $\eta \approx 1.4\%$ [179]. Theoretically, $\eta \sim 12\%$ should be possible with graphene as the photoactive material [180].

An even larger number of functions can be covered by graphene in DSSCs. other than as TC windows [154]. It can be incorporated into the TiO₂ photoanode to enhance charge transport, preventing recombination, thus improving the internal photocurrent efficiency [181]. Here, $\sim 7\%$ efficiency was reported, higher than that achieved with conventional nanocrystalline TiO₂ photo anodes under the

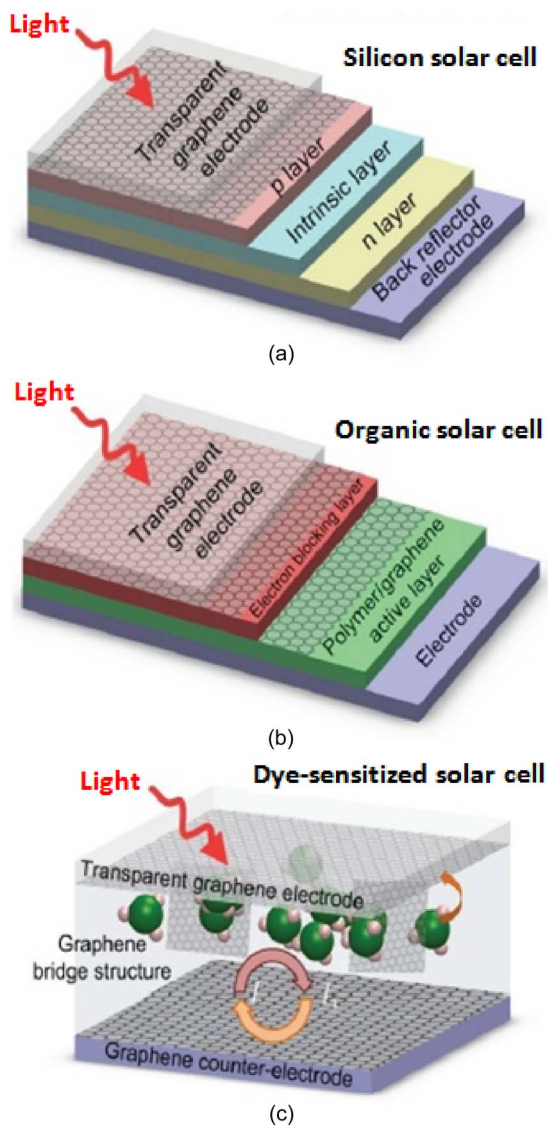


Fig. 17. Schematics of (a) inorganic, (b) organic, and (c) dye-sensitized solar cells incorporating graphene—adapted from [52].

same experimental conditions. Graphene quantum dots, with tunable absorption, are promising photoactive materials in DSSCs [182]. Further optimization is required to improve the adsorption of these molecules on TiO₂ nanoparticles, by covalently attaching binding groups to enhance charge injection.

Another option is to use graphene, with its high specific surface area [149], as a substitute for the platinum (Pt) counterelectrode. Hong et al. [183] used hybrid poly (3,4 ethylenedioxythiophene):poly (styrenesulphonate) PEDOT:PS)/GO composite to obtain $\eta = 4.5\%$, which is comparable to a Pt counterelectrode tested under the same experimental conditions [183], but achieved using a substantially cheaper material. Graphene can therefore be used to simultaneously replace both the Pt as catalyst and

ITO as conductive electrode [184]. This is another important step toward cost reduction and large-scale integration of DSSCs.

The combination of graphene with plasmonic nanostructures offers a way to increase light harvesting properties. This concept has been demonstrated in graphene-based photodetectors [185]. This is promising for mobile devices, where the small surface area requires the exploitation of materials with high efficiency in photoconversion.

In recent years, there has been a growing interest in mobile and portable computing systems, such as wearable computers, personal digital assistants, smartphones, notebooks, field computers, and sensor nodes. Despite the growth in the use of wireless connectivity and increased mobile computing, typically a mobile device still needs to be periodically charged via the electrical network. Furthermore, increase in mobile computing power and communication bandwidth has resulted in higher energy consumption [186]. Today, a key component of any mobile system is a high-power and high-energy density battery that can store sufficient energy as well as being lightweight and compact [186].

An alternative approach is a scheme where the mobile device generates some of its own power, thus reducing, or even eliminating, the need for numerous charging cycles. Manual power generation has already been used in some devices. One example is the XO-1 laptop which is targeted at school children in rural areas, where access to electricity is limited. Below is an extract from an interview given to the BBC News network by one of the XO-1 designers [187]:

“In areas without access to the grid, various contraptions have been designed to plug directly into the laptop including a solar panel, a hand crank (similar to those used on wind-up radios), a foot pedal and a pull-string recharger, similar to a starter cord on a lawnmower.”

Some powering schemes, such as manual power generation, require human intervention. This may not be practical in many applications, where devices are required to operate independently and continuously.

Solar power is a globally accessible source of energy. It allows mobile devices to operate in remote and inaccessible locations by removing the need for extensive energy delivery infrastructure. It is a safe and environmentally friendly source of energy. Solar energy harvesting systems capture, via the use of various photoconversion technologies, incident solar radiation, and use a circuit to store it in an energy storage unit. The intensity of the sunlight prior to entering the Earth’s atmosphere is $\sim 1.3 \text{ kW/m}^2$ [188]. After this, the intensity reduces, but can still be as high as 1 kW/m^2 [188]. Assuming an average light intensity of 0.5 kW/m^2 and 5 h of daylight, a solar cell array area 1 m^2 in size, with 5% system efficiency, a mobile energy

harvesting system could generate and store 125 Wh/day. A typical Li-ion battery cell used in modern laptops can store 60 Wh. Therefore, this estimate suggests that an energy harvesting system such as this can produce over twice the amount of the energy stored in a laptop battery in one day. Such a high level of energy, combined with a suitable power management system, has a potential to be a viable energy source for a range of remote devices.

A mobile solar energy harvesting system [189] requires a number of attributes to allow integration with mobile devices. It should be lightweight and durable. Mechanically flexible systems would improve durability and allow enhanced integration. A candidate for such a system is a thin-film system fabricated on flexible substrates. Thin-film-based solar cells can achieve higher power per unit mass compared with bulk solar cells (such as c-Si). For example, power density achieved from thin-film cells is in the range of 40 W/kg for triple-junction *a*-Si solar cells on plastic substrate. Fig. 18 shows a possible integration route for mobile energy systems, with a display unit, with the aim of harvesting ambient illumination or some of the optical losses within organic light emitting diode displays [190]. A fully integrated energy harvesting system would be the obvious next step, in which the energy conversation/storage devices and charging circuit, as shown in Fig. 19, are seamlessly integrated on a flexible sheet.

Complementary circuits are essential building blocks in today's electronics as they facilitate low-power operation of circuits. Although simple energy management circuits for energy harvesting can be realized using conventional unipolar electronics, the use of complementary circuitry facilitates improvement in their efficiency. Inverters are one of the most fundamental proof-of-concept complementary circuits. Chen *et al.* [191] reported air stable complementary polymer inverters fabricated

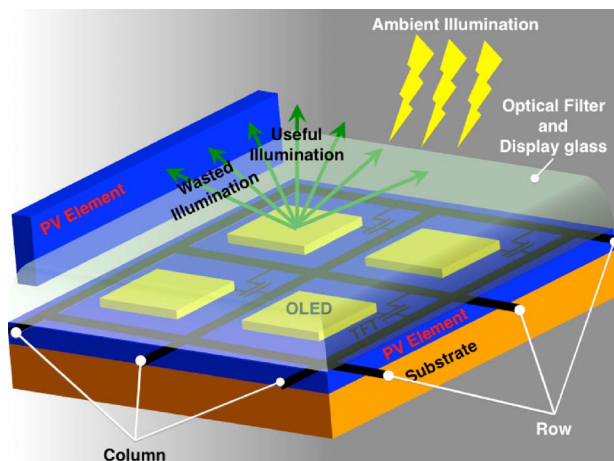


Fig. 18. A typical display system with PV mobile energy harvesting system (adapted from [190]).

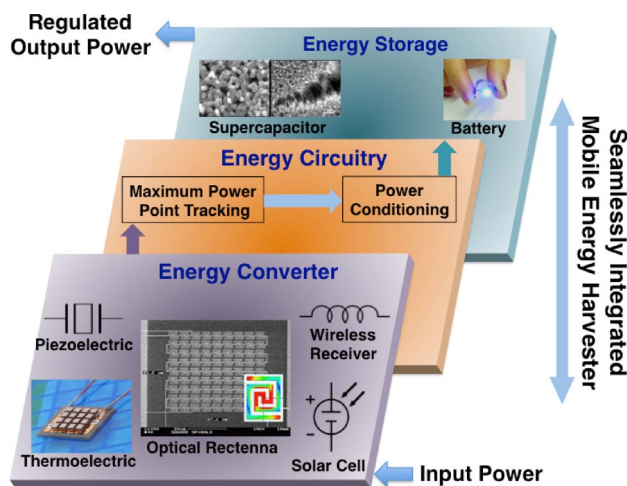


Fig. 19. System components of a flexible, wearable mobile energy harvesting system.

with printed top-gate electrodes and the semiconductors. Both *p*- and *n*-channel polymer transistors show good electric performance in ambient conditions. Atomic force microscopy found that the P (NDI2OD-T2) films were crystallized after drying. Postannealing would only reduce crystal defects and grain boundary mismatches. It was further confirmed by optical absorption spectroscopy, as the shift in the absorption peak before and after annealing was minimal. The feasibility of fabrication of low-cost polymer complementary circuits with inkjet printing in industrial environments was also shown.

VIII. WIRELESS SYSTEMS

Mobile devices offer almost seamless data connectivity, a state which is enabled by rapid progress in wireless communication networks [157], [192]. In addition to global system for mobile communications (GSM) cellular radio, it is now common for devices to be able to communicate via a range of different protocols including wireless local area networks (WLANs), Bluetooth, near-field communication (NFC), Global Positioning System (GPS; receive only), FM radio, and wireless personal area networks (WPANs). While these protocols have become important drivers for the telecommunications industry, the autonomous flexible sheet/system should be cable free and also have the ability for two-way communication.

A basic wireless communication system is shown in Fig. 20. The source signal is used to modulate a carrier radio wave whose frequency is typically in the range from 850 MHz to 5 GHz for mobile communications. The IEEE 802.11 WLAN standards cover the 2.4-, 3.6-, and 5-GHz frequency bands, and currently 2.4 GHz has attracted most attention. Fig. 20 shows that the transmitter and receiver antennas play a key role as they provide coupling to the

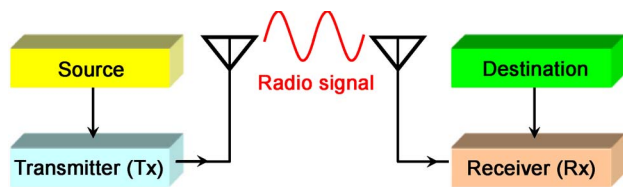


Fig. 20. General radio system diagram.

physical communications channel, which is where the signal encounters noise and other detrimental channel distortions.

Many types of antenna geometries have been employed in mobile devices, including the basic dipole. The most commonly used geometries are microstrips, patch, and planar inverted-F antennas (PIFA). These have the advantage of being very compact, conformal, and can be made resonant at several different frequencies to allow multi-band operation. In addition, their planar nature allows print-based manufacturing, advantageous when considering integration with flexible structures. Antennas are commonly fabricated on rigid substrates, since their geometry attributes which determine their resonant frequency and any mechanical distortion usually lead to undesirable detuning. New device concepts using flexible substrates (for example, polyimide, polyester, or silicones) have emerged, and so increasing attention has been paid to flexible antennas [193]–[197], which can be mounted on the nonplanar surfaces of a system. Fig. 21 demonstrates a flexible PIFA antenna and a typical simulation before and after bending. The resonant peak frequency remains unaffected [Fig. 21(b)]. Flexible and stretchable antennas have also been demonstrated for applications such as clothing textiles [198], medical applications, and flexible RFID tags [88], [199]. The key advantages of such antennas are their robustness, lightweight, and tolerance to moderate mechanical strain. As an example, polydimethylsiloxane (PDMS)—a robust silicone elastomer—is low cost, has tunable dielectric properties, and can be repeatedly strained up to ~100% and has been widely used.

Stretchable antennas have been fabricated using PDMS, which is usually cast on a photoresist mould with the desired design [198]–[200]. The PDMS structure is then peeled away and holes introduced for injection of a liquid eutectic (Galinstan: 68.5% Ga, 21.5% In, 10% Sn, $\sigma = 3.46 \times 10^6$ S/m), to form the radiating elements, as shown in Fig. 22(a), (c), and (d) [200]. The maximum antenna gain at 2.5 GHz for such an antenna was measured to be around 2.2 dBi, which is acceptable, but port impedance matching varies from device to device, especially above 40% strain, in the plane of the antenna. Another recently explored route for fabrication of stretchable PIFA antennas uses direct deposition of thin-film gold [Fig. 22(b)] onto an elastomeric substrate. Similar studies

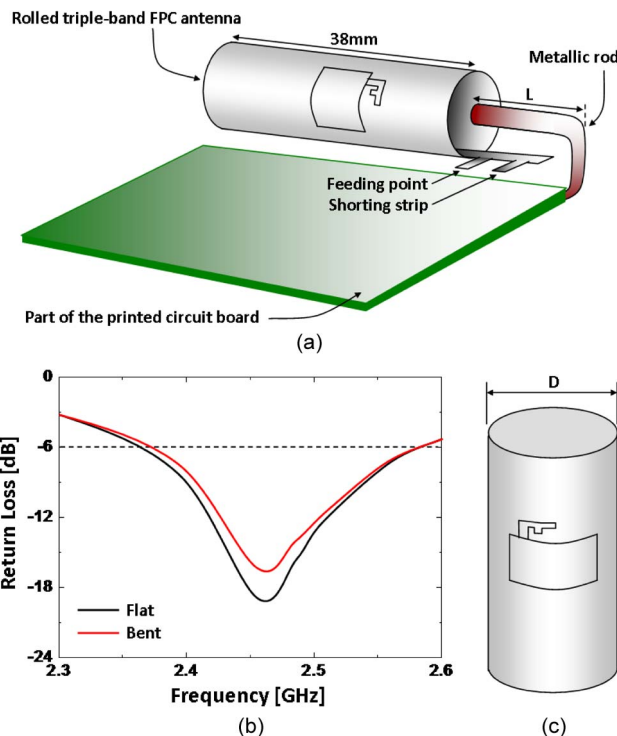


Fig. 21. (a) Geometry of a flexible PIFA triple-band antenna rolled around a cylinder [193]. (b) Bent PIFA antenna simulated and measured for return loss showing flat and bent measurement differences [195]. (c) Typical antenna rolled in a cylinder to measure the return loss. Images courtesy of Nokia Research.

have shown that the efficiency of such antennas varies with the thickness of the stretchable conducting films. Indeed, it was found that there was an optimum thickness which provides maximum gain [201].

There are, of course, some significant challenges for the design of flexible antennas still remaining. Although antennas made on flexible substrates offer many advantages, one major drawback is that their performance is very sensitive to the surroundings. The impacts of noise, shielding, and attenuation during flexing are important parameters to address. For stretchable antennas, it is important to note that the conductors such as thin-film gold [202] or nanomaterials (e.g., CNTs) have issues, whereby their impedance usually depends upon strain, which in turn affects the antenna’s resonant frequency. Compensated matching circuits are thus essential. Also designs which keep the characteristic impedance to a minimum (~50 Ω) during mechanical strain are required in order to reduce losses. Alternatively, materials with strain-dependent resistance might be appealing since they offer the opportunity to implement tunable antenna through mechanical stretching. There are several groups of researchers working in this area that have demonstrated such concepts [198]–[202]. Interesting designs employing serpentine copper interconnects

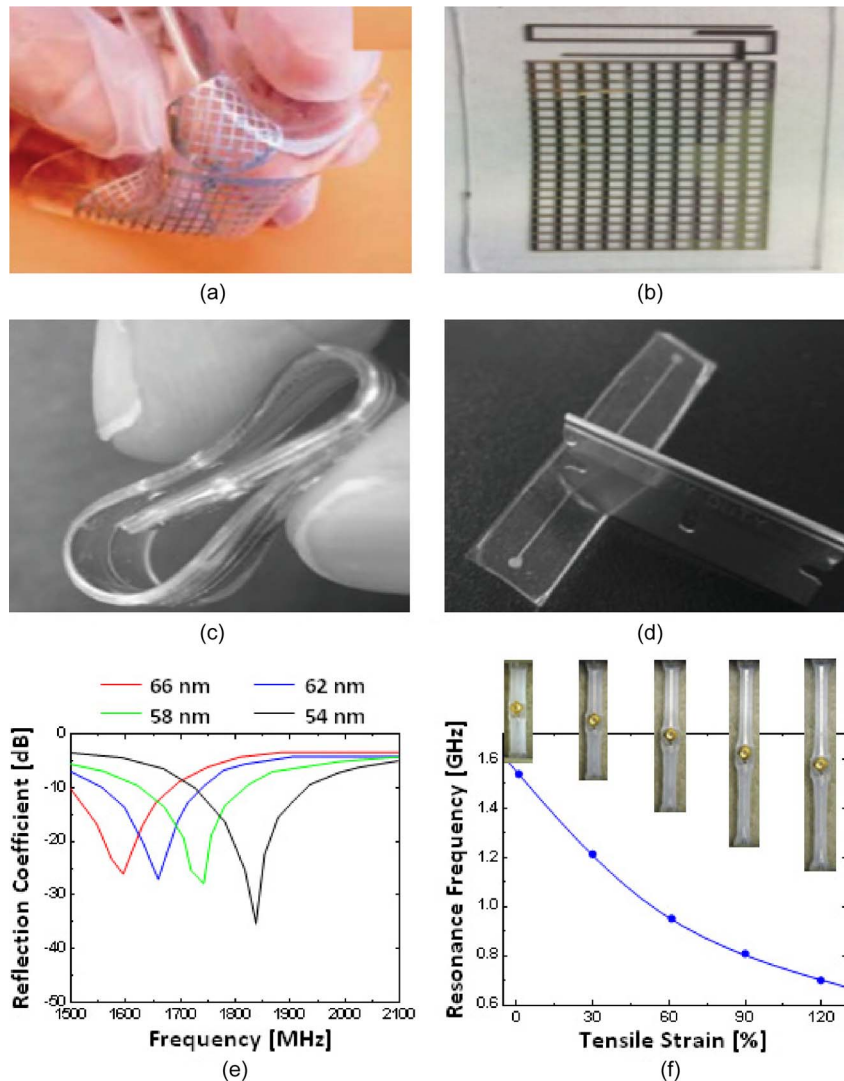


Fig. 22. (a) A stretchable antenna fabricated using a GaInSb eutectic on a PDMS substrate [198]. (b) A PIFA antenna fabricated using thin-film gold on PDMS. (c) A liquid metal antenna supported on PDMS. (d) The antenna self-heals in response to sharp cuts, such as those inflicted by a razor blade [200]. (e) Shift in frequency as the antenna is stretched along its long axis; adapted from [200]. (f) The resonance frequency of the antenna as a function of the tensile strain. The resonance frequency of the antenna decreased from 1.53 to 0.738 GHz as the antenna was stretched from l_0 to $l = 2.20 l_0$. After releasing the strain, the resonant frequency returned from 0.738 to 1.53 GHz [199].

have been used to demonstrate transmission lines for stretchable electronics up to 10-GHz range [203].

Utilization of radio spectrum bandwidth in an efficient manner is critical. Hence, the concept of cognitive radio applications is developing, where radios can operate in a broad spectral range with efficient low power consumption by continuously switching to a free operating band. This will allow more autonomous and dynamic use of the spectrum, with even greater demands on the device antennas, flexible or not. Wireless technology will offer faster and high-speed performance. Devices integrated with intelligent computing using wireless sensors will keep everything, everywhere connected thereby providing seamless operation for the users.

IX. ELECTRONICS EMBEDDED IN THE LIVING ENVIRONMENT

Buildings are responsible for high energy consumption ($\sim 40\%$ in the European Union) and large CO₂ emissions (i.e., $\sim 36\%$ in the European Union) [203]. New generations of active, controllable materials and devices with flexible form factor are being investigated to replace more conventional alternatives throughout the built environment. Controllable insulation in residential and office buildings, in accordance with the seasonal variations, can be achieved with “smart window” technologies [205]. These offer single or multiple functionalities, for example, controllable change in wavelength-dependent/independent light transmission/

reflection, direct/indirect energy saving (e.g., blocking sunlight upon heating, hence lowering air-conditioning energy consumption) [205]–[208] and even energy generation (e.g., integrated PV modules) [209], [210].

Building-integrated PV (BIPV) systems serve multiple purposes, giving an advantage over conventional PV systems. BIPV modules do not require moving parts and fuel and do not create pollutants over their life cycle.

BIPV technology has been developed and applied to glass façades or skylights for over two decades [211], [212]. The effect of BIPV modules on energy consumption must be analyzed not only in view of electricity production, but also for thermal and optical aspects [213]. Optimum design (i.e., window-to-wall ratio, relative orientation to the daily and seasonal sun position, etc.) needs must be achieved to evaluate the overall performance of smart PV windows. Electricity production and thermal (heating and cooling loads) and optical (daylight) performances are intimately interconnected.

A rapidly growing Si market has thus far dominated the PV market. The less expensive alternative *a*-Si modules suffer Staebler–Wronski (SW) degradation [214]. In a typical *a*-Si solar cell, the efficiency is reduced by up to 30% in the first six months of operation, and the fill factor falls from over 0.7 to about 0.6 [215]. The effect is temperature dependent, such that performance tends to recover in the summer months, while dropping again during winter [215]. This light-induced degradation is perhaps the most major disadvantage of *a*-Si [216]. Si and *a*-Si solar cells also suffer integration problems. Si-based solar cells are well established in rooftops or solar parks, but are not suitable for integration into windows, other than façades and shading elements. Thin-film technologies, although already produced by several companies [217], suffer similar problems. They are not fully integrated into building components, but just “building appended.” Moreover, traditional flexible thin-film systems do not usually meet the legal requirements for façade integration. Most importantly, they do not offer the degrees of freedom in terms of design, as they are difficult to tailor with respect to color or transparency. Additionally, aesthetics, while irrelevant for the main function of the devices, certainly has a significant market impact.

In this context, third-generation solar cells, such as OPVs [170] and DSSCs [171], [172], are promising alternatives to traditional PV and meet the stringent requirements for building integration [212]. Incorporation of solar modules into insulating windows will lead to a twofold benefit: on the one hand, the windows will be provided with functionality; on the other hand, PV modules packaged in the middle of double-paned windows will be hermetically sealed and isolated from water and oxygen, enhancing their stability. Indeed, longevity is the largest challenge in developing commercial BIPVs with lifetimes approaching those of the windows themselves, which are usually not replaced for decades.

Graphene is a promising candidate for the advance of third-generation solar cells, as has been highlighted throughout. It maintains its electronic [40] and optical [52] properties even under extreme bending and stretching, ideal for integration in polymeric-rigid and flexible substrates. This is important in view of integration not only in windows, but also in other building components. Given the large area requested for BIPV modules, the material cost and deposition systems play a key role. Several approaches have now been investigated to provide a steady supply of graphene in large areas and quantities, amenable for cost-effective mass applications. Indeed, besides the “low-tech” approach based on mechanical exfoliation of graphite [218], [219], which has so far produced the highest quality samples, graphene can now be produced on large and cost-effective scale by either bottom-up (epitaxial or “atom-by-atom” growth) [177], [220]–[230], or top-down (exfoliation from bulk) [231]–[235] approaches. Chemical vapor deposition [227]–[230], [235], [236] and liquid phase exfoliation [231]–[235] are the most appealing and can be integrated in a roll-to-roll processes. Liquid phase exfoliation graphene can be deposited over large areas by rod coating (Fig. 23) as well as other techniques [138], [237].

BIPVs can also be integrated with smart windows. Though the term “smart window” encompasses a wide range of devices, it is commonly referred to a narrower category, the “switchable light modulators.” Smart windows can change the light intensity or the spectral composition passing through them, while preserving transparency, or can completely switch from transparent to opaque. These can further be classified as nonelectrically (NESSWs) or electrically switchable (ESSWs) devices, the former including thermochromic [i.e., changing light transmittance upon heating], photochromic (activated upon ultraviolet (UV) illumination), and gasochromic (activated upon gas exposure, e.g., highly diluted hydrogen on WO₃ windows). However, wide adoption of NESSWs is limited due to the lack of convenient control mechanisms. ESSWs are straightforward to use and most suitable for controlled glazing in buildings. The three major smart window technologies currently available are electrochromic (EC) [205], [238], [239], suspended particle (SPD) [205], [240], and polymer dispersed liquid crystal (PDLC) [205], [241], [242].

In EC devices using transition metal oxides (which are large bandgap semiconductors, and hence, visually transparent), the injection of electrons or protons through a pair of transparent TC layers induces strong absorption in the visible spectrum, resulting in a color change [205], [238], [239]. The main drawback of EC devices is their relatively slow response time, usually in the range of several tens of seconds up to several minutes [243]. SPDs use rod-shaped particles, suspended in an organic liquid or gel, bound between a pair of TC layers [205], [240]. The particles change their orientation under applied electric field, thereby controlling the light transmittance [205], [243].

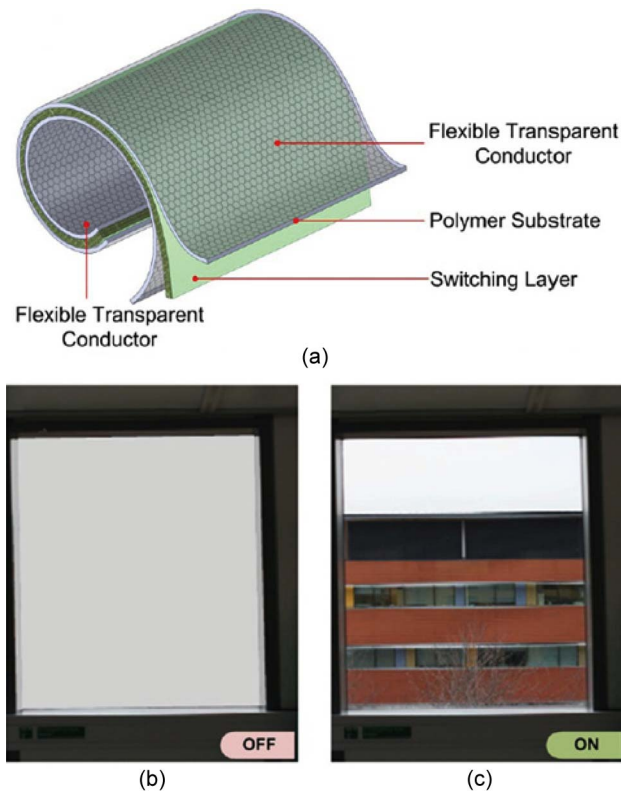


Fig. 23. (a) General schematic of flexible ESSWs. The switching layer can have a single or multiple functional layer, depending on the window type. A mockup of an undyed PDLC-based ESSW when the device is in the (b) frosted or off state, and (c) transparent or on state.

[244]. SPDs allow gradual control of transmittance, an attractive feature for ESSWs, though critical issues like cyclic durability and particle instability in suspension have hampered their development [205]. PDLCs employ liquid crystal (LC) droplets embedded in a polymer, sandwiched between two TCs [242]. An electric field through the TC electrodes controls the overall alignment direction of LC molecules, allowing light modulation through the device [242]. Though PDLCs are faster (around tens of milliseconds) and good control in transmittance can be achieved using dyes, their main drawbacks are clarity in the ON state and UV stability of common LC molecules [205], [243]. All these devices have their own strengths and weaknesses and have been sporadically implemented in different market segments. However, their widespread adoption for glazing smart buildings is limited by their long-term reliability and large areas required (several squared meters) [205]. Production of large-area active thin films in all these devices is challenging, driving the costs up to \$1000 per squared meter [205], [245]. Advancement of large-area deposition of active materials on flexible substrates is expected to bring the production cost down to several hundred dollars per squared meter [205], [245]. The other critical factor is the requirement of very large-

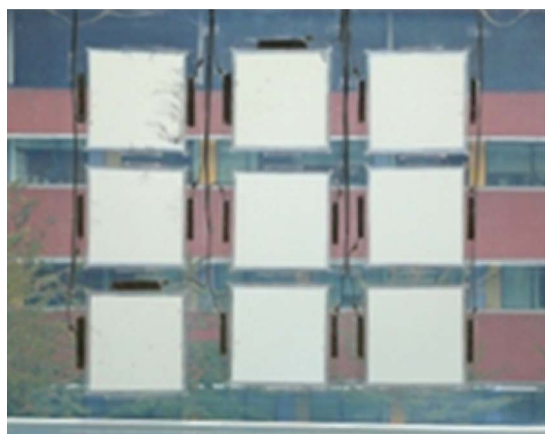
area TCs. Graphene may be used as TCs for these applications, providing low reflectivity and high optical transmittance ($> 80\%$), bringing the price below \$100 per squared meter, the target price for mass commercialization [205], [245]. Provided the functional layers are flexible, graphene will enable fully flexible smart windows. While both CVD and liquid phase exfoliated (LPE) graphene [205] are suitable, given the moderate sheet resistance required for this application ($< 1 \text{ k}\Omega/\text{sq.}$ for SPDs and PDLCs, $< 0.1 \text{ k}\Omega/\text{sq.}$ for ECs) [52], [177], combined with the necessary large areas, roll-to-roll fabricated TCs on polymeric substrates from LPE graphene are more likely to dominate flexible or easily retractable smart windows and related applications.

A graphene-based flexible PDLC smart window was recently demonstrated [237]. The device has a contrast ratio (ratio between ON and OFF transmittance) > 230 , with $\sim 60\%$ ON transmittance across the visible spectrum, and is able to operate under repeated flexion. The same graphene-based TCs can be easily applied to other types of flexible smart windows without any performance penalties.

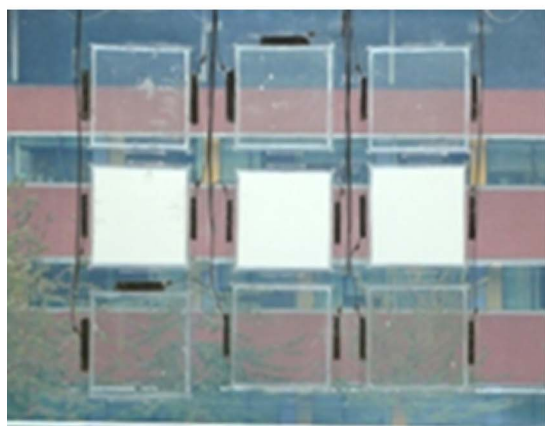
In addition to incorporation of flexible TCs, LC-based smart windows can be further improved by employing a more advanced active switching layer. Using a new generation of high-performance Smectic A liquid crystal materials and recently developed know-how in the fabrication of LC device structures on plastic, electrically controllable optical film for use on windows that will enable the control of solar radiation entering a building and will provide digital display of information at low-resolution has been demonstrated, as shown in Fig. 24. It has the advantages of being light in weight, retrofitting compatible, bistable for a zero energy footprint when not switching, highly transparent in its clear state (the apparent haze when cleared was due to the substrate in use), and capable of color changing for smart façade and ambient decoration.

Smart window technologies are also being investigated in automobiles/aircraft and information display markets. EC rear view mirrors with controllable glare have long been produced. Smart window technologies are currently being used in high-end automobiles and trains [246], [247], as well as for showcasing displays and privacy purposes inside residential and business settings. EC devices have been introduced in the passenger windows of the Boeing 787 [248]. Indeed, a futuristic concept recently unveiled by Airbus [249] focuses not only on user comfort, noise level, and fuel efficiency, but also on controllable cabin transparency according to “lighting conditions.” Such radical designs offer a glimpse of what this flexible thin-film technology can evolve into in the near future.

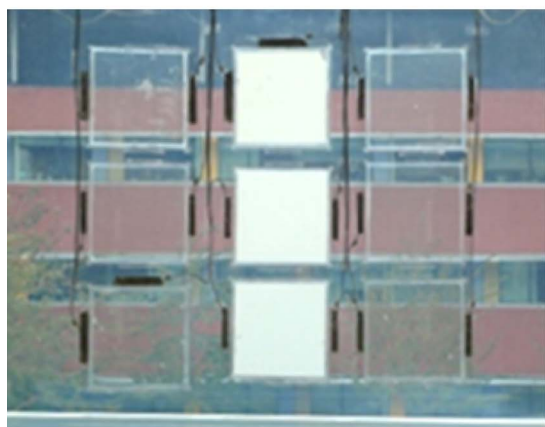
Distributed photosensors, seamlessly integrated within a building, is an essential feature of the future living environment. The information from these sensors is used in the building management system to create the “ideal” living environment. Organic TFTs provide one possible platform for photodetection with device photosensitivity as



(a)



(b)



(c)

Fig. 24. $3 \times 3 \text{ m}^2$ plastic laminated optical control film-panels-based Sma liquid crystal materials as assembled on a ethylene tetrafluoroethylene (ETFE) sheet. The apparent haze in the cleared state was due to the substrate in use. Courtesy of U.K. Technology Strategic Board (TSB) PICWIN Project.

a key figure of merit. Photoresponse of organic TFTs using PQT-12 as the organic semiconductor has been investigated using monochromatic illumination at a wavelength which matches thin-film’s absorption peak [250]. Here,

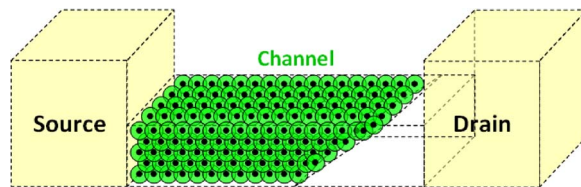


Fig. 25. A sketch of polarons in the channel when “useful polaron density” reaches a threshold value. In this situation, the distance between two black dots corresponds to the polaron diameter. Adopted from [251].

unlike normal phototransistors, the drain current does not increase monotonically with light intensity. Rather, it tends to decrease after reaching a maximum. This oversaturation behavior can be explained by considering the useful polaron density to show that the photo-generated electrons and holes, in the form of polarons, interact with each other to trigger a recombination and annihilation which dominates generation when the polarons are closely packed, as shown in Fig. 25. The departure of the useful polaron density from its linear dependence on light intensity is associated with the average gap between polarons equaling their mean free path. Using the corresponding threshold values of useful polaron density, $1.6 \times 10^{17} \text{ cm}^{-3}$ and $2.2 \times 10^{17} \text{ cm}^{-3}$, the polaron diameter and mean free path can be calculated as 19 and 2 nm, respectively. Potential applications of such behavior include resolving details of weak light intensities without oversaturation due to nearby high light intensity.

The apparent shift of threshold voltage of flexible organic TFTs under light illumination has been explained successfully using a model detailed in [251]. The apparent threshold shift comes from the increase in total current due to the photo-generated current. The validity and the consistency of this model were confirmed by a number of measures, including an agreement between the apparent threshold voltages of the device under illumination and those calculated from computer models. Note that there has been indeed a photo-generated current in organic thin-film transistors, and that in these systems, where electron and hole mobilities are similar, the apparent shift of threshold voltage of the device under illumination is entirely due to the photo-generated current, and the intrinsic threshold voltage remains constant, both under illumination and dark ambients. For the case where electron and hole mobilities are different, the intrinsic threshold voltage is likely to change when an organic thin film transistor is under illumination, as does the apparent threshold voltage.

X. ELECTRONICS FOR HOSTILE ENVIRONMENTS

As our living environment evolves with time, we increasingly encounter ever more hostile environments where the

inherent benefits from the application of thin-film flexible electronics becomes essential. For instance, consider the accelerating pace of climate change [252], which has resulted in an overall reduction in global rainfall [253] leading to a shortage of fresh water supplies. This, combined with the growing global population, has put substantial pressure on existing agriculture infrastructure leading to increased food and commodity prices [254]. One approach in mitigating the effect of fresh water shortage is conversion of abundant seawater into fresh water via desalination [255].

Although a number of technologies exist to solve this problem, their adoption has been limited to the developed nations due to the high cost associated with the energy-intensive processes and inherent lack of low-cost scalability [256]. A number of reports have suggested that electrical processes, based on parallel plate capacitive structures, can be used as an alternative [257]. Fig. 26 summarizes this basic concept. A bias is applied across parallel thin films with seawater flowing in the interelectrode space. This induces an electric field across the seawater, leading to a drift in ionic contaminants toward the electrodes with opposite charge polarities. Through the use of sponge-like secondary electrodes, it is possible to adsorb and immobilize these free ions leading to water purification. This desalination process, compared to other technologies available, primarily benefits from low energy consumption. Furthermore, the low-cost, large-area fabrication processes inherent in thin-film flexible electronics facilitate the creation of ultrahigh throughput systems at minimal expense, as required for globally accessible fresh water production.

Increasing concerns on the global energy crisis, climate change, decreasing availability of fossil fuels, and environmental issues motivate research toward sustainable and renewable energy resources. The key is the development of efficient energy conversion and storage devices. Energy management, used to decouple the timing of generation

and consumption of electric energy, is also fundamental for cost reduction and increasing income from electricity and heat generation.

Renewable energy was estimated to account for half of the newly installed electric capacity worldwide in 2010 and has become progressively more important with a total of 19.4% of the global electricity production, increasing by $\sim 21\%$ since 2009.

However, renewable energy from wind, wave, tidal, and solar sources is intrinsically intermittent. It is not always readily available. For instance, although harvesting energy from the sun is clean and safe, the supply follows annual and diurnal cycles. This can cause design and engineering problems in supply grids, in physical balancing for maximum power transfers and in overall power capability, stability, and security. Solar energy must be used as soon as it is harvested or suitably stored in a highly efficient, low-leakage devices. Hydrostorage offers one simple solution here. The effectiveness of local energy management can be greatly improved by integrating storage units with a local management system. This can also drive the costs down as well as opening up new control possibilities.

The thin-film nature of PV cells combined with the possibility of their fabrication on lightweight and flexible substrates has allowed the development of high energy density solar cell arrays (W/kg) [258] which when combined with disorder thin-film semiconductors (such as *a*-Si:H [259], [260]) resilience to high energy particles (typically found outside the atmosphere) makes them ideal for use in hostile environments, such as in space exploration. Until now, however, their low energy per unit area (W/m²) has marginalized their adoption in favor of ultrahigh efficiency GaAs solar cells [261] with comparable energy densities [262]. However, the development of recent proposals in spacecraft layout, which incorporates large area, and flexible features such as solar sails [263], could pave the way for the use of thin-film solar cells in space exploration.

In addition to energy generation, that potential for large area, roll-to-roll, low-cost deposition technique on flexible substrates suggests that thin films and flexible electronics could be used in systems for space-waste collection [264]. The “cascade effect” in space debris predicts that when debris collisions produce large numbers of objects those objects may undergo further collisions producing even more debris leading to a power-law growth in the amount of space debris [265]. This chain reaction, which could lead to the closure of some of the more popular satellite navigation and communications orbits within decades [266], had been the subject of intense research by numerous international space agencies. One possible solution recently proposed by the JAXA and Nitto Seimo Co. consists of a conductive and flexible net in Earth orbit [267], capable of collecting such debris entering its path. The net’s multilayered structure generates and stores charge, which, when interacting with

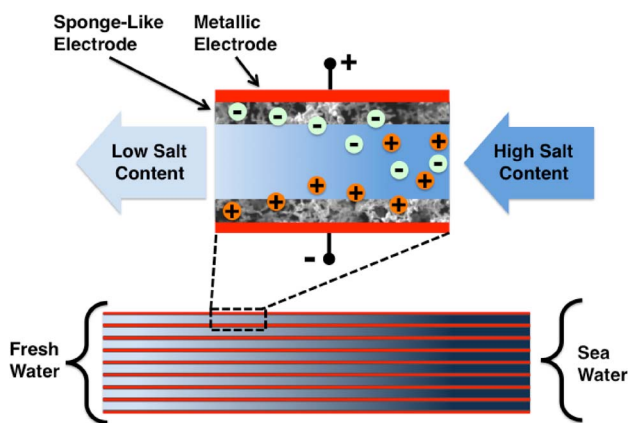


Fig. 26. A water desalination system with low energy consumption based on capacitive technology.

the Earth's magnetic field, leads to a deceleration and subsequent reduction in the net's orbit. Eventually, the net and debris re-enter Earth atmosphere and burn up, leaving negligible residue. Here the durability and strength of the net is critically important, and can be engineered through the combination of various nanostructures while also including appropriate coating technologies to optimize its functionality.

Flexible electronics in hostile environments can also find use in military applications. Increasingly high-tech warfare requires enhanced access to energy supplies [268]. A mechanically flexible and durable product with light-weight mobile power harvesting system, as depicted in Fig. 19, is one possible solution.

XI. CONCLUSION

In this paper, we have considered some of the unique properties and applications of thin-film flexible electronics. Based on the current socioeconomic trends, we outlined some of the more likely technological future needs

and discussed the potential exploits of thin-film flexible electronics in various market sectors.

We have shown that the novel properties of thin-film, flexible electronics such as low weight, mechanical flexibility and durability, simple device integration, along with low-cost and large-area processability allow them to be utilized in a wide range of applications from space exploration to water purification, and from displays to conformally integrated automotive batteries.

Future developments in flexible thin-film technology are likely to enhance the performance of the devices discussed here, leading to more widespread applications. However, it should be noted that, as with any prediction on the scale attempted here, unforeseen global developments may lead to inaccuracies in some of the assumptions made. ■

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REFERENCES

- [1] T. D. Anthopoulos, S. Setayesh, E. Smits, M. Cölle, E. Cantatore, B. de Boer, P. W. M. Blom, and D. M. de Leeuw, "Air-stable complementary-like circuits based on organic ambipolar transistors," *Adv. Mater.*, vol. 18, no. 14, pp. 1900–1904, Jul. 2006.
- [2] H. Yin, S. Kim, C. J. Kim, J. C. Park, I. Song, S.-W. Kim, S.-H. Lee, and Y. Park, "Bootstrapped ring oscillator with propagation delay time below 1.0 nsec/stage by standard 0.5 μ m bottom-gate amorphous Ga₂O₃-In₂O₃-ZnO TFT technology," in *Proc. Electron Devices Meeting*, San Francisco, CA, 2008, DOI: 10.1109/IEDM.2008.4796619.
- [3] G. Kawachi, Y. Nakazaki, H. Ogawa, M. Jyumonji, N. Akita, M. Hiramatsu, K. Azuma, T. Warabisako, and M. Matsumura, "Characterization of high-performance polycrystalline silicon complementary metal-oxide-semiconductor circuits," *Jpn. J. Appl. Phys.*, vol. 46, no. 1, pp. 51–55, Jan. 2007.
- [4] R. Hayashi, M. Ofuji, N. Kaji, K. Takahashi, K. Abe, H. Yabuta, M. Sano, H. Kumomi, K. Nomura, T. Kamiya, M. Hirano, and H. Hosono, "Circuits using uniform TFTs based on amorphous In-Ga-Zn-O," *J. Soc. Inf. Display*, vol. 15, no. 11, pp. 915–921, 2007.
- [5] D. J. Gundlach, J. E. Royer, S. K. Park, S. Subramanian, O. D. Jurchescu, B. H. Hamadani, A. J. Moad, R. J. Kline, L. C. Teague, O. Kirillov, C. A. Richter, J. G. Kushmerick, L. J. Richter, S. R. Parkin, T. N. Jackson, and J. E. Anthony, "Contact-induced crystallinity for high-performance soluble acene-based transistors and circuits," *Nature Mater.*, vol. 7, no. 3, pp. 216–221, Feb. 2008.
- [6] R. E. Proano, R. S. Misage, and D. G. Ast, "Development and electrical properties of undoped polycrystalline silicon thin-film transistors," *IEEE Trans. Electron Devices*, vol. 36, no. 9, pp. 1915–1922, Sep. 1989.
- [7] H. Hayashi, M. Kunii, M. Suzuki, Y. Kanaya, M. Kuki, M. Minegishi, T. Urazono, M. Fujino, T. Noguchi, and M. Yamazaki, "Fabrication of low-temperature bottom-gate poly-Si TFTs on large-area substrate by linear-beam excimer laser crystallization and ion doping method," in *Proc. Int. Electron Devices Meeting*, Dec. 10–13, 1995, pp. 829–832.
- [8] A. Suresh, P. Wellenius, V. Baliga, H. Luo, L. M. Lunardi, and J. F. Muth, "Fast all-transparent integrated circuits based on indium gallium zinc oxide thin-film transistors," *IEEE Electron Device Lett.*, vol. 31, no. 4, pp. 317–319, Apr. 2010.
- [9] D. Zhao, D. A. Mourey, and T. N. Jackson, "Fast flexible plastic substrate ZnO circuits," *IEEE Electron Device Lett.*, vol. 31, no. 4, pp. 323–325, Apr. 2010.
- [10] M. Ofuji, K. Abe, H. Shimizu, N. Kaji, R. Hayashi, M. Sano, H. Kumomi, K. Nomura, T. Kamiya, and H. Hosono, "Fast thin-film transistor circuits based on amorphous oxide semiconductor," *IEEE Electron Device Lett.*, vol. 28, no. 4, pp. 273–275, Apr. 2007.
- [11] S. D. Brotherton, C. Glasse, C. Glaister, P. Green, F. Rohlfing, and J. R. Ayres, "High-speed, short-channel polycrystalline silicon thin-film transistors," *Appl. Phys. Lett.*, vol. 84, no. 2, pp. 293–295, 2004.
- [12] T. Noguchi, H. Hayashi, and T. Ohshima, "Low temperature polysilicon super-thin-film transistor (LSFT)," *Jpn. J. Appl. Phys.*, vol. 25, no. 2, pt. 2, pp. L121–L123, Feb. 1986.
- [13] F. Eder, H. Klauk, M. Halik, U. Zschieschang, G. Schmid, and C. Dehm, "Organic electronics on paper," *Appl. Phys. Lett.*, vol. 84, no. 14, pp. 2673–2675, 2004.
- [14] P. F. Baude, D. A. Ender, M. A. Haase, T. W. Kelley, D. V. Myles, and S. D. Theiss, "Pentacene-based radio-frequency identification circuitry," *Appl. Phys. Lett.*, vol. 82, no. 22, pp. 3964–3966, 2003.
- [15] D. Zielke, A. C. Hübler, U. Hahn, N. Brandt, M. Bartzsch, U. Fügmann, T. Fischer, J. Veres, and S. Ogier, "Polymer-based organic field-effect transistor using offset printed source/drain structures," *Appl. Phys. Lett.*, vol. 87, no. 12, pp. 123508-1–123508-3, 2005.
- [16] A. C. Huebler, F. Doetz, H. Kempa, H. E. Katz, M. Bartzsch, N. Brandt, I. Hennig, U. Fügmann, S. Vaidyanathan, J. Granstrom, S. Liu, A. Sydorenko, T. Zillger, G. Schmidt, K. Preissler, E. Reichmanis, P. Eckerle, F. Richter, T. Fischer, and U. Hahn, "Ring oscillator fabricated completely by means of mass-printing technologies," *Organic Electron.*, vol. 8, no. 5, pp. 480–486, Oct. 2007.
- [17] K. H. Cherenack, B. Hekmatshoar, J. C. Sturm, and S. Wagner, "Self-aligned amorphous silicon thin-film transistors fabricated on clear plastic at 300 °C," *IEEE Trans. Electron Devices*, vol. 57, no. 10, pp. 2381–2389, Oct. 2010.
- [18] K. Hiranaka, T. Yamaguchi, and S. Yanagisawa, "Self-alignment processed amorphous silicon ring oscillators," *IEEE Electron Device Lett.*, vol. 5, no. 7, pp. 224–225, Jul. 1984.
- [19] S. K. Park, J. E. Anthony, and T. N. Jackson, "Solution-processed TIPS-pentacene organic thin-film-transistor circuits," *IEEE Electron Device Lett.*, vol. 28, no. 10, pp. 877–879, Oct. 2007.
- [20] R. E. Presley, D. Hong, H. Q. Chiang, C. M. Hung, R. L. Hoffman, and J. F. Wager, "Transparent ring oscillator based on indium gallium oxide thin-film transistors," *Solid-State Electron.*, vol. 50, no. 3, pp. 500–503, Mar. 2006.
- [21] D. B. Thomasson, M. Bonse, J.-R. Huang, C. R. Wronski, and T. N. Jackson, "Tri-layer a-Si:H integrated circuits on polymeric substrates," in *Tech. Dig. Int. Electron Devices Meeting*, Dec. 6–9, 1998, pp. 253–256.
- [22] P. Servati, A. Nathan, and G. A. J. Amarutunga, "Generalized transport-band field-effect mobility in disordered organic and inorganic semiconductors," *Phys. Rev. B*, vol. 74, no. 24, Dec. 2006, 245210.

- [23] A. Ahnood, K. Ghaffarzadeh, A. Nathan, P. Servati, F. Li, M. R. Esmaeili-Rad, and A. Sazonov, "Non-ohmic contact resistance and field-effect mobility in nanocrystalline silicon thin film transistors," *Appl. Phys. Lett.*, vol. 93, no. 16, pp. 163503-1-163503-3, Oct. 2008.
- [24] J. Stott, A. Kumatani, T. Minari, K. Tsukagoshi, S. Heutz, G. Aeppli, and A. Nathan, "Bottom-contact pentacene thin-film transistors on silicon nitride," *IEEE Electron Device Lett.*, vol. 32, no. 9, pp. 1305-1307, Sep. 2011.
- [25] A. Ahnood, G. R. Chaji, A. Sazonov, and A. Nathan, "Effect of threshold voltage instability on field effect mobility in thin film transistors deduced from constant current measurements," *Appl. Phys. Lett.*, vol. 95, no. 6, pp. 063506-1-063506-3, 2009.
- [26] S. Y. Park, B. J. Kim, K. Kim, M. S. Kang, K.-H. Lim, T. I. Lee, J. M. Myoung, H. K. Baik, J. H. Cho, and Y. S. Kim, "Low-temperature, solution-processed and alkali metal doped ZnO for high-performance thin-film transistors," *Adv. Mater.*, vol. 24, no. 6, pp. 834-838, Feb. 2012.
- [27] R. G. Gordon, "Criteria for choosing transparent conductors," *Mater. Res. Soc. Bull.*, vol. 25, no. 08, pp. 52-57, Jan. 2011.
- [28] K. H. Kim, S. J. Park, A. Y. Kim, and J. Jang, "Growth of large-grain poly-Si by FE-SMC," *J. Non-Crystalline Solids*, vol. 299-302, pp. 3-86, Apr. 2002.
- [29] S. Y. Yoon, S. J. Park, K. H. Kim, and J. Jang, "Metal-induced crystallization of amorphous silicon," *Thin Solid Films*, vol. 383, no. 1-2, pp. 34-38, Feb. 2001.
- [30] H. J. Lee, A. Sazonov, and A. Nathan, "Leakage current mechanisms in top-gate nanocrystalline silicon thin film transistors," *Appl. Phys. Lett.*, vol. 92, no. 8, 2008, 083509.
- [31] F. M. Li, G.-W., Hsieh, S. Dalal, M. C. Newton, J. E. Stott, P. Hiralal, A. Nathan, P. A. Warburton, H. E. Unalan, P. Beecher, A. J. Flewitt, I. Robinson, G. Amaratunga, and W. I. Milne, "Zinc oxide nanostructures and high electron mobility nanocomposite thin film transistors," *IEEE Trans. Electron Devices*, vol. 55, no. 11, pp. 3001-3011, Nov. 2008.
- [32] Y. D. Park, J. A. Lim, Y. Jang, M. Hwang, H. S. Lee, D. H. Lee, H.-J. Lee, J.-B. Baek, and K. Cho, "Enhancement of the field-effect mobility of poly(3-hexylthiophene)/functionalized carbon nanotube hybrid transistors," *Organic Electron.*, vol. 9, no. 3, pp. 317-322, Jun. 2008.
- [33] S.-H. Hur, O. O. Park, and J. A. Rogers, "Extreme bendability of single-walled carbon nanotube networks transferred from high-temperature growth substrates to plastic and their use in thin-film transistors," *Appl. Phys. Lett.*, vol. 86, no. 24, 2005, 243502.
- [34] G.-W. Hsieh, J. Wang, K. Ogata, J. Robertson, S. Hofmann, and W. I. Milne, "Stretched contact printing of one-dimensional nanostructures for hybrid inorganic-organic field effect transistors," *J. Phys. Chem. C*, vol. 116, no. 12, pp. 7118-7125, Feb. 2012.
- [35] M. R. Esmaeili-Rad, F. Li, A. Sazonov, and A. Nathan, "Stability of nanocrystalline silicon bottom-gate thin film transistors with silicon nitride gate dielectric," *J. Appl. Phys.*, vol. 102, no. 6, 2007, 064512.
- [36] M. Bauza, A. Ahnood, F. M. Li, Y. Vygranenko, M. R. Esmaeili-Rad, G. Chaji, A. Sazonov, J. Robertson, W. I. Milne, and A. Nathan, "Photo-induced instability of nanocrystalline silicon TFTs," *IEEE J. Display Technol.*, vol. 6, no. 12, pp. 589-591, Dec. 2010.
- [37] K. Ghaffarzadeh, A. Nathan, J. Robertson, S. Kim, S. Jeon, C. Kim, U.-I. Chung, and J.-H. Lee, "Instability in threshold voltage and subthreshold behavior in Hf-In-Zn-O thin film transistors induced by bias-and light-stress," *Appl. Phys. Lett.*, vol. 97, pp. 113504-1-113504-3, no. 11, 2010, 113504.
- [38] M. Bauza, N. P. Mandal, A. Ahnood, A. Sazonov, and A. Nathan, "Light-induced metastability in thin nanocrystalline silicon films," *Philosoph. Mag.*, vol. 89, no. 28, p. 2531, 2009.
- [39] Y.-M. Lin, K. A. Jenkins, A. Valdes-Garcia, J. P. Small, D. B. Farmer, and P. Avouris, "Operation of graphene transistors at gigahertz frequencies," *Nano Lett.*, vol. 9, no. 1, pp. 422-426, Jan. 2009.
- [40] A. K. Geim and K. S. Novoselov, "The rise of graphene," *Nature Mater.*, vol. 6, no. 3, pp. 183-191, Mar. 2007.
- [41] B. Radisavljevic, A. Radenovic, J. Brivio, V. Giacometti, and A. Kis, "Single-layer MoS₂ transistors," *Nature Nanotechnol.*, vol. 6, no. 3, pp. 147-150, Jan. 2011.
- [42] L. Song, L. Ci, H. Lu, P. B. Sorokin, C. Jin, J. Ni, A. G. Kvashnin, D. G. Kvashnin, J. Lou, B. I. Yakobson, and P. M. Ajayan, "Large scale growth and characterization of atomic hexagonal boron nitride layers," *Nano Lett.*, vol. 10, no. 8, pp. 3209-3215, Aug. 2010.
- [43] M. Moradi, A. A. Fomani, and A. Nathan, "Effect of gate dielectric scaling in nanometer scale vertical thin film transistors," *Appl. Phys. Lett.*, vol. 99, no. 22, 2011, 223503.
- [44] S. P. Li, D. P. Chu, C. J. Newsome, D. M. Russell, T. Kugler, M. Ishida, and T. Shimoda, "Short-channel polymer field-effect-transistor fabrication using spin-coating-induced edge template and ink-jet printing," *Appl. Phys. Lett.*, vol. 87, no. 23, 2005, 232111.
- [45] T. Takenobu, N. Miura, S.-Y. Lu, H. Okimoto, T. Asano, M. Shiraishi, and Y. Iwasa, "Ink-jet printing of carbon nanotube thin-film transistors on flexible plastic substrates," *Appl. Phys. Exp.*, vol. 2, Feb. 2009, 025005.
- [46] F. Torrisi, T. Hasan, W. Wu, Z. Sun, A. Lombardo, T. Kulmala, G. W. Hshieh, S. J. Jung, F. Bonaccorso, P. J. Paul, D. P. Chu, and A. C. Ferrari, "Ink-jet printed graphene electronics," *ACS Nano*, vol. 6, no. 4, pp. 2992-3006, Apr. 2012.
- [47] S. Li, W. Chen, D. Chu, and S. Roy, "Self-aligned high-resolution printed polymer transistors," *Adv. Mater.*, vol. 23, no. 35, pp. 4107-4110, Sep. 2011.
- [48] M. J. Kelly, "Intrinsic top-down unmanufacturability," *Nanotechnology*, vol. 22, no. 24, Jun. 2011, 245303.
- [49] G.-W. Hsieh, F. M. Li, P. Beecher, A. Nathan, Y. Wu, B. S. Ong, and W. I. Milne, "High performance nanocomposite thin film transistors with bilayer carbon nanotube-polythiophene active channel by ink-jet printing," *J. Appl. Phys.*, vol. 106, no. 12, 2009, 123706.
- [50] T. Hasan, Z. Sun, F. Wang, F. Bonaccorso, P. H. Tan, A. G. Rozhin, and A. C. Ferrari, "Nanotube-polymer composites for ultrafast photonics," *Adv. Mater.*, vol. 21, no. 38-39, pp. 3874-3899, Oct. 2009.
- [51] Z. Sun, T. Hasan, F. Torrisi, D. Popa, G. Privitera, F. Wang, F. Bonaccorso, D. M. Basko, and A. C. Ferrari, "Graphene mode-locked ultrafast laser," *ACS Nano*, vol. 4, no. 2, pp. 803-810, Feb. 2010.
- [52] F. Bonaccorso, Z. Sun, T. Hasan, and A. C. Ferrari, "Graphene photonics and optoelectronics," *Nature Photon.*, vol. 4, no. 9, pp. 611-622, Aug. 2010.
- [53] M. Reibold, P. Paufler, A. A. Levin, W. Kochmann, N. Pätzke, and D. C. Meyer, "Materials: Carbon nanotubes in an ancient Damascus sabre," *Nature*, vol. 444, no. 7117, pp. 286-286, Nov. 2006.
- [54] M. Martín-Torres, T. Rehren, and I. C. Freestone, "Mullite and the mystery of Hessian wares," *Nature*, vol. 444, no. 7118, pp. 437-438, Nov. 2006.
- [55] M. Reibold, P. Paufler, A. A. Levin, W. Kochmann, N. Pätzke, and D. C. Meyer, "Materials: Carbon nanotubes in an ancient Damascus sabre," *Nature*, vol. 444, no. 7117, pp. 286-286, Nov. 2006.
- [56] M. Martín-Torres, T. Rehren, and I. C. Freestone, "Mullite and the mystery of Hessian wares," *Nature*, vol. 444, no. 7118, pp. 437-438, Nov. 2006.
- [57] A. Stierle and A. M. Molenbroek, "Novel in situ probes for nanocatalysis," *Mater. Res. Soc. Bull.*, vol. 32, no. 12, pp. 1001-1009, Jan. 2011.
- [58] S. Hofmann, R. Sharma, C. Ducati, G. Du, C. Mattevi, C. Cepek, M. Cantoro, S. Pisana, A. Parvez, F. Cervantes-Sodi, A. C. Ferrari, R. Dunin-Borkowski, S. Lizzit, L. Petaccia, A. Goldoni, and J. Robertson, "In situ observations of catalyst dynamics during surface-bound carbon nanotube nucleation," *Nano Lett.*, vol. 7, no. 3, pp. 602-608, Mar. 2007.
- [59] S. Hofmann, R. Sharma, C. T. Wirth, F. Cervantes-Sodi, C. Ducati, T. Kasama, R. E. Dunin-Borkowski, J. Drucker, P. Bennett, and J. Robertson, "Ledge-flow-controlled catalyst interface dynamics during Si nanowire growth," *Nature Mater.*, vol. 7, no. 5, pp. 372-375, Mar. 2008.
- [60] P. L. Gai, R. Sharma, and F. M. Ross, "Environmental (S)TEM studies of gas-liquid-solid interactions under reaction conditions," *Mater. Res. Soc. Bull.*, vol. 33, no. 02, pp. 107-114, Jan. 2011.
- [61] S. Hofmann, R. Blume, C. T. Wirth, M. Cantoro, R. Sharma, C. Ducati, M. Hävecker, S. Zafeirotas, P. Schnoerch, A. Oestereich, D. Teschner, M. Albrecht, A. Knop-Gericke, R. Schlögl, and J. Robertson, "State of transition metal catalysts during carbon nanotube growth," *J. Phys. Chem. C*, vol. 113, no. 5, pp. 1648-1656, Feb. 2009.
- [62] R. S. Weatherup, B. C. Bayer, R. Blume, C. Ducati, C. Baetz, R. Schlögl, and S. Hofmann, "In situ characterization of alloy catalysts for low-temperature graphene growth," *Nano Lett.*, vol. 11, no. 10, pp. 4154-4160, Oct. 2011.
- [63] D.-H. Kim, J. Xiao, J. Song, Y. Huang, and J. A. Rogers, "Stretchable, curvilinear electronics based on inorganic materials," *Adv. Mater.*, vol. 22, no. 19, pp. 2108-2124, Jan. 2010.
- [64] S. P. Lacour, S. Wagner, Z. Huang, and Z. Suo, "Stretchable gold conductors on elastomeric substrates," *Appl. Phys. Lett.*, vol. 82, no. 15, pp. 2404-2406, 2003.
- [65] A. Flewitt and A. Nathan, "Thin-film silicon materials and devices for large-area and

- flexible solar cells and electronics," in *Tutorial, MRS Spring Meeting*, San Francisco, CA, 2009.
- [66] R. Martins, A. Nathan, R. Barros, L. Pereira, P. Barquinha, N. Correia, R. Costa, A. Ahnood, I. Ferreira, and E. Fortunato, "Complementary metal oxide semiconductor technology with and on paper," *Adv. Mater.*, vol. 23, no. 39, pp. 4491–4496, Oct. 2011.
- [67] J. Hiner, *Good Product Desing: The 10 Principles of Dieter Rams*, Oct. 9, 2011. [Online]. Available: <http://www.jasonhiner.com/blog/2011/10/9/good-product-design-the-10-principles-of-dieter-rams.html>
- [68] P. Kotler and G. A. Rath, "Design: A powerful but neglected strategic tool," *J. Business Strategy*, vol. 5, no. 2, pp. 16–21, 1984.
- [69] G. Gemser, "How integrating industrial design in the product development process impacts on company performance," *J. Product Innovation Manage.*, vol. 18, no. 1, pp. 28–38, Jan. 2001.
- [70] J. H. Hertenstein, M. B. Platt, and D. R. Brown, "Valuing design: Enhancing corporate performance through design effectiveness," *Design Manage. J. (Former Ser.)*, vol. 12, no. 3, pp. 10–19, Jun. 2010.
- [71] G. Cox, "Cox review of creativity in business: Building on the UK's strengths," HM Treasury, London, U.K., Executive Summary, 2005.
- [72] D. Sainsbury, "The race to the top: A review of Government's science and innovation policies," HM Treasury, London, U.K., 2007.
- [73] C. Enterprise, "Plastic logic introduces the plastic logic 100, bringing innovation to the future of education in Russia," Sep. 21, 2011.
- [74] N. Kumarchauhan, "Philips fluid smartphone with flexible OLED display," Aug. 18, 2010.
- [75] F. Axisa, P. M. Schmitt, C. Gehin, G. Delhomme, E. McAdams, and A. Dittmar, "Flexible technologies and smart clothing for citizen medicine, home healthcare, and disease prevention," *IEEE Trans. Inf. Technol. Biomed.*, vol. 9, no. 3, pp. 325–336, Sep. 2005.
- [76] R. S. H. Istepanian, E. Jovanov, and Y. T. Zhang, "Guest editorial introduction to the special section on m-health: Beyond seamless mobility and global wireless health-care connectivity," *IEEE Trans. Inf. Technol. Biomed.*, vol. 8, no. 4, pp. 405–414, Dec. 2004.
- [77] S. S. Lane, B. D. Kuppermann, I. H. Fine, M. B. Hamill, J. F. Gordon, R. S. Chuck, R. S. Hoffman, M. Packer, and D. D. Koch, "A prospective multicenter clinical trial to evaluate the safety and effectiveness of the implantable miniature telescope," *Amer. J. Ophthalmol.*, vol. 137, no. 6, pp. 993–1001, Jun. 2004.
- [78] C. W. Turner, B. J. Gantz, C. Vidal, A. Behrens, and B. A. Henry, "Speech recognition in noise for cochlear implant listeners: Benefits of residual acoustic hearing," *J. Acoust. Soc. Amer.*, vol. 115, no. 4, pp. 1729–1735, 2004.
- [79] T. Guenther, N. H. Lovell, and G. J. Suaning, "Bionic vision: System architectures—A review," *Expert Rev. Med. Devices*, vol. 9, pp. 33–48, Jan. 2012.
- [80] D. Purves, *Neuroscience*. Sunderland, MA: Sinauer, 2008.
- [81] P. M. Chute and M. E. Nevins, *The Parents' Guide to Cochlear Implants*. Washington, DC: Gallaudet Univ. Press, 2002.
- [82] S. Frings and J. Bradley, *Transduction Channels in Sensory Cells*. Weinheim, Germany: Wiley-VCH, 2004, p. 155.
- [83] F. M. Matschinsky, "Banting lecture 1995. A lesson in metabolic regulation inspired by the glucokinase glucose sensor paradigm," *Diabetes*, vol. 45, no. 2, pp. 223–241, Feb. 1996.
- [84] N. Chaudhari, H. Yang, C. Lamp, E. Delay, C. Cartford, T. Than, and S. Roper, "The taste of monosodium glutamate: Membrane receptors in taste buds," *J. Neurosci.*, vol. 16, no. 12, pp. 3817–3826, Jun. 1996.
- [85] J. B. Baxter and E. S. Aydil, "Nanowire-based dye-sensitized solar cells," *Appl. Phys. Lett.*, vol. 86, no. 5, 2005, 053114.
- [86] M. Law, L. E. Greene, J. C. Johnson, R. Saykally, and P. Yang, "Nanowire dye-sensitized solar cells," *Nature Mater.*, vol. 4, no. 6, pp. 455–459, May 2005.
- [87] H. Rensmo, K. Keis, H. Lindström, S. Södergren, A. Solbrand, A. Hagfeldt, S.-E. Lindquist, L. N. Wang, and M. Muhammed, "High light-to-energy conversion efficiencies for solar cells based on nanostructured ZnO electrodes," *J. Phys. Chem. B*, vol. 101, no. 14, pp. 2598–2601, Apr. 1997.
- [88] K. Myny, S. Steudel, P. Vicca, M. J. Beenhakers, N. A. J. M. van Aerle, G. H. Gelinck, J. Genoe, W. Dehaene, and P. Heremans, "Plastic circuits and tags for 13.56 MHz radio-frequency communication," *Solid-State Electron.*, vol. 53, no. 12, pp. 1220–1226, Dec. 2009.
- [89] M. Kaempgen, C. K. Chan, J. Ma, Y. Cui, and G. Gruner, "Film supercapacitors using single-walled carbon nanotubes," *Nano Lett.*, vol. 9, no. 5, pp. 1872–1876, May 2009.
- [90] J. B. Bates, N. J. Dudney, B. Neudecker, A. Ueda, and C. D. Evans, "Thin-film lithium and lithium-ion batteries," *Solid State Ionics*, vol. 135, no. 1–4, pp. 33–45, Nov. 2000.
- [91] J. G. E. Gardeniers and A. van den Berg, "Lab-on-a-chip systems for biomedical and environmental monitoring," *Anal. Bioanal. Chem.*, vol. 378, no. 7, pp. 1700–1703, Apr. 2004.
- [92] V. Srinivasan, V. K. Pamula, and R. B. Fair, "An integrated digital microfluidic lab-on-a-chip for clinical diagnostics on human physiological fluids," *Lab-on-a-Chip*, vol. 4, no. 4, pp. 310–315, 2004.
- [93] B. H. Weigl, R. L. Bardell, and C. R. Cabrera, "Lab-on-a-chip for drug development," *Adv. Drug Delivery Rev.*, vol. 55, no. 3, pp. 349–377, Feb. 2003.
- [94] Y. Q. Fu, J. K. Luo, X. Y. Du, A. J. Flewitt, Y. Li, G. H. Markx, A. J. Walton, and W. I. Milne, "Recent developments on ZnO films for acoustic wave based bio-sensing and microfluidic applications: A review," *Sens. Actuators B, Chem.*, vol. 143, no. 2, pp. 606–619, Jan. 2010.
- [95] X. Y. Du, Y. Q. Fu, J. K. Luo, A. J. Flewitt, and W. I. Milne, "Microfluidic pumps employing surface acoustic waves generated in ZnO thin films," *J. Appl. Phys.*, vol. 105, no. 2, 2009, 024508.
- [96] J. Luo, Y. R. Fu, X. Du, D. Lee, S. Maeng, A. Flewitt, and B. Milne, "ZnO thin film surface acoustic wave based lab-on-a-chip," in *Proc. Mater. Res. Soc. Symp.*, Jan. 2011, vol. 1222, 1222-DD01-05.
- [97] D. S. Lee, Y. Q. Fu, S. Maeng, X. Y. Du, S. C. Tan, J. K. Luo, A. J. Flewitt, S. H. Kim, N. M. Park, Y. J. Choi, H. C. Yoon, S. Y. Oh, and W. I. Milne, "Integrated ZnO surface acoustic wave microfluidic and biosensor system," in *Proc. IEEE Int. Electron Devices Meeting*, Dec. 10–12, 2007, pp. 851–854.
- [98] J. K. Luo, G. M. Ashley, L. G. Gancedo, P. B. Kirby, A. J. Flewitt, and W. I. Milne, "Film bulk acoustic resonator nanosensors for multi-task sensing," *Int. J. Nanomanufact.*, vol. 7, no. 5/6, pp. 448–462, 2011.
- [99] L. Garcia-Gancedo, F. Al-Naimi, A. Flewitt, W. Wilne, G. Ashley, J. Luo, X. Zhao, and J. Lu, "ZnO-based FBAR resonators with carbon nanotube electrodes," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 58, no. 11, pp. 2438–2445, Nov. 2011.
- [100] R. Truckenmüller, S. Giselbrecht, C. van Blitterswijk, N. Dambrowsky, E. Gottwald, T. Mappes, A. Rolletschek, V. Saile, C. Trautmann, K.-F. Weibezahn, and A. Welle, "Flexible fluidic microchips based on thermoformed and locally modified thin polymer films," *Lab-on-a-Chip*, vol. 8, no. 9, pp. 1570–1579, 2008.
- [101] M. Focke, D. Kosse, C. Müller, H. Reinecke, R. Zengerle, and F. von Stetten, "Lab-on-a-foil: Microfluidics on thin and flexible films," *Lab Chip*, vol. 10, no. 11, pp. 1365–1386, Jun. 2010.
- [102] C. J. Rydh and B. A. Sandén, "Energy analysis of batteries in photovoltaic systems. Part I: Performance and energy requirements," *Energy Conv. Manage.*, vol. 46, no. 11–12, pp. 1957–1979, Jul. 2005.
- [103] G. Mom, *The Electric Vehicle: Technology and Expectations in the Automobile Age*. Baltimore, MD: Johns Hopkins Univ. Press, 2004.
- [104] M. S. Dresselhaus and I. L. Thomas, "Alternative energy technologies," *Nature*, vol. 414, no. 6861, pp. 332–337, Nov. 2001.
- [105] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," *Proc. IEEE*, vol. 95, no. 4, pp. 704–718, Apr. 2007.
- [106] J. Romm, "The car and fuel of the future," *Energy Policy*, vol. 34, no. 17, pp. 2609–2614, Nov. 2006.
- [107] A. S. Aricò, P. Bruce, B. Scrosati, J.-M. Tarascon, and W. van Schalkwijk, "Nanostructured materials for advanced energy conversion and storage devices," *Nature Mater.*, vol. 4, no. 5, pp. 366–377, May 2005.
- [108] P. A. Nelson and J. R. Owen, "A high-performance supercapacitor/battery hybrid incorporating templated mesoporous electrodes," *J. Electrochem. Soc.*, vol. 150, no. 10, pp. A1313–A1317, 2003.
- [109] P. Liu, E. Sherman, and A. Jacobsen, "Design and fabrication of multifunctional structural batteries," *J. Power Sources*, vol. 189, no. 1, pp. 646–650, Apr. 2009.
- [110] J. F. Snyder, R. H. Carter, and E. D. Wetzal, "Electrochemical and mechanical behavior in mechanically robust solid polymer electrolytes for use in multifunctional structural batteries," *Chem. Mater.*, vol. 19, no. 15, pp. 3793–3801, Jul. 2007.
- [111] L. Christodoulou and J. D. Venables, "Multifunctional material systems: The first generation," *JOM J. Minerals Metals Mater. Soc.*, vol. 55, no. 12, pp. 39–45, Dec. 2003.
- [112] J. P. Thomas and M. A. Qidwai, "The design and application of multifunctional structure-battery materials systems," *JOM J. Minerals Metals Mater. Soc.*, vol. 57, no. 3, pp. 18–24, Mar. 2005.
- [113] O. Berder, P. Quemerai, O. Sentieys, J. Astier, T. D. Nguyen, J. Menard, G. Le Mestre, Y. Le Roux, Y. Kokar, G. Zaharia, R. Benzerga, X. Castet, M. Himdi, G. E. Zein, S. Jegou,

- P. Cosquer, and M. Bernard, "Cooperative Communications Between Vehicles and Intelligent Road Signs," in *Proc. 8th Int. Conf. ITS Telecommun.*, Oct. 24, 2008, pp. 121–126.
- [114] IPENZ Conference, Institution of Professional Engineers New Zealand, and CSP Pacific (Firm)Engineering, Providing the Foundations for Society, Wellington, New Zealand, Papers Presented in the Technical Programme, Feb.9–13, 1996.
- [115] J.-M. Liu, T. M. Lee, C.-H. Wen, and C.-M. Leu, "High-performance organic-inorganic hybrid plastic substrate for flexible displays and electronics," *J. Soc. Inf. Display*, vol. 19, no. 1, pp. 63–69, 2011.
- [116] T. Yamada, Y. Tsubata, C. Sekine, and T. Ohnishi, "Invited paper: Recent progress in light-emitting polymers for full color OLEDs," in *SID Symp. Dig. Tech. Papers*, 2008, vol. 39, no. 1, pp. 404–406.
- [117] M.-C. Choi, Y. Kim, and C.-S. Ha, "Polymers for flexible displays: From material selection to device applications," *Progr. Polymer Sci.*, vol. 33, no. 6, pp. 581–630, Jun. 2008.
- [118] S. Utsunomiya, T. Kamakura, M. Kasuga, M. Kimura, W. Miyazawa, S. Inoue, and T. Shimoda, "21.3: Flexible color AM-OLED display fabricated using Surface Free Technology by Laser Ablation/Annealing (SUFTLA) and ink-jet printing technology," in *SID Symp. Dig. Tech. Papers*, 2003, vol. 34, no. 1, pp. 864–867.
- [119] R. Street, W. Wong, S. Ready, M. Chabinyk, A. Arias, S. Limb, A. Salleo, and R. Lujan, "Jet printing flexible displays," *Mater. Today*, vol. 9, no. 4, pp. 32–37, Apr. 2006.
- [120] B.-J. de Gans, P. C. Duineveld, and U. S. Schubert, "Inkjet printing of polymers: State of the art and future developments," *Adv. Mater.*, vol. 16, no. 3, pp. 203–213, Feb. 2004.
- [121] Y.-Y. Noh, X. Cheng, H. Sirringhaus, J. I. Sohn, M. E. Welland, and D. J. Kang, "Ink-jet printed ZnO nanowire field effect transistors," *Appl. Phys. Lett.*, vol. 91, no. 4, 2007043109.
- [122] P. Beecher, P. Servati, A. Rozhin, A. Colli, V. Scardaci, S. Pisana, T. Hasan, A. J. Flewitt, J. Robertson, G. W. Hsieh, F. M. Li, A. Nathan, A. C. Ferrari, and W. I. Milne, "Ink-jet printing of carbon nanotube thin film transistors," *J. Appl. Phys.*, vol. 102, no. 4, 2007, 043710.
- [123] W. Westerman, J. Elisa, and A. Hedge, "Multi-touch: A new tactile 2D gesture interface for human-computer interaction," in *Proc. Human Factors Ergonom. Soc. Annu. Meeting*, 2001, vol. 1, pp. 632–636.
- [124] W. Westerman, "Hand tracking, finger identification, and chordic manipulation on a multi-touch surface," Ph.D. dissertation. Dept. Elec. Eng., Univ. Delaware, Newark, DE, 1999.
- [125] T. Kaaresoja and J. Linjama, "Perception of short tactile pulses generated by a vibration motor in a mobile phone," in *Proc. Eurohaptics Conf./Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, Mar. 18–20, 2005, pp. 471–472.
- [126] L. M. Brown and T. Kaaresoja, "Feel who's talking," in *Proc. Extended Abstracts Conf. Human Factors Comput. Syst.*, 2006, pp. 604–609.
- [127] E. Hoggan, S. A. Brewster, and J. Johnston, "Investigating the effectiveness of tactile feedback for mobile touchscreens," in *Proc. Conf. Human Factors Comput. Syst.*, 2008, pp. 1573–1582.
- [128] T.-H. Yang, D. Pyo, S.-Y. Kim, Y.-J. Cho, Y. D. Bae, Y. M. Lee, J. S. Lee, E. H. Lee, and D.-S. Kwon, "A new subminiature impact actuator for mobile devices," in *Proc. IEEE World Haptics Conf.*, Jun. 21–24, 2011, pp. 95–100.
- [129] D.-S. Kwon, T.-H. Yang, and Y.-J. Cho, "Mechatronics technology in mobile devices," *IEEE Ind. Electron. Mag.*, vol. 4, no. 2, pp. 36–41, Jun. 2010.
- [130] R. D. Melen and J. D. Meindl, "Electrocuteaneous stimulation in a reading aid for the blind," *IEEE Trans. Biomed. Eng.*, vol. BME-18, no. 1, pp. 1–3, Jan. 1971.
- [131] R. Butikofer and P. D. Lawrence, "Electrocuteaneous nerve stimulation—Part I: Model and experiment," *IEEE Trans. Biomed. Eng.*, vol. BME-25, no. 6, pp. 526–531, Nov. 1978.
- [132] K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita, and W. J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 1, pp. 1–16, Jan. 1991.
- [133] E. Mallinckrodt, A. L. Hughes, and W. Sleator, "Perception by the skin of electrically induced vibrations," *Science*, vol. 118, no. 3062, pp. 277–278, Sep. 1953.
- [134] K. A. Kaczmarek, K. Nammi, A. K. Agarwal, M. E. Tyler, S. J. Haase, and D. J. Beebe, "Polarity effect in electrovibration for tactile display," *IEEE Trans. Biomed. Eng.*, vol. 53, no. 10, pp. 2047–2054, Oct. 2006.
- [135] A. K. Agarwal, K. Nammi, K. A. Kaczmarek, M. E. Tyler, and D. J. Beebe, "A hybrid natural/artificial electrostatic actuator for tactile stimulation," in *Proc. 2nd Annu. Int. IEEE-EMB Special Topic Conf. Microtechnol. Med. Biol.*, 2002, pp. 341–345.
- [136] O. Bau, I. Poupyrev, A. Israr, and C. Harrison, "TeslaTouch: Electro-vibration for touch surfaces," in *Proc. User Interface Software and Technology*, 2010, pp. 283–292.
- [137] S. S. Sabri, P. L. Lévesque, C. M. Aguirre, J. Guillemette, R. Martel, and T. Szkopek, "Graphene field effect transistors with parylene gate dielectric," *Appl. Phys. Lett.*, vol. 95, no. 24, 2009, 242104.
- [138] T. Hasan, P. Beecher, Z. Radivojevic, C. Bower, S. Haque, F. Bonaccorso, W. Richards, G. Privitera, O. Trushkevych, F. Torrisi, A. C. Ferrari, and P. Andrew, "Transparent electrostatic tactile surfaces based on graphene," 2011, submitted to E-MRS Spring Meeting.
- [139] C. K. Chan, H. Peng, G. Liu, K. McIlwrath, X. F. Zhang, R. A. Huggins, and Y. Cui, "High-performance lithium battery anodes using silicon nanowires," *Nature Nanotechnol.*, vol. 3, no. 1, pp. 31–35, Dec. 2007.
- [140] E. Yoo and H. Zhou, "Li-air rechargeable battery based on metal-free graphene nanosheet catalysts," *ACS Nano*, vol. 5, no. 4, pp. 3020–3026, Apr. 2011.
- [141] H. Zhang, X. Yu, and P. V. Braun, "Three-dimensional bicontinuous ultrafast-charge and -discharge bulk battery electrodes," *Nature Nanotechnol.*, vol. 6, no. 5, pp. 277–281, Mar. 2011.
- [142] L.-F. Cui, Y. Yang, C.-M. Hsu, and Y. Cui, "Carbon-silicon core-shell nanowires as high capacity electrode for lithium ion batteries," *Nano Lett.*, vol. 9, no. 9, pp. 3370–3374, Sep. 2009.
- [143] P. Hiralal, H. Wang, H. E. Unalan, Y. Liu, M. Rouvala, D. Wei, P. Andrew, and G. A. J. Amaralunga, "Enhanced supercapacitors from hierarchical carbon nanotube and nanohorn architectures," *J. Mater. Chem.*, vol. 21, no. 44, pp. 17810–17815, 2011.
- [144] F. Croce, G. B. Appetecchi, L. Persi, and B. Scrosati, "Nanocomposite polymer electrolytes for lithium batteries," *Nature*, vol. 394, pp. 456–458, 1998.
- [145] P. Hiralal, S. Imaizumi, H. E. Unalan, H. Matsumoto, M. Minagawa, M. Rouvala, A. Tanioka, and G. A. J. Amaralunga, "Nanomaterial-enhanced all-solid flexible zinc-carbon batteries," *ACS Nano*, vol. 4, no. 5, pp. 2730–2734, May 2010.
- [146] M. Kaltenbrunner, G. Kettlgruber, C. Siket, R. Schwödiauer, and S. Bauer, "Arrays of ultracompliant electrochemical dry gel cells for stretchable electronics," *Adv. Mater.*, vol. 22, no. 18, pp. 2065–2067, Mar. 2010.
- [147] E. Yoo, J. Kim, E. Hosono, H. Zhou, T. Kudo, and I. Honma, "Large reversible Li storage of graphene nanosheet families for use in rechargeable lithium ion batteries," *Nano Lett.*, vol. 8, no. 8, pp. 2277–2282, Aug. 2008.
- [148] B. Z. Jang, C. Liu, D. Neff, Z. Yu, M. C. Wang, W. Xiong, and A. Zhamu, "Graphene surface-enabled lithium ion-exchanging cells: Next-generation high-power energy storage devices," *Nano Lett.*, vol. 11, no. 9, pp. 3785–3791, Sep. 2011.
- [149] M. D. Stoller, S. Park, Y. Zhu, J. An, and R. S. Ruoff, "Graphene-based ultracapacitors," *Nano Lett.*, vol. 8, no. 10, pp. 3498–3502, Oct. 2008.
- [150] Y. Zhu, S. Murali, M. D. Stoller, K. J. Ganesh, W. Cai, P. J. Ferreira, A. Pirkle, R. M. Wallace, K. A. Cychoz, M. Thommes, D. Su, E. A. Stach, and R. S. Ruoff, "Carbon-based supercapacitors produced by activation of graphene," *Science*, vol. 332, no. 6037, pp. 1537–1541, May 2011.
- [151] C. Liu, Z. Yu, D. Neff, A. Zhamu, and B. Z. Jang, "Graphene-based supercapacitor with an ultrahigh energy density," *Nano Lett.*, vol. 10, no. 12, pp. 4863–4868, Dec. 2010.
- [152] Q. Wu, Y. Xu, Z. Yao, A. Liu, and G. Shi, "Supercapacitors based on flexible graphene/polyaniline nanofiber composite films," *ACS Nano*, vol. 4, no. 4, pp. 1963–1970, Apr. 2010.
- [153] Y. H. Ng, A. Iwase, A. Kudo, and R. Amal, "Reducing graphene oxide on a visible-light BiVO₄ photocatalyst for an enhanced photoelectrochemical water splitting," *J. Phys. Chem. Lett.*, vol. 1, no. 17, pp. 2607–2612, Sep. 2010.
- [154] X. Wang, L. Zhi, and K. Müllen, "Transparent, conductive graphene electrodes for dye-sensitized solar cells," *Nano Lett.*, vol. 8, no. 1, pp. 323–327, Jan. 2008.
- [155] J. S. Bunch, A. M. van der Zande, S. S. Verbridge, I. W. Frank, D. M. Tanenbaum, J. M. Parpia, H. G. Craighead, and P. L. McEuen, "Electromechanical resonators from graphene sheets," *Science*, vol. 315, no. 5811, pp. 490–493, Jan. 2007.
- [156] G. Yu, L. Hu, M. Vosguerichian, H. Wang, X. Xie, J. R. McDonough, X. Cui, Y. Cui, and Z. Bao, "Solution-processed graphene/MnO₂ nanostructured textiles for high-performance electrochemical capacitors," *Nano Lett.*, vol. 11, no. 7, pp. 2905–2911, Jul. 2011.
- [157] T. Ryhänen, *Nanotechnologies for Future Mobile Devices*. Cambridge, U.K.: Cambridge Univ. Press, 2010.

- [158] M. Winter and R. J. Brodd, "What are batteries, fuel cells, and supercapacitors?" *Chem. Rev.*, vol. 104, no. 10, pp. 4245–4270, Oct. 2004.
- [159] P. Simon and Y. Gogotsi, "Materials for electrochemical capacitors," *Nature Mater.*, vol. 7, no. 11, pp. 845–854, Nov. 2008.
- [160] S. P. Beeby, R. N. Torah, M. J. Tudor, P. Glynn-Jones, T. O'Donnell, C. R. Saha, and S. Roy, "A micro electromagnetic generator for vibration energy harvesting," *J. Micromech. Microeng.*, vol. 17, no. 7, pp. 1257–1265, Jul. 2007.
- [161] M. T. Penella and M. Gasulla, "A review of commercial energy harvesters for autonomous sensors," in *Proc. Instrum. Meas. Technol. Conf.*, May 1–3, 2007, DOI: 10.1109/IMTC.2007.379234.
- [162] J. M. Donelan, Q. Li, V. Naing, J. A. Hoffer, D. J. Weber, and A. D. Kuo, "Biomechanical energy harvesting: Generating electricity during walking with minimal user effort," *Science*, vol. 319, no. 5864, pp. 807–810, Feb. 2008.
- [163] A. Hagfeldt and M. Grätzel, "Molecular photovoltaics," *Accounts Chem. Res.*, vol. 33, no. 5, pp. 269–277, May 2000.
- [164] D. M. Chapin, C. S. Fuller, and G. L. Pearson, "A new silicon p-n junction photocell for converting solar radiation into electrical power," *J. Appl. Phys.*, vol. 25, no. 5, pp. 676–677, 1954.
- [165] M. A. Green, K. Emery, K. Bücher, D. L. King, and S. Igarí, "Solar cell efficiency tables (version 14)," *Progr. Photovoltaics, Res. Appl.*, vol. 7, no. 4, pp. 321–326, Jul. 1999.
- [166] L. M. Peter, "Towards sustainable photovoltaics: The search for new materials," *Philosoph. Trans. Roy. Soc. A, Math. Phys. Eng. Sci.*, vol. 369, no. 1942, pp. 1840–1856, Apr. 2011.
- [167] D. E. Carlson and C. R. Wronski, "Amorphous silicon solar cell," *Appl. Phys. Lett.*, vol. 28, no. 11, pp. 671–673, 1976.
- [168] J. Lebrun, "Thin film cadmium telluride solar cell," in *Proc. Int. Conf. Phys. Chem. Semicond. Heterojunctions Layer Structures*, 1970, pp. IV-163–IV-170.
- [169] L. L. Kazmerski, F. R. White, and G. K. Morgan, "Thin-film $\text{CuInSe}_2/\text{CdS}$ heterojunction solar cells," *Appl. Phys. Lett.*, vol. 29, no. 4, pp. 268–270, 1976.
- [170] H. Hoppe and N. S. Sariciftci, "Organic solar cells: An overview," *J. Mater. Res.*, vol. 19, no. 7, pp. 1924–1945, Mar. 2011.
- [171] B. O'Regan and M. Grätzel, "A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films," *Nature*, vol. 353, no. 6346, pp. 737–740, Oct. 1991.
- [172] J. Chen, C. Li, D. W. Zhao, W. Lei, Y. Zhang, M. T. Cole, D. P. Chu, B. P. Wang, Y. P. Cui, X. W. Sun, and W. I. Milne, "A quantum dot sensitized solar cell based on vertically aligned carbon nanotube templated ZnO arrays," *Electrochem. Commun.*, vol. 12, no. 10, pp. 1432–1435, Oct. 2010.
- [173] F. C. Krebs, "All solution roll-to-roll processed polymer solar cells free from indium-tin-oxide and vacuum coating steps," *Organic Electron.*, vol. 10, no. 5, pp. 761–768, Aug. 2009.
- [174] X. Li, H. Zhu, K. Wang, A. Cao, J. Wei, C. Li, Y. Jia, Z. Li, X. Li, and D. Wu, "Graphene-on-silicon Schottky junction solar cells," *Adv. Mater.*, vol. 22, no. 25, pp. 2743–2748, Apr. 2010.
- [175] X. Wang, L. Zhi, N. Tsao, Ž. Tomović, J. Li, and K. Müllen, "Transparent carbon films as electrodes in organic solar cells," *Angewandte Chemie Int. Ed.*, vol. 47, no. 16, pp. 2990–2992, Apr. 2008.
- [176] L. G. De Arco, Y. Zhang, C. W. Schlenker, K. Ryu, M. E. Thompson, and C. Zhou, "Continuous, highly flexible, and transparent graphene films by chemical vapor deposition for organic photovoltaics," *ACS Nano*, vol. 4, no. 5, pp. 2865–2873, May 2010.
- [177] S. Bae, H. Kim, Y. Lee, X. Xu, J.-S. Park, Y. Zheng, J. Balakrishnan, T. Lei, H. R. Kim, Y. I. Song, Y.-J. Kim, K. S. Kim, B. Özyilmaz, J.-H. Ahn, B. H. Hong, and S. Iijima, "Roll-to-roll production of 30-inch graphene films for transparent electrodes," *Nature Nanotechnol.*, vol. 5, no. 8, pp. 574–578, Jun. 2010.
- [178] Y. Zhu, Z. Sun, Z. Yan, Z. Jin, and J. M. Tour, "Rational design of hybrid graphene films for high-performance transparent electrodes," *ACS Nano*, vol. 5, no. 8, pp. 6472–6479, Aug. 2011.
- [179] Z. Liu, Q. Liu, Y. Huang, Y. Ma, S. Yin, X. Zhang, W. Sun, and Y. Chen, "Organic photovoltaic devices based on a novel acceptor material: Graphene," *Adv. Mater.*, vol. 20, no. 20, pp. 3924–3930, Oct. 2008.
- [180] V. Yong and J. M. Tour, "Theoretical efficiency of nanostructured graphene-based photovoltaics," *Small*, vol. 6, no. 2, pp. 313–318, Jan. 2010.
- [181] N. Yang, J. Zhai, D. Wang, Y. Chen, and L. Jiang, "Two-dimensional graphene bridges enhanced photoinduced charge transport in dye-sensitized solar cells," *ACS Nano*, vol. 4, no. 2, pp. 887–894, Feb. 2010.
- [182] X. Yan, X. Cui, B. Li, and L. Li, "Large, solution-processable graphene quantum dots as light absorbers for photovoltaics," *Nano Lett.*, vol. 10, no. 5, pp. 1869–1873, May 2010.
- [183] W. Hong, Y. Xu, G. Lu, C. Li, and G. Shi, "Transparent graphene/PEDOT-PSS composite films as counter electrodes of dye-sensitized solar cells," *Electrochem. Commun.*, vol. 10, no. 10, pp. 1555–1558, Oct. 2008.
- [184] F. Bonaccorso, G. Calogero, G. Privitera, O. M. Marago, P. G. Gucciardi, G. D. Marco, and A. C. Ferrari, "Graphene-based natural dye sensitized solar cells," *Grapene 2011*, Spain, pp. 23–24, Apr. 2011.
- [185] T. J. Echtermeyer, L. Britnell, P. K. Jasnós, A. Lombardo, R. V. Gorbachev, A. N. Grigorenko, A. K. Geim, A. C. Ferrari, and K. S. Novoselov, "Strong plasmonic enhancement of photovoltage in graphene," *Nature Commun.*, vol. 2, pp. 458–462, Aug. 2011.
- [186] D. Duchamp, "Issues in wireless mobile computing," in *Proc. 3rd Workshop Workstation Oper. Syst.*, 1992, pp. 2–10.
- [187] Factfile: XO Laptop, BBC, Jul. 23, 2007.
- [188] A. Leitner, *Fuel From the Sky: Solar Power's Potential for Western Energy Supply*, Jul. 2002.
- [189] A. Ahnood and A. Nathan, "Flat-panel compatible photovoltaic energy harvesting system," *IEEE J. Display Technol.*, vol. 8, no. 4, pp. 204–211, Apr. 2012.
- [190] A. Nathan and G. Chaji, "Display system with a solar cell and device having the same," U.S. Patent WO/2009/079798.
- [191] W. N. Chen, D. P. Chu, and S. P. Li, "Air stable complementary polymer circuits fabricated in ambient condition by inkjet printing," *Organic Electron.*, vol. 13, no. 1, pp. 98–103, Jan. 2012.
- [192] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.
- [193] X. Zhang and A. Zhao, "More stabilized triple-band antenna with a rolled radiating arm and a metallic rod for mobile applications," *Microw. Opt. Technol. Lett.*, vol. 51, no. 4, pp. 891–894, Apr. 2009.
- [194] A. Zhao, J. Xue, C. Jing, and A. Salo, "The use of Murata's ceramic bluetooth antenna for wrist device based on flexible printed circuit boards," in *Proc. 1st Eur. Wireless Technol. Conf.*, 2008, pp. 334–337.
- [195] X. Zhang, A. Zhao, and J. Wang, "Research on the characteristics of flexible antennas for general applications," in *Proc. Int. Conf. Microw. Millimeter Wave Technol.*, Nanjing, China, 2008, pp. 1814–1814.
- [196] S. W. Bae, H. K. Yoon, W. S. Kang, Y. J. Yoon, and C.-H. Lee, "A flexible monopole antenna with band-notch function for UWB systems," in *Proc. Asia-Pacific Microw. Conf.*, Bangkok, Thailand, 2007, DOI: 10.1109/APMC.2007.4554928.
- [197] A. Tronquo, H. Rogier, C. Hertleer, and L. Van Langenhove, "Robust planar textile antenna for wireless body LANs operating in 2.45 GHz ISM band," *Electron. Lett.*, vol. 42, no. 3, pp. 142–143, 2006.
- [198] S. Cheng, Z. Wu, P. Hallbjörner, K. Hjort, and A. Rydberg, "Foldable and stretchable liquid metal planar inverted cone antenna," *IEEE Trans. Antennas Propag.*, vol. 57, no. 12, pp. 3765–3771, Dec. 2009.
- [199] M. Kubo, X. Li, C. Kim, and M. Hashimoto, B. J. Wiley, D. Ham, and G. M. Whitesides, "Stretchable microfluidic radiofrequency antennas," *Adv. Mater.*, vol. 22, no. 25, pp. 2749–2752, Apr. 2010.
- [200] J.-H. So, J. Thelen, A. Qusba, G. J. Hayes, G. Lazzi, and M. D. Dickey, "Reversibly deformable and mechanically tunable fluidic antennas," *Adv. Funct. Mater.*, vol. 19, no. 22, pp. 3632–3637, Nov. 2009.
- [201] Q. Liu, K. L. Ford, and R. Langley, "Elastic antennas by metallised elastomers," in *Proc. Antennas Propag. Conf.*, Loughborough, U.K., Nov. 8–9, 2010, pp. 421–424.
- [202] J. A. Rogers, T. Someya, and Y. Huang, "Materials and mechanics for stretchable electronics," *Science*, vol. 327, no. 5973, pp. 1603–1607, Mar. 2010.
- [203] B. Huyghe, H. Rogier, J. Vanfleteren, and F. Axisa, "Design and manufacturing of stretchable high-frequency interconnects," *IEEE Trans. Adv. Packag.*, vol. 31, no. 4, pp. 802–808, Nov. 2008.
- [204] European Commission, *Energy Efficiency Plan 2011*, Brussels, Belgium, 2011.
- [205] C. Lampert, "Smart switchable glazing for solar energy and daylight control," *Solar Energy Mater. Solar Cells*, vol. 52, no. 3–4, pp. 207–221, Apr. 1998.
- [206] H. Watanabe, "Intelligent window using a hydrogel layer for energy efficiency," *Solar Energy Mater. Solar Cells*, vol. 54, no. 1–4, pp. 203–211, Jul. 1998.
- [207] P. S. Drzaic, "Polymer dispersed nematic liquid crystal for large area displays and light valves," *J. Appl. Phys.*, vol. 60, no. 6, pp. 2142–2148, 1986.
- [208] D. R. Rosseinsky and R. J. Mortimer, "ChemInform abstract: Electrochromic systems and the prospects for devices," *Adv. Mater.*, vol. 13, pp. 783–793, 2001.
- [209] J. Bullock, "Semi-transparent a-SiC:H solar cells for self-powered photovoltaic-electrochromic devices,"

- J. Non-Crystalline Solids*, vol. 198–200, pp. 1163–1167, May 1996.
- [210] S. Deb, “Stand-alone photovoltaic-powered electrochromic smart window,” *Electrochimica Acta*, vol. 46, no. 13–14, pp. 2125–2130, Apr. 2001.
- [211] O. Chehab, “The intelligent façade photovoltaic and architecture,” *Renewable Energy*, vol. 5, no. 1–4, pp. 188–204, Aug. 1994.
- [212] F. Sick and T. Erge, “International energy agency. Solar heating and cooling programme,” in *Photovoltaics in Buildings: A Design Handbook for Architects and Engineers*. London, U.K.: James & James, 1996.
- [213] T. Miyazaki, A. Akisawa, and T. Kashiwagi, “Energy savings of office buildings by the use of semi-transparent solar cells for windows,” *Renewable Energy*, vol. 30, no. 3, pp. 281–304, Mar. 2005.
- [214] D. L. Staebler and C. R. Wronski, “Optically induced conductivity changes in discharge-produced hydrogenated amorphous silicon,” *J. Appl. Phys.*, vol. 51, no. 6, pp. 3262–3268, 1980.
- [215] Y. Uchida and Y. Sakai, “Light induced effects in a-Si:H films and solar cells,” in *Proc. Mater. Res. Soc. Symp.*, 1986, vol. 70, pp. 577–585.
- [216] J. Nelson, *The Physics of Solar Cells*. London, U.K.: Imperial College Press, 2004.
- [217] S. Strong, *Building Integrated Photovoltaics (BIPV)*, Dec. 27, 2011.
- [218] K. S. Novoselov, “Two-dimensional atomic crystals,” *Proc. Nat. Acad. Sci.*, vol. 102, no. 30, pp. 10451–10453, Jul. 2005.
- [219] K. S. Novoselov, “Electric field effect in atomically thin carbon films,” *Science*, vol. 306, no. 5696, pp. 666–669, Oct. 2004.
- [220] E. G. Acheson, “Manufacture of graphite,” U.S., Patent 56832329-Sep-1896.
- [221] C. Berger, Z. Song, T. Li, X. Li, A. Y. Ogbazghi, R. Feng, Z. Dai, A. N. Marchenkov, E. H. Conrad, P. N. First, and W. A. de Heer, “Ultrathin epitaxial graphite: 2D electron gas properties and a route toward graphene-based nanoelectronics,” *J. Phys. Chem. B*, vol. 108, no. 52, pp. 19912–19916, Dec. 2004.
- [222] K. V. Emtsev, A. Bostwick, K. Horn, J. Jobst, G. L. Kellogg, L. Ley, J. L. McChesney, T. Ohta, S. A. Reshanov, J. Röhrl, E. Rotenberg, A. K. Schmid, D. Waldmann, H. B. Weber, and T. Seyller, “Towards wafer-size graphene layers by atmospheric pressure graphitization of silicon carbide,” *Nature Mater.*, vol. 8, no. 3, pp. 203–207, Feb. 2009.
- [223] L. C. Isett and J. M. Blakely, “Segregation isosteres for carbon at the (100) surface of nickel,” *Surface Sci.*, vol. 58, no. 2, pp. 397–414, Jan. 1976.
- [224] C. Oshima and A. Nagashima, “Ultra-thin epitaxial films of graphite and hexagonal boron nitride on solid surfaces,” *J. Phys., Condensed Matter*, vol. 9, no. 1, pp. 1–20, Jan. 1997.
- [225] P. W. Sutter, J.-I. Flege, and E. A. Sutter, “Epitaxial graphene on ruthenium,” *Nature Mater.*, vol. 7, no. 5, pp. 406–411, Apr. 2008.
- [226] L. Zhi and K. Müllen, “A bottom-up approach from molecular nanographenes to unconventional carbon materials,” *J. Mater. Chem.*, vol. 18, no. 13, pp. 1472–1484, 2008.
- [227] V. J. Kehrler, Jr. and H. Leidheiser, Jr., “The catalytic decomposition of carbon monoxide on large metallic single crystals,” *J. Phys. Chem.*, vol. 58, no. 7, pp. 550–555, 1954.
- [228] A. Reina, X. Jia, J. Ho, D. Nezich, H. Son, V. Bulovic, M. S. Dresselhaus, and J. Kong, “Large area, few-layer graphene films on arbitrary substrates by chemical vapor deposition,” *Nano Lett.*, vol. 9, no. 1, pp. 30–35, Jan. 2009.
- [229] K. S. Kim, Y. Zhao, H. Jang, S. Y. Lee, J. M. Kim, K. S. Kim, J.-H. Ahn, P. Kim, J.-Y. Choi, and B. H. Hong, “Large-scale pattern growth of graphene films for stretchable transparent electrodes,” *Nature*, vol. 457, no. 7230, pp. 706–710, Jan. 2009.
- [230] X. Li, W. Cai, J. An, S. Kim, J. Nah, D. Yang, R. Piner, A. Velamakanni, I. Jung, E. Tutuc, S. K. Banerjee, L. Colombo, and R. S. Ruoff, “Large-area synthesis of high-quality and uniform graphene films on copper foils,” *Science*, vol. 324, no. 5932, pp. 1312–1314, May 2009.
- [231] C. Vallés, C. Drummond, H. Saadaoui, C. A. Furtado, M. He, O. Roubeau, L. Ortolani, M. Monthieux, and A. Pénicaud, “Solutions of negatively charged graphene sheets and ribbons,” *J. Amer. Chem. Soc.*, vol. 130, no. 47, pp. 15802–15804, Nov. 2008.
- [232] S. Stankovich, D. A. Dikin, G. H. B. Dommett, K. M. Kohlhaas, E. J. Zimney, E. A. Stach, R. D. Piner, S. T. Nguyen, and R. S. Ruoff, “Graphene-based composite materials,” *Nature*, vol. 442, no. 7100, pp. 282–286, Jul. 2006.
- [233] A. A. Green and M. C. Hersam, “Solution phase production of graphene with controlled thickness via density differentiation,” *Nano Lett.*, vol. 9, no. 12, pp. 4031–4036, Dec. 2009.
- [234] O. M. Maragó, F. Bonaccorso, R. Saija, G. Privitera, P. G. Gucciardi, M. A. Iatì, G. Calogero, P. H. Jones, F. Borghese, P. Denti, V. Nicolosi, and A. C. Ferrari, “Brownian motion of graphene,” *ACS Nano*, vol. 4, no. 12, pp. 7515–7523, Dec. 2010.
- [235] Y. Hernandez, V. Nicolosi, M. Lotya, F. M. Blighe, Z. Sun, S. De, I. T. McGovern, B. Holland, M. Byrne, Y. K. Gun'Ko, J. J. Boland, P. Niraj, G. Duesberg, S. Krishnamurthy, R. Goodhue, J. Hutchison, V. Scardaci, A. C. Ferrari, and J. N. Coleman, “High-yield production of graphene by liquid-phase exfoliation of graphite,” *Nature Nanotechnol.*, vol. 3, no. 9, pp. 563–568, Aug. 2008.
- [236] A. Obraztsov, E. Obraztsova, A. Tyurnina, and A. Zolotukhin, “Chemical vapor deposition of thin graphite films of nanometer thickness,” *Carbon*, vol. 45, no. 10, pp. 2017–2021, Sep. 2007.
- [237] T. Hasan, A. Dyadyusha, Z. Sun, G. Privitera, F. Bonaccorso, F. Torrisi, W. Richards, T. Kulmala, W. Wu, O. Trushkevych, D. P. Chu, and A. C. Ferrari, “A graphene based electrically switchable, flexible smart window,” *Nature Graphene Conference*, Cambridge, MA, USA, May 2011.
- [238] C. G. Granqvist, E. Avendaño, and A. Azens, “Electrochromic coatings and devices: Survey of some recent advances,” *Thin Solid Films*, vol. 442, no. 1–2, pp. 201–211, Oct. 2003.
- [239] S. K. Deb and R. F. Shaw, “Electro-optical device having variable optical density,” U.S. Patent RE2819915-Oct-1974.
- [240] R. Vergaz, J. M. S. Pena, D. Barrios, I. Pérez, and J. C. Torres, “Electrooptical behaviour and control of a suspended particle device,” *Opto-Electron. Rev.*, vol. 15, no. 3, pp. 154–158, Sep. 2007.
- [241] J. W. Doane, A. Golemme, J. L. West, J. B. Whitehead, and B.-G. Wu, “Polymer dispersed liquid crystals for display application,” *Molecular Crystals Liquid Crystals Incorporating Nonlinear Optics*, vol. 165, no. 1, pp. 511–532, Dec. 1988.
- [242] J. L. Ferguson, “Encapsulated liquid crystal and method,” U.S. Patent 4 435 047, 1984.
- [243] C. M. Lampert, “Chromogenic smart materials,” *Mater. Today*, vol. 7, no. 3, pp. 28–35, Mar. 2004.
- [244] B.-S. Yu, “Developments in suspended particle devices (SPD),” in *Proc. Soc. Photo—Opt. Instrum. Eng.*, 1997, vol. 3138, pp. 217–225.
- [245] A. Azens, E. Avendaño, J. Backholm, L. Berggren, G. Gustavsson, R. Karmhag, G. A. Niklasson, A. Roos, and C. G. Granqvist, “Flexible foils with electrochromic coatings: Science, technology and applications,” *Mater. Sci. Eng. B*, vol. 119, no. 3, pp. 214–223, Jun. 2005.
- [246] Ferrari, *Superamerica*, Dec. 16, 2011.
- [247] Maybach, *Engineering|Roof Systems|Maybach Manufaktur*, Dec. 16, 2011.
- [248] Boeing, *Boeing: Commercial Airplanes—787 Dreamliner—International Team Dream*, Dec. 16, 2010. [Online]. Available: http://www.boeing.com/commercial/787family/dev_team.html
- [249] Airbus, *The Future by Airbus—Concept Plane Cabin*, Dec. 12, 2010.
- [250] K. Wasapinyokul, W. I. Milne, and D. P. Chu, “Photoresponse and saturation behavior of organic thin film transistors,” *J. Appl. Phys.*, vol. 105, no. 2, 2009, 024509.
- [251] K. Wasapinyokul, W. I. Milne, and D. P. Chu, “Origin of the threshold voltage shift of organic thin-film transistors under light illumination,” *J. Appl. Phys.*, vol. 109, no. 8, 2011, 084510.
- [252] P. M. Cox, R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell, “Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model,” *Nature*, vol. 408, no. 6809, pp. 184–187, Nov. 2000.
- [253] S. Solomon, G.-K. Plattner, R. Knutti, and P. Friedlingstein, “Irreversible climate change due to carbon dioxide emissions,” *Proc. Nat. Acad. Sci.*, vol. 106, no. 6, pp. 1704–1709, Jan. 2009.
- [254] C. J. Vorosmarty, “Global water resources: Vulnerability from climate change and population growth,” *Science*, vol. 289, no. 5477, pp. 284–288, Jul. 2000.
- [255] Y. Zhou, “Evaluating the costs of desalination and water transport,” *Water Resources Res.*, vol. 41, no. 3, pp. 1–10, 2005.
- [256] G. Meerganz von Medeazza, “Water desalination as a long-term sustainable solution to alleviate global freshwater scarcity? A north-south approach,” *Desalination*, vol. 169, no. 3, pp. 287–301, Oct. 2004.
- [257] T. J. Welgemoed and C. F. Schutte, “Capacitive deionization technology: An alternative desalination solution,” *Desalination*, vol. 183, no. 1–3, pp. 327–340, Nov. 2005.
- [258] A. Vijn, X. Yang, W. Du, and X. Deng, “Triple-junction amorphous silicon-based flexible solar minimodule with integrated interconnects,” *Solar Energy Mater. Solar Cells*, vol. 90, no. 16, pp. 2657–2664, Oct. 2006.
- [259] N. Wyrsh, S. Dunand, C. Miazza, A. Shah, G. Anelli, M. Despeisse, A. Garrigos, P. Jarron, J. Kaplon, D. Moraes,

- S. C. Commichau, G. Dissertori, and G. M. Viertel, "Thin-film silicon detectors for particle detection," *Phys. Stat. Sol. (c)*, vol. 1, no. 5, pp. 1284–1291, Mar. 2004.
- [260] A. Miresghhi, G. Cho, J. S. Drewery, W. S. Hong, T. Jing, H. Lee, S. N. Kaplan, and V. Perez-Mendez, "High efficiency neutron sensitive amorphous silicon pixel detectors," *IEEE Trans. Nuclear Sci.*, vol. 41, no. 4, pp. 915–921, Aug. 1994.
- [261] M. A. Green, "Third generation photovoltaics: Solar cells for 2020 and beyond," *Physica E, Low-Dimensional Syst. Nanostructures*, vol. 14, no. 1–2, pp. 65–70, Apr. 2002.
- [262] N. S. Fatemi, H. E. Pollard, H. Q. Hou, and P. R. Sharps, "Solar array trades between very high-efficiency multi-junction and Si space solar cells," in *Conf. Record 28th IEEE Photovoltaic Specialists Conf.*, 2000, pp. 1083–1086.
- [263] Y. Tsuda, O. Mori, R. Funase, H. Sawada, T. Yamamoto, T. Saiki, T. Endo, and J. Kawaguchi, "Flight status of IKAROS deep space solar sail demonstrator," *Acta Astronautica*, vol. 69, no. 9–10, pp. 833–840, Nov. 2011.
- [264] M. Williamson, "Space junk makes an impact," *Inst. Electr. Eng. Rev.*, vol. 52, no. 1, pp. 40–44, 2006.
- [265] D. J. Kessler, "Collisional cascading: The limits of population growth in low earth orbit," *Adv. Space Res.*, vol. 11, no. 12, pp. 63–66, Jan. 1991.
- [266] H. Klinkrad, P. Wegener, C. Wiedemann, J. Bendisch, and H. Krag, "Modeling of the current space debris environment," in *Space Debris*. Berlin, Germany: Springer-Verlag, pp. 59–114.
- [267] D. Normile, "Space age fish tale gets lost in translation," *ScienceInsider*, Apr. 2, 2011.
- [268] Q. Zhang and H. Hofmann, "Harvesting electric energy during walking with a backpack: Physiological, ergonomie, biomechanical, and electromechanical materials, devices, and system considerations," Dept. Electr. Eng. Mater. Res. Inst., Pennsylvania State Univ., University Park, PA, Final Program Rep. ADA428873, 2005.

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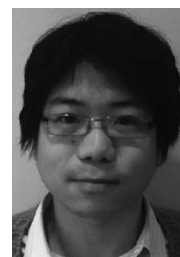
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