Nano Day: Celebrating the Next Decade of Nanoscience and Nanotechnology

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Nano Day: Celebrating the Next Decade of Nanoscience and Nanotechnology

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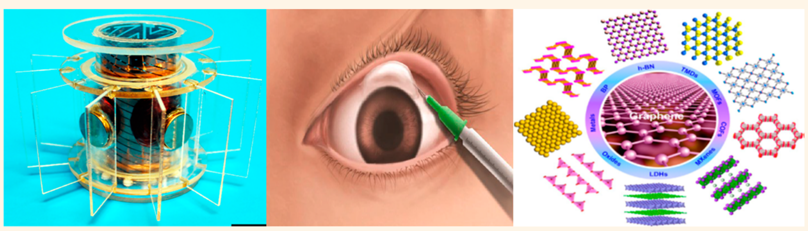

ABSTRACT: **Nanoscience and nanotechnology are poised to contribute to a wide range of fields, from health and medicine to electronics, energy, security, and more. These contributions come both directly in the form of new materials, interfaces, tools, and even properties as well as indirectly by connecting fields together. We celebrate how far we have come, and here, we look at what is to come over the next decade that will leverage the strong and growing base that we have built in nanoscience and nanotechnology.**

A global study was performed in 2010 to assess the first 10 years of the National Nanotechnology Initiative (NNI) and to provide a vision for the next decade of work in this field, ultimately culminating in a report entitled "Nanotechnology Research Directions for Societal Needs in 2020".[1] In the area of nanomaterials, several goals were outlined for 2020 including (1) synthesis, separation, fractionation, and purification in an effort to realize a library of nanomaterials with monodispersity in composition, size, and shape; (2) improvements in nanomanufacturing issues including scale-up, cost, sustainability, energy efficiency, process control, and quality control; (3) harvesting nanostructures from natural, sustainable, and earth-abundant raw materials; (4) combinatorial and computational approaches that enable efficient exploration of the vast phase space for nanocomposites including the size, shape, and composition of the nanoconstituents, role of defects, surface functionalization, and matrix; and (5) the realization of hierarchical nanostructured materials with independent tunability of previously coupled properties.

As we now stand more than halfway through the 2010–2020 decade, it is worthwhile to reflect on these goals. In the area of nanomaterials, monodispersity, and nanomanufacturing, significant progress has been made in mature fields such as quantum

Received: October 3, 2016
Published: October 7, 2016

   DOI: 10.1021/acsnano.6b06655
ACS Nano 2016, 10, 9093–9103

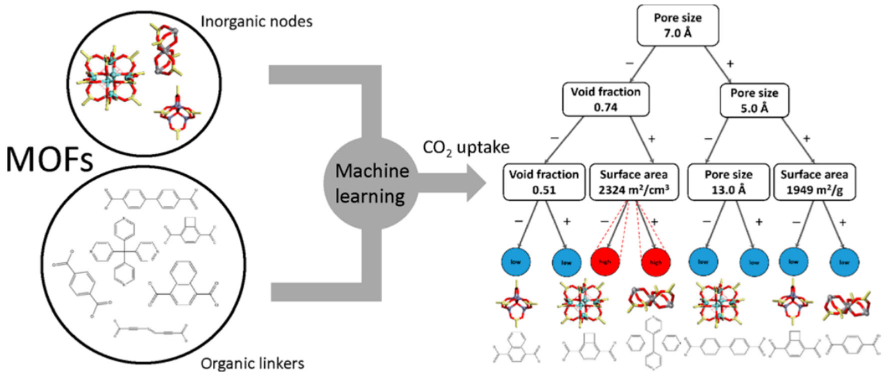

Figure 1. Materials Genome Initiative example. Metal–organic frameworks (MOFs) are nanoporous materials with exceptional host–guest properties poised for groundbreaking innovations in gas separation applications according to high-throughput screening data.[2] However, MOF structural libraries are nearly infinite in practice, and so statistical and information technology will play fundamental roles in implementing and rationalizing MOF virtual screening. Here, k-means clustering and archetypal analysis are used to identify the significant nanoporous structures in a large library of ~82 000 virtual MOFs. Quantitative structure–property relationship models of the theoretical CO_2 and N_2 uptake capacities were also developed using a calibration set of ~16 000 hypothetical MOF structures derived from the prototypes and archetype frameworks. Since uptake capacities correlated poorly to the void fraction, surface area, and pore size, these properties were used to build binary classifier predictors that successfully identify "high-performing" nanoporous materials in an external test set of ~65 000 MOFs with accuracy higher than 94%. The accuracy of the classification decreased for MOFs with fluorine substituents. The classification models can serve as efficient filtering tools to detect promising high-performing candidates at the early stage of virtual high-throughput screening of novel porous materials. Reprinted from 3. Copyright 2016 American Chemical Society.

dots, carbon nanotubes, and graphene, with many commercial vendors now offering highly homogeneous nanomaterial samples in industrial-scale quantities. Furthermore, the U.S. National Science Foundation (NSF) has recently announced its sixth year of funding for its Scalable Nanomanufacturing (SNM) program, which is helping to focus and to accelerate academic efforts in this regard. In the area of sustainability, NSF is again providing leadership through its cross-directorate initiative entitled Sustainable Chemistry, Engineering, and Materials (SusChEM). Similarly, the importance of combinatorial and computational approaches for identifying new materials has been recognized at the highest levels of government through the multiagency Materials Genome Initiative (MGI) that was announced by President Barack Obama in 2011 (Figure 1).[2] The MGI has also taken on the challenge of hierarchical materials through the National Institute of Standards and Technology (NIST)-funded Center for Hierarchical Materials Design. With strong federal support, it appears that significant progress toward the aforementioned nanomaterials goals will be achieved by the end of the decade.

While many of the projections from the 2010 global study have come to fruition, it is also informative to look in hindsight at recent developments in nanomaterials that were not anticipated. For example, other than graphene, which was the subject of the Nobel Prize in Physics in 2010, the 2010 global study was largely silent about two-dimensional (2D) nanomaterials, which was an oversight as 2D nanomaterials are among the most popular topics in nanoscience and nanotechnology today (see Figure 2 for an illustrative example).[4−8] The importance of heterostructures, not only between 2D nanomaterials but between nanomaterials of differing dimensionalities (*i.e.*, mixed-dimensional heterostructures), has also come to the forefront in the years since 2010.[9] Materials are being developed with building blocks different than atoms and molecules (*e.g.*, precise clusters and artificial atoms), leading to new ways to tailor material properties by design.[10−12] Other methods for tuning the properties of established nanomaterials (*e.g.*, by varying surface chemistry) have also become better appreciated recently.[13−16]

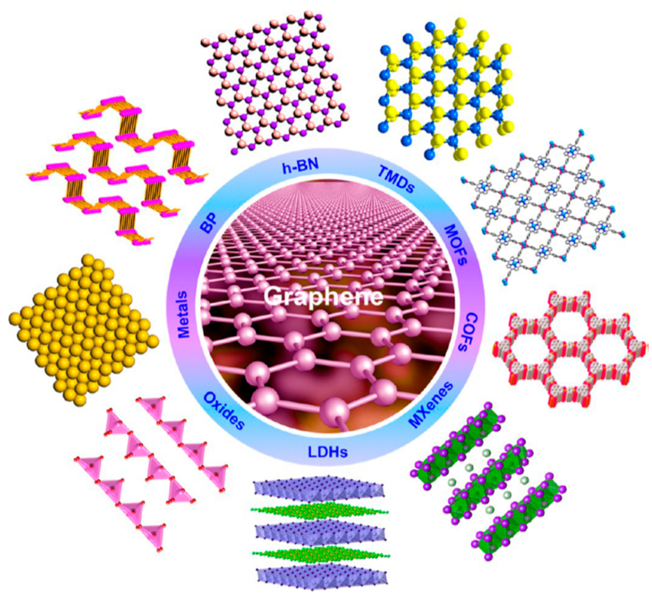

Figure 2. Schematic illustration of different kinds of typical ultrathin 2D nanomaterials, such as graphene, the hexagonal form of boron nitride, transition metal dichalcogenides, metal–organic frameworks, covalent-organic frameworks, MXenes, layered double hydroxides, oxides, metals, and black phosphorus. Reprinted from ref 6. Copyright 2015 American Chemical Society.

With many significant surprises still occurring 15 years after the initiation of the NNI, it is evident that we remain in the age of discovery for nanoscience and nanotechnology. Consequently, in addition to the targeted funding initiatives listed above, significant efforts should be devoted toward open-ended, fundamental research to ensure a favorable climate to enable currently unforeseen discoveries.

Electronics, Devices, and Fabrication. The microelectronics industry has been manufacturing products with nanoscale structures for decades; the market is currently on the order of US $500 billion annually. The continuous drive to scale micro-

DOI: 10.1021/acsnano.6b06655
ACS Nano 2016, 10, 9093−9103

electronic devices is captured by Moore's Law.[17] At present, this scaling has led to full-scale production of devices with minimum features of nominally 20 nm^2, which is 1/5 the diameter of an influenza virus.[18] The production of the devices involves a sequence of many unit processes, so reducing the size of the devices (and increasing the size of the wafers on which they are fabricated) leads to cost reduction and also generally to improved performance. Many have predicted and even announced the end of Moore's Law[19−21] because the methodology used to pattern the areas of the semiconductor, insulator, and conductor that make up these devices is reaching its physical limits. If the cost and efficiency of these devices stops improving with time, there will be a significant perturbation in global economics.

Note that related scaling down has taken place in the manufacturing of magnetic storage devices. The number of bits that can be stored per unit area on these devices has increased at a compound annual growth rate between 40 and 90% for many decades.[22] This scaling is facing a physical limit, as well, the superparamagnetic limit. New methods and/or materials must be developed to increase areal density while preserving the archival nature of this form of information storage,[23,24] and there is also a need to reduce power consumption. The huge data farms that are based on these devices consume a significant fraction of all of the power generated at this writing. They currently consume between 70 and 80 billion kW·h per year.[25] The trend toward cloud computing and "big data" will surely demand ever increasing amounts of archival information storage with the concomitant demand on power. It is important to study alternative methods for handling these data. Optical interconnects and photonic information transfer, for example, offer one approach to reducing energy loss to heat, and studies on alternative low-cost designs for archival information storage are warranted.

The semiconductor and the information storage patterning problems are related. A low-cost, high-resolution patterning process is required. The current processes are all based on photolithography. Alternative approaches including electron-beam (e-beam), X-ray, and ion-beam techniques of various sorts have been proposed, explored, and, in almost all cases, have been abandoned. Those processes that are still under consideration may be too costly to operate.[26,27] Very different approaches to this kind of imaging are also being explored, including, for example, imprint (molding) techniques[28] and the directed self-assembly of block copolymers.[29]

While it seems unlikely at this point that a high-volume e-beam writing tool will emerge, there is nonetheless a need to improve e-beam writing as it is used to generate the masters, masks, and reticles upon which all other high-volume patterning methodologies ultimately depend. Electron-beam lithography is the primary pattern generator. There is a need to develop writing tools that can produce masters with improved pattern placement accuracy at a rate that is commercially viable. New approaches to stage design, beam optics, and metrology are needed.

The economics of e-beam writing are such that commercial entities are not inspired to pursue costly development studies: so few of these tools are ultimately sold that the profit cannot support the research and development costs. The same is true of the resist materials that are used for e-beam patterning. Resist companies are not inspired to conduct fundamental research in this area because the volume of sales is simply too low.

Scaling of semiconductor devices has been done to date in the *x,y* (surface) plane. There is general recognition that three-dimensional (3D) device structures offer the next pathway to increased performance and lower cost.[30] However, stacking these devices carries daunting challenges, among these is heat management. High-speed logic devices generate quite a lot of heat, and if they are stacked, new means must be found to minimize heat generation and to maximize heat dissipation. Both of these problems demand new materials. Materials scientists have learned to conduct electrons very efficiently; they now need to learn to conduct phonons with equal efficiency. The advent of boron nitride nanotubes[31] offers some hope in that regard.

There are also great opportunities in creative design of devices for data processing and information storage. The first cross-bar-type memories are appearing.[32,33] These include magnetic random-access memories[34] and analogs, resistive random-access memories[35] of various designs, *etc.* Again, the key to enabling each of these exciting design concepts is the development of new materials.

There is also a need to pursue new approaches to system design and the devices that are used for information storage processing, such as neural networks, holographic systems, those based on photorefractive materials, quantum computing, *etc.* However, there is still a lot of "room at the bottom" for major improvements in the classical von Neuman type systems that power today's world. So, basic research related to materials for microelectronics and studies related to high-resolution patterning for semiconductor manufacturing could have a huge payoff in terms of influence on society. These strategies are classic high-risk/high-return undertakings, but because the potential for the return is incredibly high, these strategies cannot be ignored.

Integration and Applications. Top-down fabrication and bottom-up assembly enable the construction of nanoscale structures. Advances in both approaches have been driven by technology to increase device density, by curiosity to understand, and by innovation to exploit the size-dependent chemical and physical properties practically that arise at the nanoscale. Today, we embrace the best of both worlds, which have delivered from the top-down high-performance silicon electronics and high-density magnetic storage and, more recently, have delivered from the bottom-up high-color purity quantum-dot displays and high-sensitivity nanoparticle home pregnancy tests.

We look to a future in which technology is increasingly pervasive and empowers a "smart world", that is, where technology enables us to increase the efficiency of our use of resources and ensures the safety of our planet and the health and well-being of people worldwide. Developing the physical basis of a smart world will require fundamental scientific exploration and engineering of materials, devices, and manufacturing processes. We look toward a focus on the science and engineering of integration in which we exploit today's advances in nanoscale materials and both top-down and bottom-up fabrication methodologies to translate materials synthesis and property discovery into technologies.[36] We also look to enable processes that permit greater precision and complexity in our control over the size, shape, and composition of materials and devices across multiple length scales, from the nano- to the macroscale, to realize combinations of physical properties not found in natural materials and that are enhanced by physical phenomena operative at these different length scales.[37]

Advances in materials, devices, and manufacturing for a smart world will impact applications in industry sectors including energy, consumer staples, information technology, telecommunications, transportation, and healthcare. In all these cases, we anticipate that consumers will see "nano-enabled" products

DOI: 10.1021/acsnano.6b06655
ACS Nano 2016, 10, 9093−9103

rather than nanotechnology products.[38−40] This difference has important consequences for the field, as discussed below.

Energy. The high surface area and tunable chemical and physical properties of nanoscale structures promise technologies that capture, convert, and store energy with greater efficiency and transduce energy and matter of different forms, such as between radiant, thermal, electrical, chemical, and mechanical energy forms and between compounds, chemicals, and fuels.

Sustainable and efficient large-scale energy production is required to meet the perpetually increasing worldwide demand for energy, while ensuring the safety of our planet. For example, the sun produces 1.2×10^5 TW of energy, enough energy in an hour to power our planet for a year. The unique and size-dependent properties of nanoscale materials and the low-cost fabrication of their devices promise to advance solar technologies. Silicon solar cells have dominated the marketplace and are effective at converting visible light into electricity. However, approximately one-third of solar output is in the infrared, below the band gap of silicon, and while strategies have been developed and devices have been demonstrated, this range is not utilized commercially in photovoltaic devices.[41] The excess kinetic energy of carriers created by short-wavelength photons is lost to heat. One route is to improve the efficiency of silicon solar cells by adding nanoparticle coatings[42] and nanostructuring their surfaces to convert spectrally and to absorb the broad-band radiation of the sun more effectively.[43] Another route is to divide up the broad-band solar spectrum using (nanoscale) optics to route different colors of light to different solar cells or to stack different solar cells in tandem. Here, colloidal quantum-dot solar cells that capture and convert infrared light may provide a cost-effective route to collect light that is missed by silicon cells.[44] Finally, organic−inorganic hybrid perovskites are relative newcomers, providing an alternative semiconductor materials class, that have demonstrated remarkable efficiencies in solar cells in a short time frame.[45] The future of these technologies requires materials development and integration. The best quantum-dot and perovskite solar cells contain lead, which poses concerns of toxicity especially for large-area devices such as solar cells, and many spectral converters contain costly rare-earth elements.

Another route to harvest sunlight and yet manage the broad spectrum of the sun is to convert solar energy into heat and then emit the heat in a narrow band where it can be used efficiently to create electricity through thermophotovoltaics. Identifying a material that absorbs light from many angles with energies across the solar spectrum, emits light in a narrow band, and is stable at high temperature is challenging. However, recent reports of nanostructuring high-temperature metals are promising[46,47] to address this issue as nanostructuring the metals is used to tailor the optical properties of the materials. Materials and fabrication processes that are economical and allow these structures to be integrated in devices are needed.

> Recent advances show promise in capturing energy from wind and waves as well as scavenging smaller amounts of energy from human or animal motion.

Waste thermal energy is created by engines and in large server farms. Thermoelectric devices may recover thermal energy and convert it into electricity. However, to be economically viable, new materials with higher thermoelectric figures of merit, or equivalently, efficiencies, are needed. Thermoelectric materials must transport electrical charge, yet not thermal energy. Nanostructured materials and low-dimensional structures have the greatest potential to enhance the thermoelectric figure of merit as these systems (1) reduce thermal conductivity by creating a high density of interfaces to scatter acoustic phonons, (2) increase thermopower by energy filtering, and (3) enhance electrical conductivity by increasing the density of states near the conduction and valence band edge.[48−50] Investment is needed to design thermally stable, nontoxic, and "electronically engineered" nanomaterials, to probe the physics of charge and heat in these materials, and to translate these materials into devices and systems.

In another example, catalysts are used to lower the energetic barrier and thereby accelerate the rate of chemical reactions. Metal nanocrystals are used as heterogeneous catalysts in the conversion of light to fuel and of chemical compounds to electricity, and in the production of chemical and pharmaceutical compounds. Most conventional, industrial nanocrystalline catalysts are structurally poorly defined. However, research has shown through synthetic control over the size, shape, composition, and internal structure of nanocrystals and through advanced structural and electronic probes that the arrangement and type of surface atoms presented by the crystal facets may be used to improve reactivity and selectivity.[51] The activity of the metal catalyst may be further enhanced by their placement on or connection to solid metal oxide supports. Careful experimental design and high-resolution structural probes are uncovering the sites at the interface between the metal nanocrystal and metal oxide support responsible for the improved activity.[52] Synthesis of bimetallic nanocrystals is also showing increased activity and may lower the use of otherwise expensive metals. Looking forward, research is needed to explore the stability of high-performance shaped nanocrystals over time and in different operating environments, the impact of intentional or unintentional surface species on the catalyst activity, and the design of catalyst oxide supports to push activity and selectivity. To translate research achievements into industrial practicality, synthetic methods that produce nanocrystals with the control in size, shape, composition, and structure must be scaled up.

Electrical Energy Storage. Electrochemical energy storage, involving both batteries and capacitors, has the potential to be strongly impacted by nanometer-scale materials on the 5−10 year time scale, based upon our accelerating research and research funding globally in this area.[53] Carbon nanotubes have already found their major application as a conductive additive in the battery industry, and activated carbons with 1−2 nm pore sizes are used as active electrode materials in a majority of supercapacitors.[54] Graphene and other 2D materials are entering the market when thin film and flexible devices are required. Wider use of carbon and organic materials makes batteries greener and more sustainable.[55] However, we can expect much greater impact based on the vigorous research and development effort in this area.

The energy and power available from lithium ion batteries are both likely to be increased substantially. The constraint requiring electrode materials to be conductive is lifted at the nanoscale, as long as these materials can be efficiently dispersed onto a highly conductive current collector. Examples include semiconducting silicon anodes and insulating sulfur cathodes supported on carbon, which offer substantial increases to the energy provided

DOI: 10.1021/acsnano.6b06655
ACS Nano 2016, 10, 9093−9103

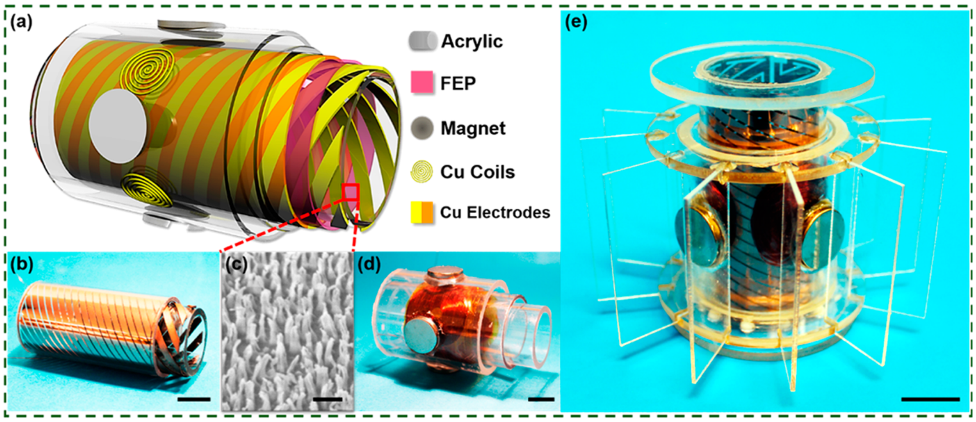

Figure 3. Structural design of a blue-energy hybrid nanogenerator.[67] (a) Schematic illustration of the functional components of the hybrid nanogenerator, which consists of a spiral interdigitated electrode triboelectric nanogenerator (S-TENG) and a wrap-around electromagnetic generator (W-EMG). Photographs of (b) as-fabricated S-TENG and (d) as-fabricated W-EMG (both scale bars are 2 cm). (c) Scanning electron microscope image of the flourinated ethylene propylene polymer nanowires in the S-TENG (scale bar, 500 nm). (e) Photograph of an as-fabricated hybrid nanogenerator (scale bar, 2 cm). Reprinted from ref 67. Copyright 2016 American Chemical Society.

by conventional graphite anodes and cobalt oxide cathodes, respectively. Increased cyclic battery lifetimes due to minimization of strain that leads to increases in resistance and failure of the current battery electrodes can also be achieved by nanostructuring.[56,57] The question remains open as to whether nanotechnology can reliably suppress formation of lithium dendrites, making Li metal batteries more safe.

Lithium abundance has been cited as a barrier to the continued use of the element in batteries, but a 2015 U.S. Geological Survey report estimated that a 365 year supply of lithium exists if it continues to be produced and consumed at current rates. Nevertheless, new battery chemistries based upon sodium, potassium, and magnesium ions are being researched. Taking into account the low mobility of Mg^{2+}, Al^{3+}, and other multivalent ions in conventional battery materials, nanotechnology can offer the solution—highly conductive 2D sheets that enable fast intercalation/deintercalation of ions.[57]

Finally, electrochemical capacitors utilizing surface redox will compete with batteries in many applications due to a much higher power, much faster charging, longer lifetime, and ever increasing amount of the energy stored by these devices.[58]

In terms of their utility as electrode materials for electrical energy storage, the Achilles heal of nanomaterials is durability. Smaller particles can degrade faster if they are involved in irreversible reactions. Voltage plateaus on galvanostatic charge—discharge curves often disappear when nanomaterials are used and pseudocapacitive behavior is observed,[57] forcing electrical engineers who design devices to deal with the changing voltages as the devices discharge. However, the potential benefits from the use of nanomaterials in energy storage greatly exceed their drawbacks.

CO_2 Adsorption by Nanoporous Materials and Catalytic Conversion. Capture and sequestration of carbon dioxide are viewed as a way to decrease the effect of human activities on the environment and to minimize the global warming. The challenges in the field are enormous, first due to the scale, as many tons of CO_2 must be captured. However, capture and conversion of CO_2 at smaller scales, such as in spacecraft, has already been done for a long time. Chemical fixation, physisorption, and catalytic or electrocatalytic conversion to biofuels or other useful products are the main directions being explored. Capture of CO_2 by physisorption is required in most cases before catalytic conversion, with a temperature or pressure swing used to release the gas. Of course, large volumes require the use of earth-abundant and inexpensive materials, as well as inexpensive (free) sources of energy such as waste heat or solar energy. Since the capture of CO_2 is done using nanoporous materials (molecular sponges) and catalytic CO_2 conversion occurs at the interfaces with catalytic surfaces, nanotechnology can and must contribute to solving this global challenge.

The most commonly used and studied materials include porous carbons, zeolites, mesoporous silicates, and metal—organic frameworks (MOFs). Carbon, such as activated charcoal, is and probably will remain the least expensive sorbent. However, the heat of adsorption and the amount of CO_2 adsorbed strongly depend on the pore size.[59] Therefore, pore sizes must be tuned to smaller than 1 nm with angstrom accuracy to maximize the amount of CO_2 adsorbed; this is likely the most straightforward means to provide large-volume CO_2 capture. Alternatively, by modification of the cations in zeolites and/or introduction of surface functional groups that increase the heat of adsorption of CO_2, such as amines, the amount of CO_2 captured and the strength of adsorption of these porous materials can be increased.[60] Cation-exchanged zeolites are already finding industrial-scale applications. Amino-functionalized mesoporous silicates have high affinities for CO_2, but they need to be placed into a completely CO_2-free environment for full regeneration. At the same time, similarly modified MOFs also have high CO_2 adsorption capacities, being promising candidates for a plant-scale use, if large-scale and economical syntheses become available. Chemical and temperature stability, as well presence of a variety of other, often chemically active gases in power plants, and other CO_2 exhausts create an additional challenge. Pelletization of porous materials or manufacturing of large particles with hierarchical porosity—macropores for fast transport and nanopores for adsorption—add engineering challenges to this already difficult problem.

Beyond storing captured CO_2 underground, there is an ongoing effort to use sunlight in concert with catalysts to transform CO_2 chemically into value-added fuels such as alcohols. Natural photosynthesis performs this function but does so slowly and with low sunlight-to-fuel efficiency.[61] In analogy to natural photosynthesis, which involves fixation of CO_2 to sugars, semiconductor electrode surfaces can be used to

DOI: 10.1021/acsnano.6b06655
ACS Nano 2016, 10, 9093−9103

achieve the solar-driven photoelectrochemical conversion of H_2O and CO_2 to useful chemicals and solar fuels.[62] Hydrogenation of CO_2 to form formate and methanol on nanostructured catalysts offers another path to CO_2 conversion.[63] Electrocatalytic reduction of CO_2 to CO can be done without the use of noble metal catalysts with, for example, nanostructured tin or bismuth electrodes in the presence of ionic liquid,[64] but electrocatalysis requires inexpensive sources of electricity that can be provided by solar or wind energy.

Recent advances show promise in capturing energy from wind and waves[65−67] as well as scavenging smaller amounts of energy from human or animal motion (Figure 3).[68,69] Many of these devices take advantage of voltages generated using cleverly engineered systems that take advantage of piezoelectric and triboelectric effects.[68] In the upcoming years, powering numerous distributed devices will be central to the Internet of Things, and self-powered devices have significant advantages over wired or battery power. For wearable technology that is becoming ubiquitous, self-power has significant advantages over batteries.[67] Look for further development of these ideas and strategies.

Nanomedicine. One of the most promising and exciting areas of application for nanomaterials is the design of engineered nanoparticles to address disease and to monitor and to protect human health. The ability to construct nanoparticles within the range of approximately 20−200 nm in size has enabled the design of materials that are large enough to avoid the rapid clearance rates of typical small molecules through the kidney but small enough to be retained in the body based on a range of physiological changes, morphological, or biochemical differences that are found in different tissue types or in the presence of specific diseases or disorders. Because there are broad ranges of materials systems and functionalities that can be introduced to nanoparticles, it is possible to tune this class of materials to target specific organs in the body for treatment, imaging, and early detection.

One of the most promising and exciting areas of application for nanomaterials is the design of engineered nanoparticles to address disease and to monitor and to protect human health.

Some of the earliest strides in nanomedicine have been in the critical and yet highly challenging area of cancer treatment. By taking liposomal formulations to encapsulate known chemotherapy drugs, it is possible to show improvements in preclinical studies in targeting efficacy[70] and accumulation in tumors, as well as lowered toxicity of the drug. These findings led to a revolution, with studies investigating a wide range of different nanoparticle systems. The concept of cancer-targeting nanoparticle systems was originally based on (1) the encapsulation of the therapeutic to protect the drug from interacting with proteins in the bloodstream or healthy cells until uptake in the tumor and (2) the use of nanoparticle size designed to accumulate in tumors through their transport through the leaks in the defective vasculature of solid tumors. Additional functionality can be added to nanoparticles by introducing ligands that bind selectively to receptors overexpressed on tumors. Key advantages of nanoparticle delivery include the ability to create depots with combinations of synergistic drugs, all of which may be delivered to the same cell at a predetermined dose and timing.

Ultimately, some of the first nanomedicine systems made it to the clinic, and recent studies examining the impact of these materials indicate that there are measurable gains in safety and lowered toxicity in most studies for early drugs such as Doxil[71] *versus* conventional doxorubicin for first-line treatment of metastatic breast cancer.[72] On the other hand, increases in drug efficacy in the clinic[71,73] and, specifically, increased accumulation in tumors have not been readily and consistently demonstrated,[74] and tumor targeting that has been observed can be quite variable from patient to patient,[75] although there are also cases reported recently of human studies in which accumulation of nanoparticles has been observed and activity of drug within the tumor detected.[76]

Although there are significant challenges that are introduced in these and other recent studies, there is much to learn that can inspire future work in nanomedicine (for one example, see Figure 4). First, it is important to recognize that, despite these difficulties, much is gained from lowering the toxicity of drugs used against cancer and other aggressive diseases. Furthermore, even small enhancements in tumor accumulation of drugs could be meaningful for treatment. The use of nanoparticle systems with improved stability and more controlled release that is initiated by pH changes, enzymes present in the tumor environment, or other biochemical differences that are known to exist in tumor tissues can further improve the controlled encapsulation of toxic drugs until they reach their target, thus furthering this advantage and potentially increasing the therapeutic window of many key drugs and making numbers of previously insoluble or otherwise unavailable drug molecules

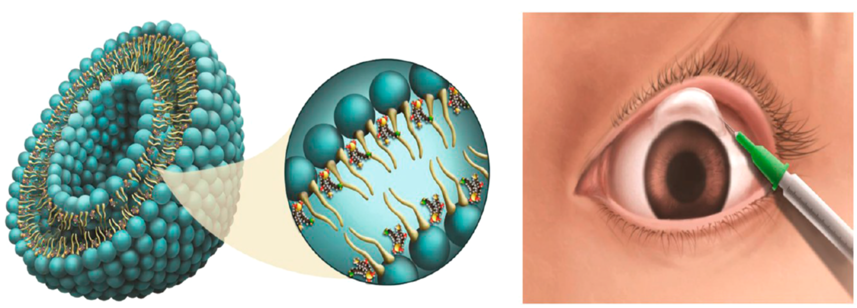

Figure 4. Liposomal nanomedicine for glaucoma.[77] Left: Schematic representation of a liposome with latanoprost incorporated in the bilayers. Right: Schematic representation of a subconjunctival injection into the patient's eye beneath the upper eyelid. A small bleb is seen where the liposomal formulation has been administered; it usually disappears within 30 min. Reprinted from ref 77. Copyright 2014 American Chemical Society.

DOI: 10.1021/acsnano.6b06655
ACS Nano 2016, 10, 9093−9103

viable for treatment. Nanoparticles also enable the encapsulation of sensitive cargo such as RNA and DNA, which enable genetic approaches that are not viable or effective using the free drug in these cases.

Important recent findings in human clinical trials provide insight into the challenges we face in the future in the design of nanoparticle systems as well as potential guides for future design and characterization. As we understand more about the dynamic nature of blood vessels generated by the tumor, it becomes clear that we will need to design nanoparticle systems capable of getting across the tumor blood vessels effectively, with or without the assistance of additional triggers such as photoirradiation or thermal exposure. In the meantime, the use of molecular ligands on nanoparticle surfaces can lead to increases in therapeutic uptake, but first the endothelial and extracellular matrix barriers must be penetrated effectively. Taking advantage of other aspects of the tumor microenvironment—the presence of specific enzymes, the hypoxic condition that can lower pH, and other differences—and generating dynamic nanomaterials that can present different functional groups at different points in delivery are of interest. Additional areas of interest include the modification of nanoparticle shape, stiffness, and size to increase transport across important barriers. New research is focusing on these elements of design, and with the assistance of more advanced and realistic preclinical animal models of the disease, more effective delivery and targeting should be achievable.

> The field is poised to make contributions far beyond the nanoscale worlds that we explore in our everyday work. That is what we celebrate with Nano Day and every day.

What we have learned in the area of cancer can be translated to targeting many organs in the body. There are several exciting possibilities that involve the design of nanoparticles to circulate in the bloodstream for extended time periods based on surface charge, degree of hydration, and materials properties, and ultimately to accumulate in a specific organ. Nanoparticles can be designed to target infectious disease; for example, nanomaterials may target the lung to deliver potent antibiotics, or anti-inflammatory drugs could address bacterial or viral infection. Most highly inflamed tissues exhibit a number of features that can be used as the basis for tissue targeting, so nanoparticle systems might be designed to address wound sites in infarction or other conditions or to alleviate fibrosis. One of the great challenges at this time is finding a means of getting nanoparticles across the tight junctions of the blood−brain barrier, which would then enable treatment of cancers such as glioblastoma, and more effective therapeutic and genetic treatments of neurological disorders such as Parkinson's disease and Alzheimer's disease. Direct injection of nanoparticles into the synovial fluid in joints might enable engineered nanomaterials to penetrate cartilage to deliver growth factors to address arthritis, and nanoparticles that target the lymph nodes and lymphatic system might be engaged as a means of engaging the immune system and activating or lowering its activity to address vaccines or autoimmune disorders. These areas of medicine, including the use of immuno-oncology to activate the body's immune system to attack tumor cells, are some of the most rapidly growing, and we anticipate seeing new nanomaterials innovations that address these grand challenges.

Consumer Staples. *Food.* In 2009, the United Nations Food and Agriculture Organization (UNFAO) reported the grand challenge "How to Feed the World in 2050" in response to the rapid growth in global population and with pressures on our food supply from urbanization, climate change, and increased biofuel production.[78] In 2013, the UNFAO highlighted the further loss in the available food as one-third of food produced is wasted in the supply chain.[79] The challenge is to ensure not only food security but also its safety as food contamination causes illness and is economically costly. The large surface-to-volume ratio inherent to nanoscale materials makes them highly sensitive to changes at their surfaces and therefore exceptional building blocks of sensor technologies.[80] For example, the color of plasmonic metal nanostructures, the conductivity of semiconductor nanostructures, and the resonance frequency of mechanical cantilevers depend on the dielectric function, charge, and mass of matter at their surfaces. Sensor technologies may be designed that exploit changes at the surface of nanostructures so they respond to variations in the environmental and detect disease-causing pathogens before they spread. Nanoscale sensor technologies also promise to allow optimization of our use of natural resources and agrochemicals. Investment in research to design nanoscale systems for the application space of food security and safety and the opportunity to bring together scientific experts in nanoscale and food science and engineering with industry is needed to develop and translate science into technology.

Water. The principles of nanotechnology have been used in water desalination and purification for a long time. Clay and activated charcoal, which are the most common materials for large-scale water filtration and purification, are nanomaterials—a natural 2D material and a nanoporous carbon, respectively. Reverse osmosis is widely used in countries like Israel for water desalination, and the semipermeable polymer membranes separate water from dissolved ions at the sub-nanometer scale.

So, it is only natural that modern nanotechnology is poised to make major contributions through supplying clean water globally. First, making membranes from 2D materials, such as graphene oxide, offers an advantage in water transport rate, as much thinner membranes can be prepared compared to polymers.[81−85] A few-microns-thick graphene oxide membrane can sieve ions and organic molecules with hydration radii larger than 4.5 Å.[84] The ion rejection and water transport rates in membranes made of 2D materials can be controlled by changing the flake size, interlayer spacing, and the membrane thickness.[82,86] New nanomaterials, such as titanium carbide MXene,[87] can provide even better selectivity and faster water transport compared to graphene oxide. They can also offer resistance to biofouling.[88]

Pushing the scales further down, single layers of graphene with sub-nanometer diameter holes have been shown to improve the water flow rate further and could lead to the development of ultrathin filters for improved desalination or water purification.[89]

> Nanotechnology is poised to make major contributions through supplying clean water globally.

The permeability of such filters is greater than that of conventional membranes, leading to less energy spent on water

DOI: 10.1021/acsnano.6b06655
ACS Nano 2016, 10, 9093−9103

filtration/desalination. The quick and energy-efficient production of pure water from brackish water, seawater, or other contaminated sources (fracking water, industrial waste, *etc.*) would be easiest with atomically thin membranes perforated with pores just large enough to pass water molecules and small enough to block salts and organics. However, producing membranes with atomically controlled pore sizes at a practical scale is still a challenge. Therefore, 2D laminates may offer a more practical solution to water desalination and filtration in the foreseeable future.

Moreover, it was recently shown that electrostatic-charge-induced water gating can realize the transition between an open, conductive state and a closed, nonconductive state by regulating the surface charge density through a process that involves alternating capillary evaporation and capillary condensation. This process is sufficiently simple to be used in water desalination.[89]

The unique material properties that emerge at the nanoscale may also enable solutions to treat pollutants in water for which existing technologies are inefficient or ineffective. Removal of radioactive elements, lead, or arsenic is the challenge that nanotechnology is able to address. Realization of these approaches may take us a long way, but when we develop atomically precise manufacturing of membranes for water treatment, we may gain unlimited access to drinking water.

Nano Safety. Nanotechnology environmental health and safety (nanoEHS) is an important consideration for the acceptance and advancement of these emerging technologies. Concern is often expressed about the level of uncertainty regarding the safety of nanomaterials, which is incongruent with the expenditure of 6−7% of the federal budget for the NNI on nanoEHS.[90] While this investment sparked many new discoveries regarding nanosafety, the large number of new materials, rapid growth of the field, and requirement for new scientific approaches for hazard assessment have created a backlog in new safety assessment methods that can be used to develop a comprehensive governance system. The current status of nanoEHS includes (1) a case-by-case analysis of newly introduced materials, while a large number of new products are appearing; (2) a lack of systematic hazard and risk profiling of broad categories of nanomaterials in order to perform grouping or read-across; (3) the use of descriptive animal studies for regulatory decision-making instead of 21st century toxicological approaches that use more mechanistic screening approaches that also consider the actual physicochemical properties of nanomaterials; (4) a lack of comprehensive information about the actual range of pristine or nanoenabled materials that have entered the marketplace, their lifecycle analysis, and the exposure circumstances that could lead to adverse outcomes in workers, consumers, and the environment; (5) a lack of sufficient instrumentation and methodological approaches, dosimetry assessment, and detection of the presence of nanomaterials in complex biological and environmental conditions; (6) a lack of validated test procedures that could be widely implemented as actionable data on which regulation is based; and (7) a regulatory environment in which nanomaterials are considered to be new chemical substances in spite of their complicated one-dimensional (1D), 2D, and 3D physicochemical properties.[91,92]

However, in spite of our backlog of knowledge in comprehensively addressing the issues of nanomaterial hazard, exposure, and dose assessment as well as lifecycle analysis, we have witnessed the emergence of more mechanism-based approaches and nonvertebrate or alternative test strategies (ATS) over the last ~5 years. Alternative testing strategies decrease animal use and speed up the rate of material testing through the use of predictive toxicological approaches, adverse outcome pathways, high-throughput screening, *in silico* computational data handling and modeling tools, and tiered hazard assessment approaches. Recent reform of the U.S. Toxic Substances Control Act[93] calls for the use of new 21st century safety assessment approaches that include ATS, high-throughput screening, computational analysis, and tiered risk assessment. Similar changes are being made elsewhere in the world. To obtain more exposure information in humans and the environment, it is important that tools be developed to detect nanomaterials in complex exposure environments, as well as for dosimetry life-cycle assessment. Information on exposure and dosimetry can be used together with ATS for tiered risk assessment and regulatory decision analysis. Transparency about the type of scientific data that are useful and can be submitted to the regulatory agencies to make affirmative safety and hazard decisions for nanomaterials will help to improve the level of uncertainty and expedite cooperation between academia, industry, and regulators. This collaboration could facilitate material access to the marketplace and the establishment of the multidisciplinary cooperation and expertise that is required to address the important safe implementation of nanotechnology.

Nanotechnology environmental health and safety is an important consideration for the acceptance and advancement of these emerging technologies.

Education and Outreach. Education in nanoscience and nanotechnology to date has largely developed by having students in core or related disciplines get their regular training then come to learn other fields and "cross-train". Debate continues as to whether there should be a core curriculum in the field and education experiments are being run to assess the value of such courses of study.[94]

Public perception and understanding of nanoscience and nanotechnology remain problematic in the sense that there is a lack of awareness of the goals and capabilities of these fields. It is incumbent upon members of the community to share what and how we do. The many nanocenters around the world have special roles to play in this regard, as they commonly have sustained outreach efforts and the infrastructure to connect with the public locally and beyond.[95]

Communication across Fields. A key contribution to science and technology has been establishing communication across fields. Nanoscience and nanotechnology have, by necessity, brought together scientists, engineers, clinicians, and others to work together, first on developing the field by developing new tools, methods, and materials,[96] then on understanding new phenomena discovered, and ultimately on exploring where these advances could be applied in the areas described above as well as in other areas of science, engineering, and medicine. It is because of these communication skills and interest in the grand challenges faced by other fields that major efforts such as the U.S. BRAIN Initiative, the National Microbiome Initiative, and the Brain-Inspired Computation Initiative in the U.S., the Graphene Flagship in the European Union, and the national efforts in graphene and other 2D materials in Singapore and elsewhere were developed with leadership from nanoscience and nanotechnology.[97−101] We anticipate that this trend will continue. As scientists, engineers,

DOI: 10.1021/acsnano.6b06655
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and authors (and with our fellow editors), we regularly discuss and debate where the next significant opportunities are for nanoscience and nanotechnology.[102] The community is regularly engaged worldwide to take up these challenges, and the field is poised to make contributions far beyond the nanoscale worlds that we explore in our everyday work. That is what we celebrate with Nano Day and every day.

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ACKNOWLEDGMENTS

The authors thank Ms. Holly Bunje for help in preparation of this Nano Focus.

REFERENCES

(1) Roco, M. C.; Mirkin, C. A.; Hersam, M. C. *Nanotechnology Research Directions for Societal Needs*; Springer: Dordrecht, The Netherlands, 2011; ISBN 978-94-007-1167-9.

(2) https://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf.

(3) Fernandez, M.; Barnard, A. S. Geometrical Properties Can Predict CO_2 and N_2 Adsorption Performance of Metal−Organic Frameworks (MOFs) at Low Pressure. *ACS Comb. Sci.* **2016**, *18*, 243−252.

(4) Butler, S. Z.; Hollen, S. M.; Cao, L.; Cui, Y.; Gupta, J. A.; Gutiérrez, H. R.; Heinz, T. F.; Hong, S. S.; Huang, J.; Ismach, A. F.; Johnston-Halperin, E.; Kuno, M.; Plashnitsa, V. V.; Robinson, R. D.; Ruoff, R. S.; Salahuddin, S.; Shan, J.; Shi, L.; Spencer, M. G.; Terrones, M.; et al. Progress, Challenges, and Opportunities in Two-Dimensional Materials Beyond Graphene. *ACS Nano* **2013**, *7*, 2898−2926.

(5) Bhimanapati, G. R.; Lin, Z.; Meunier, V.; Jung, Y.; Cha, J.; Das, S.; Xiao, D.; Son, Y.; Strano, M. S.; Cooper, V. R.; Liang, L.; Louie, S. G.; Ringe, E.; Zhou, W.; Kim, S. S.; Naik, R. R.; Sumpter, B. G.; Terrones, H.; Xia, F.; Wang, Y.; et al. Recent Advances in Two-Dimensional Materials beyond Graphene. *ACS Nano* **2015**, *9*, 11509−11539.

(6) Zhang, H. Ultrathin Two-Dimensional Nanomaterials. *ACS Nano* **2015**, *9*, 9451−9469.

(7) Andrews, A. M.; Liao, W.-S.; Weiss, P. S. Double-Sided Opportunities Using Chemical Lift-Off Lithography. *Acc. Chem. Res.* **2016**, *49*, 1449−1457.

(8) Wee, A. T. S.; Hersam, M. C.; Chhowalla, M.; Gogotsi, Y. An Update from Flatland. *ACS Nano* **2016**, *10*, 8121−8123.

(9) Jariwala, D.; Marks, T. J.; Hersam, M. C. Mixed-Dimensional van der Waals Heterostructures. *Nat. Mater.* **2016**, DOI: 10.1038/nmat4703.

(10) Claridge, S. A.; Castleman, A. W.; Khanna, S. N.; Murray, C. B.; Sen, A.; Weiss, P. S. Cluster-Assembled Materials. *ACS Nano* **2009**, *3*, 244−255.

(11) Mandal, S.; Reber, A. C.; Qian, M.; Weiss, P. S.; Khanna, S. N.; Sen, A. Controlling the Band Gap Energy of Cluster-Assembled Materials. *Acc. Chem. Res.* **2013**, *46*, 2385−2395.

(12) Jones, M. R.; Seeman, N. C.; Mirkin, C. A. Programmable Materials and the Nature of the DNA Bond. *Science* **2015**, *347*, 1260901.

(13) Hersam, M. C. The Reemergence of Chemistry for Post-Graphene Two-Dimensional Nanomaterials. *ACS Nano* **2015**, *9*, 4661−4663.

(14) Ryder, C. R.; Wood, J. D.; Wells, S. A.; Hersam, M. C. Chemically Tailoring Semiconducting Two-Dimensional Transition Metal Dichalcogenides and Black Phosphorus. *ACS Nano* **2016**, *10*, 3900−3917.

(15) Kagan, C. R.; Lifshitz, E.; Sargent, E. H.; Talapin, D. V. Building Devices from Colloidal Quantum Dots. *Science* **2016**, *353*, 885.

(16) Mochalin, V.; Shenderova, O.; Ho, D.; Gogotsi, Y. The Properties and Applications of Nanodiamonds. *Nat. Nanotechnol.* **2012**, *7*, 11−23.

(17) http://www.intel.com/content/www/us/en/silicon-innovations/moores-law-technology.html.

(18) Hammarlund, P.; Martinez, A. J.; Bajwa, A. A.; Hill, D. L.; Hallnor, E.; Jiang, H.; Dixon, M.; Derr, M.; Hunsaker, M.; Kumar, R.; et al. Haswell: The Fourth-Generation Intel Core Processor. *IEEE Micro* **2014**, *34*, 6−20.

(19) http://spectrum.ieee.org/semiconductors/processors/the-multiple-lives-of-moores-law.

(20) Schulz, M. The End of the Road for Silicon? *Nature* **1999**, *399*, 729−730.

(21) Wood, R. Future Hard Disk Drive Systems. *J. Magn. Magn. Mater.* **2009**, *321*, 555−561.

(22) Dobisz, E. A.; Bandic, Z. Z.; Wu, T.-W.; Albrecht, T. Patterned Media: Nanofabrication Challenges of Future Disk Drives. *Proc. IEEE* **2008**, *96*, 1836−1846.

(23) Ruiz, R.; Kang, H.; Detcheverry, F. A.; Dobisz, E.; Kercher, D. S.; Albrecht, T. R.; de Pablo, J. J.; Nealey, P. F. Density Multiplication and Improved Lithography by Directed Block Copolymer Assembly. *Science* **2008**, *321*, 936−939.

(24) Yang, X.; Wan, L.; Xiao, S.; Xu, Y.; Weller, D. K. Directed Block Copolymer Assembly *versus* Electron Beam Lithography for Bit-Patterned Media with Areal Density of 1 Terabit/Inch^2 and Beyond. *ACS Nano* **2009**, *3*, 1844−1858.

(25) http://www.datacenterknowledge.com/archives/2016/06/27/heres-how-much-energy-all-us-data-centers-consume/.

(26) http://www.eetimes.com/document.asp?doc_id=1257963.

(27) http://www.electronicsweekly.com/news/business/finance/euv-cost-14bn-counting-2014-04/.

(28) Sreenivasan, S. V. Nanoscale Manufacturing Enabled by Imprint Lithography. *MRS Bull.* **2008**, *33*, 854−863.

(29) Bates, C. M.; Maher, M. J.; Janes, D. W.; Ellison, C. J.; Willson, C. G. Block Copolymer Lithography. *Macromolecules* **2014**, *47*, 2−12.

(30) http://www.extremetech.com/computing/119843-the-future-of-computers-3d-chip-stacking.

(31) Golberg, D.; Bando, Y.; Tang, C. C.; Zhi, C. Y. Boron Nitride Nanotubes. *Adv. Mater.* **2007**, *19*, 2413−2432.

(32) Zhao, W. S.; Portal, J. M.; Kang, W.; Moreau, M.; Zhang, Y.; Aziza, H.; Klein, J.-O.; Wang, Z. H.; Querlioz, D.; Deleruyelle, D.; Bocquet, M.; Ravelosona, D.; Muller, C.; Chappert, C. Design and Analysis of Crossbar Architecture Based on Complementary Resistive Switching Non-Volatile Memory Cells. *J. Para. Dist. Comp* **2014**, *74*, 2484−2496.

(33) Knechtel, J.; Markov, I. L.; Lienig, J. Assembling 2-D Blocks Into 3-D Chips. *IEEE Trans. Comp.-Aid. Des. Integr. Circ. Sys.* **2012**, *31*, 228−241.

(34) http://www.eetimes.com/author.asp?doc_id=1323466.

(35) http://www.computerworld.com/article/2859266/a-terabyte-on-a-postage-stamp-rram-heads-into-commercialization.html.

(36) Choi, J.-H.; Wang, H.; Oh, S. J.; Paik, T.; Sung, P.; Sung, J.; Ye, X.; Zhao, T.; Diroll, B. T.; Murray, C. B.; Kagan, C. R. Exploiting the Colloidal Nanocrystal Library to Construct Electronic Devices. *Science* **2016**, *352*, 205−208.

(37) Chen, W.; Tymchenko, M.; Gopalan, P.; Ye, X.; Wu, Y.; Zhang, M.; Murray, C. B.; Alu, A.; Kagan, C. R. Large-Area Nanoimprinted Colloidal Au Nanocrystal-Based Nanoantennas for Ultrathin Polarizing Plasmonic Metasurfaces. *Nano Lett.* **2015**, *15*, 5254−5260.

(38) Weiss, P. S. What Can Nano Do? *ACS Nano* **2013**, *7*, 9507−9508.

(39) Möhwald, H.; Weiss, P. S. Is Nano a Bubble? *ACS Nano* **2015**, *9*, 9427−9428.

(40) Mulvaney, P.; Weiss, P. S. Have Nanoscience and Nanotechnology Delivered? *ACS Nano* **2016**, *10*, 7225−7226.

(41) Chen, C.-C.; Dou, L.; Zhu, R.; Chung, C.-H.; Song, T.-B.; Zheng, Y. B.; Hawks, S.; Li, G.; Weiss, P. S.; Yang, Y. Visibly Transparent Polymer Solar Cells Produced by Solution Processing. *ACS Nano* **2012**, *6*, 7185−7190.

(42) Briggs, J. A.; Atre, A. C.; Dionne, J. A. Narrow-Bandwidth Solar Upconversion: Case Studies of Existing Systems and Generalized Fundamental Limits. *J. Appl. Phys.* **2013**, *113*, 124509.

(43) Atwater, H. A.; Polman, A. Plasmonics for Improved Photovoltaic Devices. *Nat. Mater.* **2010**, *9*, 205−213.

(44) Sargent, E. H. Infrared Photovoltaics Made by Solution Processing. *Nat. Photonics* **2009**, *3*, 325−331.

DOI: 10.1021/acsnano.6b06655
ACS Nano 2016, 10, 9093−9103

(45) Liu, M.; Johnston, M. B.; Snaith, H. J. Efficient Planar Heterojunction Perovskite Solar Cells by Vapour Deposition. *Nature* **2013**, *501*, 395−398.
(46) Arpin, K. A.; Losego, M. D.; Cloud, A. N.; Ning, H.; Mallek, J.; Sergeant, N. P.; Zhu, L.; Yu, Z.; Kalanyan, B.; Parsons, G. N.; Girolami, G. S.; Abelson, J. R.; Fan, S.; Braun, P. V. Three-Dimensional Self-Assembled Photonic Crystals with High Temperature Stability for Thermal Emission Modification. *Nat. Commun.* **2013**, *4*, 2630.
(47) Chou, J. B.; Yeng, Y. X.; Lee, Y. E.; Lenert, A.; Rinnerbauer, V.; Celanovic, I.; Soljačić, M.; Fang, N. X.; Wang, E. N.; Kim, S.-G. Enabling Ideal Selective Solar Absorption with 2D Metallic Dielectric Photonic Crystals. *Adv. Mater.* **2014**, *26*, 8041−8045.
(48) Dresselhaus, M. S.; Chen, G.; Tang, M. Y.; Yang, R.; Lee, H.; Wang, D.; Ren, Z.; Fleurial, J.-P.; Gogna, P. New Directions for Low-Dimensional Thermoelectric Materials. *Adv. Mater.* **2007**, *19*, 1043−1053.
(49) Medlin, D. L.; Snyder, G. J. Interfaces in Bulk Thermoelectric Materials. *Curr. Opin. Colloid Interface Sci.* **2009**, *14*, 226−235.
(50) Minnich, A. J.; Dresselhaus, M. S.; Ren, Z. F.; Chen, G. Bulk Nanostructured Thermoelectric Materials: Current Research and Future Prospects. *Energy Environ. Sci.* **2009**, *2*, 466−479.
(51) Penner, R. M.; Gogotsi, Y. The Rising and Receding Fortunes of Electrochemists. *ACS Nano* **2016**, *10*, 3875−3876.
(52) Ruditskiy, A.; Peng, H.-C.; Xia, Y. Shape-Controlled Metal Nanocrystals for Heterogeneous Catalysis. *Annu. Rev. Chem. Biomol. Eng.* **2016**, *7*, 327−348.
(53) Cargnello, M.; Doan-Nguyen, V. V. T.; Gordon, T. R.; Diaz, R. E.; Stach, E. A.; Gorte, R. J.; Fornasiero, P.; Murray, C. B. Control of Metal Nanocrystal Size Reveals Metal-Support Interface Role for Ceria Catalysts. *Science* **2013**, *341*, 771−773.
(54) Gogotsi, Y. Not Just Graphene: The Wonderful World of Carbon and Related Nanomaterials. *MRS Bull.* **2015**, *40*, 1110−1121.
(55) Larcher, D.; Tarascon, J.-M. Towards Greener and More Sustainable Batteries for Electrical Energy Storage. *Nat. Chem.* **2014**, *7*, 19−29.
(56) Gogotsi, Y. What Nano Can Do for Energy Storage. *ACS Nano* **2014**, *8*, 5369−5371.
(57) Lukatskaya, M. R.; Dunn, B.; Gogotsi, Y. Multidimensional Materials and Device Architectures for Future Hybrid Energy Storage. *Nat. Commun.* **2016**, *7*, 12647.
(58) Salanne, M.; Rotenberg, B.; Naoi, K.; Kaneko, K.; Taberna, P.-L.; Grey, C. P.; Dunn, B.; Simon, P. Efficient Storage Mechanisms for Building Better Supercapacitors. *Nat. Energy* **2016**, *1*, 16070.
(59) Presser, V.; McDonough, J.; Yeon, S.-H.; Gogotsi, Y. Effect of Pore Size on Carbon Dioxide Sorption by Carbide Derived Carbon. *Energy Environ. Sci.* **2011**, *4*, 3059−3066.
(60) Gargiulo, N.; Pepe, F.; Caputo, D. CO_2 Adsorption by Functionalized Nanoporous Materials: A Review. *J. Nanosci. Nanotechnol.* **2014**, *14*, 1811−1822.
(61) Lewis, N. S. Introduction: Solar Energy Conversion. *Chem. Rev.* **2015**, *115*, 12631−12632.
(62) White, J. L.; Baruch, M. F.; Pander, J. E., III; Hu, Y.; Fortmeyer, I. C.; Park, J. E.; Zhang, T.; Liao, K.; Gu, J.; Yan, Y.; Shaw, T. W.; Abelev, E.; Bocarsly, A. B. Light-Driven Heterogeneous Reduction of Carbon Dioxide: Photocatalysts and Photoelectrodes. *Chem. Rev.* **2015**, *115*, 12888−12935.
(63) Wang, W.-H.; Himeda, Y.; Muckerman, J. T.; Manbeck, G. F.; Fujita, E. CO_2 Hydrogenation to Formate and Methanol as an Alternative to Photo- and Electrochemical CO_2 Reduction. *Chem. Rev.* **2015**, *115*, 12936−12973.
(64) Medina-Ramos, J.; Pupillo, R. C.; Keane, T. P.; DiMeglio, J. L.; Rosenthal, J. Efficient Conversion of CO_2 to CO Using Tin and Other Inexpensive and Easily Prepared Post-Transition Metal Catalysts. *J. Am. Chem. Soc.* **2015**, *137*, 5021−5027.
(65) Chen, J.; Yang, J.; Li, Z.; Fan, X.; Zi, Y.; Jing, Q.; Guo, H.; Wen, Z.; Pradel, K. C.; Niu, S.; Wang, Z. L. Networks of Triboelectric Nanogenerators for Harvesting Water Wave Energy: A Potential Approach toward Blue Energy. *ACS Nano* **2015**, *9*, 3324−3331.
(66) Wang, S.; Wang, X.; Wang, Z. L.; Yang, Y. Efficient Scavenging of Solar and Wind Energies in a Smart City. *ACS Nano* **2016**, *10*, 5696−5700.
(67) Wen, Z.; Guo, H.; Zi, Y.; Yeh, M.-H.; Wang, X.; Deng, J.; Wang, J.; Li, S.; Hu, C.; Zhu, L.; Wang, Z. L. Harvesting Broad Frequency Band Blue Energy by a Triboelectric−Electromagnetic Hybrid Nanogenerator. *ACS Nano* **2016**, *10*, 6526−6534.
(68) Kim, K. N.; Chun, J.; Kim, J. W.; Lee, K. Y.; Park, J.-U.; Kim, S.-W.; Wang, Z. L.; Baik, J. M. Highly Stretchable 2D Fabrics for Wearable Triboelectric Nanogenerator under Harsh Environments. *ACS Nano* **2015**, *9*, 6394−6400.
(69) Zhong, J.; Zhang, Y.; Zhong, Q.; Hu, Q.; Hu, B.; Wang, Z. L.; Zhou, J. Fiber-Based Generator for Wearable Electronics and Mobile Medication. *ACS Nano* **2014**, *8*, 6273−6280.
(70) Cabanes, A.; Even-Chen, S.; Zimberoff, J.; Barenholz, Y.; Kedar, E.; Gabizon, A. Enhancement of Antitumor Activity of Polyethylene Glycol-Coated Liposomal Doxorubicin with Soluble and Liposomal Interleukin 21. *Clin. Cancer Res.* **1999**, *5*, 687−693.
(71) O'Brien, M. E. R. Reduced Cardiotoxicity and Comparable Efficacy in a Phase III Trial of PEGylated Liposomal Doxorubicin HCl (CAELYXTM/Doxil") *versus* Conventional Doxorubicin for First-Line Treatment of Metastatic Breast Cancer. *Ann. Oncol.* **2004**, *15*, 440−449.
(72) Safra, T.; Muggia, F.; Jeffers, S.; Tsao-Wei, D. D.; Groshen, S.; Lyass, O.; Henderson, R.; Berry, G.; Gabizon, A. PEGylated Liposomal Doxorubicin (Doxil): Reduced Clinical Cardiotoxicity in Patients Reaching or Exceeding Cumulative Doses of 500 mg/m^2. *Ann. Oncol.* **2000**, *11*, 1029−1033.
(73) Hunault-Berger, M.; Leguay, T.; Thomas, X.; Legrand, O.; Huguet, F.; Bonmati, C.; Escoffre-Barbe, M.; Legros, L.; Turlure, P.; Chevallier, P.; Larosa, F.; Garban, F.; Reman, O.; Rousselot, P.; Dhédin, N.; Delannoy, A.; Lafage-Pochitaloff, M.; Béné, M. C.; Ifrah, N.; Dombret, H. A Randomized Study of PEGylated Liposomal Doxorubicin versus Continuous-Infusion Doxorubicin in Elderly Patients with Acute Lymphoblastic Leukemia: The GRAALL-SA1 Study. *Haematologica* **2011**, *96*, 245−252.
(74) Prabhakar, U.; Maeda, H.; Jain, R. K.; Sevick-Muraca, E. M.; Zamboni, W.; Farokhzad, O. C.; Barry, S. T.; Gabizon, A.; Grodzinski, P.; Blakey, D. C. Challenges and Key Considerations of the Enhanced Permeability and Retention Effect for Nanomedicine Drug Delivery in Oncology. *Cancer Res.* **2013**, *73*, 2412−2417.
(75) Harrington, K. J.; Mohammadtaghi, S.; Uster, P. S.; Glass, D.; Peters, A. M.; Vile, R. G.; Stewart, J. S. W. Effective Targeting of Solid Tumors in Patients with Locally Advanced Cancers by Radiolabeled PEGylated Liposomes. *Clin. Cancer Res.* **2001**, *7*, 243−254.
(76) Clark, A. J.; Wiley, D. T.; Zuckerman, J. E.; Webster, P.; Chao, J.; Lin, J.; Yen, Y.; Davis, M. E. CRLX101 Nanoparticles Localize in Human Tumors and Not in Adjacent, Nonneoplastic Tissue after Intravenous Dosing. *Proc. Natl. Acad. Sci. U. S. A.* **2016**, *113*, 3850−3854.
(77) Natarajan, J. V.; Darwitan, A.; Barathi, V. A.; Ang, M.; Htoon, H. M.; Boey, F.; Tam, K. C.; Wong, T. T.; Venkatraman, S. S. Sustained Drug Release in Nanomedicine: A Long-Acting Nanocarrier-Based Formulation for Glaucoma. *ACS Nano* **2014**, *8*, 419−429.
(78) Food and Agriculture Organization. *How to Feed the World in 2050 Executive Summary*, 2009; pp 1−35; http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf
(79) Section, U. N. N. S. UN News - UN Report: *One-Third of World's Food Wasted Annually, at Great Economic, Environmental Cost*, 2013.
(80) Kagan, C. R. At the Nexus of Food Security and Safety: Opportunities for Nanoscience and Nanotechnology. *ACS Nano* **2016**, *10*, 2985−2986.
(81) Li, H.; Song, Z.; Zhang, X.; Huang, Y.; Li, S.; Mao, Y.; Ploehn, H. J.; Bao, Y.; Yu, M. Ultrathin, Molecular-Sieving Graphene Oxide Membranes for Selective Hydrogen Separation. *Science* **2013**, *342*, 95−98.
(82) Sun, P.; Zheng, F.; Zhu, M.; Song, Z.; Wang, K.; Zhong, M.; Wu, D.; Little, R. B.; Xu, Z.; Zhu, H. Selective Trans-Membrane Transport of Alkali and Alkaline Earth Cations through Graphene Oxide Membranes Based on Cation−π Interactions. *ACS Nano* **2014**, *8*, 850−859.

DOI: 10.1021/acsnano.6b06655
ACS Nano 2016, 10, 9093−9103

(83) Joshi, R. K.; Carbone, P.; Wang, F. C.; Kravets, V. G.; Su, Y.; Grigorieva, I. V.; Wu, H. A.; Geim, A. K.; Nair, R. R. Precise and Ultrafast Molecular Sieving through Graphene Oxide Membranes. *Science* **2014**, *343*, 752−754.
(84) Huang, L.; Zhang, M.; Li, C.; Shi, G. Graphene-Based Membranes for Molecular Separation. *J. Phys. Chem. Lett.* **2015**, *6*, 2806−2815.
(85) Sun, P.; Zhu, M.; Wang, K.; Zhong, M.; Wei, J.; Wu, D.; Xu, Z.; Zhu, H. Selective Ion Penetration of Graphene Oxide Membranes. *ACS Nano* **2013**, *7*, 428−437.
(86) Ren, C. E.; Hatzell, K. B.; Alhabeb, M.; Ling, Z.; Mahmoud, K. A.; Gogotsi, Y. Charge- and Size-Selective Ion Sieving through $Ti_3C_2T_X$ MXene Membranes. *J. Phys. Chem. Lett.* **2015**, *6*, 4026−4031.
(87) Rasool, K.; Helal, M.; Ali, A.; Ren, C. E.; Gogotsi, Y.; Mahmoud, K. A. Antibacterial Activity of $Ti_3C_2T_X$ MXene. *ACS Nano* **2016**, *10*, 3674−3684.
(88) Xiao, K.; Zhou, Y.; Kong, X.-Y.; Xie, G.; Li, P.; Zhang, Z.; Wen, L.; Jiang, L. Electrostatic-Charge- and Electric-Field-Induced Smart Gating for Water Transportation. *ACS Nano* **2016**, DOI: 10.1021/acsnano.6b05682.
(89) O'Hern, S. C.; Boutilier, M. S. H.; Idrobo, J.-C.; Song, Y.; Kong, J.; Laoui, T.; Atieh, M.; Karnik, R. Selective Ionic Transport through Tunable Subnanometer Pores in Single-Layer Graphene Membranes. *Nano Lett.* **2014**, *14*, 1234−1241.
(90) National Nanotechnology Initiative: Environmental, Health, And Safety Research Strategy, October 2011; http://www.nano.gov/sites/default/files/pub_resource/nni_2011_ehs_research_strategy.pdf.
(91) Nel, A.; Parak, W. J.; Chan, W. C. W.; Xia, T.; Hersam, M. C.; Brinker, C. J.; Zink, J. I.; Pinkerton, K. E.; Baer, D. R.; Weiss, P. S. Where Are We Heading in Nanotechnology Environmental Health and Safety and Materials Characterization? *ACS Nano* **2015**, *9*, 5627−5630.
(92) Lee, J.; Mahendra, S.; Alvarez, P. J. J. Nanomaterials in the Construction Industry: A Review of Their Applications and Environmental Health and Safety Considerations. *ACS Nano* **2010**, *4*, 3580−3590.
(93) Frank, R. Lautenberg Chemical Safety for the 21st Century Act. January 4th, 2016; https://www.epa.gov/sites/production/files/2016-06/documents/bills-114hr2576eah.pdf.
(94) Jackman, J. A.; Cho, D.-J.; Lee, J.; Chen, J. M.; Besenbacher, F.; Bonnell, D. A.; Hersam, M. C.; Weiss, P. S.; Cho, N.-J. Nanotechnology Education for the Global World: Training the Leaders of Tomorrow. *ACS Nano* **2016**, *10*, 5595−5599.
(95) Hersam, M. C.; Lee, S.-T.; Nel, A. E.; Rogach, A.; Buriak, J. M.; Weiss, P. S. Big Roles for Nanocenters. *ACS Nano* **2015**, *9*, 8639−8640.
(96) Weiss, P. S. New Tools Lead to New Science. *ACS Nano* **2012**, *6*, 1877−1879.
(97) Alivisatos, A. P.; Chun, M.; Church, G. M.; Deisseroth, K.; Donoghue, J. P.; Greenspan, R. J.; McEuen, P. L.; Roukes, M. L.; Sejnowski, T. J.; Weiss, P. S.; et al. The Brain Activity Map. *Science* **2013**, *339*, 1284−1285.
(98) Alivisatos, A. P.; Andrews, A. M.; Boyden, E. S.; Chun, M.; Church, G. M.; Deisseroth, K.; Donoghue, J. P.; Fraser, S. E.; Lippincott-Schwartz, J.; Looger, L. L.; Masmanidis, S.; McEuen, P. L.; Nurmikko, A. V.; Park, H.; Peterka, D. J.; Reid, C.; Roukes, M. L.; Scherer, A.; Schnitzer, M.; Sejnowski, T. J.; et al. Nanotools for Neuroscience and Brain Activity Mapping. *ACS Nano* **2013**, *7*, 1850−1866.
(99) Biteen, J. S.; Blainey, P. C.; Cardon, Z. G.; Chun, M.; Church, G. M.; Dorrestein, P. C.; Fraser, S. E.; Gilbert, J. A.; Jansson, J. K.; Knight, R.; Miller, J. F.; Ozcan, A.; Prather, K. A.; Ruby, E. G.; Silver, P. A.; Taha, S.; van den Engh, G.; Weiss, P. S.; Wong, G. C. L.; et al. Tools for the Microbiome: Nano and Beyond. *ACS Nano* **2016**, *10*, 6−37.
(100) Javey, A.; Weiss, P. S. Mimicking the Human Brain and More: New Grand Challenge Initiatives. *ACS Nano* **2015**, *9*, 10533−10536.
(101) Wee, A. T. S. Graphene: The Game Changer? *ACS Nano* **2012**, *6*, 5739−5741.
(102) Parak, W. J.; Nel, A. E.; Weiss, P. S. Grand Challenges for Nanoscience and Nanotechnology. *ACS Nano* **2015**, *9*, 6637−6640.

DOI: 10.1021/acsnano.6b06655
ACS Nano 2016, 10, 9093−9103