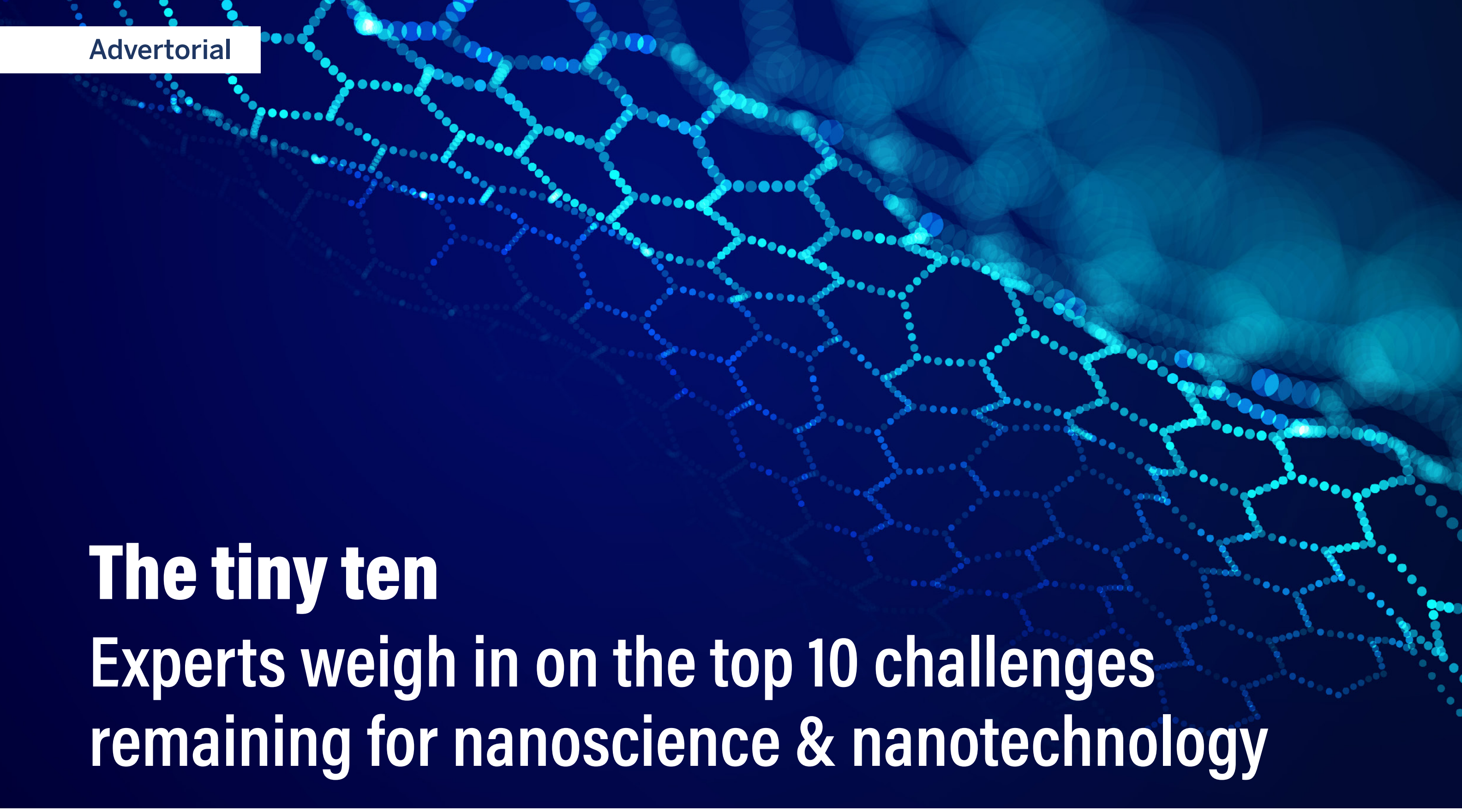
Advertorial



The tiny ten

Experts weigh in on the top 10 challenges remaining for nanoscience & nanotechnology

The promise of nanotechnology, the engineering of machines and systems at the nanoscale, is anything but tiny. Over the past decade alone, there has been an explosion in research on how to design and build components that solve problems across almost every sector, and nanotechnology innovations have led to huge advancements in our quest to address humanity's grand challenges, from healthcare to water to food security.

Like any area of scholarship, there are still so many unknowns. And yet, there are more talented scientists and engineers endeavoring to better comprehend and harness the power of nanotechnology than ever before. The future is bright for nanotechnology and its applications.

In celebration of its 20th anniversary, the National Center for Nanoscience and Technology, China (NCNST), a subsidiary of the prestigious Chinese Academy of Sciences, partnered with *Science* Custom Publishing to survey nanoscience experts from the journal and across the globe about the most knotty and fascinating questions that still need to be answered if we are to advance nanotechnology in society.

1. Will scientists develop a nanotheory combining aspects of quantum and macroscale physics that can reliably predict the nanoscale behavior of materials?

It's no secret that physicists are obsessed with the Standard Model of Particle Physics, which describes the nature of matter at the smallest of small levels. Similarly, nanoscientists, who obviously want to better comprehend and predict the nature and behavior of nanomaterials, are also invested in a unified theory that combines features of macroscale physics and quantum physics, where things get a little odd. Materials at the nanoscale have unusual optical, magnetic, and electronic features. The challenge for nanoengineers and nanoscientists is to forge pathways to a clear understanding of what exactly is happening in the nanoworld, so they can more strategically and effectively harness the power of nanotechnology.

The endeavor is anything but simple: scientists want to investigate whether there is a unified theory to bridge continuum theory and molecular-level quantum mechanics, so they can accurately describe (albeit theoretically) the multiscale structure of nanomaterials.

This is ambitious, to say the least, and requires vigorous, transdisciplinary, cross-border partnerships, with significant infrastructure investments in the research. Countries like China, Japan, the U.S., the U.K., and Germany are galvanizing scientists with their efforts to elucidate the connection and correlation between quantum physics and macroscale physics, and in doing so, are getting one step closer (albeit a nanostep) to a possible unified theory of the behavior of materials.

2. What characteristics of nanomaterials are relevant with respect to toxicity and how can they be controlled under different environmental conditions?

There are three dominant parameters that determine toxicity of a conventional material: chemical composition, chemical structure, and dose. But how do these variables change or factor into determining whether a nanomaterial is toxic? And at the nanoscale, do these dominant parameters still control toxicity? What new information or variables do we need to rationally describe the toxicological behaviors of nanomaterials in vivo?

The issue of concern around toxicity is critical, given the preponderance of nanoparticles and nanomachinery in biological systems. For example, scientists have demonstrated how injecting certain types of nanoparticles in humans can enable better visualization, diagnosis, and treatment of disease. The field of nanomedicine is accelerating at the speed of human ingenuity, so it behooves us to take a careful and thorough examination of the driving factors of toxicity influenced by nanoparticles and nanomachinery.

Fortunately, both scientists and policy makers are taking this very seriously. In the U.S., the National Center for Toxicological Research has specific nanotechnology programs to evaluate and conduct toxicology studies on nanomaterials, and in China, NCNST has a Key Laboratory for Biological Effects of Nanomaterials and Nanosafety. With mobilization of the intellectual resources in agencies such as these, we are well-equipped to address important questions associated with toxicology and nanotechnology.

3. How can we effectively utilize nanoscience to understand biology?

The work of life often starts at the nanoscale. How can we effectively utilize nanoscience and nanotechnology to delve into the intricate processes within cells, create seamless connections with organelles and macromolecules, and ultimately achieve groundbreaking advances in the field of biology? These are the exciting questions driving intense innovation in nanotechnology today.

At the heart of investigations into how nanotechnology can help us better comprehend life sciences is interdisciplinarity. Scholars and engineers from many different, seemingly disparate fields are aligned and needed for this endeavor because of its complexity. By investing in research that brings together biologists, materials engineers, mechanical engineers, physicists, plant scientists, and even ecologists, neuroscientists, and physician-scientists, we can build stronger research networks that can properly address mighty problems in biology: as each specialist learns the language and culture of the others, they are able to take a comprehensive approach to exploring biology through nanotechnology.

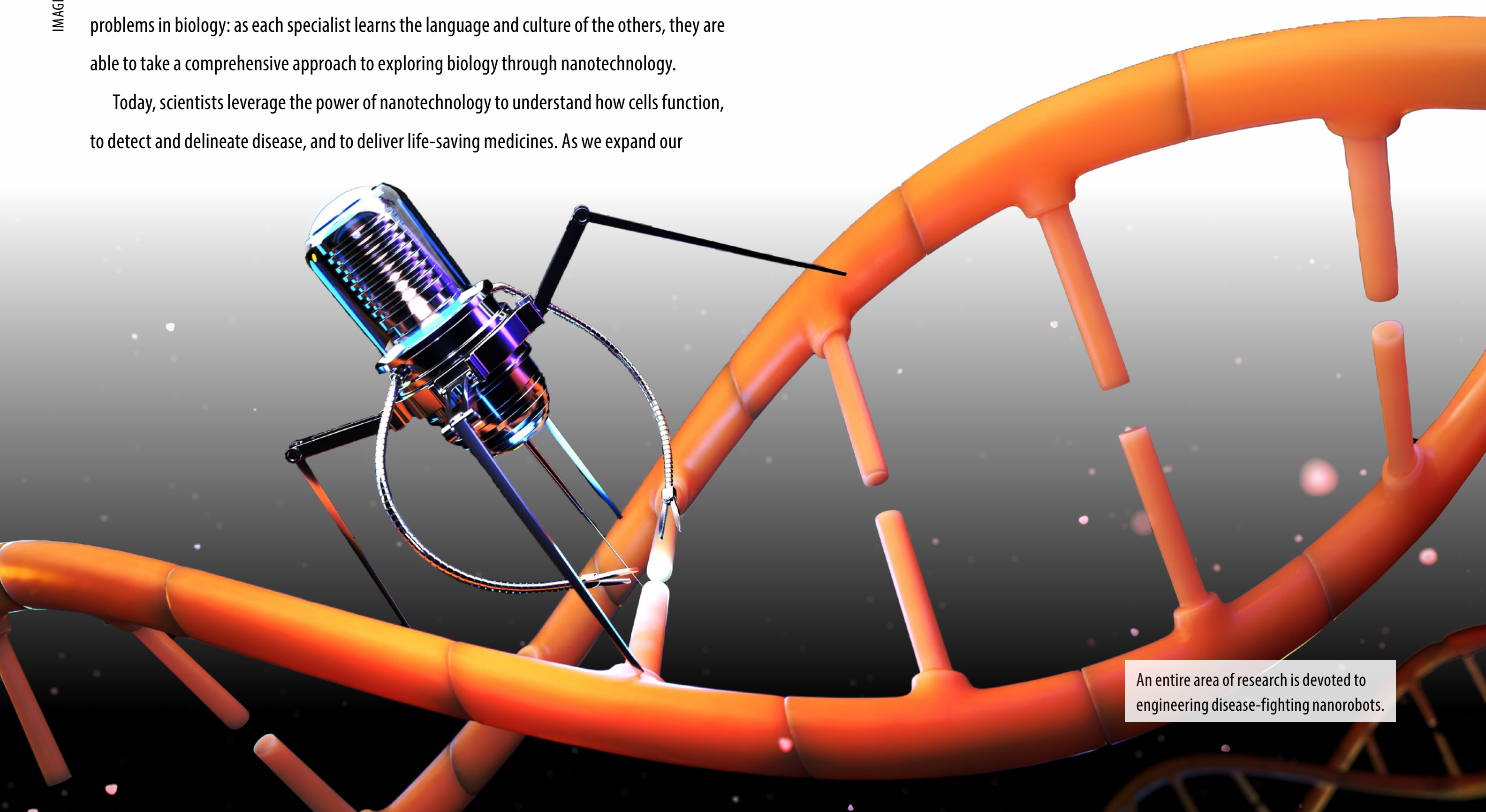
Today, scientists leverage the power of nanotechnology to understand how cells function, to detect and delineate disease, and to deliver life-saving medicines. As we expand our traverse of the nanoworld, there is no doubt that more insights about our biological makeup will emerge.

4. How will nanotechnology change the practice of medicine?

Nanotechnology has been utilized in medicine for decades; the first FDA-approved nanomedicine, composed of synthetic nanoparticles, was released in 1990. Since then, nanoscience has significantly contributed to new pharmaceuticals, devices, and other interventions in spectacular ways. But there are still many unanswered questions that scientists and engineers must tackle to advance nanomedicine and bio-nano devices in the future.

For example, one of the biggest concerns with using nanotechnology in humans is being able to properly predict its behavior. This is especially critical given that the nature of nanomedicine involves introducing foreign objects into biological systems. Researchers recognize that to unlock the full potential of nanotechnology in medicine we will need to comprehensively grasp and engineer the degradation and metabolism rates of nanomaterials so we can match the natural process of tissue regeneration and disease treatment. Moreover, we need to understand how nanoparticles participate in and influence biological processes, as compared to traditional substances such as ions and molecules.

Beyond the medicines themselves is an entire area of research devoted to engineering disease-fighting nanorobots and other nano-devices from basic biological building blocks with sophisticated intelligence. There is no doubt: a new era of healthcare technology, buttressed by nanotechnology, is upon us.



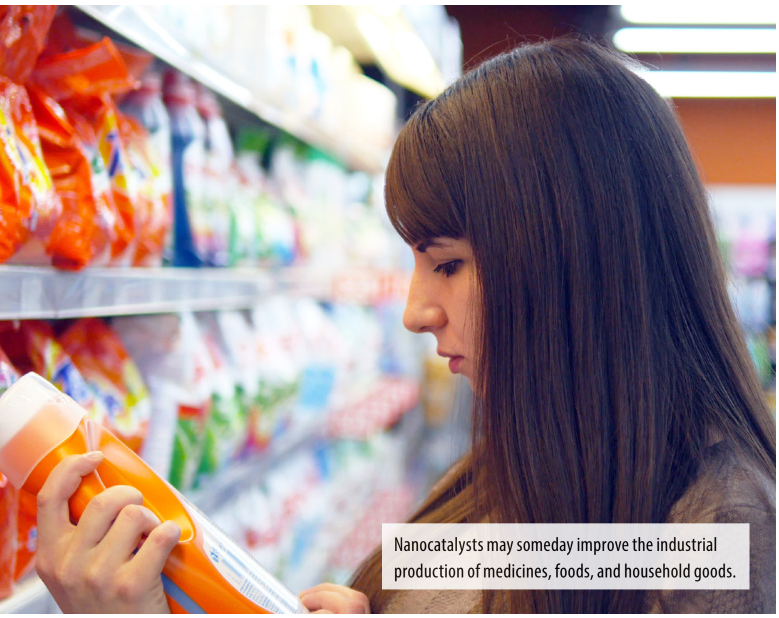
An entire area of research is devoted to engineering disease-fighting nanorobots.

IMAGE: © SABISAFTOIU/SHUTTERSTOCK.COM

5. What will scientists learn about nanomaterials at their surface and interface using new visualization technologies?

One would think that the structure on the surface of a nanoparticle is not complicated, given its size. And yet, in many ways, it mirrors a complex system, and varies with time, size, and composition. Since a nanoparticle's surface has the most interaction with the surrounding environment, this tends to be where the action is as far as function. With this in mind, experts are attempting to generate as much knowledge as possible about the surface of nanomaterials and how to manipulate key features at the surface. This is a vital step in advancing nanoscience because if we don't truly and fully understand the surface, how can we harness its features for the betterment of humanity?

A twist in this intricate affair? There may be more room for the unknown on the nanosurface. Fortunately, there are numerous visualization tools and methodologies with which materials scientists and physicists are experimenting to uncover the truth. They also want to know how to directly observe the ultrafast energy transfer and electron processes at the nanoscale, and how to visualize the time-space catalytic processes of the catalytic active center at atomic/molecular scale. Ultimately, any information gleaned can assist in developing new standards or rules in nano-based quantification and mechanisms to implement them in real-life measurement.



Nanocatalysts may someday improve the industrial production of medicines, foods, and household goods.

6. How will nanotechnology change how we make catalysts and the types of catalysts we can make?

From the dawn of nanoscience, chemistry has played a critical role in advancing the science of the small. While chemists and chemical engineers have contributed to the growth of nanoscience, drawing on their expertise in chemical synthesis and characterization, they have also grown excited by the potential to harness nanotechnology for one of the most essential components of chemical science: catalysis.

A catalyst is a substance that speeds up a chemical reaction. Catalysts are required ingredients for many applications of chemistry in society, from medicines to food to household goods. But what about at the nanoscale? How do catalysts operate? Scientists already appreciate that nanocatalysts, catalysts constructed of nanoparticles, are useful substitutes for traditional catalysts: these workhorses have a significant and active surface area, leading to better interactivity with reactants.

But to improve the efficiency of nanoparticles as catalysts, scholars are scrutinizing different materials that can be used to build the catalysts and experimenting with various methods of synthesis. They are also tackling the challenge of making these catalysts as green as possible, while managing their toxicity. There is still much to uncover about the foundational mechanisms of catalysts, which will most certainly shed much needed light into the burgeoning world of nanocatalysts.

7. How can we achieve atomic precision in nanoscale objects?

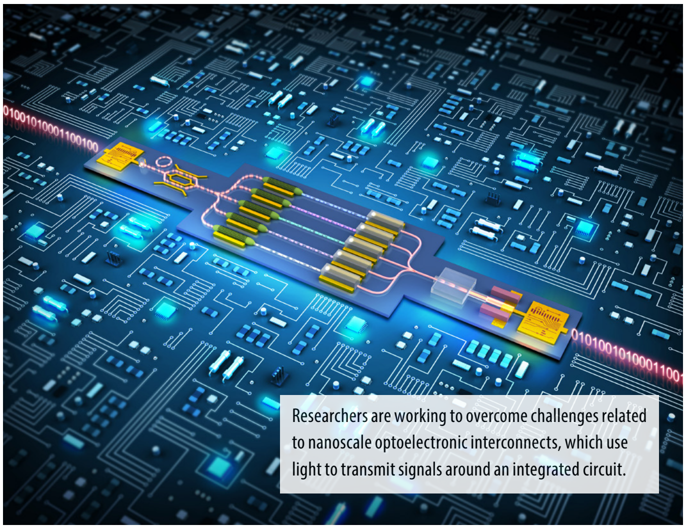
Imagine building an object, be it a module, machine, or something more mundane. What are the smallest pieces that can be used to construct it? In atomic precision manufacturing, atoms become the building blocks. Now, let's say we want to craft a nanocomponent. How can we achieve atomic precision in nanoscale objects? Although scanning probe methods can manipulate atoms on surfaces, and small clusters can be synthesized with regular atomic structures, for larger nanoparticles, can methods that achieve greater precision be developed? How do we combine methods of precise atomistic control at the nanoscale when the tools used to manipulate the materials are at the centimeter scale or larger?

Experts from chemistry, manufacturing, computing, optics, and materials science are coalescing to propose how novel fabrication methodologies can build nano-objects with precision. They hope to expand synthetic methods for inorganic materials to avoid the use of organic coatings, and control the phase and particle shape, to improve the effectiveness of nanomaterials. Their insights, culled from a combination of experimental and theoretical approaches, are fostering more interesting investigations at larger scales, where they hope to identify new ways of controlling the growth of nanoparticles and nanofilms on substrates, and create hierarchal, multifunctional, or emergently functional structures.

8. How is nanotechnology going to transform computation with optoelectronic integration?

Nanotechnology has already transformed computation in profound ways. Engineers have been designing, constructing, and using circuits with nanoscale components for decades, which has greatly contributed to the advancement of all areas of technology. At the heart of most computational systems is the goal of manipulating light at the nanoscale, in service of executing faster and more energy efficient and powerful computer machinery.

Nanoplasmonics, "the study of optical phenomena in the nanoscale vicinity of metal surfaces," as noted in *Physics Today* over 10 years ago, holds great potential for impacting computing. Although still a relatively nascent field, physicists and optical scientists wonder if nanoplasmonics can live up to its full potential to enable precise manipulation of light, which would lead to faster and more robust supercomputers, able to solve tall-order problems. Among the many unanswered questions in nanoplasmonics, the most urgent include: can we really fabricate photonic/plasmonic circuits that will improve communications, computing, information storage, lasing, and cloaking? Will researchers finally develop a nanomaterial that can extend the electron spin polarization for a longer time and realize quantum computing at room temperature? How can scientists scale down magnetic-based logic and data-storage devices? With every nano bit of knowledge we gain, we assure a big future of computers that leverage the tiny like never before.



Researchers are working to overcome challenges related to nanoscale optoelectronic interconnects, which use light to transmit signals around an integrated circuit.

IMAGE: PROVIDED BY NCNST

9. How can nanotechnology transform electronics and what is the energy consumption limit for future electronic devices?

From 3D printed batteries and nanosensors to bioelectronic materials that can flex and shapeshift while maintaining high functionality, nanotechnology in electronics is pervasive in society. But while innovations in nanotechnology have allowed electronics to accomplish tasks more quickly, and be more stable, secure, robust, and energy-efficient than ever before, there are still knotty obstacles to overcome to unleash the full power of nanoelectronics. This has led to huge investments in nanoscience research as it applies to electronic components, from chips in mobile devices to programs that run the most sophisticated AI and machine learning systems.

Scientists are perplexed by how to take the next step in advancing electronics at the nanoscale, which will require achieving an on-chip optoelectronic interconnect that overcomes the diffraction limit. This is crucial because the diffraction limit impacts how a chip operates and stores data using light. As chips get smaller, and components edge into the nanoscale and beyond, the science, engineering, and craftsmanship that needs to be undertaken to produce nanoelectronics becomes more complicated, challenging, and expensive. But given that the global nanoelectronics market is projected to exceed $31 billion by 2030, as noted by Virtue Market Research, we can expect more strategic partnerships to push the field.

10. Can nanotechnology support global sustainability goals?

One of the most fascinating aspects of nanotechnology is that we can leverage the power of the super small to solve big problems facing humans, and it doesn't get much more macro than climate change. But the lynchpin for nanotechnology to strategically and holistically improve sustainability efforts is that it must become truly carbon neutral, and provide more environmental benefits than costs.

There are already efforts in materials science, chemistry, and mechanical engineering to produce nanotechnology that is more environmentally friendly. But there is another, very exciting promise here: ambitious researchers in nanoscience and nanotechnology are utilizing approaches, tools, and techniques from this arena to address some of humanity's grand challenges in sustainability, including initiatives in green energy, wastewater treatment, drought- and pest-resistant crops, and greenhouse gas reduction. Because nanotechnology organically intertwines with, bolsters, and grows from so many other STEM disciplines, its capacity to address global sustainability concerns are seemingly unending. And that is the power and promise of nanotechnology—it may be mini but its potential solutions are mammoth.

***Identifying these urgent questions in nanoscience & nanotechnology was the collective work of many people. Acknowledgement in particular goes to (in alphabetical order):**

Chunli Bai (Chinese Academy of Sciences)
Xinhe Bao (University of Science and Technology of China)
Jeffrey Brinker (New Mexico's Flagship University)
Chunying Chen (National Center for Nanoscience and Technology)
Xiaodong Chen (Nanyang Technological University)
Qing Dai (National Center for Nanoscience and Technology)
Bengt Fadeel (Karolinska Institutet)
Taeghwan Hyeon (Seoul National University)
Lei Jiang (Technical Institute of Physics and Chemistry, Chinese Academy of Sciences)
Nicholas A. Kotov (University of Michigan)
Haiwon Lee (Hanyang University)
Jinghong Li (Tsinghua University)
Yunqi Liu (Institute of Chemistry, Chinese Academy of Sciences)
Sushanta Mitra (University of Waterloo)
Guangjun Nie (National Center for Nanoscience and Technology)
Teri W. Odom (Northwestern University)
Danny Porath (The Hebrew University of Jerusalem)
Andrey Rogach (City University of Hong Kong)
Vincent Rotello (University of Massachusetts Amherst)
Jianlin Shi (Shanghai Institute of Ceramics, Chinese Academy of Sciences)
Zhiyong Tang (National Center for Nanoscience and Technology)
Paul Weiss (University of California, Los Angeles)
Andrew Whittaker (The University of Queensland)
Vivian Wing-Wah Yam (The University of Hong Kong)
Xiyun Yan (Institute of Biophysics, Chinese Academy of Sciences)
Jihong Yu (Jilin University)
Yuliang Zhao (National Center for Nanoscience and Technology)