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Citation: APL Materials 3, 061001 (2015); doi: 10.1063/1.4922549
View online: http://dx.doi.org/10.1063/1.4922549
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Commentary: Nanoarchitectonics—Think about NANO again

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(Received 9 May 2015; accepted 3 June 2015; published online 16 June 2015)

Undoubtedly, nanotechnology has been a key concept in the scientific community since the late 20th century and has significantly promoted the current science and technology. However, if we want to further develop materials science, we need to think about NANO again, as nanoscale phenomena appear to be more complex than we have expected. Based on the rapid progress of observation tools, such as various probe microscopes, we can now observe, analyze, and even manipulate objects at the nanoscale level. We can fabricate microscopic objects under conditions similar to the macroscopic regime, because in the micrometer-scale, objects are basically free from uncertainties such as thermal and statistical fluctuations or quantum effects. The control and assembly of nanoscale objects are, however, not fully mastered yet, and their behaviors are still not well understood.\(^1\) The control over these components at the nanometer scale requires the combination of physical and chemical interactions. The ways to handle nano-materials should be different from those known for microtechnology. We must discard our initial expectations to establish nano-scale technology by a simple extension of microtechnology.

The stimulation of a paradigm shift and/or the creation of a new path of research are often effectively induced through the proposal of new concepts. For example, the single term nanotechnology undoubtedly successfully motivated current extensive research trends in small-scale science and technology. Although we only recognized the importance of nanotechnologies in the past few decades, theories, observation apparatuses, and fabrication tools related to the nanoscale world have been well innovated before the popularization of the term nanotechnology. All these separate efforts were combined into a bigger flow, united by this single concept, quoting, for example, words from Richards Feynman, proposals from Kim Eric Drexler, and politic statements from Bill Clinton. These historical facts indicate that clarifying a key concept, such as nanotechnology, can successfully activate, facilitate, and motivate the development of science and technology.

The “post-nanotechnology era” now requires new concepts to be proposed. For example, a paradigm shift in house and building construction from carpenter work, such as cutting materials and attaching parts, to architectonics was achieved in our living world. A similar conceptual change has to be initiated in the nanoscale world, from nanotechnology to nanoarchitectonics.\(^2\) The terminology of this concept was first proposed by Masakazu Aono in the year 2000 at the 1st International Symposium on Nanoarchitectonics Using Suprainteractions in Tsukuba, Japan. This involves the preparation of functional materials and fabrication of advanced systems by the harmonization of various actions, including accurate control of atomic and molecular arrangements, chemistry-based (reaction-based) materials conversion, spontaneous self-assembly/organization, and control over the structure through the application of various physical stimuli. The obtained materials would then sometimes show unexpected properties due to mutual interactions between the components and various nanoscale uncertainties.

As mentioned above, nanoarchitectonics is a basic concept that covers a wide range of science and technology. Recent literature on nanoarchitectonics deals with various research subjects, including (i) materials innovation such as supramolecular assemblies,\(^3\) nanostructured materials,\(^4\) and nanocarbons,\(^5\) (ii) fabrication of nanostructures with both organic and inorganic components,\(^6\) (iii) advanced applications such as sensing,\(^7\) batteries,\(^8\) catalysis,\(^9\) and capacitors,\(^10\) and...
In order to exemplify innovative topics initiated by nanoarchitectonics, three challenges are briefly explained below.

Atomic-level nanoarchitectonic switch designs have been developed based on nanoscopic arrangements of metal and semiconductor materials and atomic diffusion upon electrochemical reactions (Figure 1(a)). They include non-volatile three-terminal atomic transistor, on-demand function-selectable atomic switch, and synapse-like atomic switch junction. These switches often show unusual behaviour that is totally different from what is observed in macroscopic electrical switches. Moreover, they are not based on simple ON/OFF operations. For example, the synapse-like atomic switch junction can show two types of plasticity: short-term plasticity and long-term potentiation. Their operation is based on non-digital chemical reactions, and their switching behaviour is far from linear. The observed switching behaviour is conceptually close to brain functions in contrast to conventional artificial switches. This stimulates further developments toward new artificial neuromorphic computational systems without any pre-programming.

Typical features to architect materials with nanosized components can be seen in materials synthesis from various kinds of nanosheets. In these strategies, nanosheets with different properties can be assembled into layer-structured materials with a specific sequence, which often shows novel functions in individual components. In addition, controlling the inter-sheet distance upon appropriate physical/chemical inputs, such as swelling, can lead to the fabrication of

FIG. 1. Functional systems with nanoarchitectonic design at various dimensions: (a) atomic-level, (b) materials level, and (c) dimension-bridging.
The example illustrated in Figure 1(b) is an architected gel composite with oriented nanosheet components, which exhibit highly anisotropic mechanical properties. Applying a strong magnetic field induces the alignment of titanate charged nanosheets inside the polymer gel. This special orientation can be fixed by cross linking. The compression of the composite can be suppressed when an orthogonal force is applied, while lateral deformation can be easily induced through parallel shear forces. Surprisingly, this exotic material is constructed from rather simple components, nanosheets and polymers, through harmonizing multiple kinds of physical principles, self-organization, alignment in external magnetic field, and chemical reaction.

Architecting functional components makes it possible to control dynamically harmonized actions of functional objects such as molecular machines. In the example of Figure 1(c), molecular machines were placed at the dynamic air-water interface, where macroscopic mechanical stimuli (compression and expansion) can be applied only in a lateral direction and induce harmonized motion of the molecular machines within a two-dimensional plane. In this quasi-two-dimensional architecture, in-plane directions of molecularly thin films have macroscopically visible dimensions, but the film thickness is restricted to the molecular scale. This two-dimensional nanoarchitectonics actually connects macroscopic mechanical motions and molecular-level functionalities. In this particular case, molecular machines such as reversible capture and release of guest molecules can be operated by macroscopic operations such as hand-level motions. Similar systems enable us to finely tune molecular receptor structures upon mechanical motions to realize precise discriminations of amino acids and nucleotides. These unusual techniques can bridge systems within a billionth-of-a-meter length scale, which is why they are named as hand-operating nanotechnologies.

Finally, the impact of proposing nanoarchitectonics is here measured from indirect-research viewpoints using statistical parameters. Recently, Elsevier introduced a new indicator called Field-Weighted Citation Impact (FWCI) that can normalize citation counts depending on the level of focus in corresponding fields. By using this parameter, comparing the quality of papers of individual
research centers in different fields becomes possible. As expected, top-ranked universities such as Massachusetts Institute of Technology (MIT), University of California Berkeley, and Harvard University show high FWCI values (Figure 2). For example, the calculated FWCI values for MIT and Research Center for Materials Nanoarchitectonics (MANA) are both around 2.5, which means that the papers published from these institutes are cited almost 150% more than expected from the world average (FWCI = 1). The presented statistical data provide evidence that approaches based on nanoarchitectonics have successfully created a world-top-level research impact within these last few years. The elaboration of this new research concept in the research community has now become an accomplishment that is hard to ignore. In nano-research, nanoarchitectonics has provided a new paradigm that goes beyond the previously established concepts of nanotechnology. Let us think about NANO again with nanoarchitectonics.


