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# Change Thinking toward Nanoarchitectonics

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## 1.1 From Nanotechnology to Nanoarchitectonics

Innovations in science and technology are initiated by necessity. We say that necessity is the mother of invention. In addition, finding and preparing new materials have seriously affected the progress and development of science and technology. What we want and what we have are driving forces of innovations in science and technology. We wanted to see the stars in the universe. This desire created a telescope, but it could be invented only with transparent glass materials and their fabrication. Further technological progresses led to incredible innovations. Development of microscale fabrication techniques of similar materials such as silicon opened up a huge technological success in integrated electric circuits. The latter developments induced progress that led to the current information technology (IT) revolution. Therefore, the mother of science and technology would be a social reform with advanced computers. We now expect that further advancements in the nanoscale region would create large-scale progress in science and technology, the so-called nanotechnology. With nanotechnology, various dreams are expected to come true.

Initiation of the nanotechnology concept is generally said to have come from the words "*There*'s *plenty* of room at the bottom," which anticipated the current trends in the science of nanosized objects. Much later, advancements in analytical tools such as various microscopies, including high-resolution electron microscopes and scanning probe microscopies, enabled us to directly observe nanoscale objects and structures. Although various scientific efforts in the area of nanoscale objects resulted in huge scientific progress, technological improvements even in the microscale created immense progress in micro-device technologies. Micro-devices with high density of functional structures have been mostly fabricated by the so-called top-down fabrication techniques. However, we have already realized the fatal problems in this success story. According to Moore's law, fabrication and miniaturization of device structures at the current rate in silicon-based technology will encounter the physical limits of device

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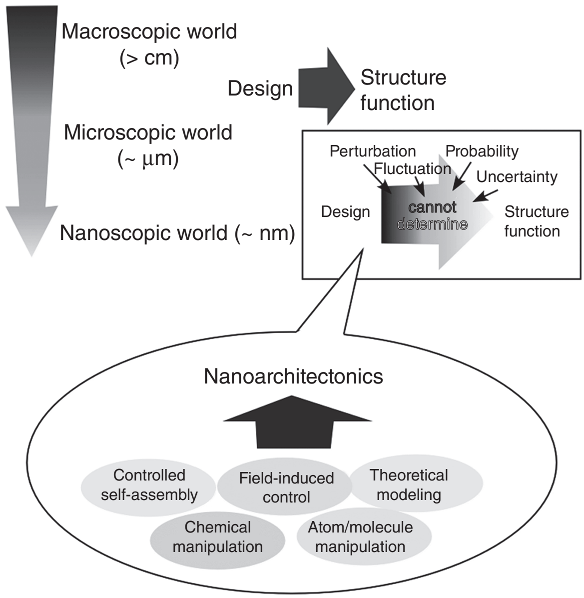


**Figure 1.1** Fabrication characteristics at different size scales and nanoarchitectonics concept.

dimensions in the very near future. The alternate approach, the bottom-up approach, to architect functional systems from nanoscale units is now awaited.

## 1.2 Way of Nanoarchitectonics

A paradigm shift from technology to architectonics in nanoscale science and technology is necessary. This will result in the historical turning point from nanotechnology to nanoarchitectonics.

In order to clarify the fundamental meaning of nanoarchitectonics, we briefly compare material creation and fabrication in all the scales (Figure 1.1). In the macroscopic scale (visible-scale worlds), our craft hobbies, carpentry work, and building construction can be done according to their design drawing and blueprints. We can create and fabricate materials and structures with 100% probability if we just obey the appropriate design. We can easily expect fabrication results from design. This principle can be applicable to fabrications in microscopic scales also. Fabrication in the microscopic invisible scale, the so-called microfabrication, can be done with advanced technologies such as photolithography. These fabrication processes within invisible scales can be also done exactly based on predetermined structural design. Fabrication of microscale objects exactly reflects their design drawings in microfabrication techniques. We can basically assign and expect structures and properties of the fabricated objects from their predesigned drawings in microscopic scale.

When the scale of systems is reduced to submicron scale and nanoscale, unexpected disturbances and fluctuations have significant influences and fabrication of materials and systems become partially uncontrollable. Therefore, these fabrication processes are not always done decisively according to their predesigned drawings. Materials in nanoscale regions cannot fundamentally exclude the influence of thermal/statistical fluctuations and mutual interactions. These uncontrollable factors are inevitably included between component atoms, molecules, and materials.

Therefore, fabrication of materials and functionalization of systems have to be done with a new paradigm, nanoarchitectonics [1–7]. This novel terminology, nanoarchitectonics (nano + architecto + nics), in this meaning, was first used by Masakazu Aono in the year 2000 at the *1st International Symposium on Nanoarchitectonics Using Suprainteractions* in Tsukuba, Japan. In scientific literature, Hecht first used this terminology in the title in 2003.

## 1.3 Materials Nanoarchitectonics

Materials production and fabrication with nanoarchitectonics can be generally done by concerted harmonization of various interactions. These fabrication effects have to be accomplished together with various techniques to control materials organization, which stimulates spontaneous processes such as self-assembly and self-organization. Methods and techniques in nanoarchitectonics include regulation and manipulation of structures as in atomic/molecular manipulation, chemical (organic reaction) and physicochemical modification, and organization upon application of external physical stimuli. Harmonization and combination of these effects and techniques correspond to architecting systems and materials rather than to a simple assembly of techniques (technology).

Nanoarchitectonics approaches are roughly summarized as follows.

1) Reliable nanomaterials or nanosystems are created by organizing nanoscale structures (nanoparts), even with some unavoidable unreliability.
2) The main players are not the individual nanoparts but their interactions, which cause a new functionality to emerge.
3) Unexpected emergent functionalities can result from assembling or organizing a huge number of nanoparts.
4) A new theoretical field, including conventional first-principles computations, is combined with novel bold approximations.

In these days, nanoarchitectonics for materials, or materials nanoarchitectonics, has spread to many fields including molecular machines and nanocars [8], amphiphilic assembly [9, 10], control of molecular inclusion [11, 12], supramolecular recognition [13–15], thin-film fabrications and functions [16–22], graphene fabrication [23], nanocarbon assembly [24–26], synthesis of mesoporous materials [27, 28], fabrication of hybrid materials and integrated systems [29–33], catalysis [34, 35], environmental remediation [36], photocatalytic removal of pollutants [37, 38], optoelectronic applications [39, 40], capacitors [41], batteries [42, 43], sensors [44–46], heterojunctions for photonic functions [47], assembly of biomolecules such as biomimetic light harvesting [48], DNA and enzymes [49–51], nucleic acid delivery [52], drug delivery [53], cell adhesion control [54], nanomedicine [55], biological applications of inorganic materials

[56], bioimaging [57, 58], and dynamic functions from molecules to structures of macroscopic size [59, 60].

## References


1 Aono, M. (2011) *Sci. Technol. Adv. Mater.*, **12**, 040301.
2 Aono, M., Bando, Y., and Ariga, K. (2012) *Adv. Mater.*, **24**, 150.
3 Ariga, K., Ji, Q., Hill, J.P., Bando, Y., and Aono, M. (2012) *NPG Asia Mater.*, **4**, e17.
4 Aono, M. and Ariga, K. (2016) *Adv. Mater.*, **28**, 989.
5 Ariga, K., Li, M., Richards, G.J., and Hill, J.P. (2011) *J. Nanosci. Nanotechnol.*, **11**, 1.
6 Ramanathan, M., Hong, K., Ji, Q., Yonamine, Y., Hill, J.P., and Ariga, K. (2014) *J. Nanosci. Nanotechnol.*, **14**, 390.
7 Ariga, K. and Aono, M. (2016) *Jpn. J. Appl. Phys.*, **55**, 1102A6.
8 Shirai, Y., Minami, K., Nakanishi, W., Yonamine, Y., Joachim, C., and Ariga, K. (2016) *Jpn. J. Appl. Phys.*, **55**, 1102A2.
9 Ramanathan, M., Shrestha, L.K., Mori, T., Ji, Q., Hill, J.P., and Ariga, K. (2013) *Phys. Chem. Chem. Phys.*, **15**, 10580.
10 Shrestha, L.K., Strzelczyk, K.M., Shrestha, R.G., Ichikawa, K., Aramaki, K., Hill, J.P., and Ariga, K. (2015) *Nanotechnology*, **26**, 204002.
11 Zerkoune, L., Angelova, A., and Lesieur, S. (2014) *Nanomaterials*, **4**, 741.
12 Ariga, K., Naito, M., Ji, Q., and Payra, D. (2016) *CrystEngComm*, **18**, 4890.
13 Pandeeswar, M., Khare, H., Ramakumar, S., and Govindaraju, T. (2015) *Chem. Commun.*, **51**, 8315.
14 Zhang, L., Wang, T., Shen, Z., and Liu, M. (2016) *Adv. Mater.*, **28**, 1044.
15 Ariga, K. (2016) *ChemNanoMat*, **2**, 333.
16 Ariga, K., Lee, M.V., Mori, T., Yu, X.-Y., and Hill, J.P. (2010) *Adv. Colloid Interface Sci.*, **154**, 20.
17 Mori, T., Sakakibara, K., Endo, H., Akada, M., Okamoto, K., Shundo, A., Lee, M.V., Ji, Q., Fujisawa, T., Oka, K., Matsumoto, M., Sakai, H., Abe, M., Hill, J.P., and Ariga, K. (2013) *Langmuir*, **29**, 7239.
18 Hamoudi, H. (2014) *RSC Adv.*, **4**, 22035.
19 Ariga, K., Yamauchi, Y., Rydzek, G., Ji, Q., Yonamine, Y., Wu, K.C.-W., and Hill, J.P. (2014) *Chem. Lett.*, **43**, 36.
20 Hamoudi, H. (2014) *Nanoscale Res. Lett.*, **9**, 287.
21 Ariga, K., Ji, Q., Nakanishi, W., and Hill, J.P. (2015) *J. Inorg. Organomet. Polym. Mater.*, **25**, 466.
22 Rydzek, G., Ji, Q., Li, M., Schaaf, P., Hill, J.P., Boulmedais, F., and Ariga, K. (2015) *Nano Today*, **10**, 138.
23 Pan, H., Zhu, S., and Mao, L. (2015) *J. Inorg. Organomet. Polym. Mater.*, **25**, 179.
24 Shrestha, L.K., Ji, Q., Mori, T., Miyazawa, K., Yamauchi, Y., Hill, J.P., and Ariga, K. (2013) *Chem. Asian J.*, **8**, 1662.
25 Nakanishi, W., Minami, K., Shrestha, L.K., Ji, Q., Hill, J.P., and Ariga, K. (2014) *Nano Today*, **9**, 378.

26 Shrestha, L.K., Shrestha, R.G., Hill, J.P., Tsuruoka, T., Ji, Q., Nishimura, T., and Ariga, K. (2016) *Langmuir*, **32**, 12511.
27 Ariga, K., Vinu, A., Yamauchi, Y., Ji, Q., and Hill, J.P. (2012) *Bull. Chem. Soc. Jpn.*, **85**, 1.
28 Malgras, V., Ji, Q., Kamachi, Y., Mori, T., Shieh, F.-K., Wu, K.C.W., Ariga, K., and Yamauchi, Y. (2015) *Bull. Chem. Soc. Jpn.*, **88**, 1171.
29 Wang, K.L., Galatsis, K., Ostroumov, R., Khitun, A., Zhao, Z., and Han, S. (2008) *Proc. IEEE*, **96**, 212.
30 Govindaraju, T. and Avinash, N.B. (2012) *Nanoscale*, **4**, 6102.
31 Rajendran, R., Shrestha, L.K., Minami, K., Subramanian, M., Jayavel, R., and Ariga, K. (2014) *J. Mater. Chem.*, **A2**, 18480.
32 Cordier, S., Grasset, F., Molard, Y., Amela-Cortes, M., Boukherroub, R., Savaine, S., Mortier, M., Ohashi, N., Saito, N., and Haneda, H. (2015) *J. Inorg. Organomet. Polym. Mater.*, **25**, 189.
33 Ariga, K., Malgras, V., Ji, Q., Zakaria, M.B., and Yamauchi, Y. (2016) *Coord. Chem. Rev.*, **320–321**, 139.
34 Abe, H., Liu, J., and Ariga, K. (2016) *Mater. Today*, **19**, 12.
35 Ariga, K., Ishihara, S., and Abe, H. (2017) *CrystEngComm*, **18**, 6770.
36 Ariga, K., Ishihara, S., Abe, H., Li, M., and Hill, J.P. (2012) *J. Mater. Chem.*, **22**, 2369.
37 Puscasu, C.M., Carja, G., and Zaharia, C. (2015) *Int. J. Mater. Prod. Technol.*, **51**, 228.
38 Puscasu, C.-M., Seftel, E.M., Mertens, M., Cool, P., and Carja, G. (2015) *J. Inorg. Organomet. Polym. Mater.*, **25**, 259.
39 Chen, X., Li, P., Tong, H., Kako, T., and Ye, J. (2011) *Sci. Technol. Adv. Mater.*, **12**, 044604.
40 Pandeeswar, M. and Govindaraju, T. (2015) *J. Inorg. Organomet. Polym. Mater.*, **25**, 293.
41 Rajendran, R., Shrestha, L.K., Kumar, R.M., Jayavel, R., Hill, J.P., and Ariga, K. (2015) *J. Inorg. Organomet. Polym. Mater.*, **25**, 267.
42 Takada, K. (2013) *Langmuir*, **29**, 7538.
43 Takada, K., Ohta, N., and Tateyama, Y. (2015) *J. Inorg. Organomet. Polym. Mater.*, **25**, 205.
44 Ariga, K., Yamauchi, Y., Ji, Q., Yonamine, Y., and Hill, J.P. (2014) *APL Mater.*, **2**, 030701.
45 Ishihara, S., Labuta, J., Van Rossom, W., Ishikawa, D., Minami, K., Hill, J.P., and Ariga, K. (2014) *Phys. Chem. Chem. Phys.*, **16**, 9713.
46 Ariga, K., Minami, K., and Shrestha, L.K. (2016) *Analyst*, **141**, 2629.
47 Li, Y.J., Yan, Y., Zhao, Y.S., and Yao, J. (2016) *Adv. Mater.*, **28**, 1319.
48 Zou, Q., Liu, K., Abbas, M., and Yan, Y. (2016) *Adv. Mater.*, **28**, 1031.
49 Ariga, K., Ji, Q., Mori, T., Naito, M., Yamauchi, Y., Abe, H., and Hill, J.P. (2013) *Chem. Soc. Rev.*, **42**, 6322.
50 Howorka, S. (2013) *Langmuir*, **29**, 7344.
51 Avinash, M.B. and Govindaraju, T. (2014) *Nanoscale*, **6**, 13348.
52 Molla, M.R. and Levkin, P.A. (2016) *Adv. Mater.*, **28**, 1159.
53 Ariga, K., Kawakami, K., Ebara, M., Kotsuchibashi, Y., Ji, Q., and Hill, J.P. (2014) *New J. Chem.*, **38**, 5149.

54 Psarra, E., Konig, U., Ueda, Y., Bellmann, C., Janke, A., Bittrich, E., Eichhorn, K.J., and Uhlmann, P. (2015) *ACS Appl. Mater. Interfaces*, **7**, 12516.
55 Kujawa, P. and Winnik, F.M. (2013) *Langmuir*, **29**, 7354.
56 Ariga, K., Ji, Q., McShane, M.J., Lvov, Y.M., Vinu, A., and Hill, J.P. (2012) *Chem. Mater.*, **24**, 728.
57 Pandey, A.P., Girase, N.M., Patil, M.D., Patil, P.O., Patil, D.A., and Deshmukh, P.K. (2014) *J. Nanosci. Nanotechnol.*, **14**, 828.
58 Komatsu, H., Akamatsu, M., Ji, Q., Hill, J.P., and Ariga, K. (2015) *Disp. Imaging*, **2**, 3.
59 Ariga, K., Mori, T., and Hill, J.P. (2013) *Langmuir*, **29**, 8459.
60 Ariga, K., Li, J., Fei, J., Ji, Q., and Hill, J.P. (2016) *Adv. Mater.*, **28**, 1251.