【Grant-in-Aid for Scientific Research (S)】

Nanoscale Element Substitution Science: Construction of Mega Library and Development of Cutting-edge Functions

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Purpose and Background of the Research

●Outline of the Research

Nanoscale inorganic materials are requisite to science, technology, and industry because they have been practically used in a wide range of fields, including luminescent materials, plasmonic materials, heterogeneous solid catalysts, and permanent magnets. In particular, with the arrival of a sustainable hydrogen society just around the corner, the role of nanoparticles (NPs) is becoming increasingly important as optical and electronic materials and solid catalysts. The NPs investigated so far are limited to those with thermodynamically stable structures synthesized by an extension of conventional structure control, such as particle size, shape, and composition, although they have high degree of structural freedom. From the viewpoints of atomic arrangement and crystal phase assembly of inorganic materials, inorganic NPs still have many unexplored physical and chemical properties. It is necessary to develop new and innovative materials based on structural control beyond the conventional methods (Figure 1).

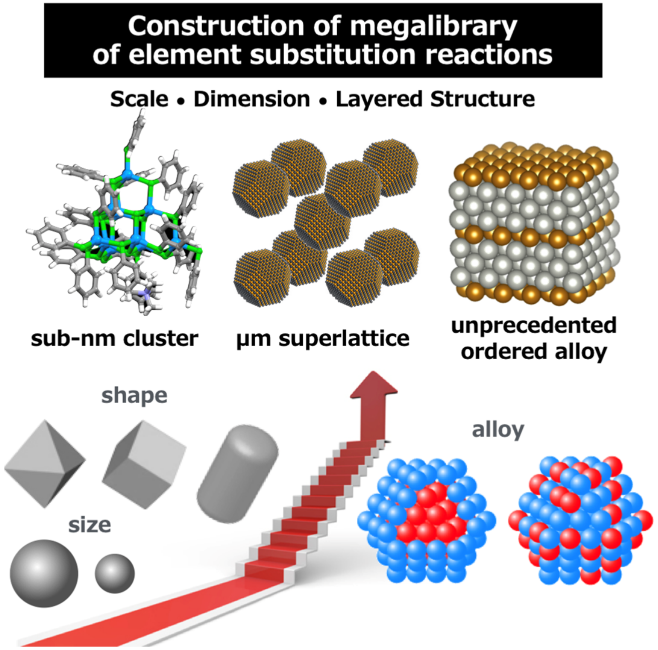

Figure 1. Unprecedented nanomaterials with cutting-edge function formed with element substitution reactions.

Although it is almost impossible to obtain thermodynamically metastable structures through one-step chemical synthesis, two-step chemical synthesis (post-treatment), that is, element substitution, is adopted to create metastable structures of inorganic materials, as demonstrated so far. In this research, the element substitution reactions are extended as follows. (1) Ion exchange reactions are carried out for sub-nm (less than 1/100,000th of a hair) clusters to tens of micrometers ionic NP aggregates (superlattices) to create a mega library of (metastable) ionic nanomaterials that have superior physical and catalytic properties to conventional ionic NPs by significantly modulating the electronic structures while maintaining their morphologies. (2) Various kinds of unprecedented ordered alloy NPs are synthesized by utilizing the interelement miscibility between metal elements to overwhelmingly surpass the physical and catalytic properties of conventional metal NPs. Through these studies, the scope of a new material science in the concept of "modulation of the ground-state electronic structure (electronic structure of materials in a most stable state)", called "Nanoscale Element Substitution Science," will be greatly expanded and unexplored nanomaterials with cutting-edge functions will be created.

Expected Research Achievements

So far, this PI has pioneered element substitution science for inorganic NPs ranging from several nanometers to tens of nanometers, but if we can extend simple element substitution reactions to nanomaterials ranging from sub-nm to several tens of micrometers, it will be possible to construct a mega library of metastable ionic crystalline materials (Figure 2). This also enables in-situ structural transformation of semiconductor devices as well as the isolated ionic clusters and NPs. For example, only the structure of the NPs can be changed while maintaining the single electron island or superlattice device structure of the ionic NPs fixed between the electrodes. In addition, the construction of a mega library of unprecedented alloy NPs (Figure 3) should make a major contribution to the development of novel magnetic materials for high-performance motors, highly active and durable oxygen reduction catalysts for polymer electrolyte fuel cells, and highly active and durable hydrogen evolution catalysts for water electolysis.

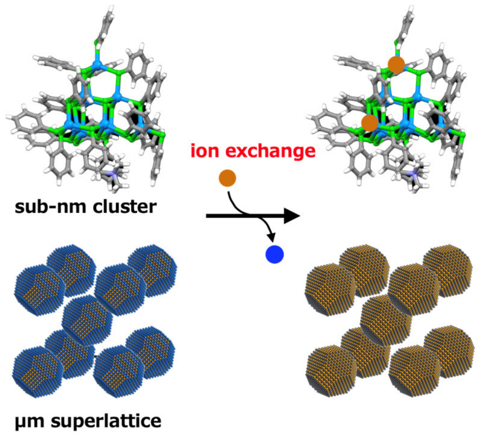

Figure 2. Element substitution of ionic NPs across a wide range of scales.

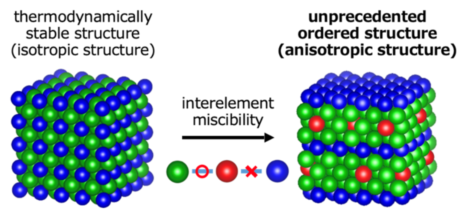

Figure 3. Synthesis of unprecedented ordered alloy NPs using interelement miscibility.

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