Transformative Nanotechnology Manufacturing Technology: Focus on Postprint

Authors: National Center for Nanoscience and Technology

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Abstract

The exotic phenomena and laws exhibited by materials at the nanoscale will transform the existing frameworks of relevant theories, ushering human understanding of the material world into a new stage and heralding a new technological revolution. The transition from nanotechnology to nano-industry manufacturing technology will accelerate China' s development from a major nanotechnology country to a nanotechnology powerhouse, promoting the development of related strategic emerging industries. The National Medium- and Long-Term Program for Science and Technology Development (2006-2020) states that nanotechnology is one of the fields where China "has the potential to achieve leapfrog development" .

Full Text

Preamble

Strategic Priority Research Program (Category A) of the Chinese Academy of Sciences, ChinaXiv Partner Journal: Focus on Transformative Nanomanufacturing Technologies

1. Background and Significance

Nanotechnology reveals extraordinary phenomena and laws at the nanoscale that challenge existing theoretical frameworks, ushering human understanding of the material world into a new era and heralding a new technological revolution. The transition from nanoscience to nanomanufacturing technologies will accelerate China' s evolution from a major participant to a global leader in nanotechnology, fostering the growth of strategic emerging industries. The National Medium- and Long-Term Program for Scientific and Technological Development (2006–2020) identifies nanotechnology as one of the fields "with potential for leapfrog development."

To promote nanotechnology' s transformative impact on key industrial sectors, the Chinese Academy of Sciences launched the Strategic Priority Research Program (Category A) "Focus on Transformative Nanomanufacturing Technologies" (hereinafter referred to as the "Nanomanufacturing Program"). Over the past three years, the program has established innovation and industrial chains centered on core technological breakthroughs, with comprehensive supporting systems to drive major advances in manufacturing technologies. The program aims to become a critical enabler of "Made in China 2025." Through clear annual work plans and milestone evaluation metrics, strengthened dynamic assessment and third-party testing, and rigorous process management, the program has fully achieved its predetermined objectives, with some technical indicators reaching world-advanced levels. During the pilot-scale and industrial demonstration phases, the program has strengthened patent applications for key technological achievements, gradually building and optimizing patent portfolios to provide a solid foundation for integrated research and industrial chain construction.

The program is structured across three hierarchical levels:

(1) **Strategic Leading Nanotechnologies**: Focusing on new energy and advanced manufacturing, the program has deployed Project 1 "Long-Endurance Power Lithium Batteries" and Project 2 "Nano Green Printing and Device Manufacturing Technologies."

(2) **Key Breakthrough Nanotechnologies**: Building upon core technologies that have already achieved advanced levels and significant industrial impact, the program has deployed Project 3 "Applications of Nanostructures in Specific Energy, Environment, and Health Fields."

(3) **Nanomanufacturing Common and Evaluation Technologies**: Addressing critical and common technologies with important implications for nanomanufacturing applications, the program has deployed Project 4 "Nanomanufacturing Common Technologies and Standardization Systems."

[Figure 1: see original paper]

2.1 Development of New Material System Lithium-Ion Batteries Based on Nanotechnology and Next-Generation High-Energy-Density Metal Lithium Batteries at World-Advanced Levels

Third-generation lithium-ion batteries upgrade the conventional graphite carbon anode to silicon-based anodes. Meanwhile, the recent emergence of lithium-rich manganese-based cathode materials with discharge specific capacities reaching 300 mAh/g has opened new possibilities for developing high-energy-density lithium-ion batteries of 350–400 Wh/kg.

The Nanomanufacturing Program has conducted coordinated research on key materials and battery manufacturing technologies for high-energy-density power lithium-ion batteries, including cathodes, anodes, separators, electrolytes, and conductive additives. The technical indicators have reached internationally advanced levels, with key technologies completing pilot-scale testing [Figure 2: see original paper]. A collaborative team from the Ningbo Institute of Materials Technology and Engineering and the Institute of Physics, Chinese Academy of Sciences, has developed a pouch lithium-ion battery using nano-silicon-carbon materials as the anode, lithium-rich materials as the cathode, 5 V electrolyte, and high-voltage-resistant separators. The single-cell battery achieves a capacity of 24 Ah, with a gravimetric energy density of 374 Wh/kg and volumetric energy density of 577 Wh/L.

The high-capacity silicon anode material has established a strategic partnership with Jiangxi Zichen Technology Co., Ltd., with a pilot-scale research base built at the enterprise, achieving 500 kg per batch production capability. The developed materials have entered the enterprise' s product supply chain and are being tested by multiple companies, with potential product integration in 2017. High-capacity lithium-rich cathode materials have entered the pilot-scale stage, leading to the establishment of Ningbo Fuli Materials Technology Co., Ltd. Electrolytes and separators have also addressed stability issues for use in high-voltage material systems and are undergoing scaled integration. Meanwhile, key technical indicators for all-solid-state batteries, lithium-sulfur batteries, and lithium-air batteries remain at world-advanced levels.

2.3 Nano-Confined Single-Iron Catalysts Applied to Direct Natural Gas-to-Ethylene Conversion

The research team has achieved original academic results with significant application prospects. Using abundant and inexpensive natural gas as an alternative to petroleum for producing liquid fuels and basic chemicals represents a major focus for both academia and industry. However, methane molecules with tetrahedral symmetry are the most stable organic small molecules in nature, and their selective activation and directional conversion constitute a worldwide challenge, hailed as the "Holy Grail" in catalysis and chemistry.

A team from the Dalian Institute of Chemical Physics, Chinese Academy of Sciences, has made breakthroughs in applying nano-confined single-iron catalysts to direct natural gas-to-ethylene conversion. The approach embeds highly catalytically active single-site low-valence iron atoms into silica or silicon carbide lattices through two carbon atoms and one silicon atom, forming a thermally stable catalytic active center. Methane molecules undergo catalytic activation and dehydrogenation at the coordinatively unsaturated single-iron sites, generating surface-adsorbed methyl species that further desorb from the catalyst surface to form highly active methyl radicals. These radicals undergo radical coupling reactions in the gas phase to produce ethylene and other high-carbon aromatic molecules such as benzene and naphthalene.

Compared with conventional natural gas conversion routes, this research completely eliminates the energy-intensive syngas preparation process, achieving 100% carbon atom utilization efficiency. Following publication of the findings in *Science*, numerous domestic and international scientific journals and news media reported on the "world-changing technology." The project has established cooperation agreements with China National Petroleum Corporation and Saudi Basic Industries Corporation (SABIC) to build R&D bases and promote industrialization.

2.4 Breakthroughs in Several Nanomanufacturing Technologies with Partial Industrialization

(1) Advanced Manufacturing Domain

The Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, has for the first time in China overcome key technical challenges in continuous-printing rapid prototyping of three-dimensional objects, developing a proprietary continuous-printing digital projection 3D printer prototype that solves the international challenge of achieving strong, tough, and high-fatigue-performance 3D-printed titanium alloys. The Suzhou Institute of Nano-Tech and Nano-Bionics has developed embedded nano-material printed metal mesh flexible transparent conductive films with conductivity over 100 times higher than conventional ITO flexible transparent conductive films. The research team has partnered with domestic touch screen leader "O-Film" to achieve mass production of new metal mesh touch screens. The Suzhou institute has also developed piezoelectric high-density multi-nozzle experimental MEMS inkjet printheads, solving bottleneck problems that have hindered China' s inkjet printing industry for years. Additionally, the team has overcome key technologies for gallium nitride-based blue lasers, successfully developing blue lasers with output power exceeding 1W, leading to the establishment of Suzhou Naray Photonics Co., Ltd. to promote GaN-based laser industrialization.

(2) Energy and Environment Domain

The Institute of Chemistry, Chinese Academy of Sciences, has for the first time internationally proposed organic-inorganic nano-hybrid technology for pour point depression and viscosity reduction of waxy crude oil. The team designed and synthesized a novel nano-pour point depressant along with its production and application process, which has been officially deployed on oil pipelines including the Renjing and Shilan lines, saving the nation over 170 million yuan and winning the 2013 American Society of Engineers Global Pipeline Award. The National Center for Nanoscience and Technology and the Institute of Process Engineering have developed nano-epoxy composite materials whose electrical insulation performance and other key indicators meet national standards, with anti-pollution flashover coatings for power grids establishing a 200-ton/year pilot production line. The Institute of

Chemistry has also established centralized (100 tons/day) and decentralized (300 liters/day) photocatalytic/adsorption integrated micro-polluted water purification processes and equipment, completing field demonstrations in pastoral areas of Inner Mongolia and drinking water purification projects in Hunan, Ningxia, and Shandong, providing safe drinking water for over 2,000 people.

(3) Healthcare Domain

The Shanghai Institute of Materia Medica, Chinese Academy of Sciences, has formulated the domestically-owned innovative non-nucleoside hepatitis B drug isothiafludine into a nano-suspension formulation, increasing its oral bioavailability from 4% to 27%. As a Class 1.1 chemical drug, it has obtained clinical approval. The Institute of Biophysics, Chinese Academy of Sciences, has developed an injectable alprostadil micelle using micelle technology to establish a nano-particle drug delivery system, which as China' s first micelle formulation has obtained clinical approval and entered Phase II clinical trials. The National Center for Nanoscience and Technology has applied microfluidic nano-immunoassay chips to combined detection of AFP (alpha-fetoprotein) and CEA (carcinoembryonic antigen), with chip products entering clinical approval procedures. The Institute of Biophysics has successfully developed the world' s first complete proteome microarray for *Mycobacterium tuberculosis* and related instruments, providing powerful tools for vaccine and drug development.

3. Originality

Centered on the Nanomanufacturing Program' s overall objectives and addressing critical technical problems in national strategic domains such as new energy vehicles, green printing, energy, and health, the program has solved key issues in energy and environment through interfacial (composition, structure, and charge) regulation of nanomaterials, achieving scaled production and application of corresponding nanomaterials to drive development in related industries.

During power battery development, the team has over the past three years initially solved structural stability issues during cycling of high-capacity cathode materials, voltage decay problems, compatibility issues between high-voltage cathode materials and electrolytes during cycling, interfacial stability problems, and transition metal ion migration issues. The team has also addressed volume deformation control and interfacial stability issues during preparation and use of silicon-based anode materials, and independently developed automated manufacturing equipment for lithium-ion power batteries.

For the future development of printing manufacturing, the Institute of Chemistry research team has achieved nano-scale fine patterning and functional device fabrication through innovative research on nano-materials and printing technologies, further extending green printing from traditional paper products to printed electronics and photonic devices. This will fundamentally solve severe environmental pollution caused by exposure-etching processes in traditional manufacturing and drive technological transformation and green development across numerous important industries. In 2016, Professor Yanlin Song received the Asian Chemical Society Federation "Distinguished Contribution to Economic Advancement" Award in recognition of his successful translation of chemical applications to economic development.

Bao Xinhe and his team have achieved breakthroughs in direct methane conversion to olefins and high-value chemicals, as well as direct high-selectivity preparation of chemicals from coal via syngas, proposing new pathways for efficient and clean conversion and utilization of natural gas and coal. In 2016, the team received the "Outstanding Achievement Award in Natural Gas Conversion" from the International Natural Gas Conversion Committee. Committee Chairman Professor Krijn de Jong from the Netherlands commented that "the related work represents an important breakthrough in carbon-one catalysis concepts over the past century and will certainly lead new directions in this field."

Furthermore, the program team' s innovations in material preparation methods, processing and manufacturing technologies, and industrial cooperation models have driven nanotechnology applications in energy, environment, advanced manufacturing, and healthcare. Based on the Nanomanufacturing Program research, various research teams have undertaken national key R&D programs in 2016, including the "Nanotechnology" and "New Energy Vehicles" special programs.

5. Recommendations for Future National Discipline, Industry Advancement, and Talent Development

(1) Prioritize Nanotechnologies with Rapid Progress and Large Development Space

Nanotechnology represents a crucial research field that aligns well with the development concepts of "innovation, coordination, green development, openness, and sharing." Nano green printing actively promotes the transformation of traditional printing toward "greening, functionalization, three-dimensionalization, and device integration." New materials and technologies for power lithium batteries create higher-efficiency power sources with improved energy utilization. Innovations in nano-catalyzed anaerobic methane-to-ethylene conversion represent disruptive technological breakthroughs internationally.

(2) Promote a "Nano-Plus" Development Model for Future Nanotechnology

The program should simultaneously drive breakthroughs in major fundamental questions of broad interest to the nanoscience community to achieve scientific excellence, while actively promoting transformative industrial applications of nanotechnology to serve major national and social needs. The program will further organize China's nanotechnology R&D forces around key technical issues of national importance and enterprise concern, selecting core technologies in important domains to provide an innovation foundation in new materials, new components, new systems, and integration. This will strengthen connections with national major industries and integration between nanotechnology and defense science and technology, contributing to the high-quality realization of "Made in China 2025."

High-energy-density lithium-ion batteries and metal lithium batteries represent important research directions in advanced battery technology, with significant implications for developing electric vehicles, advanced consumer electronics, smart grids, and other applications. Through systematic efforts over the past three years, the Chinese Academy of Sciences Nanomanufacturing Program' s "Long-Endurance Power Lithium Batteries" project has achieved major breakthroughs from basic research to practical application. The project has obtained important results in reducing voltage decay of lithium-rich cathode materials, developing cyclic high-capacity lithium-rich manganese-based cathodes, high-voltage spinel lithium nickel manganese oxide, walnut-structured nano-silicon-carbon anode materials, ionic conductor-coated separators, fluorinated esters, ionic liquid composite high-voltage electrolytes, and high-energy-density lithium-ion batteries, solid-state batteries, lithium-sulfur batteries, and lithium-air batteries—reaching world-advanced levels. Through interdisciplinary collaboration, dynamic management, and extensive cooperation with domestic and international R&D institutions and enterprises, the project has effectively advanced China' s power battery research and development, earning broad international recognition and acclaim.

Liu Jun, Director and Senior Scientist, Energy and Materials Technology Division, Pacific Northwest National Laboratory, USA. Long-term researcher of lithium-ion batteries, metal lithium batteries, solid-state lithium batteries, and flow batteries. Principal Investigator of the US DOE Battery 500 Program (2016–2020), a $50 million project jointly executed by 4 US national laboratories and 5 universities to develop next-generation power batteries with energy density reaching 500 Wh/kg. Author of 350 papers and holder of 55 US patents.

China has achieved globally remarkable results in nanotechnology after years of investment, with nanotechnology papers ranking first worldwide. However, translating nanoscience research achievements into nanotechnology industries has become a global challenge in recent years. The Chinese Academy of Sciences has provided a complete solution to this challenge through its Nanomanufacturing Program. As China' s national team for scientific development, CAS has taken the lead in advancing its accumulated nanotechnology research achievements toward industrialization. The program has achieved

remarkable results within three years of implementation. I am primarily engaged in green printing manufacturing for electronics applications and am particularly familiar with the program' s nano green printing and device manufacturing direction. The research team has applied its years of nanomaterials research to green printing additive manufacturing, creating entirely new printing plate-making technology and developing pollution-free printing inks that fundamentally transform the heavily polluting traditional printing production methods. Printed electronics technology represents the application of green additive printing to electronics manufacturing—a transformative development for traditional electronics fabrication. The research team has developed printable nano-conductive materials and high-resolution printing methods, successfully applying printed high-resolution metal mesh to flexible transparent conductive film manufacturing and subsequently to touch screen applications. The program's achievements in green printing plate-making and printed metal mesh transparent conductive films are internationally leading. Most commendably, these achievements have all been industrialized, with related products already entering the market. Green printed circuit technology and 3D printing technology based on green printing and additive manufacturing concepts have also achieved critical breakthroughs during the program' s three-year implementation, laying a foundation for further industrialization. The Chinese Academy of Sciences has set a global example by implementing a strategic priority program to focus on core issues in translating research to industry, working closely with industry and guiding technological development from a whole industrial chain perspective. I hope this program will achieve even greater success in the next two years and contribute to China' s transformation into an innovative nation.

Cheng Yibing, Academician of the Australian Academy of Engineering, Professor at Monash University, Director of the Monash University Branch of the Australian Centre for Advanced Photovoltaics, Researcher at the Australian Centre of Excellence in Exciton Science, "Thousand Talents Program" Professor, Director of the Printed Optoelectronics Laboratory at Wuhan University of Technology. Internationally renowned expert in ceramic materials and printable solar cells with over 400 publications and 20 patents. Currently leading multiple Australian national-level printable solar cell R&D projects.

Note: Figure translations are in progress. See original paper for figures.