



World Young Scientist Summit
**4th Frontier Forum of
Manufacturing Paradigm III 2025**
2025世界青年科学家峰会
第四届制造范式III前沿论坛

会议指南

主办单位
国际纳米制造学会

Hosts
The International Society for Nanomanufacturing

协办单位
浙江大学机械工程学院

Co-organizers
School of Mechanical Engineering, Zhejiang University

2025.10.24-26
中国·温州
OCTOBER 24-26, 2025
WENZHOU, CHINA

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01

CONFERENCE INTRODUCTION

大会概况





1.1 Organization

Sponsor
主办单位



国际纳米制造学会

The International Society for Nanomanufacturing

Co-organizer
协办单位



浙江大学机械工程学院

School of Mechanical Engineering, Zhejiang University



1.2 Conference Committee

Honorary Advisors

Huayong Yang	Academician , Zhejiang University
Han Ding	Academician , Huazhong University of Science and Technology
Lan Jiang	Academician , Beijing Institute of Technology
Gao Wei	Academician , Tohoku University, Japan
Xuejun Zhang	Academician , Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences
Fengzhou Fang	Academician , University College Dublin, Ireland

Steering Committee

General Chair:

Yuanliu Chen (Zhejiang University)	Xiaokang Liu (Chongqing University of Technology)
Yongda Yan (Harbin Institute of Technology)	Benny Cheung (The Hong Kong Polytechnic University)
Rong Chen (Huazhong University of Science and Technology)	Xichun Luo (University of Strathclyde)

Members:

Yuki Shimizu (Hokkaido University)	Suet To (The Hong Kong Polytechnic University)
Shuming Yang (Xi'an Jiaotong University)	Wei Yuan (South China University of Technology)
Qidai Chen (Jilin University)	Jufang Zhang (University College Dublin)
Chunguang Hu (Tianjin University)	Hailong Cui (China Academy of Engineering Physics)
Min Lai (Tianjin University)	Jining Sun (Dalian University of Technology)
Xinghui Li (Tsinghua University)	Wenlong Lu (Huazhong University of Science and Technology)
Ziran Chen (Chongqing University of Technology)	Hui Deng (Southern University of Science and Technology)

Conference Secretary

Chair:

Zhongwei Li (Zhejiang University) TEL. 17857111230

Members:

Siqi Yu (Zhejiang University) TEL. 18643468448
Xiaoying Zhang (Zhejiang University) TEL. 13328568373
Yangyang Li (Zhejiang University) TEL. 13396976025



1.3 Manufacturing paradigm III

“Manufacturing Paradigm III: Manufacturing objectives and processes are directly focused on atoms, spanning the macro- through the micro- to the nanoscale. This paradigm is centered on manufacturing based on atomic-scale removal, migration, and addition, integrating the entire production chain from atoms to final products. The fundamental technology of Manufacturing Paradigm III is atomic and close-to-atomic scale manufacturing (ACSM), also known as atomic scale manufacturing.”

Fengzhou Fang



Scientists Forum of ISNM

On September 23–24, 2019, Tianjin University hosted the inaugural High-End Forum on Atomic and Close-to-Atomic Manufacture (ACSM), marking the first dedicated symposium on atomic-scale manufacturing technologies. Later, on December 2–5, 2021, the China Association for Science and Technology organized the first Young Scientist Symposium on ACSM—China’s first national-level academic event primarily focused on early-career researchers in the field. The second Young Scientist Symposium successfully convened at the Southern University of Science and Technology on May 23–24, 2024.

The Forum on Manufacturing Paradigm III, formed by unifying the High-End Forum and the Young Scientist Symposium, represents a strategic integration of academic resources. This consolidation establishes a structured platform for cross-generational collaboration, formally launching a series of International Forums on Manufacturing Paradigm III to drive disruptive innovations across both fundamental research and applied investigations

Evolution of the International Forum of Manufacturing Paradigm III

The evolution of manufacturing technology is characterized by a progressive refinement of precision—from microscale to nanoscale and ultimately to atomic resolution, where functional features are governed at the atomic and molecular level. This paradigm shift necessitates a transition from macroscopic empirical statistics to fundamental particle interaction mechanisms, as quantum effects and atomic-scale material behaviors increasingly dictate process dynamics. While modern manufacturing has traditionally been rooted in classical mechanics and macroscopic analysis, next-generation technologies—defined as Atomic and Close-to-Atomic Scale Manufacturing—are driven by interdisciplinary convergence.

In 2012, Professor Fengzhou Fang, former President of CIRP, conceptualized a tripartite framework for manufacturing paradigms, establishing ACSM as the foundation of a new technological era known as Manufacturing III. This fundamental trajectory of manufacturing innovation underscores the inevitability of atomic-scale manufacturing as an emergent technological epoch.

To promote interdisciplinary collaboration and support early-career researchers, the current symposium integrates the former High-End Forum and the Young Scientist Symposium into a unified platform—the International Forum of Manufacturing Paradigm III. This global event will facilitate the dissemination of cutting-edge advancements in ACSM methodologies, address core challenges in disruptive technology development, and foster theoretical and experimental innovations across fundamental mechanism, process physics, instrumentation, and metrological verification frameworks.



02

TECHNICAL PROGRAM

大会日程



2.1 Conferecne Venue

温州君廷酒店
地址：温州市瓯海区潘桥街道宁波路3009号
Grand Barony Wenzhou
Address: 3009 Ningbo Road, Panqiao Subdistrict, Ouhai District, Wenzhou

2.2 Program at a Glance

Date	Time	Conference Program
Day1 October 24	09:00-22:00	On-site registration 君廷酒店一楼 1st floor of Grand Barony
	18:00-20:00	Buffet dinner 二楼塞纳宫 Saina Room at 2nd floor
Day2 October 25	09:00-11:45	2025 World Young Scientist Summit Plenary Session (optional) 瓯海奥体中心 Ouhai Olympic Sports Center
	12:00-13:00	Buffet lunch 二楼塞纳宫 Saina Room at 2nd floor
	14:00-14:15	Opening Ceremony of Manufacturing Paradigm III Frontier Forum 四楼君廷厅 Juntong Room at 4th floor
	14:15-18:00	Manufacturing Paradigm III Frontier Forum Keynote speeches and Invited presentations 四楼君廷厅 Juntong Room at 4th floor
	18:00-20:00	Banquet 三楼君悦厅 Junyue Room at 3rd floor
Day3 October 26	08:30-12:25	Forum on Manufacturing Paradigm III Keynote speeches and Invited presentations 四楼君廷厅 Juntong Room at 4th floor
	12:30-13:30	Buffet lunch 二楼塞纳宫 Saina Room at 2nd floor
	14:00-14:30	Presentation of the 5th and 6th Forum of Manufacturing Paradigms III 四楼君廷厅 Juntong Room at 4th floor
	14:40-17:00	Manufacturing Paradigm III round table discussions 四楼君廷2厅 Juntong Room 2 at 4th floor & ACSM Doctor Forum 四楼君廷厅 Juntong Room at 4th floor
	18:00-20:00	Farewell dinner 三楼君悦厅 Junyue Room at 3rd floor



2.3 Program Details

Afternoon of October 25 2025

四楼君廷厅 Junting Room at 4th floor

14:00-14:15	Opening ceremony : • Jiliang Guo, Vice President of the Zhejiang Association for Science and Technology • Wei Gao, President of the International Society for Nanomanufacturing • Xiaokang Liu, President of the Youth Committee, the International Society for Nanomanufacturing • Group photo	Session chair: Yuanliu Chen (Zhejiang University)
14:15-14:40	Keynote speech: • Atomic and close-to-atomic measurement technologies for semiconductor manufacturing Wei Gao (Tohoku University)	Session chair: Xiaokang Liu (Chongqing University of Technology)
14:40-15:05	Keynote speech: • Atomic scale design and fabrication of materials Shigeo Maruyama (The University of Tokyo)	
15:05-15:30	Keynote speech: • Optical sensor technologies for precision positioning in nanomanufacturing Yuki Shimizu (Hokkaido University)	
Tea break		
15:45-16:00	Invited presentation: • Atomic and close-to-atomic scale polishing Lei Chen (Southwest Jiaotong University)	Session chair: Rong Chen (Huazhong University of Science and Technology)
16:00-16:15	Invited presentation: • 5+ axis ultraprecision machining technology Xinquan Zhang (Shanghai Jiaotong University)	



Afternoon of October 25 2025

四楼君廷厅 Junting Room at 4th floor

16:15-16:30	Invited presentation: • Advanced manufacturing from micro/nano to atomic scale for life science and healthcare: a personal perception Nan Zhang (University College Dublin)	Session chair: Rong Chen (Huazhong University of Science and Technology)
16:30-16:45	Invited presentation: • Atomic-scale fabrication of flexible electronic devices based on directed assembly Zhimin Chai (Tsinghua University)	
16:45-17:00	Invited presentation: • Some understanding on core propositions of ACSM and its applications in enabling innovative devices Jufan Zhang (University College Dublin)	Session chair: Xichun Luo (University of Strathclyde)
17:00-17:15	Invited presentation: • Grating interferometer: the dominant positioning strategy in atomic and close-to-atomic scale manufacturing Xinghui Li (Tsinghua University)	
17:15-17:30	Invited presentation: • Atomic and close-to-atomic scale manufacturing based on laser and ion beam Jinshi Wang (Tianjin University)	
17:30-17:45	Invited presentation: • Atomic-level surface reconstruction of quantum dots for active-matrix display manufacturing Xingliang Dai (Zhejiang University)	
17:45-18:00	Invited presentation: • The development and application of close-to-atomic sputtering epitaxy technology Ruyi Zhang (Ningbo Institute of Materials Technology and Engineering)	



Morning of October 26 2025

四楼君廷厅 Junting Room at 4th floor

8:30-8:55	Keynote speech: • Atomic-level manufacturing and future industries Huayong Yang (Zhejiang University)	Session chair: Fengzhou Fang (University College Dublin)
8:55-9:20	Keynote speech: • Artificial Intelligence across manufacturing paradigms József Váncza (Hungarian Academy of Sciences)	
9:20-9:45	Keynote speech: • Preliminary introduction to atomic and close-to-atomic scale manufacturing Xichun Luo (University of Strathclyde)	Session chair: Yongda Yan (Harbin Institute of Technology)
9:45-10:10	Keynote speech: • Visualized atomic scale manufacturing Litao Sun (Southeast University)	
10:10-10:35	Keynote speech: • Advances in multi-physical field coupling polishing of diamond for atomic-scale damage-free surfaces Benny C.F. Cheung (The Hong Kong Polytechnic University)	
Tea break		
10:50-11:15	Keynote speech: • ACSM for AI-era: area-selective deposition and synergistic processing in integrated circuits Rong Chen (Huazhong University of Science and Technology)	Session chair: Shuming Yang (Xi'an Jiaotong University)
11:15-11:40	Keynote speech: • Multi-energy field assisted ultra-precision machining of difficult-to-cut materials Suet To (The Hong Kong Polytechnic University)	



Morning of October 26 2025

四楼君廷厅 Junting Room at 4th floor

11:40-11:55	Invited presentation: • Single-atom magnetometry for tailored atomic-scale magnetism Lihui Zhou (Germany Max Planck Institute)	Session chair: Wei Yuan (South China University of Technology)
11:55-12:10	Invited presentation: • Application of in-situ micromechanics in manufacturing processes Zhirong Liao (The University of Nottingham)	
12:10-12:25	Invited presentation: • Deep learning-enhanced plasma figuring with nano-metric accuracy Hui Deng (Southern University of Science and Technology)	

Afternoon of October 26 2025

四楼君廷厅 Junting Room at 4th floor

14:00-14:30	• The Initiative for Young Scientists on ACSM • Presentation of the 5th Forum of Manufacturing Paradigms III • Presentation of the 6th Forum of Manufacturing Paradigms III	Session chair: Yuanliu Chen
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Afternoon of October 26 2025

四楼君廷2厅 Junting Room 2 at 4th floor

14:40-17:00	• Round table discussions	President: Fengzhou Fang
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Afternoon of October 26 2025

四楼君廷厅 Junting Room at 4th floor

ACSM Doctor Forum

14:40-14:55	Oral presentation: • Neural absolute testing for Fizeau Interferometry Xi Wang (Shanghai Jiao Tong University)	Session chair: Kaiyng Xia (Zhejiang University)
14:55-15:10	Oral presentation: • Different Shapes of Menisci Emerging During Evaporation: Picolitre Droplets Showing Diversities in Cylindrical Wells Zhida Huang (Moganshan Institute of Geomagnetism Large-scale Scientific Facility of Zhejiang Province)	
15:10-15:25	Oral presentation: • A time-optimal force-velocity cooperative planning method for robotic deterministic polishing of optical components Wenhao Li (Huazhong University of Science and Technology)	
15:25-15:40	Oral presentation: • Frictional dynamics of tool-chip interactions in ultra-precision cutting of titanium alloy utilizing a PFPE-coated diamond tool Shiquan Liu (Zhejiang University)	
15:40-15:55	Oral presentation: • High-Precision Grating Interferometers for ACSM Positioning Can Cui (Tsinghua University)	

Tea break



Afternoon of October 26 2025

四楼君廷厅 Junting Room at 4th floor

16:10-16:25	Oral presentation: • On-machine laser polishing of diamond turned metal surfaces Zelong Jia (Shanghai Jiao Tong University)	Session chair: Genshen Liu (Zhejiang University)
16:25-16:40	Oral presentation: • Mechanical properties and high-temperature thermal stability of various nano-whiskers reinforced unfired refractories grown in-situ by dynamic gradient temperature: finite element simulation and experimental design Wenhao Li (Shanghai University)	
16:40-16:55	Oral presentation: • Corner smoothing and force-feedrate planning method for pseudo-random polishing trajectories considering surface form accuracy and dynamic constraints Bin Teng (Huazhong University of Science and Technology)	
16:55-17:10	Oral presentation: • Fabrication of atomic-scale structures by tip induced local oxidation Yangyang Li (Zhejiang University)	



03

SPEECHES INTRODUCTION

报告介绍



3.1 Keynote speeches

Huayong Yang (Zhejiang University)



Biography: Huayong Yang obtained his Ph.D. in Fluid Power Transmission and Control from the University of Bath in the UK in 1988. Later, he/she joined the National Nuclear Company of the United Kingdom to engage in postdoctoral work. After returning to China in 1989, I conducted postdoctoral research at the State Key Laboratory of Fluid Power and Mechatronic Systems (Zhejiang University). After completing his postdoctoral research in 1991, he remained at the Department of Mechanical Engineering of Zhejiang University to teach, successively holding the positions of associate professor and professor. In 1997, he served as the director of the State Key Laboratory of Fluid Power and Control at Zhejiang University (until 2001). In 1999, he/she was selected into the first and second tiers of the "Hundred, Thousand, and Ten Thousand Talents Project" by the Ministry of Personnel of the People's Republic of China. In 2000, he served as the director of the National Engineering Research Center for Electro-Hydraulic Control Technology. In 2004, he/she was awarded the National Science Fund for Distinguished Young Scholars. In 2008, he/she was selected as a Distinguished Expert of Zhejiang Province. He was elected as an academican of the Chinese Academy of Engineering in 2013. In 2017, it was awarded the National Innovation and Excellence Award. In May 2024, he/she was selected as one of the first "National Science and Technology Innovation Masters"

Title: Atomic-level manufacturing and future industries

Abstract: Manufacturing is the lifeblood of a nation's economy and people's livelihood, and also a key underpinning for building global competitiveness in future industries. Currently, manufacturing is moving toward high-end, intelligent, and green development. From the perspective of product manufacturing precision, manufacturing accuracy continues to break through physical limits, leaping from macroscopic, mesoscopic, and micro-nano scales to atomic-level precision, which has given rise to atomic-level manufacturing with paradigm-shifting significance. Atomic-level manufacturing is a transformative manufacturing paradigm that involves precisely applying energy to atoms, achieving large-scale manipulation of atoms to realize the confined removal or ordered assembly of atoms, and ultimately producing products with extraordinary properties.

Wei Gao (Tohoku University)



Biography: Wei Gao received his Bachelor from Shanghai Jiao Tong University in 1986, followed by MSc and Ph. D from Tohoku University in 1991 and 1994, respectively. He is currently a professor in Tohoku University. His research interests lie primarily in precision nanometrology. He is an author of the books “Precision Nanometrology” (Springer), “Surface Metrology for Micro- and Nanofabrication” (Elsevier), “Optical Metrology for Precision Engineering” (De Gruyter). He was awarded the Prize for Science and Technology from the Japanese government (MEXT) in 2019.

He is a Fellow of CIRP, ISNM, JSPE, JSME and EAJ (The Engineering Academy of Japan)

Title: Atomic and close-to-atomic measurement technologies for semiconductor manufacturing

Abstract: Atomic and close-to-atomic scale manufacturing (ACSM), initiated by Prof. Fengzhou Fang, aims to realize cost-effective, deterministic, and scalable manufacturing of next-generation products with atomic-level precision by addressing quantum uncertainty in atomic-level material manipulation (removal, migration, and addition). It is the fundamental technology for opening a new manufacturing paradigm. Measurement is one of the cornerstones for making ACSM possible. In this keynote presentation, atomic and close-to-atomic measurement technologies for semiconductor manufacturing, which is an important field of ACSM, are presented. Three-dimensional (3D) optical and non-optical microscopes are the major imaging tools for monitoring integrated circuits (IC) devices. Non-optical microscopes including scanning probe microscope, electronic microscope and X-ray microscope are also important imaging tools. Spectroscopic ellipsometry plays a crucial role in measurement of thin film thickness in a large variety of semiconductor manufacturing processes. Such measurement technologies will be highlighted.

József Váncza (Hungarian Academy of Sciences)



Biography: Dr. József Váncza graduated from the Faculty of Electrical Engineering of the Budapest University of Technology and Economics (BME), Hungary in 1984 and received his PhD in Mechanical Engineering in 1994. Since his graduation, he has been working at the Institute for Computer Science and Automation (SZTAKI), where he is Head of the Research Laboratory for Engineering and Business Intelligence. His research interests include engineering applications of artificial intelligence, production informatics, cyber-physical manufacturing systems, human-robot collaboration, cooperative and sustainable production in networks and platforms. He was awarded among others with the Order of Merit of the Hungarian

Republic, Knight Cross (2008), the Dennis Gábor Prize for Innovation (2021) and the Rudolf Kálmán Prize (2025). He has been involved in university education for three decades, teaching at the Faculty of Mechanical Engineering of BME where he is Honorary Professor. He is Fellow of the International Academy for Production Engineering (CIRP), where he has been Chair of the Production Systems and Organisations Committee (2016–2019) and is now Chair of the Editorial Committee and member of the Council. He is Fellow of the International Academy of Engineering and Technology (AET), associate editor of the CIRP Journal of Manufacturing Science and Technology and the Robotics and Computer-Integrated Manufacturing journals. He published 240+ papers which received 6800+ references as well as registered 8 international patents. He was elected as Vice-president of CIRP in August 2025.

Title: Artificial Intelligence across Manufacturing Paradigms

Abstract: The immense potential of applying artificial intelligence (AI) techniques to manufacturing problems was recognized right at the inception of this research field. AI tools and techniques have been widely adopted in all areas of production engineering, including product and production system design, process planning and control, and the organization and management of production networks. AI and manufacturing have seen mutual and accelerated growth since the turn of the 21st century thanks to the dominant approach of task-oriented, rational agents. The talk will present how the concept of rational agents – which are embedded in an environment, make observations and change the environment with actions to optimize their utility – contributed to the development and success of what we know as cyber-physical production systems. Natural extensions in the areas of robotics, learning and multi-agent systems, as well as the growing potential (and dangers) of generative AI methods, will also be presented. While AI's significant contribution to the advancement of manufacturing which relies on classical theories – the Manufacturing Paradigm II – is broadly acknowledged, signs of its impact on manufacturing at the atomic and close-to-atomic scales – the Manufacturing Paradigm III – are less evident thus far. The talk will analyze the potential reasons for this difference and provide recommendations for transferring some AI techniques across manufacturing paradigms. Finally, it will be discussed how Manufacturing III could contribute to advancing the computational technologies that AI needs as a foundation.

Shigeo Maruyama (The University of Tokyo)



Biography: Shigeo Maruyama received his Ph.D. from the University of Tokyo in 1988. He worked as a Research Associate until 1991, as a Lecturer for a year, as an Associate Professor from 1993, as a full Professor from 2004, and as a Distinguished Professor from 2014 at School of Engineering, the University of Tokyo. Since 2025, he has been Emeritus Professor at the University of Tokyo. He joined Professor Richard Smalley's group at Rice University as a visiting fellow for about 2 years from 1989. He was also assigned as a visiting professor at Ecole Centrale Paris in 2006, the cross-appointment fellow for advanced industrial science and technology (AIST) from 2015 to 2021, a guest professor at Peking University from 2016 to 2017, and a Qiushi Guest Professor at Zhejiang University from 2024. From 2025, after retirement from the University of Tokyo he is working as a project Professor of Nagoya University and later is appointed as a Qiushi Chair Professor at Zhejiang University, School of Mechanical Engineering.

Title: Atomic scale design and fabrication of materials

Abstract: I will introduce the current and future design and fabrication techniques of new materials such as atomic clusters, carbon nanotubes, 1-dimensional heterostructures. Good example is the 1-dimensional van der Waals heterostructures. We need to combine bottom up self-assembly and top-down fabrication by chemical vapor deposition, photolithography, electron beam manufacturing, laser beam technology. The design of materials based on stability and functionality is the key for the fabrication.

Benny C.F. Cheung (The Hong Kong Polytechnic University)



Biography: Professor Benny C.F. Cheung is the Chair Professor of Ultra-precision Machining and Metrology at the Department of Industrial and Systems Engineering of The Hong Kong Polytechnic University. Currently, he is the Director of State Key Laboratory of Ultra-precision Machining Technology and the Director of The Hong Kong Polytechnic University-Wenzhou Technology and Innovation Research Institute. He is also a elected Fellow of the International Academy for Production Engineering (CIRP Fellow) and a College of Fellow of the American Society for Precision Engineering (ASPE College of Fellow). His main research interests include ultra-precision machining, precision metrology and smart precision manufacturing. He received Joseph Whitworth Prize 2010 and A M Strickland Prize 2017 by The Institution of Mechanical Engineers, UK, Bank of China Hong Kong Science and Technology Innovation Prize 2023 – Advanced Manufacturing, etc.

Title: Advances in Multi-Physical Field Coupling Polishing of Diamond for Atomic-Scale Damage-Free Surfaces

Abstract: Diamond is renowned for its high stability in extreme environments such as high temperatures, high pressures, and strong corrosive conditions, which makes it demonstrate irreplaceable superior performance in quantum devices, high-power optical systems, and ultra-high-frequency electronic devices. Nevertheless, its intrinsic brittleness, difficulty in material removal, and vulnerability to damage caused by processing severely limit its practical applications. Polishing technology serves as a critical approach for achieving ultra-smooth, high-quality diamond surfaces. This presentation systematically reviews the advances of polishing technologies for diamond, addressing the challenges of controlling sub-nanometer roughness and surface/subsurface damage-free, with a focus on the need for atomic-level surface integrity. It envisions key development directions for diamond polishing from the perspectives of multi-physical field coupling polishing mechanism innovation and intelligent control of atomic-scale manufacturing processes.

Litao Sun (Southeast University)



Biography: Litao Sun is a distinguished professor and vice president at Southeast University. He received his Ph.D. degree in 2005 from the Shanghai Institute of Applied Physics, Chinese Academy of Sciences, and conducted postdoctoral research at the University of Mainz in Germany. Prof. Sun obtained the National Science Fund for Distinguished Youth Scholars and was awarded the Changjiang Distinguished Professor at Southeast University. He is currently the director of the Key Laboratory of Micro-Electro-Mechanical System of Ministry of Education. Prof.

Sun has been engaged in research on micro-nano electronic materials and devices, visualized atomic-scale manufacturing, in-situ electron microscopy, etc. He published 3 academic books and more than 300 journal papers, including 2 in Science, 25 in Nature and Nature series journals. He was listed as the Highly Cited Researcher since 2018. Prof. Sun won the First Prize of Jiangsu Provincial Science and Technology Awards, the Xplorer Prize, the China Industry-University-Research Cooperation Innovation and Promotion Award, and the First Prize of Invention and Entrepreneurship Award.

Title: Visualized atomic scale manufacturing

Abstract: A fundamental understanding on the atomic-scale manufacturing requires the capability to capture real-time structural evolution under complex processing conditions, including various external fields and environments. By setting up an nano-laboratory inside a transmission electron microscope (TEM), we developed in-situ TEM based techniques capable of simultaneous fabrication and observation at the atomic scale, enabling manufacturing to become visible, understandable and controllable. Through these methodologies, the studies directly reveal new phenomena and underlying mechanisms in several manufacturing processes including electron-beam-assisted processing, electrically/thermally-driven processing. These results provide the foundation for atomic-precision processing and the on-demand construction of materials and structures, thus opening up opportunities for developing novel fabrication strategies as well as new materials and devices.

Xichun Luo (University of Strathclyde)



Biography: Xichun Luo is a Professor in Ultra Precision Manufacturing, Technical Director of Centre for Precision Manufacturing at the University of Strathclyde, UK. His research interests include ultra-precision machining, micro, nano, atomic and close-to-atomic scale manufacturing. Prof. Luo won International Association of Advanced Materials (IAAM) Scientist Medal in 2024 and the Institution of Mechanical Engineers (IMechE) 2015 Ludwig Mond Prize for research and development of novel digital tools for micro & nanomanufacturing. He has over 260 publications and four patents. Prof. Luo is a Fellow of the International Society for Nanomanufacturing, International Academy of Engineering and Technology, International Association of Advanced Materials. He is an Associate Editor for Proceedings of IMechE Part C: Journal of Mechanical Engineering Science, Journal of Micromanufacturing, Manufacturing Review and Nanomanufacturing and Metrology, and an editorial board member for Micromachines and International Journal of Extreme Manufacturing.

Title: Preliminary introduction to atomic and close-to- atomic scale manufacturing

Abstract: This talk introduces a research framework, including scientific issues and research of atomic and close-to-atomic scale manufacturing (ACSM), which aims to realize cost-effective, deterministic, and scalable manufacturing of next-generation products with atomic-level precision by addressing quantum uncertainty in atomic-level material manipulation (removal, migration, and addition). ACSM is regarded as the fundamental technology for opening a new manufacturing paradigm. Underpinning fundamental knowledge and theory and potential industrially viable processing technologies for realising ACSM will also be presented in this talk, followed by scientific and technological challenges, and future research perspectives.

Yuki Shimizu (Hokkaido University)



Biography: Yuki Shimizu received his MS in precision engineering from Tohoku University, Japan, in 2002. He spent his career at Hitachi Ltd. from 2002 to 2011. He received his Ph.D. in Mechanical Engineering from Nagoya University, Japan, in 2009. He had been an associate professor in the Department of Finemechanics at Tohoku University, Japan. Currently, he is a professor in the Division of Mechanical and Aerospace Engineering at Hokkaido University, Japan. His research interest includes precision dimensional metrology and optical metrology. He is a member of

the International Society for NanoManufacturing (ISNM, fellow), the Japan Society for Precision Engineering (JSPE), the Japan Society of Mechanical Engineers (JSME, fellow), and the Japanese Society of Tribologists (JAST).

Title: Optical Sensor Technologies for Precision Positioning in Nanomanufacturing

Abstract: Precision positioning technology is important as an infrastructure technology underpinning cutting-edge science, technology, and nanomanufacturing. This presentation introduces scale calibration methods, precision angle measurement techniques, and multi-axis measurement approaches to enhance the precision of displacement measurement based on optical encoders utilizing diffraction scale gratings, which are widely employed in precision positioning technology.

Suet To (The Hong Kong Polytechnic University)



Biography: To Suet is a Professor in the Department of Industrial and Systems Engineering of the PolyU, an Associate Director of the State Key Laboratory of Ultra-precision Machining Technology and Advanced Optics Manufacturing Center, and Director of PCB and Functional Materials Characterization Laboratory. She is also a Committee Member of the Asian Society for Precision Engineering and Nanotechnology (ASPEN), Member of the Chinese Mechanical Engineering Society (CMES), and Member of The International Academy for Production Engineering (CIRP). She also serves as the editorial board member of several international

journals. Her main research directions include research on ultra-precision machining of micro-nano structural functional surfaces; research on multi-field-assisted ultra-precision machining of difficult-to-cut materials; and smart manufacturing of ultra-precision machining technology. Prof. To has undertaken more than 20 key research projects as principal investigator. Her research outcomes are well-recognized. She has published five research books and more than 350 international journal papers, was ranked as the World's Top 2% most-cited scientists 2024 by Stanford University. Her research outcomes were granted the Natural Science Award and Scientific and Technological Progress Award by the Higher Education Outstanding Scientific Research Output Awards by the Ministry of Education of the PRC, as well as three times, as a supervising teacher, received the Hiwin Doctoral Dissertation Award from the Chinese Mechanical Engineering Society. Prof. To has been granted 13 patents as the first inventor and was invited to be the keynote or invited speaker at several international conferences.

Title: Multi-energy Field Assisted Ultra-precision Machining of Difficult-to-Cut Materials

Abstract: Ultra-precision machining technology based on single-point diamond turning (SPDT) and ultra-precision freeform machining have become an indispensable tool for the design and the manufacture of high- technology and high-precision lenses. The process is capable of producing components with micrometer to sub-micrometer form accuracy and surface roughness in the nanometer range. With the fast growing development of machining technology, ultra-precision machining technology is used not only for manufacturing symmetrical spherical and aspheric workpieces, but also to produce some very complex and non-symmetrical microstructures. This presentation mainly introduces Professor To's research team research achievements in the field of ultra-precision machining. These include the study of ultraprecision machining and the combination of physical energy fields such as magnetic fields, ultrasonic, laser, and electric fields on difficult-to-machine and hard and brittle materials, as well as the theory and methods of ultraprecision machining of micro/nano structures.

Rong Chen (Huazhong University of Science and Technology)



Biography: Rong Chen is a full professor at Huazhong University of Science and Technology with the School of Mechanical Science and Engineering, by courtesy of China-EU Institute for clean and renewable energy of HUST, and college of future technologies. She received her M.Sc. and Ph.D. degrees from Stanford, B.S. from University of Science and Technology of China. She was a senior research scientist at Intel Labs before she joined HUST. Her research focuses on atomic level manufacturing, by understanding surface science, and applying to a range of problems in semiconductor manufacturing, nanotechnology, and sustainable energy. Prof. Chen is currently served as the associate editor of Int. J. Extrem. Manuf., editor of

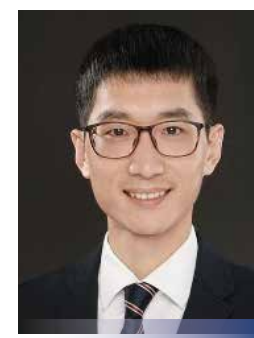
Physica B: condensed matter, editorial board member of Chem. Mater., J. Am. Vac. Technol. A&B, Nano-manufacturing and Metrology, Moore and More, etc. She has also served as Guest Editor for three journal special issues, Chair or Committee Member for six international conferences, Reviewer for more than 60 prestigious journals including Nature, Nature Rev. Methods. Prof. Chen is the recipient of Tencent Xplorer award, Science and Technology Award for Chinese Youth, Qishui Distinguished Young Scholars, Distinguished Young Investigator of China Frontiers of Engineering, as well as IEEE SMC 2020 Distinguished Academic Contribution Award, the special gold prize (with the congratulations of the jury) of Geneva International Inventions, the Simon Karecki award of Semiconductor Research Association, the Texas Instruments Woman's Fellowship for Leadership in Microelectronics, etc.

Title: ACSM for AI-Era: Area-Selective Deposition and Synergistic Processing in Integrated Circuits

Abstract: Artificial intelligence is reshaping computation, driving unprecedented demand for specialized chips with higher density, faster interconnects, and energy-efficient architectures. Meeting these requirements pushes relentless miniaturization and 3D integration in the semiconductor industry. Yet, conventional top-down fabrication—relying on repeated cycles of deposition, lithography, and etching—now faces critical bottlenecks, including edge-placement errors and escalating process complexity. Atomic layer processes—covering both deposition and etching—offer atomic- and near-atomic-scale precision for building advanced device structures. Among them, area-selective deposition (ASD) is particularly promising, as it enables targeted material growth only at predefined surface sites, thereby addressing alignment challenges in scaled transistors through precise dielectric and metal patterning. This presentation will discuss recent strategies for achieving selectivity, including inherent selectivity, inhibitor-assisted approaches, and surface reaction kinetics, which govern deposition specificity and reliability. As a bottom-up ACSM paradigm, ASD provides a viable route to extend Moore's Law while supporting the design of advanced AI-era integrated circuits. By integrating area-selective and synergistic atomic layer processes, ASD is rapidly emerging as a versatile platform for precision manufacturing and innovation across the semiconductor industry.

3.2 Invited presentations

Xinquan Zhang (Shanghai Jiao Tong University)



Biography: Zhang Xinquan, co-founder and CTO of Leading Optics, is a tenured Associate Professor at Shanghai Jiao Tong University and a corresponding member of the International Academy for Production Engineering (CIRP). He graduated from Harbin Institute of Technology with a bachelor's degree and obtained his Ph.D. in Mechanical Engineering from the National University of Singapore. From 2013 to 2019, he worked as a research scientist and head of the Ultra-Precision Machining Laboratory at the Singapore Institute of Manufacturing Technology. During that time, he also served as a doctoral supervisor at the National University of Singapore.

In 2019, he joined the School of Mechanical Engineering at Shanghai Jiao Tong University and co-founded Leading Optics. Zhang Xinquan has been engaged in cutting-edge theoretical research and innovative process exploration in the field of ultra-precision machining. He has made significant achievements in solving scientific and engineering challenges related to key optical devices and complex micro-nano structures in ultra-precision cutting. His contributions include the development of a new type of ultra-precision diamond turning technique, which was awarded the "Best Research Achievement Award" by the Singapore Institute of Manufacturing Technology. Zhang has also been selected as a participant in the National Overseas High-Level Talents Program (Youth Project).

Title: 5+ Axis Ultraprecision Machining Technology

Abstract: Optical microstructural surfaces are evolving towards extreme features such as multiscale and large-scale, serving as effective supplements to traditional continuous optical surfaces, thereby achieving compound functionality and enhanced utility. However, when processing such advanced optical structures, traditional milling techniques based on 5-axis ultra-precision machine tools face various issues, such as severe tool interference and low processing efficiency. In this study, a "5+" axis ultra-precision machining technology is proposed. By adding an auxiliary swing A axis and an auxiliary aligning U axis to the classical 5-axis ultra-precision machine tool architecture and combining the coordinated control of the auxiliary axes with the 5-axis machine tool, dynamic adjustment of the spatial attitude and rotational state of the diamond tool is achieved. This technology significantly improves the processing efficiency of multiscale Fresnel structures and large-scale micro-lens arrays by an order of magnitude or more.



Hui Deng (Southern University of Science and Technology)



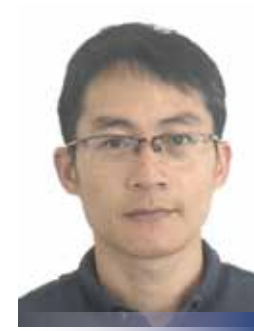
Biography: Dr. Deng Hui received his bachelor's degree in mechanical engineering from Huazhong University of Science and Technology in 2010. After that, he studied in Osaka University, Japan for about 6 years and received the master and Ph.D. degree in precision engineering in 2013 and 2016 respectively. Dr. Deng's research interest is focusing on atomic-scale manufacturing using plasma including atom-selective etching, atomic-scale surface reconstruction, modification-assisted polishing and so on.

Title: Deep learning-enhanced plasma figuring with nanometric accuracy

Abstract: Plasma figuring is promising ultraprecision machining approach for optical components due to its superior properties like damage-free, atmospheric work condition, variable removal function and so on. However, the plasma etching process is affected by many factors make it difficult to realize the accuracy convergence. To solve this problem, deep learning was utilized to realize a fast accuracy convergence. This talk will introduce some results of the deep learning enhanced plasma figuring process.



Lihui Zhou (Germany Max Planck Institute)



Biography: Lihui Zhou received his PhD from the University of Hamburg in Germany. In 2017 he was promoted as a Group Leader and Senior Scientist at the Max-Planck Institute for Solid State Research. His research focuses on low-dimensional physics and the exploration of quantum materials assembled by MBE/PLD and atomic manipulation using home-built scanning probe microscopy. His work, published in high-impact journals e.g. Science (cover), Physical Review Letters (Editors' Suggestion), Nature Physics, Nature Communications, Phys. Rev. B (Kaleidoscope), and Journal of Physics D (cover), has been recognized with awards at reputed conferences e.g. MMM and JEMS.

Title: Single-Atom Magnetometry for Tailored Atomic-Scale Magnetism

Abstract: The advancement of atomic manufacturing calls for techniques that combine atomically precise fabrication with characterization of unprecedented sensitivity and spatial resolution. Magnetism is fundamental to modern technologies, from power generation and motors to data storage and spin-based information processing. In this talk, I will present single-atom magnetometry implemented in a sensor-integrated scanning tunnelling microscope, which enables quantitative probing of both ground- and excited-state magnetic properties of individual atoms. By integrating atomic manipulation, this approach further allows the atom-by-atom construction of tailored magnetic nanostructures, offering a versatile platform for engineered spin functionality. I will discuss its implications for quantum materials research, where magnetic interactions often govern emergent phenomena, and outline possible pathways toward scalable atomic-scale spin architectures.

Zhirong Liao (The University of Nottingham)



Biography: Prof. Zhirong Liao finished his PhD study at Harbin Institute of Technology and joined the Rolls-Royce UTC in Manufacturing and On-Wing Technology, University of Nottingham, as a research fellow in 2016. He was awarded a Nottingham Research Fellowship and started his independent academic career at the University of Nottingham in 2019, and was promoted to Associate Professor in 2022 and Chair Professor in 2025. His research area mainly focuses on conventional and nonconventional manufacturing technologies with conscious of materials science. His expertise covers machining, laser materials processing, micromechanics, machine tools, sensing, and precision engineering. He has been awarded more than £9 million research grants as PI and Col. His research has been applied to aerospace, automotive and medical engineering sectors. He is the winner of Rising Star of the University of Nottingham Knowledge Exchange and Impact Awards (2018-2024). He is an Associate Member of the International Academy for Production Engineering (CIRP), Chairman of CIRP UK, Member of the Institution of Mechanical Engineers (IMechE). Prof. Zhirong Liao is also the Associate Editor of the International Journal of Machine Tools and Manufacture (Impact factor 18.8), and Senior Editor of the Journal of Materials Processing Technology (impact factor 7.5), which are top journals in the manufacturing field. He has also been involved in the evaluation panel of many national and international funding agencies from UK, Hongkong, EU, German and Czech Republic. He published >100 papers in top journals (e.g., Materials Today, Nature Comm, IJMTM, Acta Mater, Engineering) with a h-index of 35.

Title: Application of in-situ micromechanics in manufacturing processes

Abstract: In-situ micromechanics is a new developed advanced technology and significantly supports the understanding of materials insights under micro-nano scale. However, it has been mainly used by materials community to characterise the mechanical properties of new materials while rarely used by the manufacturing community to support the manufacturing technology development. University of Nottingham, with its closed partnership with micromechanics industry, has been conducting significant research in this area. This talk gives a brief introduction of the recent advancements in the research of in-situ micromechanics application in manufacturing processes at the university of Nottingham. It will cover two aspects: (i) understanding the phenomena occurring in the workpiece (sub) surfaces after manufacturing operation by performing very high resolution micro-mechanical testing (e.g. compression/bending of micro-pillars/beams); (ii) studying the material removal mechanisms at micrometric level using common indenters or dedicated edges to understand how the workpiece materials (e.g. groups/single grains) react to cutting conditions.

Nan Zhang (University College Dublin)



Biography: Prof. Nan Zhang is an Associate Professor in the School of Mechanical and Materials Engineering at University College Dublin (UCD), Ireland. His research spans polymer micro/nano manufacturing, atomic and close-to-atomic scale manufacturing, precision-engineered plastic microfluidic chips, nanomedicine, and diagnostic technologies. Dr. Zhang has authored over 80 publications in leading journals and holds multiple PCT patents, several of which have been successfully commercialized. His contributions have been recognised with prestigious honors such as the 2024 NovaUCD Invention of the Year Award and the IAAM Scientist Medal from the International Association of Advanced Materials. In 2025, he was shortlisted for the European Research Council Consolidator Grant for his pioneering research in nanomedicine and atomic-scale manufacturing.

Title: Advanced Manufacturing from Micro/Nano to Atomic Scale for Life Science and Healthcare: a personal perception

Abstract: Atomic and Close-to-atomic Scale Manufacturing (ACSM) is an emerging direction in the area of advanced manufacturing. This talk traces a personal journey from micro/nano manufacturing to ACSM, highlighting translational opportunities in life sciences and healthcare. The presenter will share his own thinking and a blur map on how the ACSM can potentially contribute to and revolutionise the breakthrough in life science. Potential ideas and case studies will be discussed.

Lei Chen (Southwest Jiaotong University)

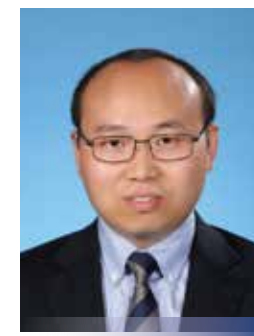


Biography: Lei Chen is currently Professor of Southwest Jiaotong University (SWJTU), China. He received Ph. D. degree from SWJTU in 2013 and acted as a visiting scholar in The Pennsylvania State University (USA). His current research interests involve atomic scale polishing and tribology. He is the author and co-author of 100+ original research papers published in journals such as Nature Communications, PRL, PNAS, ACS nano et al. He got the first prize of natural science of Ministry of Education (2022), the best paper award in tribology (one paper per year in China). He is in charge of more than 30 projects, including NSFC-outstanding youth foundation and National Key Research and Development Program of China. He is the editor board members of 6 journals including Chin J Mech Eng-en, Industrial Lubrication and Tribology, Nanomanufacturing and Metrology, Nanotechnology and Precision Engineering.

Title: Atomic and Close-to-atomic Scale Polishing

Abstract: Atomic scale polishing refers to a controlled polishing technique with material removal accuracy at the atomic scale. As the feature sizes of advanced chips continue to shrink, achieving atomic-scale surface roughness on wafers has become essential to ensure lithography resolution. Moreover, controlling the polishing removal accuracy of interconnected heterogeneous surface materials at the atomic level is critical for precise endpoint detection, which directly impacts chip yield. Furthermore, in fields such as high-end equipment and aerospace, the demand for extended service life and high reliability of core components under extreme conditions imposes even stricter requirements on manufacturing precision. Atomic and close-to-atomic scale polishing, with its damage-free processing at atomic-scale accuracy, holds the potential to create surfaces with specialized functional and performance characteristics. This offers a promising pathway to overcome existing performance limits under service conditions.

Zhimin Chai (Tsinghua University)



Biography: Zhimin Chai is an Associate Professor in the Department of Mechanical Engineering at Tsinghua University. He earned his Bachelor's degree in Mechanical Engineering and Automation from Jilin University in 2009. Subsequently, he was admitted to Tsinghua University, where he pursued his Ph.D. in the Department of Mechanical Engineering under the supervision of Professor Xinchun Lu, graduating in January 2015. After completing his doctorate, he conducted postdoctoral research at George Washington University (2015) and later served as a Postdoctoral Researcher and Senior Research Scientist at the Center for High-rate Nanomanufacturing, Northeastern University (2015–2020). In December 2020, he joined the Department of Mechanical Engineering at Tsinghua University. His primary research focuses on atomic-scale manufacturing based on directed assembly. He has revealed the mechanisms of directed transport of atomic building blocks under external fields and proposed novel principles and methods for atomic-scale fabrication, such as surface energy-directed assembly and interfacial convective assembly. Dr. Chai serves as a Young Editorial Board Member for Exploration and Tribology and holds the position of Secretary for the Asian International Conference on Tribology. He has been recognized with several prestigious awards, including the Overseas Young Scholar Fund and the Wen Shizhu Maple Leaf Award for Outstanding Young Scholar.

Title: Atomic-scale Fabrication of Flexible Electronic Devices Based on Directed Assembly

Abstract: The advent of emerging technologies—such as wearable devices, flexible displays, and electronic skins—is driving a shift in electronic devices from rigid to flexible forms, thereby creating a growing demand for flexible electronic fabrication. While conventional silicon-based integrated circuit processes offer extremely high precision, they are incompatible with flexible substrates due to their reliance on vacuum and high-temperature steps. In contrast, solution-based printed electronics operate under ambient conditions, enabling low-cost, large-area manufacturing on flexible substrates. However, this approach faces challenges such as limited resolution, poor pattern fidelity, and non-uniform thickness, which severely constrain the integration density of flexible electronics. To overcome these limitations, this study introduces a directed-assembly-based process for the atomic-scale fabrication of flexible electronic devices. This method employs external fields to drive the selective assembly of atomic-scale building blocks in predefined substrate regions, forming functional patterned structures. Using this directed assembly approach, we have successfully achieved fully solution-processed metal-oxide thin-film transistors and logic gate circuits on both silicon wafers and flexible substrates, with pattern thickness controlled at the atomic level.

Jinshi Wang (Tianjin University)



Biography: Dr. Jinshi Wang is an associate research fellow in the school of precision instruments and opto-electronics engineering, Tianjin University. His research focuses on ACSM (by energy beams) and ultraprecision diamond machining, especially the investigation of fundamental mechanisms and development of advanced technologies for difficult-to-process materials. He is the associate member of The International Academy for Production Engineering (CIRP), the member of International Society for Nanomanufacturing (ISNM) and Chinese Mechanical Engineering Society. He is also a youth member of editorial board for the journal of Nanomanufacturing and Metrology.

Title: Atomic and close-to-atomic scale manufacturing based on laser and ion beam

Abstract: Atomic and close-to-atomic scale manufacturing (ACSM) is a fundamental transformative technology in manufacturing III, aiming at removing, adding and manipulating atoms in a controllable manner to achieve ultimate precision of surfaces/structures or create novel materials. For the top-down approach, material removal determines the surface finishing, subsurface damage, shape accuracy and feature size. This talk presents our recent work on atomic scale removal by laser irradiation, including fundamental studies to obtain a deep understanding based on which the feasibility and challenging can be clarified. A novel method, diffusion-assisted etching, is developed to significantly improve the repeatability of sub-1 nm removal. We also concern the generation of atomically smooth surface on nanostructures by using ion beam enhanced etching, leading to a selective and self-limited process that is critical especially for difficult-to-process materials.

Jufan Zhang (University College Dublin)



Biography: Dr. Jufan Zhang is a Principal Investigator at Centre of Micro/Nano Manufacturing Technology (MNMT-Dublin) of University College Dublin, a Funded Investigator at Research Ireland I-Form Centre for Advanced Manufacturing and at Research Ireland C $\square$ RAM Research Centre for Medical Devices. He has secured 4 million euro research funding as the sole PI in the last 5 years from the EU, Ireland, industry and international funding agency, and contributed to more funding as the Co-PI. His research interests include solid-state nanopore manufacturing and nanopore-enabled biomedical detections, design and manufacturing of micro-structured medical devices (such as microneedles, artificial joints), geometric optical waveguide for AR display, atomic and close-to-atomic scale manufacturing (ACSM). He is a member of the International Society for Nanomanufacturing (ISNM), the International Academy of Engineering and Technology (AET), the Irish Manufacturing Council (IMC), the Una Europa Self-Steering Committee on Future Materials.

Title: Some Understanding on Core Propositions of ACSM and its Applications in Enabling Innovative Devices

Abstract: Since Manufacturing III – the Third Paradigm of Manufacturing was proposed, this new theory has been widely disseminated within global manufacturing research communities and continuously inspired new ideas. Atomic and Close-to-Atomic Scale Manufacturing (ACSM) is recognized as one of the key enabling technologies to develop Manufacturing III. However, as a new realm in manufacturing research, ACSM is still at its fledging stage and requires intensive efforts for further exploration and development. Down to such a microscopic scale, fundamentals of manufacturing shifts from classical Newtonian mechanics to quantum mechanics, while the object of manufacturing transitions from continuous materials to discrete atoms. Although this offers fantastic opportunity to explore manufacturing down to the fundamental components of matters, conventional manufacturing theory is disrupted which creates numerous challenges to be solved based on long-term interdisciplinary collaboration – manufacturing may not work effectively as an independent discipline anymore. This talk presents some personal understanding on the core propositions of ACSM and some possible applications of ACSM in advancing atom scale devices and enabling innovative applications.

Ruyi Zhang (Ningbo Institute of Materials Technology and Engineering)



Biography: Ruyi Zhang is an Associate Research Fellow at the Laboratory of Atomic-Scale and Micro & Nano Manufacturing, Ningbo Institute of Materials Technology and Engineering (NIMTE), the Chinese Academy of Sciences (CAS). He received his Ph. D. degree in microelectronics and solid-state electronics from Xi'an Jiaotong University, China. His research focuses on the sputtering epitaxy technology with close-to-atomic precision and functional films/nanostructures with plasmonic applications. He has published over 60 papers in journals including Nano Lett., ACS Photonics, ACS Appl. Mater. Interfaces, etc., and holds 15 authorized or pending invention patents.

Title: The development and application of close-to-atomic sputtering epitaxy technology

Abstract: High-quality epitaxial films with close-to-atomic precision can hardly be attained by conventional sputtering technology due to severe bombardment effect by sputtered particles with high kinetic energy (around 1000 eV). In recent years, we have significantly lowered the kinetic energy in our self-developed close-to-atomic sputtering epitaxy systems, yielding epitaxial films with extremely high crystalline qualities comparable to that of molecular beam epitaxy and pulsed laser deposition. For example, La:BaSnO₃ epitaxial films, a novel perovskite transparent conducting oxide film, with record-high crystalline quality and electron mobility as well as multilayer hyperbolic meta-materials with ultrahigh figure of merits have been successfully fabricated by our systems. In addition to the layered films, our sputtering system can also fabricate single-crystalline nanostructure arrays with high-density (10¹²/cm²), sub-10 nm lateral sizes, and sub 1 nm gaps, which is very challenging for either “top-down” or “bottom-up” technologies. The single-crystalline nanostructure arrays made of transition-metal nitrides demonstrate many intriguing properties, such as plasmonic hyperbolic dispersion, superhydrophilicity, surface enhanced Raman spectroscopy, and perfect light absorption, which can be widely applied in many nanophotonic, sensing, photothermal conversion devices.

Xingliang Dai (Zhejiang University)



Biography: Xingliang Dai, PhD, Researcher of the Hundred Talents Program at Zhejiang University. In 2012 and 2017, he obtained a Bachelor's and a PhD degree from Zhejiang University. His research focuses on quantum dot luminescent materials and electroluminescent display chips in the research group of Academician Zhizhen Ye at the School of Materials Science and Engineering, Zhejiang University. So far, he has published more than 30 papers as the first/corresponding author in Nature, Nat. Nanotechnol., Nat. Electron., Nat. Commun., Sci. Adv., Adv. Mater., Angew. Chem., with more than 7000 citations. Undertaking projects such as the National Natural Science Foundation of China, the Leading Wild Goose Project in Zhejiang Province, and the sub-project of the National Key Research and Development Program, selected for the 7th "Youth Talent Support Project" of the Chinese Association for Science and Technology and the Zhejiang University Qizhen Outstanding Young Scholar.

Title: Atomic-level Surface Reconstruction of Quantum Dots for Active-Matrix Display Manufacturing

Abstract: The research focuses on active-matrix quantum dot display chips and has achieved breakthroughs in LED luminous efficacy, lifetime, and response time, as well as in integrated display with TFT. To solve the challenge of controlling surface defects, we constructed a core-shell structure for metal-halide quantum dots, designed inert conjugated ligands. We reconstructed the nanosurface through Atomic-level etching, achieving records in LED luminous efficacy and lifetime. Besides, we developed a copper halide-based efficient and ultra-wide spectral emission material system, clarified the multi-level efficient charge transfer luminescence mechanism, and innovated in-situ synthesis-deposition technology to overcome the difficulties in material dissolution and high-temperature decomposition, achieving a single material-based brightest warm-white LED. This technology provides an alternative solution for full-color display. To overcome the ion migration, we developed in-situ film-forming passivation with pseudo-halides and customized TFT electronic circuitry for quantum-dot LEDs, realizing the first international microsecond-response active-matrix quantum dot display chip. The achievements have been commented as “marks an important step toward the practical applications and would be very insightful for following up work.”



Xinghui Li (Tsinghua University)



Biography: Prof. Xinghui Li is the Associate Professor at Shenzhen International Graduate School (SIGS), Tsinghua University, Shenzhen, China, where he leads the “Optical Precision Nanometrology” Group. Prof. Li received his Ph.D. degree in Nanomechanics from Tohoku University, Japan (2014), M. S. degree in Mechatronics Engineering from Xi’an Jiaotong University, China (2011), and B.S. degree in Mechanical Design, Manufacturing and its Automation from Wuhan University, China (2008). From 2014, Prof. Li worked as a postdoctoral fellow, Lecturer, Assistant Professor and Associate Professor in current institution.

Prof. Li is an innovative scientist with extensive experience on grating interferometry, grating lithography fabrication, spectrum analysis and chromatic sensing, imaging processing and 3D reconstruction. He has published more than 200 journal/conference papers in top international journals, including IEEE T-IP, IEEE T-CSVT, MINE, Journal of Mechanical Systems, International Journal of Extreme Manufacturing, Computers in Industry, etc, and attracting more than 3000 citation and an H-index 36. He has been granted by NSFC, Provincial Key Project, Outstanding Funding from National Postdoctoral Committee, etc. He has been selected as “World Top 2% Scientist” (2023–2025 single year, especially listed in Top 0.2% in 2025 in area of Optoelectronics & Photonics), awarded “Highly Cited Award”, “Outstanding Contribution Award” of Journal NMME, etc.

Title: Grating interferometer: The dominant positioning strategy in atomic and close-to- atomic scale manufacturing

Abstract: The rapid evolution of manufacturing technologies has entered its third phase, with a focus on atomic and close-to-atomic scale manufacturing (ACSM), a pivotal advancement driving progress in precision fabrication. One of the cores of ACSM is ultra-precise positioning technologies, which are critical for achieving the required precision and efficiency in nanoscale manufacturing. Grating interferometer has emerged as the leading strategy due to its accuracy, scalability, and stability. Recent advancements in this technology have further solidified its role as a dominant solution in ultra-precision metrology. This review provides an overview of grating interferometer as a positioning tool for ACSM, starting with its application domains and advantages, followed by a detailed explanation of its fundamental principles. We then present a comprehensive comparison of different representative grating interferometers. Additionally, we perform quantitative multi-source measurement error analysis, discuss methods for compensating errors, and explore various phase measurement techniques. Finally, we conclude with a forward-looking perspective on the future development of grating interferometer, highlighting emerging trends and potential breakthroughs.



04

TRANSPORTATION AND WEATHER

路线与天气





4.1 Transportation

1) From Wenzhou International Airport to Wenzhou Junting Hotel (Approx. 27 km)

(1) Taxi: Take a taxi from T1/T2 Terminal. Cost around RMB 60–80, journey time about 35 minutes.

(2) Light Rail S1 Line: Go down to B1 level inside the airport, follow signs for the S1 Light Rail line. Take the S1 light rail towards Tongling/Downtown/High-speed Rail South Station. Get off at Wenzhou South Station. Journey time about 45 minutes, fare approx. RMB 9.

(3) Airport Shuttle Bus: Take the Airport Express Bus Direct Line from T1/T2 Terminal to Wenzhou South Railway Station (operates 10:00–19:00). Journey time about 50 minutes.

2) From Wenzhou South Railway Station (High-Speed Rail Station) to Wenzhou Junting Hotel (Approx. 0.3 km) (Recommended to use East Exit)

(1) East Exit: Exit the station, walk straight ahead to the service counter, turn right to the overpass entrance. Walk along the overpass for 5–10 minutes directly to the hotel's second floor (Grand Hotel).

(2) West Exit: Head north for 90 meters, turn right and walk 50 meters, continue straight for 20 meters, descend into the underground passage, walk straight for 150 meters, continue straight, ascend the underground passage for 40 meters, turn right and walk 90 meters, turn left and walk 80 meters, cross the road and turn right, walk 320 meters, turn left front and walk 160 meters to reach Wenzhou Junting Hotel.



3) From Wenzhou Railway Station to Wenzhou Junting Hotel (Approx. 9.9 km)

(1) Taxi: Fare approx. RMB 30, journey time about 30 minutes.

(2) Bus: Take bus B102 from the "Huoche Wenzhou Zhan Guangchang" (Wenzhou Railway Station Plaza) stop. Get off at the "Wenzhou Da Xiang Cheng" (Wenzhou Elephant City) stop. Walk to the hotel via the overpass.

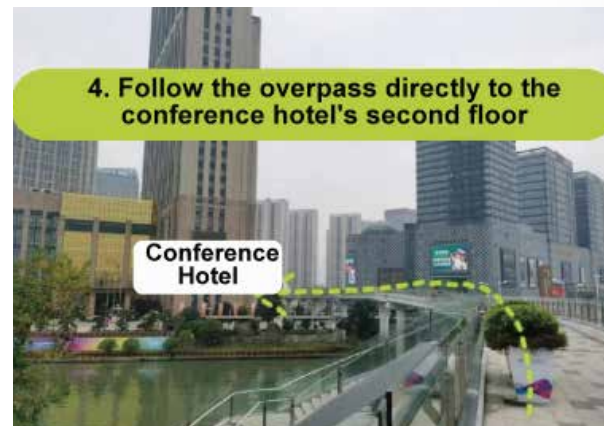
4) From Wenzhou North Station (Yongjia) to Wenzhou Junting Hotel (Approx. 22 km)

(1) Taxi: Fare approx. RMB 40, journey time about 35 minutes.

(2) Bus: Walk 2.1 km from Wenzhou North Station exit to the "Qianshi Cun" (Qianshi Village) stop. Take Yongjia Bus 60 to the "Shibajia Zhi Lukou (BRT)" stop. Transfer to B1 Bus. Get off at the "Huoche Nanzhan Gongjia Shuniu Zhan" (Wenzhou South Railway Station Public Transport Hub) stop. Walk 270 meters to Wenzhou Junting Hotel.

Note: Self-driving guests, please collect your free parking validation code at the Front Desk on the hotel's second floor.

Attached: Walking guide diagram from the East Exit (Recommended walking route)



Wenzhou Weather

Fri 24

Day

26°



14%
N 15 km/h

Partly cloudy. High 26°C. Winds N at 10 to 15 km/h.

Humidity
60%

UV Index
6 of 11

Sunrise
06:03

Sunset
17:20

Night

18°



34%
NNW 11 km/h

Showers. Low 18°C. Winds NNW at 10 to 15 km/h. Chance of rain 30%.

Humidity
75%

UV Index
0 of 11

Moonrise
08:22

Moonset
18:45

Waxing Crescent

Sat 25

Day

28°



19%
N 11 km/h

Mostly cloudy. High 28°C. Winds N at 10 to 15 km/h.

Humidity
62%

UV Index
5 of 11

Sunrise
06:03

Sunset
17:19

Night

19°



18%
NNW 9 km/h

Partly cloudy. Low 19°C. Winds light and variable.

Humidity
75%

UV Index
0 of 11

Moonrise
09:18

Moonset
19:30

Waxing Crescent

Sun 26

Day

27°



8%
N 12 km/h

Partly cloudy. High 27°C. Winds N at 10 to 15 km/h.

Humidity
57%

UV Index
6 of 11

Sunrise
06:04

Sunset
17:18

Night

17°



8%
NNW 10 km/h

Partly cloudy. Low 17°C. Winds light and variable.

Humidity
69%

UV Index
0 of 11

Moonrise
10:13

Moonset
20:19

Waxing Crescent

05

ATTACHMENTS

附录



ISNM



Springer

Nanomanufacturing and Metrology



Impact Factor **4.5**
Ranked Q1 in JCR 2024

The Journal of International Society of Nanomanufacturing (ISNM)

The First Impact Factor (2024): 4.5
Ranking:

16/79 Q1 Instruments & Instrumentation
25/71 Q2 Engineering Manufacturing

Scope includes but is not limited to

- Atomic and Close-to-Atomic Scale Manufacturing(ACSM)
- Atomic and Close-to-Atomic Scale Metrology
- Atomic Layer Deposition (ALD)
- Electrochemical Manufacturing
- Materials Characterization
- Precision & Ultra-Precision Manufacturing & Metrology
- Optical 3D Measurement
- Micro/Nano Manufacturing & Metrology
- Micro/Nano Electromechanical Systems (MEMS/NEMS)
- Semiconductor Processing & Metrology
- Laser-Based Manufacturing & Metrology
- Intelligent Manufacturing & Sensing
- Additive & Bio-Manufacturing
- Advanced Functional Surfaces & Characterization



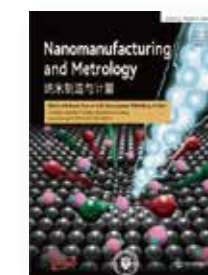
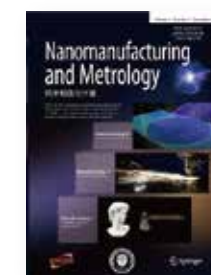
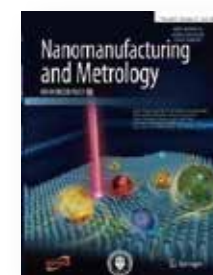
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Executive editor :
Prof. Wei Gao

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19th August 2024

Presidential Address at the 73rd CIRP General Assembly

New Era of Disruptive Development of Manufacturing Technology

Fengzhou Fang
(Thessaloniki, Greece)

Distinguished Guests, Ladies and Gentlemen, Dear Colleagues, and Friends,

It is with great pleasure that I welcome all of you to the 73rd CIRP General Assembly here in the beautiful city of Thessaloniki. It is truly an honor to stand before you today and witness such a gathering of distinguished individuals from academia and industry. Your presence demonstrates your commitment to the promotion of production engineering and manufacturing.

Your dedication and hard work in your respective fields are the cornerstones of our shared progress. Without your singular contributions, the advancements we celebrate today would not have been possible.

A special word of thanks goes to the government officers and the University President for their kind welcome addresses. Warm appreciation goes to our invited performance group, whose exceptional talent has considerably contributed to the vibrancy of our opening ceremony and set a wonderful tone for what promises to be an inspiring and fruitful assembly. Very importantly, I would like to thank our accompanying persons, whose support and understanding have given us the confidence to continue exploring our vision.

In the early 1980s, I began my career as a university academic. During that time, I often bit off more than I could chew and rather naively believed that I knew many things.

In the 1990s, I fortunately had the opportunity to join CIRP activities. I thank Professors G. Zhang, Z. Yuan, and V. Venkatesh for sponsoring me to join this unique academy.

At that point, I began to realize how little I actually knew.

Over the past three decades within CIRP, I have had the privilege of gaining a deeper understanding of this prestigious organization and getting to know you, my esteemed colleagues. I have come to the humbling realization that, in truth, “I know nothing.”

1. Enlightenment from Ancient Civilization

This humbling journey of discovery echoes the wisdom of ancient Greek philosophy. Socrates famously stated, “I know that I know nothing.” This profound insight has been a guiding principle in my life, forever reminding me of the importance of lifelong learning and humility.

Over 40 years of work, I have come to appreciate that my painstakingly-gathered insights were already understood by the ancient Greeks thousands of years ago. This revelation underscores the timeless brilliance of Greek wisdom and its enduring impact on our understanding of knowledge and growth.

Greece—a country known for its far-reaching contributions to philosophy, science, and arts—offers a unique blend of ancient heritage and modern innovation. Its geographical location at the crossroads of Europe, Asia, and Africa has made it a melting pot of cultures and ideas. Its rich history, dating back



millennia, is marked by the achievements of legendary figures such as Socrates, Plato, and Aristotle. The ancient Greeks pondered the mysteries of life and explored the nature of matter. As early as the 5th century BCE, Democritus identified the concept of the atom, envisioning the fundamental building blocks of the universe. This early atomic understanding was a remarkable leap in understanding the physical world.

Amazingly, in the same era, Laozi, the founder of Daoism, articulated a parallel notion from the eastern part of the globe. Laozi described “Dao” as something undifferentiated yet complete, existing before the universe and earth. His insights into the Dao emphasized its pervasive and unchanging nature, serving as the essence from which all existence emanates.

Western and Eastern philosophy from this era reflected a great reverence for the mysteries of existence and a deep understanding of the cosmos. Their concurrent explorations of the nature of matter reveal the timeless wisdom and intellectual curiosity of ancient civilizations. These philosophers also laid the groundwork for our thoughts, and their influence continues to resonate in the modern era.

We are privileged to host this assembly in the historic city of Thessaloniki, a city steeped in remarkable history and culture. As the city was introduced in the welcome address earlier, I will not discuss it again; however, I recommend that you explore the World Heritage Sites of the city and immerse yourselves in its historical and cultural treasures.

Nonetheless, we are honored to have this assembly hosted by the Aristotle University of Thessaloniki. I express my deepest gratitude to our local CIRP members and the organizing team for their outstanding efforts in organizing this event. Special thanks to our organizing chair, Professor Michailidis, and his wife for their exemplary leadership.

2. History and Tradition of CIRP

As we embark on this assembly, let us reflect on the history and traditions of CIRP. CIRP is a global network of leading researchers and industrial experts in production engineering. Our mission is to advance the science and practice of production engineering, fostering innovation and excellence in the field.

Established in Paris in 1951, CIRP has a rich history spanning over 7 decades. During this time, it has become a globally recognized, leading academy for its contributions to production engineering research and innovation. CIRP brings together experts from around the world, promoting international collaboration and knowledge exchange. This global network allows us to address complex challenges and drive progress. At present, we have 450 fellows and personal members, more than 170 corporate members, and 80 research affiliates.

Our commitment to excellence is reflected in our members’ rigorous scientific contributions. CIRP’s role in advancing production engineering is unparalleled, and we continue to set the international standard for research and development.

Over the past thirty years, I have been delighted to gain a profound understanding of this esteemed organization. In my opinion, CIRP transcends being merely an academy; in reality, it embodies a school in addition to a professional family.

As an academy, CIRP fosters and advances science and technology in production engineering. We provide leadership within the scientific community, setting standards and pushing the boundaries of innovative research. The pioneering work of our distinguished colleagues has made remarkable contributions to the field and will continue to lead the way.

As a school, we learn from each other and grow together. Here, we are all perpetual learners. I will continue to learn from each of you, gaining insights into technical expertise and innovative approaches. The notable figures, breakthrough research, and collaborations within CIRP have substantially influenced my personal and professional growth. This shared knowledge and constant learning are what



make CIRP a unique educational institution.

Most importantly, over time, I discovered that CIRP is more than a professional organization; it is very much a family. The companionship and support we offer our members is unique. This familial atmosphere fosters a sense of belonging and drives us to reach greater heights. We are united by our professional interests, mutual support, and friendship. This sense of community is a vital component of our shared humanity and is what makes CIRP truly unique.

I have a long list of colleagues and mentors who are leaders in production engineering research. I hold them in my thoughts now and will cherish their influence forever.

3. Progress Made in the Past Year

When we examine the central role of CIRP in manufacturing, we find that the organization is deeply committed to advancing production engineering through pioneering research and innovation. CIRP is at the forefront of driving scientific excellence in our field. Our research initiatives have discovered breakthroughs in efficiency, quality, and sustainability in production processes.

Moreover, we serve as a crucial bridge between academia and industry, facilitating collaboration and knowledge exchange to drive industrial progress. The impact of CIRP extends beyond mere academic inquiry. We are a catalyst for change, driving the adoption of new technologies and methodologies in this industry. By bridging the gap between research and application, CIRP ensures that scientific advancements translate into tangible benefits for society. Our collaborative approach collates experts from various disciplines, fostering the cross-pollination of ideas and accelerating the development of innovative solutions.

In the past year, CIRP has made remarkable progress. One of our major accomplishments has been the establishment of the CIRP School, which nurtures the next generation of manufacturing leaders. By providing a platform for nurturing young talent, we can ensure a secure future for our academy. On behalf of the Council, I thank Dr. Balsamo and the team for their dedicated efforts.

In 2017, CIRP launched the first edition of its comprehensive curriculum, setting a benchmark for excellent manufacturing research. This year, in response to the rapid advances in science and technology, we introduce the second edition. This updated edition reflects our commitment to staying at the cutting edge of research and innovation. I extend my heartfelt gratitude to Professors Gao and Anwer and their team for bringing this vision to fruition.

Publications are always important in our academy. The Council has assigned a Publication Working Group to further develop CIRP publications; progress updates will follow in due course. We deeply appreciate Professor Denkena and the team for their outstanding discoveries. Thanks to the leadership of Professor Tollio, the CIRP Novel Topics Editorial Committee also published the first volume of the CIRP Novel Topics in Production Engineering early this year.

Throughout the past year, we have conducted several CIRP conferences, each advancing our collective knowledge. These conferences have facilitated the exchange of ideas, thereby fostering innovation and collaboration. The conferences were well-organized, and the presentations were of high quality. On behalf of the Council, I appreciate all the organizing committees and participants for their tremendous efforts, which turned all these events into great successes.

4. New Paradigm of Manufacturing Advancement

Today, we stand at the forefront of a technological revolution that is reshaping the landscape of manufacturing. Advances in sustainable, digital, and additive manufacturing—as well as in biomanufacturing, space manufacturing, and manufacturing ethics—are not only transforming how we manufacture but also redefining what is possible. These innovations improve productivity and lay the foundation for a future where manufacturing is more smart, flexible, and sustainable than ever before.



Moving forward, we envision a future shaped by technologies that push the boundaries of what is possible. Smart manufacturing, powered by artificial intelligence, considerably optimizes decision-making processes and streamlines production workflows. Artificial intelligence will have a notable influence on every aspect of our daily lives and industrial development. We explore quantum computing and quantum technology in manufacturing, and this unparalleled computational power translates to faster simulations, optimized processes, and accelerated research and development cycles.

Concerning new horizons, the future promises a shift toward a new paradigm of manufacturing advancement, namely, Manufacturing III. Manipulating matter at the atomic scale enhances manufacturing precision, decreases the minimum functional features, and opens doors to entirely new materials, functionality, and performance. This capability is poised to revolutionize industries, potentially paving the way for extending the frontiers of discovery and applications.

As we stand at the intersection of these transformative technologies, we are witnessing the dawn of a new manufacturing era.

I wish all of you highly successful meetings; may you engage in enriching research exchanges, enjoy meaningful dialogue, and forge many new connections that will drive our field forward.

With great pleasure and anticipation, I hereby declare the 73rd CIRP General Assembly officially open.

Thank you!

Fengzhou Fang

President (2023-2024)
International Academy for Production Engineering (CIRP)



On the Three Paradigms of Manufacturing Advancement

Fengzhou Fang^{1,2}

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Dear young scientists

Good morning! Before we begin our discussions, I would like to share my thoughts regarding the three paradigms of manufacturing advancement.

Since my college days and even earlier, I have been fascinated by the concept of a “salon”, a gathering of like-minded people. My interest was rooted in my impression of the Copenhagen group, which organized a salon that allowed everyone to freely express their thoughts on a particular topic. The last two days of our forum mainly focused on presentations, and each presentation was excellent. The success of this forum was owed to the outstanding achievements of our young scientists, and we extend our special thanks to the China Association for Science and Technology for providing this platform. Today, however, we aim to return to the original spirit of the salon, that is, the free discussion of everyone’s ideas. I hope that we can regularly organize such activities in the future and everyone is happy to freely express themselves and share their views.

The theme of today’s salon is “atomic and close-to-atomic scale manufacturing (ACSM)”. The idea of ACSM can be traced back to the end of 2011 and the beginning of 2012 when the concept of “Industry 4.0” was proposed in Germany. Around that time, a German friend of mine

inquired, “What do you think of Industry 4.0, or how do you understand Industry 4.0?” Back then, I was unfamiliar with the context of Industry 4.0, and thus, it started piquing my attention. I aimed to gain insights into the background and further comprehend the third, second, and first industrial revolutions. I spent most of my time perusing related books and articles to understand Industry 4.0. As my understanding of this new stage of industry development deepened, I discovered the inherent laws of manufacturing advancement.

Let me explain the evolution of core components in computers as an example. Everyone has witnessed a visible change from early vacuum tubes to transistors to the chips we use today. The most tangible experience initially transpired with radios: the radios I saw when I was young were massive and only had simple functions. They could broadcast a few stations but had a lot of noise because their main components consisted of bulky vacuum tubes. The vacuum tube was considered the core industrial component at that time. However, another type of component, the transistor, emerged immediately afterward. For convenience, we consider vacuum tubes and transistors as the first- and second-generation core components, respectively. The invention of the transistor led to the production of smaller radios with substantially improved performance. The additional functions prompted everyone to start using transistor radios. Similarly, vacuum tubes became rare in the industry, and transistors have been widely utilized. Afterward, third-generation components consisting of integrated circuits or chips emerged.

The current core components include chips, and based on previous experiences, we can expect the fourth generation to emerge. What should this next generation of core components be, and can we start researching them now? I began reading relevant literature and consulted scientists in physics, chemistry, and biology. Despite the different perspectives on various fields, these inquiries implied the existing debate regarding the next generation of core components. However, their realization will require novel manufacturing processes. A conclusion reached at that time was the

guaranteed involvement of ACSM for the next generation of core components.

Another example is the continuous upgrading of processing technology. After working as a university academic in 1982, I assisted students in their factory internships, where we practiced production in the workshop daily. In those days, the precision of workpieces made by experienced craftsmen was approximately a few tens of micrometers. Later, it improved to roughly a dozen micrometers and later to micrometer and submicrometer levels. Their constant improvement finally led to the current precision reaching the single-digit nanometer level. Manufacturing technology has been continuously developing, and to date, the terms “micro/nano manufacturing” or “nanomanufacturing” are often used. However, the basic theory and its foundation remain unchanged. Another advancement from the nanometer scale will inevitably lead to the scale of “atoms” where classic theories are no longer completely applicable. At this scale, the discrete and quantum nature of atoms will affect the features being produced, and therefore, the fundamentals must be different. Thus, from a theoretical perspective, the foundations of precision or ultraprecision manufacturing are the same, but in ACSM, a different foundation is required. Therefore, given the development of manufacturing technology, the “foundation” of precision and ultraprecision manufacturing is essentially different from that of ACSM.

Although I used chips as an example of a typical product, I want to avoid creating a misconception that only chips require ACSM. Often, science and technology lead the way and drive the demand. For example, scanning tunneling microscopy drove the development of nanotechnology, and the emergence of graphene induced the rapid growth of low-dimensional materials. In the history of technology development, the emergence of cutting-edge capabilities laid the path for previously unthinkable applications. To date, an increasingly higher number of fields require ACSM technology. A few years ago, this demand was thought to still be in the distant future, and I assumed that the market might gradually emerge after tens of years. Instead, the reality has far exceeded our expectations. Applications of ACSM in various fields have recently emerged. Thus, our imagination lags behind the pace of technology, and a new era is possibly about to begin. Hence, one must keep an open mind when ACSM is discussed.

Manufacturing development follows certain rules and often follows a distinct pathway. We first need to understand what manufacturing is before clarifying this pathway. This term is ubiquitous in our daily lives and undoubtedly important. Manufacturing refers to the entire production process from raw materials to the final products. Two key factors must be considered when discussing manufacturing: functionality and performance. First, the functionality of the product needs to be determined. Whether it is a

computer or a car, its function is specified. Next, performance requirements must be identified, which are ensured through precision, feature structure, and material performance. Interpreting manufacturing at the atomic and close-to-atomic scale (ACS) only regarding precision or feature size will not be sufficiently comprehensive. ACSM encompasses these aspects but includes the dimensions of material removal, migration, and addition and the damage caused by manufacturing to surfaces and interfaces. Only when these requirements are met can ACSM be considered a complete manufacturing process. For example, when discussing manufacturing at ACS, some may argue that atomic manufacturing already exists and that IBM could move atoms using probes long ago. However, is this atomic-level manipulation considered manufacturing? Similarly, discussions on atomic-level processes have been ongoing in materials and chemistry for a long time, but are they about manufacturing? Reflection on these concepts will be beneficial for clarifying manufacturing technologies. In the new field of manufacturing at ACS, “materials” refers to the basic building blocks of matter, namely, atoms. Thus, manufacturing and material fabrication have already naturally merged in this new field.

History reveals that the development of modern manufacturing had a specific jump-off point in time, namely, during the First Industrial Revolution in the 1760s. However, manufacturing existed before then and was not a novel concept. Some people may assume that manufacturing has always existed and therefore fail to grasp the importance of studying its concept. Given its long history and the fact that manufacturing back then was different from modern manufacturing, clarification is necessary to determine how these manufacturing types vary. Manufacturing before the Industrial Revolution was based on personal experience and skills, and the products made were, to some extent, works of art. For illustration, let us consider the machines designed by Leonardo da Vinci. From today’s perspective, Leonardo’s works are still considered sophisticated machines. Leonardo’s creations were unique, but others might not be able to create the same. Similarly, Michelangelo’s statue of David is a work that only an artist can create. Thus, the statue was an artistic stage, and we categorized it as the first stage of manufacturing advancement. Afterward, machines were introduced and allowed the replication of objects. One person can reproduce the creation of another individual. At this point, manufacturing was considered technology. In line with the development of other related technologies, the manufacturing accuracy increased from classical manufacturing to precision manufacturing and finally to nanomanufacturing. However, regardless of the extent of improvement, manufacturing is still based on a quantitative change, and the basic theory did not undergo fundamental changes. Yet, moving forward from nanomanufacturing, the core fundamental theory changes.

Fengzhou Fang, the Editor-in-Chief of Nanomanufacturing and Metrology, delivered the keynote speech at the Young Scientists Salon on “Atomic and Close-to-atomic Scale Manufacturing” held in Chengdu on December 3–5, 2021. Below is an English language translation of the speech originally published in the Journal of Tianjin University (Science and Technology) [1]. Permission was granted by Tianjin University.

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Following all considerations outlined thus far, manufacturing technologies can be divided into three different stages: the early phase (“artistic”, Manufacturing I), the second stage where the classical theory applies (Manufacturing II), and finally, a new era where the classical theory breaks down and quantum physics emerges (Manufacturing III). However, the three manufacturing phases are not replacements for each other but coexist in the modern age. In other words, manufacturing advancement has three paradigms, each with its enormous application areas. For example, when it comes to the third stage, the second stage, including digital, intelligent, and additive manufacturing, as well as characterization and testing, is still in use parallel to and in support of the new stage, with each relying on its own fundamental theory. Given the relationship between “1” and “0” to understand the manufacturing of products, here, “1” can represent the core consideration of production, which includes meeting the precision of its function and performance, structural dimensions, removal, migration, and addition of materials. “0” denotes the consideration of product improvement, for example, through digital, intelligent, and sustainable manufacturing, to control costs and increase efficiency while still achieving the core function and performance of a product. However, if “1” is not met, regardless of how often “0” is achieved, the product will remain unqualified, which implies the lack of a complete manufacturing process. As a result, the connotation of the manufacturing paradigms is clarified, and “atomic and atomic-to-atomic scale manufacturing” in “Manufacturing III” is the new field that takes on the role of “1”. We refer to it as the fundamental technology of “Manufacturing III”.

The second manufacturing stage involves the so-called Fourth Industrial Revolution or Industry 4.0. However, considering the “core foundation”, the concepts remained the same. ACSM is the core of “Manufacturing III” and based on radically different principles of physics and engineering, it represents a groundbreaking point in manufacturing and, as such, an actual revolution.

Finally, with this new manufacturing paradigm, will all future products be made at the atomic scale? The answer is not necessary. Notably, although the three manufacturing paradigms will continue to coexist until a considerable period in the foreseeable future, “Manufacturing II” will still

play a dominant role. However, the demands for high-performance large-scale scientific projects and the next generation of chips will certainly rely on “Manufacturing III”.

In conclusion, we have discussed the background behind the three paradigms of manufacturing advancement and the concept of ACSM. This discussion with young scientists at this salon has been a great pleasure, and I hope that future forums will contribute to clarifying our thoughts.

Author Contributions The author read and approved the final manuscript.

Declaration

Competing Interests This article is an English language translation of the keynote speech originally published in the Journal of Tianjin University (Science and Technology). Permission was granted by Tianjin University. The author declares no competing interests.

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Editorial

Atomic and close-to-atomic scale manufacturing: perspectives and measures

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Abstract

This article presents the three paradigms of manufacturing advancement: Manufacturing I, craft-based manufacturing by hand, as in the Stone, Bronze, and Iron Ages, in which manufacturing precision was at the millimeter scale; Manufacturing II, precision-controllable manufacturing using machinery whereby the scales of material removal, migration, and addition were reduced from millimeters to micrometers and even nanometers; and Manufacturing III, manufacturing objectives and processes are directly focused on atoms, spanning the macro through the micro- to the nanoscale, whereby manufacturing is based on removal, migration, and addition at the atomic scale, namely, atomic and close-to-atomic scale manufacturing (ACSM). A typical characteristic of ACSM is that energy directly impacts the atom to be removed, migrated, and added. ACSM, as the next generation of manufacturing technology, will be employed to build atomic-scale features for required functions and performance with the capacity of mass production. It will be the leading development trend in manufacturing technology and will play a significant role in the manufacture of high-end components and future products.

Keywords: atomic and close-to-atomic scale, ACSM, manufacturing III, development trend

1. Background and significance

1.1. Historical development of manufacturing

Throughout history, no revolution was possible without technical innovation; and the advancement of developed countries is inseparable from industrial transformation. Manufacturing is the core of industrial production, while the products that are made meet the material and spiritual needs of humans. Manufacturing is defined as the entire process of making products from raw materials that satisfy the users' demands, and the key is to obtain the required performance and fulfill the usage requirement of the products. Significant progress can be made only if people grasp the law of manufacturing technology development and take the lead in future development trends. History of mankind has been accompanied by the development of manufacturing, while the history of



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Figure 1. The three phases of manufacturing development.

manufacturing consists of the following three main phases, according to its precision and inherent law of development as shown in figure 1 [1].

Manufacturing I: Craft-based manufacturing by hand, as in the Stone, Bronze, and Iron Ages, in which manufacturing precision is at the millimeter scale.

As early as the Stone Age, mankind made living supplies with stone tools [2, 3]. By the Bronze and Iron Ages, people began to develop tools for mining, smelting, and casting to meet the demands of the agricultural economy and to make textile machinery, hydraulic machinery, and transport vehicles, etc [4, 5]. People have been crafting tools and other products in primitive workshops for a long period of time. Gradually, the means of production was conventionalized, and simple division of labor was formed. This was the first development phase of manufacturing technology, i.e. Manufacturing I, which was a handcraft art. The manufacturing precision was determined by experience and was at the millimeter scale. Mass and repeatable production was not possible in this ‘manufacturing’ phase.

Manufacturing II: Precision-controllable manufacturing using machinery whereby the material removal, migration, and addition scales were reduced from millimeters to micrometers and even nanometers.

Manufacturing technology advanced continually with the progress of industrialization. Basic manufacturing theory was based on classical mechanics, formed progressively, and improved from time to time. The minimum material to be removed in contemporary machining has been reduced from millimeters to micrometers and even nanometers [6]. In the late 18th century, the industrial revolution, represented by the successful development of the Watt steam engine technology and tooling machines, propelled machinery to replace manual labor. The combination of mechanical technology and steam engines spawned modern manufacturing methods, which drove social transformation from agricultural and handcraft to industrialization and mechanically driven manufacturing.

The saying, ‘The sun never sets on the British Empire,’ was formed because the UK pioneered this industrial revolution [7]; and it quickly developed in Europe at the same time. The appearance of the first modern production line in Cincinnati’s slaughterhouse in 1870 marked the introduction of automatic technology; and another great change in industry was achieved by production models that used electrification, assembly lines, and mass production. America soared to a superpower as it seized the opportunities that manifested during this period of time [8].

The programmable logic controller was invented in the 1960s, and the mechanical equipment used by information technology and automation control stood in the limelight of industrial production. Asian countries, e.g. Japan and South Korea, recovered quickly following World War II and joined the ranks of developed countries [9]. Today, industrial nations are exploring ‘Industry 4.0,’

which is mainly focused on the creation of ‘cyber-physical systems’ [10]. The real world is closely connected by a sensor network, which acquires and analyzes data related to design, development, and manufacturing and hence realizes the intelligent management and production for the life cycle of products and facilities. In general, although mankind has experienced several industrial revolutions in this phase, the fundamental theory of manufacturing and production is based on classical theories. They are collectively referred to as ‘Manufacturing II.’

Manufacturing III: Manufacturing objectives and processes directly focused on atoms, spanning the macro- through the micro- to the nanoscale whereby manufacturing is based on removal, migration, and addition at the atomic scale, namely, atomic and close-to-atomic scale manufacturing

One of the main elements of manufacturing is machining. When machining is scaled down from the micro/nano to the atomic level, the phenomena of material removal, migration, and addition at the atomic scale can no longer be explained by classical theories. Contemporary manufacturing technology that is characterized by classical theories, i.e. macro statistical analysis and engineering experiences, will be pushed forward to the next generation of manufacturing technology, which will be multidisciplinary and based on quantum theory. This type of atomic and close-to-atomic scale manufacturing (ACSM) is known as ‘Manufacturing III’ [11–14]. The essential attribute of Manufacturing III is distinguished from Manufacturing II by its theoretical fundamentals, in which quantum theory dominates [14, 15].

The presented differentiator between Manufacturing III and Manufacturing II has seemed the scaling difference, whereby the manufacturing precision is down to the atomic scale. However, the fundamental difference is that Manufacturing III will be built on quantum theory. Classifying a system if it is governed by classic theory or quantum theory is determined by the relationship between the de Broglie Wavelength and the system scale or the distance between the particles. If the de Broglie Wavelength is larger than the system scale or the distance between the particles, it is recognized as a quantum system. It is not sufficient if we judge a classic or quantum system by only considering the system scale. In short, there will be a process from quantitative to qualitative changes for manufacturing technology.

Manufacturing III will not replace Manufacturing I and II, but the three paradigms will exist in parallel.

1.2. Significant needs of development in science and technology

Manufacturing is the foundation of social, economic, and productive force development. Currently, there appears to be an understanding that everything is possible once people have microchips, networks, and software. Admittedly, they are important. However, microchips need to be manufactured, while high-end microchips rely on high-end manufacturing, in which high-precision lithography is the core. Microchips, networks, and software only deal with the processing (including computing), storage, and transmission of information (including data). The acquisition of information depends on sensors and various sensing devices. Without precision sensors, achieving artificial intelligence, precision navigation, and other high-end products is an empty promise. Precision actuators are also required to perform precise motion.

The further development of the current manufacturing fundamentals and technologies is facing great difficulties, while great challenges and insurmountable gaps have been brought to existing manufacturing methods that regard processing objects as continuous materials. These challenges include:

- Whether distributed nodes can continually increase density on microchips according to Moore's law.
- Development of new materials is restricted by the existing manufacturing capabilities and, consequently, restricted by the design freedom.
- The current microsystems manufacturing platform is gradually showing its insufficiency, as it cannot meet the needs of disruptive upgrade and iteration with complexification and intellectualization.

High-precision manufacturing plays a key role in the development of future technologies with high productivity. Take chips for example. To achieve high precision, manufacturing and motion control technologies are required at the nanometer level, even at the atomic and close-to-atomic scale. The advancement of science and technology has become more and more dependent on multidisciplinary development in this era of rapid change. ACSM is the cutting edge manufacturing technology in which energy is directly applied to atoms. Specific function and performance is implemented by creating atomic-scale structures, and mass production will be realized to meet the demands. It is the leading development trend of the next generation of manufacturing technology for breaking the aforementioned bottlenecks and is of great significance to future technological advancement and high-end component manufacturing [16].

Whether the next generation of core elements will be phonics chips, quantum chips, or other revolutionary components that are not yet foreseen, the need for future manufacturing technologies is inevitable once a product is launched. As the representative of the next generation of manufacturing technology, the launching, planning, and implementation of ACSM will play an important role in supporting worldwide development in science and technology and will help each individual country to seize the opportunity of developing their own manufacturing capability.

1.3. Research status

ACSM is a new field, some researchers and research organizations have already started to carry out investigations. The Defense Advanced Research Projects Agency (DARPA) in the U.S. launched the Atoms-to-Product (A2P) research program in 2014, aimed at developing methods of manufacturing by assembly that enable manufactured large-scale materials, components, and systems to retain the properties of nanomaterials [17, 18]. To solve the problem of reliability caused by the long-term interaction between electronic products and the environment, research was conducted on 'from atom to product reliability', targeted at reducing the impact of the interaction on system reliability at the atomic level [19].

In 2016, researchers from the Chinese Academy of Engineering Physics elaborated on the significance of atomic manufacturing by combining it with the constrained integrated microsystem [20]. In 2018, scientists from the University of Alberta explored how to apply machine learning in atomic manufacturing, providing solutions to promote the development of atomic-scale, low-power electronics, which is expected to make their mass production possible [21]. In 2019, Huawei established the Strategic Research Institute to officially designate atomic manufacturing as one of its key research directions, aiming to push the limits of Moore's law further by using atomic manufacturing technologies [22]. Nanjing University established an innovative research center for atomic manufacturing in 2018 [23]. Their research includes the development of a new generation of atomic clusters, two-dimensional atomic-layer crystals, and materials and devices for atomic machines.

Relevant research activities and progress were comprehensively reviewed in reference [14]. It should be noted that the foregoing 'atomic manufacturing' research is focused on the frontier of condensed matter physics. It is about the

development and design of new atomic clusters or low-dimensional functional materials whose core may be different from that in manufacturing. Manufacturing is about the entire process chain of making raw materials into products that meet users' expectations, and the key is to obtain performance (including accuracy) that satisfies end users. ACSM refers to all of the necessary steps in transforming raw materials or components into qualified products, in which manufacturing objects and processes are directly focused on atoms, spanning the macro- through the micro- to the nanoscale and whereby manufacturing is based on removal, migration, and addition at the atomic scale. ACSM aims to obtain components, devices, and systems with their expected functions through manipulation at the atomic scale. It is a real functional customization, i.e. directly manipulating atoms based on the desired functions and surmounting the limitations of existing material characteristics to achieve the expected functions deterministically.

2. Main content

2.1. Scientific value

The advancement of scientific theories and technologies is driven by questions and needs. For example, classical physics failed to explain how high velocity objects (approaching the speed of light) and the microscopic world work, leading to the creation of relativity theory and quantum mechanics, which revolutionizes mankind's understanding of the world and directly affects productivity.

Taking conventional manufacturing as another example, Ernst and Merchant put forward the classic shearing model in metal cutting as early as the 1940 s to describe the macroscopic cutting process [24]. With further expectations for precision and surface quality, ultraprecision machining was proposed to achieve material removal at the micron, and even the nanometer, level. The reduction of the removal scale has changed material deformation behavior, resulting in the failure of the classical shear model. The cutting mechanism was found to be dominated by extrusion once the material removal is down to the nanometer level [25]. In the same way, brittle materials cannot be machined by conventional cutting due to serious surface fractures and cracks; but the theoretical studies show that these materials would show plastic behavior at the nanometer scale, which provides the possibility of machining brittle crystals using nanometric machining. In another typical subtractive process, lithography has always faced the challenge of decreasing linewidth and extending Moore's law. The limitation in size has changed 1000 times in 40 years from 5 μm to 5 nm, approaching 3 nm. A series of technical innovations and breakthroughs have been made during this evolution [26], such as the development of large numerical aperture lenses, a decrease of the light source wavelength down to 13.5 nm [27], immersive lithography, and atomic layer deposition (ALD) and atomic layer etching (ALE) technologies [28].

The microchip is one of the core components that could reflect the manufacturing level. It is increasingly difficult to reduce the linewidth by optimizing the existing integrated circuit (IC) process. The feature size has reached dozens of angstroms, indicating that microchip development has approached the physical limit [29]. There will definitely be a new generation of core devices, and the manufacturing technologies of achieving the new generation of devices will be at the atomic scale. ACSM will become a leading driver of manufacturing theory and technology, just as handcrafted art played an important role in Manufacturing I and classic theory is playing a critical role in Manufacturing II. For ACSM, the processes, precision, and functional features are all at the atomic scale, in which the dispersion of matter causes the manufacturing processes to be directly influenced by the quantum effect. This is

the fundamental difference between Manufacturing III and Manufacturing I and II, as the basic theoretical system of ACSM is based on quantum theory.

ACSM breaks the explicit boundary of the three modes of addition, migration, and subtraction of materials in existing manufacturing processes and leads directly to a monatomic process in extreme situations. The basic process includes bottom-up atomic assembling, top-down atomic removal, and regulation of the electronic state, such as formation and breakage of chemical bonds. Therefore, the theoretical framework of ACSM is completely different from that of existing manufacturing processes. ACSM is not based on principles such as stress/strain, chemical equations, or traditional optics but is determined by quantum theory. Starting from the basic physical and chemical laws, ACSM redefines the concepts of manufacturing limits and precision at the atomic scale, deriving a series of new principles and technologies.

For instance, unlike existing manufacturing where energy acts on a surface of bulk material, atomic manipulation in ACSM requires energy to act directly on a single atom or cluster of atoms, and hence an extremely high spatial resolution is required in the energy field. This principle is based on the interaction mechanism between atoms and the substrate material, where the quantum effect is dominant. For manufacturing equipment, the current ultraprecision machine tools [30] and lithography machines can realize the final manufacturing precision through the precise control of macroscale objects or energy beams. ACSM processes at the atomic level may lead to an upsurge in research on machines from microscale to atomic scale.

Because of the difference between the interaction and macroscopic force, the traditional mechanical design approaches will be replaced by new schemes; and even the functional parts (or components), such as spindles and slideways, might be constructed by macromolecular chains or atomic clusters. Atomic measurements may be achieved by some existing methods, e.g. atomic force microscope, transmission electron microscope, and scanning tunneling microscope; but the measurement concept can be different in ACSM. On one hand, energy beams in some measuring instruments have already been used for processing [31]; on the other hand, the quantum characteristics of ACSM introduce the possibility that the object being measured may be affected by the measurement process, which appears to not be critical in current manufacturing. In quantum theory, measurement is broadly understood as the interaction of microscopic particles with classical objects [32]. It will both impact and affect the microscopic system, which should probably be a new feature of measurement in ACSM. In Manufacturing III, the intersectionality of ACSM in multiple fields will be more significant; and the realization of precision and performance at the atomic scale must be integrated with frontier achievements from various areas of natural science and technology.

ACSM will provide strong support for physical, chemical, and biological research and development in the microcosmic world, such as constructing more complex artificial materials, precisely controlling chemical reactions, and regulating gene fragments accurately. In 1959, the physicist, Richard Feynman, stated that, 'There's plenty of room at the bottom,' which opened a new chapter called the Nano Age. So far, some relevant devices at the atomic scale have been developed, such as molecular circuits and molecular machines [33]. As the leading technology of next-generation manufacturing, ACSM needs to learn from these devices but, more importantly, needs to develop a complete set of solutions in atomic and close-to-atomic scale from raw materials to final products that meet users' requirements. These solutions should primarily satisfy the requirements of performance, including precision, and also meet the industrial demands of high efficiency, repeatability, and cost performance.

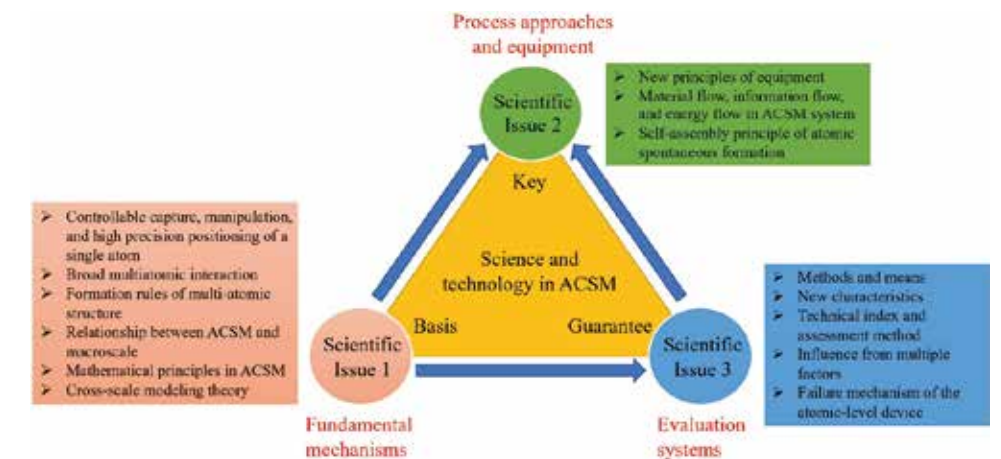


Figure 2. Main scientific and technological issues.

2.2. Main scientific and technological issues

ACSM includes all of the steps necessary to transform the original materials or components into products that meet the users' needs, which involves not only atomic precision but also the manufacturing processes of removal, migration, and addition at the atomic scale. Comprehensive ACSM studies should systematically address the three types of common scientific issues in manufacturing at the atomic and close-to-atomic scales related to its fundamental mechanisms, process approaches, and evaluation systems, as shown in figure 2.

Scientific Issue 1: Principles of manipulating a single atom, the interaction mechanism of multiple atoms, and the relationship between ACSM and contemporary manufacturing.

The key to further development of ACSM lies in understanding the intrinsic mechanism of ACSM. When the object to be manufactured is at the atomic scale, traditional macroscopic processing theories cannot accurately describe and predict the mechanism of atomic removal, migration, or addition. More innovative studies on mechanisms are in great demand. Following the idea from fundamental research to application development, scientific issues in the intrinsic mechanism can be divided into monoatomic manipulation, multiatomic interaction, and multiscale coupling theory. As the new generation of manufacturing technology, ACSM will push manufacturing precision towards the atomic scale. The structure precision and reliability of each basic unit in ACSM are determined by the capture, controllable manipulation, and high precision positioning of a single atom, which directly affects the final performance.

Therefore, one aspect in ACSM mechanism research is to understand and learn the basic rules of manipulating a single atom, including the overall process of capturing, moving, and positioning of an atom. It means that the single atom needs to be captured stably, then migrated and positioned with high precision, and finally placed at a specified position of an atomic-level device. In this way, the fabrication accuracy of ACSM can be guaranteed to the atomic scale. Particle manipulation and its related technologies are less involved in other disciplines, hence new theories and methods are of significant need.

In ACSM, atomic-level operation is needed to build single-atom or multiatom structures, realizing the ultimate function of atomic-level devices. Therefore, the second aspect in the mechanism study of ACSM lies in understanding the broad multiatomic interaction, the formation rules of multiatomic structures, and the mechanism and degree of the influence on the performance of atomic devices. This issue is key for ACSM, from fundamental theories to applied technologies.

In real physical space, both single and multiatomic structures interact with other atoms, i.e. there are one or more kinds of interactions existing in a wide range. At the macroscopic scale, objects are always subjected to gravitational forces, which can be described by Newtonian mechanics. However, the universal effects are not clear at the atomic and close-to-atomic scales. Equipped with the latest achievements in quantum theory, ACSM is expected to provide possible answers and experimental verifications for such effects. Further exploration of this issue will reveal the formation law of multiatomic structures and improve the final performance of atomic devices.

The third aspect of the mechanism study is to understand the relationship between atomic scale and the macroscale, including predicting the performance of ACSM functional devices in the macroscale. This is an important scientific issue to expand the application scope and ensure the performance of ACSM products. The macroscopic action of the device can be interpreted as the unified average performance of a large number of atoms acting simultaneously. For example, by calculating the motion of a large number of molecules, macroscopic parameters, such as the cutting force of material removal, can be predicted in molecular dynamics. There is a high degree of internal unification between the ACSM process and device performance because atoms are the common fundamental unit of both macroscale interaction and ACSM. Based on the mathematical description of atoms, the key to cross-scale research is to establish the ACSM mathematical system, e.g. creating multiscale physical and mathematical models, which is an important step in quantifying ACSM.

Scientific Issue 2: Energy directly acts on atomic basic manufacturing units

To realize ACSM, the scientific issues in the processing technique and equipment have to be solved. The ACSM manufacturing methods can be summarized as atomic removal, addition, and migration, together with other new means of manufacturing. Compared with the scientific issues in the mechanism study, this issue is the basis for the development of a large-scale, high-efficiency ACSM process. Current atomic-level processing approaches are either inefficient or have poor positioning accuracy. For example, the scanning tunneling microscope (STM) technique can manipulate one or several atoms at a time; but it is inefficient in mass production directly at the atomic scale. ALD and ALE can deposit or remove materials with atomic-layer resolution, but they are challenging when selectively depositing or removing the atoms at the position of interest. The critical scientific issue of improving efficiency and accuracy is how to apply required energy directly to a single atom or basic units of multiple atoms. For instance, the development principles of ACSM equipment need to be studied to form a manufacturing system; and the manufacturing activities need to be conducted at the scale of atomic devices. The core of this aspect is to understand and learn the movement of material flow, information flow, and energy flow in an ACSM system and to explore how to establish a universal multidimensional manufacturing system. Interatomic forces in ACSM cannot be ignored. It is important to understand and utilize the interatomic forces to study the self-assembly principle of atomic spontaneous formation of functional devices and develop both general and customized ACSM methods and equipment.

Scientific Issue 3: New characteristics of evaluation and measurements at the atomic and close-to-atomic scales

An ACSM measurement and evaluation system is another important issue to ensure the performance and reliability of ACSM products. At the atomic and close-to-atomic scales, structures in the atomic devices are maintained only by interatomic forces, which means the influence of measurement on the device should be as small as possible. The important scientific issues in the measurement

include understanding the mechanism of influence and establishing the low-influence measurement theory that meets the requirements of ACSM.

Based on improving the measurement theory, the establishment of the evaluation system will make ACSM more standard, reliable, and efficient. The evaluation system of current manufacturing is established on the basis of macro-unified indicators of collective atoms. However, the basic units having a single atom or multiatoms in ACSM have a significant impact on the final performance of the devices; and the failure mechanism of the atomic-level devices is greatly different from that of the macrodevices. Therefore, the ACSM evaluation system needs a new theory and method to support. It is a significant scientific issue to establish an evaluation system to determine the effect of different processes and manufacturing parameters on performance. The critical scientific exploration in the evaluation system will be relevant to the influence principles on the final performance of atomic devices from different ACSM processing methods and parameters.

2.3. Main objectives and content

The overall target is to implement a complete and systematic ACSM process. This manufacturing process can be employed to take the necessary steps for converting original materials or components into atomic-level, functional components or products that meet users' requirements and ensure atomic-level precision and performance throughout the process. This requires tremendous innovation and breakthroughs in all aspects, including fundamentals, process methods, equipment, testing, and evaluation system. The establishment of the basic theory system based on atomic theory is the primary goal and necessary condition for the development of ACSM. Because the manufacturing activity is at the atomic and close-to-atomic scales, which is different from the current manufacturing theory, innovative study of ACSM fundamental theory is required. Enriching and improving the large-scale, highly efficient, and highly precise process is the main target of ACSM development. The new ACSM process needs the energy to directly act on atoms to establish a multidimensional manufacturing system with certain versatility. Under the action of interatomic forces, the atoms can spontaneously form specific functional structures to achieve large-scale, highly efficient, and highly precise manufacturing. The establishment of measurement and evaluation systems is an important means of determining whether it meets the requirements. The high-precision measurement method is the premise for ensuring the performance and reliability of ACSM products. The establishment of the evaluation system can make ACSM more standard, reliable, and efficient. The ultimate goal of ACSM is to lead the manufacturing sector entirely into Manufacturing III. This requires establishment of a new paradigm in the manufacturing field created from the common problems encountered in the studies of fundamental mechanisms, process methods, equipment, measurement and evaluation systems, and the related classical concepts. Figure 3 is a framework of the main content in ACSM that integrates scientific and technological values, issues, and main goals.

3. Significant needs

As the future manufacturing technology, ACSM breaks the clear boundary of the three modes of material addition, subtraction, and migration in the existing manufacturing process. It all boils down to single-atom action in extreme circumstances. The manufacturing object, process, and precision are all at the atomic scale, so the discretization of materials will make the quantum effect have a direct impact on the manufacturing process and the products. High-precision

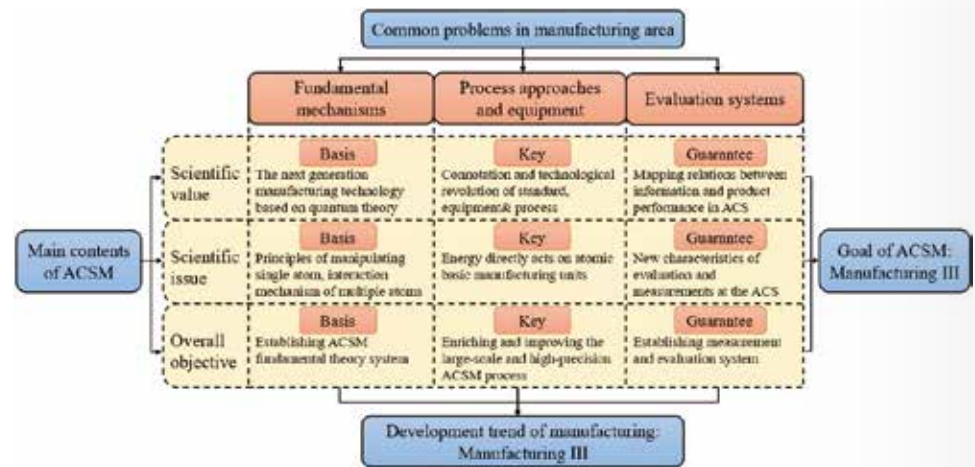


Figure 3. Main content of ACSM.

control and manipulation of an atom make it possible to process typical devices or components with extremely tiny scale and raise their performance to a new level. Such devices or components are difficult to produce by current manufacturing techniques, including chips in the post-Moore's law era (PME), cold atom gyroscopes, energy, new materials, and so on. ACSM involves multiple disciplines, such as machinery, physics, chemistry, life sciences, and materials. Devices and products manufactured are expected to be applied to various fields, such as the communications, information storage and computing, aerospace, energy, and medical sectors. In this article, PME chips and cold atom gyroscopes are taken as examples to see the emerging demands in wide industrial applications.

3.1. PME chips

The semiconductor industry has been extremely effective in developing tools and processes that work well for making digital electronics, since the benefits from atomic-scale manufacturing dramatically improve manufacturing precision and reduce the size of the structural features. Currently, the absolute precision of chip manufacturing is extremely impressive, 7 nm or even less [34], but the relative precision is about $\pm 10\%$. This poor relative precision is acceptable for digital electronics but fails for many other applications in nanoscale, which presents a major problem in technology advances in general. Thus, manufacturing precision must be further improved in the quantized nature of atomic and close-to-atomic scales. Figure 4 shows the roadmap to 1 nm by changing the transistor structure and the materials used one after another and optimizing the process. The 'IC technology scaling' part of figure 4 was developed by referring to Sarkar *et al* [35]. However, with the progress of miniaturization and integration, the manufacturing cost is rapidly increasing (it has doubled) due to the complexity of the process, in which the cost of the lithography step has increased by three times. For this reason, the manufacturing cost per transistor cannot be lowered as expected, and Moore's law is stalled.

Emerging applications drive the incentive to develop atomically precise devices and technologies; and the most compelling is the next generation of chips, i.e. PME chips. On one hand, acceptable feature size variability of the classic integrated circuit chips is expected to be on the order of 3–4 atoms of silicon, including contributions from surface imperfections, in the next 5–10 years. On the other hand, quantum [36], phonics, and DNA computing will inevitably replace binary digital electronic computing, with the demand for processing huge sets of

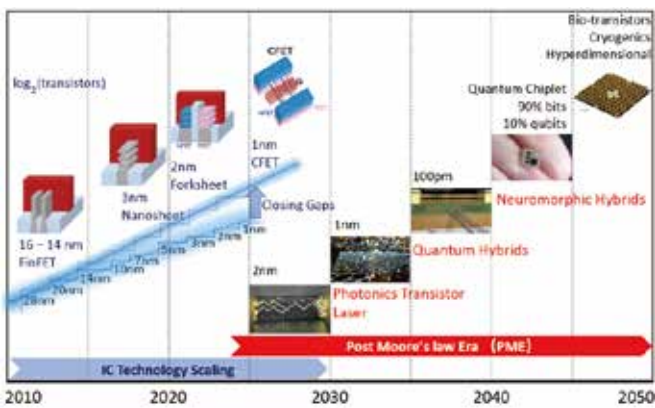


Figure 4. Technology roadmap in developing PME chips.

data in the future. Atomic precision features are critically required on those types of PME chips. The feature size of transducers and capacitors will become close to the size of an atom. PME chips based on hybrid models will also require atomic precision features. PME chips have greater information processing capabilities and the unique features of superposition and entanglement, which greatly improve the computing speed and storage capability. Taking quantum chips for instance, the technical difficulties in fabrication can be single quantum dots and highly complex quantum logic gates. Quantum dots, in a diameter of 2 nm (~ 10 atoms per cluster), are allocated on atomically flat terraces separated by steps of only 0.22 nm in height [37]. The current processing of quantum logic gates mainly depends on femtosecond laser direct writing technology, which can deposit energy in a transparent medium; but it is difficult to accurately control the splitting ratio and waveguide phase [38]. Though a number of potentially complex and useful atomically precise products have been simulated, designed, or even prototyped, there are difficulties to commercially producing them for the market because of the lack of manufacturing precision at the atomic scale.

3.2. Cold atom interferometer gyroscope

The inertial navigation system has irreplaceable advantages in the high-tech field because of its self-determination, noninterference, large informative output, and strong real-time performance. The accuracy of the gyroscope directly affects the accuracy of the positioning and altitude output of the inertial navigation system. The cold atomic interference gyro, which is realized by using the Sagnac effect of the atomic de Broglie wave, is representative of the third-generation quantum matter wave gyroscope. With its ultrahigh measurement accuracy, it is becoming a hot research area in the field of inertial measurement [39, 40].

The cold atom interferometer uses atoms as sensitive media. Atoms are cooled, trapped, and manipulated by a laser, which interferes with the atomic wave packet due to the atom's energy level and wave property. In this way, an interference phenomenon similar to ring laser gyro is formed, the final interference fringes are measured, and the rotation and acceleration information of the carrier can be obtained. Atoms have the advantages of short de Broglie wavelength, long free evolution time, and narrow response frequency; and the interferometric phenomena are more abundant than photons because of the atom's mass, internal structure, and energy level. Therefore, the measurement accuracy is significantly improved. In the field of inertial navigation, atomic gyros are theoretically at least 1000 times more sensitive than optical gyros. The drift of a conventional inertial navigation system is about 1.8 km h^{-1} , whereas the theoretical drift of an inertial

navigation system based on a cold atomic interferometer gyroscope does not exceed 10 m h^{-1} [41, 42].

In the implementation of an atomic interferometer gyroscope, atom cooling, trapping, and manipulation requires the support of many optical devices. In order to ensure the precision and performance of the gyroscope, the traditional optical devices need to be redesigned, manufactured, assembled, and packaged rigorously, which makes the device large in size, highly complex, and great in cost. To capture atoms by portable devices without sacrificing precision, photonic integrated circuits can be used instead of conventional optical systems. Compared with a conventional discrete optoelectronic processing manner, a photonic integrated chip (PIC) can reduce costs and complexity. By integrating various optical components into one single chip, a large-scale, single-chip PIC greatly improves a system's size, power efficiency, and reliability and reduces the system cost. In addition, the application of photonic integrated chips can greatly reduce the number of independent optical components required by the transmission system and can also greatly reduce the optical component packaging. Atomic interferometer gyroscopes using photonic integrated circuits can significantly reduce the system size and outperform the original free space technology by one order of magnitude in terms of angular sensitivity and dynamic range [43]. ACSM is expected to break through the bottleneck of photonic integrated circuit fabrication and realize the stable manufacturing of a new type of atomic interferometric gyroscope.

4. Summary

ACSM is a new development phase in the field of manufacturing. Its fundamental concept is to directly apply energy to atoms, obtain specific functions and performance by constructing atomic-level structures, implement batch production, and meet the users' requirements.

ACSM has a theoretical framework that is completely different from that in the existing manufacturing. The underlying layer of the framework is no longer based on principles such as stress/strain, chemical equations, or traditional optics but is determined by quantum theory. The key to the further development of ACSM lies in understanding the intrinsic mechanism of ACSM. Fundamental science provides the theoretical basis for manufacturing, and the development of manufacturing promotes the fundamental research fields. The relevant theoretical research achievements are condensed in practice, which in turn is directly fed back to these research fields.

With the IC chip density approaching its limit and many other needs for functional feature size at the atomic scale, ACSM theories and technologies need to be planned in advance and deployed. ACSM will give a new impetus to the theory and technology of manufacturing, and it will also significantly promote the development of various fields. ACSM in its true sense of meeting the functional requirements of users will be realized, and manufacturing equipment with atomic precision will be developed.

When the study is at the atomic or close-to-atomic scale, the traditional macroscopic processing theory cannot accurately describe and predict the mechanism of atom removal, migration, or addition in the processed materials. Therefore, it is necessary to conduct deep and innovative research and development. Interdisciplinary research will be the source of great scientific achievements. To understand and apply the interatomic or polyatomic processes to the actual manufacturing process, the research on ACSM requires continuous academic exchanges among many disciplines, such as mechanics, physics, chemistry, materials, and life sciences. Through the contention of different academic viewpoints and the collision, exchange, penetration, and fusion of

academic ideas, the technology of ACSMs can be rapidly established and well developed in the next 10 to 20 years.

As ACSM is a huge field in the next generation of manufacturing advancement and involves multidisciplinary areas, the view may be one-sided because of the author's limited knowledge. Through further investigation and discussion, this article hopes to initiate advancement of academia and industry in manufacturing.

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