Micro/Nano-Fabrication Laboratory

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Abstract:

Micro/nano configurations are indispensable characters in frontier devices, for example, quantum processors and nano-optical devices. However, their realization needs the nanofabricating techniques to have the capacities of high precision, extreme feature sizes, and abundant controllable of freedom. These complex demands come to be a huge challenge which hinders the further development of the related applications. In this paper, we introduce the instruments, process development, and the important advancements of Micro/Nano-Fabrication Laboratory (LMF) that located at the Synergetic Extreme Condition User Facility (SECUF). With the aims of meeting fabrication needs of micro/nano structures and devices for SECUF users, LMF is equipped with more than 50 sets of instruments ranging from lithography, etching, deposition, characterization, and their auxiliary systems. Based on the advanced equipment, LMF has developed a series of method toward multidimensional controllable nanostructures, where the minimum linewidth of the typical configurations down to 8 nm, aspect ratio reaches 18:1, and fabricating precision of atomic scale. LMF has attracted users from over 100 institutions to conduct their research in quantum, photonics, and many other fields. Especially, in quantum devices, superconducting quantum processors with qubits up to 78 have been fabricated, supporting the establishment of the Quafu quantum cloud computing cluster. In nanophotonics, users can conduct research ranging from optical quantum computing, metasurfaces, grating

waveguide, and high quality factor (Q) optical cavities. LMF serves as a platform for applications under extreme environments, providing a comprehensive strategy for users to explore the fascinating physical world.

Keywords:

Micro and nano fabrication, lithography, quantum computing, nanophotonics

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1. Introduction

Compact configuration is a crucial pursuit for quantum, photonic, and electrical devices, enabling a higher integration, stronger functionality, and reduced weight[1-4]. The goal has driven the manufacturing technologies down to nanoscale and even into the atomic scale. Frontier works have been reported that rely on nanofabrication to achieve advanced functions. The two most typical fields are the quantum computing[5,6] and nanophotonics[7,8], which are of great value for next-generation computing and communication, with the potential to drive revolutionary changes in social lifestyles. Josephson junctions (JJs), which are sandwich structure consisting of two superconducting films separated by a ~1-2 nm-thick oxide tunnel barrier, are key components in superconducting quantum computing. [9,10]. While the performance of the nanophotonics devices is directly determined by the configuration and the arrangement of the building blocks within the devices[11,12]. Both constructions are sensitive to the tiny defects and contaminations introduced during fabrication. For instance, a small defect in a JJ can lead to crosstalk and decoherence of qubits, highlighting the requirements for high precision, extreme linewidth, and high cleanness. It is indispensable to build up cleanrooms to meet the crucial fabrication demands of quantum devices and optical components.

In recent decades, micro/nanofabrication laboratories have become common-

platforms across all research fields, a number of fabrication centers have been built up by high schools, institutions of the Chinese Academy of Sciences (CAS), and high-tech enterprises. These cleanrooms mainly server researches and developments in semiconductor[13] and micro/nano electro mechanical system (MEMS/NEMS)[14]. Although quantum and optical devices have shown their value for the future, only a few laboratories focus on these advanced fields. In quantum computing, the University of Science and Technology of China has established a dedicated process line for superconducting quantum devices. As for nanophotonics, Sun Yat-sen University has developed a platform that has advantages in silicon photonics and lithium niobate (LN) photonic processing. In fact, the fabrication demands of optical nanostructures and quantum structures share more similarities than differences, as both require fabrication with clean surface, less defects, and high precision, making it possible to develop a comprehensive nanofabrication laboratory for applications ranging from fundamental research to prototype verification for both quantum and optical devices.

Synergetic Extreme Condition User Facility (SECUF) aims to provide ultra-low temperature, ultra-high pressure, and ultrafast optical-fields for users to promote in-depth development across various research areas. It is a powerful facility for users to implement frontier research including quantum effect and light-matter interaction, as well as the practical application of quantum computing chips and next-generation optical devices. The experimental realization of these studies needs the support of a powerful nanofabrication laboratory with professional techniques.

On this context, Micro/Nano-Fabrication Laboratory (LMF) has been established as a technical supporting platform. LMF aims to meet the fabrication needs of micro/nano structures and devices for SECUF users, especially for users in the field of quantum and nanooptics. More than 50 sets of instruments, including e-beam lithography (EBL), ultraviolet lithography, physical/chemical vapor deposition (P/CVD), atomic layer deposition (ALD), and inductively coupled plasma reactive ion etching (ICP), are equipped to ensure a complete fabrication capacity spanning from pattern generation, transformation, to characterization. Crucial indexes of LMF include:

the minimum linewidth of EBL down to 8 nm, the alignment precision better than 5 nm, minimum width of Si etching reaching 30 nm with a high aspect ratio of 30:1. LMF has attracted more than 100 users to conduct their researches, and more than 100 papers have been published. In the field of quantum computing, a series of quantum chips with qubits up to 78 have been built, supporting the establishment of the Quafu quantum cloud computing cluster. As for nanophotonics, LMF has fabrication capacities of large-area, complex configurations, and high precision. High-performance metasurface, non-reciprocal photonic devices, and AR/VR master have been constructed. LMF is a comprehensive fabrication platform for the fabrication of quantum chips with multi qubits and diverse optical nanodevices, assisting users in exploring physical mechanisms and commercial promotion.

2. Equipment

LMF is currently equipped with more than 50 sets of instruments, which can be further divided into 5 categories, as **Figure 1** shows. 1) lithographic unit, which can be utilized to generate resist patterns with precision down to nanoscale and processing area up to 8 inch, and further paves the way for further pattern transfer. This unit includes EBL, mask aligner (MA), and laser direct writing (DWL); 2) etching unit, enables subtractive pattern transfer through dry etching, wet etching and helps the built up of functional devices for its abundant material options. This unit is further classified into 2 sub-units. One of them is equipped with RIE and ICP, and the other one includes focused ion beam (FIB), reactive ion beam etching (RIBE), and ion beam etching (IBE); 3) deposition unit, which is designed for the growth of functional materials including metals, oxides/nitrides, semi-conductors, phase change materials and especially, superconductors, which provides a additive-based pattern transfer methods. The unit mainly includes PVD and CVD instruments like e-beam evaporation deposition (EBD), magnetron sputtering (MS), plasma-enhanced chemical vapor deposition (PECVD) and ALD; 4) characterization unit, can be used for the morphological and basic property characterization of nanostructures, including atomic force microscope (AFM), scanning electron microscope (SEM), and ellipsometer. This unit acts as a essential character for

both process parameter feedback and device performance verification; 5) auxiliary unit, equipped with laser or wheel dicing, rapid thermal annealing, etc. The functional units work together to ensure a complete fabrication capacity. Besides, a series of fabrication methods are well developed to solve the unique and harsh fabrication demands of quantum devices and nanophotonics components.

With the excellent technical level, LMF now has established the Beijing Generic Technology Platform for Optical Metasurface Device Development with the support of Beijing Municipal Science & Technology Commission. It is the first platform that focuses on the research and development of optical metasurfaces, it can also support research on many fields of the nano-optics.

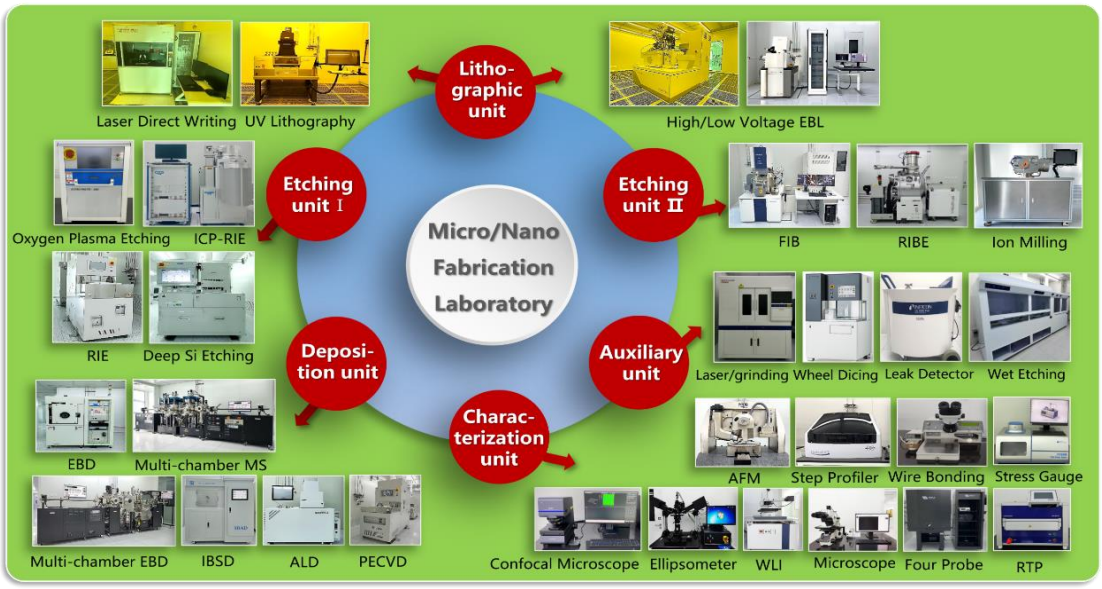


Figure 1 An overview of the instruments on LMF

1) Lithographic unit

The fabrication of functional structures and devices mainly starts from lithography, where the designed patterns take shape as resist templates. Both EBLs with voltage of 100 keV/30 keV and UV exposure including DWL and MA are equipped in the laboratory, which are utilized to construct patterns with linewidth at the nanoscale and microscale. Figure 1 depicts the instruments in lithographic unit. **Figure 2a** and **2b**

show the high-voltage EBL (Raith EBPG 5200) and low-tension EBL (Raith Eline Plus). Both systems can reach a minimum linewidth of 8 nm, as shown in the inset of **Figure 2b**. Specifically, the low-voltage EBL is a multipurpose platform, except for the exposure, it can also be applied in electron beam induced etching and deposition with a linewidth down to 60 nm. The high-voltage one is a high-speed machine, which has a maximum write field of 1 mm, with the field pitch and alignment precision at 15 nm and 5 nm respectively. The UV lithography machines are demonstrated in **Figure 2c** and **2d**, which are DWL and MA. The DWL uses a well-focused laser to directly write patterns on a sample, achieving a linewidth as narrow as sub-1 μm with a precision of 100 nm. Additionally, DWL can write height gradient structures by grayscale lithography, breaking through the limit that traditional lithography methods can only be used for planar patterns. MA is a mask aligner lithography machine, which can produce wafers up to 6 inch in several seconds with a minimum feature size of 500 nm.

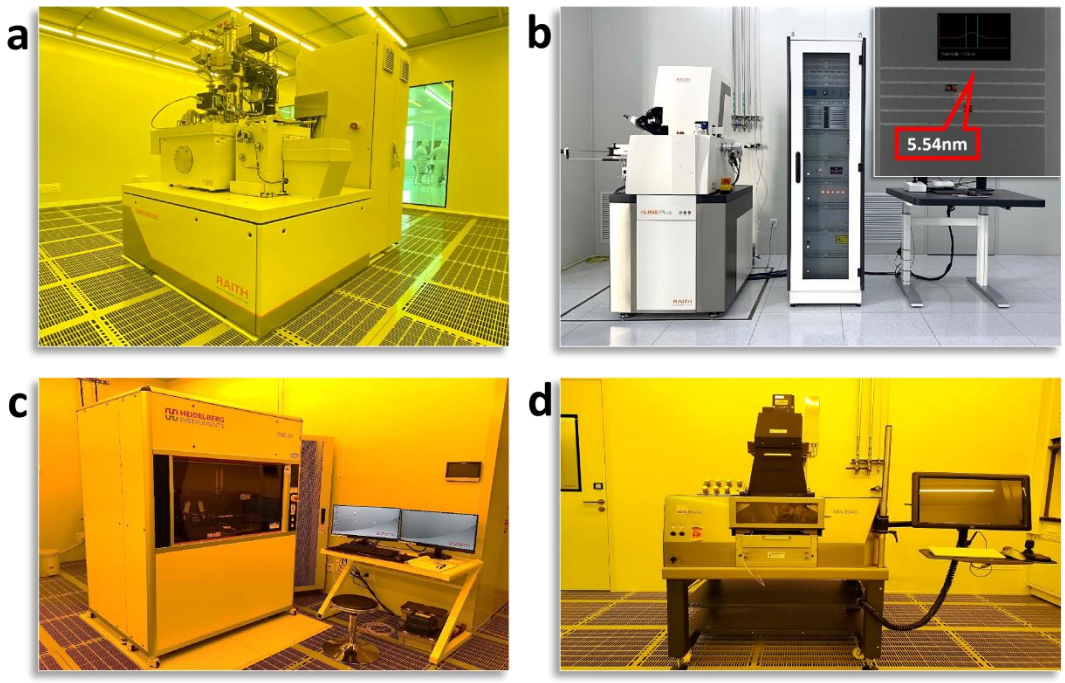


Figure 2 (a) High-voltage e-beam lithography with accelerator voltage of 100 kV ; (b) Low-voltage e-beam lithography with accelerator of 30 kV, the inset shows a pattern with line width down to 5.54 nm; (c) Laser direct writing; (d) Mask aligner.

2) Etching unit

Etching unit provides a top-down method for various target materials, for example, semiconductors like Si and InP, metals like Au and Mo, and dielectrics including Si-based materials and TiO_2. Ten instruments of this unit are divided into 2 sub-units, one of them is mainly used for physical etching, and the others are used physical-chemical or chemical etching.

Figures 3a and **3b** illustrate commonly used physical etching systems. **Figure 3a** depicts a FIB system (NX5000), which is capable of fabricating structures with feature sizes down to 10 nm through both etching and deposition in a direct writing mode. It utilizes a Ga liquid metal ion source with a resolution of 4 nm at 30 kV and can deposit materials such as C, W, and Pt. It can also be used as a SEM with a resolution of 0.7 nm at 15 kV. The system is also equipped for fabricating transmission electron microscopy (TEM) samples, offering significantly higher material removal speeds while minimizing damage. **Figure 3b** shows an IBE system (LLK-150E) that employs a collimated Ar ion beam generated by a Kaufman ion source. The stage tilt angle can vary from 0° to 90°, making it versatile for various etching applications. This system is widely used for etching oxides, metals, and semiconductors with masks to create micro-/nanostructures on substrates.

Figures 3c-i represent physical-chemical etching systems, designed for samples up to 8-inch wafers. **Figure 3c** shows a RIBE system (Hassrode Lorem R). The stage tilt angle ranges from -90° to +80°, allowing the ion beam to strike the sample surface at a certain angle. This system is especially suited for the preparation of blazing and slant gratings, with a blazing angle range from 30° to 90° and an inclination angle range of 35° to 89°. Free from the chemical limitations of traditional RIE, it is capable of etching a wide range of solid materials, including metals, alloys, compounds, dielectrics, and semiconductors. **Figure 3d** depicts an ICP metal etching system (Hassrode Pishow A), which serves as a cluster tool for 8-inch IC back-end-of-line (BEOL) metal processes. It is capable of etching a variety of materials, including metals, dielectrics, glass, Si and its compounds, and TiO_2. **Figure 3e** is another ICP system (SI 500), which is configured for processing a wide range of semiconductors, including III-V and II-VI

compound semiconductors (such as GaAs, InP, GaN, InSb), as well as lithium niobate. **Figure 3f** features the Si-based ICP (RIE-400iPB), which is specifically designed for deep silicon etching by Bosch Process. Typical structures have an aspect ratio of 30 for a 3-micron trench and an select ratio of 400 with a SiO_2 mask. Two RIE systems are equipped for metal and dielectric etching, respectively, as **Figures 3g** and **3h** show. **Figure 3i** shows a microwave plasma etching system, which is designed for the etching of resist and other organics. Finally, the wet etching station is depicted in **Figure 3j**, providing a safe wet etching platform for all kinds of materials and used for the standard cleaning of wafers.



Figure 3 (a) Focused ion beam microscopy; (b) Ion beam etching; (c) Reactive ion beam etching; (d) Inductively coupled plasma metal etching; (e) Inductively ccoupled plasma etching; (f) Inductively coupled plasma - Deep silicon etching; (g) Reactive ion matal etching; (h) Reactive ion etching; (i) Microwave plasma etching; (j) Wet etching.

3) Deposition unit

Materials deposition is of crucial importance as it builds a bridge from resist patterns to functional devices. Both PVD and CVD methods are equipped in the laboratory, and 12 instruments are introduced to enable a complete depositing capacity that covers the materials from metal to insulators. **Figure 4** shows all the instruments of the deposition unit. **Figure 4a** is a multi-chamber EBD (JEB-4), specifically designed for fabricating JJs, the building blocks of superconducting quantum processors. JEB-4 has four independent ultrahigh-vacuum chambers, including a stand-alone load lock, ion-beam chamber for etching, and an e-beam chamber for high-quality Al films and oxidation camber. **Figure 4b** shows the four-chamber magnetron sputtering system (JSP-4). It consists of one load-lock and three sputtering chambers which are refer to as SP1, SP2 and SP3. SP1 is mainly for superconducting films such as Nb and Ta. SP2 can be used to deposit ferromagnetic films, Fe, Ni, etc. SP3 is designed for sputtering Al film at liquid nitrogen temperature. Both JEB-4 and JSP-4 allow fully automatic transfer and operation. **Figure 4c** shows electron-beam evaporators (EBD). We have two EBDs. One is used to deposit metals, including Au, Ti, Pt, Cr, Ag, and Al. The other is an oxygen-enriched EBD, which allows the deposition of oxide films, SiO_2, Al_2O_3, TiO2. **Figure 4d** shows the plasma enhanced ALD (PEALD). Our PEALD produces high-quality TiO_2, Al_2O_3 and HfO_2 films, offering high conformality and thickness control. Our PECVD, shown in **Figure 4e**, can produce SiO_2, Si_3N_4 and Si films. The ion beam assisted deposition (IBAD) in our lab is often used in depositing high-quality optical coatings, such as TiO_2 and Ta_2O_5 (**Figure 4f**). The ion sputter shown in **Figure 4g,** is used to deposit thin Pt films, which is auxiliary equipment for SEM and FIB. **Figure 4h** shows the HMDS evaporator for improving the adhesiveness of photoresist.

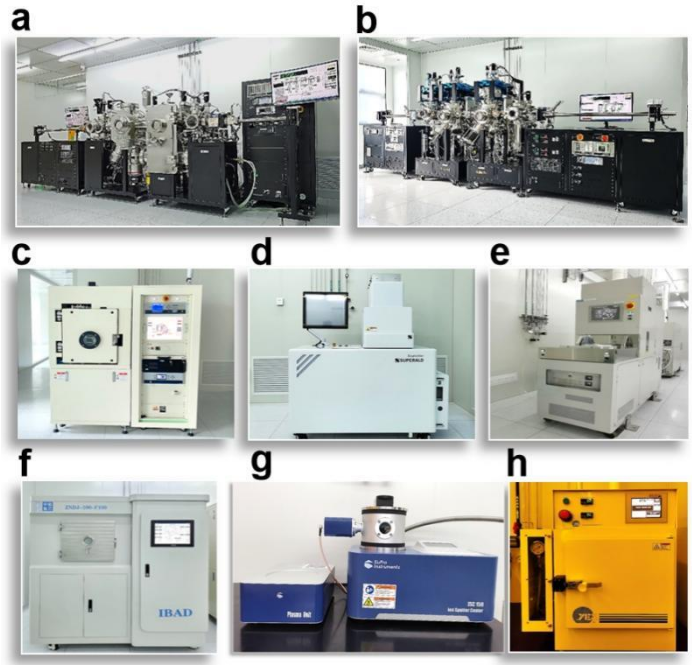


Figure 4 (a) JJ Electron Beam Evaporator with four chambers (JEB-4). (b) Magnetron Sputtering Systems with four Chambers. (c) Electron Beam Evaporator. (d) Plasma Enhanced Atomic Layer Deposition (PEALD). (e) Plasma-Enhanced Chemical vapor Deposition. (f) Ion Beam Assisted Deposition. (g) Ion Sputter. (h) HMDS Evaporator for improving the adhesiveness of photoresist.

4) Characterization unit and auxiliary unit

Characterization unit contains 13 instruments with the aim of providing a comprehensive characterization of the fabricated nanodevices and configurations in terms of morphology, basic optical and electrical properties. The auxiliary unit contains 12 systems like spin-coater, hot-plate, and wafer dicing saw. The unit acts as the necessary auxiliary to the other units, bridging the gap between equipment and samples and further ensuring the daily running of the laboratory.

The characterization unit is used for morphology and property characterization of fabricated micro/nano devices. Three conventional microscopes including metallographic microscope (**Figure 5a**), digital optical microscope (**Figure 5b**), and stereo optical microscope (**Figure 5c**) are equipped for optical observation and photography. **Figure 5d** and **Figure 5e** respectively illustrate an ultra-high-resolution

SEM and AFM; both of them provide sub-nanometer resolution for measuring line widths, hole diameters, and layer thicknesses that directly dictate electrical performance in semiconductor devices. In particular, the AFM can be used to characterize surface structure with precision at the atomic scale. Similarly, white light interferometer (WLI) and confocal laser microscope (LCM), displayed in **Figure 5f** and **Figure 5g**, can characterize the 3D morphology of microscale samples. For the measurement of film thickness, stylus profilometer (**Figure 5h**) was also introduced in our lab. **Figure 5i** shows an ellipsometer that can be used for the characterization of the index and thickness of thin films. The film thickness gauge (**Figure 5j**) provides a rapid, cost-effective alternative to ellipsometry for film thickness characterization. We also offer film a stress measurement system for measuring the stress of thin films(**Figure 5k)**. The four-probe measuring system can complete the measurement of I/V, R/V, and C/V curves of integrated circuits (**Figure 5l**).

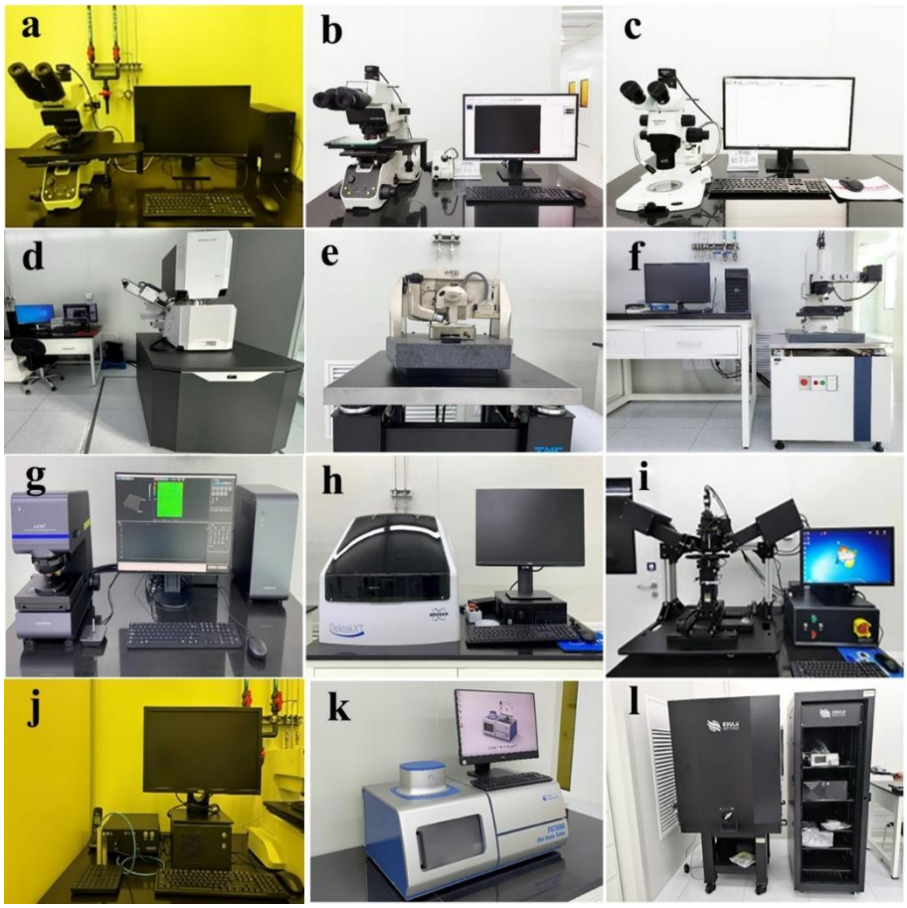


Figure 5 (a) Metallurgical Microscope. (b) Digital Optical Microscope. (c) Stereo

Optical Microscope. (d) Scanning Electron Microscope. (e) Atomic Force Microscope. (f) White Light Interferometer. (g) Laser Confocal Microscopy. (h) Stylus Profilometer. (i) Ellipsometer. (j) Film Thickness Gauge. (k) Film Stress Measurement System. (l) Four-prober measuring instrument.

The auxiliary unit supports the reliability service of the other units. The spin coater (SM-150, **Figure 6a**) and hot plate (HOT PLATE-1008, **Figure 6b**) support the coating of photoresist. Wire bonding (WB 7476D, **Figure 6c**) can be utilized in the fabrication of metallic interconnections between micro/nano devices can be achieved. The vacuum oven (EVO229, **Figure 6d**) is employed to meet the baking requirements of photoresist under vacuum. The rapid thermal processor (RTP-200, **Figure 6e**) can be used to modify properties such as lattice misalignment and film stress. The laser dicing (HDZ-GCF-1000-3025, **Figure 6f**) and wheel dicing (DAD3351, **Figure 6g**) are capable of cutting transparent and opaque substrates, respectively. Finally, the helium leak detector (UL000Fab, **Figure 6h**) is utilized for detecting the leak rate of vacuum chambers and gas lines in equipment.

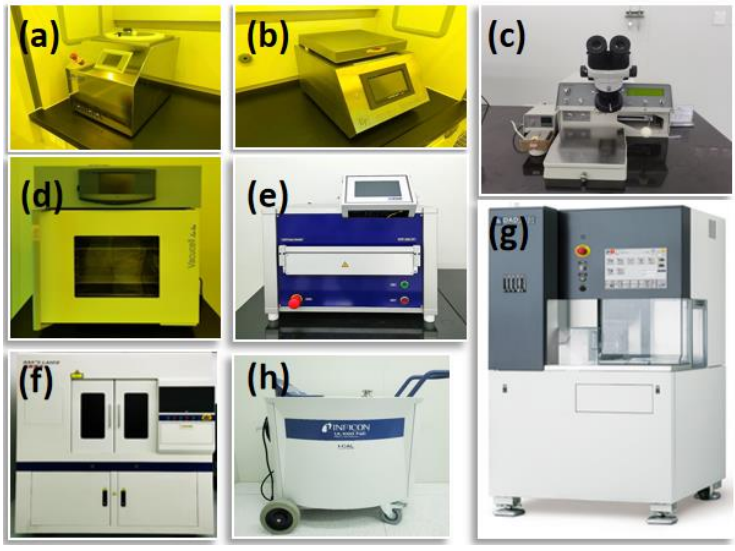


Figure 6 (a) Programmable Spin Coater. (b) Programmable Hot Plate. (c) Wire Bonder. (d) Vacuum Oven. (e) Rapid Thermal Processor. (f) Laser Dicing Saw. (g) Wheel Dicing Saw. (h) Helium Leak Detector.

3. Process development The LMF is now staffed with 6 experienced employees, who focusing on users' crucial demands of complex configurations and unique materials, especially devices that operate in extreme conditions. New methods and arts have been developed by the staff, and the corresponding results help the development of next-generation quantum chips and nanophotonics devices.

1) Extreme manufacturing of nanostructures

Frontier devices require extreme structures including those with small feature sizes or arbitrary designed configurations. LMF has developed a series of new methods to meet these demands. **Figure 7a** shows a selective peeling lithography (SPL) method for high throughput sub-5 nm gap fabrication. This method is based on a vertical spacer layer with atomic precision between the metallic films that deposited sequentially, and the nanogaps are taken shape by selectively peeling the unwanted metal by a tape. This method can fabricate sub-5 nm nnaogaps over a 4 inch wafer[15]. Moreover, based on the interaction between the focused electron beam and nanobridge, a stress that is determined by the focused electron beam is introduced and further crack the nanobrige along the grain boundary, and subnanometer gaps can be fabricated for the high precision control of stress. As shown in **Figure 7b**, an electron beam (EB) induced crack method was developed based on the sputtering effect of high-tension EB, where the nanobridge was broken along the grain boundary under the illumination of 300 keV electron beam. The narrowest gap of this method reaches on 0.7 nm, which is smaller than 2-fold of the lattice constant of Au crystal (~0.4 nm). We believe the electron beam induced crack method achieves a fabrication precision of atomic scale. Among these two method for nanogap fabrication, the SPL method provides a pathway for larger area fabrication, while the electron-beam-induced method helps the ultra-high-precision fabrication of subnanometer nanogap.

Meanwhile, intelligent design has been widely used to realize devices with arbitrary configurations, which in turn poses new requirements for nanofabrication. Here, we have overcome the difficulties in their fabrication. A method that combines

EBL and ICP etching was optimized, where structures with extremely fluctuating density, individual pixels, and continuous pattern can be built up with minimum pixel sizes down to 40 nm (**Figure 7c**). The fabrication of extreme nanogaps and arbitrary nanostructures paves a way for the design of next-generation quantum computing and optical modulation.

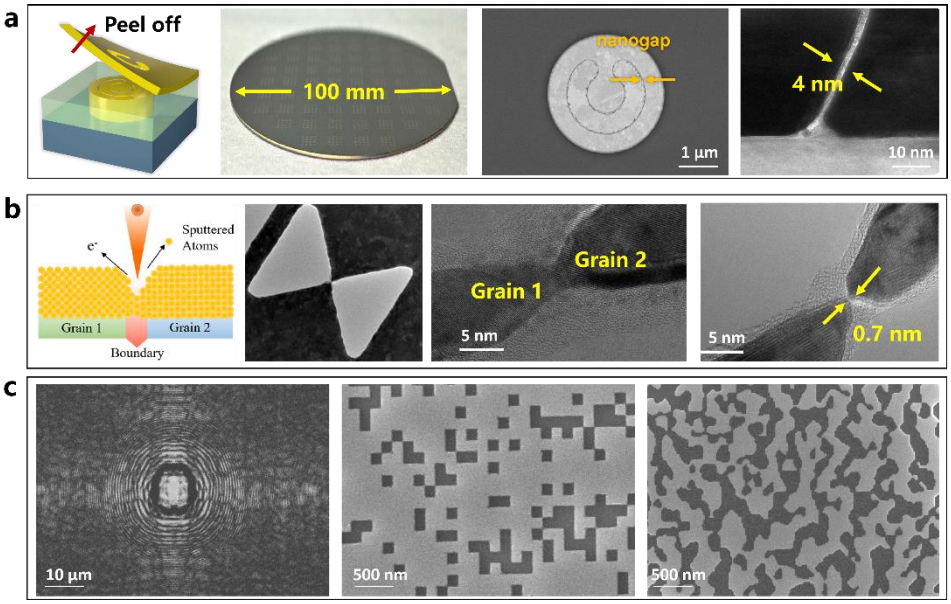


Figure 7 Extreme structures. (a) Large area sub-5 nm gaps fabricated by SPL; (b) Sub nanometer gaps of high-tension electron beam induced cracking; (c) Configurations of arbitrary patterns, including large density contrast, pixel distribution, and continuous morphology. Reproduced with permission from Ref.[15]

2) Configuration with high aspect ration

Nanostructures with high aspect ratio, as a common functional platform, show indispensable advantages in integrated circuit packaging, nano optics and photonics, sensitive sensing, and quantum light sources. LMF has developed a complete method in their fabrication. For instance, an atomic layer assembly method that combines the advantages of both the high precision of EBL and conformal deposition capacity of ALD was developed for dielectric configurations[16-18]. **Figure 8a** shows an array of TiO_2 nano-fins, which demonstrate a high aspect ratio of 18:1 with a 900 nm height but

50 nm linewidth. This method can simultaneously be used in the construction of structures with high density (76%), high precision (< 5 nm), and small linewidth (36 nm), as **Figure 8b** and **8c** shown. Apart from dielectric **(Figure 8d)**[16], high aspect ratio nanostructure can also be made of semiconductors such as amorphous Si with etching of ICP[19-23] (**Figure 8e**). Electrochemical deposition (ECD) can also be used to build high aspect ratio blocks, metallic structures with aspect ratio up to 10:1 can be formed with the help of well-defined resist masks[24]. **Figure 8g – 8i** further highlight the capacity of the methods, where nanostars and even arbitrary structures can be fabricated as high aspect ratio structures, with side-walls having a thickness down to 8 nm[16]. The nanostructures can be assembled over a large scale up to 100 mm. Corresponding results can be used in the research and development of a series of devices in optical, electronic, and even quantum devices.

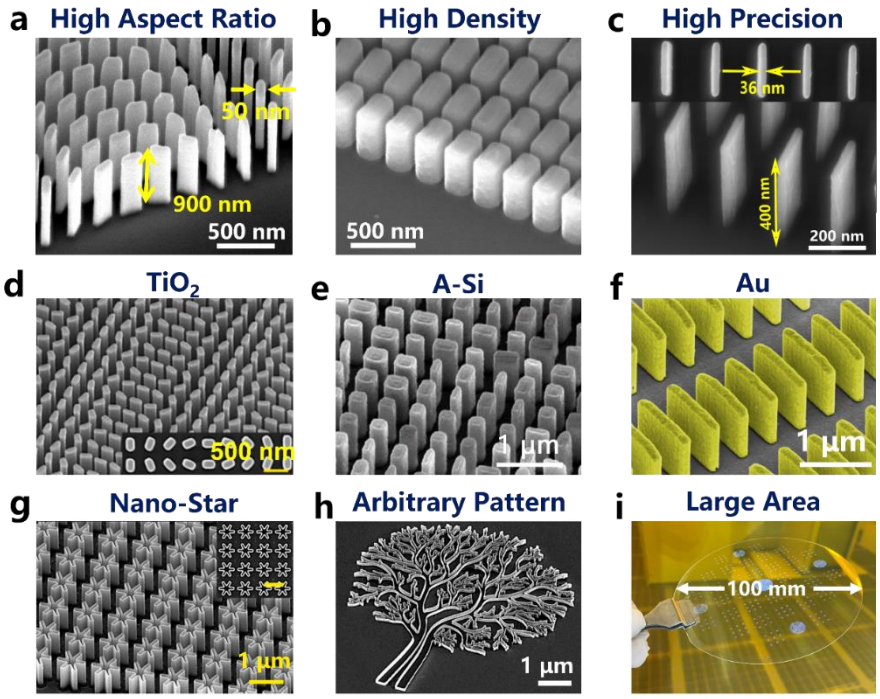


Figure 8 High aspect ratio nanostructures. (a) Nanofins with aspect ratio up to 18:1; (b) and (c) Structures with high density and precision; (d) – (f) are high aspect ratio nanostructures made of TiO_2, α-Si, and Au; (g) An array of high aspect ratio configuration of nano-stars; (h) Tree-shaped side walls; (i) A 100 mm wafer that with highly aspect-ratio nanostructures assembled on it. Reproduced with permission from

Ref.[16], [23],[24]

2) Three dimensional (3D) configurations

Compared with the structures mentioned before, 3D structures release the controllable degree along z-axis, and further offer numbers of unique properties, for example, nonreciprocal response, asymmetric propagation, etc. However, conventional planar instruments are used for structures with consistent z-axis cross-section, and can hardly meet the need for 3D structures. Here, we introduced grayscale lithography together with transfer to build up height gradient nanopillars[25]. This method can be directly applied in grayscale display, where one single nanopillar can achieve 256 gray levels by height, and thus realizing an ultra-small pixel size of 100 nm. Global gradient (different heights of different units) and local gradient (different heights in one unit) can both be fabricated by this method. The alignment lithography and multilayer resist process help the fabrication of bilayer architectures, where alignment lithography is used in the assembly of bilayer, and the patterns of both layers can be arbitrary designed[12]. Selectively, this method is also suitable for structures with spacer layer and high aspect ratio (**Figure 9)**. Slant nanostructures show increasing importance for they are fundamental to augmented and virtual reality (AR/VR). Both slanted gratings and unit cells are fabricated by the well-developed reactive ion beam etching (RIBE). The origami is a typical art that folds 2D paper into fascinating 3D structures. We have achieved origami in nanoscale based on the stress induced by FIB-matter interaction. Folding/bending configurations are formed in nanoscale with global/local irradiation. Structures with bending and folding property can also be fabricated by reasonably modulating the irradiation paths[26,27]. Fascinating 3D structures provide a new chance to regulate light, electrons, and quantum states in a highly flexible level.

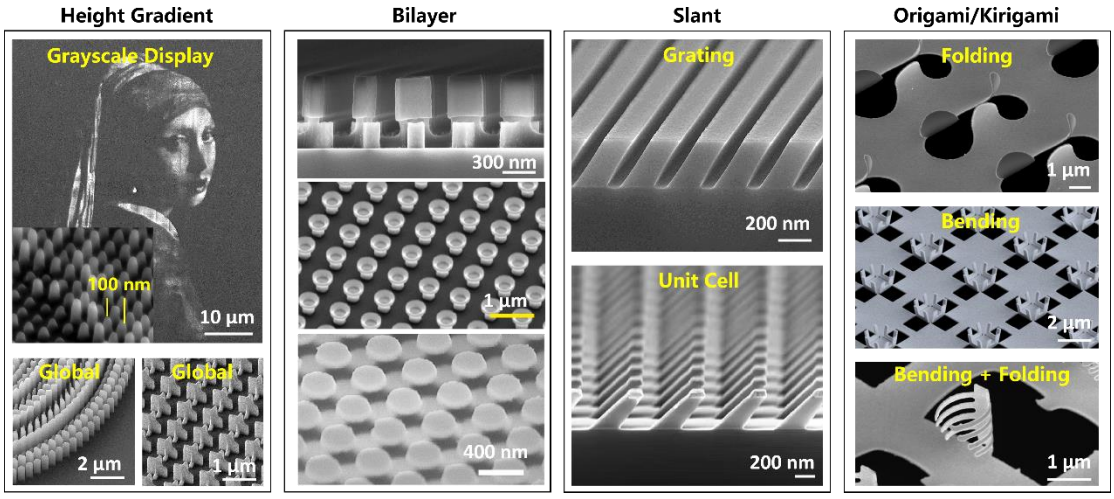


Figure 9 3D nanostructures achieving z-axis tunability by height gradient, multilayer, slant, and origami.Reproduced with permission from Ref.[12], [25]

3) High-performance films

Thin film deposition is one of the most fundamental parts in our lab. For quantum computing chips, our lab can deposit Al, Nb and Ta films, which are the most widely used superconducting materials. **Figure 10a** shows the AFM image of Nb films, which are fabricated by JSP4 in our lab. The critical temperature of our Nb films is ~9K. They have a thickness uniformity better than 95%. **Figure 10b** shows the refractive index of the dielectric film in our lab. The refractive index ranges from ~1.4 to ~5, which provides sufficient choices for optical devices and cladding layers for electronic devices. Our lab also provides phase change materials (PCM), which can be used in active control optical devices. **Figure 10c** shows the refractive index and extinction coefficients of Sb_2S_3. When undergoing phase transitions, the refractive index can change by as much as 1 and the extinction coefficients still remain a low value in the infrared region.

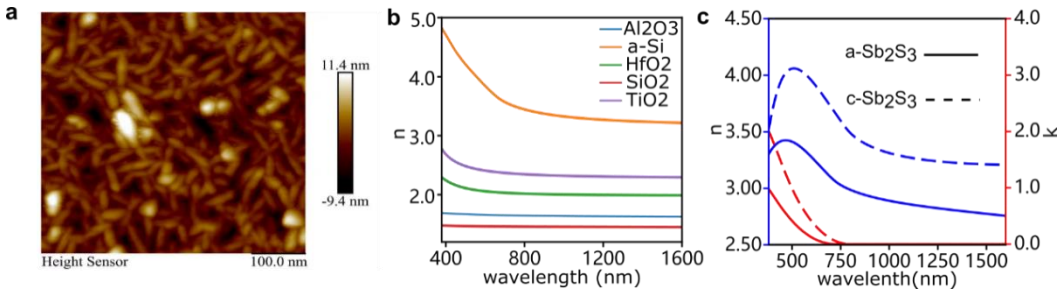


Figure 10 (a) AFM image of Nb films; (b) Refractive index of the dielectric films in our lab.; (c) Refractive index and extinction coefficient of the phase transition materials Sb_2S_3.

4. Important achievements

Recently, 282 projects out of 103 organizations were approved. As **Figure 11** shows, 27 of them come from the institutions of physics, CAS, and 18 of them come from other scientific research institutions. Meanwhile, there are also 41 users from universities. Important users are Tsinghua University, Peking University, Beijing Academy of Quantum Information Sciences, and institutions of CAS. LMF has also set up 17 projects for companies that focus on the applications and commercial expansion of devices for future life, including quantum devices and wearable optical systems. It is worth noting that LMF has attracted headquarter companies like China Electronics Technology Group Corporation (CETC), Baidu, and Goer to conduct their research. Now, LMF can meets the nanofabrication demands among integrated circuit, quantum computing, nano photonics and optics, 2D-material devices, and many other research directions. **Figure 12** highlights the most typical technical support capacity of LMF, mainly contains the complete process that starts from basic research to commercial application of quantum chips and compact optical devices.

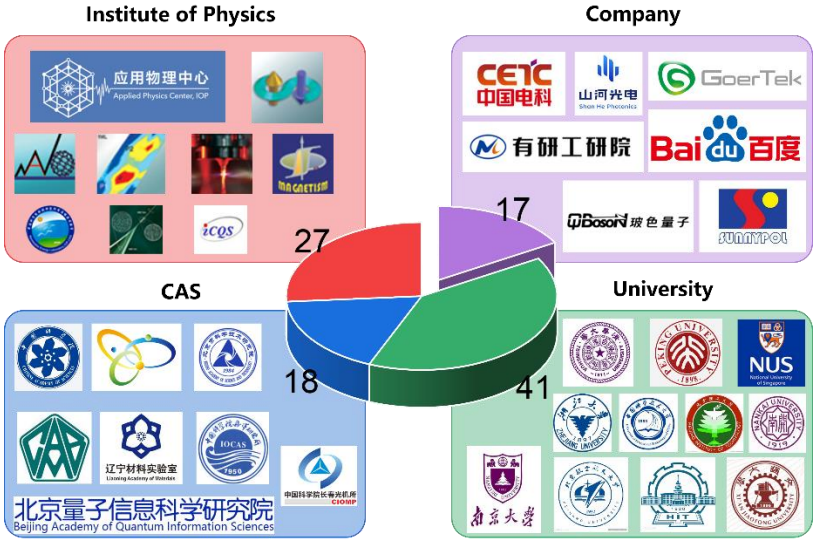


Figure 11 The users' profile of LMF

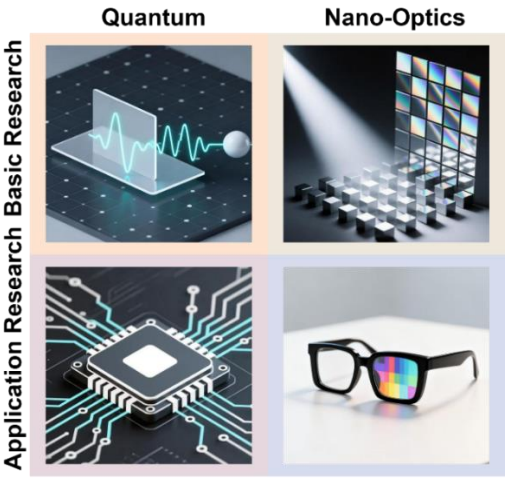


Figure 12 The major technical support capacity of LMF

The complex users' profile sets forth harsh requirements for the laboratory, requiring fabrication methods with high processing speed, excellent large-scale uniformity, and extreme linewidth. Thanks to the advance techniques, important achievements have been made by users from different fields including quantum computing, micro-nano optics, and 2D materials. Importantly, quantum chips, which are supposed to be the core of next-generation computing technology, have been established with 78 qubits, and novel quantum phenomena were observed. And diverse metasurfaces are designed and fabricated with complex configurations and arrangements. The most typical advancements in our lab are listed as follows.

1) Quantum chips

Quantum computing is widely recognized as the most promising technology for next-generation computing. Superconducting quantum computing shows a bright future in achieving scale quantum computing. The core of superconducting quantum computing is the JJ, which is a sandwiched structure where two superconducting films are separated by a dielectric layer with a thickness of ~2 nm. LMF, as a platform that is specialized for quantum computing, have overcome the bottlenecks in fabricating JJ through the most experienced researchers and complete instruments. Quantum chips

with qubits ranging from 10 to 78 have been successfully fabricated, and serve as the cornerstone for the "QuaFu" platform, which is a quantum cloud computing cluster established by Institute of Physics and Beijing Academy of Quantum Information Sciences, providing technical support for quantum research. Based on the quantum chips shown in **Figure 13a[6,28,29]**, novel quantum mechanisms have been observed.

The platform provides key technologies in quantum computing for renowned users from University of Sciences and Technology of China, Beijing Academy of Quantum Information Sciences, Quantum Science Center of Guangdong-Hongkong-Macao Greater Bay Area, and National University of Defense Technology, as well as Institute of Physcis, CAS. Among the users, Fan Heng and cooperators achieved the most remarkable results. They used the 78-qubit superconducting quantum processor with 137 couplers, Chuang-tzu 2.0, to realize the experimental observation of long-lived prethermal phases in many-body systems with tunable heating rates[28], driven by structured random protocols, characterized by n-multipolar temporal correlations (**Figure 13b**). They also directly implemented high-fidelity three-qubit gates with tunable couplers[6], as shown in **Figure 13c**. It is of great importance to achieve high-fidelity qubit readout and reset while maintaining qubit coherence. This group proposed a multiqubit processor with tunable Purcell filters, achieving flexible readout and unconditional reset with readout fidelity of 99.3%[30] **(Figure 13d**). **Figure 13e** demonstrates the quantum simulation of Hawking radiation and curved spacetime with a superconducting on-chip black hole, where the Hawking radiation that originates from the quantum walks of quasi-particle in the curved spacetime reflecting the gravitational effect was simulated[31]. **Figure 13f** further depicts a quantum simulation of topological zero modes based on the 41-qubit superconducting processor[29]. And the interplay between disorder and topology was researched with the Thouless pumping on a superconducting quantum processor, demonstrating that Thouless pumping in the presence of disorder and showing its breakdown as the strength of disorder increases[32] (**Figure 13g**).

The qubit chips developed in LMF provide valuable platforms for quantum

simulation and computing, and help to dig the fantastic quantum world with the observation of novel behaviors.

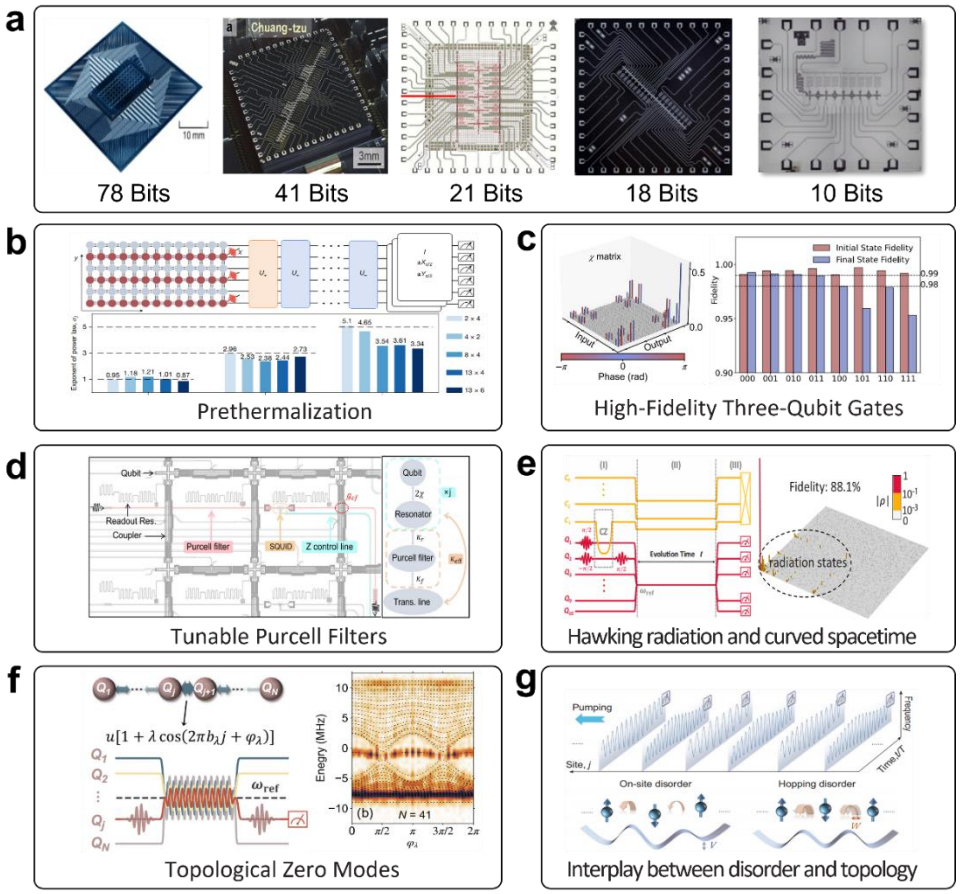


Figure 13 Quantum chips with their novel quantum behaviors. (a) The superconducting processers with different qubits fabricated by LMF; (b) Prethermalization on a 78-qubit processor; (c) High-fidelity three-qubit gates; (d) Flexible readout and unconditional reset with tunable Purcell filters; Quantum simulation of Hawking radiation and curved spacetime (e), and Topological Zero Modes (f); (g) The interplay between disorder and topology on a quantum processor. Reproduced with permission from Ref.[6], [28], [29], [30], [31], [32]

2) Nano-optical devices

Micro-nano optics is one of the most dynamic frontiers in the current field of optics, integrating cutting-edge advances in photonics and nanotechnology. It plays an irreplaceable role in a wide range of applications, including communication,

information storage, sensing and imaging, solid-state lighting, biomedicine, and green energy, among others. Photonic bound states in the continuum (BICs) enable the realization of optical resonance modes with ultra-high Q-factors, making them ideal candidates for facilitating exotic light-matter interactions. Xiangdong Zhang from Beijing Institute of Technology demonstrated the moiré BICs in one-dimensional photonic crystal (PhC) slabs with high-Q resonances and a slow decrease in Q-factors for Moiré flat-band Bloch modes[33] (**Figure 14a**). Their findings open up a new path for exploring BICs in moiré superlattices[34]. Lu Ling's team extended one-dimensional topological modulation to 2D and developed the topological-cavity surface-emitting laser (TCSEL)[35] (**Figure 14b**), which exhibits much higher peak power and a significantly narrower beam than conventional semiconductor lasers. The topological nature of the TCSEL suggests the potential for a larger, more stable single-mode device with improved manufacturing yield. Nano-kirigami offers a promising approach to fabricate 3D structure by transforming 2D patterns. LMF has demonstrated nano-kirigami structures with ultrahigh deformability. As **Figure 14c** shows, optical modulation with high contrast, low voltage, and broadband wavelength responses of these kirigami structures was achieved by Li Jiafang Group[36,37]. This approach holds potential for developing innovative optical modulation-based devices and systems. Metasurfaces, as quasi-2D artificial subwavelength structures, hold great promise for optoelectronic devices. This advancement could lead to breakthroughs in augmented and virtual reality (AR/VR), optical communication, solar energy, etc. Based on the high-aspect-ratio structures processed by LMF, Huang Lingling and co-authors have demonstrated the vast potential of metasurfaces in constructing compact, multifunctional optical systems. Their work focuses on applications such as multi-focal plane augmented reality (AR) displays[38] (**Figure 14d**), wide-field-of-view 3D holographic displays[21] (**Figure 14e**). Dirac-vortex topological cavities offer scalable mode areas, arbitrary tunable mode degeneracies, and larger free spectral range, which provide a new method for on-chip vector-beam generation[39] (**Figure 14f**). Li Beibei group of Institute of Physics, CAS reports an ultrahigh-Q optical microcavities, and constructed a comprehensive landscape spanning from ultra-narrow linewidth lasers to

large-scale quantum entanglement sources[40-42](**Figure 14g**). This demonstrates the central driving role of ultrahigh-Q microcavities in fields such as precision measurement, quantum information processing, and integrated microwave photonics.

In the near future, by integrating dispersion engineering, hybrid integration, and active control methods, these systems are expected to achieve higher-performance photonic information processing and sensing capabilities on a chip.

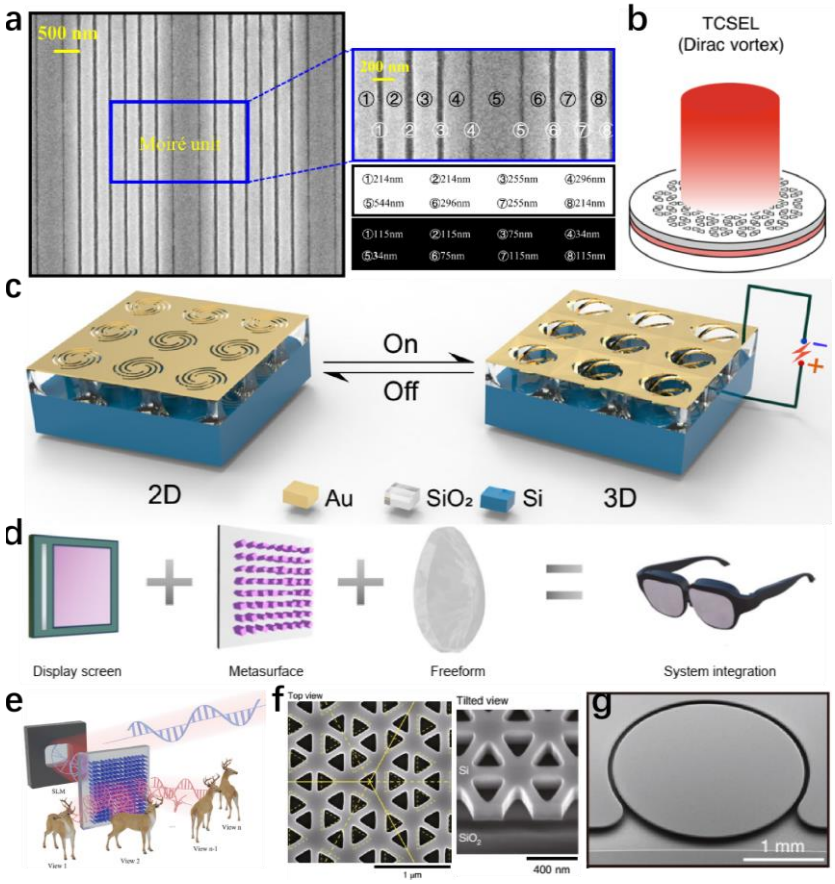


Figure 14 Nano-optical devices. (a) Nano-gratings for Moiré flat-band; (b) TCSEL; (c) Reconfigurable nnao-kirigami nanostructures for light dynamic modulation; (d) Hologram metasurfaces for near-eye display; (e) Wide-field-of-view 3D holographic displays; (f) Topological cavities; (g) High Q microcavitiy. Reproduced with permission from Ref.[21], [33], [35], [36], [39], [40]

Our lab also develops dimension-controllable nanostructures. **Figures 15a** and **15b** show the bilayer metasurfaces fabricated with EBL alignment lithography. Compared with single-layered ones, bilayer metasurfaces allow more flexible manipulation of light and can realize functions which are hard to be realized in single-layered metasurfaces. As shown in **Figure 15a**, we achieve asymmetric radiation simply by introducing a lateral shift to one layer. The bilayer metasurfaces also provide a platform to investigate interactions between two optical resonators. The work shown in **Figure 15b** indicates that two resonances supported by single layer can interfere destructively and trigger topological transition of the bound states in the continuum[12,43]. **Figure 15c** shows the high-aspect-ratio nanostructures. We use them to fabricate a multifocal metalens[44].

Besides, our lab also develops optical nanostructures made of unconventional materials. **Figure 15d** shows an optical switch based on FP resonances with a switch ratio more than 1000[45]. The core functional layer is made of GSST, a phase change material whose optical constants suffer a remarkable change during the transition from crystalline phase to amorphous phase. The phase transition of GSST can easily be realized by controlling the external temperatures, which further enables a series of new optical response[46-48]. Another new material is lithium niobate crystal (LN) film. LN has large second-order nonlinear susceptibility. We use this property to design and fabricate a nonlinear metalens[49,50], as shown in **Figure 15e**, which allows second harmonic generation and focuses the second harmonic waves at the same time. LN is an anisotropic crystal. Its refractive index presents birefringence, which has never been considered in metasurface design. In the work shown in **Figure 15f**, we consider the birefringence of LN and find that the birefringence can induce strong coupling between resonant mode[51]. We show that the hybrid mode is chiral. In this way, we have realized a chiral resonant mode on an achiral-structures by using birefringence.

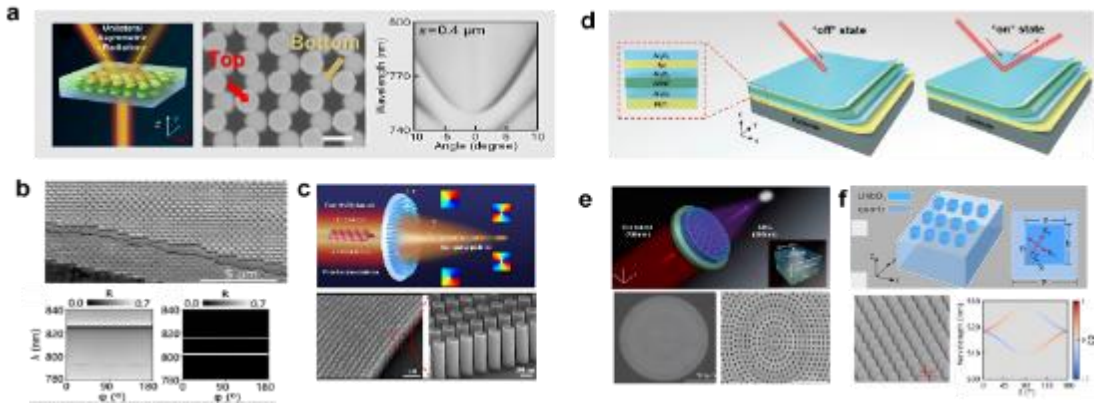


Figure 15 The development of metasurface in our Lab. (a) Bilayer metasurface with unilateral asymmetric radiation; (b) The topological transition of the BIC in bilayer metasurface; (c) Vary-focus metalens of high aspect ratio nanostrucutres; (d) Ultra-high contrast ratio optical switches based on PCM; (e) LN metalens for SHG focusing; (f) Achieving chiral resonance based on achiral nanostructures of LN crystal. Reproduced with permission from Ref.[12], [43], [44], [45], [49], [51]

3) Basic research for application

LMF also builds a bridge from basic research to commercial applications, serving users in high-tech companies among lithography machine, quantum devices, AR/VR, as well as next-generation integrated circuits. In the field of lithography, Hyper-Optics focuses on the research and development of new principles lithography machines, which uses hologram masks to replace projection lenses. LMF provides the key technique for the high precision fabrication of hologram masks which are the most crucial step for holographic imaging. The masks have been used in the I-Line and deep UV wavelengths and enable the production of a series of frontier devices. The special technique of our laboratory boosts the commercial applications of quantum devices. QBoson concentrates on the development of expandable and programmable optical quantum computing platform. They rely on the LMF to conduct research on the manufacturing of optical quantum chips, which show indispensable advantages in next-generation bio-pharmaceutical, artificial intelligence, and digital urban technologies.

LMF can also acts as a common platform with its CMOS-compatible process cluster. Prototype electronic devices made up of wide bandgap semiconductors, 2D materials with high-performance demonstrate wide potential applications. Another characteristic field is in AR/VR. As an ultramodern lifestyle, a number of companies have participated in the industrial chain of AR/VR equipment. Headquarter organizations including Goeroptics, Greater, LLvision, and Optix have conducted their research and development of their products, and new type wearable compact systems have successfully gone public. Importantly, LMF has a complete ability in manufacturing the nanoimprint masters, thus becoming a crucial link in the entire AR/VR industrial chain.

5. Conclusion

In conclusion, LMF is a dedicated technical platform for the development of quantum chips and optical components in micro/nanoscale. With the cooperative work of more than 50 sets of equipment, our laboratory has a complete capacity in the fabrication of related functional structures and devices. More than 200 users implement their researches on the platform. In quantum computing, superconducting processors with qubits up to 78 have been fabricated, where fantastic quantum behaviors have been observed for the first time. LMF also concentrates efforts on the fabrication of micro-nano optical devices. Metasurfaces and other components with complex functions are designed for the next-generation optical systems. Meanwhile, LMF provides crucial technologies for enterprise users in the field of quantum computing, AR/VR, and lithography, and thus building a bridge from laboratory to social life. LMF will continue to promote the experimental research of a series of cutting-edge topics and will provide an unparalleled opportunity for the transformation of scientific research achievements.

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