Atomic and Close-to-Atomic Scale Manufacturing: Status and Challenges

Hifza Hafeez, Wenkun Xie, Xichun Luo
Centre for Precision Manufacturing, Department of Design, Manufacturing & Engineering Management
University of Strathclyde
Glasgow, United Kingdom
xichun.luo@strath.ac.uk

Abstract— **Next-generation lithography techniques such as Extreme Ultraviolet Lithography have started to reach their physical limits and will not be able to meet the requirements of future Post-Moore Era Integrated Circuit chips that will be based on quantum, photonic, and DNA computing. These future chips and the next generation of quantum products will require sub-10nm and even atomic-scale functional features. Promising candidates for atomic and close-to-atomic scale manufacturing include well-established tip-based techniques such as Scanning Tunnelling Microscopy (STM) and Atomic Force Microscopy (AFM), however, they suffer from severely low throughput, although parallel tips have been suggested to increase the throughput. The integration of these techniques with others such as AFM in Scanning Electron Microscopy has created new hybrid techniques that have greatly enhanced the capabilities of the standalone process. On the other hand, higher throughput techniques like atomic layer etching (ALE) suffer from poor process control and defects despite being promising candidates due to the self-limiting nature of the processes. Studies into laser processing techniques are being investigated to test the feasibility of laser beam-based atomic scale precision manufacturing. Furthermore, the recent progress in quantum simulations has promoted the development of the optical tweezer towards atomic scale manufacturing.**

Keywords—ACSM, throughput, resolution, atomic-scale precision, quantum products

I. INTRODUCTION

The continuing high-speed shrinking of feature size in the nanoscale product market has pushed conventional lithography to its intrinsic limits leading to the development of next-generation lithography techniques to meet the increasing demands of the industry. Gate-all-around structures have been expected to become mainstream device structures by 2025 with early introduction in 2022 as reported by International Roadmap for Devices and Systems (IRDS2022) [1]. Additionally, along with the move to three-dimensional circuits manufacturing processes are required to achieve sub-nanometre accuracy which is being enabled by the development of heterogeneous integration techniques [1]. Although NGL techniques have advanced the achievable resolution capabilities, Extreme Ultraviolet Lithography (EUVL) is quickly approaching its physical limit (5nm) and will not be able to manufacture functional structures with the increased structural complexity required by future-generation circuits [3]. The feature size of integrated circuit (IC) chips has already reached dozens of angstroms, which indicates that microchip development has reached a physical limit imposed by the quantised nature of matter at the sub-nanometre scale [4,5]. Future chips with functional features at sub-10nm and even atomic scale are expected to take the place of IC chips in the next 50 years as IC chips will meet the technological challenges in establishing interconnections and minimising current leaks when required for further miniaturisation [3]. The progressively increasing complexity and resolution of ICs and related systems is urgently driving the research and development of new microelectronics hardware design tools, and atomically precise manufacturing and metrology techniques [1].

Post-Moore Era (PME) chips, such as quantum, photonic, and DNA computing chips, have significantly better information processing, storage, and computing speed capabilities due to the unique features of superposition and entanglement. PME chips will require atomically precise features with an acceptable feature size variability of traditional IC chips, which is predicted to be at 3-4 silicon atoms [2]. The minimum feature sizes of capacitors and transducers for PME chips will reach a single atom. Single quantum dots and complex quantum logic gates pose technical challenges in the manufacture of quantum chips. Quantum dots with a diameter of 2 nm (~ 10 atoms per cluster) are distributed over atomically flat terraces separated by 0.22 nm increments. The current processing of quantum logic gates relies primarily on femtosecond laser direct writing technology, which can deposit energy in a transparent medium; however, accurate control of the splitting ratio and waveguide phase is difficult [2]. Early efforts to develop solid-state quantum computers with two nuclear spin states and a basic quantum bit using P atoms in a silicon crystal often require atomic precision positioning of each individual P atom into the silicon substrate. However, currently, the position accuracy of the dopant is ∼10 nm [4].

Overall, driven by the increasing demand for future chips and products, research, development and innovation of next-generation manufacturing techniques that can realise cost-effective, deterministic and scalable atomic-scale manufacturing through controllable material addition subtraction, and/or translation at the close-to-atomic scale and even atomic scale which has been defined as atomic and close-to-atomic scale manufacturing (ACSM) has become a mainstream trend and a hot research topic in the field of advanced manufacturing [4].

Although tip-based techniques such as STM and AFM allow the manipulation of single atoms due to their high degree of operational control they lack high throughput capabilities. One important technological bottleneck to enabling the production of features at the single-digit nanoscale is the lack of cost-effective, scalable, deterministic,

This is a peer reviewed, accepted author manuscript of the following conference contribution: Hafeez, H., Xie, W., & Luo, X. (2023). Atomic and Close-to-Atomic Scale Manufacturing: Status and Challenges. Paper presented at *28th International Conference on Automation and Computing (ICAC2023)*, Birmingham, United Kingdom.

rapid prototyping manufacturing techniques, which pose higher requirements for nanoscale next-generation lithographic methods in terms of process control, resolution capabilities, overlay alignment accuracy, and throughput [7]. On the other hand, although several techniques such as ALE and Atomic Layer Deposition (ALD) have exhibited high-throughput capabilities they still face technological challenges in manufacturing efficiency and accuracy [2].

For this reason, in this paper, the recent progress in potential techniques to enable ACSM of future chips and products, are analysed and summarized in terms of tip-based techniques, such as STM, AFM, and hybrid techniques represented by Field Emission Scanning Probe Lithography (FE-SPL). Additionally, particle beam-based processes like Focussed Electron Beam Deposition/Etching (FEBD/E), and Focused Helium Ion Beam (FHIB) Lithography and Chemical self-limiting processes include ALE and ALD are discussed. Finally, several laser-based processes, including Laser-Induced Desorption (LID), and optical tweezers, are summarized. On this basis, the perspectives of the research and development of ACSM techniques are drawn.

II. TIP-BASED TECHNIQUES

Tip-based techniques are usually performed on a scanning probe microscope (SPM) to carry out nanofabrication by using the tip to create a pattern on a substrate [12, 13]. They have enabled innovation in maskless and close-to-atomic scale fabrication using STM and AFM [40]. SPM tips can image and control environments on a substrate surface at the sub-nanometre scales and even atomic scale [12, 13]. SPL methods are very attractive techniques to enable ACSM as they have excellent process control abilities and are simple and direct fabrication techniques [10]. They are relatively inexpensive and could enable the study of materials and processes at the nanoscale and atomic scale with unparalleled ease [11].

A. Scanning Tunnelling Microscopy

Scanning Tunnelling Microscopy (STM) allows both imaging and patterning of substrate materials and is the very first technique that was employed for material manipulation at atomic scale. This was using Xe atoms on a Ni surface after which experiments were conducted on a range of other conductive materials [3,4]. STM uses a conductive tip usually made from tungsten (W) or iridium platinum–iridium (Pt-Ir) alloy. When the tip is brought to the position with a distance of a few atomic diameters from the substrate, an applied voltage will be imposed to allow electrons to tunnel through the vacuum created between the tip-sample distance, this is known as 'quantum tunnelling'. The high sensitivity of the tunnelling current allows it to act as a feedback signal to control the gap and measure extremely small distances at the sub-atomic order [4]. The tip-sample interaction is sensitive to the proximity of the STM tip and substrate surface, allowing for the manipulation of single atoms, making it possible to measure the physical/chemical properties of atoms. The atoms can be manipulated by both lateral and vertical manipulation which is parallel or in a normal direction to the surface respectively as shown in Figure 1. [3,4].

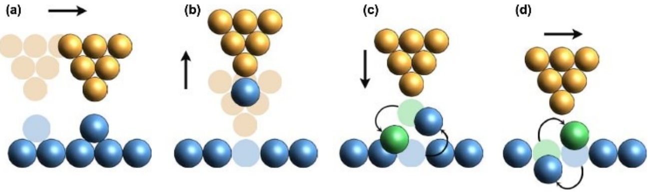

Figure 1. STM tip-based atom manipulation processes. (a) Vertical manipulation, (b) lateral manipulation, (c) vertical interchange, (d) lateral interchange. Reproduced from [3].CC BY 3.0.

STM-based atom manipulation has been used to prototype atomically precise devices, such as superconducting wires, quantum dots, and single-atom transistors, and to study quantum phenomena like electron resonators, induced chemical reactions at the single molecular level, and quantum corrals [4]. However, STM-based atom manipulation usually requires extreme environmental conditions, such as ultra-high vacuum and cryogenic operating temperatures, and capital-intensive and complex equipment. Moreover, it is also limited to conductive materials and has a low throughout due to the nature of single-atom manipulation by a single tip [4].

B. Hydrogen Depassivation Lithography

Hydrogen Depassivation Lithography (HDL) is an STM-based electron-beam (e-beam) lithography variant in which an electron source (the STM tip) provides a very small spot of electrons on a surface and self-develops a resist [5]. When the tunnelling current passes through the tip-sample gap, the Silicon (Si)-Hydrogen (H) covalent bonds are broken due to electron interaction, allowing H atoms to escape from the surface [3]. Rather than electro or magnetic deflection, the tip/beam is manipulated mechanically [5]. The H atoms are removed from the surface site-by-site by scanning the tip [3]. HDL is a variable-spot-energy, vector-scan, e-beam lithography tool. Electron-stimulated desorption is used to self-develop the H resist. A short high-temperature annealing is followed by an H passivation process in which atomic H is deposited on the Si surface at 350 °C [5]. The position and degree of desorption can be adjusted parametrically by tip scanning and tunnelling current, allowing the possibility for automation [3]. HDL is atomically precise when operated in low bias at 2-5V [5].

HDL can be used for patterned deposition of donor dopants to create tunnelling contacts, electrostatic gates, and 2D superlattices that can be used to prototype analogue quantum simulation devices for applications in studying solid-state quantum physics. Gates to set the spin state of qubits, control interaction between them, and fabrication of Single Electron Transistors (SETs) are all possible with HDL [5].

A throughput of 0.0042 $\mu m^2/h$ can be achieved through STM-based HDL at a resolution of 7.68 Ångstroms, which is too low to even make photomasks. An ultra-high vacuum environment and the use of conductive materials (Si is the most used to date) are also required. Additionally, STM based HDL can is usually difficult and unreliable with frequent tip crashes [5].

C. Scanning Tunnelling Electron Microscopy

Scanning Tunnelling Electron Microscopy (STEM) is a combination of Tunnelling Electron Microscopy and Scanning Electron Microscopy where a substrate is scanned using a highly precisely focused electron beam in a raster pattern. In-situ imaging takes place using the signal generated from the interaction between the beam and the atoms on the substrate. STEM has a spatial resolution of 0.2nm for atomic scale images. STEM is still in the early stages of development compared to STM and TEM but allows atomic-level imaging and the study of atomic-scale interactions and physics of materials [4,17].

The main problem with STEM enabling ACSM is that it does not offer a degree of control over atom movement that is comparable to STM as atoms can move in imaging [4,17]. When used to manipulate Silicon atoms in monolayer graphene it was reported that there was reduced control of the Si movement which can either jump in the wrong direction or across a few lattice sites [4, 17]. Further work is required to improve the degree of control of the electron beam by making it programmable, improving reliability, and the robustness of the process. Better control could open possibilities for new classes of materials for quantum applications [17].

D. Atomic Force Microscopy

Atomic Force Microscopy (AFM) is a versatile scanning probe lithography technique that can be used on a variety of materials, including semiconductors, metals, and insulators [3]. AFM uses the interaction force between the atomically sharp tip attached at the end of the cantilever and the substrate for imaging and metrology. Cantilever displacement can be used to characterise and measure the interaction between the tip and substrate surface. Three main operating modes are contact mode where the tip touches the surface, non-contact mode where the tip oscillates above the surface at 30-150Å, and tapping mode where the tip touches the surface briefly [4].

AFM-based atom manipulation includes two main operating modes, namely, lateral, and vertical manipulations, similar to STM. However, distinguished from STM, In AFM-based vertical manipulation, the threshold for the interaction was decreased below a specific point thermally activated interchange of atoms takes place. The operational time of this method is quicker by a factor of 10 compared to STM [4].

AFM-based lithography techniques have many advantages over STM tip-based processes, such as superior material processing capabilities with the ability to use non-conductive materials, no vacuum, or cryogenic temperatures required, simpler operating equipment, and the ability to fabricate complex patterns [4]. However, AFM also suffers from a low throughput, due to the inherent nature of the tip-based scanning process.

E. Field Emission Scanning Probe Lithography

Field Emission Scanning Probe Lithography (FE-SPL) is a hybrid technique based on an AFM which integrates Scanning Electron Microscopy (SEM) and a Focused Ion Beam (FIB) system, as shown in Figure 2. Electron Beam Induced Deposition combines electron beam lithography with a scanning probe tip-based fabrication process allowing sub-nanometre fabrication [6]. This hybrid platform allows three-dimensional tip-based scanning probe nanofabrication and imaging combined with traditional electron/ion beam nanofabrication and analysis tools [6]. Boasting eleven degrees of freedom, with the use of active cantilevers, the fabrication of nanostructures takes place with in-situ imaging. This hybrid technique potentially enables high-speed imaging with a sub-nanometre resolution and has far more varied capabilities than a stand-alone instrument and can be utilized to fabricate atomic-size devices that would otherwise be impossible. [6].

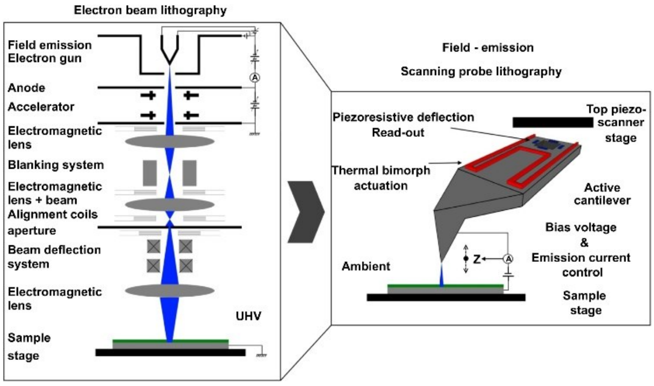

Figure 2 Traditional EBL to a new novel field-emission scanning probe lithography (FE-SPL) system. Reproduced from [7]. CC BY 4.0.

FE-SPL uses a low energy electron field which is emitted from the ultra-sharp tips of active scanning probes located a short distance close to the covered resist-covered sample. Highly confined reactions are induced in the resist layers and combined with pattern transfer techniques such as cryogenic etching [6,8]. This has enabled single digit nanofeature patterning with an effective quantum dot size of below 2nm [8].

The quick shift from AFM mode to field emission mode with low energy electrons (50eV) from the cantilever tip allows for the precise deposition of nano-features. It can be used to investigate aspects that influence deposition qualities such as electron-gas interactions for different precursors, the effects of gas pressure, and substrate temperature [6].

FE-SPL has lower costs, allows closed-loop operations, and operation in both vacuum and ambient conditions. Additionally, high overlay accuracy can be achieved, with direct writing capabilities. It is an easy method to expose electrons to a substrate. High-resolution and highly selective direct patterning can be easily achieved for single-digit devices. It is suitable for rapid nanoscale prototyping, and by using probe-based high-accuracy alignment, step-and-repeat, multistep, and multilayer lithography can be achieved. [6-9].

As with all tip-based techniques, the issue of low throughput must be addressed using parallel probes, increasing imaging areas, and capturing high frame rates for high-speed scanners through changes to the scanner system as suggested by Rangelow et.al [8].

III. PARTICLE BEAM-BASED TECHNIQUES

Particle beam-based processes using electron or ion beams are direct writing techniques that eliminate the need for a mask by directly patterning onto the photoresist material allowing for higher-resolution nanoscale patterns to be achieved [10,14]. Conventional EBL already allows arbitrary sub-10-nm patterns to be fabricated down to 1nm precision [16]. The focused beam is scanned in a controlled manner across the substrate (which is covered in an e— beam resist) and used like a ‘pencil’ to write on the film of the resist before being transferred onto the substrate using an etching process [14].

A. Focused Electron Beam Based Fabrication Processes

Focused Electron Beam based processes that have the potential for atomic scale patterning include Focused Electron Beam Etching (FEBE) and Focused Electron Beam Deposition (FEBD) with the current electron beam spot size at 0.1 nm^3 [3]. In e-beam processes, electrons in the bonds of materials are excited because of inelastic scattering which changes the structure of the material through bond breakage. When applied in precursors it enables deposition or etching [3]. Beam-induced chemical etching uses a gaseous precursor flowing over a substrate in a vacuum chamber, and an electron beam (delivered by SEM or STEM) is used simultaneously to dissociate adsorbates and generate reactive fragments which finally leads to etching or deposition [3,4]. In FEBD and FEBE, surface atoms will react to transform into volatile compounds, thereby inducing etching or non-volatile dissociations to form the deposition material respectively [3]. In two-dimensional materials, atomic patterns can be also created, and atomic scale defects can be manipulated through high-energy exposure of a single target atom to cause displacement and then manipulation by the e-beam to move the atom to the target site [3].

B. *Focused Helium Ion Beam*

Focused Helium Ion Beam (FHIB) is also a potential lithography tool enabling ACSM due to the development of low-temperature ion sources and the ability to produce ion beams with sub-nanometre spot sizes [3]. The needle-shaped helium ion sources made from single crystal metals have tips that measure a few atoms giving FHIB its ultra-fine spot size. The small atomic radius of helium has many advantages. It allows deeper implantation into substrate materials, reduces scattering at the surface giving a high lateral resolution. Additionally, less damage occurs and there is no additional deposition [3,4].

Sub-10nm patterning and features have already been demonstrated using FHIB although single atom feature size and precision are difficult to obtain in bulk substrates, which is promising to be solved by using two-dimensional (2D) materials like graphene and metal dichalcogenides which have a few atomic layers of thickness [4]. Challenges remain however with reducing the precision level below the sub-nanometre range and the effects of heating and deformation on the substrate surfaces need to be well-controlled [4].

IV. CHEMICAL SELF-LIMITING TECHNIQUES

Atomic Layer Etching (ALE) and Atomic Layer Deposition (ALD) are two main chemical self-limiting techniques with the potential to enable ACSM, due to their much larger scale of materials processing than tip-based techniques, and their self-limiting characteristics.

A. *Atomic Layer Etching*

Atomic Layer Etching (ALE) usually employs a sequence that alternates between self-limiting chemical modification processes [4], as shown in Figure 3. As described by Gao *et.al* each cycle of the ALE process consists of two reaction phases. The first reaction alters the surface layer by adsorption of precursors, and the second eliminates the reaction layer by using energy species, typically, a beam of low energy ions. Purge procedures separate these two phases in order to remove unnecessary precursors and by-products. The highest interlayer chemical bonds are weakened by the first process's chemical reactions and entirely disrupted by the second process's ionic bombardment [3]. Currently Si and hafnium oxide (HfO2) substrates with different reactants and energetic ions have been used [4].

In comparison to continuous reactive ion etching (RIE), ALE can be used to obtain the atomically precise surface or structure atomic-scale surface roughness and no subsurface damage. The ability to manage the adsorption and reaction portions of the process is an especially difficult challenge with self-limited ALE. An absorption layer is normally produced uniformly on the substrate's surface. The reaction is critical, with the threshold energy set to etch only the target materials and no other reactor materials. However, optimal atomically precise surfaces remain difficult to obtain owing to issues with selectivity, net deposition loss, surface modifications, and spontaneous etching [4]. There are no currently developed methods for error correction even though error detection is possible through inspection [5].

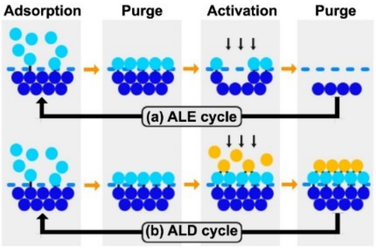

Figure 3 Chemical self-limiting processes (a) one cycle of ALE, (b) one cycle of ALD. Reproduced from [3]. CC BY 3.0.

B. *Atomic Layer Deposition*

Atomic-layer deposition (ALD) is a sequential self-limiting chemical vapor deposition (CVD) process that is cyclic [4, 5]. ALD has four steps, including adsorption, purge, activation, and finally purge again as shown in Figure 3. Pulsed gaseous precursors that are pumped into the chamber react with the substrate and react with the surface in a self-limiting process [4]. In the third step the precursor introduced is a different type (counter reactant) and is what forms a single layer of material on the substrate surface [3]. As with ALE the purge processes remove the unreacted precursors and by-products [4]. ALD can also use plasma or heat energy to speed up the chemical reaction process. Using plasma sources can start the chemical process at lower temperatures while maintaining improved film characteristics. Selective ALD can also be performed for chemical patterning by the modification of surface characteristics of substrate materials to allow patterning in selected regions [3].

The deposition in ALD is very well controlled and uniform due to the self-limiting nature of the process. It is easy to reproduce accurate thin films over the substrate due to no uniform flux being required. It is also easy to control the thickness of the layers of deposited material allowing an overall high level of manufacturing precision [5]. Large area fabrication on a variety of materials is possible with ALD without being confined by linewidth. It also has excellent conformity for high aspect ratio and three-dimensional structures, and no shadowing effects take place. ALD has found applications for the fabrication of devices, such as n-type metal oxide semiconductor epitaxy, fin field-effect transistors, high-k, and metal gates [4].

V. LASER-BASED TECHNIQUES

Laser based techniques on all scales have allowed the processing of a very wide range of materials (almost all materials) through the main material removal mechanisms of ablation, coulomb explosion, and atomic desorption at the different scales demonstrated in Figure 4. Addition, subtraction, and modification of material properties is all possible. Laser based techniques have larger outputs than

STM and tip-based techniques, do not produce surface defects like in ALE, and high levels of process control is easily achieved [18]. Ultrashort pulsed infrared femtosecond and UV nanosecond lasers have both been used in studies to attempt to achieve ablation and material modifications at single atomic layers [19,20].

A. *Laser-Induced Desorption*

Atomic desorption is the main mechanism of laser-based material removal at the atomic scale where only bonds at the topmost layer are broken. This happens through excitations and the evolution of the electronic state of the atoms dynamically. Quantum mechanics is in effect at this scale which is influenced by multiple different material characteristics [18]. Enabling controllable laser machining at the atomic scale requires the determination and optimisation of suitable parameters to achieve a sufficient excitation by single photon due to the ability to use multiple pulse widths to achieve atomic scale precision [18]. Additionally, further research is required into the impact of material properties at atomic scale on the laser machining process, such as minimal removal rate. The controllability and repeatability of the removal process is difficult due to the sensitivity of the atomic bond evolutions to small perturbations and can be improved for robustness by methods that modify the electronic states or band structures. Improving surface integrity to an acceptable level for crystalline solids could be achieved through lasers with shorter wavelengths. Beam shaping technology can also be enhanced further to increase the laser field control for better resolution [18].

B. *Optical Tweezers*

Optical tweezers are tools (light beams) which were originally developed in 1970 by Arthur Ashkin for manipulation of particles for the purpose of experimental studies. They have since been developed for other purposes like manipulation of biological molecules and laser atom cooling. Nano-optical tweezers have more recently been developed that can trap single molecules and atoms allowing the bottom-up assembly of systems built from a few atoms [21-22,24]. Light is used to trap or manipulate single molecules or even atoms by exerting a force on them. However, this becomes increasingly difficult as the size of a particle decreases but with the use of nano-optical tweezers multiple different methods have been experimented with to successfully trap molecules such as by using optical resonance to keep electric field intensity below sub-wavelength volumes [22].

Nano-tweezers are one of the best tools for studies of atomic interactions due to the flexibility and minimisation of interference in experiments [22]. They can also be used for lithography, assembly of microscopic circuits, spectroscopy, micro-rheology and photonic force microscopy, and lab-on-a-chip devices. A current and upcoming application of nano-tweezers is for quantum simulation and information processing to create arrays of trapped ions (qubits) for trapped ion quantum computing applications [21-25]. The integration of optical tweezing with holographic tweezing has also allowed increased applications in assembly of macroscopic devices and sorting of macroscopic particles. The dynamic position control offered by holographic optical tweezers can be used for quantum logic applications [21]. Additionally, the National Institute of Standards and Technology (NIST) and Joint Institute for Laboratory Astrophysics (JILA) in Colorado, USA, have also developed an atomic clock using laser tweezers to trap, control, and isolate atoms to enhance the clock's performance for future quantum applications showcasing the promising applications of this technique in furthering quantum technologies [23].

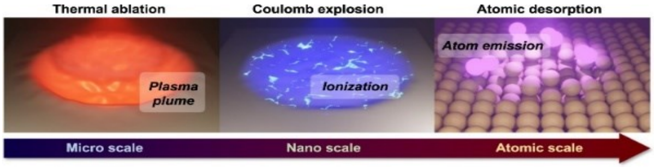

Figure 4 Laser material removal mechanisms at different scales. Reproduced from [18]. CC BY 4.0.

VI. DISCUSSION AND CONCLUSION

A. *Challenges and Future Perspectives*

In order to establish industrial viable ACSM techniques for future chips and the next generation of nanoscale and quantum products demanded by the market, it is critical to address both theoretical and techniques challenges in research, development, and innovation of innovative manufacturing techniques.

- A significant improvement in the throughput, process control capabilities, and resolution of ACSM techniques is still required for achieving cost-effective, deterministic, and scale-up manufacturing at the sub-10nm and even atomic scale.
- Tip-based techniques are still suffering from low throughput.
- Greater process control is required for particle beam-based processes including STEM and FEB processes to control the electron beam and increase resolution capabilities.
- ALE requires better process control capabilities to reduce errors resulting in a higher yield, and to be able to obtain true atomic-scale precision.
- ALE also has extremely difficult challenges in controlling the etching behaviour near the processing window and requires advancements in ALE chemistries and processes through optimizing ion energy and etch chemistry which can also improve the process throughput [28].
- Some technical challenges remain with selective ALD as it does not yet produce uniform, and complete layers consistently. A corrective step is also required for selective ALD.
- For the continued development of laser-based techniques towards atomic scale fabrication suitable parameters need to be determined and optimised. Controllability, repeatability, and surface integrity also require improvement to achieve greater processing control at the atomic level.

Future research perspectives:

- Most processes till now have predominantly focused on 2D surface features with some limited 3D capabilities at the atomic scale [25]. More efforts will be needed to enable the rapid prototyping of 3D features and atomically precise 3D fabrication.
- The development of selective ALD and anisotropic ALE processes has been identified as a key technology in enabling

3D fabrication for devices with high-aspect-ratio structures. The development of anisotropic ALE is important and will be required to meet the requirement of high-precision lateral etching for these structures and to act as a correction step for selective ALD [29,30]. Understanding how anisotropic ALE processes can create vertical profiles is a critical next step for this technology [26].

- Some technical challenges also remain with selective ALD as it does not yet produce uniform, and complete layers consistently. Additionally, the effects of processing parameters for the etching of 3D structures have not yet been clearly defined and will need further investigation [27].
- A hybrid technique combining the strengths of current ACSM processes can open up possibilities to overcome limitations of the standalone processes to achieve 3D atomic scale fabrication through the development of a process control algorithm for chemical bond formation and/or breakage.

B. Conclusion

As PME chips and quantum technologies advance, the demand for atomically precise features and manufacturing processes will increase. Hybrid approaches have been identified as promising candidates to meet the demands of having highly reliable and precise manufacturing processes. They also have the potential to pave the path forward to achieve true 3D atomic scale fabrication.

DATA STATEMENT

All data is provided in full in the reference section of this paper.

ACKNOWLEDGMENT

The authors would like to thank EPSRC (EP/V055208/1 and EP/X021963/1) for their support to this research.

REFERENCES

[1]. International roadmap for devices and systems (IRDS™) 2022 edition [Internet]. IEEE IRDS™. 2022 [cited 2023Apr24]. Available from: https://irds.ieee.org/editions/2022

[2]. Fang F. Atomic and close-to-atomic scale manufacturing: Perspectives and measures. International Journal of Extreme Manufacturing. 2020;2(3):030201.

[3]. Gao J, Luo X, A3:D13 Fang F, Sun J. Fundamentals of atomic and close-to-atomic scale manufacturing: A Review. International Journal of Extreme Manufacturing. 2021;4(1):012001.

[4]. Fang F, Zhang N, Guo D, Ehmann K, Cheung B, Liu K, et al. Towards atomic and close-to-atomic scale manufacturing. International Journal of Extreme Manufacturing. 2019;1(1):012001.

[5]. Randall JN, Owen JHG, Fuchs E, Lake J, Von Ehr JR, Ballard J, et al. Digital atomic scale fabrication an inverse Moore's law – a path to atomically precise manufacturing. Micro and Nano Engineering. 2018Nov7;1:1–14.

[6]. Holz M, Reuter C, Reum A, Ahmad A, Hofmann M, Ivanov T, et al. Atomic Force Microscope integrated into a scanning electron microscope for fabrication and metrology at the nanometer scale. Photomask Technology 2019. 2019;

[7]. Kaestner M, Rangelow IW. Scanning probe lithography on Calixarene towards single-digit nanometer fabrication. International Journal of Extreme Manufacturing. 2020;2(3):032005.

[8]. Rangelow IW, Ivanov T, Ahmad A, Kaestner M, Lenk C, Bozchalooi IS, et al. Review article: Active scanning probes: A versatile toolkit for fast imaging and emerging nanofabrication. Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena. 2017;35(6).

[9]. Rangelow IW, Ahmad A, Ivanov T, Kaestner M, Krivoshapkina Y, Angelov T, et al. Pattern-generation and pattern-transfer for single-digit Nano Devices. Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena. 2016;34(6).

[10]. Hasan, R.M.M, 2020. Nanoelectrode Lithography: Modeling, Experimental Validation, and Instrumentation. Ph.D. University of Strathclyde.

[11]. Teresa, J., 2020. Nanofabrication. IOP Publishing Ltd.

[12]. Garcia, R., Knoll, A. and Riedo, E., 2014. Advanced scanning probe lithography. Nature Nanotechnology, 9(8), pp.577-587.

[13]. Fan, P., Gao, J., Mao, H., Geng, Y., Yan, Y., Wang, Y., Goel, S. and Luo, X., 2022. Scanning Probe Lithography: State-of-the-Art and Future Perspectives. Micromachines, 13(2), p.228.

[14]. Feldman, M., 2014. Nanolithography. Woodhead Publishing Limited.

[15]. Papadopoulos, C., 2016. Nanofabrication. Cham: Springer International Publishing.

[16]. Sahin, O., Ashokkumar, M. and Ajayan, P., 2018. Micro- and nanopatterning of biomaterial surfaces. Fundamental Biomaterials: Metals, pp.67-78.

[17]. Kalinin SV, Borisevich A, Jesse S. Fire up the atom forge. Nature. 2016Nov24;539(7630):485–7.

[18]. Wang J, Fang F, An H, Wu S, Qi H, Cai Y, et al. Laser Machining Fundamentals: Micro, Nano, atomic and close-to-atomic scales. International Journal of Extreme Manufacturing. 2023;5(1):012005.

[19]. An H, Wang J, Fang F. Material removal on silicon towards atomic and close-to-atomic scale by infrared femtosecond laser. Materials Science in Semiconductor Processing. 2023;158:107368.

[20]. An H, Wang J, Fang F. Removal of sic at atomic and close-to-atomic scale by Nanosecond Ultraviolet Laser. Optics & Laser Technology. 2023Feb;158:108863.

[21]. Kolbow JD, Lindquist NC, Ertsgaard CT, Yoo D, Oh SH. Nano-optical tweezers: Methods and applications for trapping single molecules and nanoparticles. ChemPhysChem. 2021;22(14):1408–.

[22]. Andersen MF. Optical tweezers for a bottom-up assembly of few-Atom Systems. Advances in Physics: X. 2022;7(1).

[23]. Jila's bigger and better 'Tweezer clock' is super stable [Internet]. NIST. 2021 [cited 2023Apr28]. Available from: https://www.nist.gov/news-events/news/2020/12/jilas-bigger-and-better-tweezer-clock-super-stable

[24]. Stuart D. Manipulating single atoms with optical tweezers - university of oxford [Internet]. 2014 [cited 2023Apr28]. Available from: https://www2.physics.ox.ac.uk/sites/default/files/2011-08-02/dustin_thesis_twoside_pdf_66412.pdf.

[25]. Jesse S, Borisevich AY, Fowlkes JD, Lupini AR, Rack PD, Unocic RR, et al. Directing matter: Toward atomic-scale 3D nanofabrication. ACS Nano. 2016;10(6):5600–18.

[26]. T. Carver C, J. Plombon J, E. Romero P, Suri S, A. Tronic T, B. Turkot R. Atomic Layer Etching: An industry perspective. ECS Journal of Solid State Science and Technology. 2015Feb20;4(6).

[27]. Dallorto S. Enabling control of matter at the atomic level: Atomic Layer Deposition and Fluorocarbon-based Atomic Layer etching [Internet] [thesis]. 2019. Available from: https://core.ac.uk/download/pdf/286889059.pdf

[28]. None N. Workshop on Ultra-Precision Control for ultra-efficient devices (workshop report). 2022Feb9;

[29]. Kim DS, Kim JB, Ahn DW, Choe JH, Kim JS, Jung ES, et al. Atomic layer etching applications in nano-semiconductor device fabrication. Electronic Materials Letters. 2023Mar11;

[30]. Shinoda K, Miyoshi N, Kobayashi H, Miura M, Kurihara M, Maeda K, et al. Selective atomic-level etching using two heating procedures, infrared irradiation and ion bombardment, for next-generation semiconductor device manufacturing. Journal of Physics D: Applied Physics. 2017;50(19):194001.