Scanning Probe Lithography

Subjects: Engineering, Manufacturing

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High-throughput and high-accuracy nanofabrication methods are required for the ever-increasing demand for nanoelectronics, high-density data storage devices, nanophotonics, quantum computing, molecular circuitry, and scaffolds in bioengineering used for cell proliferation applications. The scanning probe lithography (SPL) nanofabrication technique is a critical nanofabrication method with great potential to evolve into a disruptive atomic-scale fabrication technology to meet these demands.

nanofabrication | scanning probe lithography (SPL) | scanning probe microscopy (SPM) | nanostructures

1. History of Scanning Probe Lithography (SPL)

The generic scanning probe microscope (SPM) is a branch of microscopy that employs a physical tip to scan the workpiece surface to reveal its topography. SPM is a versatile instrument that has been thriving since its invention in 1981 by Binning and Rohrer, leading them to win the Nobel Prize in 1986 [1]. The invention of SPM not only marked the birth of new technology for imaging and analyzing material surface at the nanoscale, but also triggered an unprecedented innovation for maskless nanofabrication or even close-to-atomic scale fabrication via the two most popular family members of SPMs: scanning tunneling microscope (STM) and atomic force microscope (AFM).

The precedent of close-to-atomic scale fabrication dates back to 1990. Eigler and Schweizer posited an atomic-scale logo of IBM by manipulating Xe atoms on a Ni workpiece for the first time by employing STM [2]. Thereafter, AFM was first utilized as a powerful machine tool to modify the material surface, such as a polycarbonate surface in 1992 [3] and a gold surface in 1997 [4]. Undergoing nearly 30 years of development, the family of SPMs has expanded rapidly, leading to innovations such as electrostatic force microscopy (EFM) [5], magnetic force microscopy (MFM) [6], fluidic force microscopy (FluidFM) [7], piezoresponse force microscopy (PFM) [8], etc. Consequently, a variety of SPL nanofabrication techniques now exist that can offer atomic manipulation, electric field emission, chemical diffusion, electrochemical reaction, thermal deposition, and mechanical scratching. To date, the SPL nanofabrication technique has been deemed a practical method to implement nanofabrication and close-to-atomic scale fabrication.

2. Application of SPL Nanofabrication Technique

2.1. Nanofluidic Science

Nanofluidic channels play a pivotal role in the field of nanofluidic science, which can offer a physical confinement environment to manipulate and analyze DNA [9] and single molecules [10]. Since the birth of the SPL nanofabrication technique, it has emerged as a rapid and flexible approach to fabricate arbitrary structures of nanofluidic channels in comparison with the previous expensive and complex EBL and FIB methods. For example, Hu et al. [11] utilized the SPL nanofabrication technique to directly fabricate an etch mask by depositing polymer nanowires on the Si surface. The nanostructures on the Si surface via single step etching were employed as a mold for the mass production of polydimethylsiloxane (PDMS) nanofluidic channel. Furthermore, a PDMS nanofluidic channel with both straight and curvilinear structures was fabricated by utilizing the SPL nanofabrication technique. Meanwhile, the SPL nanofabrication technique showed remarkable compatibility with the current nanofabrication approach.

2.2. Biomedical Application

A critical application of the SPL nanofabrication technique is to characterize the mechanical, physical, and chemical properties of cells, proteins, scaffolds [12], and 2D biological tissue/thin film [13]. Researchers employed SPM to trigger nano-indentation to establish the indentation model, the so-called Hertzian contact model, by extrapolating the mechanical compliance between tip and specimen. To this end, the elastic–plastic deformation related to linear elastic deformation of the uploading curve was measured [14]. Additionally, several physical chemistry reactions occurring at the interface between cells and scaffold were studied. Subsequently, the SPL nanofabrication technique was applied to modify the surface of the scaffold to govern cell response. Moreover, the SPL nanofabrication technique was referred to in order to have the capability to deliver nanoparticles and nanofibers using the tip as a drug carrier [15].

2.3. Quantum Computing and Data Storage Device

The technique of close-to-atomic scale SPL has been applied in various research aspects, such as quantum dot machining and single-atom data storage device machining. For example, Stefan et al. [16] employed STM to create quantum dots of single-atom precision fixed by a 2 × 2 In-vacancy reconstructive InAs (111) template surface, which was effective at controlling the position of quantum dots with zero error. The specified location of the quantum dots consisted of a chain of ionized In adatoms moved by using vertical atom manipulation of STM.

Cyrus et al. [17] succeeded in storing the data in bits in one magnetic atom. They used the STM atom manipulation technique to place an Fe or Mn atom on the non-magnetic copper-nitride film surface and created a structure of a single magnetic Fe or Mn atom surrounded by non-magnetic atoms, which could align the magnetic moment along one direction and overcome the superparamagnetic limit. Additionally, magnetic anisotropy in just one atom was also observed for the first time.

2.4. Nanoelectronics

Nanoelectronic devices with sizes ranging from 1 nm to 100 nm are essential components for nanoelectronics, such as silicon metal-oxide-semiconductor field-effect transistors (MOSFET), fin field-effect transistors (FinFET), single-electron transistors (SET) [18], and molecular circuits [19]. Lately, several strong applications in the fabrication of SET operating at room temperature (RT) have been presented by using the SPL nanofabrication technique as opposed to the previously presented transistors operating at cryo-temperatures [20]. For example, Durrani et al. [21] employed the SPL nanofabrication technique to fabricate the $Si/SiO_2/Si$ point-contact tunnel junctions with sub-10 nm size, which could achieve a deeper quantum dot potential well confinement up to 2 eV. The state of the art makes it possible to operate the SET under RT.

3. Challenges and Outlook

The SPL nanofabrication technique has already demonstrated remarkable fabrication capabilities for 2D/3D nanostructures, nanocomponents, and even single-atom memory devices. It has been successfully applied in quantum computing, nanoelectronics, and nanofluidics devices. However, there are two major challenges that have limited the commercialization of the SPL nanofabrication technique.

The first challenge is the low processing efficiency. The SPL nanofabrication technique is based on an SPM platform that is basically designed for measurement purposes in a lab environment. Due to the high precision requirement, the SPL nanofabrication technique is only used for proof-of-principle experiments so far instead of mass industrial production. In other words, it is still a high-value manufacturing method rather than a high-volume manufacturing method. For example, researchers have manufactured quantum wells and single-electron transistors (SET), which only prove that the machining precision of the SPL nanofabrication technique can meet the requirement beyond what is required for making nanoelectronic devices. In order to move towards industrial application, a necessary prerequisite is to enhance the processing efficiency dramatically. To solve this problem, recently, a new SPL nanofabrication strategy has been proposed by using a structured AFM tip [22]. With such a tool prepared by FIB, three-dimensional sin-shaped ripples were achieved with high-precision surface quality [23]. It proves the scalability of the SPL technique to fabricate nanoscale periodic patterns. Furthermore, a mix-and-match lithography approach by combining the SPL nanofabrication technique and existing nanofabrication techniques, such as wet etching, dry etching, the lift-off process, NIL, FIB, and EBL, will be a better choice to approach mass industrial production [24].

Another challenge is the smallest achievable feature. The processing structure is restricted by the size of the region where mechanical interaction or chemical reaction occurs, which is normally directly related to the tip radius. To further reduce the feature size to close-to-atomic scale, the challenge lies not only in the tip size and control and elimination of environmental effects, but also in the fundamental understanding of the manufacturing process, which is based on quantum theory rather than the continuum theory [25]. Therefore, future studies on close-to-atomic scale SPL could focus on the reduction of the interaction region by using sharper tips, reasonable material selection and preparation, environmental control, etc., as well as on the theoretical and simulation study of SPL fabrication to reflect the true determinants of the feature size to allow effective control. In addition, atomic-scale patterns are normally accompanied by weak structural stability due to a low atomic diffusion barrier caused by surface chemical reactivity and structural properties. To allow a stable and long-lasting function, the desired pattern needs special consideration of both materials and atomic structures. On the premise of ensuring processing efficiency, further reduction of the lateral dimension of the nanostructure is a thought-provoking question to realize industrial-scale production.

4. Concluding Remarks

Herein summarized the state of the art and future perspectives of scanning probe lithography techniques. The fabrication mechanism, research status, and merits and drawbacks of different SPL approaches were concluded here. The conclusions drawn are follows:

- The SPL nanofabrication technique is a unique technique offering low-cost, high-value manufacturing while achieving atomic-scale precision. It offers additional advantages such as not requiring a mask and allows direct writing on the substrate by means of various chemical, physical, diffusive, and deposition mechanisms.
- The SPL nanofabrication technique has largely been used at the laboratory level to fabricate nanoscale components at a scale envisioned by Nobel Laurette Richard Feynman, and was seen as a long-standing challenge back then even to achieve that level of precision at the nanoscale. With its current success, more efforts are required to enable commercialization of the SPL nanofabrication technique.
- A mix-and-match lithography approach by combining the SPL nanofabrication technique and the etching technique can pave the way to a cost-effective manufacturing method contrary to the currently used mass nanofabrication production techniques.
- The SPL nanofabrication technique is a critical nanofabrication method with great potential to evolve into a disruptive atomic-scale fabrication technology to meet the future demand for atomic manipulation of surfaces.

Abbreviations

SPL	Scanning probe lithography
SPM	Scanning probe microscopy
FIB	Focused ion beam
NIL	Nanoimprint lithography
EBL	Electron beam lithography
STM	Scanning tunneling microscope

AFM	Atomic force microscope
EFM	Electrostatic force microscopy
MFM	Magnetic force microscopy
FluidFM	Fluidic force microscopy
PFM	Piezoresponse force microscopy
PDMS	Polydimethylsiloxane
MOSFET	Metal-oxide-semiconductor field-effect transistor
FinFET	Fin field-effect transistor
SET	Single-electron transistor
RT	Room temperature

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