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Review on Micro- and Nanolithography Techniques and their Applications

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Abstract. This article reviews major micro- and nanolithography techniques and their applications from commercial micro devices to emerging applications in nanoscale science and engineering. Micro- and nanolithography has been the key technology in manufacturing of integrated circuits and microchips in the semiconductor industry. Such a technology is also sparking revolutionizing advancements in nanotechnology. The lithography techniques including photolithography, electron beam lithography, focused ion beam lithography, soft lithography, nanoimprint lithography and scanning probe lithography are discussed. Furthermore, their applications are summarized into four major areas: electronics and microsystems, medical and biotech, optics and photonics, and environment and energy harvesting.

Keywords: Nanolithography, photolithography, electron beam lithography, focused ion beam lithography, soft lithography, nanoimprint lithography, scanning probe lithography, dip-pen lithography, microsystems, MEMS, nanoscience, nanotechnology, nano-engineering.

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1. Introduction

For decades, micro- and nanolithography technology has been contributed to the manufacturing of integrated circuits (ICs) and microchips. This advance in the semiconductor and IC industry has led to a new paradigm of the information revolution via computers and the internet. Micro- and nanolithography is the technology that is used to create patterns with a feature size ranging from a few nanometers up to tens of millimeters. By combining lithography with other fabrication processes such as deposition and etching, a high-resolution topography can be produced while this cycle may be repeated several times to form complex micro/nanoscale structures. Lithography techniques are divided into two types by the use of masks or templates: masked lithography and maskless lithography. Masked lithography makes use of masks or molds to transfer patterns over a large area simultaneously, thus, enabling a high-throughput fabrication up to several tens of wafers/hr. The forms of masked lithography include photolithography [1-10], soft lithography [11-13], and nanoimprint lithography [14-21]. On the other hand, maskless lithography, such as electron beam lithography [22-29], focused ion beam lithography [30-33], and scanning probe lithography [34-44], fabricates arbitrary patterns by a serial writing without the use of masks. These techniques create patterns in a serial manner which allows an ultrahigh-resolution patterning of arbitrary shapes with a minimum feature size as small as a few nanometers. However, the throughput of this type is limited by its slow serial nature which makes it inappropriate for mass production.

Not only micro- and nanolithography has been the main driving technology in the semiconductor and IC industry, it also plays an increasingly important role in manufacturing of commercial microelectromechanical system (MEMS) devices [45-50] as well as prototype fabrication in emerging nanoscale science and engineering [51-56]. These applications are expected to significantly improve our quality of lives in many ways from electronic gadgets to healthcare and medical devices. Some examples of commercial MEMS products include MEMS accelerometers employed in automobiles and consumer electronic devices [45, 46], digital micromirror devices (DMD) for display applications in projectors and televisions [45, 47, 48], and MEMS pressure sensors for detecting pressures in car tires and blood vessels [49, 50]. Furthermore, nanoscience and engineering has increasingly contributed to conventional technologies by opening up alternative routes to overcome current technical barriers, to name a few of them, nanoelectronics for denser and faster computing, nanomedicine for diagnosis and treatment of many diseases including cancers [51-54], heart disease and Alzheimer's disease [55, 56], nanoelectromechanical systems for high-sensitivity and high-resolution sensing and manipulating, and nanobiosensors for ultra-low concentration and single molecular detection. Table 1 summarizes the specifications (i.e. minimum feature size and throughput) and applications of the major lithography techniques.

2. Micro- and Nanolithography Techniques

2.1. Photolithography

Photolithography has been the main workhorse in the semiconductor and IC industry [1-10]. It has been employed for pattern generation in manufacturing of ICs, microchips and commercial MEMS devices. This technique utilizes an exposure of a light-sensitive polymer (photo-resist) to ultraviolet (UV) light to define a desired pattern. Initially, UV light with wavelengths in the range of 193-436 nm is illuminated through a photomask that consists of opaque features on a transparent substrate (e.g., quartz, glass) to make an exposure on a photo-resist that is coated on a substrate [5, 6, 22]. In the exposed area, the polymer chains of photo-resist break down resulting in more soluble in a chemical solution called developer. Subsequently, the exposed photo-resist is removed in a developer to form the desired photo-resist pattern. Figure 1 depicts the schematic illustration of the main steps in photolithography. This patterned photo-resist can be used as a protective layer in subsequent etching or deposition processes to build topography on the substrate.

Table 1. Specifications and applications of the major lithography techniques.

Lithography Technique	Minimum Feature Size	Throughput	Applications
Photolithography (contact & proximity printings)	2-3 µm [22]	very high	typical patterning in laboratory level and production of various MEMS devices
Photolithography (projection printing)	a few tens of nanometers (37 nm) [2]	high - very high (60-80 wafers/hr) [1]	commercial products and advanced electronics including advanced ICs [1], CPU chips
Electron beam lithography	< 5 nm [23]	very low [1, 3] (8 hrs to write a chip pattern) [1]	masks [3]and ICs production, patterning in R&D including photonic crystals, channels for nanofluidics [23]
Focused ion beam lithography	~20 nm with a minimal lateral dimension of 5 nm [2]	very low [3]	patterning in R&D including hole arrays [125, 134], bull's-eye structure [132], plasmonic lens [137]
Soft lithography	a few tens of nanometers to micrometers [2, 13] (30 nm) [2]	high	LOCs for various applications [13, 96]
Nanoimprint lithography	6-40 nm [14, 15, 18]	high (> 5 wafers/hr) [1]	bio-sensors [17], bio-electronics [18], LOCs: nano channels, nano wires [97, 102, 104]
Dip-pen lithography	a few tens of nanometers [39, 40, 43]	very low – low, possibly medium [39]	bio-electronics [43], bio-sensors [40], gas sensors [42]

There are three forms of photolithography: contact printing, proximity printing and projection printing as schematically illustrated in Fig. 2 [1, 22]. Contact and proximity printings place the photomask in contact with or in a close proximity to the photo-resist. Generally, contact and proximity printings are capable of making patterns as small as a few micrometers. Therefore, they are typically used in the fabrication of moderate-resolution patterns especially in laboratories and small to medium-sized companies. It should be noted that photolithography in most of research works normally refers to contact or proximity printings. In contrast, a projection printing system (so-called 'stepper') utilizes an optical lens system to project a deep-UV pattern from an excimer laser (wavelength of 193 or 248 nm) on the photo-resist enabling pattern-size reduction by 2-10 times. It is capable of fabricating high-resolution patterns as small as a few tens of nanometers (37 nm) [2] at a high throughput (60-80 wafers/hr) [1]. However, it requires a sophisticated optical-lens system and precise control systems of temperature and position resulting in a very expensive setup. Thus, it is employed in manufacturing of advanced ICs and CPU chips. In recent years, immersion lithography [8], resolution enhancement technology [9] and extreme-UV lithography [10] have been developed to improve the lithography resolution of projection printing.

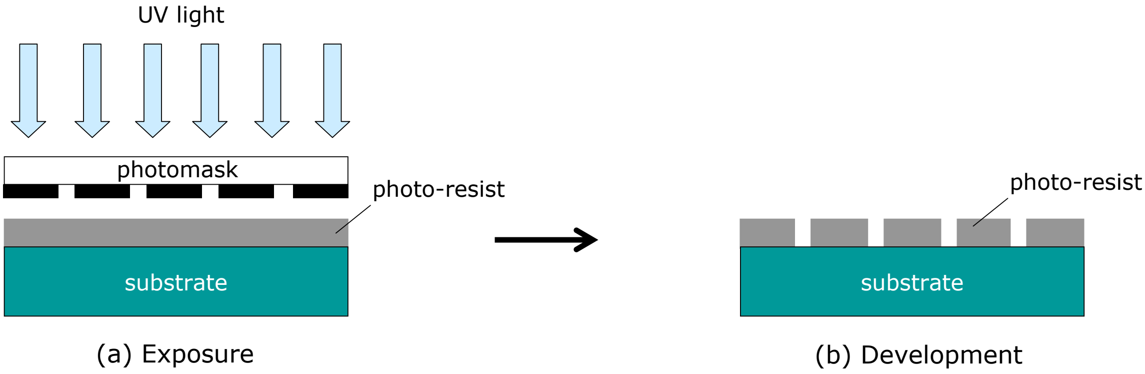


Fig. 1. Schematic illustration of the main steps in photolithography. (a) exposure step: photo-resist coated on the substrate is exposed to UV light, (b) development step: the exposed photo-resist is removed by immerging into a developer.

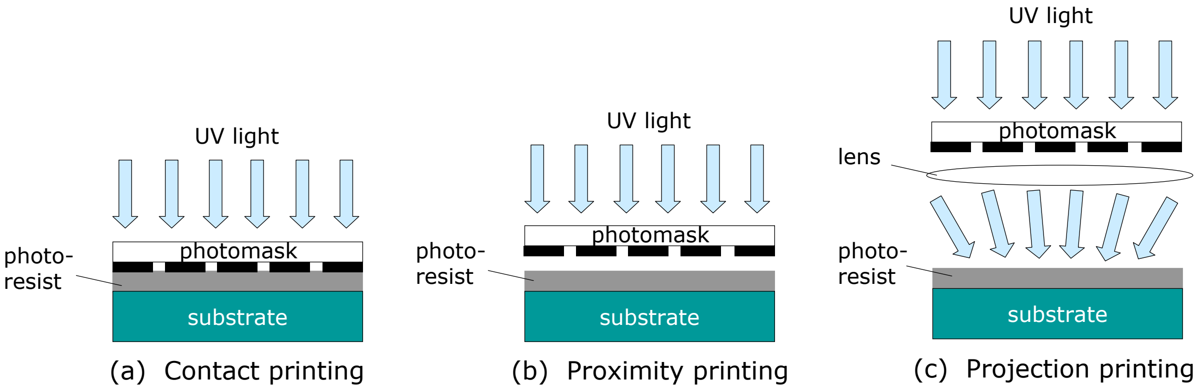
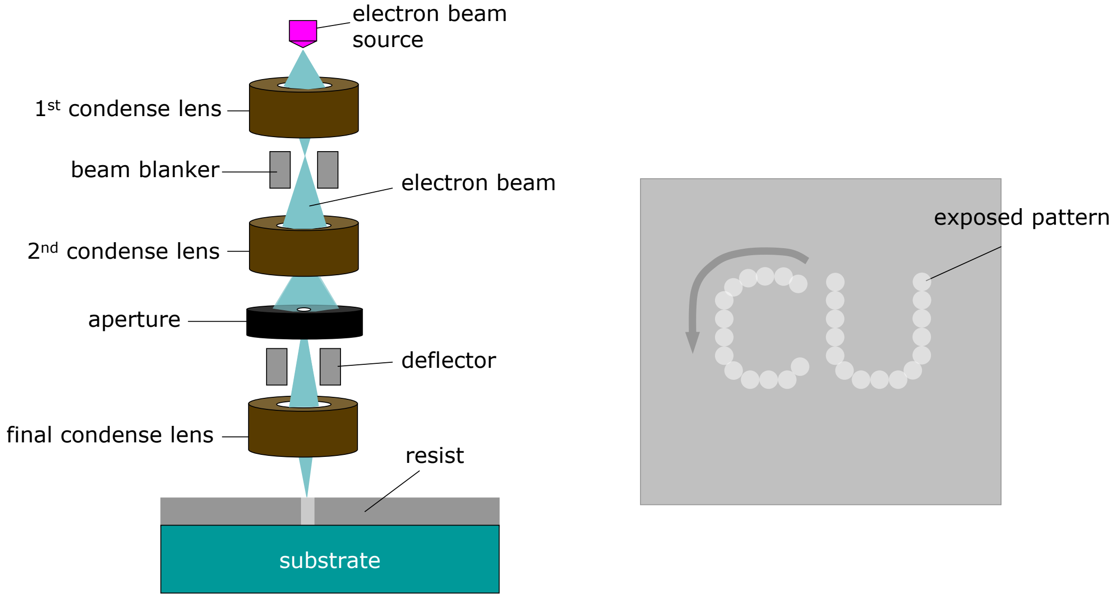


Fig. 2. Schematic illustration of three forms of photolithography: (a) contact printing; (b) proximity printing; and (c) projection printing.

2.2. Electron beam lithography and focused ion beam lithography

Electron beam and focused ion beam lithographies have been the main techniques for fabricating nanoscale patterns. Electron beam lithography [22, 23] utilizes an accelerated electron beam focusing on an electron-sensitive resist [24, 25] to make an exposure. Subsequently, this electron-beam spot with a diameter as small as a couple of nanometers is scanned on the surface of resist in a dot-by-dot fashion to generate patterns in sequence (Fig. 3). Similarly, focused-ion beam lithography utilizes an accelerated ion beam (typically gallium ion) instead of the electron beam to directly punch a metallic film on the substrate [30-33]. This is possible due to the heavy mass of ions as compared to that of electrons. Furthermore, focused ion beam systems are also employed for depositing materials such as tungsten, platinum, and carbon via ion beam induced deposition. When a precursor gas such as tungsten hexacarbonyl ($W(CO_6)$) is added into the chamber, the precursor gas is hit by the focused-ion beam leading to gas decomposition which leaves a non-volatile component (tungsten) on the surface [33]. In terms of specifications, the resolution of electron beam and focused ion beam lithography techniques are of the order of 5 - 20 nm [2, 23] due to ultra-short wavelengths of electron/ion beams in the order of a few nanometers. However, the lack of throughput limits their applications within research and mask fabrication. Therefore, these two techniques are normally used for fabricating prototypes of nanoscale structures and devices. To increase the system throughput, multiaxis electron beam lithography [26, 27] has been proposed. So far, the deployment of this technique in manufacturing process is still limited due to the difficulty in developing practical electron beam sources [1]. In the past, electron beam lithography was very expensive thus limiting the access. Recently, scanning electron microscopes were able to be equipped with pattern generator modules, thus enabling the scanning of electron beam spot within desired areas to generate nanoscale patterns as electron beam lithography systems [28, 29]. As a result, this technique has become widely used which greatly contributed to the progress in nanoscience and engineering.



(a) Side view

(b) Top view

Fig. 3. Schematic illustration of electron beam lithography. Electron beam is focused on a resist film to create a pattern by exposing dot by dot: (a) side view of the lithography setup; (b) top view of the exposed pattern by a serial writing.

2.3. Soft lithography and nanoimprint lithography

Soft lithography arose from the innovation of using a relatively soft polymer stamp to imprint a solution of molecules (ink) onto a substrate for pattern transferring. This technique requires inexpensive materials and employs non-specialized equipment. It was first introduced by Bain and Whitesides in 1989 [11]. Their pioneered work greatly contributed to the development of this technique as summarized in Ref 12 and 13. This process can be separated into two main steps: the fabrication of a patterned polymer stamp, and the use of this stamp to transfer molecules in geometries defined by the element’s relief structure. Figure 4 depicts the schematic illustration of soft lithography. The uniqueness of this technique is on the utilization of a soft stamp for pattern transferring, thus it allows a conformal contact between the stamp and the substrate resulting in a patterning capability on flexible or curved substrates.

Similar to soft lithography, nanoimprint lithography utilizes a hard mold to imprint into a polymer film for nanoscale patterning. Nanoimprint lithography has emerged as a candidate for next-generation manufacturing methods as it has great potential to circumvent the issues in photolithography, thereby, promising a high-throughput and high-resolution method with a relatively low cost [1, 3]. The details of a cost comparison can be found in Ref 1. Nanoimprint lithography was first introduced by S.Y. Chou as “hot embossing technique” enabling the definition of features with lateral sizes down to sub-10 nm [14, 15]. The procedure of imprinting lithography is shown in Fig. 5 (left). The technique heats thermoplastic polymer above its glass transition temperature enables material flow, filling the structures of a mold. After that, its temperature is lowered and the replicated patterns are solidified in place, after which the mold is removed. The most commonly used materials for mold have been quartz and silicon that are kinds of hard material. Typically, mold features are patterned by using conventional lithography techniques such as photolithography and electron beam lithography. A hard material offers a number of advantages for nanofabrication. The rigidity retains nanoscale features with minimal local deformation. Moreover, a hard mold is thermally stable at high temperature. Although nanoimprint lithography has made a great progress in a relatively short time, there are few issues to be resolved. One of them is life

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time of the mold. Heating/cooling cycles and high pressure, applied during embossing, cause stress and wear on molds. This stress also presents a problem of alignment for multi-layer fabrication. Viscosity of embossed material is also an important issue. It appears to be a limiting factor for minimizing pattern size and increasing feature density.

In 1996, nanoimprint lithography was devised through the introduction of a low-viscosity UV-curable monomer as compliant polymer layer in order to enhance fluidity of the embossed material [16]. The process is called UV-nanoimprint as schematically shown in Fig. 5 (right). After imprinting on a UV-curable monomer layer, broadband UV light radiation directly through the backside of the transparent mold causes the monomer crosslink, forming a rigid polymer. It can reduce imprint pressures significantly and avoid time consuming as well as stress induced during high temperature cycle. UV-curable monomers are very important factor for a success of UV-nanoimprint technique. For this technique, the UV-curable Amonil polymer (AMO GmbH, Germany) with a viscosity of about 50 mPas was used in many works [17-20], while a novel low-viscosity polymer with a viscosity of about one third that of Amonil and spin ability down to 150 nm thick has been recently developed [21].

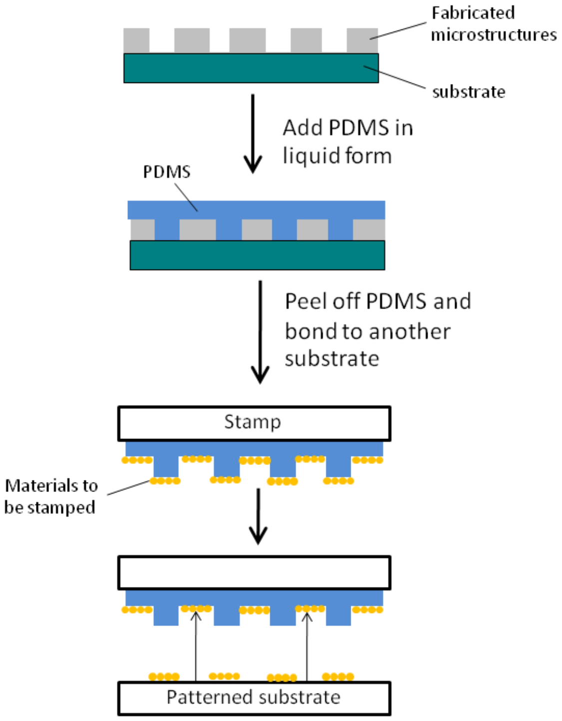

Fig. 4. Schematic illustration of soft lithography.

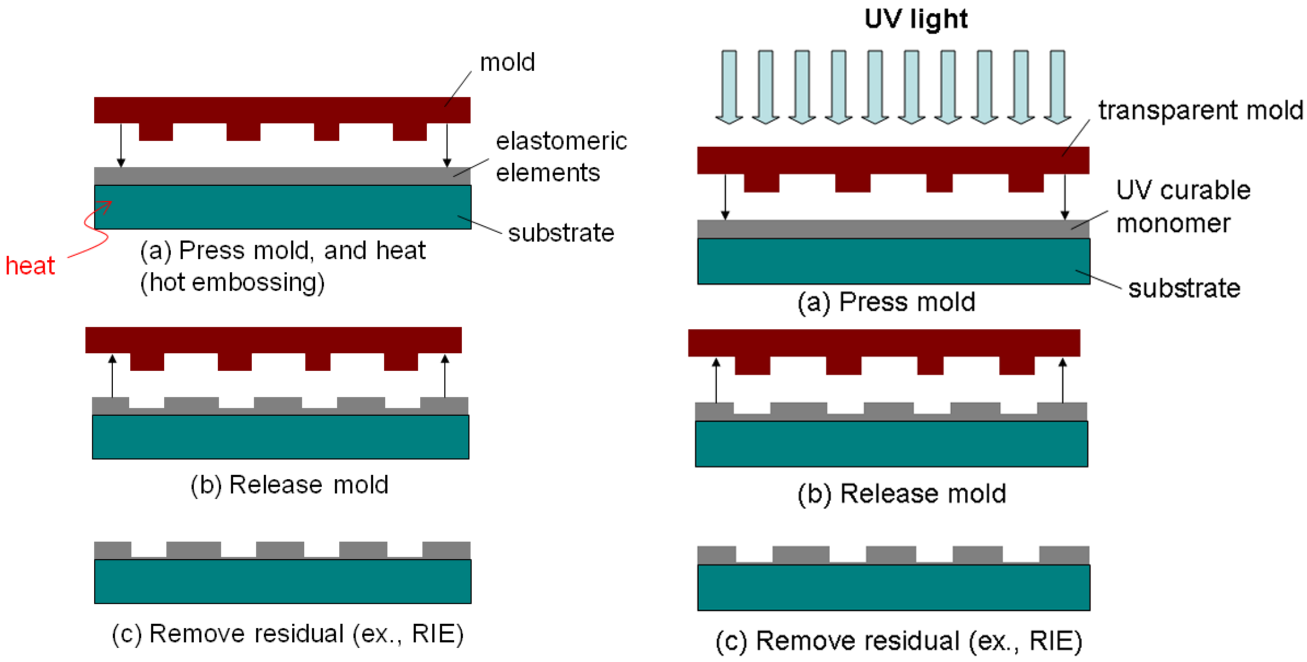

Fig. 5. Schematic illustrations of hot-embossing imprint nanolithography (left) and UV-imprint nanolithography (right).

2.4. Scanning probe lithography

Scanning probe lithography utilizes a sharp probe in an atomic force microscope (AFM) to heat, scratch, oxidize or transfer substances to the surface of a substrate for patterning nanoscale features [34-38]. Among these techniques, the approach to deposit nanoparticles or molecules selectively onto a substrate so-called dip-pen nanolithography is the most widely used [37, 38]. Dip-pen nanolithography can be performed under ambient environment without any large electromagnetic field and shear force involved. The technique was first used for transferring thiol molecules to a freshly prepared gold surface [37]. AFM probe is coated with a thin film of a chemical of interest by immersing the cantilever in a solution or by evaporation. Chemical molecules are deposited onto a substrate surface during the contact between the coated tip and the substrate. The schematic drawing for dip-pen nanolithography is shown in Fig. 6. One drawback of dip-pen technique is that its constructed area is difficult to scale up. However, in 2011, Shim et al. [39] produced an initial array of up to 4,750 silicon probe tips over an area of 1 cm^2 on an elastomer layer attached to a glass slide. It can be used to create arbitrary patterns in a massive parallel fashion without the need for a mask. It was demonstrated that a pattern of holes in a 30 nm PMMA film can be created. Traditional probe tips are made of hard materials such as silicon, silicon nitride, and PDMS elastomer while various nanomaterials can be written such as nanoparticles [40], liquid solution [41, 42], and organic materials [43]. The characteristics of dip-pen nanolithography from manufacturing aspects including processing rate, tool life, and feature quality have been recently reported [44].

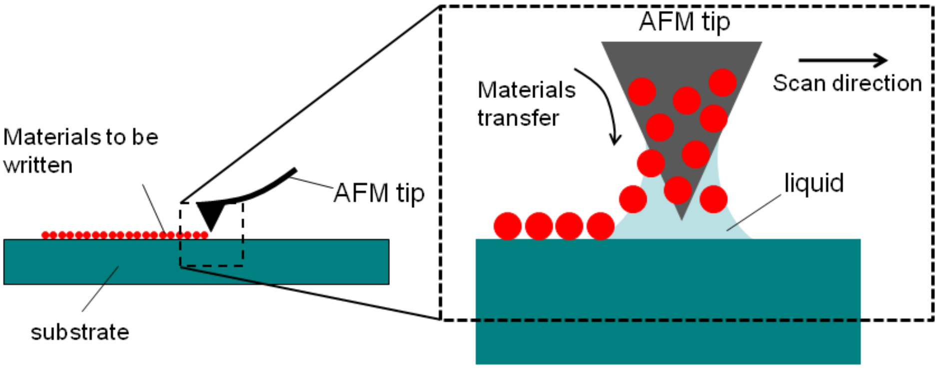

Fig. 6. Schematic illustration of dip-pen nanolithography.

3. Emerging Applications

3.1. Electronics and microsystems

In the past decades, the minimum feature size in ICs has been scaled down significantly from >10 μm in 1960s to approximately a few tens of nanometers [1] following the prediction by Gordon Moore so-called Moore’s law [57]. This success in the IC industry has sparked the remarkable evolution of the computers and the internet creating a new paradigm of the information age. The behind story of this success has been contributed by the advance of nanolithography technology, especially photolithography in the form of projection printing or stepper.

The contributions of nanolithography are not limited to the semiconductor and IC industry, but it also contributed to the advance of micro systems particularly MEMS and the rising of nanoscience and engineering. MEMS are devices or components that convert physical inputs such as acceleration, pressure, temperature into electrical output or translate electrical power to mechanical motion. MEMS devices have several advantages over conventional devices due to their small size, fast response, high resolution and sensitivity. Furthermore, the advance of micro- and nanolithography technology makes the manufacturing of MEMS devices more reproducible and inexpensive. There are numerous MEMS devices around us such as micro accelerometers [45, 46], DMD [45, 47, 48], MEMS pressure sensors [49, 50], micropumps [58-60], microvalves [61], optical switches [62, 63], inkjet heads, micrograppers [64, 65], and microactuators [66-70]. For examples, MEMS accelerometers are employed for crash-airbag deployment in automobiles and for motion detection in consumer electronic devices such as game controllers (e.g., Nintendo Wii), iPhone and other smartphones. MEMS pressure sensors are used as car tire pressure sensors, and disposable blood pressure sensors in intravenous (IV) lines. DMD chips for display applications in projectors and televisions, MEMS gyroscopes, optical switches, inkjet cartridges are some examples of commercial MEMS devices. Recent developments in MEMS technology have created great commercial potentials for micromechanical resonators [71] and nanoelectromechanical oscillators [72] for timing and frequency control, micro fuel cells as power sources for portable electronic devices [73, 74], microneedles for transdermal drug delivery [75], artificial retina microchip [76], and microfluidic devices [77, 78].

In the future, the advance in nanolithography technology will shift current electronics and micro systems into a new paradigm of nanoelectronics and nanoelectromechanical systems [79, 80] opening up a broad range of applications in various disciplines including ICs, magnetic storage, display, and sensors. Furthermore, nanomaterials such as carbon nanotubes (CNT), nanowires, nanoparticles and graphene will be increasingly essential elements in such a development. Currently nanomaterials are being employed in various electronics and micro systems including nanotubes and nanowires in logic and memory applications [81-83], nanotubes and nanoparticles in nano-sensors [84-87], CNTs and graphene sheets as next-generation transistors [88-92]. CNTs, for example, are being investigated for potentials to replace the current metal-oxide-semiconductor field-effect transistor (MOSFET) leading to denser circuitry and faster computing [88-90]. The miniaturization of the current MOSFET is facing technical barriers including electron tunneling, current leakage and power dissipation [92]. CNT field-effect transistors offer great potential to overcome these obstacles. Single-walled CNT is a graphene sheet that folds into a cylindrical shape or tube with a tube diameter of a few nanometers while its electrical properties (e.g., conductivity) heavily rely on the folding direction with respect to the honeycomb crystal lattice of graphene [92]. This quasi-one-dimensional material poses amazing electrical and transport properties which attract a lot of interest from scientific community. After the discovery of CNTs in 1991 [93], CNT transistors have been extensively studied. The CNT transistor consists of individual CNT connecting between two metal electrodes (i.e., source and drain) on a thin SiO_2 insulation layer and a heavily doped Si substrate. When the applied gate bias exceeds certain value, the electrical signal can be transferred through CNT from source to drain. CNT transistors have great potential to be much smaller than the existing MOSFET, thus enabling denser and faster computing. Although, the CNT transistors show excellent electrical properties as compared to Si transistors, there are still some problems have to be addressed for the circuit applications including the degradation of CNTs when exposed to ambient environment, the reliability when subjected to high electric field or temperature gradients, and the mass production and positioning of CNTs in the desired locations to form large circuits.

3.2. Medical and biotech

Nano- and Micro-fabrication technologies have significantly contributed to the progress in both medical diagnostics and bio technologies in recent years. Within the European Union (EU) R&D programs, there are more than 350 organizations working on micro-nano-bio systems research [94]. Their long-term projects target testing and validation in various applications: allergen detection, circulating tumor detection for breast and prostate cancer, toxin detection, leukemia, hepatitis B/liver cancer, and cardiovascular diseases are some examples. In this review, the major advanced technologies related to medical diagnostics and bio-sensing are divided into three categories: lab-on-a-chip, nanomedicine and biomedical device.

For lab-on-a-chip (LOC) system, as its name implies, this technology has the ultimate goal of fabricating entire laboratory-scale analysis workflows into a single compact chip. To achieve this goal, these fluidic chips contain a fully-integrated network of micrometer-scale fluidic components, such as channels, mixers, pumps, separators and detectors. The miniaturization of analytical unit operations often improves the analytical chemical systems’ performance. In such a small scale, flow inside the system is laminar and diffusion dominant which improves the system’s performance or obtains the system’s unique methods of operation [95]. Another obvious benefit of miniaturization is found in a reduction of liquid volumes (i.e., tested sample or chemical solution) when performing analyses in an LOC system. To drive the liquid through the system, control mechanism is needed, and it is categorized into five platforms: pressure-driven, electrokinetically-driven, centrifugally-driven, digital microfluidics, and SlipChipTM platforms [96]. Specific platforms have different characteristics which are suitable for certain applications. For example, digital microfluidics is very well suited for rapid measurement under a large number of experimental conditions, but it is not allowed for compound separation which is possible in electrokinetic systems.

Nowadays, LOC technology has almost reached a level of maturity that promises a variety of applications particularly in fluid manipulation, bio assays and biomolecular analysis. Recently, a new concept in this field which is called lab-in-a-cell (LIC) has emerged. The LIC concept relies on the basic idea of utilizing a cellular platform that appears as a natural, simple, but sophisticated laboratory, for experimental purpose similar to a standard laboratory [97]. LIC presents several advantages over LOC approach. First, a cell performs more operations and functions. Second, no mixing or pumping systems is required. From a chemistry point of view, the enzymatic machinery in a cell is able to specifically and quickly produce pure and active compounds. Finally, cells can be further engineered to tailor their activity to a specified purpose. However, LOC is still essential to serve certain tasks for LIC, for examples, cell handling or trapping, cell characterization, and accessing an intracellular content, for sampling or injection of additional compounds. There are various technical approaches to handle or trap particles and cells in LOC [98-101]. However, for cell characterization and accessing, there are mainly two approaches for single cell detection: optical and electrical methods [102] that are made of nano-scale devices integrated in LOCs. With these nano-scale devices, higher sensitivity and faster response of analytical system are two main advantages. Carbon nanotubes, nanowires, and nanochannels are employed for these tasks [103-104].

For nanomedicine, Robert and Freitas [105] give its definition as the process of diagnosing, treating, and preventing disease and traumatic injury, relieving pain, and preserving and improving human health, by using molecular tools and molecular knowledge of human body. Nanomedicine is used to address many important medical problems by using the unique characteristics of nanoscale-structured materials and simple nanodevices. Many approaches are already close to real implementation, and their subsequent incorporation into valuable medical diagnostics or clinical therapeutics is likely to occur in the near future. Some examples are immunoisolation [106], gated nanosieves [107], ultrafast DNA sequencing [108], nanoshells for drug delivery [109], and single virus detectors [110].

Due to great progress of LOC and nanomedicine technologies incorporated with other related technologies, numerous biomedical devices are successfully developed and employed in real practices of disease diagnosis and treatment. Biomedical devices recently find a lot of applications in medical field due to aging society and increase of medical costs, creating a greater need for home-based healthcare solutions and point-of-care diagnostics. These needs have led to a significant increase in the number of compact, portable, and cheap healthcare devices on a market. For examples, implantable blood pressure monitoring systems and implantable accelerometers [111] are used for recording blood pressure and for detecting a heart pacing rate for cardiac pacemaker system and send feedback to a device controller. Such implantable devices require further development of two key technologies that are material biocompatibility and flexibility of materials to be inserted into human body [112]. Another example is non-invasive devices that also have many applications especially in drug delivery. Such a device employs microelectrodes to apply a short (μs to ms) electric pulse of sufficient voltage to temporarily breakdown a permeability barrier, in this case, a skin surface. During that period when the barrier function of the membrane or skin is compromised, molecules up to several kilodaltons injected from another micro device can pass through. This kind of treatment has been reported to successfully enhance the delivery of many drugs through the skin [113]. In addition, sensor systems as well as flow strip chips for rapid diagnosis are also interesting applications. Blood glucose sensor microelectrodes integrated with a contact lens for continuous tear glucose monitoring [114], and a flow strip chip for detecting proteins derived from the blood of malaria parasites [115] are some examples.

3.3. Optics and photonics

For more than three decades, optical MEMS devices such as DMDs, optical switches, and modulators have been developed and employed in a wide range of applications. Among them, the DMDs developed by Texas Instruments Incorporated are one of the most widely used optical MEMS devices. A DMD chip consists of several hundred thousand of micro-sized mirrors corresponding to the number of pixels of the image to be displayed whilst each micromirror is about 1/5 of the size of human hair. Each micromirror can be either rotated to reflect light from a light source to the screen (ON state) or rotated to the other side to reflect light out of the screen (OFF state). By controlling the time duration of each mirror at the on/off states, this enables the brightness control of each pixel for the display application. DMD chips are widely used in projectors, TVs, and digital cinemas [45, 47, 48]. In optical communications, MEMS concept was introduced into various products to make them smaller, cheaper and better. Optical switches [116-119], optical attenuators [120], optical data modulators, filters, spectrometers [121] and tunable lasers [122] are some examples of optical MEMS devices. These devices have facilitated the rapid progress of the telecommunication industry. Furthermore, recent innovations such as microdisk resonators for multiplexing function [123], and photonic crystal technology for high-reflectivity compact mirrors [124] could further reduce the size and cost of the conventional devices [119].

In the optics community, plasmonic optics is particularly of interest due to the dispersive behavior of surface plasmons (SPs) which allows an access to shorter wavelengths while using visible light excitation. SPs are essentially collective electron oscillation at the metallic and dielectric interface [125, 126]. The extraordinary property of SPs opens up potential of high-resolution imaging/ lithography at the length scale beyond the diffraction limit. The recent discovery of extraordinary transmission through metallic sub-wavelength hole arrays has stimulated extensive interest in SPs among the scientific community [127-132]. The observed far-field transmission through a sub-wavelength hole array on silver screen in the infrared and visible wavelength range is orders of magnitude more light than the theoretical prediction by Bethe [133]. This unusual enhancement is attributed to the excitation of SPs on the metal surface which dramatically enhances the optical throughput via the sub-wavelength aperture. This opens up a broad range of possibilities and applications from nanolithography [134-137] and imaging [138-141] to chemical sensing [142-144] and biophysics [145,146]. For instance, the use of SPs assisted mask could overcome the low throughput issue of photolithography through sub-wavelength aperture [134]. Superlens, an ultrahigh-resolution lens that goes beyond the diffraction limit, is also attributed to the enhanced electric field through surface plasmon resonance while the resolution of the image is preserved resulting in a high-resolution imaging [138, 139]. For the fabrication of nanostructures, most of the time, electron beam lithography or focused ion beam lithography are used to fabricate high-resolution patterns such as nanoscale hole arrays [127, 134], bull’s eye structures [132] and plasmonic lens [137].

Localized surface plasmons are also of interest due to their localization of strong electromagnetic field in a nano-sized area so-called hot spot, normally on the edges of nanostructures. Localized surface plasmon resonance (LSPR)-based nanobiosensors are emerged as ultrahigh-sensitivity sensing devices relying on the change of surrounding refractive index or the interaction with other metallic nanostructures [147, 148]. This is a powerful tool that enables a very low concentration detection or even single molecular detection of biological samples such as proteins or DNAs. These metallic nanostructures can be fabricated by chemical reduction of metal nanoparticles, or the use of self-assembled monolayer of polystyrene nanosphere as mask and subsequent metal deposition to create metallic nanostructures so-called nanosphere lithography [149], or the utilization of interference lithography. These techniques, however, can not control the position of the metal nanostructures. On the other hand, electron beam lithography and focused ion beam lithography are employed to fabricate metallic nanostructures on desired positions with a high precision. LSPR-based nanostructures can be exploited in detecting DNA hybridization [150, 151], monitoring an intramolecular distance (molecular ruler) [152], nanolithography [153] and heat assisted magnetic recording [154].

3.4. Environment and energy harvesting

Micro- and nano devices also play a vital role in environmental monitoring. One of major devices in this area is micro gas analyzer that is used to measure gaseous species in environmental/atmospheric analysis and medical diagnostics. Nowadays, such devices are required to be performed on-site to achieve real time data analysis. Due to a miniaturization of gas analyzers in recent years, these on-site measurements became possible. Moreover, a smaller sensing device provides larger surface to volume ratio which results in its higher sensitivity and better temporal resolution. Such devices have already been successfully applied to real applications such as natural environment monitoring [155], air pollutions examination [156], explosive gas analysis, and terrorist gas detection [157]. The analysis is typically divided into wet and dry chemical methods that consist of different instruments [158]. One utilization method of gas analyzers as well as other physical, chemical or biological sensing devices is to implement them as a wireless sensor network that consists of spatially distributed autonomous sensors for collecting data and cooperatively passing their data through the network to a main control station. Such a wireless sensor network can find their utilization for many applications such as air pollution monitoring, landslide detection or structural monitoring. To operate these wireless sensors, only a small amount of energy is required, thus, leading to a new technology called energy harvesting.

Energy harvesting is the process by which energy is captured from external sources such as solar power, thermal energy, wind energy, and kinetic energy, and converted into a usable form. Although energy harvesting technology can convert only little power, it is considered to be an important new power generator due to its broaden adaptability to various free energy sources and its suitability for wireless devices. Energy harvesting can be divided into four approaches: harvesting energy from motion and vibration, harvesting energy from thermal differences, photovoltaic harvesting, and RF energy harvesting [159]. The expected power from these approaches are 4-100 $\mu W/cm^2$, 0.03-1 mW/cm^2, 0.01-10 mW/cm^2, and about 0.1 $\mu W/cm^2$, respectively, which are reasonably sufficient for a sensor node in wireless sensor network applications [160]. For converting motion or vibration, the established transduction mechanisms are based on electrostatic, piezoelectric, and electromagnetic principles. While thermal energy harvesters are based on the seebeck effect: when two junctions, made of two dissimilar conductors, experience a temperature difference, an open circuit voltage develops between them. For photovoltaic cells, they convert incoming photons into electricity, while ambient RF energy available through public telecommunication service is also a potential small power source. However, the output of energy harvester is not suitable for main power supply application because of its variations in the power and voltage overtime. Therefore, a power management circuit is required together with energy buffer such as battery for practical applications [161].

Another approach of micro power generator is the utilization of fuel energy conversion technologies similar to conventional existing technologies. The ultimate goal is to develop a portable, autonomous power-generation system with an improvement in energy density over batteries. The techniques for converting fuel energy into usable energy have been grouped into four categories: micro combustors, heat engines, rockets, and fuel cells [162]. The approaches up to date have been carried out by miniaturizing the currently used large scaled devices. For real applications, scientists and engineers need to resolve issues related to unusual phenomena at micro and nanoscale including fluid flows, heat and mass transport, combustion, as well as design and fabrication.

4. Summary

We have reviewed the major micro- and nanolithography techniques including photolithography, electron beam and focused ion beam lithographies, soft lithography, nanoimprint lithography and dip-pen lithography. Lithography technology has contributed to the advance in the semiconductor and IC industry as well as the success of commercial MEMS devices. For the past decades, photolithography has been the key technology in manufacturing of ICs, microchips and MEMS devices including micro accelerometers, DMDs, MEMS pressure sensors, micropumps, microvalves, optical switches, inkjet heads, microgrippers, and microactuators. Alternative lithography techniques have been extensively developed for specific applications: electron beam and focused ion beam lithographies for nanoscale patterning in R&D, photo-mask fabrication and ICs production, soft lithography for a wide range of LOC applications, nanoimprint lithography for bio-sensors, bio-electronics, nano channels, and nano wires, dip-pen lithography for bio-electronics, bio-sensors, and gas sensors. Among them, nanoimprint lithography has sturdily emerged as it is able to circumvent the issues in conventional lithography technology, thereby, allowing a high-throughput and high-resolution method with a relatively low cost.

Nanolithography technology is also shaping the future of nanoscience and technology. This emerging discipline provides alternative routes to overcome current technical barriers in many areas including nanoelectronics, nanomedicine, nanoelectromechanical systems, and nanobiosensors. Such a dramatic advancement in nanoscience and technology is leading to technology revolutions in a broad range from next-generation electronic devices to healthcare systems, from cosmetics to textiles, and from agriculture to high-tech businesses.

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