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Evaluation of Particle Beam Lithography for Fabrication of Metallic Nano-structures

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Abstract

Metallic nanostructures have a wide range of application from electronics to biological imaging and sensing, photonics, biomimicry and information and energy storage. Bio-functionality of natural nano-structures has recently drawn the attention of bioengineers to mimic the high-resolution nanostructures on the metallic substrate. However, hydrothermal, wet and dry etching methods have a good throughput to fabricate the metallic nano-structures, the resolution and morphology control has been restricted. Recent advances in particle beam lithography (Focused ion beam lithography and electron beam lithography) are able to fabricate the high-resolution nanostructure on metals. The advantage of particle beam lithography is to control the nanostructure morphology via optimizing the process variable. This paper reviewed the throughput and resolution of particle beam lithography including Electron beam lithography (EBL), focused ion beam milling (FIB) and Ion Beam Induced Deposition (IBID) to fabricate metallic nano-structure sub-200nm pattern. The outcome of this research could guide bioengineers to select the best approach to fabricate sub-200nm features on the metallic substrate.

Keywords: Metallic nanostructure, Nano-fabrication, Electron beam lithography and focused ion beam milling

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1. Introduction

Miniaturization in biological, electrical and biomedical devices motivates bioengineers and scientist to fabricate in nano-scale (Jaggessar, Shahali, Mathew, & Yarlagadda, 2017). Different geometry of nanostructures like nano-pillars (Hasan, Raj, Yadav, & Chatterjee, 2015), nanowires (Jaggessar et al., 2018) and nanodots (Dong et al., 2016) have been fabricated for different applications, from bioactivity and antibacterial to data storage purposes. Current methods like reactive ion etching and hydrothermal etching may have high throughput, but controlling the geometry in sun-nanometer is a big challenge. Particle beam lithography (PBL) is a suitable method for fabrication of nano-scale feature with high geometry controllability. Particle beam lithography (PBL) operates high energized particle instead of a beam to fabricate nano-structure with high-resolution. Electron Beam Lithography (EBL) and Focused Ion Beam (FIB) are the two main subclasses of Particle beam lithography which are integrated with electron and Ion, respectively. Particles with higher energy (>2 KeV) and nano-scale wavelength can reduce the diffraction which restricts the resolution in photolithography, thereby sub-10nm resolution is achievable in PBL (Broers, Hoole, & Ryan, 1996; Rodríguez-Hernández & Cortajarena, 2015). Another supremacy of particle beam lithography over photolithography is that it is a direct write method which does not need a mask, offering excellent flexibility in the feature design (Broers et al., 1996). In this paper, the advantages, disadvantages and capabilities of particle beam lithography including Electron beam lithography (EBL), focused ion beam milling (FIB) and Ion Beam Induced Deposition (IBID) will be reviewed.

Nomenclature

PBL	Particle beam lithography
EBL	Electron Beam Lithography
FIB	Focused Ion Beam
LMIS	liquid metal ion source
SE	Secondary Electron
GFIS	Gas field ion source
HIM	Helium ion Microscopy
SEM	Scanning electron Microscopy
IBID	Beam Induced Deposition

2. Electron Beam lithography (EBL)

EBL is the predominant method for producing nano-pattern because of its lower proximity effect and high resolution and throughput (Maas et al., 2010). In EBL, the electron beam can be glanced off from the substrate to image the surface or can be used to fabricate the resist which is deposited on the substrate. Because of the low energy of electrons, EBL can fabricate polymer resist such as PMMA, PEG and PAA. As shown in Figure 1, the electron can produce negative mode lithography by crosslinking as well as positive mode lithography by degradation depending on the type of the mask (Cheng, 2008; Perkins, 2006). The developer solution is used to remove the undesirable area. EBL can fabricate the various feature dimensions (1 mm - 10 nm) on quite a large area. Considering the size of the resist molecule and area of scattering, too many secondary electrons can affect other areas on the resist. The resolution depends on the molecule-size of the resist, scattering range and secondary electrons. The secondary electrons through the backscattering can affect other areas on the resist. As shown in Fig 1, the positive tone is suitable to make nano-patterns with different geometry by coating the lift-off area using electron beam evaporation coating technique (Rodríguez-Hernández & Cortajarena, 2015).

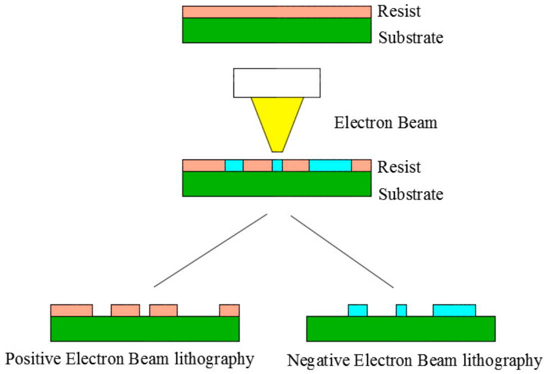


Fig. 1. The principle of Electron beam lithography.

3. Focused ion beam (FIB) lithography or FIB-milling

Focused ion beam milling is a high-resolution fabrication method (10-30 nm) to image and fabricate different materials (e.g. polymer, silicon wafer and metal). The principle of FIB is the same as SEM except that ions including Ga^+, Ne^+ or He^+ have been used instead of the electrons in case of SEM and EBL. (Rodríguez-Hernández and Cortajarena, 2015). As shown in Figure 2, interaction volume of gallium, electron and helium are different. Interaction volume related to secondary electrons (SE) created by focused He^+ beam is much smaller than e- and Ga^+ , meaning that Helium ion microscope (HIM) has better resolution for imaging compare to SEM and Ga^+-FIB. On the other hand, Ga^+ has high mass which can create considerable scattering on the surface. HIM can also scatter the surface at 30 KeV and because He^+ has low mass, it is advantageous to fabricate small features in the sub-nanometres scale (Hlawacek, Veligura, van Gastel, & Poelsema, 2014).

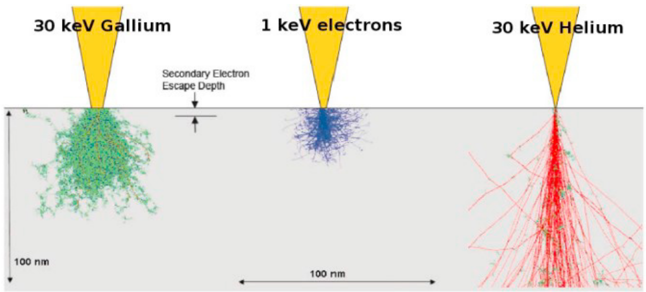


Fig. 2. Interaction volume difference among charged particles beam used for imaging (Hlawacek et al., 2014).

However, the fabrication throughput of FIB is less than EBL, no need to mask and provider, making FIB a high-resolution fabrication method due to its lower interaction area. In addition to the semiconductor industry, FIB is extensively developed in different science applications like biomaterial and biological matter. In biological applications, cells, biomaterials and their interfaces can be visualized, analysed, milled and prepared for further techniques such as TEM (Grandfield & Engqvist, 2012). The FIB instrument is composed of a sample stage, a vacuum chamber, and the source of liquid metal ion, the column of ion, detectors and system of gas delivery (Giannuzzi, 2006). Although FIB milling is advantageous because of lower proximity and higher sensitivity compared to electron beam lithography, the major drawback of FIB is the low resolution caused by the large beam diameter of Ga^+ ion, causing surface damage and contamination from ion implantation (Maas et al., 2010).

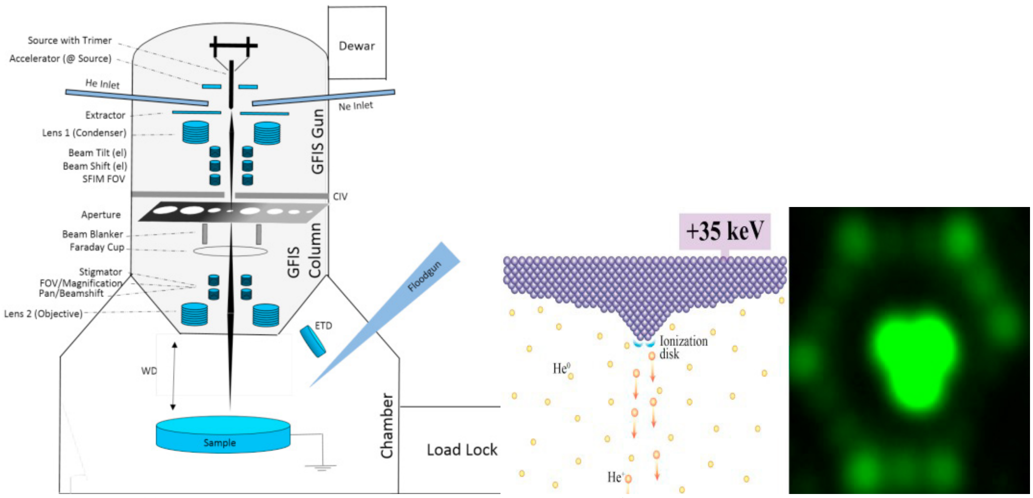
3.1 Ga^+-FIB Milling

Ga^+-FIB Milling has been used for more than 20 years in the semiconductor industry. A precisely focused Ga ion

beam can be applied at a low level of beam current for imaging or at higher levels of beam current for milling process as well as TEM sample preparation (Suutala, 2013; Volkert & Minor, 2007). Ga^+ is currently the most common liquid metal ion source (LMIS) for FIB instruments due to low melting point, low vapour pressure, unique mechanical, electrical, and vacuum features. Jarmar et al. employed Ga^+-FIB lift-out method to characterize the cross-sectional analysis of dental implants using TEM (Jarmar et al., 2008). Wu et al. applied FIB for fabricating the nano-pillar InGaN/GaN used in semiconductor materials. FIB milling can produce nano-pillars with the diameter of 95 nm and the length of 150 –160 nm. In this research, the voltage of 30 KeV, 300 pA beam current was applied for the FIB process.
Nanoholes with diameter 80 nm to 490 nm were fabricated on biocompatible and biodegradable PLLA polymer using Ga^+ FIB whereas debris and thermal deformation were controlled by the current to decrease induced heat (Oyama et al., 2013). The major drawback of FIB is a low resolution because of Ga^+ ion large beam diameter, causing surface damage and contamination due to ion implantation (Maas et al., 2010).

3.2 He^+-FIB and Ne^+-FIB milling

Helium Ion Microscopy (HIM) utilizes sub-nanometre spot size through the gas field ion source (GFIS) for precise and high-resolution imaging of biological surfaces, electrical circuits and solar cell nano-structure without contamination and surface damage (Hlawacek et al., 2014; Maas et al., 2010). He^+ and Ne^+ ion are both heavier than the electron (7000 and 40000 times respectively), resulting in less diffraction of He^+ and Ne^+ than electrons. However, one of the major problems in SEM is diffraction, which restricts final spot size, He+ and Ne^+ ion beam is not affected by diffraction and they can be focused to a very small point. The source tip is composed of three atoms, and it is called trimer as shown in Fig 3. Cryogenic tip cooling is applied to HIM source to slow down the gas so that gas atoms can stay in a spot close to the source tip where they can be ionized and the floodgun in HIM produces an electron beam (negative charge) (Hines & Wolf, 2016)
The generated electron beam is placed on the sample in a way that electron beam charge compensates the positive charge built-up from the ion beam (He^+ or Ne^+). So, floodgun provides the capability of imaging a non-conductive sample which can be beneficial for biological samples (Joens et al., 2013, Hines and Wolf, 2016). The significant parameters which affect high-resolution imaging with HIM are the focus, astigmatism, scan size, dwell time/ scan speed, averaging and filter, contrast and brightness, working distance and flood gun parameters (Hines & Wolf, 2016).



(a) (b)

Fig. 3. (a) Schematic of Orion NanoFab column Schematic of GFIS. Ionization occurred mainly at the most sticking out corner and edge atoms. (b) Image of the atoms at the end of the source tip (trimer) emitting helium ions (Hines & Wolf, 2016; Hlawacek et al., 2014).

He^+-FIB and Ne^+-FIB are also efficient tools for patterning, milling and depositing of sub-nanometre features with higher resolution on a substrate. He^+-FIB milling can fabricate extremely fine sub-nanometre structures in nano-optics (Melli et al., 2013). Melli compared resolution of Ga^+-FIB milling (Ga^+-FIB) and He^+-FIB milling to fabricate coaxial optical antenna. In this research, He^+-FIB fabricated 8 nm gap on a gold resonator, whereas Ga^+-FIB just can fabricate a 30 nm gap (Melli et al., 2013). However, He^+-FIB milling has a lower sputtering rate compared to Ga^+-FIB due to its lower mass and momentum but it can fabricate nano-patterns with higher resolution around 5 nm (Scholder et al., 2013). Significant parameters like beam alignment, beam overlap, voltage, aperture, spot size, dwell time, the number of passes and dose affect the patterning process. It is necessary that the ion beam is aligned properly before starting patterning. If the beam is astigmatic or unfocused, the fabricated features will be larger, disordered shapes at various milling depths (Hines and Wolf, 2016). Ion dose is an important parameter which determines the depth of milling and can be obtained from Eq1.

$$Dose\,[\frac{nC}{\mu m^2}] = \frac{I(pA)\times T(\sec)}{1000\times A(\mu m^2)} \quad (1)$$

In Eq. 1, N is the number of ions, I is beam current in (pA), T is the dwell time, elemental charge (1.602×10^{-19} C (coulomb)), and A is milling area.
However, He^+-FIB has lower sputter rate compared to Ga^+ due to lower mass, helium ion tends to implant ion on semiconductor and metal like titanium. To overcome this issue, Ne^+ can fabricate the nano-feature unambiguously without swelling due to shallower penetration depth (Ananth et al.). The only disadvantage of Ne^+ is its stability compared to He^+ as He^+ can remain stable for more than a week but Ne^+ is only stable for few hours in a day.

3.3 Ion Beam Induced Deposition (IBID)

Ion beam also can be applied to deposit metallic 3D dimensional nano-structures on the substrate. This method is direct writing and it does not require any mask or resist. The basis of this method is the same as FIB except that the ion beam (e.g. Ga^+ or He^+) decompose the precursor gaseous molecules leading to deposition of the non-volatile element like Pt or Ti on the substrate. IBID is able to fabricate a versatile 3D structure with high aspect ratio. Chen fabricated nanopillars with 40nm diameter and 1.35µm height using He^+ while by using Ga^+, only 140nm diameter pillar was achievable. (Chen, 2010).

This paper reviews the capability, advantage and limitation of particle ion beam lithography and deposition and the result summarized in table 1 in order to overview and better process the selection criteria to fabricate metallic nanostructure.

Table 1. Resolution, throughput, advantage and limitation of PBL methods.

PBL method	Resolution	Throughput	Advantage	Limitation
EBL	***	***	High throughput	-Need resist (polymer electron resist) -Low aspect ratio for close nano-structure
Ga^+-FIB	**	**	Metal Direct writing	-Surface damage and contamination
He^+-FIB	****	*	Metal Direct writing	Low throughput
Ne^+-FIB	***	**	Metal Direct writing	Ne^+ Low stability
IBID (Ga^+)	***	**	- Direct writing -3D versatile nano-structure	-High aspect ratio -Low surface roughness
IBID (He^+)	****	*	- Direct writing -3D versatile nano-structure -Smooth surface	-High aspect ratio

4. Conclusions

In this review paper, capabilities, advantages and limitations of particle beam lithography (e.g. EBL, Ga^+-FIB, He^+-FIB, Ne^+-FIB and IBID) for fabrication metallic nano-structure have been reviewed, and the following conclusions have been made:

1. All methods of Particle Beam Lithography (PBL) and deposition has been studied, including EBL, Ga^+-FIB, He^+-FIB, Ne^+-FIB and IBID. Electron beam lithography is the best technique to fabricate high-resolution (less than 100nm feature) and high throughput metallic nanostructure. In this method, EBL can fabricate any structure on resist (positive mode) and the metal coating is used to deposit metal on the fabricated area.
2. Ga^+ focused beam milling can produce direct writing with good throughput but the resolution is limited (better for more than 100nm) and it creates surface damage and contamination.
3. He^+ focused beam milling is a suitable method to fabricate sub-nanometre (<5nm) feature like gap cut on metal like gold. However, He^+-FIB produce swelling on titanium, in this case, Ne^+ is the best option to fabricate small area on titanium but with low source stability.
4. Ion Beam Induced Deposition (IBID) can fabricate the high aspect ratio nano-feature among other methods with versatile 3D geometry. He^+ Ion Beam Induced Deposition (IBID) can deposit the better surface quality for with higher resolution compared to Ga^+ ion.

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