Focused ion beam direct fabrication of micro-optical elements: features compared with laser beam and electron beam direct writing

Yongqi Fu, Ngoi Kok Ann Bryan

Abstract— **Three types of focused ion beam machine: focused ion beam milling (FIB milling), focused ion beam lithography (FIB lithography), and focused ion beam direct deposition (FIB deposition), are described in detail to compare with electron beam lithography (EBL) and laser beam direct writing (LBW). A diffractive optical element (DOE) with continuous relief, six-annulus, relief depth of 1.17µm, and diameter of 65 µm, fabricated by use of the FIB milling, is cited as an example to illustrate the FIB milling and the comparison with the EBL and the LBW. Micro-cylindrical lens with dimension of 2.8µm×7.5µm×0.95µm in width, length and height, *NA*=0.2, is given as another fabrication example to illustrate the FIB deposition, which is a unique function for all the direct writing methods. They are all superiors to the EBL and the LBW in the case that optical elements need to be directly fabricated in local area of a device.**

Index Terms— **optical design and fabrication, diffractive optics, microstrcture fabrication**

I. Introduction

THERE are three different approaches for direct microfabrication by use of focused ion beam technology, FIB lithography, FIB milling, and FIB deposition. Different methods have their own inherent advantages and shortages. In some cases, the FIB lithography and the FIB milling are similar to the EBL, and the LBW.

Sometimes, user or the development of a method was driven by the equipment, which is available in laboratory at that time, and sometimes a new idea caused the emergence of a new method. Each method has its advantages and handicaps. A general comparison among them is not easy and the use of different criteria is more helpful. In this paper, we combine concrete fabrication examples to introduce fabrication performance and inherent limitations of the FIB lithography, FIB milling and FIB deposition compared with the EBL and the LBW.

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Because of limitation of our machine (Micrion 9500 EX) with maximum ion energy of 50 keV, which is only suitable for the FIB milling and the FIB deposition, we cannot give a good example from our machine for resist exposing by the FIB lithography in this paper.

Combining with fabrication examples of micro-optical elements with continuous relief, the features of the FIB lithography, FIB milling, and FIB deposition are illustrated in detail, and compared with the EBL and the LBW so as to give a clear outline for the readers involved in the area of microoptics direct fabrication.

II. FIB Lithography

FIB lithography can directly expose photoresist (e.g. PMMA) or implant ions in a defined area on any substrate and then modeling via wet chemical etching.

The focused ion beam writing can be divided into the FIB milling and focused ion beam implantation (also called FIB lithography. Working principle of the FIB milling is reverse to the FIB lithography. For the FIB milling, ion sputtering plays a dominant role with an ion energy between 30~50 keV, and ion implantation is only a side effect in the process. In the contrary, for the FIB lithography, ion implantation plays a dominant role with the ion energy higher than 100 keV, and the ion sputtering should be as low as possible (no surface physical damage needed) in this case. After ion implantation, the area with implanted Ga^+ is inertness to chemical solution and can be used as protective layer in wet etching. Therefore, the FIB lithography is more effective to fabricate binary grating with fine line and small period, especially in fabrication of Brag grating in laser diode, e.g. DFB laser and DBR tunable laser,[1~3] because of limitation of implantation depth that cannot be over 1 µm for current focused ion beam equipment. Thus, the FIB lithography with implantation function is not suitable to direct write optical elements with sag height or relief depth larger than 1 µm. Another application of FIB lithography is fabrication of waveguide. Principle is that refractive index of implanted area is larger than that of non-implanted area. Optical path can be formed by use of FIB lithography in terms of designed route in glass (commonly used material is quartz). It is difficult to fabricate the optical element with a continuous relief (especially for refractive lens) for the FIB lithography because of this restriction.

The FIB lithography has three apparent advantages over the EBL and the LBW as follows:

a) Many resists are found to be more sensitive to ions than electrons. This was felt to be an important advantage of FIB lithography which should increase resist exposure rates, giving significantly enhanced throughput. FIB lithography should be particularly useful in direct write applications.
b) Using EBL, the major factor limiting the reduction of minimum feature sizes and increase of packing densities is the so-called proximity effect. This effect, due to backscattered electrons, in principle, should be absent in FIB lithography and provides a second potential advantage driving its development.
c) FIB lithography is direct fabrication on substrate, and photoresist layer is unnecessary.
d) FIB lithography can be used before, after or as a step in any lithography process to offer specific customization of other lithographic techniques as a process step or during a prototyping phase.

The proximity effect in EBL is caused by backscattered electrons from the substrate, which give rise to a resist exposure profile wider at the substrate / resist interface than at the surface of the resist layer, and its compensation method is complicated.[9] The proximity effect broadening is negligible in FIB lithography resist exposure. But some broadening of resist exposure profiles can still occur, as a result of recoil atoms entering the resist from the substrate, under the influence of the energetic ions. The effect will be more apparent for heavier ions, for which nuclear stopping is greater and recoil events are more likely. Thus Si and Ga ions are more prone to produce profiles broadened by recoil atoms than the significantly light ions, such as Be^+.
In addition, for FIB lithography with implantation function, the substrate with implanted pattern needs thermally treated

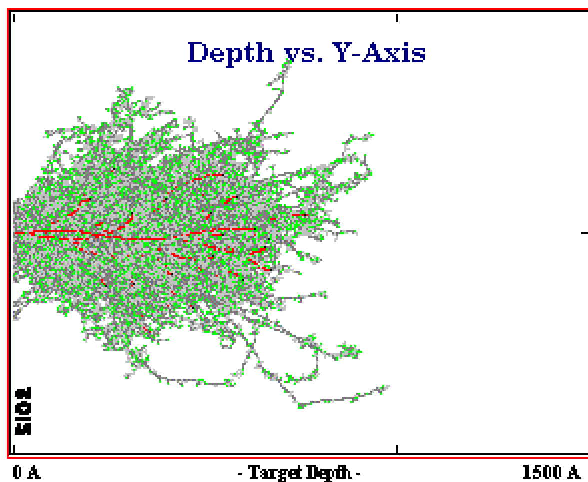


Fig.1 Result of Monte Carlo simulation of Ga^+ distribution on surface of fused silica with energy of 50 keV and ion incident angle of 0° simulated by professional software of SRIM2000

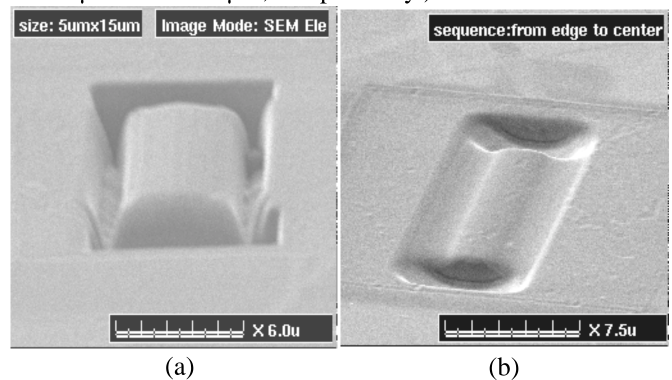
by a rapid thermal annealing step (700 °C, 60s) to avoid ions spreading continuously in the implanted area, as shown in Fig.1, which will cause defined lines broadening. This is crucial for fabrication of Bragg grating of DFB by use of FIB lithography, in which the thermal annealing intermix selectively the quantum wells in the implanted areas. The intermixing increases the band gap by the energy of about 40 meV.[2] The modulation of the band-edge absorption between implanted and non-implanted areas forms an absorption grating.

For FIB lithography exposure on resist, ion dose of ~10^{12} cm^{-2} are the minimum required for good lithography.[4] For the ion beam with Gaussian profile, the outer regions of the beam become more important with increasing dose. However, at very low doses, the lines begin to break up. This discontinuous region is due to the statistical noise effect, and limits the range of resists sensitive, which are useful for submicron lithography, e.g. the diffractive optical element with submicron feature size. Normally, it is not necessary to use the FIB lithography exposes resist first, and then transfer the pattern to substrate because of the function of single-step direct writing of the FIB milling.

III. FIB MILLING

A. Redeposition effect and milling sequences

The FIB milling is a pure physical collision process between ions and molecules of substrate. Effect of implantation should be as little as possible. It works with low ion energy because of this reason, e.g. 50 keV. Working distance in milling is 24 mm with beam current of 4 nA, dwell time of 0.6 µs, scanning speed of 20 ms/frame, and beam spot size of 30 nm.
The influence of redeposition effect is a main factor for the FIB milling. It depends on the solid angle for the escaping secondary products. It will cause the actual milling depth to be less than the designed depth. Therefore, milling sequence becomes essential for fabrication of micro-optical element with continuous relief due to this effect, as shown in Fig.2 (a) and (b). Fig.3 is an example of a diffractive optical element (DOE with designed microlens parameters of focal length, f_0, numerical aperture, *NA*, relief depth, and feature size for wavelength of 632.8 nm as 125µm, 0.2, 1.17 µm and 4.5µm, respectively.) with six annulus



(a) (b)

Fig.2 Results comparison for different milling sequence. (a) milling sequence from center to edge (b) milling sequence from edge to center.

fabricated by FIB milling with milling sequence of from center to edge. It can be seen that the old milled areas and annulus were filled with redeposit material sputtered from the newly milled annulus, which causes depth of the old annulus being reduced. Fig.4 is the other example opposite

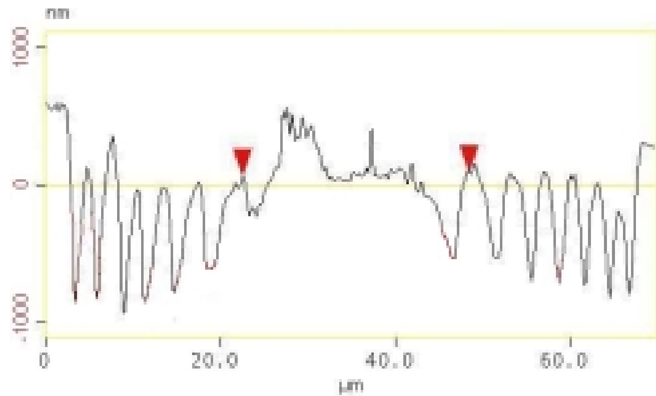


Fig.3 Diffractive optical element with six annulus and diameter of 65 μm fabricated by FIB milling with milling sequence from center to edge under ion energy of 50 keV on the diamond film, measured by AFM.

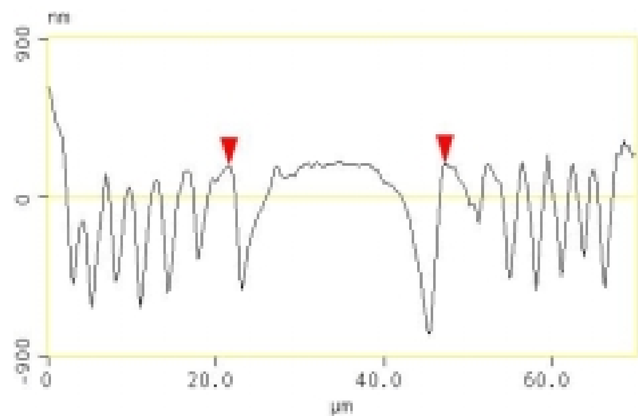


Fig.4 Diffractive optical element with six annulus and diameter of 65 μm fabricated by FIB milling with milling sequence from edge to center under ion energy of 50 keV on the diamond film, measured by AFM.

to that of Fig.3. The milling sequence is from edge to center. It shows that the depth of outer zones were reduced

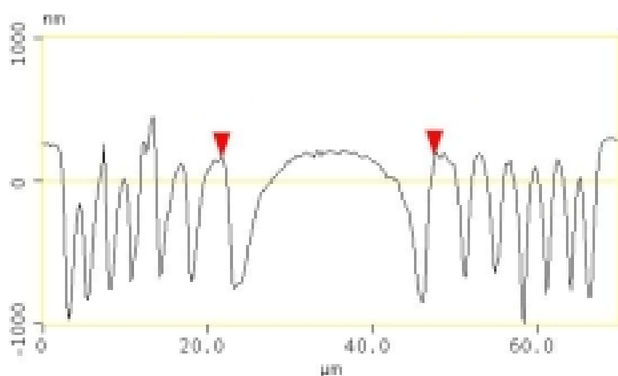


Fig.5 Diffractive optical element with six annulus and diameter of 65 μm fabricated by FIB milling with modified milling sequence under ion energy of 50 keV in glass of BK7, measured by use of AFM.

due to filling of redeposit residue from newly milled annulus. To overcome this problem, we mill the centered convex area using the sequence of from edge to center, and then change the sequence to from center to edge for the annulus. The stage was tilted to a certain angle (e.g.5°) to

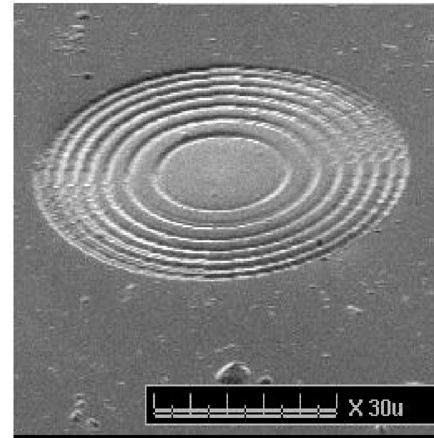


Fig.6 SEM micrograph of Diffractive optical element with six annulus and diameter of 65 μm fabricated by FIB milling with milling sequence from edge to center under ion energy of 50 keV in diamond film.

compensate the tilt of sidewall. The DOE after modified FIB milling is shown in Fig.5 and Fig.6. It can be seen that the redeposition effect is degraded greatly.

Another commonly used method to degrade the redeposition effect for FIB milling is using chemical assistant etching, e.g. Cl_2, XeF_2. Aspect ratio (ratio of depth to width) can be increased from 5:1 to 10:1 for FIB milling without and with gas, respectively. But this method needs larger working distance from ion column to the sample surface so as to produce larger space for placement of gas pipes. It causes degradation of milling resolution. Therefore, it is not recommended for DOE milling, especially for the DOE with feature size around 1 μm.

B. Writing time and cost of FIB milling

It takes about 30 min. finishing the DOE by the FIB milling with only a single-step. For the EBL and the LBW, total fabrication time plus pattern transfer to the substrate is far longer than 30 min. The LBW on hybrid solgel film for microlens fabrication is single-step fabrication and cheaper than the FIB milling and the EBL. Assuming the same continuous surface relief to be fabricated, the writing time and the price of the equipment determine the cost of its fabrication to a large extend. If we calculate the fabrication cost in terms of equipment price and all consumable parts, gases and material, the FIB milling cost is about $300/hour for our machine with model of Micrion 9500 EX.

It takes about 3 days to fabricated a 10×10 array of micro-diffractive lens by the FIB milling. However, the fabrication expenditure can be reduced greatly by directly fabricate the corresponding mold array for mass production—replication.

Considering commercial equipment, their price for the different methods differs widely. Usual prices are: FIB milling: $0.5~2 million, e-beam writer: $2~5 million, and laser writer: $ 0.5~1 million.

In addition, for the EBL and the LBW, the pattern

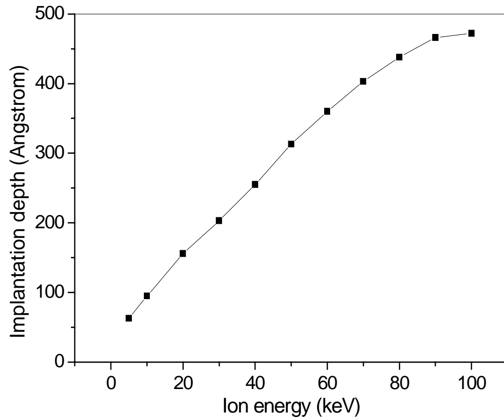


Fig.7 Simulation results of ion implantation depth vs. ion energy in direction of longitudinal.

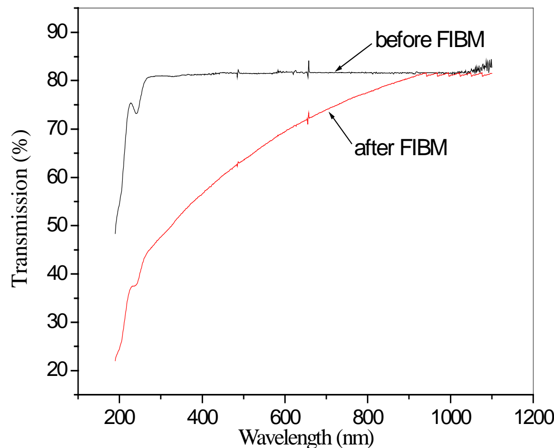


Fig.8 Transmission measured using UV-VIS spectrophotometer for diamond film before and after FIB milling. Comparison of diamond film measured before and after FIB processing with ion energy of 50keV.

transfer from written resist to substrate experiences a complicated process, in which profile fidelity strongly depends on the ratio (*C*) of etching speed and corresponding resist mask pattern. For example, for pattern transfer of microcylindrical lens array, required resist mask pattern should be shape of microprism, elliptical cylinder microlens, cylinder microlens, and parabolic cylinder microlens in the cases of C>>1, $C\neq1$, 0<<C<1, and C>>1or C<<1, respectively. After ion beam etching, nonuniformity is less than 0.5%.[6] It means that the transfer process is sensitive to the shape of mask pattern for different C in practice.

The FIB milling is superior to the EBL and the LBW in the case of device modification, e.g. photonics devices, [6, 7] where microlens can be directly fabricated in partial area, and without damage to neighboring structure or area.

B. Optical properties

More or less of Ga^+ implantation may occur during the FIB milling that will affect transmission of the film, as shown in Fig.7. It is a Ga^+ distribution in substrate simulated by professional software of SRIM2000 on surface of substrate with energy of 50 keV and ion incident angle of 0°. Scale of target depth represents the range of ion implantation in diamond film. Implantation depth increases linearly with ion energy.

Fig.8 is transmission comparison of the diamond film measured before and after FIB processing measured by use of UV-VIS transmittance spectrum (UV-VIS spectrophotometer). It can be seen that variation of transmission before and after the FIB milling is a few in the infrared region. The variation is apparent for the visible wavelength region. Transmission is stable with value of about 82% in the region of near infrared that can meet requirement of conventional optical system. The film after the FIB milling is more suitable for infrared applications. Measured refractive index change of the diamond-like film before and after the FIB milling by use of ellipsometer (Mizojiri Kogaku) equipped with He-Ne laser are 1.44524, and 1.44975 for wavelength of 1446.2nm, respectively. The variation after the FIB milling is caused due to more or less Ga^+ implantation under ion energy of 50 keV. The change is still permissible for conventional optical usage.

This problem does not exist for the EBL and the LBW because the resist layer will be removed by use of ion reactive etching (RIE) after pattern transferring. Bonding energy of molecules is already damage by the chemical gas, and band gap is reduced before ion sputtering. There is few implanted ions remain in surface of substrate after sputtering. Therefore, ion implantation can be ignored for the RIE process.

In addition, the diameter of optical element fabricated by the FIB milling is greatly limited by its memory size fixed on electric circuit board for some current commercial FIB machines, e.g., for the FIB machine with model of Micrion 9500EX, 9000, and 9100 etc., the maximum diameter it can reach is no more than 200 μm due to the fixed memory size of 4 MB used for bitmap function unless we increase the pixels space, but this will sacrifice the writing resolution. This maybe the reason that current focused ion beam machine is originally designed for applications of IC chip modification and semiconductor failure analysis. 4 MB is large enough for the applications. Only a few use it for two-dimensional or three-dimensional microfabrication, especially in micro-optics. It is difficult to mill a large pattern by spelling each small pattern together via moving stage step by step due to low moving accuracy of the stage, only ±1 μm, which is far insufficient for requirement of profile accuracy.

IV. MICROFABRICATION BY FIB DEPOSITION

SiO_2 can be deposited directly to form a required pattern by FIB deposition. The source gas is decomposed by an ion beam and adsorbed on the surface of the substrate. The entire process is controlled by a computer program, generally based on the relationship between the ion-beam

energy and the deposited thickness. The whole process can be carried out automatically using the software program. Fig.9 is an example of micro-cylindrical lens with dimension of 2.8μm×7.5μm, *NA*=0.2, deposited by FIB

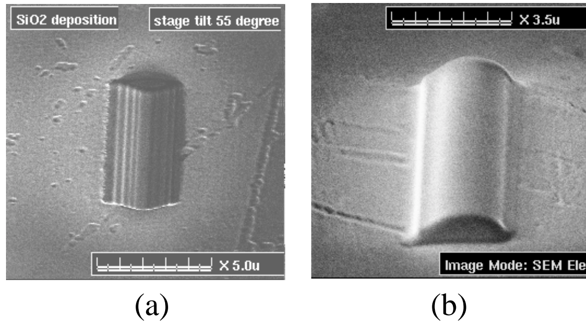


Fig.9 SEM microphotograph of micro-cylindrical lens with numerical aperture (NA) of 0.4 by SiO_2 deposition in the view angle of 30°. (a) without post processing, (b) with post processing.

deposition. Experiments were carried out using our FIB machine (Micrion 9500EX), with an ion source of liquid gallium integrated with a scanning electron microscope (SEM), energy-dispersive X-ray spectrometer (EDX) facilities, and gas-assisted etching (GAE). This apparatus uses a focused Ga^+ ion beam with energy between 5~50 keV, a probe current of 4 pA~19.7 nA, and a beam-limiting aperture size between 25~350 μm. For the smallest beam current, the beam can be focused down to 7 nm in diameter at full width at half maximum (FWHM). By changing the dwell time under different beam-limiting aperture sizes and controlling the actual beam current error to be less than 10% of the corresponding theoretical value, different deposition results were obtained with precursor gases of 1,3,5,7 tetramethylcyclotetrasiloxane (TMCTS) and H_2O for the SiO_2 microlens deposition. The accelerating voltage and working distance was 50 kV, and 27 mm, respectively, and the chamber base pressure was maintained at 9.1×10^{-6} Torr during the whole deposition process.

The designed continuous profile of the micro-cylindrical lens is divided into many thin layers for the sake of fabrication, which compose of the lens three-dimensional profile using the discrete layers. Each layer is rectangular, with a different size for each different section. The micro-cylindrical lens is composed of many deposited SiO_2 films with rectangular shape and different sizes, which corresponds to slices with discrete thickness in terms of the sag of the lens, in which the lens was formed by covering layer by layer. Finally, the microlens can be obtained by post-processing after completing the deposition of all layers, which are overlapped from bottom to top. After finishing of the top layer, post processing is performed to form the final required form with smooth surface, as shown in Fig.9. It can be seen that the post processing is crucial to form the final required shape.

Two key factors determine quality of the microlens: implanted Ga^+, and the percentage of Si and O_2. The former factor exists in both the milling and deposition process due to unavoidable ion implantation that affects the transmission to a certain extent, and the latter factor is mainly for the deposition of SiO_2 film. They affect the microlens transmission directly, as shown in Fig.10, in

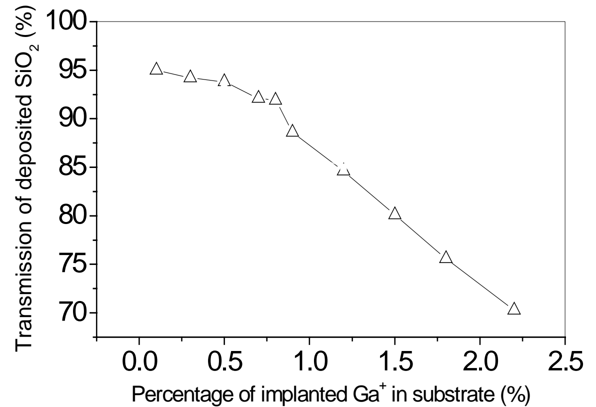


Fig.10 Experimental result of transmission vs. implanted Ga^+ percentage in the SiO_2 film deposition for wavelength of 633 nm.

which the percentage of Ga and transmission were measured by use of a electron dispersion X-ray spectrometer (EDX), and a transmittance spectrum (UV-VIS spectrophotometer HP8453), respectively. In addition, the 'overspray" effect caused by high energy secondary electron's contributing to the deposition process outside the ion beam pattern will also affect the quality. This effect is considerable when the solid escape angle is limited (for example at the bottom of trench).

The increasing of the implanted Ga^+ is intensive for the milling process because the focused Ga^+ beam directly collides with the substrate, leading to more Ga^+ implantation. Therefore, the percentage of Ga^+ is different for milling and deposition processes under the same ion dose; the amount of implanted Ga^+ is more for the milling process than for deposition. For deposition of the SiO_2 film, the film is formed by the role of adsorption. The beam intensity is attenuated more or less during the process of decomposition and adsorption, which causes less Ga^+ to be implanted than for milling under the same dwell time. The Ga staining can be effectively compensated for by using methods such as adaptive milling patterns and post process cleaning steps. The use of I_2 or Cl_2 is also highly effective at removing implanted Ga^+.

In addition, density of ion pixels (also called pixel spaces in scan directions of horizontal and vertical) is also important that determines the process is milling or deposition. If the density is too high, e.g. pixel spaces of 0.009 μm in directions of horizontal and vertical for beam spot size of 20 nm, the deposition process will transfer to milling process because the act of milling still play a dominant role and the gas is not decomposed completely in this case. Therefore, the density for deposition should be far less than that of the milling process. Normally, it is 10 times of the milling mode. On the other hand, refresh time for deposition should be large enough in order to ensure the

complete decomposition, it is set to be 2000~4000 μs more often.[8]

The FIB deposition is a unique function of focused ion beam machine for microlens fabrication.[11] It can directly add material in terms of designed pattern by programmable controlling. However, it is difficult to be used to deposit DOE due to difficulty of precisely controlling of the deposition process for the annulus with continuous relief. For the reposition of round pattern, periphery of the pattern is very rough, which causes worse surface roughness and relief accuracy during the process of overlapping layer by layer.

Table 1 is a general fabrication performance comparison among the FIB lithography, FIB deposition, FIB milling, EBL, and LBW in the specifications of fabricated feature size, depth of focus, resolution, typical surface roughness, profile accuracy, etc.

V. DISCUSSIONS AND SUMMARY

The three direct writing methods of focused ion beam machine, FIB lithography, FIB deposition, and FIB milling, as well as the EBL and the LBW, are well adapted for fabrication of micro-optical elements with continuous relief. They are all superiors to the EBL and the LBW in the case that optical elements need to be fabricated in partial area of device. But limitations still exists for them. The DOE with feature size of submicron is difficult for the FIB lithjography exposing on resist. The FIB deposition is limited for a DOE fabrication. The FIB milling cannot realize fabrication for the optical elements with large size (diameter >200 μm) due to the limitation of the memory size for bitmap function use. They are all more expensive than the LBW.

Because of thermal annealing needed at high temperature after the FIB lithography, some semiconductor device cannot undergo the high temperature due to inside packaging structure (e.g. solder bumps will melt under the temperature) or characteristics variation of quantum wells. This limits its application to a certain extent, especially for the device of partial modification required via the FIB lithography. Fabrication of the Bragg grating in DFB laser diode is the typical application of this method in photonics and optics area.

The common features of the three methods are all single-step fabrication compared with the EBL and the LBW with two steps (exposure and pattern transfer) unless the hybrid solgel film or other photopolymer is used for single-step writing of the LBW. They are all useful for rapid prototyping of microlens with continuous relief. In addition, they can be used for post processing in partial area of device, unlike the EBL and the LBW writing on wafer level.

Regarding the cost, it is meaningful only when they are used for mass production. From this point of view, fabrication of microlens mold is their potential and promising application. The FIB lithography is not suitable for the application. Only the FIB milling can realize one-step fabrication. The EBL and the LBW are all need to form the mold by vacuum evaporation coating (produce seeding layer) and electroplating (commonly used material is Nickel) after exposure. [11]

However, some features still need to be further improved, especially in the transition from micro-optics to ‘macro-optics’. The development of a suitable data standard, well adapted to the diversity and specific features of two-dimensional and three-dimensional relief and direct usable by the equipment is an important task for future work. In addition, computer hardware with large memory size and stage with high moving accuracy are essential for large area pattern generation.

Table 1 Performance comparison for microfabrication of optical elements with continuous relief among the methods of FIB lithography, FIB deposition, FIB milling, the EBL, and the LBW

Items	**FIB LITHOGRAPHY**	**FIB MILLING**	**FIB DEPOSITION**	**LBW (He-Cd)**	**EBL**
Depth of focus	~20 μm	~20 μm	~20 μm	<2 μm	~8-10 μm
Number of transfer steps	Single-step	Single-step	Single-step	two / one for hybrid solgel film	two
Resolution	~7 nm	~7 nm	~7 nm	>1 μm	2~5 nm [10]
Profile accuracy	<0.1 μm	<0.1 μm	<0.5 μm	<0.1 μm	<0.1 μm
Typical surface roughness (rms)	≤2 nm (in area of 1×1 μm^2)	≤2 nm (in area of 1×1 μm^2)	≤2 nm (in area of 1×1 μm^2)	25-100 nm (depending upon microstructure and *NA*) [10]	1.5 nm (in area of 1×1 μm^2)
Writing material	Resist	Any material	SiO_2	Resist / hybrid solgel film	Resist (PMMA)
Maximum relief height	< DOF (depends on lateral size for exposure on resist)	< DOF (depends on lateral size)	≤1 μm / layer	3.2 μm (~6 μm max.) [10]	<5 μm
Maximum *NA* for micro-optical element	~ 0.5	~ 0.5	~ 0.6 (for refractive lens only)	~ 0.5 (PMFE with 8π phase step) [11]	~ 0.5

Feature size	~ 1µm	~ 1µm	-	4~5 µm	< 1 µm [12]
Equipment cost	$0.5~2M.	$0.5~2M.	$0.5~2M.	$0.5~1M.	$2~5M.
Typical energy	≥100keV	50keV	50keV	-	10~20keV

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