Paper

Fabrication of Diffractive Optical Elements on a Si Chip by Imprint Lithography using Novel Mold

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Fabrication of a fine diffractive optical element on a Si chip is demonstrated using imprint lithography. A chirped diffraction grating, which has modulated pitched pattern with curved cross section is fabricated by an electron beam lithography, where the exposure dose profile is automatically optimized by computer aided system. Using the resist pattern as an etching mask, anisotropic dry etching is performed to transfer the resist pattern profile to the Si chip. The etched Si substrate is used as a mold in the imprint lithography. The Si mold is pressed to a thin polymer (Poly methyl methacrylate) on a Si chip. After releasing the mold, a fine diffractive optical pattern is successfully transferred to the thin polymer. This method is exceedingly useful for fabrication of integrated diffractive optical elements with electric circuits on a Si chip.

Keywords: chirped diffraction gratings, electron-beam lithography, proximity correction, imprint lithography, mold, dry etching

1. INTRODUCTION

Replication is one of the most important technologies for mass production of diffractive optical elements (DOE). There have been reported several methods to fabricate DOE by replications [1]. On the other hand, an optical-electric integration system is indispensable for the next generation's informational processing system. However, using the conventional replication method, the DOE is fabricated separately and they might be assembled one by one on a Si chip. This paper demonstrates a fabrication of DOE on a Si chip by imprint lithography using IC's processed Si mold.

One of the difficulties for the replication of DOE lies on fabrication of a master plate, which has specific cross sectional profiles for DOE. Electron beam lithography is one of the most promising technologies to fabricate an arbitrary resist cross sectional profile as a master structure of the DOE. However, designing an exposure dose distribution for a specific DOE is extremely difficult because of the back scattering electrons caused proximity effects during electron beam exposure [2]. Several methods were reported to correct the proximity effects [3]-[5] but their effective area is limited such as a thin resist exposure. We proposed a progressive dose optimization system in electron beam lithography taking the resist development into consideration [6][7]. Using the proposed method, a resist pattern for chirped diffraction grating is fabricated on Si substrate and the Si substrate is etched by a anisotropic plasma etching to fabricate a Si mold with fine chirped diffraction grating for imprint lithography.

To transfer the mold pattern, the mold is pressed to the thin PMMA (poly-methlymethacrylate) on Si chip. Fabrication of a fine chirped grating on Si chip is demonstrated by imprint lithography.

2. MOLD FABRICATION

2.1 Mold fabrication process by the conventional IC's process

Electron beam lithography is one of the most practical methods to fabricate various cross-sectional resist profiles because the exposure dose distribution is easily modulated. Figure 1 shows the schematic view of the proposed process to fabricate a mold with modified cross-sectional profiles for imprint lithography.

First, a resist pattern on Si substrate is formed using modulated dose exposure by electron beam lithography. Next, the Si substrate is anisotropicaly etched by a plasma etching system to transfer the resist cross sectional profile to the Si substrate. Finally, fluorine polymer is coated to avoid adhesion problem during imprint lithography. In this case, the resist cross sectional profile is the inversion of the desired profile of the DOE because the profile is inverted by imprint process. The details of each process are described in the next sections.

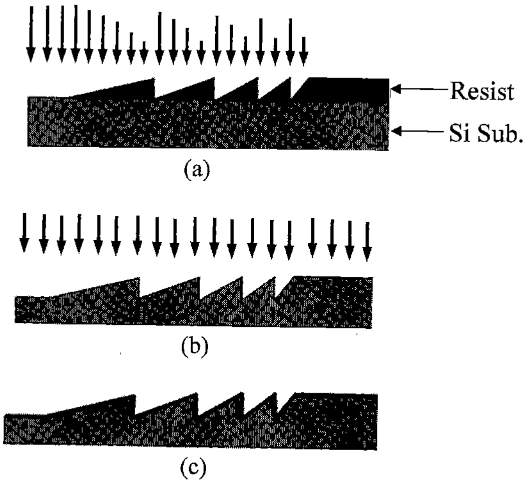


Fig.1 Mold fabrication process by modulated EB exposure and Si etching.
(a) Electron beam lithography by modulated dose exposure
(b) Dry etching by the neutral loop discharge method (Cl_2)
(c) Fluorine polymer coating

2.2 Optimization of exposure dose profile for non symmetric diffractive optical element

We have developed an automatic dose optimization system for a positive electron beam resists obtaining modified resist cross-sectional profiles in direct electron beam lithography [6][7]. Figure 2 shows the block diagram of the proposed system. After setting an initial exposure dose distribution, the absorbed energy distribution $E(x,z)$ is calculated based on Monte Carlo simulation taking account of the electron scattering in the resist [2]. Next, a resist development simulation is performed to predict the resist cross-sectional profile $P(x_i)$ after development, where x_i is the horizontal position. The exposure dose $\delta_{i,n}$ at each position is corrected to be

$$\delta_{i,n} = \delta_{i,n-1}\frac{\tilde{E}_t(x_i)}{\tilde{E}(x_i)}, \qquad (1)$$

where $\tilde{E}(x_i)$ and $\tilde{E}_t(x_i)$ are the calculated mean absorbed energy densities from the resist initial surface to the current and target surfaces, respectively.

The resist cross-sectional profile is evaluated by the following evaluation function;

$$\phi_i = W_i(P(x_i)-P_t(x_i))^2, \qquad (2)$$

where Wi is a weight. The iteration process is completed when the total evaluation value $\sum_i \phi_i$ becomes sufficiently small.

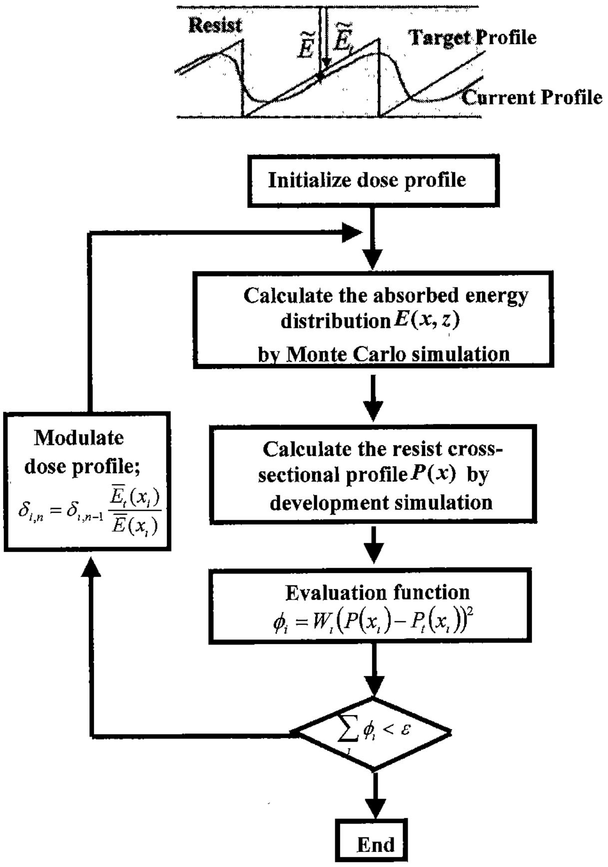
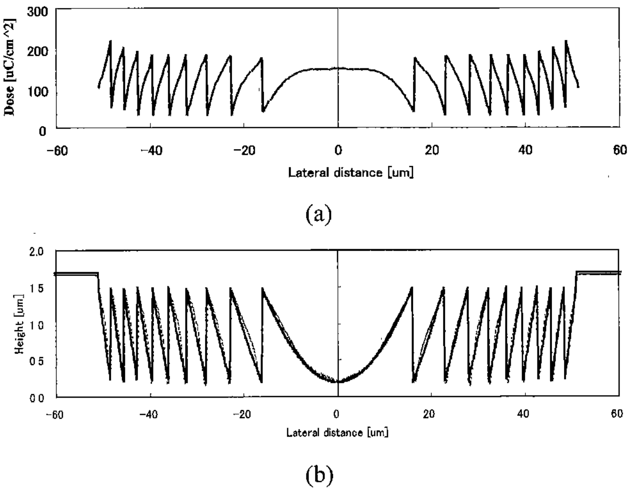


Fig.2 Dose optimization procedure to obtain arbitrary resist cross sectional profiles by an electron beam lithography.

The proposed system takes not only the proximity effects by electron scattering for arbitrary exposure patterns, but also the resist development process to predict the resist cross-sectional profiles after development into account.



(a)

(b)

Fig.3 Dose optimization results for inverted chirped diffraction grating pattern.

(a) Optimized exposure dose profile for inverted chirped diffraction grating. The resist is 1.7 μ m PMMA on Si. The exposure beam energy is 50KeV.

(b) Cross sectional profiles of the target structure (dashed line) and optimized result (solid line).

Figure 3 (a) shows the optimized dose profile for an inverted chirped diffraction grating. The minimum pitch is 2.0 μ m and the resist thickness is 1.7 μ m. The target profile and the optimized resist cross sectional profile after development are shown in Fig.3 (b). An inverted chirped pattern is successfully fabricated according to the simulation. The average error is around 93nm. The error becomes large at the steep edges.

Figure 4 shows experimental result of the resist cross sectional profiles by optimized dose exposure. The electron beam exposure system is JEOL JBX-5000 and the resist is PMMA (OEBR-1000). An inverted chirped diffraction grating is successfully obtained. The solid line shows the simulation result of the dose optimization system, which agrees well with the experimental result. It is confirmed that the dose optimization system is fairly effective even for a pitch-modulated pattern like chirped diffraction grating.

2.3 Fabrication of a Si mold

To transfer the resist cross sectional profile to a Si mold, a Si substrate is etched by a neutral magnetic loop discharge plasma etching system using Cl_2 gas, where the resist is used as an etching mask as in the Fig.1[8]. In this system, the resist is isotropically etched but Si is almost vertically etched. The measured etching ratios for the Si and the resist (OEBR-1000) are about 0.36 μ m/min and 0.7 μ m/min, respectively.

The cross sectional profile of the Si substrate after plasma etching is simulated using a cell removal model, which takes the anisotropic properties into consideration [9]. In this case, the resist is etched isotropically and the Si is etched anisotropically for only vertical direction. Figure 5 shows the simulation result of the Si substrate after plasma etching. The side-wall of the pattern is relatively inclined because the resist is etched isotropically. Also, the height of the transferred pattern is decreased because the etching rate of the Si is smaller than that of the resist.

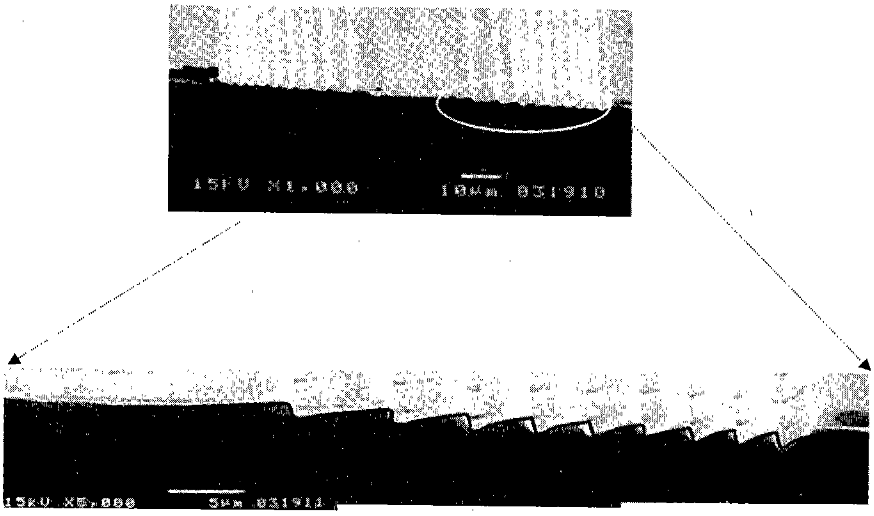


Fig.4 Experimental result of the resist cross sectional profiles by modulated dose exposure. The solid line shows the simulation result by the dose optimization system [6][7].

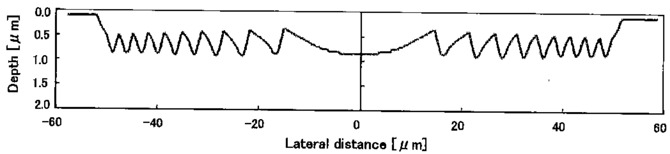


Fig5. Simulated cross sectional profile after Si anisotropic dry etching.

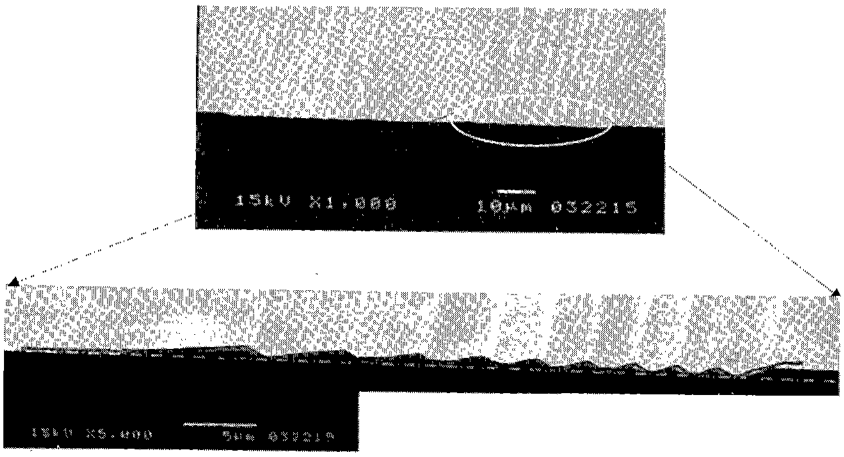


Fig.6 Experimental result of the Si substrate after plasma etching. The inverted chirped diffraction grating is successfully formed. The solid line shows the simulation result, which agrees fairly well with the experimental result

Figure 6 shows the experimental result after plasma etching. The resist cross sectional profile is successfully transferred to the Si substrate but the corners are rounded and the height of the pattern is decreased. This is because that the etching ratio of the resist is larger than that of Si substrate. As demonstrated above, a non-symmetric cross sectional futures are transferred to the Si substrate using the dose optimized electron beam lithography and the anisotropy plasma etching.

Finally, a fluoropolymer is coated on the Si surface to avoid the adhesion problem [10]. Figure 7 shows a process flow of a surface treatment by silane-coupling agent. The mold is cleaned by H_2SO_4/H_2O_2 boiling and UV-ozone exposure to remove organic contamination. Then, the mold is dipped into the 0.1 w% perfluoropolyether-silane (PFPE-S) diluted by perfluorohexane (C_6F_{14}) for 1min at room temperature in air atmosphere. After dipping into the PFPE-S, the mold is left in the high humidity atmosphere (65 ℃ ,95%) for 1 h. In this process, the perfluoropolyether molecular layer is formed on the mold surface by M-O-Si-R bond.

Figure 8 shows a water droplet on surface treated by the silane-coupling agent. The contact angle is about 114 degree, which shows excellent performance for releasing.

As discussed above, a fine mold for inverted chirped diffraction grating, which has non symmetric cross sectional profile, is successfully fabricated.

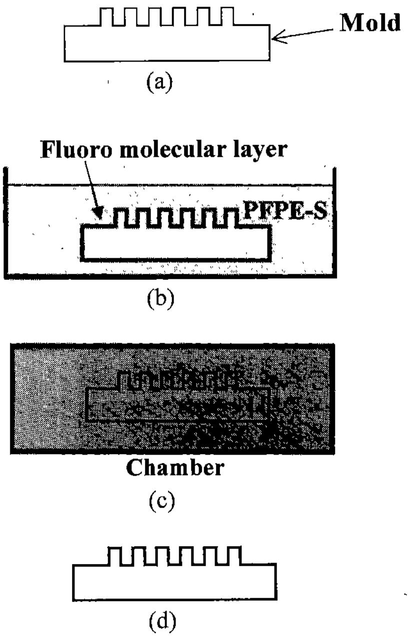


Fig.7 Process flow of the surface treatment by a PFPE-S (perfluoropolyether-silane)
(a) Surface cleaning
(b) Dipping into a diluted PFPE-S (1 min)
(c) Keeping in a humidity atmosphere (65℃, 95%, 1h)
(d) Rinse and dry

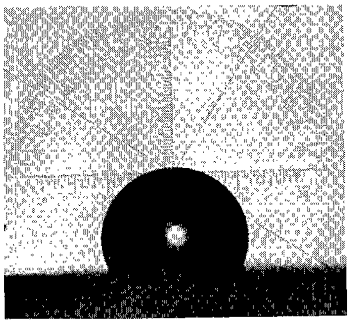


Fig.8 Water droplet on surface treated through silane-coupling agent by PFPE-S. The contact angle is about 114 degree.

3. PATTERN TRANSFER BY IMPRINT LITHOGRAPHY

3.1 Process of the imprint lithography

There are several methods for imprint lithography [11][12]. We use a thermal hardening process proposed by S. Chou [11] to transfer a master pattern to a resist on a Si chip.

Figure 9 shows experimental procedure. First, a $1.7\,\mu$m thick PMMA (poly methyl methacrylate, M_w=600,000) is coated on a Si chip and baked at 170℃ for 30 min by a hot plate. Then, the Si chip and the mold are heated up to 170℃. Next, the mold is pressed into the polymer on the Si chip at around 90 MPa and hold for 5 min. Then, the mold and the Si chip are cooled down by water cooling to be 60℃ and hold 5 min keeping the imprinting pressure. Finally, the mold is released from the polymer.

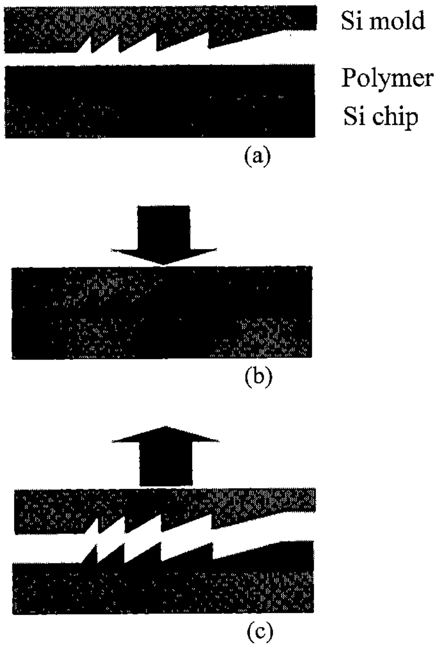


Fig.9 Replicated pattern fabrication on Si substrate using imprint lithography.
(a) Resist coating on Si chip and pre-heating (170℃)
(b) Press mold to the resist (90MPa, 5min)
(c) Cool down and Release mold

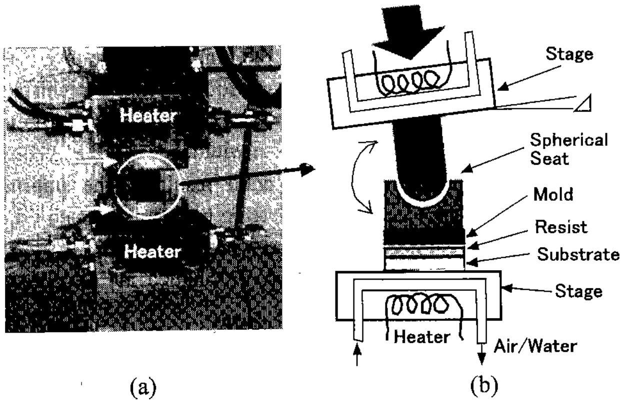


Fig.10 Schematic view of the imprinting system.
(a) Overview of the imprint system
(b) Details of the imprint system.

In the imprint process, we use an air press machine. Figure 10 (a) shows the photo of the modified hot-press machine. The surfaces of the stages are finished by mirror polished and the temperature of the stages is controlled.

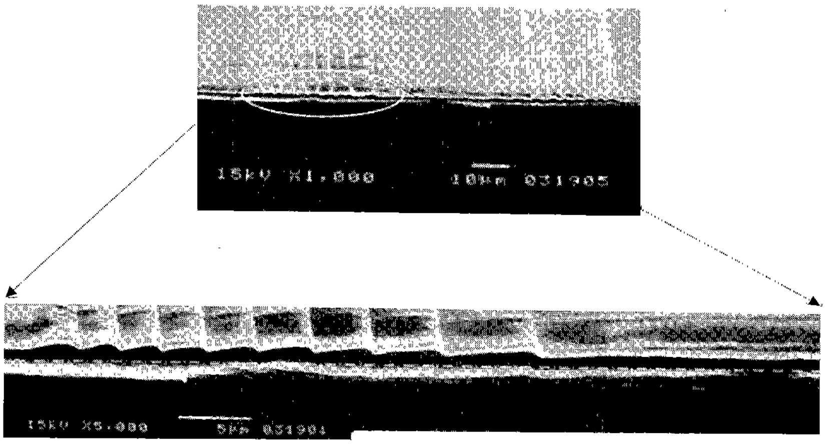
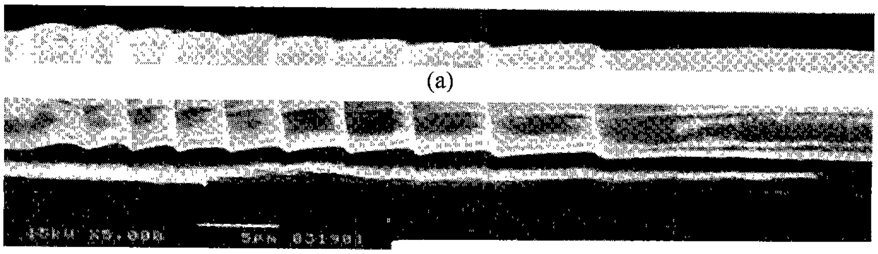


Fig.11 Replicated result by imprint lithography using chirped diffraction grating mold



(a)

(b)

Fig.12 Comparison between the mold cross-section and imprinted pattern on Si substrate
(a) Cross section of the mold
(b) Cross section of the imprinted pattern on Si chip

In the imprinting process, the surface of the mold should be parallel to the surface of the Si chip. So, a spherical seat is placed upon the mold as shown in Fig. 10 (b).

3.2 Experimental result

Using the above discussed mold, the chirped diffraction grating is transferred on a Si chip by the imprint lithography. In this experiment, the mold size is 5mm square and four chirped diffraction grating patterns are formed in the mold. Each pattern is 2.0mm in length and about 100 μ m in width.

Figure 11 shows the experimental result of the imprint lithography. A chirped diffraction grating pattern is formed on a Si chip by imprint lithography. However, the pattern profile is not so fine because the mold pattern is rounded at the plasma etching process.

To compare the imprinted pattern profile with the mold profile, we investigate both SEM images are shown in the Fig.12. The mold cross sectional profile is precisely replicated to the PMMA on the Si chip. This shows that the imprint process is successfully done without any problems.

4. CONCLUSIONS

A typical DOE pattern such as chirped diffraction grating is successfully fabricated on a Si chip by imprint lithography using a novel Si mold, which is fabricated by automatically dose optimized electron beam exposure. Using the Si mold, chirped diffraction grating is transferred on a Si chip by the imprint lithography. This method is expected to fabricate an optic-electric integration system on a Si chip.

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REFERENCES

1. H. Herzing ,*Micro-optics*, Taylor & Francis, London ,1997.
2. T.Chang ,"Proximity effect in electron-beam lithography", *J.Vac. Sci. Technol.* **12**, pp.1271-1275, 1976.
3. W.Daschner, M.Larsson and S.H.Lee: "Fabrication of monolithic diffractive optical elements by the use of e-beam direct write on an analog resist and a single chemically assisted ion-beam-etching step," *Appl. Opt.* **34**, pp. 2534-2539,1995.

4. P.D.Maker and R.E.Muller: “Phase holograms in polymethyl methacrylate,” *J. Vac. Sci. Technol.* **B10**, pp. 2516-2519,1992.
5. F.Nikolajeff, J.Bengtsson, M.Larsson, M.Ekberg and S.Hard: “Measuring and modeling the proximity effect in direct-write electron-beam lithography kinoforms,” *Appl. Opt.* **34** , pp. 897-903,1995.
6. Y.Hirai, H.Kikuta, M.Okano, T.Yotsuya and K.Yamamoto: “Automatic dose optimization system for resist cross-sectional profile in a electron beam lithography,” *Jpn. J. Appl. Phys.* **39** , pp. 6831-6835,2000.
7. M. Okano, T. Yotsuya, Y.Hirai, H.Kikuta, and K.Yamamoto, “ Precise Proximity Correction for Fabricating Chirped Diffraction Gratings with the Direct-Writing Electron-Beam Lithography”, *Proc.* of *SPIE* **4440**,(San Diego, July, 2001) pp.268-27, .2001.
8. H.Toyota, K.Takahara, M.Okano, T.Yotsuya and H.Kikuta, "Fabrication of microcone array for antireflection structured surface using metal dotted pattern," *Jpn. J. Appl. Phys.* **40** Part 2, pp.L747-L749,2001.
9. Y.Hirai, S.Tomida, K.Ikeda, M.Sasago, M.Endo, S.Hayama and N.Nomura: “Three-dimensional resist process simulator PEACE (Photo and Electron Beam Lithography Analyzing Computer Engineering System),” *IEEE Trans.on CAD*, **10** ,pp. 802-807, 1991.
10. Y.Hirai, S.Yoshida, A.Okamoto, Y.Tanaka, M.Endo, S.Irie, H.Nakagawa, and M.Sasago, “Mold Surface Treatment for Imprint Lithography”, *j. of Photopolymer Sci. Technol.*, **14**, pp.457-462, 2001.
11. S. Chou, P. Krauss and P. Renstrom: “Nanoimprint lithography”,*J. Vac. Sci. Technol.* **B14**, pp.4129 –4133 ,1996.
12. M. Colburn, S. Johnson, M. Stewart, S. Damle, B. J. Choi, T. Bailey, M. Wedlake, T.Michaelson, S.V. Sreenivasan, J. Ekerdt, C.G. Willson; "Step and Flash Imprint Lithography: An alternative approach to high resolution patterning." Proc. SPIE **3676**, pp.379-389 ,1999.
13. Y.Hirai, Y.Kanemaki, K.Murata and Y.Tanaka, ‘Novel Mold Fabrication for Nano-Imprint Lithography to Fabricate Single-electron Tunneling Devices’, *Jpn. J. Appl. Phys.* **38**, pp.7272-7275, 1999.
14. Y.Hirai, Y.Kanemaki, M.Fujiwara, T.Yotsuya and Y.Tanaka, ‘Fine pattern imprint lithography using dimpled mold’, *J. photopolymer Sci. and Technol.*13, pp.435-440, 2000.

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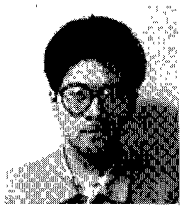

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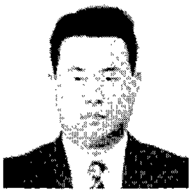

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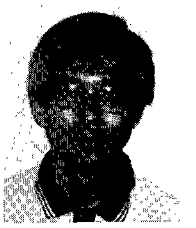

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