Fidelity of Photo-nanoimprint

Hiroshi Hiroshima

MIRAI, Advanced Semiconductor Research Center (ASRC),
National Institute of advanced Industrial Science and Technology (AIST),
1-1-1 Umezono, Tsukuba, Ibaraki, 305-8568 Japan
hirosim@ni.aist.go.jp

Patterns were fabricated by photo-nanoimprint using a Si mold having extremely
smooth patterns with a line edge roughness (LER) of 0.58 nm. The LERs of
photo-nanoimprint patterns were evaluated by an off-line analysis of scanning electron
microscope images using the scaling analysis. The LER of photo-nanoimprint pattern
for UV exposure dose of 0.01 – 1 J/cm² is not affected by the exposure dose and takes as
low as 0.64 - 0.78 nm. Analyses of LER using white noise subtraction revealed that the
LER profile originated in the Si mold pattern of the scaling analysis is preserved in
photo-nanoimprint patterns.

Keywords: photo-nanoimprint, line edge roughness, scaling analysis, white noise

1. Introduction

Lithography is the core technology for downsizing of electronic devices. Photo
lithography extends its length of a reign by an immersion technology and other new lithographic
technologies are under development. Recently, nanoimprint lithography [1] became a candidate
for next generation lithography due to its high resolution, high productivity and high
cost-performance. The nanoimprint is classified broadly into two categories (i.e. thermal-
nanoimprint [1-3] and photo-nanoimprint [4-6]) and both can produce sub-10 nm patterns. The
preferable method for lithography is photo-nanoimprint because of being free from
thermal cycle indispensable for thermal-nanoimprint. As the dimension of electronic
devices enters the sub-100 nm, the line-edge roughness (LER) becomes a great issue of device
fabrication [7]. Generally, lithography includes development process using a liquid developer in
which resists soluble or insoluble by photon or electron irradiations are processed. In the
developer, resist molecules are dissolved with their solubility resulting the resist roughness
(corresponding the resist molecule’s dimensions [8]. On the contrary, the surface roughness of
patterns fabricated by nanoimprint basically depends on the surface roughness of the mold
since no dissolution process is applied. Photo-curable liquid polymers, which are used
for photo-nanoimprint, decrease in the volume typically by a few to around ten percent in the
solidification process and uneven contraction might degrade pattern quality such as LER.
Here, the fidelity of photo-nanoimprint is discussed by careful evaluation of LERs.

2. Experiment

The photo-nanoimprint process is shown in Fig. 1. The Si mold used here is made of a Si
(110) substrate and fabricated by an alkaline anisotropic etching where the etched line and
space patterns parallel to <112> direction have

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Figure 1. Photo-nanoimprint process for an opaque mold

smooth and vertical side walls due to extremely slow etching rate of Si (111) surface [9]. In this experiment, a mold having patterns with a pitch of 240 nm and a depth of 200 nm was used. The mold surface was treated with chlorinatedfluoroalkylmethylsiloxane to prevent solidified polymer from adhering. As the Si mold is opaque, quartz which is transparent to UV light is used as a substrate. Photo-curable polymer (PAK-01, Toyo Gosei Co.) with a volume of 0.5 μl was dropped on a quartz plate and the Si mold was pressed on the sample with a pressure of 0.6 MPa. Through the quartz plate, the photo-curable polymer was exposed to UV light with a wavelength of 365 nm from a mercury lamp with exposure dose ranging from 0.01 to 1 J/cm². The exposure range in this experiment was determined by a preliminary experimental result that the photo-curable polymer starts curing at 10 mJ/cm² and it is almost completely cured at 100 mJ/cm² with a volume shrunk of about 7% and our typical exposure dose of 1 J/cm². To prevent charge up phenomenon during scanning electron microscope (SEM) observation, Ti with a thickness of 10 nm was evaporated for the photo-nanoimprint patterns on quartz plates. An SEM (S-4500, Hitach Co.) was used for image capture with a magnification of 60,000 where the image was composed of 1024 x 960 pixels with a pixel size of 2 nm x 1.6 nm and 256 gray levels. The images were saved in TIFF format.

3 Off-line Analysis of SEM images
3.1 Edge Detection
To evaluate the LER, the edge position should be precisely determined from a captured SEM image. A given row (i.e. a given electron beam scanning line) of an image consists of a relation between the intensity and the horizontal position. Firstly, the maximum intensity value and the background intensity value in the row were determined. In this case, the background intensity was selected to the intensity at 20 percentile of the intensities (e.g. the 20th lowest intensity in case of 100 intensities). There are two candidates for an edge position at which the intensity is half of the maximum intensity and the outer one whose position is in the right edge position was selected. The edge position was then determined with sub-pixel resolution by a linear interpolation using two neighboring data without noise reduction. The edge detection was applied to all rows and a series of line edges
3.2 Scaling Analysis

In the calculation of LER, a least square fit (LSF) line was firstly determined for a given part of a set of line edges and the root mean square (RMS) of a distance between an edge position and the LSF line is calculated. A window which includes the part of the set of line edges is characterized by the window size and the window position and the RMS value is a function of the window. The RMS value is varied with the window position even in the case of a fixed window size, therefore, the averaged RMS for a window size is obtained by calculations of RMSs for all possible window positions. Then, the averaged RMSs are obtained for all possible window sizes. The analysis of the RMS as a function of the window size plotted in a log-log scale is called scaling analysis of LER, where the window size is called scale. Figure 2 shows a schematic illustration of a scaling analysis of LER of a resist. Typically the LER obeys in a power law in the small scale region due to its fractal nature and stabilizes to a value in the large scale region. By the scaling analysis of LER, three parameters ($\alpha$: roughness exponent, $L$: correlation length, $\sigma$: sigma value) which characterize the LER can be derived if it has a fractal nature and a bounded roughness [10]. Typically, $\alpha$ takes 0-1, $L$ takes 50-100 nm, and $\sigma$ takes larger than 2 nm for common resists [11, 12].

4. Results and Discussions

Figure 3 shows an SEM image of patterns fabricated in a Si mold. The line patterns are incomparably smoother than those of photo resists or electron beam resists. The edge detection process reveals the small fluctuation of the line edge as shown in Fig.4. The LER seems to be mainly composed of a low frequency component with a length of several hundred nm and a high frequency component with a length of sub-10 nm. The origin of the former component may be due to the fluctuation of the line pattern itself and that of the latter may be due to mechanical vibrations during capture of the SEM image. The amplitude of LER is much smaller than that of photo-resists.

Figure 5 shows the scaling analysis of the LER (open circle). The LER increases in the scale less than 10 nm and shows saturating behavior within the scale smaller than 300 nm and increases again in the scale larger than 300 nm. The increase in the larger scale region is due to the low frequency component of the edges.
Figure 5. Scaling analysis of LER for Si pattern (open circle), photo-nanoimprint pattern (closed circle), and simulated white noise with a standard deviation of 0.6 nm (cross).

as shown in Fig. 4. We use the sigma value at the scale of 300 nm to exclude the influence of the mender from pattern to pattern when we refer to the LER value except to the case of the scale explicitly mentioned. The LER of the Si mold pattern was 0.58 nm. The LER increases in the small scale region, however, no power low behavior is observed in contrast to that of common resists shown in Fig. 2. To understand the LER behavior in the small scale region, the scaling analysis for a simulated white noise was carried out. The result of the white noise with a standard deviation of 0.6 nm is shown in Fig. 5 (cross). It is found that the result does not show a constant value and there is non linear behavior in the small scale region due to the impact of small number of data (e.g. the smallest scale includes 3 data). Therefore, we think that the non linear behavior of the LER of the Si mold pattern in the small scale region does not include information related to the correlation length.

Figure 6 shows an SEM image of patterns fabricated by photo-nanoimprint with an exposure dose of 1 J/cm². The patterns look extremely smooth as that of the Si mold pattern. Such extremely smooth patterns have not been fabricated by the other lithography. The scaling analysis of the LER of the photo-nanoimprint pattern is shown in Fig. 5 (closed circle). We expected that the LER of photo-nanoimprint pattern would show a behavior similar to that of common resists, however, the result was almost same to that of Si mold pattern. No correlation length exists as no power low behavior is observed in the small scale region similar to that of the Si mold. The LER value of the photo-nanoimprint pattern was 0.64 nm and it is about one third of the typical LER value for common resists.

A great concern is the LER behavior related to the exposed dose in photo-nanoimprint. The scaling analyses of photo-nanoimprint patterns with different exposure dose are shown in Fig. 7. The profiles of LER are very similar and the LER values are 0.64 - 0.78 nm. It is found that the LER of photo-nanoimprint patterns is quite low and insensitive to the exposure dose. It means that uniformity of UV exposure is not required even for such low LER pattern fabrication if the exposure dose exceeds a threshold dose for curing. The robustness of photo-nanoimprint is a convenient feature for real applications.

In detail observation, the profile of the LER of Si mold pattern is slightly different from those of photo-nanoimprint patterns. What we focused on is the variations of the LER values at
the minimum scale. The value of Si mold pattern is larger than those of the photo-nanoimprint patterns. The value must be mainly affected by the component related to the vibration of SEM image so that the component may also affect the profile of the LER. For precise LER evaluation, it is important to keep the vibration level enough small compared to the LERs under evaluation, however, it is difficult to reduce the vibration level in SEM images as it already approaches an unreachably low. Here, we subtract the vibration on the assumption that that the vibration is white noise and the minimum LER value is determined by the vibration. The sigma value of the vibration (the white noise) can be determine by comparing the minimum LER value with that of the white noise shown in Fig. 5. An LER value experimentally obtained is considered as a square root of sum of the squared value of an LER excluding vibration and the squared value of the vibration. Thus, the modified LER value without vibration can be calculated. The scaling analyses of the modified LER are shown in Figure 8. The modified LER profile for Si mold pattern becomes similar to those for photo-nanoimprint patterns. However, the modified LER value for Si mold pattern is 0.42 nm while those for photo-nanoimprint patterns are 0.62 - 0.75 nm. The shift of the profiles of the modified LER means the spatial frequency spectrum of the LER originated in the Si mold pattern is preserved but the amplitude is increased by a factor of 1.5 for photo-nanoimprint samples. The larger LER values for photo-nanoimprint patterns are the results of combination of not only photo-nanoimprint process itself but electron beam inspection with Ti deposition. It has been found that the most probable reason is Ti deposition as reported elsewhere [13]. The real fidelity of photo-nanoimprint will be revealed only by a high precision atomic force microscopy [14].

5. Conclusions
By using extremely smooth Si mold fabricated by an anisotropic wet etching, extremely smooth patterns with the LER of 0.64 - 0.78 nm were obtained by photo-nanoimprint. On contrary to common resists, no correlation length exists in the scaling analysis of LER not only for Si mold patterns but also for photo-nanoimprint patterns. The method using a white noise based on some assumptions revealed that the profile of the scaling analysis of
LER is preserved through the photo-nanoimprint process. The LER of photo-nanoimprint pattern is independent to UV exposure dose for curing and the robust nature is very convenient to real applications.

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