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# Characterization for the photomask fabrication based on a high-resolution technique with a non-chemically amplified resist and a post-exposure bake

Hidetatsu Miyoshi [a,b], Jun Taniguchi [a]

[a] *Department of Applied Electronics, Tokyo University of Science, 6-3-1 Niijyuku, Katsushika-ku, Tokyo 125-8585, Japan*
[b] *Intel Corporation, Technology Manufacturing Group Japan, 5-6 Tokodai, Tsukuba-shi, Ibaraki-ken 300-2635, Japan*

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## ABSTRACT

A high-resolution technique has been developed for the fabrication of photomasks for 10 nm logic nodes and beyond. Current mask manufacturing techniques use a chemically amplified resist (CAR) material that has a complex mechanism of acid generation; this complicates the criteria for selecting the polymer and the quencher for industrial purposes. It is therefore important to validate non-CAR materials as alternative solutions for mask fabrication. In this research, we used diluted ZEP520A as a non-CAR material in conjunction with a JBX9000 variable-shaped electron-beam (VSB) lithography tool. Additionally, a post-exposure bake (PEB), routinely used in mask fabrication, was also applied. We investigated the effects of the PEB temperature on the fabrication of masks from non-CAR resists, and we demonstrated the feasibility of using a PEB as a high-resolution technique. The critical dimensions (CDs) for 1:1 line-and-space, isolated space, and isolated line patterns on a diluted ZEP520A resist were measured and showed a shrinkage, an extension effect, and retention of the integrity of the shape after the PEB process, respectively. Furthermore, the line-edge roughness (LER) of the 1:1 line-and-space and isolated space CDs was improved by approximately 40% by optimizing the PEB temperature. We investigated the process characteristics of this PEB annealing effect by examining the hardness of the cured resist with and without exposure to PEB at various temperatures, with the aim of elucidating the underlying mechanism. Optimizing the PEB temperature of the non-CAR increased the resist contrast, annealing the resist and improving the LER. This permitted us to demonstrate an advanced fabrication technique capable of high resolutions of the order of 20 nm. The insights gained from the optimization of the PEB process might be useful in advanced methods of fabricating masks of the next generation.

## 1. Introduction

The trend in scaling of integrated circuits known as Moore's law is likely to continue for the forthcoming 10- and 7-nm nodes [1]. The latest edition of the *International Technology Roadmap for Semiconductors* (ITRS) set out challenging requirements for 10 nm logic nodes in terms of subresolution feature sizes for photomasks, and it calls for high resolutions of the order of 40 nm [2]. Furthermore, to develop masks of the next generation, we expect that it will be necessary to achieve even greater degrees of super-resolution.

Currently, chemically amplified resists (CARs) are normally used in the manufacture of masks. To pattern these resists, a photochemical acid generator (PAG) produces an acid, which dissolves the resist in a controlled manner through catalytic reactions. This process enables high sensitivity and high resolution. However, there are concerns regarding post-coating delay stability, post-exposure delay stability, and other effects resulting from the use of the CAR material itself, including the complex mechanism of acid generation [3]; these factors complicate the criteria for selecting the polymer and the quencher for industrial purposes. Furthermore, there remains a problem with respect to the surface roughness of the patterned resists. This is referred to as line-edge roughness (LER) or line-width roughness. Understanding the details of LER is important for material and process design, and the causes of LER have been intensively investigated during the past 20 years [4,5]. Consequently, to assist in ensuring proper decision making and the development of more-robust acceptance criteria for alternatives to the existing CAR-based approach to mask manufacture, it is important to make a careful evaluation of non-CAR photoresist materials that do not contain PAGs.

We examined the fabrication of high-resolution masks by variable-shaped electron-beam (VSB) lithography using a JBX9000 instrument (JEOL Ltd., Tokyo) with ZEP520A (Zeon Corporation, Tokyo) as a positive electron-beam non-CAR [6]. Furthermore, as a part of our ongoing efforts to develop high-resolution fabrication techniques, we also studied the use of a post-exposure bake (PEB), a process that is known to cause an annealing effect in spin-coated films on glass [7]. Typically, PEB is used to increase the sensitivity of resists containing CAR materials. In our researches, we used the PEB method in mask fabrication from non-CAR resists, and we demonstrated its feasibility as a high-

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*E-mail address:* hidetatsu.miyoshi@intel.com (H. Miyoshi).

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resolution technique. To investigate the mechanisms of the improvements in resolution and LER capability through the annealing effects of a PEB, we examined the contrast curve of the resist and we characterized the process by means of atomic force microscopy (AFM). An annealing process is necessary to transform the non-CAR resist material to harden its structure [8]. By studying how annealing affected the microhardness of the polymer in literature, we found that it changed with the annealing temperature [8,9].

## 2. Experimental details

Quartz substrates coated with a 60-nm-thick layer of chromium were used as mask blanks. ZEP520A diluted 1:1 with ZEP-A thinner [98% methoxybenzene (anisole)] was used as a non-CAR resist sample. Dilution of the resist might lead to issues of process instability and could affect the LER; it therefore has the potential of being detrimental to the overall quality of the exposure. However, dilution is necessary to produce thin films of the resist to prevent pattern collapse. The diluted resist was coated onto the mask blanks by using a coating tool (CTS8000, Sigmameltec Ltd., Kanagawa) operated at a rotation speed of 1500 rpm for 2 s during the dropping step of the resist and at 1000 rpm for 60 s during the main step. This produced a controlled film thickness of less than 50 nm. After application, the resist was baked at 180 °C for 600 s in an oven on the same tool before it was subjected to the electron-beam lithography (EBL) process.

A JBX9000 50-kV EBL tool (JEOL Ltd.) was used for the electron-beam exposure, because this is one of the most advanced 6-inch mask-writing variable-shaped beam tools that is commercially available. The overall performance of this writing tool has been thoroughly assessed on various types of resist, permitting full exploitation of the advanced proximity-effect correction capabilities of the system and careful optimization of the overall process [10–12]. The mask pattern layout that we used in this experiment consisted of eight regions, including a 1:1 line-and-space (LS) pattern, an isolated space (IS) pattern, and an isolated line (IL) pattern [13]. Once the EBL process had been completed, several masks were processed for validation of the PEB process, which was performed at temperatures of 90, 120, 135, or 150 °C for 600 s in an oven.

After the PEB, the samples were developed by soaking in ZED-N50 (>99% pentyl acetate; Zeon Chemicals L.P., Louisville, KY) for 80 s at room temperature (20–23 °C). The samples were subsequently rinsed in 9% propan-2-ol for 20 s and then dried.

To determine the variations in the critical dimensions (CD), we used a CD scanning electron microscope for photomask applications (LWM9000; Leica Microsystems GmbH, Wetzlar) [14]. The proprietary electron optics technology and improved detection system of this microscope permit repeatable subnanometric CD measurements to be made by almost completely eliminating any effects associated with charging or contamination. Measurements were performed at five different locations for each pattern size (design CD 100, 70, 50, 44, 40 nm or lower measurable pattern size) for the LS, IS, and IL patterns to examine the repeatability and reproducibility of the CD measurements. The measurements were performed at a beam energy of 500 eV with a probe current of −4.8 pA. The usual SEM magnification was 200,000× although a value of 75,000× was used in some cases when required.

To investigate the LER improvement, we examined the contrast curve. We used a specific mask layout to measure the film thickness and the resist dissolution rate. Measurements were performed at 24 locations (one site = 8.9 × 8.9 mm) on each mask blank. Doses of 0 to 300 μC/cm$^2$ were randomly applied to the various measurement sites, and the thickness of the film remaining after the PEB and development process was measure.

Additionally, we examined various characteristics of the process to elucidate the mechanism for achieving a high-resolution by this technique. By using AFM, we were able to study the effects of a PEB on the surface roughness under the various resist conditions during the process of photomask fabrication.

## 3. Results and discussion

### 3.1. Dependence of the critical dimensions on the post-exposure bake and resist sensitivity

Fig. 1 shows top-down SEM images for design CD values of 100 nm for the LS pattern (164 μC/cm$^2$), the IS pattern (239 μC/cm$^2$), and the IL pattern (126 μC/cm$^2$), together with their dependence on the PEB temperature. For the 1:1 LS pattern, there were no significant differences between the CD values for samples subjected to PEB at 90 °C and those of samples not subjected to a PEB. However, there was a

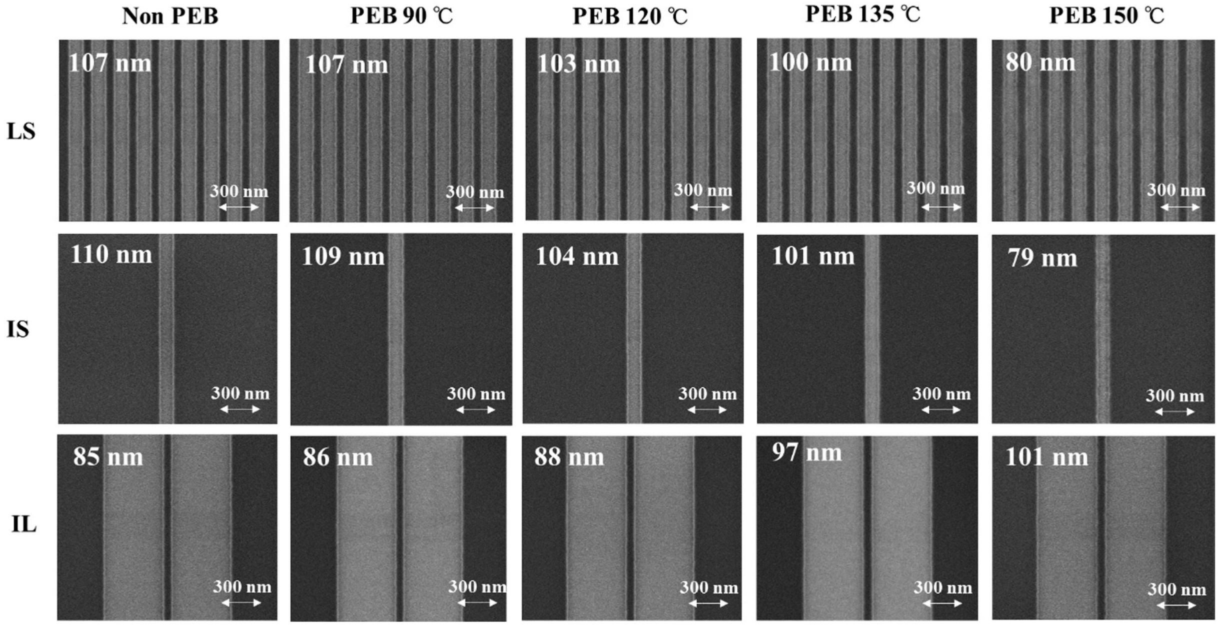

**Fig. 1.** Top-down SEM images showing the PEB temperature dependences for LS, IS, and IL patterns (design CD: 100 nm; magnification: 75,000×). LS and IS patterns were measured by space CD, IL pattern was measured by line width.