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Printability of defects in Talbot lithography

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ABSTRACT

We conduct a simulation and experiment to investigate the effect of a defect on the pattern size around the defect in ArF Talbot lithography proposed for submicron pattern transfer. We confirm that the focal depth is more than 1 micron even if a defective mask is used. Talbot lithography with a 1:1 mask is more resistant than reduction projection lithography against the effects of mask defects.

1. Introduction

Two types of tool are used in photolithography. One is a contact aligner and the other is a projection stepper. Using a contact aligner, mask patterns are transferred to a wafer in the same way that a shadow picture is produced by illuminating a mask with a light source. The light source is normally an ultraviolet lamp. The resolution of the photolithography using a contact aligner varies according to the gap between the mask and wafer and is around 1 μm for hard-contact exposure and around 3 μm for proximity exposure. Because hard-contact exposure is likely to suffer from defects, proximity exposure is preferable for non-defect printing in semiconductor lithography. Using a projection aligner, mask patterns are transferred to the wafer through projection optics, and resolution is determined by the source wavelength λ and numerical aperture (NA) [1]. An immersion-type exposure tool of an ArF light source, whose NA can be larger than 1, can resolve patterns having a half-pitch of around 40 nm [2]. To obtain higher resolution, attempts are being made to use sources of light with shorter wavelength such as a 13.5-nm extreme ultraviolet light source [3]. The immersion tool is large and has to adopt fine-tuned optics. The extreme ultraviolet light source is sophisticated and large, and the extreme ultraviolet tool is very expensive.

Here, we focus on submicron patterning. There are many applications of this pattern size, such as gratings, photonic devices, and imaging sensors. So far, a stepper has been widely used for this pattern size because a contact printer is unable to resolve such patterns, yet the use of a contact printer in this case would greatly reduce processing costs. The reduction of the cost per bit is a concern for semiconductor manufacturers [4]. Even if a mature process design rule has already been established, there will be an incentive to move to a less expensive process.

Talbot lithography has been proposed as a method of submicron pattern transfer that employs a similar tool but different principle compared with proximity exposure. The Talbot effect refers to the inference of rays from a grating on a mask [5]. The imaging point of Talbot lithography is repeated in the direction of light propagation at a period of the Talbot distance [6]. This has been called self-imaging [7]. If Talbot lithography is available for submicron pattern transfer then it will be of benefit to semiconductor manufacturing. The characteristics of Talbot lithography have been revealed in past works [8–13]; specifically, experiments revealed that it is possible to make a clear submicron resist pattern using an ArF laser [14], a defect pattern is unlikely to be transferred [15], and the resolution limit is around the wavelength of the light source [16,17]. A defect must not be printed or be allowed to affect the size of the pattern around the defect. The defect issue is one of the most serious concerns in semiconductor manufacturing. In this report, we discuss the effect of a defect on the pattern size in a simulation and experiment.

2. Simulation conditions and experimental setup

In the present study, one-dimensional patterns are transferred using a 193 nm light source.

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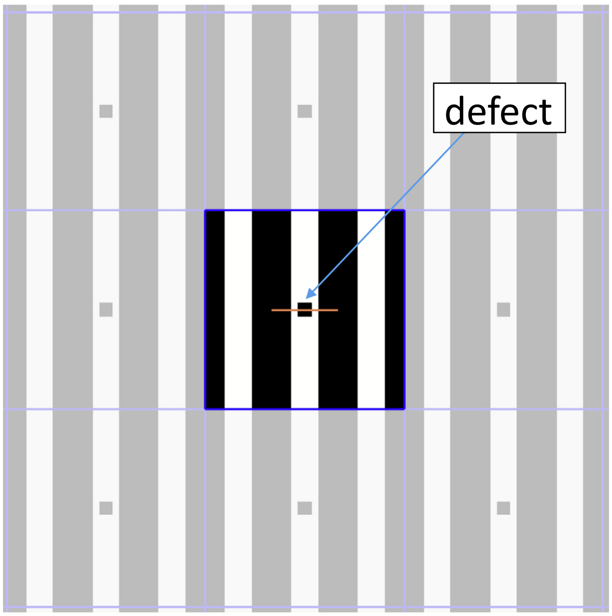

Fig. 1. Mask structure of a submicron pattern assumed in simulation.

In the simulation, three pitches of a one-dimensional 920-nm-pitch pattern are designed in an area of 2760 × 2760 nm on the wafer scale; the wafer scale refers to the size on the wafer in contrast to the size on the mask. The mask structure of a submicron pattern assumed for simulation is shown in Fig. 1. Each Cr line is 550 nm wide. One dark defect is set at the center of this area. The boundary condition of the optical simulation is periodic. This means a defect repeating with a certain period of the simulation area, 3 times the grating period in two directions, is chosen. Using this mask, simulation is performed for 1:1 Talbot lithography and 4:1 projection lithography. The simulation of projection lithography assumes the use of an ArF laser source and NA0.6/sigma 0.7 reduction optics. In the experiment, we design a mask having the same periodical pitch as the mask in the simulation. The wavelength of the light source is 193 nm. Chemically amplified resist is used for pattern transfer on a Si wafer with a bottom anti-reflecting coating. Experiment is performed only for 1:1 Talbot lithography. The Talbot distance Z_T of the imaging point is expressed as:

$$Z_T = \frac{2p^2}{\lambda}, \tag{1}$$

where p is the pattern pitch and λ is the wavelength. Here, the Talbot distance is 8770 nm. The experiment conducting Talbot lithography is repeated at different distances, which are measured by gap sensors.

3. Simulation and experiment results

Fig. 2 shows the optical intensity of a Talbot carpet simulated employing the finite-difference time-domain (FDTD) method. The figure shows the results for a spatial range of 13,156 μm including from $Z_T - 1/2Z_T$ to $Z_T + 1/2Z_T$ obtained with a mask illuminated by light having transverse electric polarization, which matches the polarization of the source used in the experiment. Although the source is not strictly a point source in practice, a point source is assumed here. This assumption means the source is coherent. An imaging plane can be seen at 8770 nm below the mask.

Figs. 3a and 3b show (a) the intensity at the resist surface simulated for Talbot lithography and (b) the top view of the resist in atomic force microscopy (AFM) using the mask shown in Fig. 1.

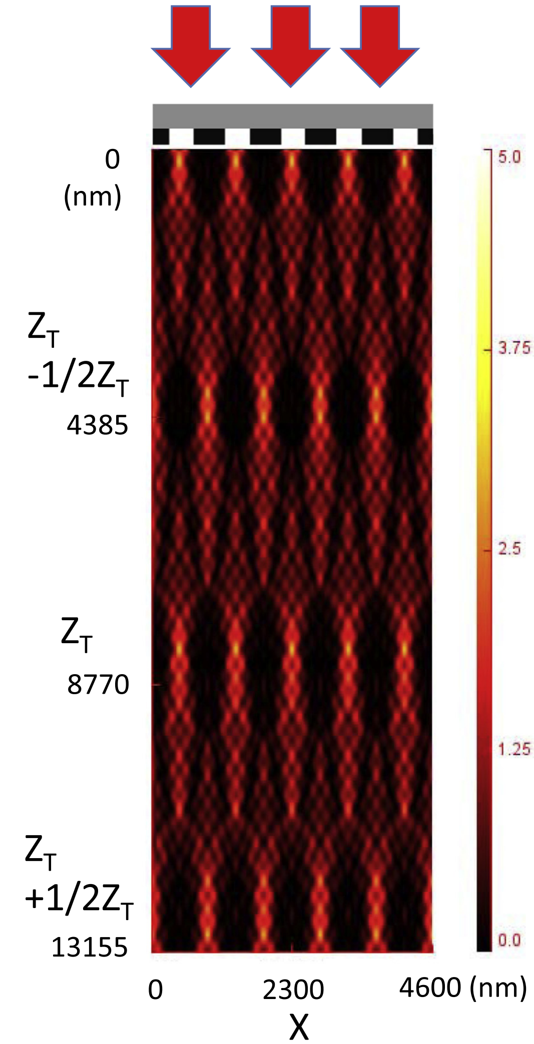

Fig. 2. Optical intensity of a Talbot carpet obtained employing the FDTD method.

The top view of the resist in the AFM measurement is the experimental results. Each figure is shown for the case of a non-defective mask and a mask having a dark 185 × 185 nm defect in the z range from $-1/2Z_T$ to $+1/2Z_T$. There is some intensity fluctuation of the defective mask even at Z_T in the simulation, but the resist line does not fluctuate as much as the defect size in the experiment. The depth of focus (DOF) is greater than $1/8Z_T$ (1.1 μm) regardless of the mask defect. At $-1/4Z_T$ and $+1/8Z_T$, the transferred pattern is split and the pattern fluctuation is larger than that at Z_T in the defective mask. At $\pm 1/2Z_T$, the pattern contrast is reversed.

Fig. 4 shows simulation results of optical intensities at the focal point in Talbot lithography and projection lithography. Here, the light source is assumed to be an unpolarized ArF laser in both cases. The illumination NA of the light source is assumed to be 0.002 in Talbot lithography. The areas shown in Fig. 4 are extracted from three periods of the line. The defect size is zero, 185 × 185 nm, and 370 × 370 nm on the wafer scale. Talbot lithography, which transfers patterns at the same magnification, is compared with projection lithography having a reduction ratio of 4:1. When the defect size is zero, the intensities of the Talbot lithography and projection lithography do not differ greatly. When the defect size is 185 × 185 nm, the intensity at the defect position is weaker in projection lithography than in Talbot lithography. However, in Talbot lithography, the effect extends slightly to the neighboring pattern, whereas it does not extend in projection lithography. When the