Abstract

In this paper, we consider the composition of integrated circuit patterns using dense arrays of mirrors. Typically the mirrors are 10–100 wavelengths in size and are demagnified some to form slightly sub-resolution spots or pixels at the wafer. The mirrors are actuated to modulate the light intensity. We consider both pure phase mirrors, moved in piston-like fashion, and tilting mirrors, which provide a mix of amplitude and phase modulation. We compare the image quality and useful process window for DUV or EUV imaging of typical features. The performance of both mirror types is similar when operated in gray-scale analog mode to provide arbitrary image placement and feature sizing, but for a given feature one mirror type will have slightly superior performance. Simple piston mirrors have a disadvantage with respect to image shift with defocus for certain features. A new type of mirror arrangement, termed the double-piston mirror, can equal or better the performance of tilt mirrors in all situations examined.

Keywords: MEMS; Optical lithography; Pattern generation; Direct write; Maskless

1. Introduction

Largely owing to the high cost of masks for lithography, there is a recent strong interest in maskless lithography, especially for ASIC applications. Fig. 1 is a schematic of a conceptual maskless lithography tool. It has much in common with a recently announced commercial pattern generator for high resolution, the Sigma® Tool by Micronic Inc. [1]. The mechanics and optics are also similar to a conventional lithography tool except that the moving mask stage is replaced by a mirror array designed to function as an electronic mask. A high-speed data path connects the mirror array to a computer containing the pattern information. For DUV or EUV operation the light source is pulsed, therefore the pixel information arriving from the data path must be stored locally, presumable in a DRAM array with cells corresponding 1:1 with the mirrors. The DRAM is loaded with data in the interval between flashes. In the two insets, two possible mirror forms are depicted. In one form the mirrors modulate the image intensity by tilting, and in the second by a piston-like motion. In the latter case the modulation occurs purely because of interference or phase effects. An array of sub resolution piston mirrors reflects zero light through the pupil if every mirror is dephased from its neighbors by $\lambda/4$, that is the optical path difference (OPD) at all mirror boundaries is just $\lambda/2$. Similarly, an array of tilting mirrors reflects zero intensity if each
mirror is tilted precisely the amount such that the OPD from center to edge is $\lambda/2$ [1–3]. In this paper we present simulation results comparing the imaging performance of the two mirror types and suggest a third architecture combining the advantages of both piston and tilt mirrors.

2. Performance simulation for image formation using piston and tilt mirrors

Throughput: whether tilting or piston mirrors are used, the throughput is limited by the combination of the source repetition rate and the number of mirrors available for parallel transmission of pixel intensity information. If we assume a writing throughput of 1 cm$^2$/s is required and use a source operating at frequency $f$, then the minimum number of mirrors in the array is $1/(f \times s^2)$ where $s$ is the pixel size (the demagnified size of the writing mirror spot, at the wafer). High-throughput systems must print “on the fly”, making blur a key system parameter (the maximum scan velocity equals blur$/\tau$, where $\tau$ is the pulse length). Table 1 provides two system examples: one for DUV printing of 40–50 nm minimum features using 25 nm spots and one for EUV printing of 20–25 nm minimum features with 12 nm spots. Aggressive source frequencies and short pulse lengths are assumed of 8 and 10 kHz, and 8 and 3 ns, respectively, for DUV and EUV operation. A very large number of mirrors is required.

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<th>DUV</th>
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<tr>
<td>Scan speed (cm/s)</td>
<td>62.5</td>
<td>50</td>
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<tr>
<td>Photon pulse length (ns)</td>
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<td>Photon pulse frequency (kHz)</td>
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<td>Edge blur (nm)</td>
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<td>Flash rectangle height (cm)</td>
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The overall constraint is a writing rate of 1 cm$^2$/s, or about five 300 mm wafers per hour ignoring overhead.

Resolution: because phase and amplitude information can be transmitted by mirror arrays, just as for masks, it is not surprising that a number of studies have suggested that the image quality available from such a system can be comparable to the best images from masks, including the benefits of reticle enhancement techniques (RET), optical proximity correction (OPC), and specialized illumination “tricks” [1–5]. Thus it is our expectation that practical lithography can be practiced at $K_1$ factors in the range of 0.35–0.5 with such systems (wherein $K_1$ is defined by the lithographers equation $S = K_1 \lambda/NA$, in which $S$ is the feature size, $\lambda$ the wavelength, and NA the numerical aperture). Fig. 2 shows an example of a two-dimensional pattern composed with an array of tilting mirrors, in which the mirror sizes are in the range of one-half the minimum feature size and the imaging is attempted at $K_1 = 0.4$. As shown in Fig. 2(a), it is desired to place one line end rather close to a nearby line, with the consequence that the image of both the line end and the nearby line will be distorted because of their close proximity. If the mirror tilts are computed ignoring this proximity effect, the resulting image contours will be distorted as shown in Fig. 2(b). But it is possible to recompute the desired mirror tilts, taking into

Fig. 1. A conceptual maskless lithography system. The pattern information in the electronic mask is provided by means of a high-speed data path (not shown). An array of either tilting or piston mirrors may be used as the light modulator.

Table 1

The operating parameters of two possible scanning maskless lithography systems

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account the proximity and largely eliminate the distortion, with the result shown in Fig. 2(c). Although the image of Fig. 2(c) is clearly superior to that of (b), it is neither unique nor optimum; the mirror tilts may be computed with a variety of possible optimum conditions in mind, and the resulting image will differ accordingly.

Fig. 2 demonstrates the use of gray scaling, which is the analog control of intensity by means of analog selection of mirror tilt. With gray scaling, it is possible both to place the line edges off the mirror grid (as is done here) and to perform OPC as illustrated above. (Not illustrated here is the further ability to improve imaging by “overtilting”, to be discussed below [5].) It is somewhat surprising that gray scaling can shift line edges without significantly degrading them, but precision simulation of image intensities verifies this fact [1–5].

A major issue for consideration of the system designer is the choice of mirror architecture. The source-frequency and pulse length limitations have already been summarized in connection with Table 1, assuming about 2 mirror spots per minimum feature. The mirror type and physical mirror size must also be selected. In Table 1, the latter was chosen as 5 μm for DUV operation and 1.2 μm for EUV, largely governed by mirror dynamics and operating voltage considerations [6]. Thus the magnification is fixed, and only the actuation style (e.g., tilting or piston) remains to be selected. A number of studies are in progress on this question, and the remaining portion of this paper with present simulated imaging performance examples bearing on this subject. The overriding factor in selection of mirror type is the control it offers in critical dimension (CD) over the full process window, considering especially exposure dose variation and focus variation. Thus we examine image fidelity and construct exposure – defocus plots for the acceptable range of CD, typically ±10%.

Fig. 3 illustrates an exposure-focus plot for dense lines and spaces printed at a $K_1$ of 0.45. It indicates that for these conditions the CD for either tilt or piston mirrors is maintained within a ±10% tolerance over an exposure latitude of 25% and a defocus range of 3 Raleigh units. If the exposure latitude is reduced to ±20%, the defocus tolerance increases to 5 U. This particular simulation was run for 20 nm lines on a 44 nm pitch at 13.4 nm with NA = 0.3, but except for high NA
(polarization effects) is valid for any $\lambda$ and NA and feature size satisfying $K_1 = 0.45$ and using the same ratio of feature size/pitch (e.g., essentially the same results would be obtained at 193 nm and NA = 0.6, printing 145 nm features on a 160 nm pitch using 80 nm mirror spots). The illumination conditions must also be preserved in scaling the wavelength; here we use quadrapole illumination to achieve the exceptional range of defocus.

In the “tight pitch” example above there is almost no difference between piston and tilting mirrors. However, in some cases the tilting mirrors can increase the process window. Fig. 4 shows the process window for a nearly isolated space (a single clear area in a dark-field) at a $K_1$ of 0.4 under three different mirror conditions. The two “standard” conditions, using either piston mirrors or tilting mirrors with an OPD of $\lambda/2$, produces essentially identical process windows. But if the latter are “overtilted”, for example to an OPD of $0.75\lambda$, then a condition much like that with an attenuating phase-shift mask obtains; the background light increases, but because it is out of phase with the bright line, it increases edge acuity and produces a larger process window. The steeper line slope and larger contrast with overtilt can be seen directly from the intensity profile plotted in Fig. 4(b). Here several percent of process latitude is gained at any defocus condition by the “overtilting” No analogous trick has been discovered for the simple piston mirrors. Simulation of isolated lines (dark areas in a clear field) also shows nearly equivalent performance for piston and tilt mirrors, and the overtilt trick is less useful since it results in an undesired increase in linewidth.

Piston mirrors also offer a unique advantage under some conditions. One special case is the generation of a very narrow line by means of a phase edge. Fig. 5 illustrates the image created by a simple $\lambda/2$ phase edge using piston mirrors (e.g., all the mirrors to the left of the line are “up” and all the mirrors to the right are “down”). In this EUV example with $\lambda = 13.4$ nm, a 12.9 nm line is produced, corresponding to an effective $K_1$ of 0.29. As wonderful as this result seems, such lines have limited usefulness because they cannot be moved off grid, they require a second exposure to

Fig. 4. Process window example at 193 nm. (a) Exposure latitude versus defocus for a nearly isolated space (dark field) using DUV exposure at NA of 0.7 and disk illumination. The 100 nm feature is composed with 55 nm spots at 193 nm ($K_1 = 0.4$). Three mirror arrangements are simulated: simple piston motion with OPD in the range 0 to 0.5$\lambda$, simple tilt motion with OPD in the range 0 to 0.5$\lambda$, and tilt motion with OPD in the range 0 to 0.75$\lambda$ (“overtilt”). (b) The image intensity profiles for the three conditions above.

Fig. 5. Aerial image of a pure phase edge created with piston mirrors in the EUV (13.4 nm). A CD of 12.9 nm corresponds to an effective $K_1$ of 0.29.
terminate them effectively, and they have a limited range over which the CD can be controlled.

Small two-dimensional features such as contacts offer a severe test for both piston and tilt mirror composition [7]. In particular, when such contacts are moved off-grid it is challenging to find mirror positions that do not lead to image position shift with defocus. Fig. 6(a) illustrates the problem using piston mirrors. The phases are indicated as shades of gray on a mirror map, and iso-intensity contours on an image intensity plot show the resulting contact position. As the contact center is moved diagonally by adjusting the phases, the center of the contact moves as desired, but the contact becomes distorted and shifts with focus. No set of mirror positions has been found which completely eliminates this shift. Fig. 6(b) show similar plots for contacts composed with tilting mirrors. The defocus-induced distortion is less, and is further reduced if the mirror tilt directions are alternated along each row. Overtilt can be used to further reduce the drift as well as optimize contact size, but is not shown here for simplicity. The rather fundamental difference between piston and tilt mirrors stems from the relatively greater phase asymmetry produced by off-grid patterns.

Fig. 6. Phase maps, and image contours for the composition of an off-grid contact scanned through focus. The image is compared for three different mirror types. (a) Simple piston mirrors. (b) Tilt mirrors arranged in rows with alternating tilt directions. (c) Double-piston mirrors operated in a balanced mode (each simple piston mirror split into two, with one half moving up and the other half moving an identical distance down). (d) A plot of the drift of the contact center is plotted versus defocus. In all cases maximum symmetry is attempted by alternating mirror tilt or piston motion directions along rows.
composed with piston mirrors. Tilting mirrors have nearly canceling positive and negative phase contributions from the left and right sides. On the other hand the phase imbalance produced by piston mirrors can be useful as illustrated by the phase line example.

A modification of the piston mirror architecture can achieve the same low focus drift enjoyed by the tilt structures. Conceptually each piston mirror is split into two sections, and in balanced operation one part would move up and the other part an equal distance down. Fig. 6(c) illustrates the concept with the composition of the same off-grid contact. In Fig. 6(d) the image drift is plotted versus defocus. It can be seen that both tilt mirrors and double-piston mirrors (operated in the balanced mode) eliminate focus drift. While the number of physical structures is doubled in the double-piston structure, the information required to set mirror positions (and thus the data bandwidth) is unchanged.

3. Summary

In the composition of horizontal and vertical line patterns for integrated circuits piston and tilt mirrors have generally equivalent performance, measured as the size of the exposure latitude versus defocus process window. But for some patterns, operation of tilt mirrors with overtilt has distinct advantages and produces higher contrast images with larger process windows. Piston mirror composition also suffers from a larger shift of image position with defocus for two-dimensional features such as contacts when printed off grid. A new type of mirror configuration, called the double piston mirror is proposed in which each mirror is replaced by two rectangular mirrors. If each half of the mirror pair moves symmetrically in opposite directions, mimicking the motion of a tilt mirror, we call the operation a pseudo-tilt motion. Such piston arrays operated in this fashion overcome the image shift limitation, and also can be use with overmodulation, to increase image contrast analogous to tilting mirrors operated with overtilt.

References