Talbot Lithography as an Alternative for Contact Lithography for Submicron Features

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ABSTRACT

In this paper we show that using optical photolithography it's possible to obtain submicron features for periodic structures using the Talbot effect. To use the Talbot effect without the need of an absolute distance measurement between the mask and the wafer we integrate over several exposures for varying wafer mask distances. Here we discuss the salient features of 'integrated Talbot lithography'. Particularly, we show that to obtain good contrasts an excellent control of the illumination light is essential; for this we use the MO Exposure Optics (MOEO) developed by SUSS MicroOptics (SMO). Finally we show that 1µm and 0.55µm diameter holes can be made using this technique.

Keywords: Photolithography, Talbot Lithography, Submicron Lithography.

1. INTRODUCTION

More integration and new technologies increasingly require features sizes at the submicron scale. For example diffractive optics, plasmonic structures and photonic crystals all require features smaller than the wavelength of the light they are manipulating. Moreover, submicron feature sizes are needed for emerging applications in the bio/green technology sectors for example for filters and membranes for cell growth. To obtain submicron feature size in the laboratory environment focused ion beam lithography is often used, however this remains a slow serial process which is prohibitively expensive for bulk production. Interference lithography, which uses the interference of two or more mutually coherent UV beams to generate periodic patterns, needs to have the optical configuration modified each time for different printing patterns. Other methods such as bottom up approaches or nano imprint method do offer low cost solutions for large scale production but these methods are often plagued by defects and contamination. Stepper lithography on the other hand can allow submicron feature sizes, with high throughput; however, the upfront cost of these machines is prohibitive for many companies.

In this paper we show that a mask aligner, which is common piece of equipment in many clean rooms, can create periodic micron and submicron structures in large gap lithography. The key to this technique is the Fresnel interference which results in a replication of the periodic pattern imposed at the aperture a fixed distance away. This distance is called the Talbot distance after Henry James Talbot who first observed this effect in 1836 [1]. The Talbot distance depends on the type of pattern, the periodic length of the pattern and the wavelength of the illumination light; the effect was first described mathematically by Rayleigh in 1881 [2]. There has already been some work published on Talbot lithography [3-7] including a recent paper by Case *et al.* [8] which gives a very clear explanation of this phenomenon, an example of which is shown in Figure 1.

In this paper we concentrate on the implementation of Talbot Photolithography for small scale production. In doing this we examine the setup, ease of use, reproducibility, homogeneity and comment on the limitations of our approach.

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2. SETTING UP TALBOT PHOTOLITHOGRAPHY

Self-imaging of periodic structures can be modeled based on diffraction theory and Fourier techniques. Figure 1 shows the propagation of light through a linear periodic array. The example shown has a period of 1.0µm with a slit width of 300nm. The wavelength of the illuminating light is assumed to be 365nm (i.e. i-line). As the replication of the pattern at the mask is dependent on the integrity of Fresnel diffraction it is imperative to have a good control of the illumination light for Talbot photolithography, i.e. a uniform intensity and a low angular divergence. These conditions result in a better contrast of the features.

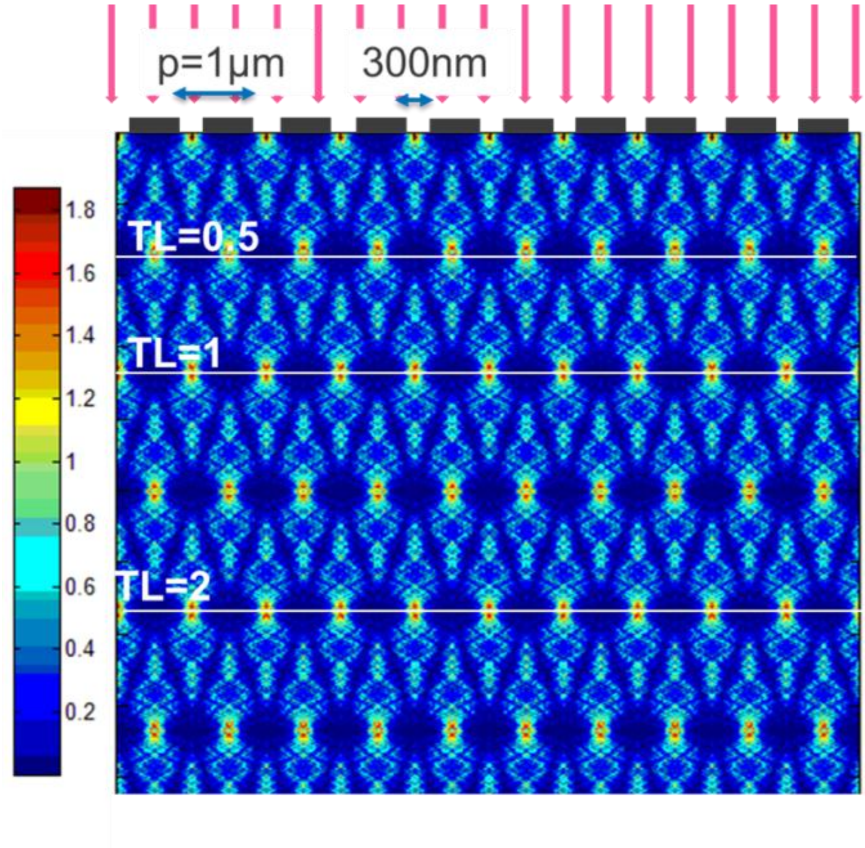

Figure 1. Simulations of light passing through a linear grating of period 1µm and a slit width of 300nm. i-line illumination is assumed (365nm). The paraxial approximation is used to clearly show the Talbot effect. Lines are shown at the Talbot and half Talbot Lengths (TL). For this linear grating the Talbot length is 5.5µm ($TL_{linear} = 2P^2/\lambda$) .

In order to obtain a good control of the illumination light we have installed an exposure optics system from SMO [9]. The MO Exposure Optics (MOEO) system uses two Köhler integrators, and an angular selection plate to control the light, see figure 2. The first Köhler integrator decouples the illumination from the lamp position. The second Köhler integrator ensures uniform illumination of the mask. Although there are other advantages of the MOEO for mask aligners (see www.sussmo.ch/), for integrated Talbot photolithography the key features of the MO exposure optics are that it has excellent light uniformity (+/-2%), and that the illumination angle of the light can be chosen [7].

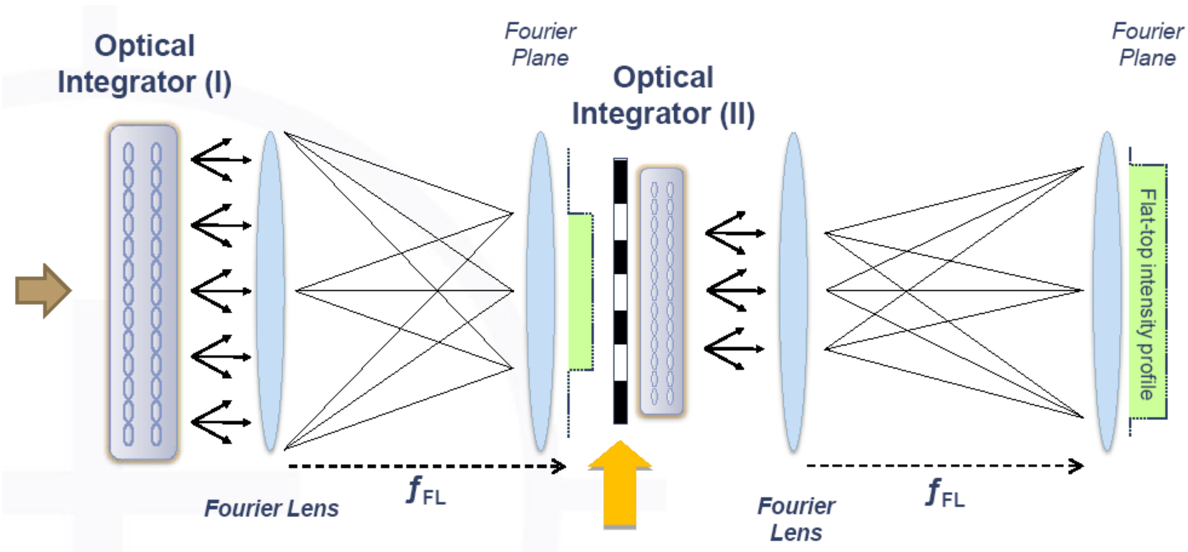

Figure 2. (a) Schematic of the MO Exposure Optics developed by SMO. Two Köhler optical integrators are used to create highly uniform illumination. The arrow shows where an angle defining element can be added to choose the angular illumination that is wanted.

The basic mechanics of a Köhler integrator is the imaging of a first array of sub apertures by the corresponding lenses of the second array. More precisely a first lens array divides the light into multiple images of the light source in the aperture plane. It also serves as an array of field diaphragms defining the illumination area of the object plane. The second lens array is located in the aperture plane and serves as an array of aperture diaphragms. The lenses of the second array and the condenser lens image the individual field diaphragms of the object plane. The quality of the superposed images of these sub apertures strongly influences the flat top uniformity. Increasing the number of lenses will improve the quality of the homogeneous intensity distribution. However if lenses are too small diffraction effects will significantly distort the flat top uniformity.

Once a good illumination is installed and a periodic pattern is placed on the mask all that remains is to position the wafer to be exposed at a Talbot plane, for example by placing a wafer at the TL=1 plane shown in figure 1. In doing this it is easy to obtain contrasts of 0.9 or higher [11]. However, placing a wafer at exactly a Talbot plane is not trivial; it requires good parallelism between the wafer and the mask, and a precise distance measurement, both of which need to have submicron resolution for periods of one micron or less.

In order to overcome this complexity, it is possible to integrate the exposure, by a series of multiple exposures along the z-direction, over the Talbot distance. This reduces the contrast, as illustrated in Figure 3. However ‘Integrated Talbot Photolithography’ (see also www.eulitha.ch) has the advantage that a precise measurement between the wafer and mask (in the z-direction) is no longer needed and it also reduces the necessary parallelism constraints between them. It should be noted that making this integration for a linear periodic system halves the period of the structures, this can be seen from figure 1 & 3.

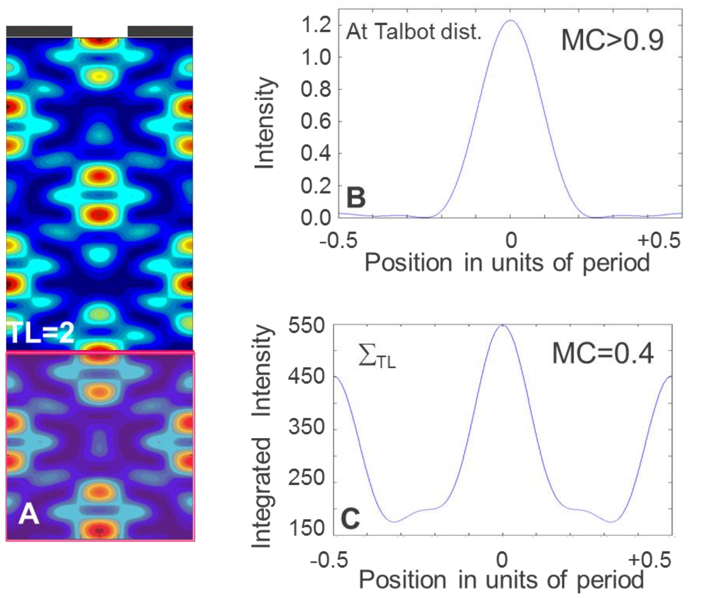

Figure 3. (A) Map of intensity of light passing through a linear grating assuming no paraxial approximation. Many of the features seen in the paraxial approximation in figure 1 are washed out. By placing a wafer for exposure at the TL=2 line an intensity is seen as shown in (B). Here the contrast between I_{max} and I_{min} can be greater than 0.9. However alignment is very difficult. An alternative way to do Talbot photolithography is to integrate the light over 1 Talbot length, i.e. lightly shaded pink area in (A). The integrated intensity, shown in (C), shows a halving of the period and a reduced contrast. However the advantage is that no distance measurement is needed between the wafer and the mask.

To summarize, to enable the Talbot photolithography we made three modifications to our mask aligner system:

1. Firstly we installed a SUSS MO Exposure Optics to improve the homogeneity and control the numerical aperture of the illumination. This optic was installed retro-actively and the optic could also improve the critical dimension of standard photolithography processes (www.suss-microoptics.com.

2. The second modification was made to the mask aligner software to allow us to move and expose the wafer at several different z-positions allowing ‘integrated’ Talbot photolithography. This removed the need to measure the distance between the mask and the wafer and relaxed the constraints on the parallelism between the wafer and the mask.

3. The third modification made was to change the motor in the mask aligner to allow us to move in step sizes of 200nm, previous step sizes were limited to 1µm. This allowed us to obtain the necessary number of steps to converge to a uniform exposure for shorter Talbot lengths, necessary for submicron feature sizes. An alternative approach to this step exposure would be a continuous exposure over the entire Talbot length [3].

In the next section of this paper we show a working example of integrated Talbot photolithography.

3. AN EXAMPLE: MEMBRANES FOR BIOLOGICAL APPLICATIONS

Background

As a test of small scale production we chose bio-membranes. These membranes are comprised of 500nm thick suspended silicon nitride (Si_3N_4) membrane, on a silicon support. A process flow and optical images are shown in figure 4. A typical use of these porous membranes is to test the toxicity of metallic nanoparticles on cells. In such a case a layer of barrier cells (such as lung air/body barrier) are grown on the porous membranes. When the cells are healthy they form a tight layer, and when damaged the tight junction begins to degrade. This difference can be measured through a potential difference measurement. Thus nanoparticles can be placed one side of the cells and it can be tested whether the cells remain healthy and if the nanoparticles are transported across the cells and through the membrane.

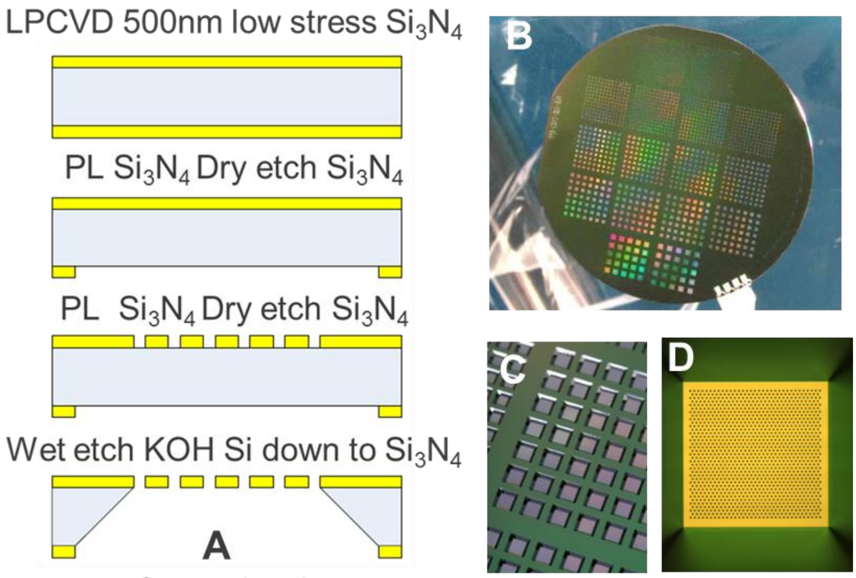

Figure 4. (A) Process Flow. (B) Optical image of a whole image. (C) Image of several membranes each of which are a few millimeters in side. (D) An image of a membrane showing the hexagonal pattern.

When growing barrier cells it is important that the holes remain small this way the cell membrane barrier is not affected by the holes and the barrier cells maintain their natural polarity. We chose a hexagonal pattern with a 3µm period membrane with a 1µm hole-diameter, as a motif for the membranes. The Talbot length for this hexagonal array is 35µm ($TL=3d^2/2\lambda$).

Processing Parameters

In order to obtain a reproducible result for discretized integrated Talbot photolithography it was necessary to choose the necessary step size. The step size will depend strongly on the period and the wavelength which define the Talbot length. Figure 5(a), shows the contrast versus the variation in the number of steps in one Talbot length for three different angular spreads of the mask illumination. These calculations were made with LAB software from GenISys. Generally we see that there is a large variation in contrast for a small number of steps. This is consistent with the intensity diagram seen in Figure 3 where the wafer could fall at a high or low intensity point. However as the number of steps increases there is a convergence to a contrast of 0.4. It should be noted that the final contrast possible will depend on the ratio of the hole size to the period. For very large slits the contrast drops dramatically. For very small slit widths < λ/2 very little light passes through the holes and the exposure times become impractically long. We find that the best contrasts are for fill factors of approximately 30%.

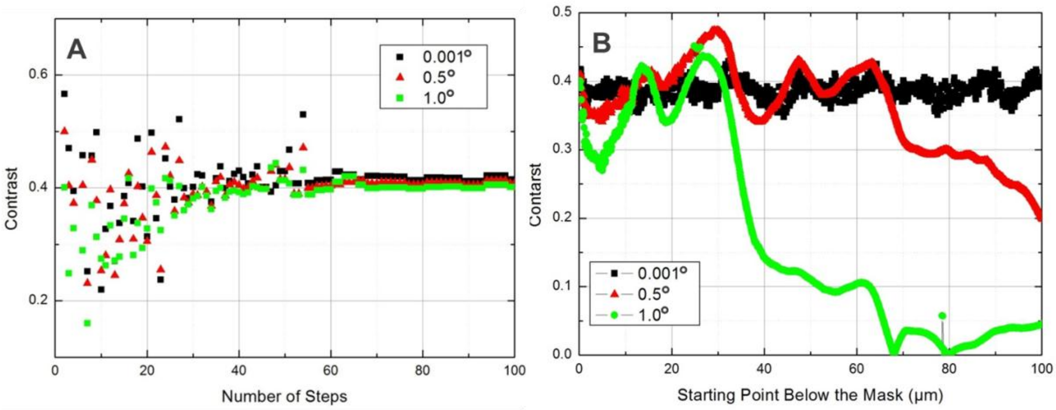

Figure 5. Theoretical calculations made with Lab (GenISys Software). Calculations are made for a hexagonal pattern of period 3µm and hole diameter of 1µm. (A) Contrast versus number of steps in one Talbot length for three different angular spreads 0.001°, 0.5° and 1.0° (B) Contrast versus wafer starting position below the mask for three different angular spreads 0.001°, 0.5° and 1.0°.

A second effect that can be seen from the contrast versus number of steps curve in Figure 5(a) is that for variation in contrast when only a small number of steps are used is larger for light with a smaller angular divergence. This may seem surprising at first, but actually it can be understood by the fact that the smaller the angular divergence the more fine the substructure is in the intensity patter (i.e. the intensity patter is less washed-out) and therefore the stronger the variation in contrast.

A second parameter that was investigated was the start position of the wafer relative to the mask, as part of the advantage of integrated Talbot lithography is that it is a non-contact photolithography. However the integrity of the interference decreases with distance, as can be seen in figure 5(b). Therefore it is necessary to find a compromise in that start position of the wafer so that it is far enough away to be in non-contact but it is still close enough to obtain good contrasts. Figure 5 shows the effect of the angular spread in the illumination light is very strong, with an angle of only 0.5° if the start position is more than 60µm away from the mask the contrast drops, moreover for 1.0° the effect already occurs around 30µm and the drop in contrasts are dramatic.

So to conclude assuming an angular spread of the illumination light of 0.5° it is possible with a 1µm step size to starting between 10-20µm away to obtain a contrast of 0.4 for the structures.

Results

The parameters set allow us to create 1µm holes in non-contact in 800nm thick photoresist. This allows the transfer of the 1µm holes easily into the silicon nitride. Figure 6(A) shows the good homogeneity across the wafer, the interference fringes can clearly be seen in the photoresist. An anti-reflection coating is being investigated to remove these; however in the transfer to 500nm of silicon nitride this effect is only cosmetic.

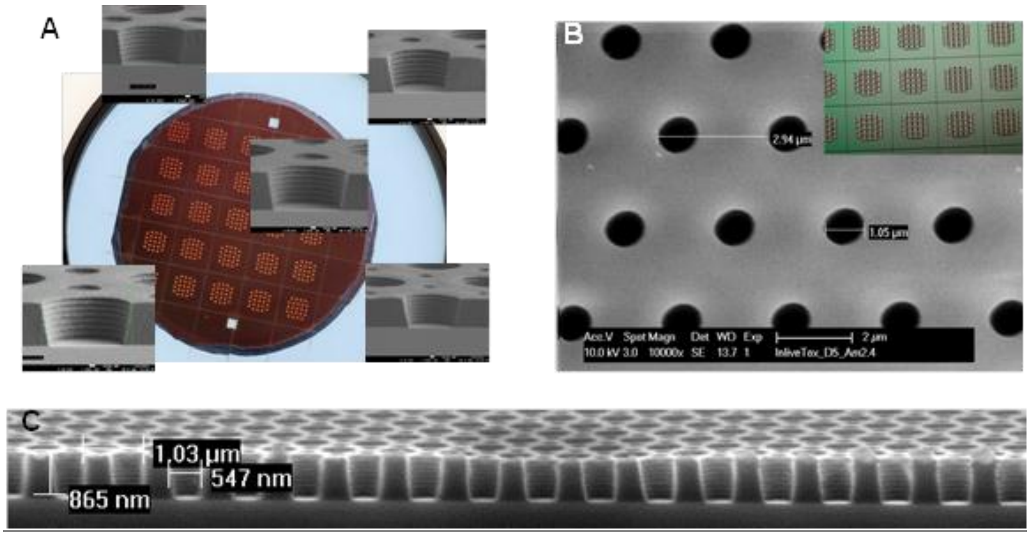

Figure 6. Optical and scanning microscope images. (A) Shows the homogeneity across the wafer of 1µm holes, this was also found to be reproducibly between wafers. (B) Top image of the same wafers. Inset shows the membranes on a fully processed wafer. (C) Shows the next process not discussed here showing 550nm holes with a 1µm period in 850nm of photoresist.

Figure 6 (b) shows the top view of the wafer showing the 1µm holes and the 3µm period hexagonal patter. The inset shows the fully processed wafer. Further processing for submicron features have also been made using step sizes down to 200nm and starting at 10µm distance from the wafer an example is given in figure 6 (C) where a 550nm hole is seen in a 1µm period in 850nm of photoresist.

4. CONCLUSIONS & OUTLOOK

In conclusion we have studied the integrated Talbot photolithography as a method to obtain micron and submicron structures using large-gap proximity lithography in a mask aligner. Using an integrated Talbot photolithography removes the need to know the absolute distance between the mask and the wafer.

In this work we see that improvements could be made by using continuous movement along the z-axis for exposures. Also, an anti-reflection coating on the wafer would remove some of the structure in the photoresist from standing waves. Finally a thinner photoresist layer would allow even higher resolution structures to be made

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