Polarization contact: concept and initial assessment

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ABSTRACT

Simulations using the aerial image simulator SPLAT are performed to analyze various structures for printing contacts, motivated by trying to condense the double exposure of two lines into a single exposure. The polarization contact uses polarization bars in the arms of two crossed orthogonal lines as a means to generate a contact in a single exposure. Characterizations of the contact structures are possible by investigating their normalized unit contours. From cutlines of these contours, each structure can be understood based solely on their geometries. The scaling property of optical systems allows these unit spread functions to ultimately characterize its behavior. The structures are similar in their response to 1 Rayleigh unit of defocus, with each structure having an intensity ratio of peak defocus to perfect focus of about 0.79. Dense contacts are generated using a polarization-phase carpet that condenses a double exposure with phase shifting into a single exposure, at a cost of 75% less throughput.

Keywords: lithography, polarization, bars, double exposure, contacts, cross, pointspread, linespread

1. INTRODUCTION

It is a well known fact from optics that the linespread function is thinner than the corresponding pointspread function. In recent years, researchers have tried to use this property of diffraction to realize smaller contacts by the double exposure of two
orthogonal lines, with each exposure at 50% intensity. The idea is to generate two linespread functions that will be thinner than a corresponding point spread function for that size contact. The requirement of two exposures, however, limits the usefulness of the double exposure because of alignment issues, mask costs, and overall time efficiency. The polarization contact is a novel approach to try and achieve the benefits of the double exposure with only a single exposure.

Crossed-polarized thin intersecting orthogonal lines are introduced and evaluated as a means of projection printing contacts on binary masks with a single exposure to produce contacts at reduced sizes consistent with the minimum linewidth of a technology node. In projection printing the image of a single small isolated opening is fundamentally limited by the point spread function of the optical system. Using the fact that the line spread function is smaller than the point spread function, the sequential exposure of horizontal and vertical lines has allowed resist openings smaller than standard contacts to be produced in extracting resist parameters. Polarization has also been introduced as a means of controlling interactions between openings on masks. This paper proposes the use of polarization controlling structures in intersecting lines to form reduced size contacts by means of a single exposure.

Section 2 of this paper further explains the structures investigated for this paper. It describes the basic methodology used for the investigation, along with parameters and metrics used for the evaluation of each structure. Section 3 characterizes the underlying structures of the methods by examining the normalized contours of the structures. These normalized contours are referred to as unit spread contours, with their corresponding cut lines in the center referred to as their unit spread functions, consistent with the linespread
and pointspread terminology. The unit contours and unit spread functions give better understandings of the fundamental behavior of such structures based solely on their geometries. Section 4 discusses the throughputs of the contact structures, relative sidelobe intensities, and the practical benefits of the structures. Section 5 re-evaluates the open cross structure for higher $k_1$ values and shows that the blending of the polarization contact and the open cross is possible, allowing for the benefits of both structures to be gained simultaneously. Section 6 investigates the effects of defocus on the peak intensities of the original structures and the modified open cross. Section 7 introduces the concept of a polarization-phase carpet for printing dense contacts. It will be shown that the double exposure for dense contacts can be done in one exposure, printing $k_1$ pitch contacts through frequency doubling at a cost of throughput.

2. BACKGROUND

It has been demonstrated that bar structures placed within features have the ability to polarize incident light on the mask.[6] These polarization bars allow one polarization to pass through the feature normally, while the other polarization is reflected. In addition to the reflection of one polarization, a further decrease in intensity at the wafer is due to the bars themselves, with this decrease in intensity scaling approximately as the square of the relative open areas. It was shown that throughputs of 33% to 40% are still achievable with such structures.

Figure 1 shows the structure of the polarization contact. To achieve the effects of the double exposure, polarization bars were placed inside the arms of a cross. These bars will polarize the incoming light by reflecting one polarization. The transmitted intensity within each of the arms will be smaller than the center of the cross, which remains open
to the full intensity. In this manner, we have exposed two orthogonal lines in one exposure, each with about 33% of the clear field intensity. Three methods, the polarization cross (single exposure at full intensity), the double exposure (two exposures at 50% intensity), and an open cross (no polarization bars in the arms – one exposure at full intensity), were compared with two other structures, a normal square contact and an open line, to gauge their effectiveness.

Simulations using the aerial image simulator SPLAT were used for the investigations of the contact structures. The dimensions of the contact structures in this paper are in units of $\lambda/\text{NA}$ for an assumed $k_1$ value of 0.5. All simulations were run with a partial coherence factor of $\sigma = 0.5$, unless otherwise stated. The aerial images for each structure were calculated for an assumed optical system of 4X, with dimensions of $k_1$ on the wafer.

3. CHARACTERIZATION OF STRUCTURES

Investigation of the unit contours of the aerial images enables a better understanding of how each structure behaves, and allows a fundamental characterization of each structure based solely on the geometry. Figure 2 shows the unit contours for the three structures, along with an open line and a square contact. Each structure had a line width equal to $k_1=0.5$ in units of $\lambda/\text{NA}$, with a partial coherence factor $\sigma = 0.5$. The arm lengths for the cross structures, as well as the double exposure, were all 1.25 $\lambda/\text{NA}$. It is seen that all three structures produce a bright central region for the contact, with varying degrees of sidelobe intensities. More insight into each structure can be achieved by looking at cut lines across the center of the structures. Figure 3 plots all cutlines for comparison. The open cross has the largest relative sidelobe intensities at 0.65, followed
by the double exposure at 0.55, and the polarization cross at 0.33. The polarization cross has a thinnest spread of the three methods and the lowest sidelobe intensities. It is important to note that all methods produce wider unit spread functions than a normal square contact. This demonstrates a largely misunderstood concept. The sequential exposure of two lines, or any other process involving the intersection of two lines to print contacts, will produce a unit spread function that is wider than a normal contact. By exposing one line at 50% intensity, the peak of the line spread function drops by half, while the zeros remain intact, thus decreasing the slope by two-fold. The second exposure adds a background DC component of 50% to the intensity, broadening the FWHM to the position of the zeros. This does not imply that there are not benefits to be gained from the double exposure, or other similar processes, but merely that these benefits are not derived from obtaining narrower functions.

4. THROUGHPUTS

In addition to the basic feature spread shape, the peak intensity for throughput is also important. Figure 4 shows the peak intensity values in the center of the structures for various $k_1$ values. The open cross dominates throughput over the other methods, but pays a heavy price in sidelobe intensity at high $k_1$ values. At lower $k_1$ values, the sidelobe intensities for the open cross reduce drastically, with the central peak still maintaining large throughput. Thus, for operating at low $k_1$ values, the open cross has the largest throughput and low sidelobes, (ie. .44 at $k_1=0.3$). The polarization cross has consistently low sidelobes throughout the $k_1$ spectrum, but also has the lowest peak intensity in the central region over those values, both properties stemming from the attenuation of electric field within the arms. The double exposure is a nice intermediary between the
two extremes, with constant 0.55 intensity sidelobes over the \( k_1 \) values and decent throughputs. However, it can be argued that both the polarization cross and the open cross are operating in two extreme regions: the polarization cross has too much attenuation of the electric field in the arms, detrimentally affecting the central peak, while the open cross does not have enough attenuation of the electric field in the arms, resulting in very large sidelobe intensities (at higher \( k_1 \) values). A blend of the two extremes might be highly beneficial.

5. THE MODIFIED OPEN CROSS

The polarization cross uses polarization as a means to attenuate the electric field in the arms, and thus reduces the sidelobe intensities. However, lowering the sidelobe intensities is not tied directly to polarization itself, rather, polarization is a means to achieve the attenuation of the fields in the arms and it is this attenuation that lowers the sidelobe intensities. Therefore, the open cross might be modified to attenuate the electric field in the arms to lower the large sidelobes, while still maintaining high throughput. Since the electric field that passes through a structure scales with the area of the structure, attenuation of the fields could be achieved by reducing the area of the arms.[6] Figure 1 shows the modified cross, with arm widths at 0.5\( k_1 \), reducing the area in the arms by half compared with the original open cross, while maintaining the original contact size. A comparison of the unit spread functions for the previous methods with the newly modified cross at half the arm area, shows promising results. The structure has very low sidelobe intensities at 0.3, even lower than the polarization cross. Looking also at the throughput, the structure still maintains the high throughput of the original open cross, with a peak central intensity at 0.842 that is higher than both the double exposure and the
polarization cross. Thus, the modified cross is a successful blend of high throughput and low sidelobe intensities with only a single exposure.

6. DEFOCUS

While the structures have been characterized based on peak intensities and relative sidelobe intensities, it would also be useful to understand the effects of focus on these structures. Figure 5 shows a bargraph of the ratios of peak intensity with 1 Rayleigh unit (0.25 waves) of defocus relative to the peak intensity in perfect focus. All structures are affected about the same as a square contact, with the polarization cross at 0.80, the modified open cross at 0.79, and the double exposure at 0.76.

7. DENSE CONTACTS

It has been demonstrated that dense contacts can be made using double exposure techniques augmented with phase shifting masks.[7,8] The exposure of two parallel lines of opposite phase can be used with a second exposure, rotated 90 degrees, to produce dense contacts. Condensing the process into one exposure would eliminate the issues associated with realignment and also enhance time efficiency. Figure 6 introduces a novel structure we have called a polarization-phase carpet, where polarization has been introduced as a means for condensing the process into one exposure. If each exposure is assigned a polarization, the two exposures can be superimposed on top of each other. The overlapping of two 0 degree regions and two 180 degree regions remain at their respective phases. In the areas of phase conflicts (ie, the overlap of a 0 and 180 degree region), the square must be shared equally and symmetrically with 0 and 180 degree regions. This has been accomplished by splitting the square into four triangles, two of each phase. The opposite phase areas are kept from canceling each other at the center by
polarization bars that keep the electric fields spatially orthogonal. These polarization bars enable the region under the phase conflicted areas to retain some intensity. The regions of similar phases must be brought down in intensity such that these regions are transmitting as much intensity as the phase conflicted regions. When this occurs, the two regions now transmit identical intensities and a cancellation of the electric fields occurs which produces a frequency doubling at the wafer. This frequency doubling enables the polarization-phase carpet to reproduce the shape of the aerial image for the double exposure using only a single exposure, allowing $k_1$ pitch contacts to be produced.

Figure 7 shows a contour plot of the polarization-phase carpet as a repeating field. The cost of condensing the double exposure process into a single exposure is the resultant lower throughput. The peak intensity of the contacts is only .3175 of the clear field intensity. Investigating the unit contours of the repeating structure, it is seen that the background intensity is 56% of the peak contact intensity, giving a contrast of nearly 2 to 1. This is consistent with the double exposure, which also has a background intensity of 56% of the peak contact intensity, but the double exposure has a much larger throughput of 1.27 of the clear field intensity. The unit spread function of the polarization-phase carpet can be seen in Figure 8. This normalized cutline is slightly thinner than the other methods introduced. In fact, it is quite similar to a square contact even though two orthogonal feature images are being added. In a sense, the two-fold increase in slope due to the use of phase-shifting, roughly compensates for the two-fold loss in slope due to the addition of the second orthogonal feature. This, however, comes at a heavy throughput loss.
The effects of defocus were also investigated for this structure. At 1 Rayleigh unit of defocus, the ratio of intensities between defocused and perfect focus is .945, showing that the structure is quite robust to defocus effects. Since the polarization-phase carpet gives four wave interference with equal off axis angles, this good focus behavior is expected.

8. CONCLUSION

Using the aerial image simulator SPLAT, various structures were examined to determine their effectiveness at printing contacts. The structures were characterized at a fundamental level based solely on their respective geometries by analyzing their unit spread functions. It is shown that the common belief that two intersecting lines can produce a smaller unit spread function than a normal contact is false. The background DC component of the orthogonal line will compress the spread function from 0.5 to 1.0, resulting in a broader unit spread function than a normal contact. However, working within constraints of the lithographic process (ie, relatively constant input brightness), the intersecting line structures can play an important role in printing contacts. The large gain in throughput for such structures gives tremendous advantages over normal contacts, allowing greater flexibility during processing. For $k_1 = 0.5$ and $\sigma = 0.5$, the polarization cross had the smallest sidelobes relative to the peak central intensity at 0.33, followed by the double exposure at 0.55, and the open cross at 0.65. The relative sidelobe intensities for the double exposure are constant throughout the range of $k_1$ values, and the sidelobe intensities for the polarization cross remain in the range of 0.3 - 0.45. However, the sidelobe intensities for the open cross are large for large $k_1$ and small for small $k_1$. The open cross can be modified by thinning out the arms while leaving the contact region
intact, thus allowing for smaller throughputs in the arms and decreasing the sidelobes. In this manner, the modified open cross can be programmed to specific sidelobe intensities, based on needed specifications. By thinning the arms to 0.5k₁ at k₁ = 0.5, the relative sidelobe intensities dropped to .3 and still maintained a larger throughput than the double exposure and the polarization cross. Defocus effects were investigated and all structures were found to be affected relatively the same, with ratios of peak intensities of defocus and perfect focus being about 0.79. A new structure called a polarization-phase carpet can print dense contacts by duplicating the effects of a phase-shifting double exposure in just a single exposure. Polarization bars are used in conjunction with phase shifting regions such that the blending of the two exposures allows a frequency doubling to occur at the wafer, producing k₁ pitch contacts with a 2 to 1 contrast ratio. The price of condensing the process into a single exposure is the resultant throughput at 0.32 of the clear field value, which is 75% less than the double exposure method. The unit spread function is wider than the normal contact, but slightly thinner than the previous structures’ spreads. The polarization-phase carpet is quite robust to defocus effects, with an intensity ratio of defocus to perfect focus equal to 0.945.

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REFERENCES

Figure 1. Structures studied for printing contacts.

- Open Cross
- Double Exposure
- Polarization Cross
- Modified Cross
Figure 2: Unit contours of a square contact, open line, open cross, double exposure, and polarization cross.
Figure 3. Unit spread functions of the methods. Cutlines down the center of the unit contours.
Figure 4. Central peak intensities of the various methods for different $k_1$ values.
Figure 5. Bargraph of ratios of peak intensity for 1 Rayleigh unit of defocus to perfect focus for various methods.
Figure 6. Structure of the polarization-phase carpet. Horizontal bars transmit vertical polarization, and vertical bars pass the horizontal polarization.
Figure 7. Contour of the polarization-phase carpet for $k_1=0.7$. 
Figure 8. Unit spread function of the polarization-phase carpet plotted alongside the other methods.