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The effects of partial coherence on the imaging of lines on photoresist

Robert Douglas Watso

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THE EFFECTS OF PARTIAL COHERENCE ON THE IMAGING OF LINES ON PHOTORESIST

by

Robert D. Watso

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in the School of Photographic Arts and Sciences in the College of Graphic Arts and Photography of the Rochester Institute of Technology

Signature of Author ....................................................
Robert Douglas Watso
Imaging and Photographic Science

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Name Illegible
Thesis Advisor

Accepted by .................................................................
Name Illegible
Supervisor, Undergraduate Research
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ROCHESTER INSTITUTE OF TECHNOLOGY
COLLEGE OF GRAPHIC ARTS AND PHOTOGRAPHY

Title of Thesis: The Effects of Partial Coherence On the Imaging of Lines On Photoresist

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Robert D. Watso

Date ........ April 16, 1985...........
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ABSTRACT

A series of images of a AMI/RIT resolution mask was imaged at the following partial coherence values: 0.7, 0.65, 0.6, 0.55, 0.5, 0.45, 0.4, and 0.35. The line-width and slope of the 10 micron lines imaged at each particular partial coherence value was analyzed and evaluated. The slope of the developed photoresist sidewall improved significantly with a decrease in partial coherent illumination, except for the 0.7 to 0.65, range while the line-width decreased.
ACKNOWLEDGEMENTS

The author would like to sincerely thank all those who contributed to the successful completion of this thesis.

A special thanks goes to 'Kitt' Ausschnitt of the GCA Corporation, in Burlington, Massachusetts, who agreed to act as thesis advisor for this project, and gave his valuable support and materials.

Also very much appreciated were the time, resources, materials, and general support received from David Holbrook from the GCA Corporation, Andover, Massachusetts.

Also greatly appreciated were the time, and materials received from Setha Olson and Pat Renyolds both from the GCA Corporation, Burlington, Massachusetts.

A thank you to the CIA for funding the thesis.

A final thank you to Lynn Fuller, Head of Microelectronics at RIT, for the use of his equipment.
DEDICATION

To Mom and Dad, for all their support and love.
LIST OF FIGURES

Figure Number

1. Photoresist Thickness Variations ............ 2
2. Coherent Illumination ...................... 3
3. Modulation vs. Spatial Frequency .......... 4
4. Abbe Theory of Image Formation ............. 5
5. Aerial Image Intensity ...................... 6
6. AMI/RIT Resolution Mask .................... 9
7. Nanoline Graph ............................ 11
# Table of Contents

**Release Form** ................................................................. ii

**Abstract** ............................................................................. iii

**Acknowledgements** .............................................................. iv

**Dedication** ............................................................................ v

**List of Figures** ................................................................. vi

I. **Introduction** ................................................................. 1
   - Partial Coherent Illumination ........................................... 2
   - Problems With Partial Coherent Illumination ................. 4

II. **Experimental** ................................................................. 8
   - A. Equipment and Materials .......................................... 8
   - B. Imaging System ....................................................... 9
   - C. Exposure .............................................................. 10
   - D. Sample Processing .................................................. 11
   - E. Line-width Measurement ......................................... 11
   - F. Scanning Electron Microscope Analysis ..................... 12

III. **Results** ...................................................................... 14
   - A. Irradiance vs. Partial Coherence ............................... 14
   - B. Line-width vs. Partial Coherence ............................... 15
   - C. Photointensity vs. Scanning Distance ....................... 16
I. INTRODUCTION

Line-width control at micron and submicron geometries is one of the present goals of microlithography. For state-of-the-art devices, a line-width on the order of 1 micron must be controlled to within 5% over the entire wafer. Line-width control at these geometries greatly increases the good-chip yield on a wafer.

Since the late 1970's step-and-repeat projection systems (steppers) have been available with a partial spatial coherence value of 0.7 resulting in controllable CD's (critical dimensions) down to 1.5 microns. It is only a matter of time until improvements in accuracy and control will push steppers, already with automatic focusing and the ability to align every die separately, over the submicron production-imaging barrier. Control is the cornerstone of any imaging system in production as the higher the CD variability the lower the good-chip yield. Critical dimension control depends on many of the imaging and processing system parameters. However, the most important and the least controllable of all the parameters on the production line is resist thickness variation. Changes in resist thickness which are
especially large over profile steps, see figure 1, will produce variations in focus and exposure which yield larger or smaller line-widths from nominal. 4,5,6,7

Figure 1.

![Diagram of Resist and Substrate](image)

Photoresist Thickness Variations

Partial Coherent Illumination

In 1977, J.D. Cuthbert showed what A. Offner had proposed in 1971. 2 Cuthbert showed that a decrease in partial coherence improved resist line-width insensitivity to variations in focus and exposure, while resulting in resist line-width closer to mask line-width. 5 This decreasing of partial coherence to improve critical dimension control has been verified many times since then. 8,9

Illumination is coherent when all light rays in a light bundle are traveling with the same phase relative to each other, see figure 2.
When the light rays in the light bundle are traveling in a random phase with respect to each other the illumination is considered incoherent. Partial coherent illumination is between the two extremes of phase difference.

Partial coherence is defined as the following ratio:

\[ \varphi = \frac{\text{NA}_C}{\text{NA}_O} = \frac{\sin \alpha_C}{\sin \alpha_O} \]

Where \( \text{NA}_C \), the numerical aperture of the condenser system, defines the angular wedge of plane waves illuminating the mask. \( \text{NA}_O \), the numerical aperture of the objective lens defines the acceptance angle of the objective lens. The shorter the path difference of the light rays in the light bundle the smaller the phase difference between the light rays illuminating the mask.

Total spatially incoherent illumination, \( \varphi = \infty \), is approximated at \( \varphi = 1 \), as the illumination from the source fills the entire acceptance angle of the objective lens. A smaller partial coherence value results in a smaller angular range of light waves incident at any point on the mask, thus the illumination from the source fills only part of the acceptance angle of the objective lens.
lens. The lower the partial coherence value the higher the degree of coherence. Spatially coherent illumination, \( \nabla = 0 \), is approached as the ratio of the numerical aperture of the condenser system to the numerical aperture of the objective lens approaches zero.\(^5\)

NOTE: For this thesis a lower \( \nabla \) value represents a decrease in partial coherent illumination.

Problems With Partial Coherent Illumination

Increasing the partial coherence in an imaging system while solving several problems also creates several. As partial coherence is decreased, image intensity is decreased, thus leading to longer exposure times.\(^5\) Also, decreasing partial coherence cuts off high spatial frequencies as shown in figure 3, a graph of modulation of image intensity vs spatial frequency of the object for different partial coherence values.\(^2\)

Fig. 3 Modulation \( M \) of image intensity vs. spatial frequency for different values of \( \nabla \).

\[
M = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}
\]
The reason for the cutoff of the high spatial frequencies is that because of diffraction the higher orders of the diffraction patterns fall outside the finial collecting lens, thus if the first order diffraction patterns are not collected by the lens no image of the object that diffracted the light will be produced. This is shown in the below figure of the Abbe theory of image formation.

Figure 4.

Abbe Theory of Image Formation

This reduction of frequency response should cause some degradation at the line-edges and corners of features on the resist, as the line-edges and corners contain the highest spatial frequency.\(^5,8\)

The reconstituted image cannot be characterized only by its modulation. The partial coherence also influences the profile of the aerial image reconstituted by the lens. The absolute values of the minimum and maximum intensities are the principal parameters that define the image. The aerial image intensity of a grating of 1
micron lines and spaces for partial coherence values of 1.0, 0.5, and 0.1 is shown in figure 5.²

Figure 5.

Aerial image intensity $I(x)$ of a grating of 1 micron lines and spaces for $\gamma = 0.1, 0.5,$ and 1.0.

Figure 5 shows that as the partial coherence is decreased the illumination intensity in the middle of the line is increased. This increase in intensity causes a dramatic increase in the maximum development rate in the middle of the line. The vertical resist development is thus much faster than lateral resist development.

If a decreased partial coherence value is to be employed in projection printing for greater control in imaging of micron and submicron geometries, its effect on photoresist line-width will have to be known; as large degradations in the photoresist may cause overetching of the substrate which can alter the designed resistance of the device or cause an open circuit in the finished chip. Knowing the effect that decreasing partial coherence has on line-width and sidewall slope it may be used to give
greater control of both. Analysing the effects of decreasing the partial coherent illumination of a projection printer on photoresist line-width and sidewall slope was the purpose of the thesis.
II. EXPERIMENTAL

A. Equipment and Materials

All of the materials used were provided by the GCA corporation. These included a Ziess 10x rediction lens, a GCA 10x resolution mask, a Shott heat absorbing filter, 25 4" wafers with SiO grown and coated with Shipley 1400-S photoresist. Lab facilities were provided by the Microelectronics Department in the College of Engineering and by the Imaging and Photographic Science Department in the College of Graphic Arts and Photography; both colleges are part of the Rochester Institute of Technology. The equipment used in the lab facilities included the following: a GCA Wafertac; a GCA Mann photorepeater; a Nanometrics optical line-width measuring system; a 10x AMI/RIT resolution mask; an ISI Mini-scanning electron microscope; a Cambridge scanning electron microscope; Kodak 809 Micropositive developer; a Nikon Measurescope; ISI Sputter/coater; and a Optronic Laboratories spectral radiometer.
B. Imaging System

With minor modifications a GCA Mann photorepeater was used as the imaging system. The minor modifications included the placement of an adjustable aperture between the fiber bundle and the condenser lens, see Appendix for exact placement of aperture. A change in the aperture size of the adjustable aperture enabled the partial coherent illumination on the 10x AMI/RIT resolution mask to be varied. An illustration of the AMI/RIT mask is given in the figure below.

Figure 6.

AMI/RIT Mask

The photorepeater stage also had to be modified to accept 4" wafers as the photorepeater was designed to expose masks not wafers. The shutter speed of the photorepeater was then calibrated, see Appendix. The irradiance at each aperture setting i.e. at each partial coherence was determined using a radiometer, given in the Appendix. The spectral irradiance of the mercury bulb was determined using a spectral radiometer, see Appendix.
C. Exposure

The photoresist coated wafers were prebaked at 95 °C for 40 sec on the GCA Wafertrac. A focus/exposure array was imaged using the AMI/RIT 10x resolution mask at the designed partial coherence of the photorepeater, 0.7, on 3 wafers. Observing the focus/exposure array on the developed 3 wafers yielded that each wafer had a different best focus/exposure. This was believed to be caused by different SiO₂ layer thicknesses. The problem of different SiO₂ thicknesses was eliminated by breaking each wafer in half, as half was used to determine best focus/exposure and the other half was imaged at that best focus/exposure. The best focus/exposure die was determined as being that threshold focus/exposure, at $\gamma = 0.7$, which 'just' cleared the exposed photoresist between the '9 micron' unexposed photoresist lines.

The 10x AMI/RIT resolution mask was imaged at the threshold best focus/exposure for each wafer at the following partial coherent illumination values: 0.7, 0.65, 0.60, 0.55, 0.50, 0.45, 0.40, and 0.35. The amount of exposure was kept the same for each partial coherence value by using the irradiance vs. partial coherent graph, see page 14, to adjust the exposure time accordingly.
D. Sample Processing

Exposed wafer samples were developed in Kodak Micropositive 809 developer diluted 1:1 with de-ionized water at 20 °C. Immersion processing was used employing continuous agitation in a 100 ml petri dish for 1 min. The developer was changed after every wafer sample was developed. The wafer samples were then immersed in running de-ionized water for 5 min. The samples were subsequently dried under an air jet.

E. Line-width Measurement

Accurate line-width measurement is essential. The Nanoline III optical line-width measurement system was used to measure photoresist lines down to 9 microns. The Nanoline III system can measure down to 0.5 microns (± 0.05 microns). The Nanoline was programmed to measure the photoresist line from minimum reflected photointensity to minimum reflected photointensity, as this is the most accurate, see figure 7.

Figure 7.

Substrate

![Diagram of Resist and Reflectance](attachment:image.png)
See Appendix for the computer program used in the Nanoline III. The Nanoline also allowed the degree of slope of the photoresist sidewalls to be analyzed.

F. Scanning Electron Microscope Analysis

Before the ISI Mini-SEM (Scanning Electron Microscope) could be used it had to be repaired. Repairing the Mini-SEM entailed tracking down with an oscilloscope the malfunctioning parts. The parts replaced were: a 2.2 F capacitor; a 100 resistor; 2 crimped wires; the electron gun filament; and the entire SEM column.

Each die sample to be SEMed was broken and painted to a 1 cm sample holder. The photoresist showed signs of charging on the first sample SEMed. The second sample was coated using the ISI Sputter/coater with 400 A of gold to prevent charging. A SEM photograph of the second sample is shown below and on the following page.
As seen from the SEM photographs, charging of the photoresist would make SEM analysis inconclusive. Even doubling the amount of gold sputtered on the wafer sample to 800 Å; the SEM photographs were still inconclusive. Sputtering more than 800 Å of gold would change the slope of the photoresist sidewalls, due to the build-up of gold.
III. RESULTS

IRRADIANCE VS. PARTIAL COHERENT ILLUMINATION

![Graph showing irradiance vs. partial coherent illumination](image-url)
LINEWIDTH VS. PARTIAL COHERENT ILLUMINATION

![Graph showing the relationship between line-width and partial coherent illumination. The x-axis represents partial coherent illumination ranging from 0.35 to 0.70, while the y-axis represents line-width in microns. The graph shows a linear increase in line-width as the illumination increases.]
\[ \nu = 0.7 \]

* of datapoints = 7

\[
\begin{align*}
\text{mean} &= 11.93429 \\
\text{mode} &= 11.94000 \\
\text{midrange} &= 11.93500 \\
\text{range} &= 11.91000 \text{ to } 11.96000 \\
\text{variance} &= 0.00033 \\
\text{standard deviation} &= 0.01813
\end{align*}
\]

# of datapoints = 7, mean = 11.93429, sdev = 0.01813

90% Confidence Interval -\( \rightarrow \) 11.93429 +/- 0.01331

95% Confidence Interval -\( \rightarrow \) 11.93429 +/- 0.01676

99% Confidence Interval -\( \rightarrow \) 11.93429 +/- 0.02540

* initial datapoints = 7, sdev = 0.01813, ERROR = 0.02000

90% Recommended Sample Size \( \rightarrow \) 3

95% Recommended Sample Size \( \rightarrow \) 5

99% Recommended Sample Size \( \rightarrow \) 11
\( \sigma = 0.65 \)

# of datapoints = 7
mean = 11.91143
mode = 11.88000
midrange = 11.92000
range = 11.89000 to 11.95000
variance = 0.00045
standard deviation = 0.02116

* initial datapoints = 7  sdev = 0.02116  ERROR = 0.02000
90% Recommanded Sample Size -> 4
95% Recommanded Sample Size -> 7
99% Recommanded Sample Size -> 15
\[ \mathcal{V} = 0.6 \]

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td># of datapoints</td>
<td>&gt;</td>
</tr>
<tr>
<td>mean</td>
<td>11.87143</td>
</tr>
<tr>
<td>mode</td>
<td>11.88000</td>
</tr>
<tr>
<td>midrange</td>
<td>11.87500</td>
</tr>
<tr>
<td>range</td>
<td>11.83000 to 11.92000</td>
</tr>
<tr>
<td>variance</td>
<td>0.00108</td>
</tr>
<tr>
<td>standard deviation</td>
<td>0.03288</td>
</tr>
</tbody>
</table>

| # of datapoints    | 7             |
| mean               | 11.87143      |
| sdev               | 0.03288       |
| 90% Confidence Interval | 11.87143 +/- 0.02414 |
| 95% Confidence Interval | 11.87143 +/- 0.03041 |
| 99% Confidence Interval | 11.87143 +/- 0.04607 |

<table>
<thead>
<tr>
<th>* initial datapoints = 7</th>
<th>sdev = 0.03288</th>
<th>ERROR = 0.02000</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% Recommended Sample Size</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>95% Recommended Sample Size</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>99% Recommended Sample Size</td>
<td>37</td>
<td></td>
</tr>
</tbody>
</table>
\( \nabla = 0.55 \)

Mean = 11.77000

Mode = 11.75000

Midrange = 11.78000

Range = 11.75000 to 11.81000

Variance = 0.00043

Standard Deviation = 0.02082

# of datapoints = 7

Mean = 11.77000

Sdev = 0.02082

90% Confidence Interval \( \rightarrow \) 11.77000 +/- 0.01529

95% Confidence Interval \( \rightarrow \) 11.77000 +/- 0.01925

99% Confidence Interval \( \rightarrow \) 11.77000 +/- 0.02917

# initial datapoints = 7

Sdev = 0.02082

Error = 0.02000

90% Recommended Sample Size \( \rightarrow \) 4

95% Recommended Sample Size \( \rightarrow \) 6

99% Recommended Sample Size \( \rightarrow \) 15
\( \gamma = 0.5 \)

* of datapoints = 7
mean = 11.66143
mode = 11.65000
midrange = 11.67000
range = 11.65000 to 11.69000
variance = 0.00028
standard deviation = 0.01676

# of datapoints = 7 mean = 11.66143 sdev = 0.01676
90% Confidence Interval -> 11.66143 +/- 0.01231
95% Confidence Interval -> 11.66143 +/- 0.01550
99% Confidence Interval -> 11.66143 +/- 0.02348

* initial datapoints = 7 sdev = 0.01676 ERROR = 0.02000
90% Recommended Sample Size -> 3
95% Recommended Sample Size -> 4
99% Recommended Sample Size -> 10
\[ \nabla = 0.45 \]

# of datapoints = 7
mean = 11.53286
mode = 11.55000
midrange = 11.51500
range = 11.47000 to 11.56000
variance = 0.00089
standard deviation = 0.02984

# of datapoints = 7
mean = 11.53286
sdev = 0.02984

90% Confidence Interval \(\Rightarrow\) 11.53286 \(+/-\) 0.02191
95% Confidence Interval \(\Rightarrow\) 11.53286 \(+/-\) 0.02760
99% Confidence Interval \(\Rightarrow\) 11.53286 \(+/-\) 0.04181

* initial datapoints = 7
sdev = 0.02984
ERROR = 0.02000

90% Recommended Sample Size \(\Rightarrow\) 8
95% Recommended Sample Size \(\Rightarrow\) 13
99% Recommended Sample Size \(\Rightarrow\) 31
\( \nu = 0.4 \)

- Number of datapoints = 7
- Mean = 11.29857
- Mode = 11.31000
- Midrange = 11.29500
- Range = 11.27000 to 11.32000
- Variance = 0.00031
- Standard deviation = 0.01773

90% Confidence Interval: 11.29857 +/- 0.01302
95% Confidence Interval: 11.29857 +/- 0.01640
99% Confidence Interval: 11.29857 +/- 0.02484

* Initial datapoints = 7  sdev = 0.01773  ERROR = 0.02000

- 90% Recommended Sample Size -> 3
- 95% Recommended Sample Size -> 5
- 99% Recommended Sample Size -> 11
\( \sigma = 0.35 \)

* of datapoints = 7
mean = 11.41286
mode = 11.38000
midrange = 11.42000
range = 11.38000 to 11.46000
variance = 0.00089
standard deviation = 0.02984

* of datapoints = 7  mean = 11.41286  sdev = 0.02984
90% Confidence Interval -> 11.41286 +/- 0.02191
95% Confidence Interval -> 11.41286 +/- 0.02760
99% Confidence Interval -> 11.41286 +/- 0.04181

* initial datapoints = 7  sdev = 0.02984  ERROR = 0.02000
90% Recommended Sample Size -> 8
95% Recommended Sample Size -> 13
99% Recommended Sample Size -> 31
Null Hypothesis: mean₁ - mean₂ = 0; for alpha = 0.05  
Alternative Hypothesis: the population means are significantly different

iter # of points for sample #1 -> 7  \( \bar{x} = 0.7 \)
iter # of points for sample #2 -> 7  \( \bar{x} = 0.65 \)
iter mean of sample #1 ->  11.93429
iter mean of sample #2 -> 11.91571
iter standard deviation of sample #1 -> 0.01813
iter standard deviation of sample #2 -> 0.02573

\( t = 1.56125 \)

FAIL TO REJECT: Means Have Not Proven Significantly Different *

Null Hypothesis: mean₁ - mean₂ = 0; for alpha = 0.05  
Alternative Hypothesis: the population means are significantly different

iter # of points for sample #1 -> 7  \( \bar{x} = 0.6 \)
iter # of points for sample #2 -> 7  \( \bar{x} = 0.65 \)
iter mean of sample #1 ->  11.87000
iter mean of sample #2 -> 11.91571
iter standard deviation of sample #1 -> 0.03512
iter standard deviation of sample #2 -> 0.02573

table = 2.20100  \( t = -2.77824 \)

* REJECT THE NULL: Means Are Significantly Different *

Null Hypothesis: mean₁ - mean₂ = 0; for alpha = 0.05  
Alternative Hypothesis: the population means are significantly different

iter # of points for sample #1 -> 7  \( \bar{x} = 0.6 \)
iter # of points for sample #2 -> 7  \( \bar{x} = 0.55 \)
iter mean of sample #1 ->  11.87000
iter mean of sample #2 -> 11.77000
iter standard deviation of sample #1 -> 0.03512
iter standard deviation of sample #2 -> 0.02082

\( t = 6.48074 \)

* REJECT THE NULL: Means Are Significantly Different *
Null Hypothesis: $\mu_1 - \mu_2 = 0$; for alpha = 0.05
Alternative Hypothesis: the population means are significantly different

Inter # of points for sample #1 -> 7  $t = 0.50$
Inter # of points for sample #2 -> 7  $t = 0.55$
Inter mean of sample #1 -> 11.66143
Inter mean of sample #2 -> 11.77000
Inter standard deviation of sample #1 -> 0.01676
Inter standard deviation of sample #2 -> 0.02082
table = 2.20100  t = -10.74802

* REJECT THE NULL: Means Are Significantly Different *

Null Hypothesis: $\mu_1 - \mu_2 = 0$; for alpha = 0.05
Alternative Hypothesis: the population means are significantly different

Inter # of points for sample #1 -> 7  $t = 0.50$
Inter # of points for sample #2 -> 7  $t = 0.45$
Inter mean of sample #1 -> 11.53286
Inter mean of sample #2 -> 11.41286
Inter standard deviation of sample #1 -> 0.02984
Inter standard deviation of sample #2 -> 0.02984
table = 2.20100  t = 9.93883

* REJECT THE NULL: Means Are Significantly Different *

Null Hypothesis: $\mu_1 - \mu_2 = 0$; for alpha = 0.05
Alternative Hypothesis: the population means are significantly different

Inter # of points for sample #1 -> 7  $t = 0.45$
Inter # of points for sample #2 -> 7  $t = 0.40$
Inter mean of sample #1 -> 11.53286
Inter mean of sample #2 -> 11.41286
Inter standard deviation of sample #1 -> 0.02984
Inter standard deviation of sample #2 -> 0.02984
table = 2.20100  t = 7.52322

* REJECT THE NULL: Means Are Significantly Different *
Null Hypothesis: \( \text{mean}_1 - \text{mean}_2 = 0 \); for alpha = 0.05  
Alternative Hypothesis: the population means are significantly different

<table>
<thead>
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<th>Inter # of points for sample #1</th>
<th>7</th>
<th>( V = 0.35 )</th>
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</thead>
<tbody>
<tr>
<td>Inter # of points for sample #2</td>
<td>7</td>
<td>( V = 0.40 )</td>
</tr>
<tr>
<td>Inter mean of sample #1</td>
<td>11.29857</td>
<td></td>
</tr>
<tr>
<td>Inter mean of sample #2</td>
<td>11.41286</td>
<td></td>
</tr>
<tr>
<td>Inter standard deviation of sample #1</td>
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<td></td>
</tr>
<tr>
<td>Inter standard deviation of sample #2</td>
<td>0.02984</td>
<td></td>
</tr>
</tbody>
</table>

\(-table = 2.20100 \quad t = -8.71144\)

* REJECT THE NULL: Means Are Significantly Different *

Null Hypothesis: \( \text{mean}_1 - \text{mean}_2 = 0 \); for alpha = 0.05  
Alternative Hypothesis: the population means are significantly different

<table>
<thead>
<tr>
<th>Inter # of points for sample #1</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter # of points for sample #2</td>
<td>7</td>
</tr>
<tr>
<td>Inter mean of sample #1</td>
<td>11.87000 ( V = 0.3 )</td>
</tr>
<tr>
<td>Inter mean of sample #2</td>
<td>11.33429 ( V = 0.7 )</td>
</tr>
<tr>
<td>Inter standard deviation of sample #1</td>
<td>0.03512</td>
</tr>
<tr>
<td>Inter standard deviation of sample #2</td>
<td>0.01813</td>
</tr>
</tbody>
</table>

\(-table = 2.20100 \quad t = -4.30364\)

* REJECT THE NULL: Means Are Significantly Different *
MTB > PLOT C2 VS C1

C2
12.00+
-
-
11.70+
-
-
LINE- WIDTH
-
11.40+
-
-
11.10+
0.30 0.40 0.50 0.60 0.70 0.80
PARTIAL COHERENCE

MTB > REGRESS C2 1 C1

THE REGRESSION EQUATION IS
C2 = 10.7 + 1.92 C1

<table>
<thead>
<tr>
<th>COLUMN</th>
<th>COEFFICIENT</th>
<th>ST. DEV.</th>
<th>T-RATIO =</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>OF COEF.</td>
<td>COEF/S.D.</td>
</tr>
<tr>
<td>C1</td>
<td>10.6666</td>
<td>0.0803</td>
<td>132.91</td>
</tr>
<tr>
<td></td>
<td>1.9186</td>
<td>0.1493</td>
<td>12.85</td>
</tr>
</tbody>
</table>

S = 0.04939

R-SQUARED = 96.5 PERCENT
R-SQUARED = 95.9 PERCENT, ADJUSTED FOR D.F.

ANALYSIS OF VARIANCE

<table>
<thead>
<tr>
<th>DUE TO</th>
<th>DF</th>
<th>SS</th>
<th>MS = SS/DF</th>
</tr>
</thead>
<tbody>
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</table>

R DENOTES AN OBS. WITH A LARGE ST. RES.
IV. Discussion

The R-squared value of 0.955 indicates that line-width has a high degree of correlation with partial coherent illumination. The means of all line-widths, except from the 0.7 and 0.65 partial coherent illumination, were proven significantly different. The 0.7 and 0.65 partial coherent illumination line-width values will be discussed later.

Due to the fact that the 10 micron lines on the 10x AMI/RIT resolution mask are actually 100 micron lines the cutoff of high spacial frequency is an unlikely reason for the smaller line-widths with lower partial coherence. The smaller line-widths are explained by the change of the aerial image intensity with decreasing partial coherent illumination, see the below graph.

Image intensity profile at the edge of an opaque line in a 10 \( \mu \)m lines and spaces grating.
Seen in the above graph of image intensity vs. distance for a 1 micron line, as the partial coherence value decreases the image intensity in the middle of the space is increases. The increase in image intensity in the middle of the space causes an increase in the rate of vertical development compared to lateral development. This increase in the rate of vertical development increases the slope of the developed photoresist sidewalls. The increase in sidewall slope is verified by the Nanoline III graphs of reflected photointensity vs. distance across the line. The steeper the gradient on the Nanoline III graphs the greater the slope of the photoresist sidewalls. The photoresist lines imaged at a 0.35 partial coherent value yielded the steepest gradient on the Nanoline III graphs while the photoresist lines imaged at a 0.7 partial coherent illumination value had the widest gradient.

The reason why all of the developed photoresist lines were larger than the 10 micron lines that they should have been using the 10x AMI/RIT resolution mask was due to underdevelopment of the wafer samples. The underdevelopment of the wafer samples probably exaggerated the effects of lowering the partial coherent illumination of the projection printer on the slope of the developed photoresist sidewalls ie. photoresist line-width. Observed from the graph of line-width vs. partial coherence the maximum line-width was 11.92 microns at a partial coherence of 0.7 and the minimum line-width was 11.31 microns at a partial coherence of 0.35. Correct development would have yielded a smaller difference
in line-width from 0.7 to 0.35 partial coherence values.

The effect of more line-width control with decreasing partial coherent illumination as stated by J.D. Cutberth, was not observed. The 0.6, 0.45, and 0.40 partial coherence values had standard deviations of 0.03 microns while the 0.7 and 0.65 partial coherence values had standard deviations of 0.02 microns. The line-width control should increase with decreasing partial coherent illumination as the rate of vertical to lateral development increases. The reason for conflict may be experimental error as the Nanoline III measures to +- 0.05 microns.
V. CONCLUSION

The major positive aspect of decreasing the partial coherent illumination in projection printers is the straighter sidewall profiles obtained. Decreasing the partial coherent illumination of the projection printer from 0.7 to 0.65 yielded no significant change in line-width i.e. no significant change of developed photoresist sidewall slope. A very small change or no change in the aerial image intensity in the 0.7 to 0.65 partial coherent values would yield no significant change in line-widths. The partial coherence should be lowered to 0.55 as this would significantly increase the sidewall slope with only a 30 percent reduction of irradiance.
VI. REFERENCES


Figure References


APPENDIX

PROGRAM FOR NANOMETRICS NANOLINE III

PARAMETERS FOR TEST

BOBFRT

ESP NUMBER: 3

STD 1 REAL VAL:

20.0V

STD 1 MFRS VAL:

2.4V

STD 2 REAL VAL:

10.00

STD 2 MFRS VAL:

1.45

MINIMUM WIDTH:

.0U

SPEC. MINIMUM:

.0U

SPEC. MAXIMUM:

100.00

SCALE FACTOR:

0
### Aperture Table

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<td>0.55</td>
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<tr>
<td>1.0</td>
<td>0.4</td>
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<tr>
<td>0.8</td>
<td>0.35</td>
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GCA 1795 Photorepeater Description
from the previous page

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<td>2</td>
<td>Fiber optic housing</td>
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<tr>
<td>3</td>
<td>Screw</td>
</tr>
<tr>
<td>4</td>
<td>Master reticle platen</td>
</tr>
<tr>
<td>5</td>
<td>Fiber optic bundle</td>
</tr>
<tr>
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<td>Condensing tube</td>
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<td>7</td>
<td>Knurled lock screw</td>
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<td>Objective lens holder</td>
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<td>Adjustable aperture</td>
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Spectral Irradiance of Hg Source
VITA

Robert Douglas Watso was born in Apollo, Pennsylvania. He was raised in Cortland, Ohio and Simsbury, Connecticut, where he attended Simsbury High School. Subsequently, he attended college at the Rochester Institute of Technology, in Rochester, New York, to pursue a Bachelor of Science degree in Imaging and Photographic Science, with a concentration on photonic microlithography.