Applications of Machine Learning for Defect Metrology

Abdul Qadeer Rehan
National Institute of Standards and Technology
Advisor: Bryan Barnes
Optics-based Patterned Defect Metrology

• Metrology: the scientific study of measurement

• Metrology Challenge:
  ➢ Fabricate 300 mm wafers
  ➢ Inspect sub 10 nm defects

• Metrology Solution: Optical methods
  ✓ Repeatability
  ✓ Non-destructive and fast
  ❑ Images are unresolved

Scanning electron micrograph

TEOS hard mask, polysilicon, TiN, HfO$_2$ on silicon
Sub-wavelength Detection of Defects

- **Form Birefringence** is the induced difference, due to geometrical factors, in refractive index between different polarizations of light traveling through or reflecting off a periodically structured material.

- Patterned defects perturb this periodicity and are often detectable using optics.
Images collected with Dr. Martin Sohn (NIST) at $\lambda = 193$ nm.

One out of 76 images as a function of focus.

Image Processing

1. Fourier Transform
2. Fourier Shift
3. Highpass Filter + Lowpass Filter
4. Fourier Shift
Inverse Fourier Transform performed after reversing the coordinate shift within python *(not shown).*
Machine Learning - Results

4 Defect types
2 Dies
3 Experimental repeats
2 linear light polarizations
Able to train our model on each individual defect type.
Our model was able to classify defects and no-defect across repeats for the same defect.
Initial identification of A defects using these images.

Confusion matrix for A Defect

<table>
<thead>
<tr>
<th>Defect</th>
<th>Test within repeat</th>
<th>Test across repeat</th>
</tr>
</thead>
<tbody>
<tr>
<td>By</td>
<td>1.0</td>
<td>0.995</td>
</tr>
<tr>
<td>Bx</td>
<td>1.0</td>
<td>0.993</td>
</tr>
<tr>
<td>A</td>
<td>1.0</td>
<td>0.999</td>
</tr>
<tr>
<td>J</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Bibliography


• Ananthan Raghunathan, Steve Bennett, Harlem O. Stamper, John G. Hartley, Abraham Arceo, Mark Johnson, Chris Deeb, Dilip Patel, Jim Nadeau. “13nm gate Intentional Defect Array (IDA) wafer patterning by e-beam lithography for defect metrology evaluation” (10 March 2011)

Questions?
Previous Work

- Simulated high spatial-frequency scattering off structures with two-dimensional periodicity.

- Detectability varied with wavelength

<table>
<thead>
<tr>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 nm</td>
</tr>
<tr>
<td>47 nm</td>
</tr>
<tr>
<td>122 nm</td>
</tr>
<tr>
<td>157 nm</td>
</tr>
<tr>
<td>193 nm</td>
</tr>
</tbody>
</table>
Image Processing – Fourier Transform

After a coordinate shift within python (not shown).
Image Processing – High / Low Pass Filters
Machine Learning – Convolutional Layer

Input Image

Feature Detector

Feature Map
Machine Learning – Convolutional Layer

Input Image

Feature Detector

Feature Map
Machine Learning – Max Pooling

Feature Map

Max Pooling

Pooled Feature Map
Machine Learning – Flattening

Pooled Feature Map

Flattening

```
1 1 0
4 2 1
0 2 1
```

```
1 1 0 4 2 1 0 2 1
```
Machine Learning – Convolutional Layer

Sharpen:

```
0 0 1 0
0 1 5 1
0 1 0 0
0 0 0 0
```

Blur:

```
0 0 0 0
0 1 1 0
0 1 1 0
0 0 0 0
```

Emboss:

```
-2 1 0
-1 1 1
0 1 2
```

Edge Detect:

```
1 0
1 1 1
0 1 0
```
Image Processing – Fourier Transform

Problem
Image Processing – Fourier Shift

Problem

Machine Learning for Defect Metrology
Machine Learning - Results

Cross defect classification for Defect A

Count vs. Data

- No Defect
- Defect
Machine Learning for Defect Metrology

Defect Image

Original Image

Activation of 1\textsuperscript{st} CL

1\textsuperscript{st} Pooling Layer

Activation of 2\textsuperscript{nd} CL

2\textsuperscript{nd} Pooling Layer

Flattened Layer

Fully Connected Layer

Final Output

No Defect Image
Machine Learning - Results

Trained: Defect A Repeat 1, Tested: Defect A Repeat 2
## Confusion Matrices

<table>
<thead>
<tr>
<th></th>
<th>By</th>
<th>Bx</th>
<th>A</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[3294 66]</td>
<td>[2149 11]</td>
<td>[720 0]</td>
<td>[2396 4]</td>
</tr>
<tr>
<td></td>
<td>[0 3360]</td>
<td>[0 2160]</td>
<td>[1 719]</td>
<td>[25 2375]</td>
</tr>
<tr>
<td></td>
<td>[3210 0]</td>
<td>[2595 45]</td>
<td>[3120 0]</td>
<td>[3043 77]</td>
</tr>
<tr>
<td></td>
<td>[0 3210]</td>
<td>[13 2627]</td>
<td>[6 3114]</td>
<td>[0 3120]</td>
</tr>
<tr>
<td></td>
<td>[2638 2]</td>
<td>[2640 0]</td>
<td>[2880 0]</td>
<td>[2400 0]</td>
</tr>
<tr>
<td></td>
<td>[0 2640]</td>
<td>[33 2607]</td>
<td>[565 2315]</td>
<td>[84 2316]</td>
</tr>
</tbody>
</table>