Applications of Machine Learning for Defect Metrology

NIST

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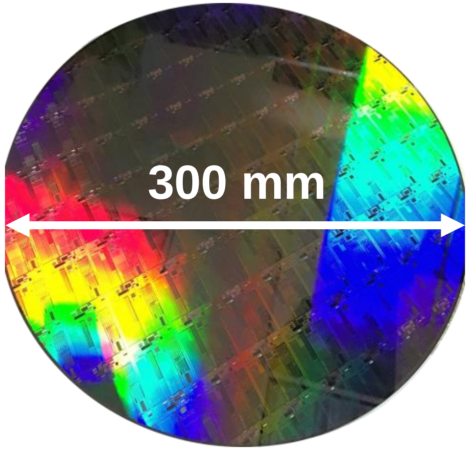
SPS SOCIETY OF PHYSICS STUDENTS
An organization of the American Institute of Physics

Optics-based Patterned Defect Metrology

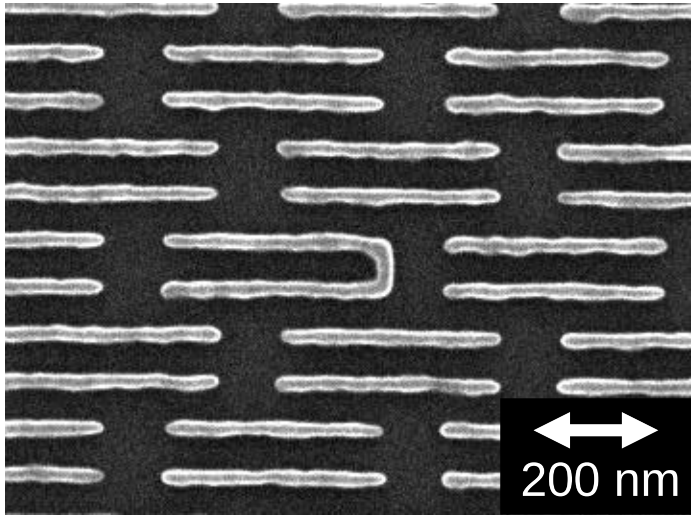
- Metrology: the scientific study of measurement

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

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



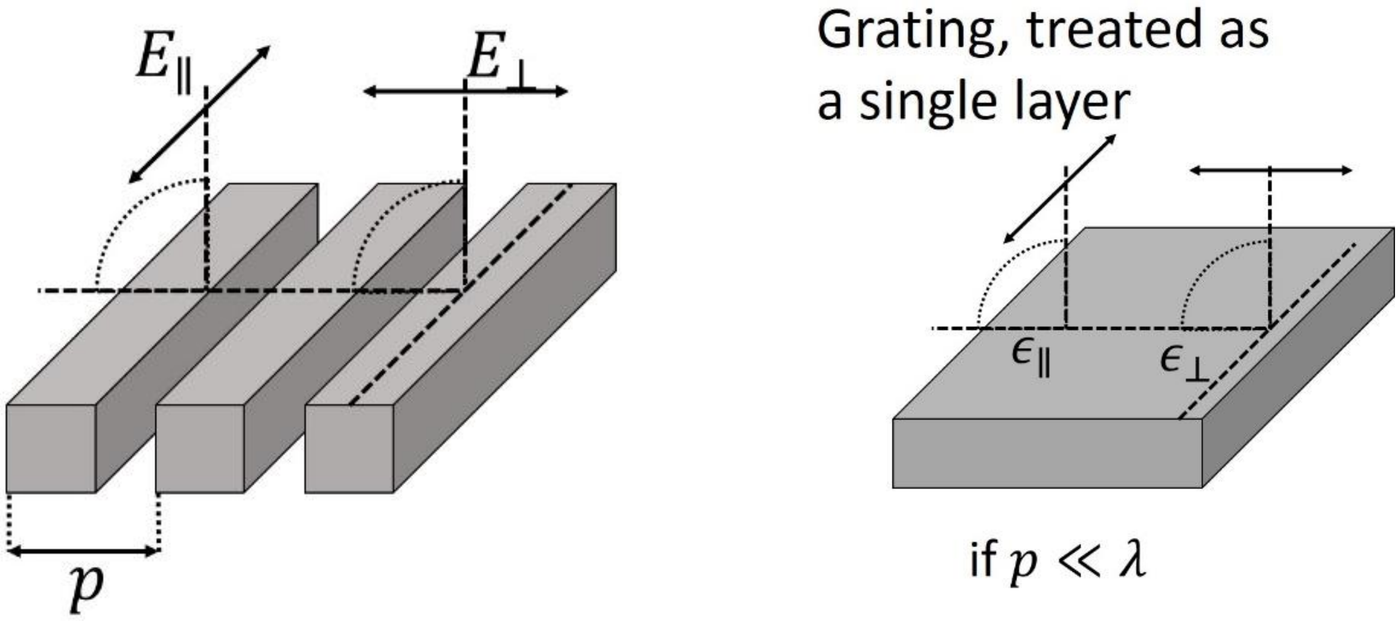
Scanning electron micrograph



TEOS hard mask, polysilicon, TiN, HfO_2 on silicon

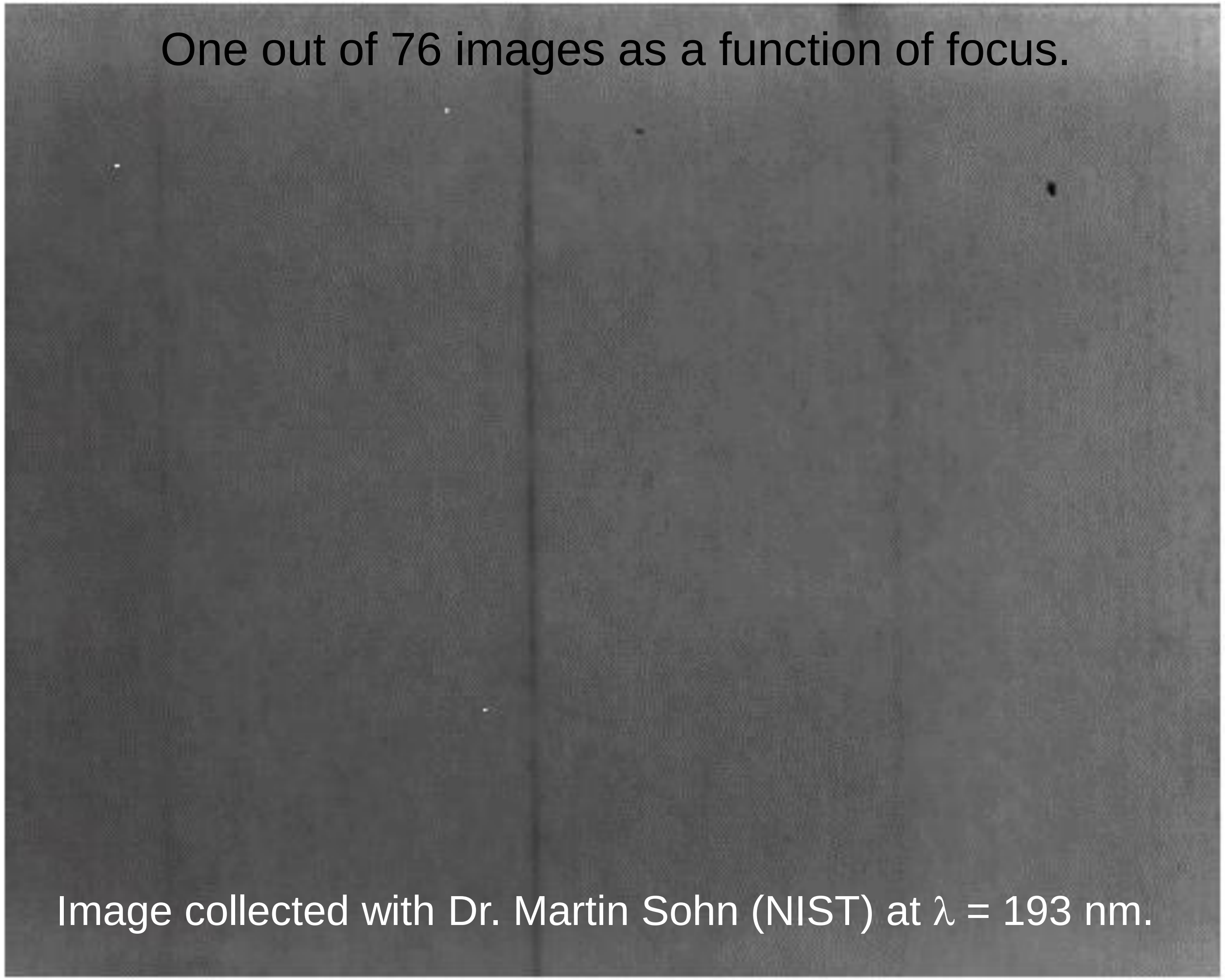
Sub-wavelength Detection of Defects

- **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.



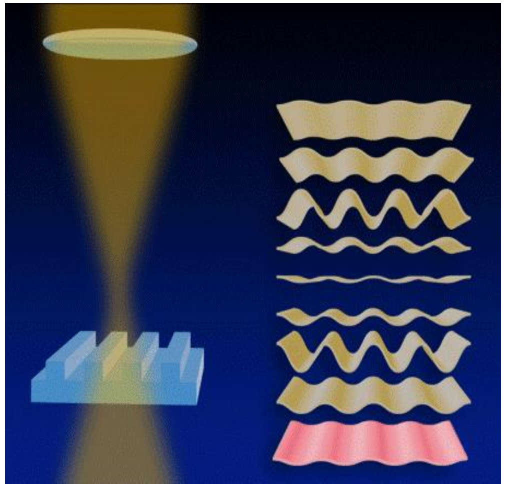
- **Patterned defects perturb this periodicity and are often detectable using optics.**

Raw Images



One out of 76 images as a function of focus.

Image collected with Dr. Martin Sohn (NIST) at λ = 193 nm.

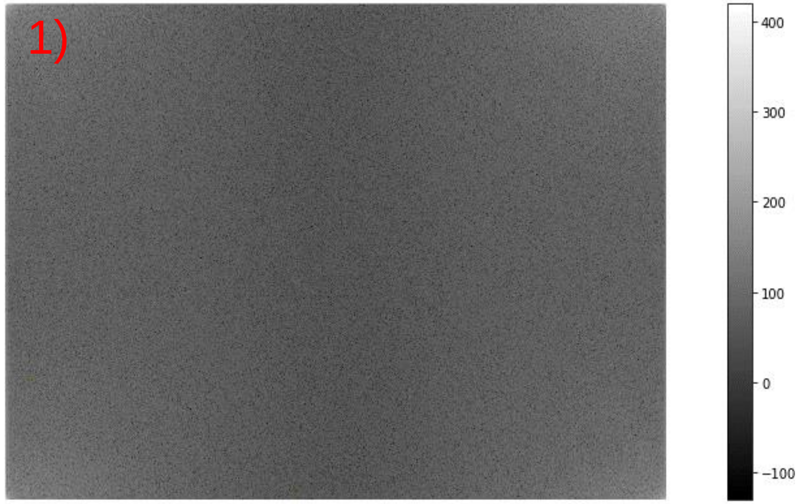


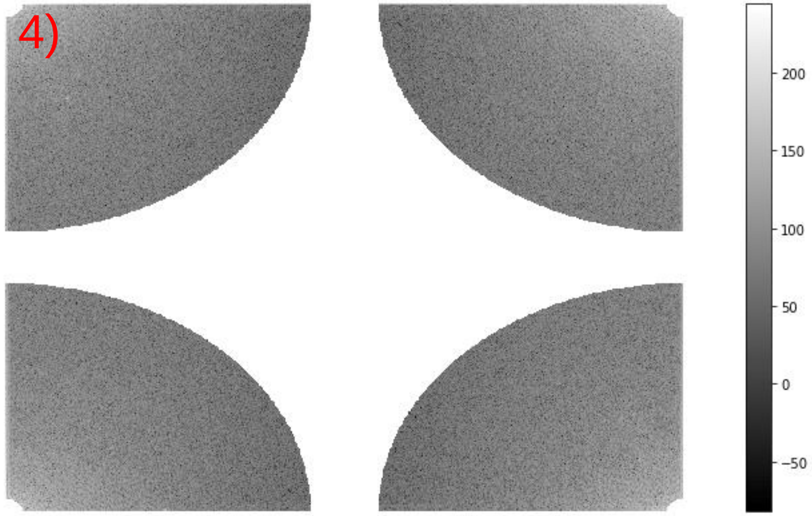
R. M. Silver et al., "High-resolution optical metrology," Proc. SPIE **5752**, 67-79 (2005).

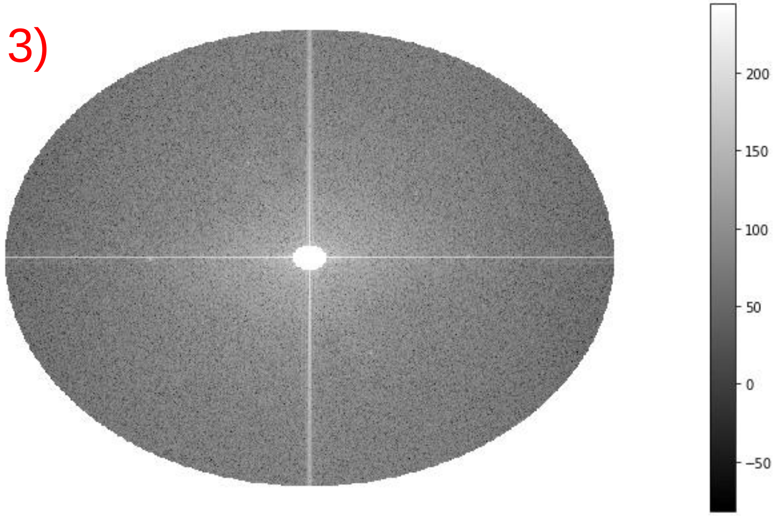
Images coll croscopy (SEM).

Image Processing

1. Fourier Transform
2. Fourier Shift
3. Highpass Filter + Lowpass Filter
4. Fourier Shift


1)


4)


3)

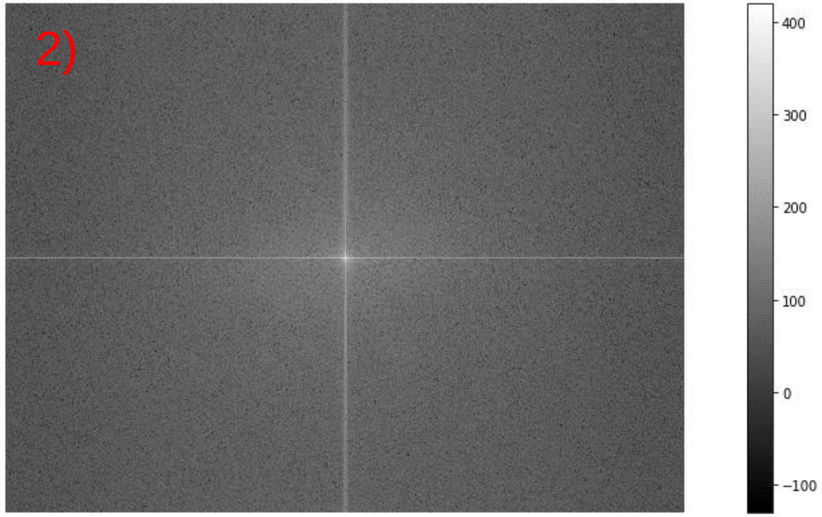
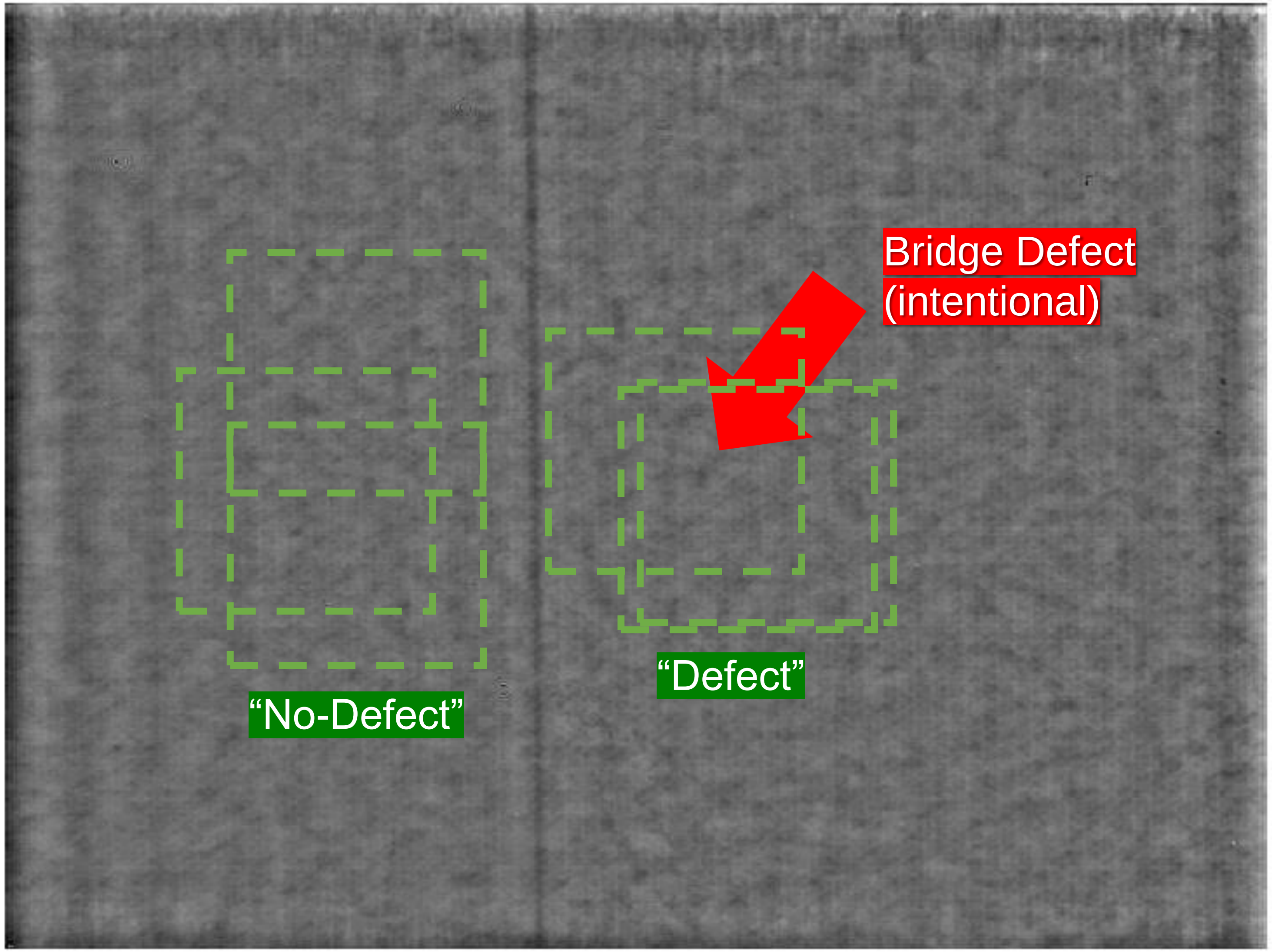
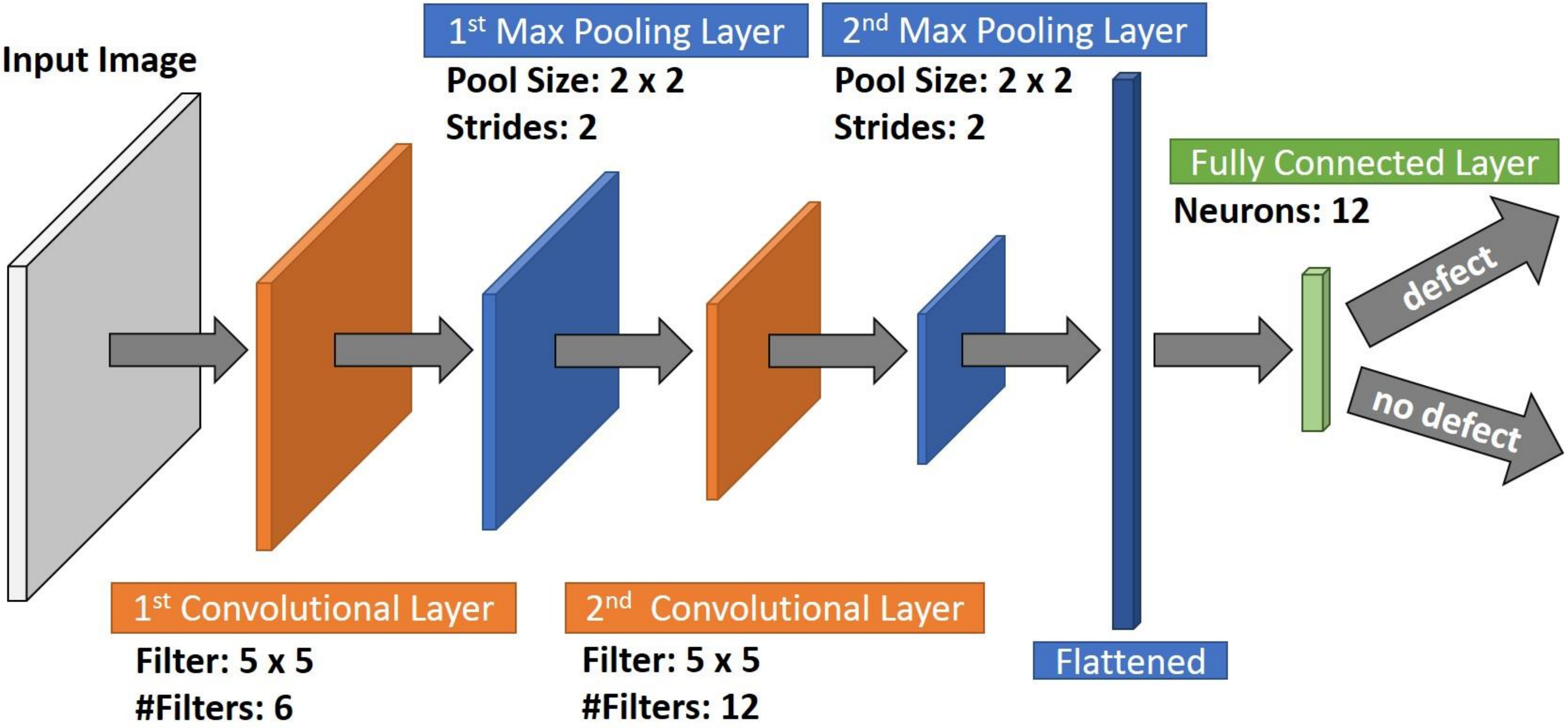

2)

Image Processing – Inverse Fourier Transform



Inverse Fourier Transform performed after reversing the coordinate shift within `python` *(not shown).*

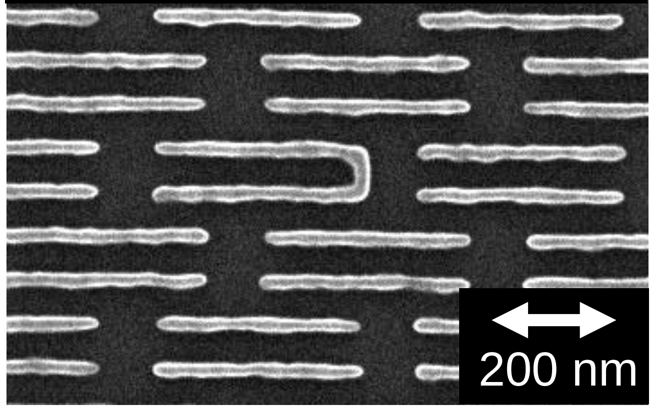
Machine Learning



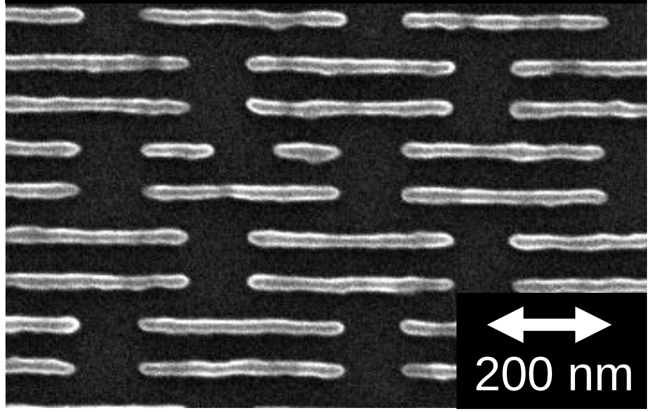
M.-A. Henn, H. Zhou, R. M. Silver, and B. M. Barnes, "Applications of machine learning at the limits of form-dependent scattering for defect metrology," Proc. SPIE **10959**, 109590Z, (2019)

Machine Learning - Results

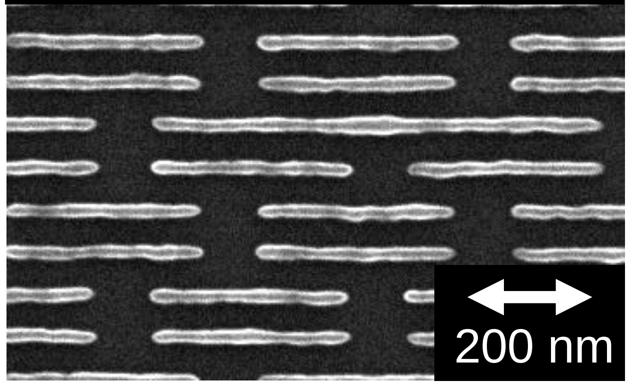
“By” Bridge Y direction



“J” Missing line segment

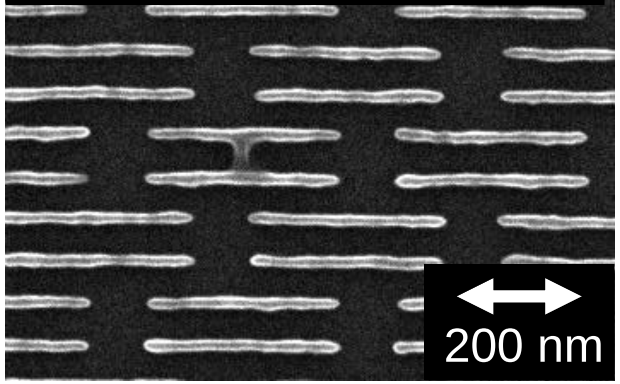


“Bx” Bridge X direction



4 Defect types
2 Dies
3 Experimental repeats
2 linear light polarizations

“A” Island between lines

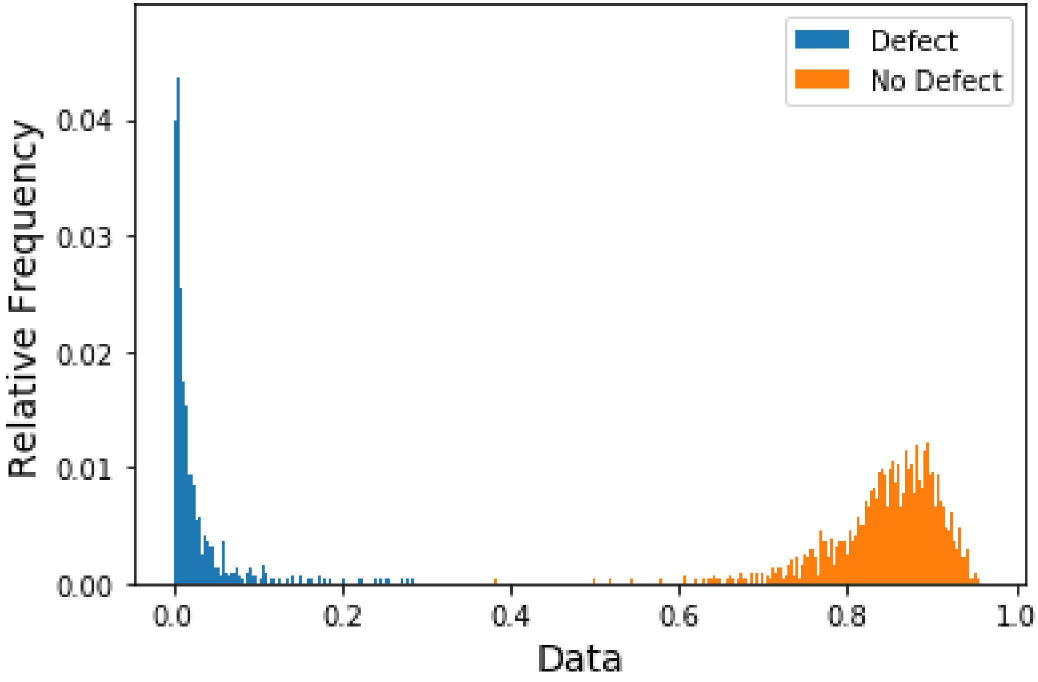


Machine Learning - Results

- ✓ 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.

$$\begin{bmatrix} Defect & No\ Defect \\ 720 & 0 \\ 1 & 719 \end{bmatrix}$$

Confusion matrix for A Defect



Defect	Test within repeat	Test across repeat
By	1.0	0.995
Bx	1.0	0.993
A	1.0	0.999
J	1.0	1.0

Bibliography

- Mark-Alexander Henn, Hui Zhou, Richard M. Silver, Bryan M. Barnes, "Applications of machine learning at the limits of form-dependent scattering for defect metrology," Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII, 109590Z (26 March 2019); doi: 10.1117/12.2517285

- Bryan M. Barnes, Mark-Alexander Henn, Martin Y. Sohn, Hui Zhou, and Richard M. Silver “Assessing Form-Dependent Optical Scattering at Vacuum- and Extreme-Ultraviolet Wavelengths of Nanostructures with Two-Dimensional Periodicity” Phys. Rev. Applied **11**, 064056 –(24 June 2019)

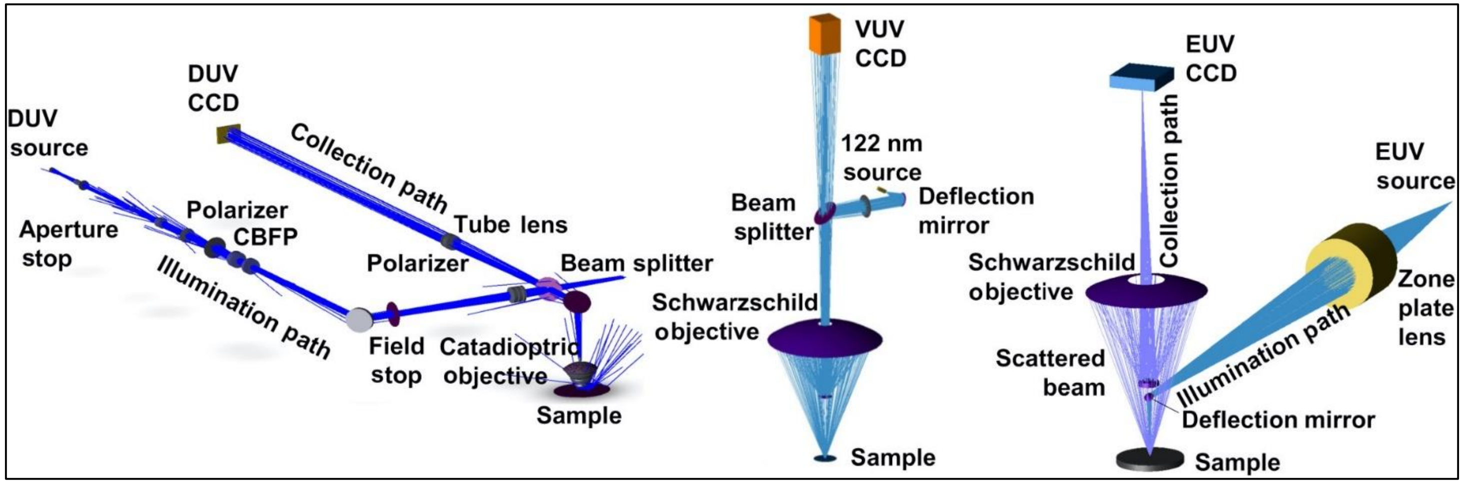
- Ananthan Raghunathan, Steve Bennett, Harlem O. Stamper, John G. Hartley, Abraham Arceo, Mark Johnson, Chris Deeb, Dilip Patel, Jim Nadeau. “13nm gate Intentional Defect Array (IDA) wafer patterning by e-beam lithography for defect metrology evaluation ” (10 March 2011)

- SuperDataScience Team. “Convolutional Neural Networks (CNN),” August 17, 2108. https://www.superdatascience.com/blogs/the-ultimate-guide-to-convolutional-neural-networks-cnn.

Questions?

Previous Work

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



- Detectability varied with wavelength

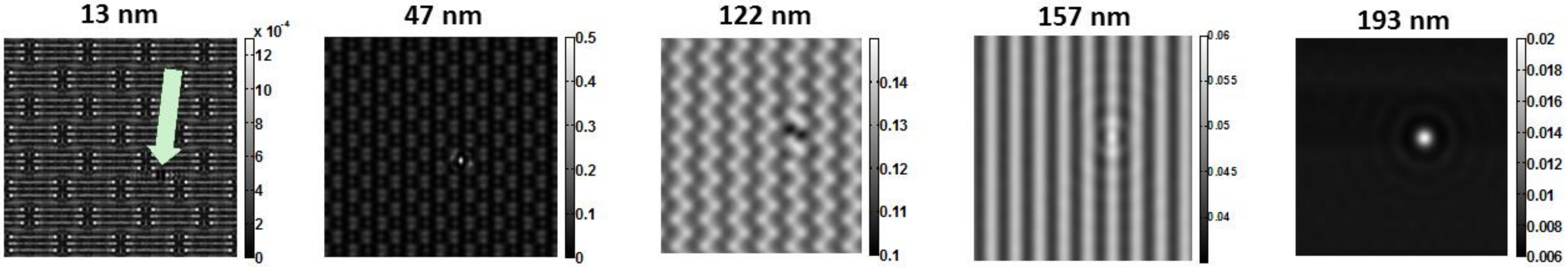
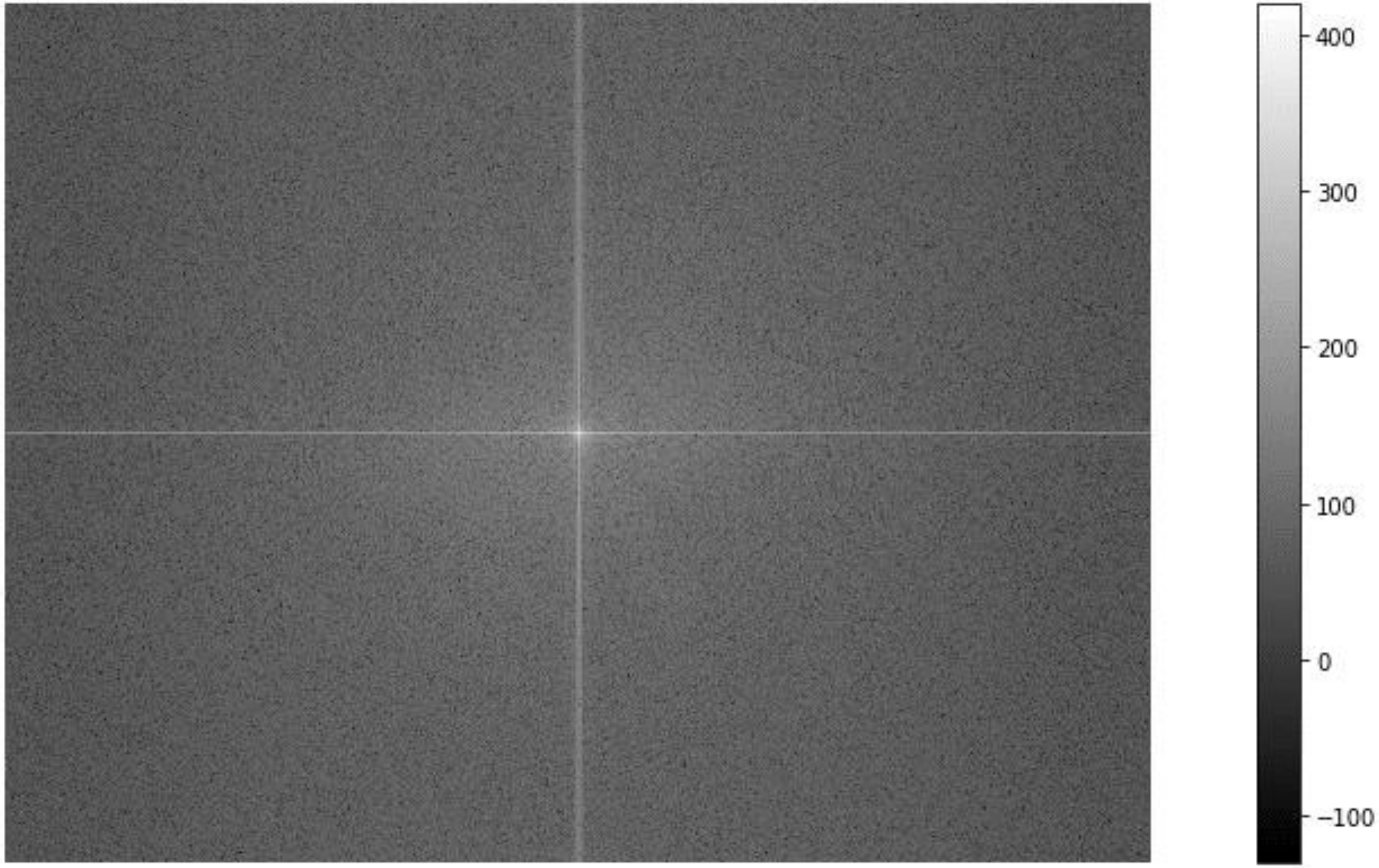
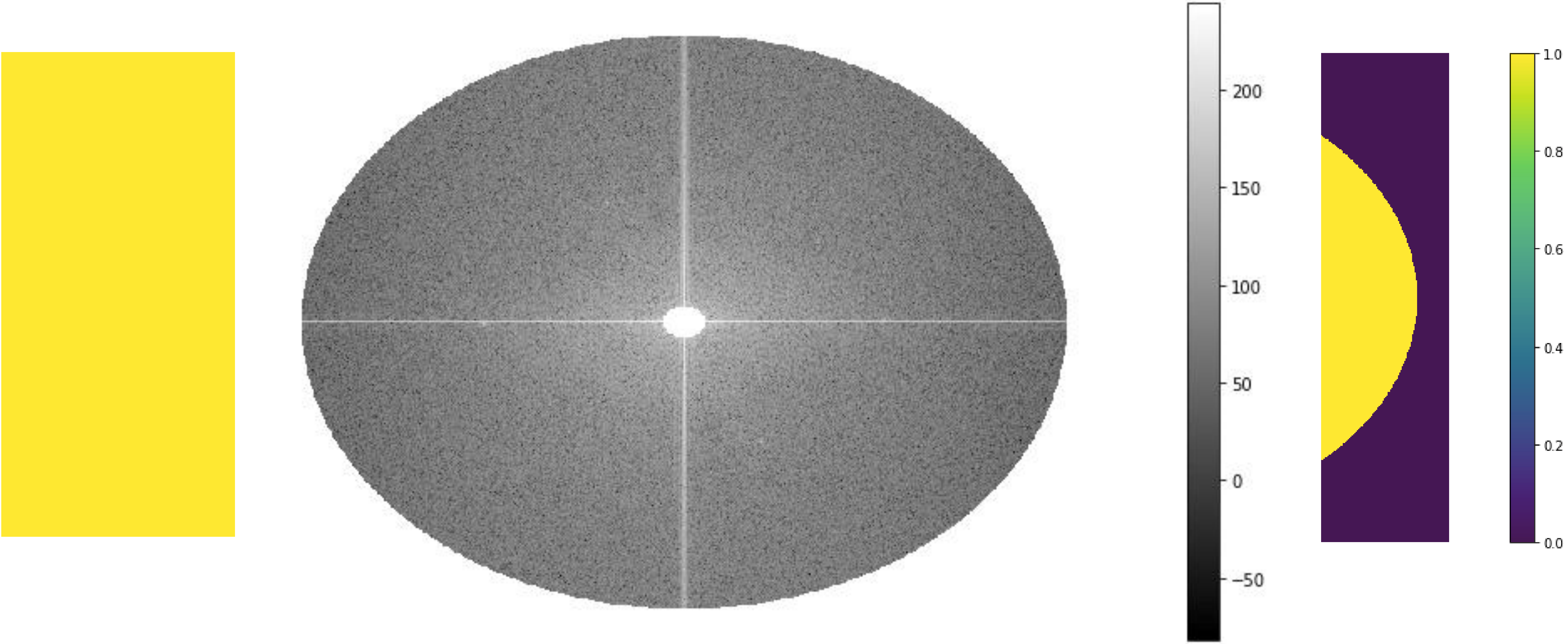


Image Processing – Fourier Transform

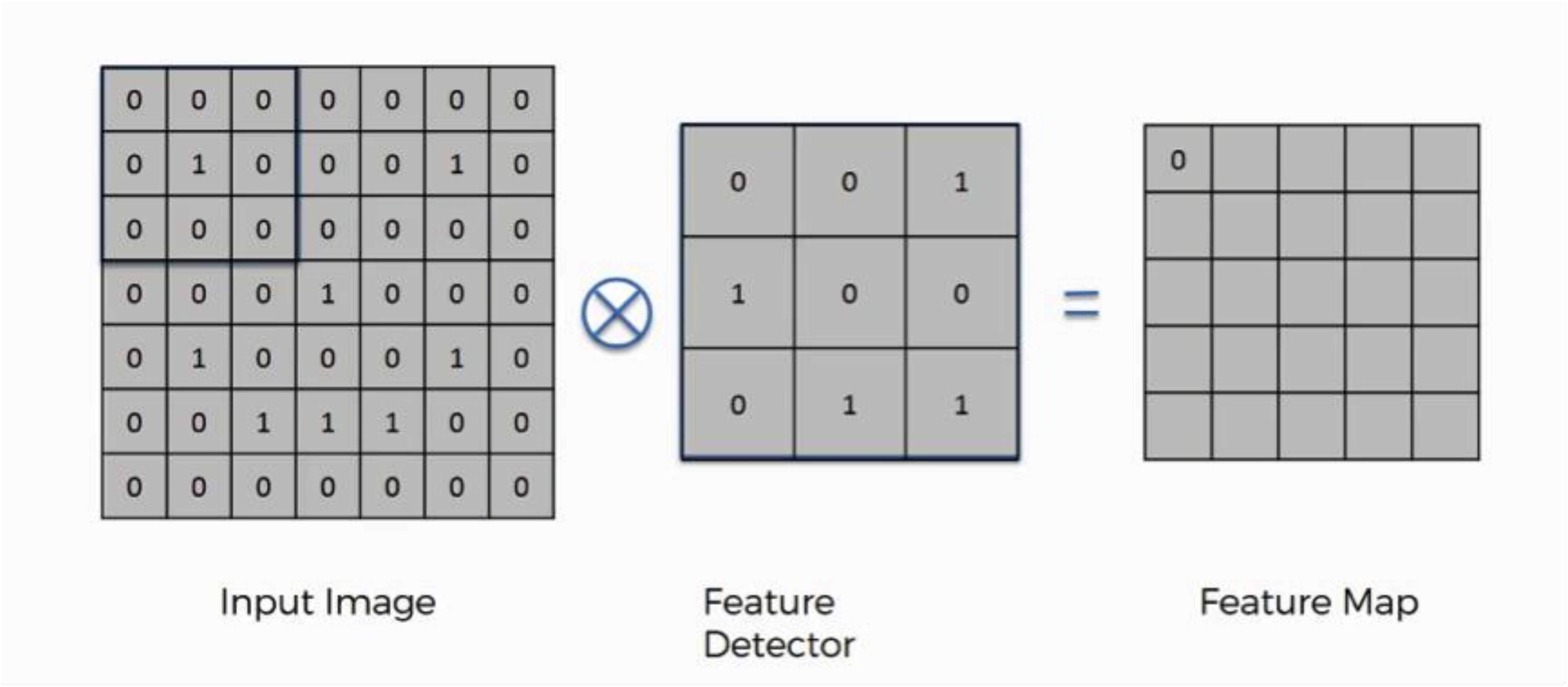


After a coordinate shift within `python` *(not shown)*.

Image Processing – High / Low Pass Filters



Machine Learning – Convolutional Layer

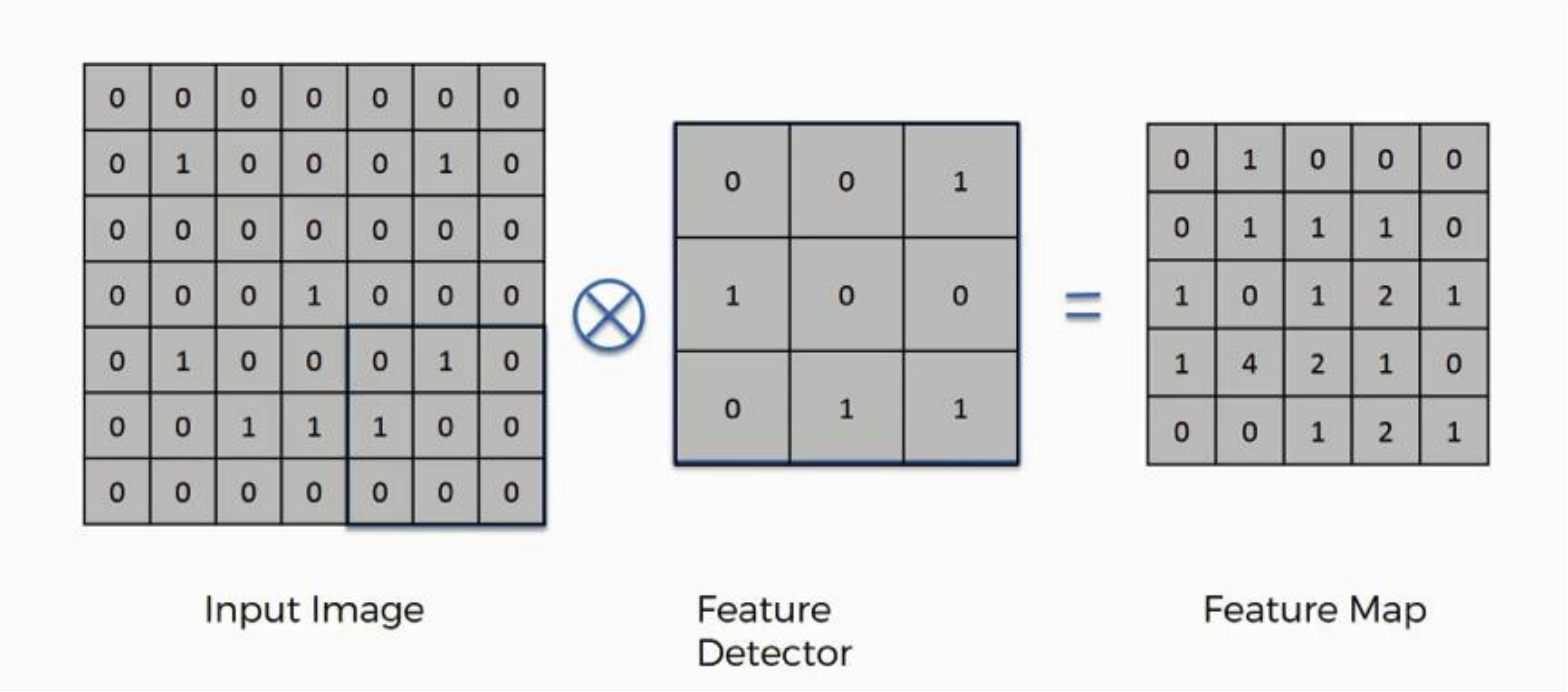


0	0	0	0	0	0	0
0	1	0	0	0	1	0
0	0	0	0	0	0	0
0	0	0	1	0	0	0
0	1	0	0	0	1	0
0	0	1	1	1	0	0
0	0	0	0	0	0	0

0	0	1
1	0	0
0	1	1

0				

Machine Learning – Convolutional Layer



0	0	0	0	0	0	0
0	1	0	0	0	1	0
0	0	0	0	0	0	0
0	0	0	1	0	0	0
0	1	0	0	0	1	0
0	0	1	1	1	0	0
0	0	0	0	0	0	0

Input Image

$\otimes$

0	0	1
1	0	0
0	1	1

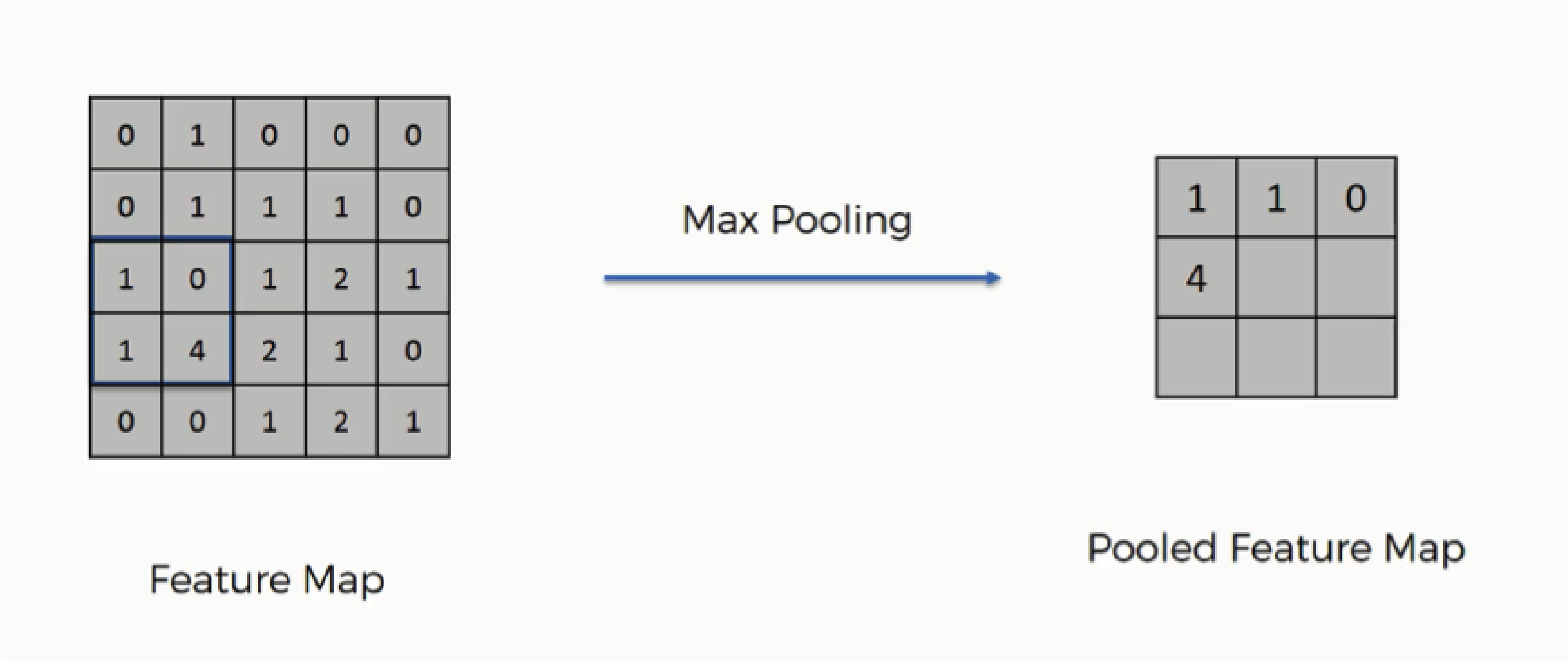
Feature Detector

=

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

Feature Map

Machine Learning – Max Pooling



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

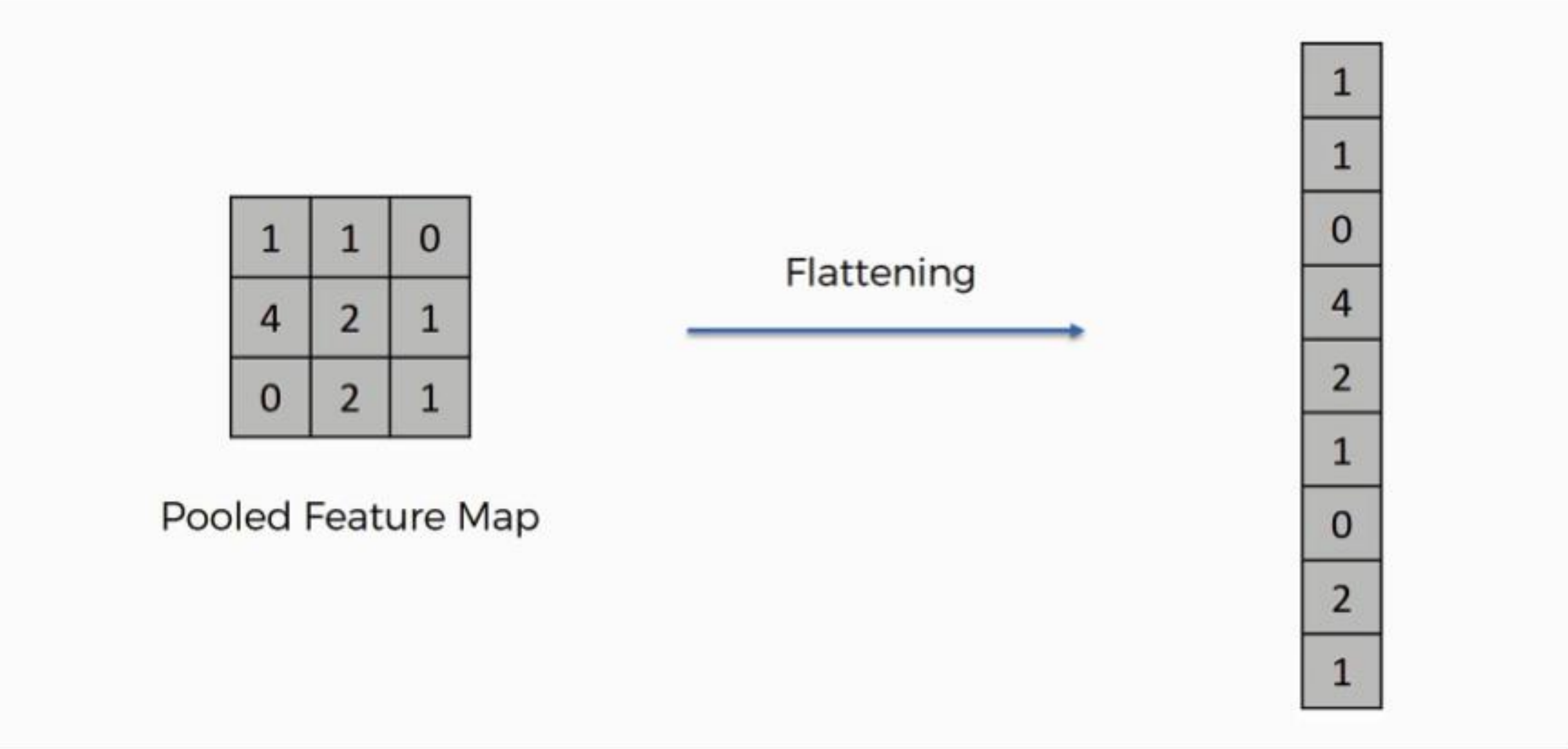
Feature Map

Max Pooling

1	1	0
4		

Pooled Feature Map

Machine Learning – Flattening



Machine Learning – Convolutional Layer

Sharpen:

0	0	0	0	0
0	0	-1	0	0
0	-1	5	-1	0
0	0	-1	0	0
0	0	0	0	0

Blur:

0	0	0	0	0
0	1	1	1	0
0	1	1	1	0
0	1	1	1	0
0	0	0	0	0

Emboss:

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

Edge Detect:

	0	1	0	
	1	-4	1	
	0	1	0	

Image Processing – Fourier Transform

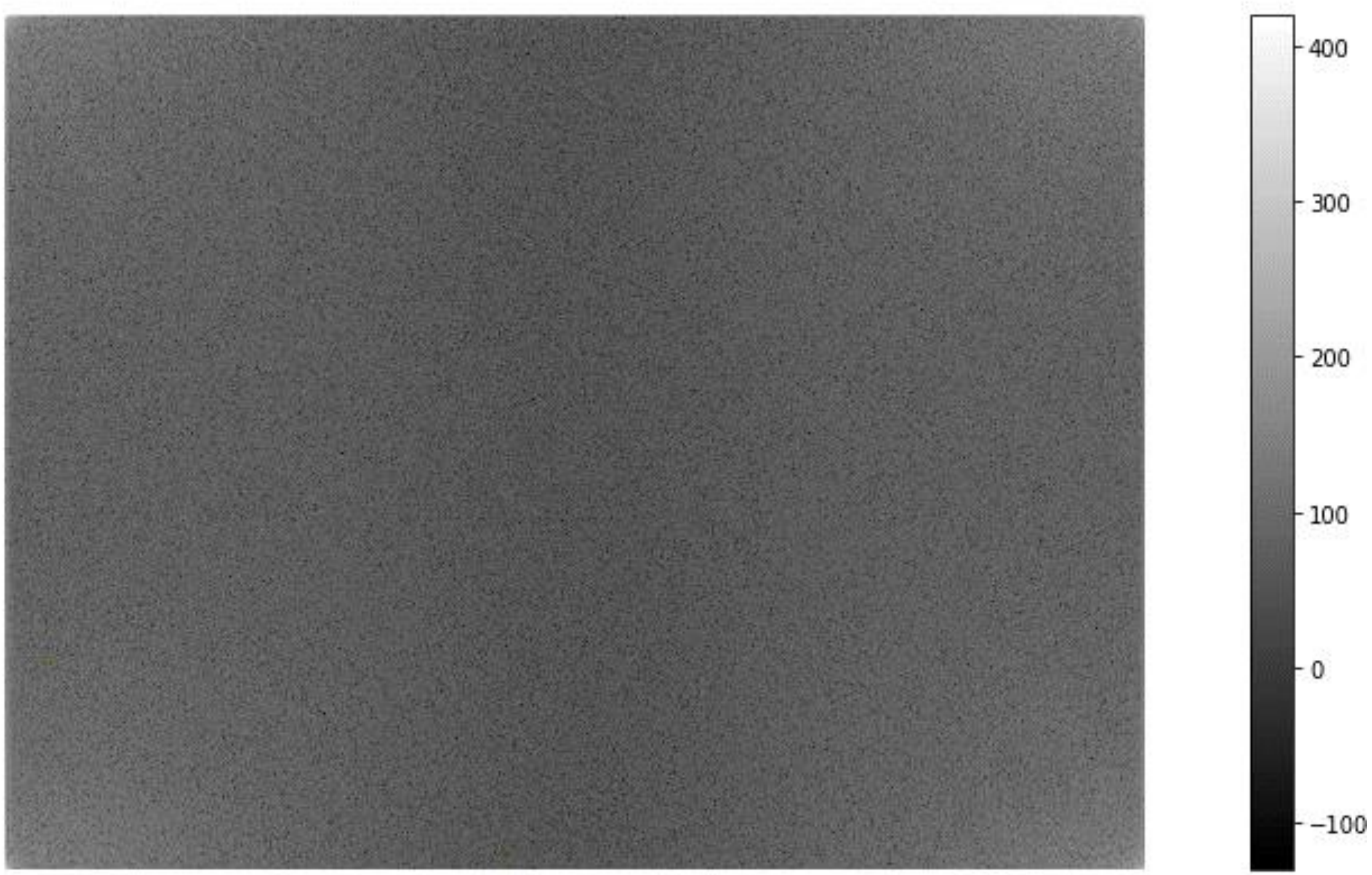
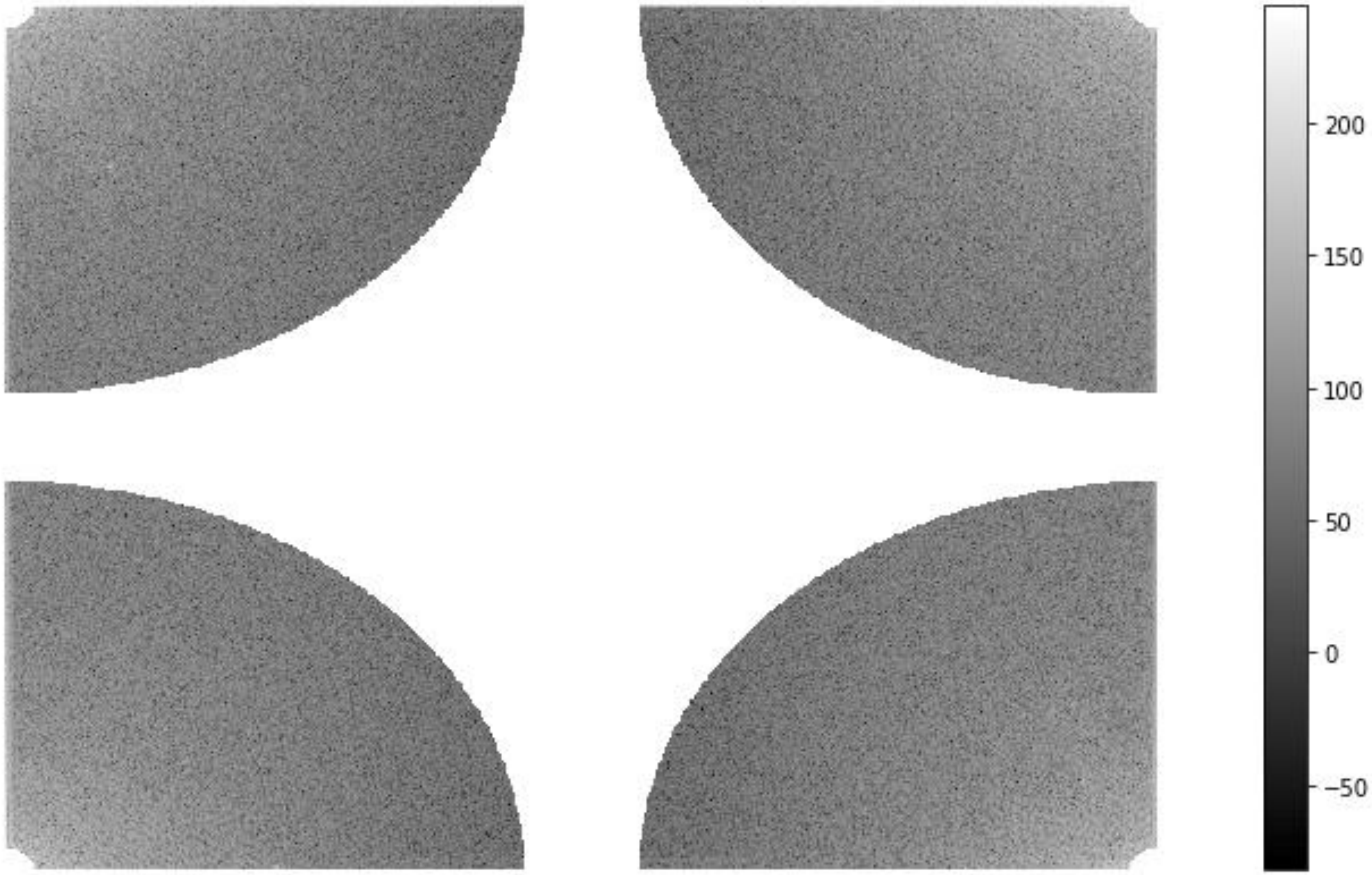
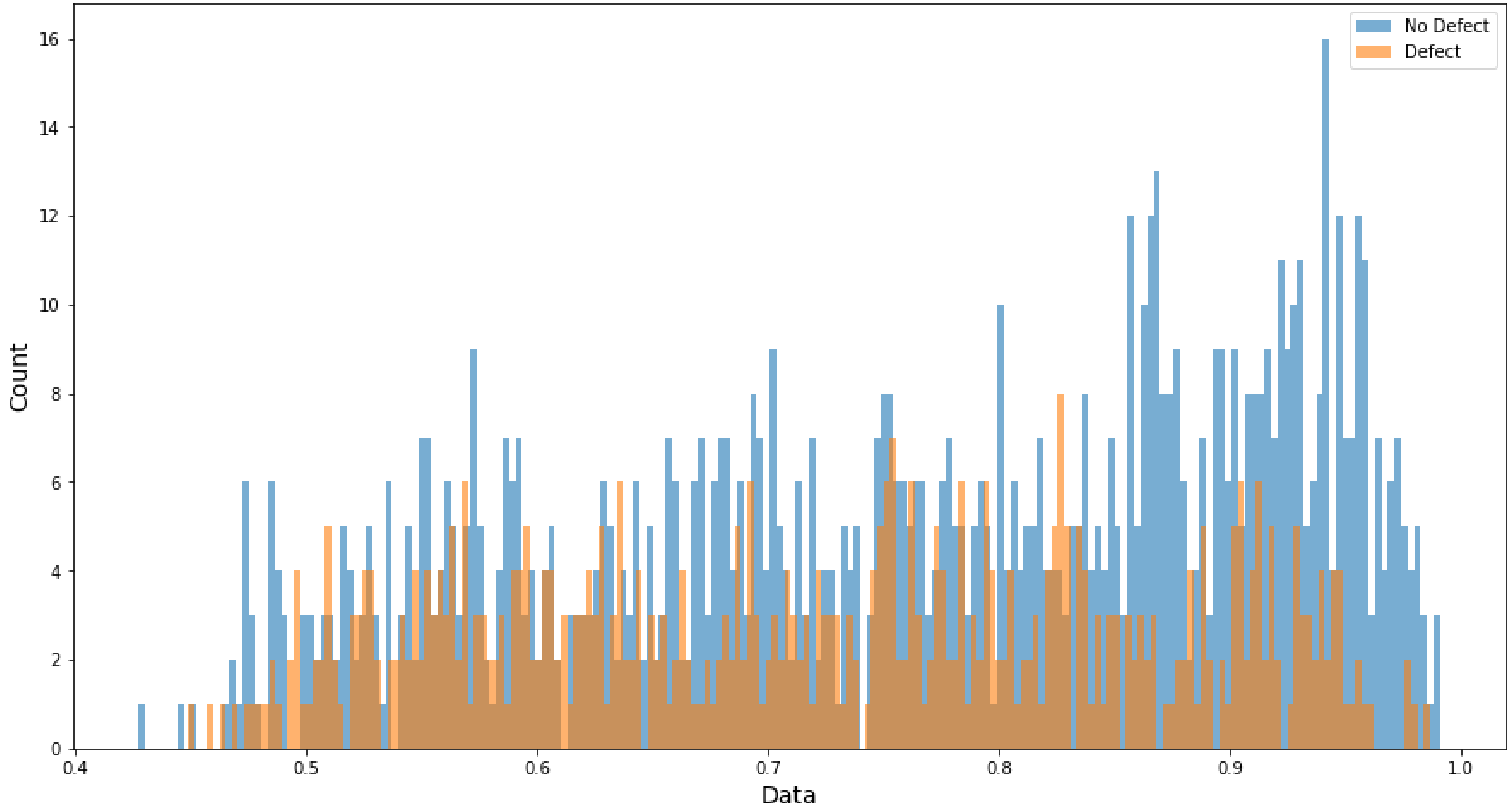


Image Processing – Fourier Shift

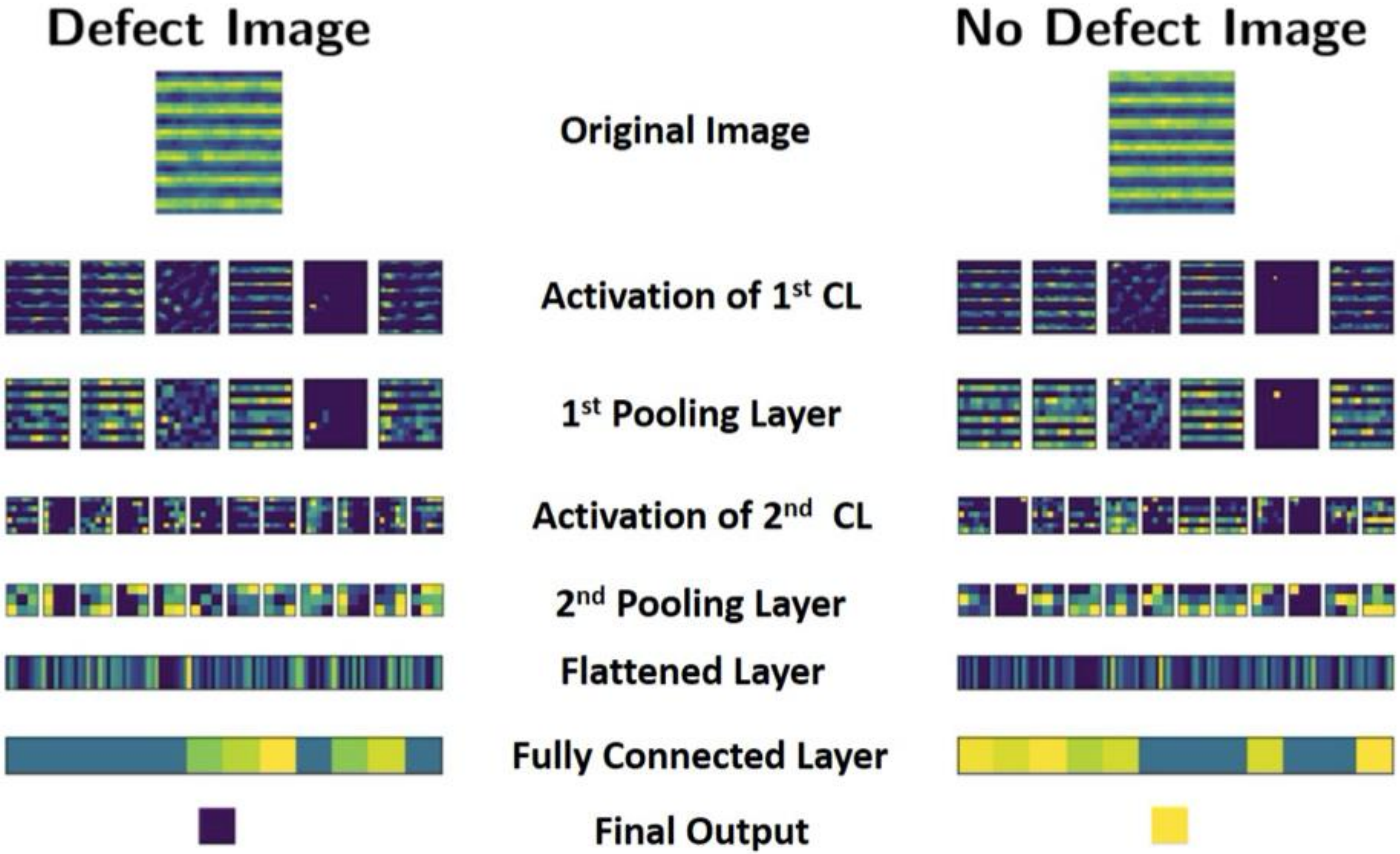


Machine Learning - Results

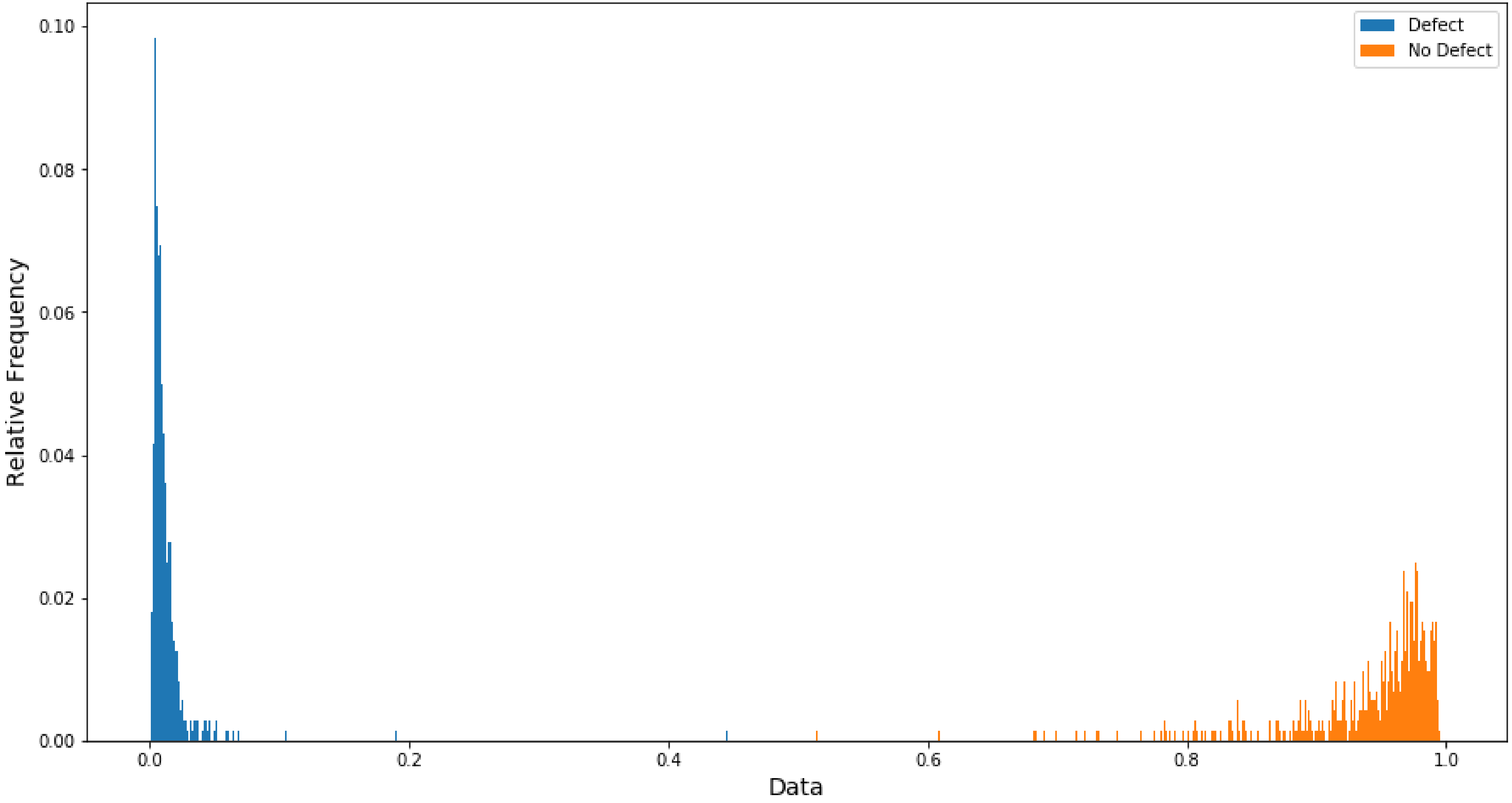


Cross defect classification for Defect A

Machine Learning



Machine Learning - Results



Trained: Defect A Repeat 1, Tested: Defect A Repeat 2

Confusion Matrices

By	Bx	A	J
$\begin{bmatrix}3294 & 66 \\ 0 & 3360\end{bmatrix}$	$\begin{bmatrix}2149 & 11 \\ 0 & 2160\end{bmatrix}$	$\begin{bmatrix}720 & 0 \\ 1 & 719\end{bmatrix}$	$\begin{bmatrix}2396 & 4 \\ 25 & 2375\end{bmatrix}$
$\begin{bmatrix}3210 & 0 \\ 0 & 3210\end{bmatrix}$	$\begin{bmatrix}2595 & 45 \\ 13 & 2627\end{bmatrix}$	$\begin{bmatrix}3120 & 0 \\ 6 & 3114\end{bmatrix}$	$\begin{bmatrix}3043 & 77 \\ 0 & 3120\end{bmatrix}$
$\begin{bmatrix}2638 & 2 \\ 0 & 2640\end{bmatrix}$	$\begin{bmatrix}2640 & 0 \\ 33 & 2607\end{bmatrix}$	$\begin{bmatrix}2880 & 0 \\ 565 & 2315\end{bmatrix}$	$\begin{bmatrix}2400 & 0 \\ 84 & 2316\end{bmatrix}$