Contact Pitch and Location Prediction for Directed Self-Assembly Template Verification

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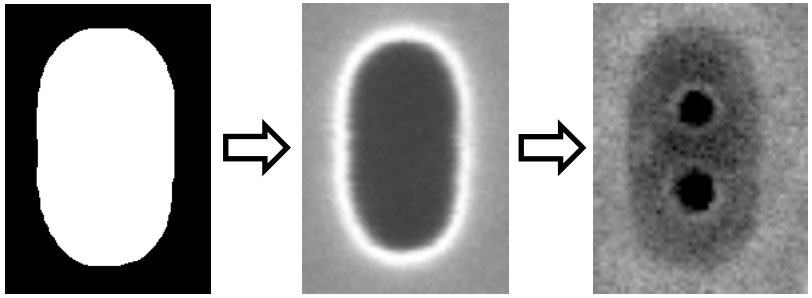
Background

- Directed Self-Assembly (DSA) is promising for contact holes patterning in 7 nm node



(a) Mask (b) Template (c) Contacts

Fig. 1: Contact patterning with DSA

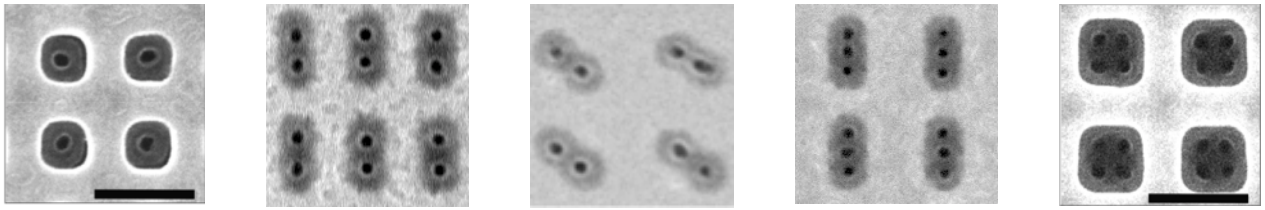
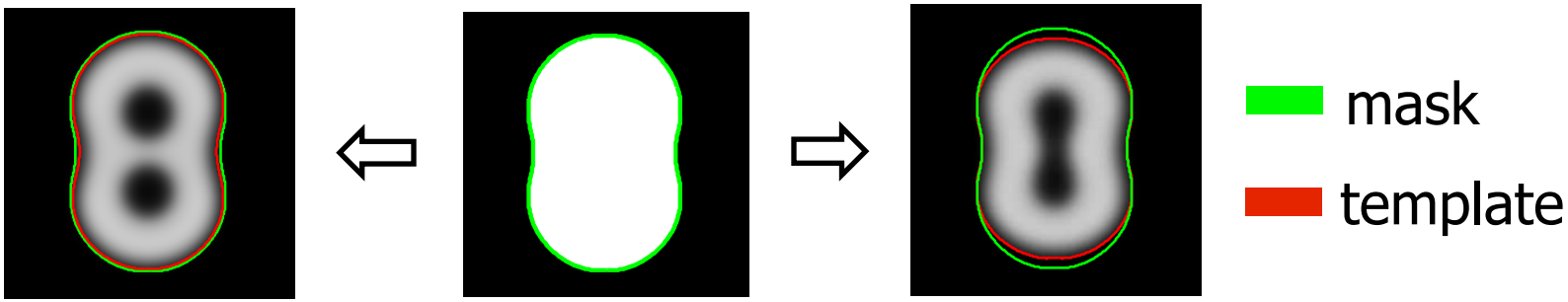


Fig. 2: Contact patterns formed by various DSA templates

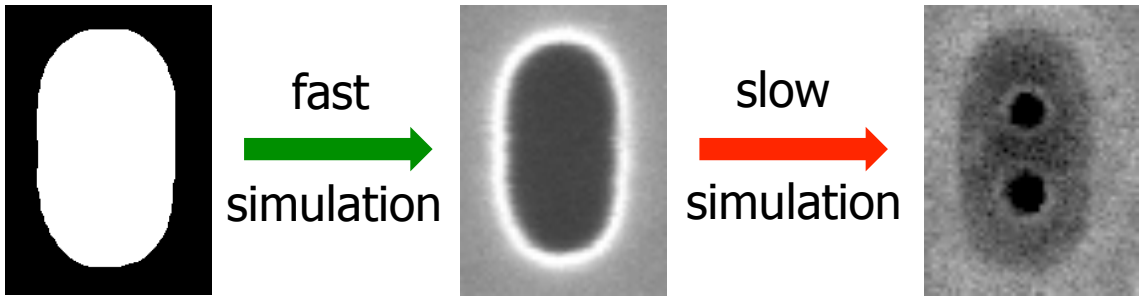
DSA Verification: Motivation

- Variation in template and process can cause serious problem



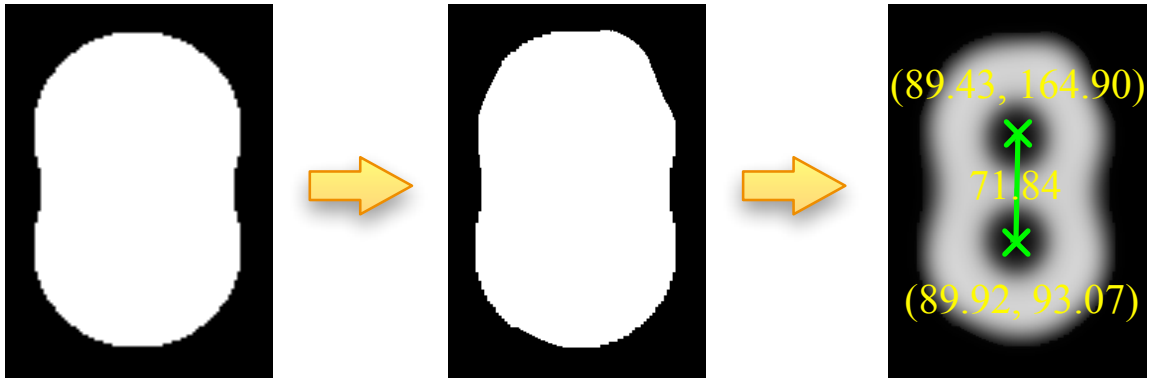
Small variation Intended mask Large variation

- Challenge in DSA verification



(a) Mask (b) Template (c) Contacts

Contact Pitch and Location Prediction



(a) Original mask. (b) DSA template printed. (c) Prediction results.

Fig 1. : problem illustration

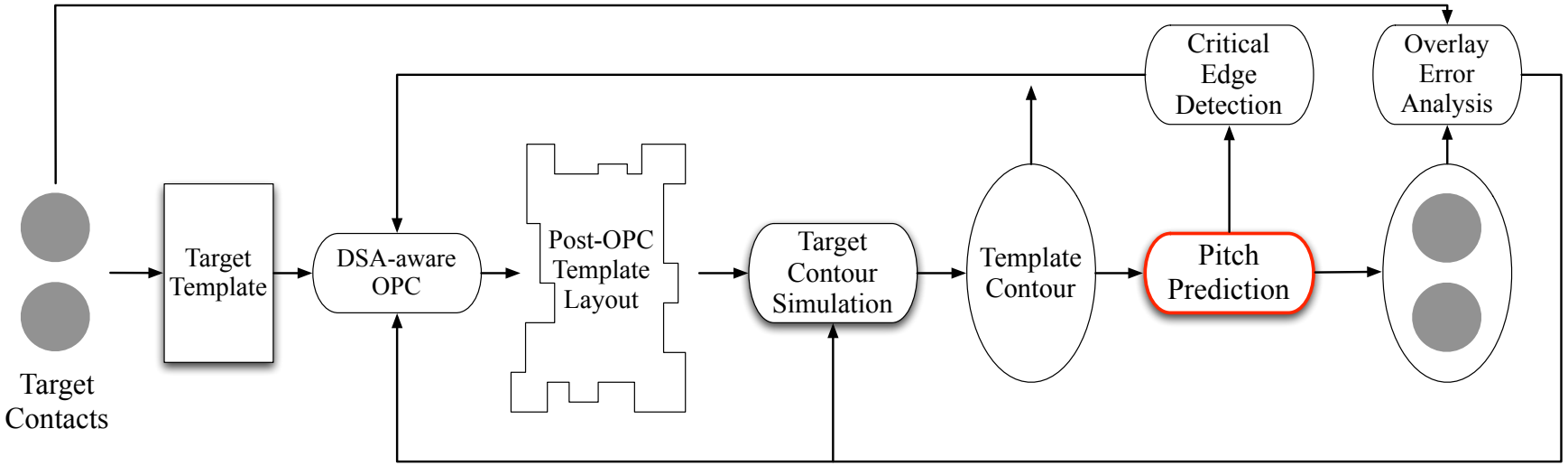
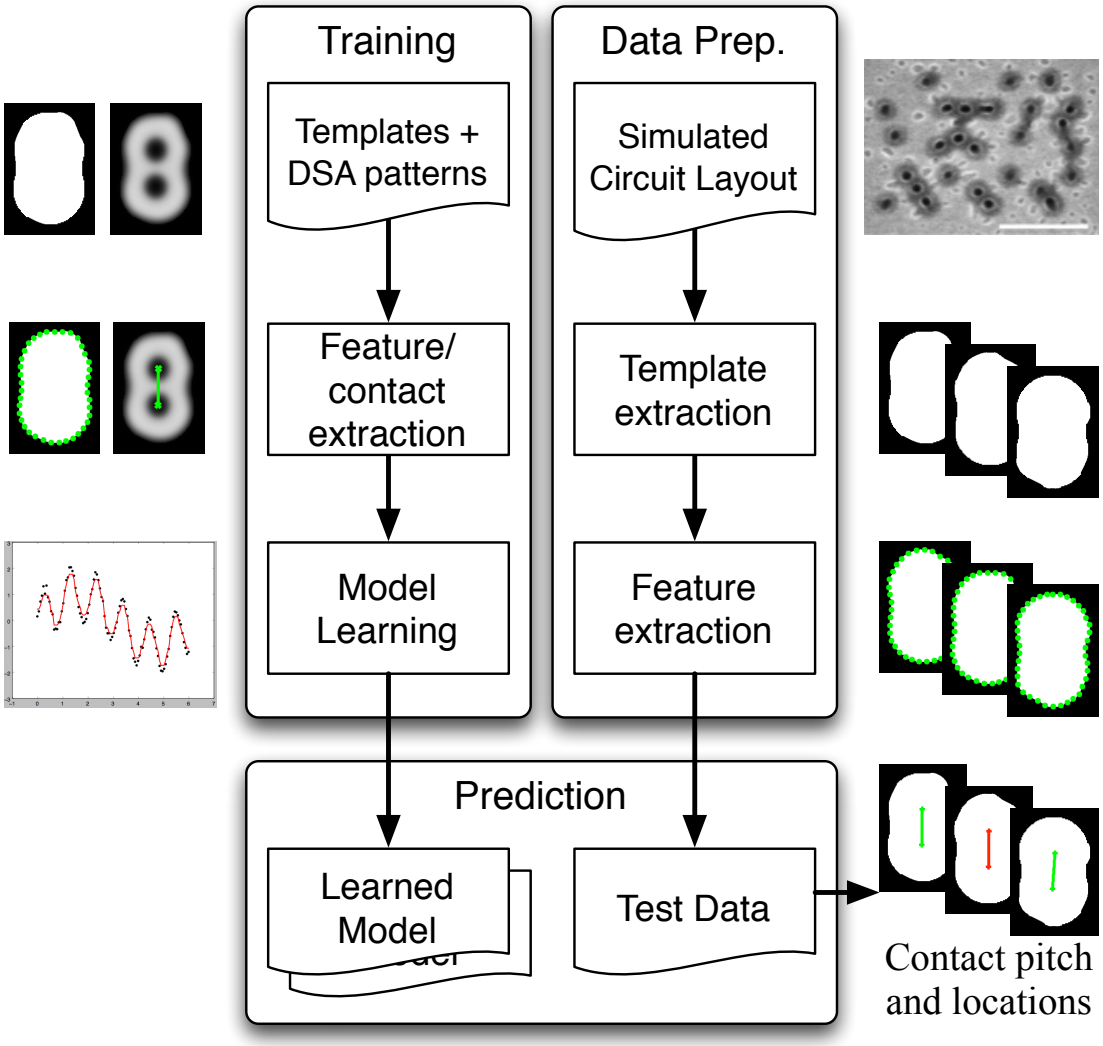
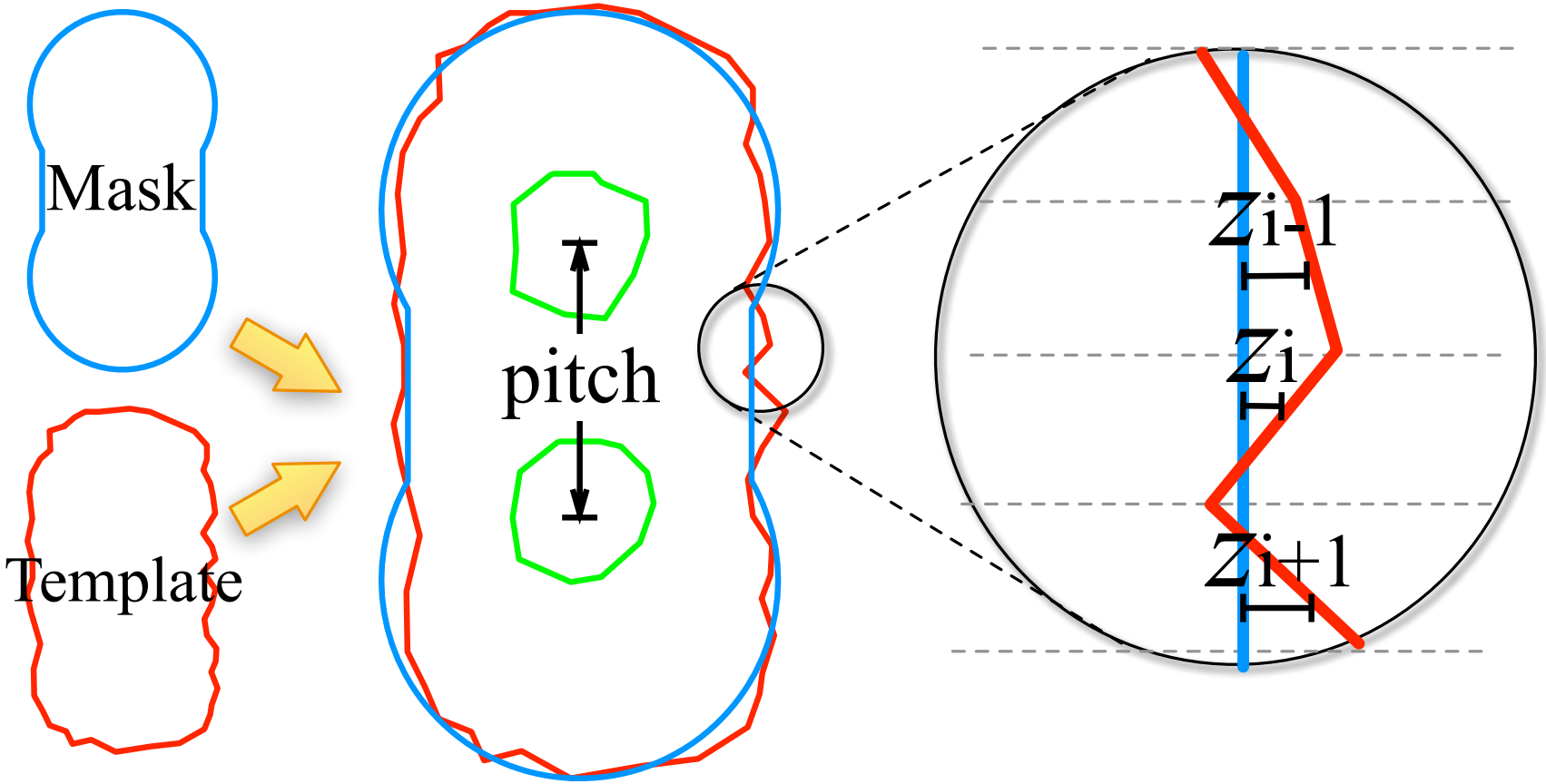


Fig 2. : DSA-aware resolution enhancement flow

Machine Learning based Prediction Flow

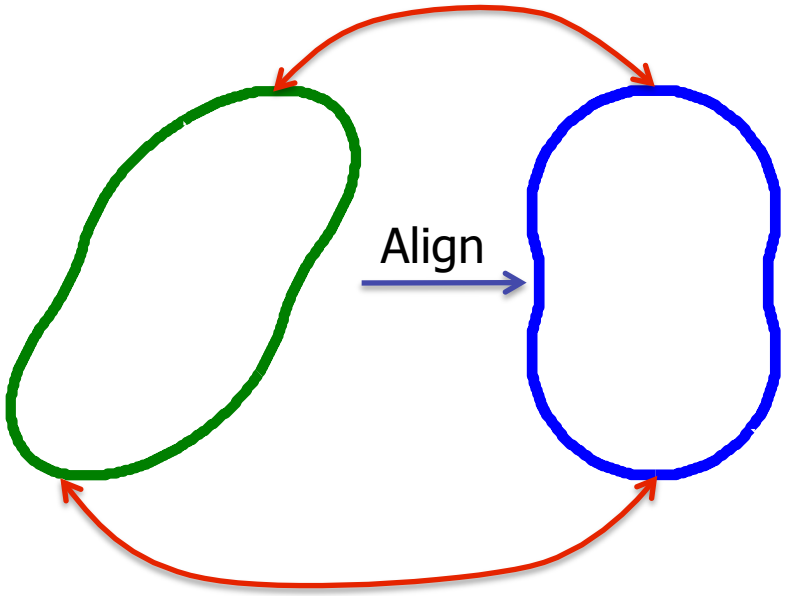


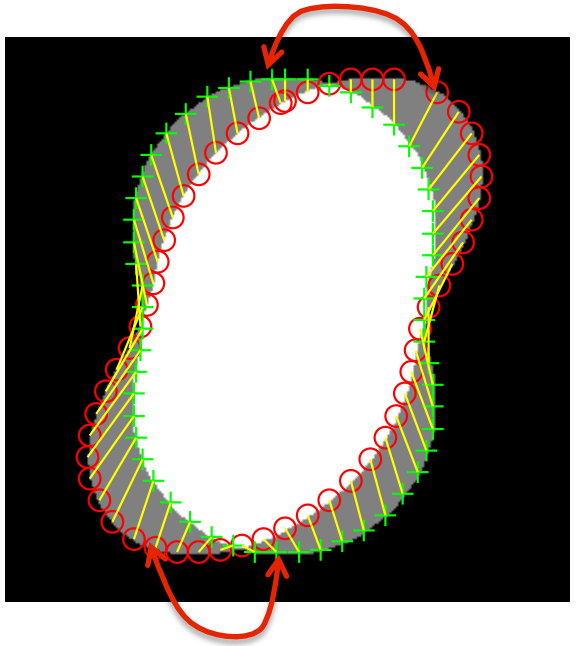
Edge Sensitivity based DSA Model



Aligning Mask and Template

- Aligning two shapes
- Dynamic Time Warping (DTW)
  - Dynamic programming based
- Problem: min dist match ≠ correct match





Adapting DTW to Work

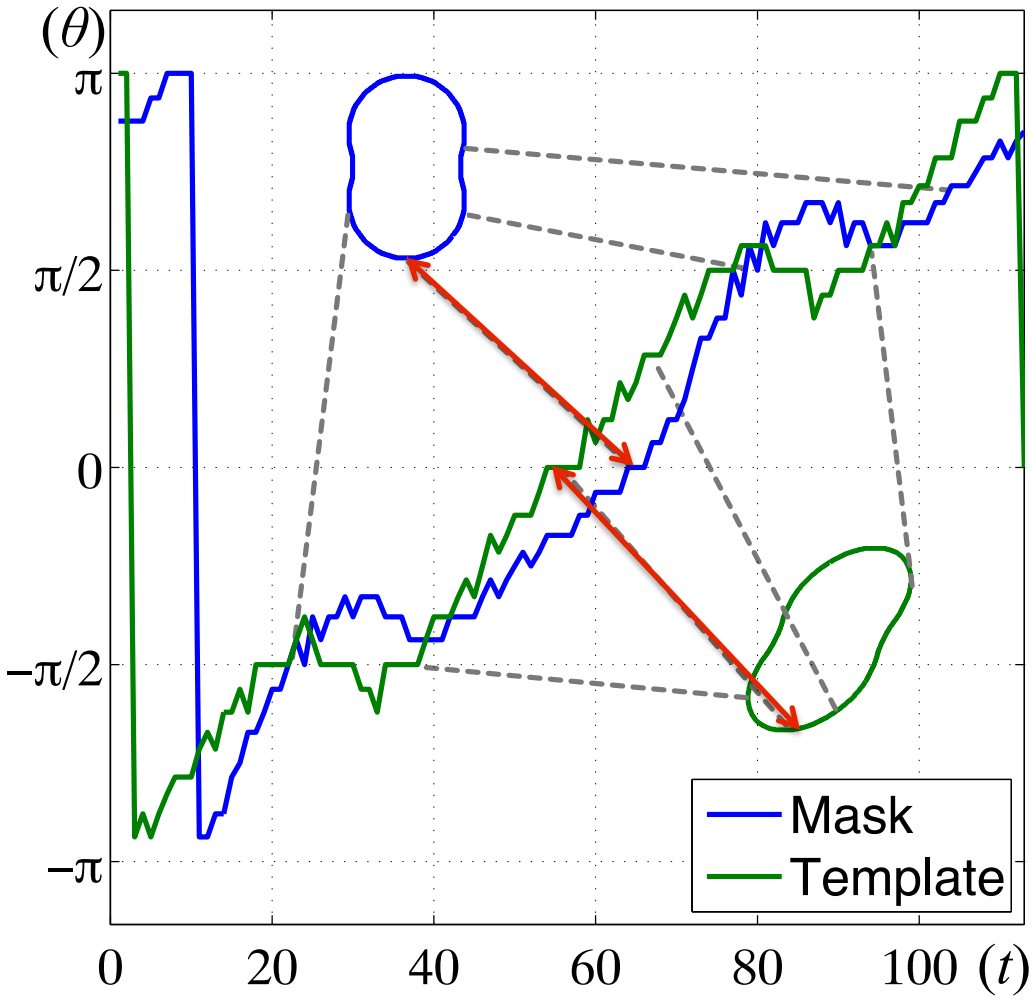
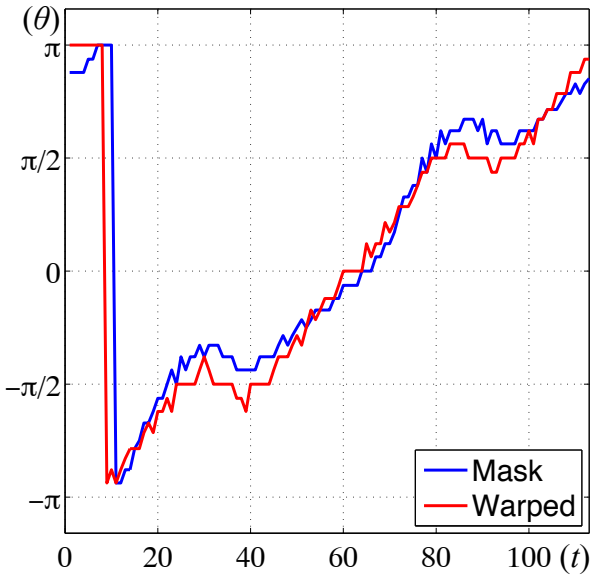
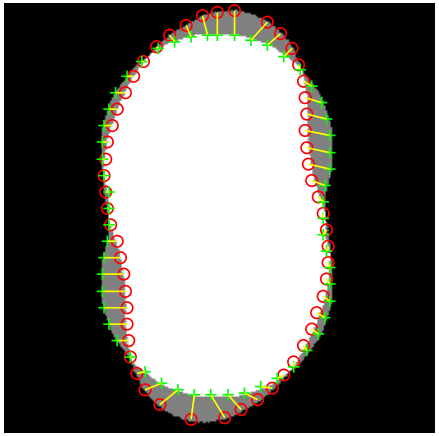
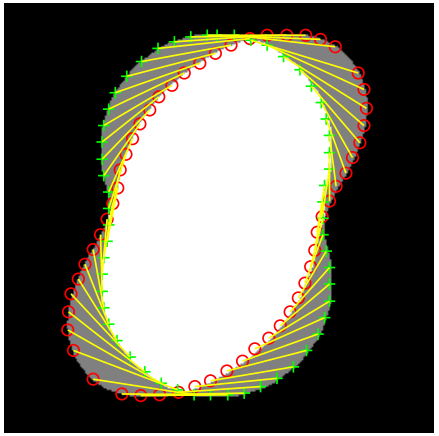


Fig 1: Converting 2D to pseudo time series

Matched Points Features

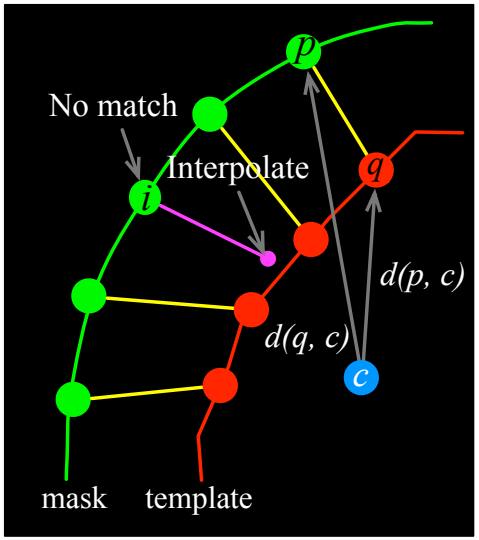


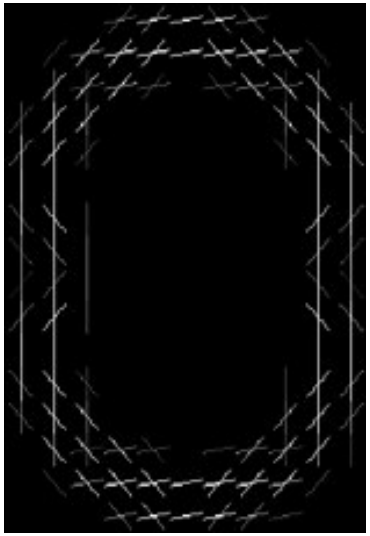




Other Features

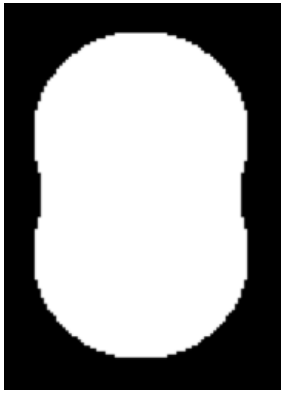
- Point Distance Feature
  - '+' if far away from mask
  - '-' if inside mask
- Filling missing values
- Edge Orientation Feature
  - Histogram of Gradient

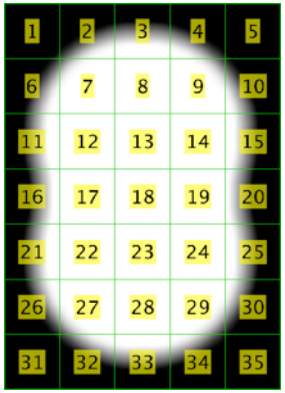


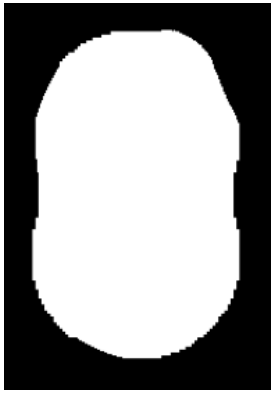


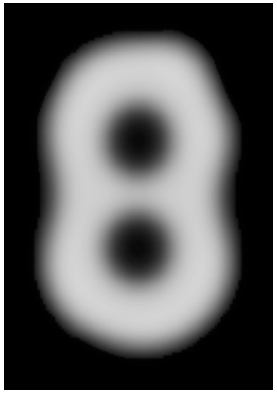
Data Preparation

- Add variation to an ideal mask to generate templates (with variation)
  - Gaussian filter to blur boundary
  - Strategy to random threshold the regions
  - Smooth out the boundary connections
- DSA simulator to generate contact
- Labels (pitch size and hole locations) can be detected using computer vision techniques.



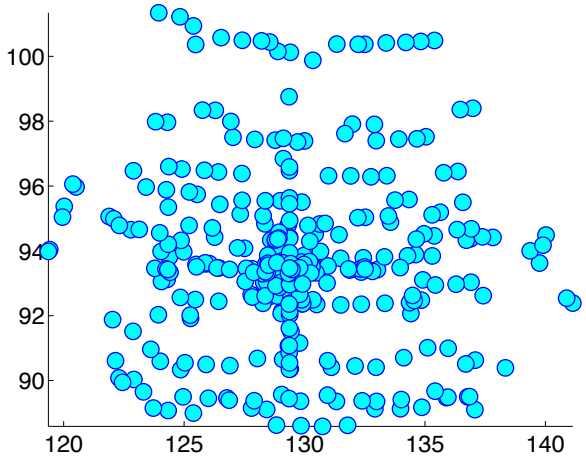






Data Preparation: Quality

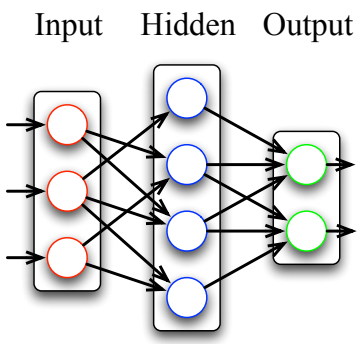
- Data is critical for training a good model
  - Accurate and contain as little noise as possible
  - Enough variance in the feature and output space
  - Size matters for model complexity

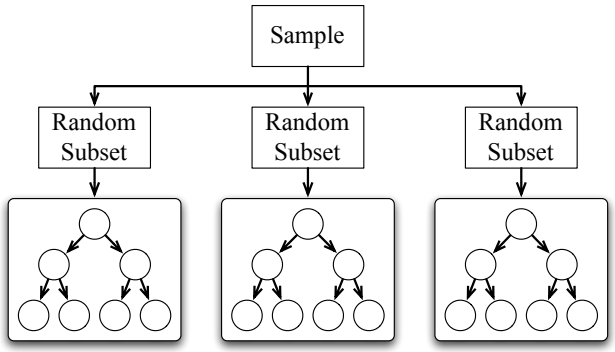


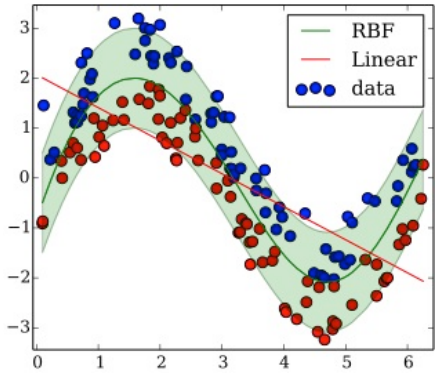
# Samples	u	σ	# MP	# PD	# HOG
1193	71.7485	4.3398	1114	557	428

Machine Learning Algorithms

- Compare with different feature combinations using 10-fold cross-validation
- Artificial Neural Network (ANN)
- Random Forest (RF)
- Support Vector Regression (SVR)







Experimental Results - I

- Performance Metric: Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{z}_i - z_i)^2}$$

- Comparison of algorithms and feature combinations for *Pitch Size* Model
  - Random Forest (RF), Artificial Neural Network (ANN), Support Vector Regression (SVR)
  - Matched Points (MP), Point Distance (PD), Histogram of Gradient (HOG)

Name	MP	Time (s)	PD	Time (s)	HOG	Time (s)	MP+HOG	Time (s)	PD+HOG	Time (s)
RF	0.292	55.037	0.347	28.044	0.367	18.382	0.329	70.982	0.419	43.964
ANN	0.148	388.969	0.312	251.62	0.17	33.766	0.14	713.38	0.125	446.23
SVR	0.285	1.656	0.387	1.178	0.233	1.185	0.148	2.577	0.24	2.256

Experimental Results - II

- *Contact Location* Prediction Results

Name	x_1	y_1	x_2	y_2	Mean†	Pitch‡	Time (s)
ANN	0.132	0.145	0.157	0.201	0.158	0.194	64.596
RF	0.476	0.361	0.398	0.351	0.396	0.376	30.297
SVR	0.117	0.137	0.117	0.135	0.126	0.153	0.846

* (x_1, y_1) and (x_2, y_2) denote the 2D coordinates of the contacts.
† Mean error over all the predicted coordinates.
‡ Computed as the euclidean distance between predicted contact locations.

Feature Selection and Model Tuning

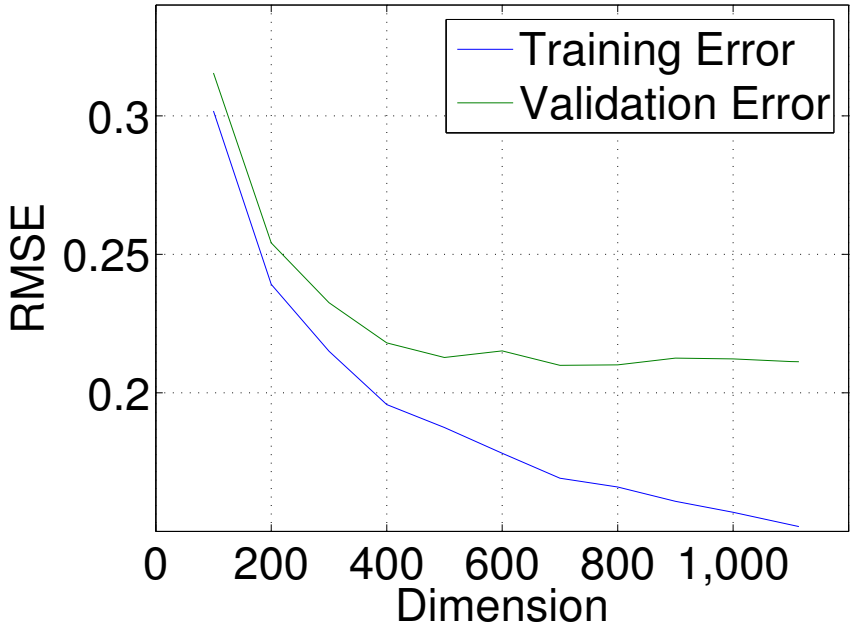


Fig 1: Model Selection

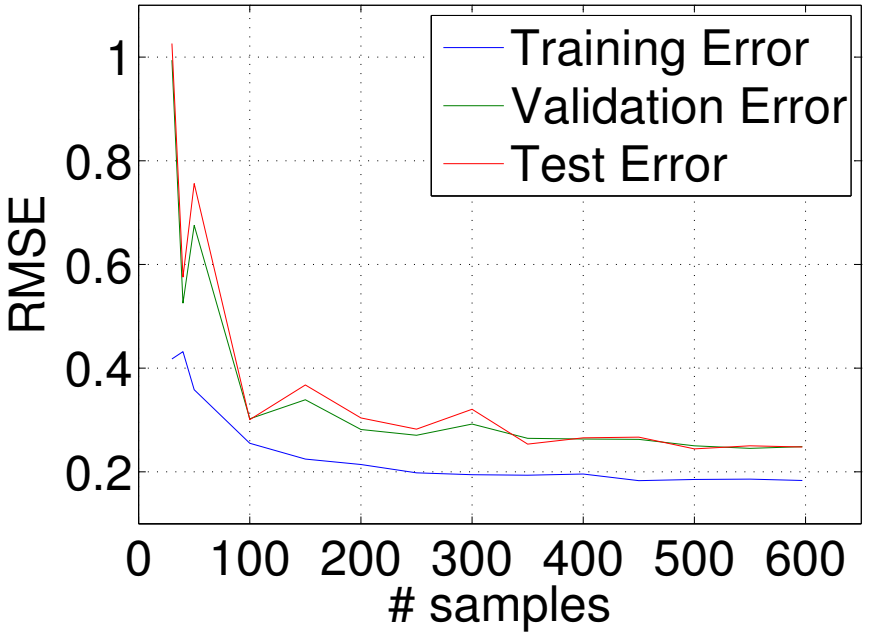


Fig 2: Learning Curve

Name	x_1	y_1	x_2	y_2	Mean†	Pitch‡	Time (s)
ANN	0.132	0.145	0.157	0.201	0.158	0.194	64.596
RF	0.476	0.361	0.398	0.351	0.396	0.376	30.297
SVR	0.117	0.137	0.117	0.135	0.126	0.153	0.846

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Performance of Tuned Model

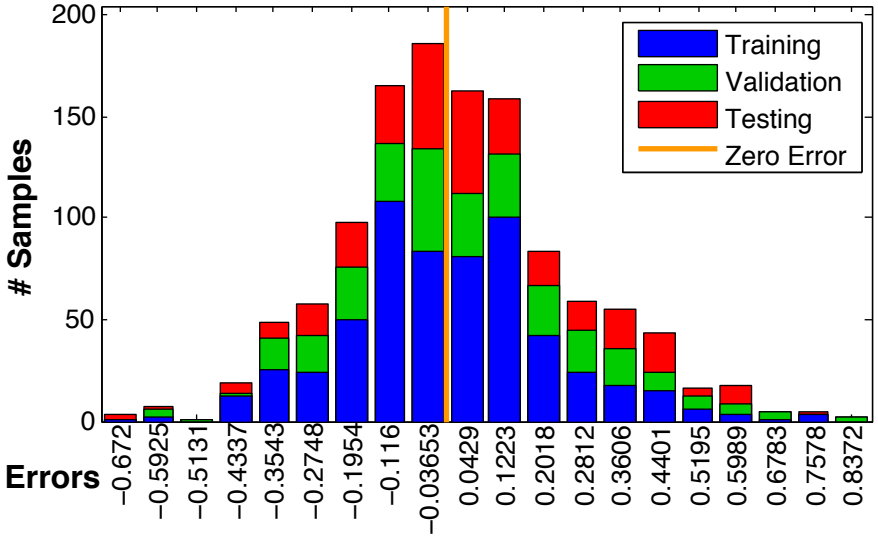

Fig 1: Error histogram of predicted values

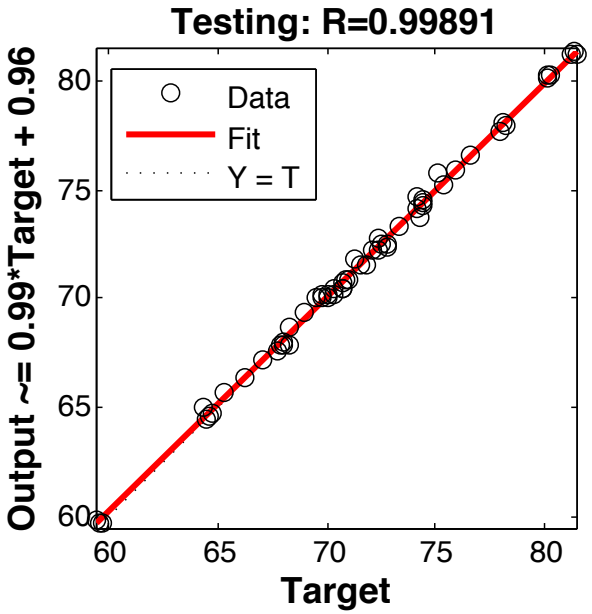

Fig 2: Regression plot of tuned model

- Most errors distribute around zero error
- RMSE = 0.135, overall nearly perfect
- Only a few outliners (37) beyond 0.5 unit but smaller than 1.
- Fitted line in regression plot very close to 1

Conclusion

- DSA is a promising lithography in patterning contact holes at 7 nm node
- Lithography verification is crucial for the success of DSA
- Studied pitch size and contact location prediction problem
- Proposed a machine learning based approach, including DSA model and features
- Performed extensive experiment and demonstrated effectiveness and efficiency of ML-based approach