# Topographic Image Analysis of Surface Morphology as a Function of Cooling Rate in (Nd,Li)$TiO_3$ Thin Films

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## Objective:

Determine trends in size, shape, and distribution of surface features at different height levels in order to determine possible mechanisms and kinetics of feature formation as a function of cooling rate.

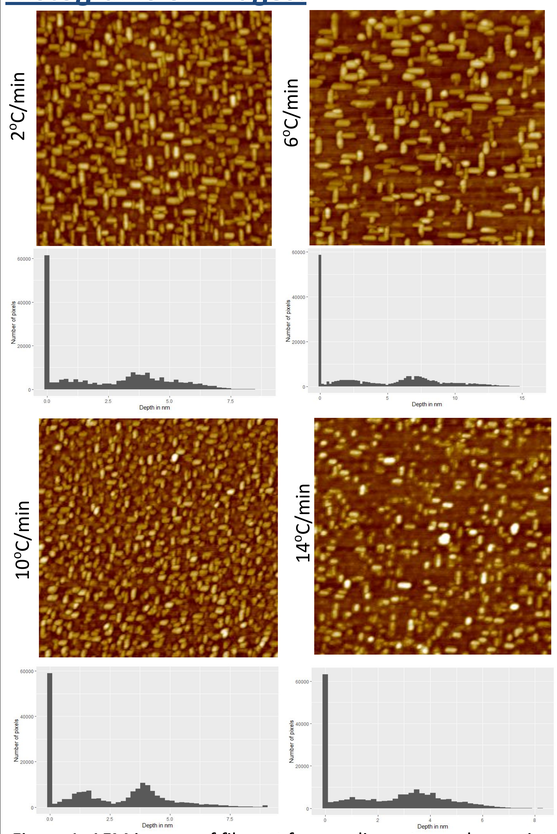
## Motivation:

(Nd,Li)$TiO_3$ system forms checkerboard structures by self assembly in bulk under equilibrium cooling. We are investigating the possibility of control of such self-assembly in epitaxial films by using the strain associated with lattice and thermal expansion mismatch.

## Background:

- (Nd,Li)$TiO_3$ thin films deposited by Pulsed Laser Deposition were cooled at different rates following deposition ranging from 2°C/min to 14°C/min.
- Films were smooth on the surface up to above a critical thickness ($t_c$).
- The critical thickness is a function of cooling rate.
- Atomic Force Microscopy was used to identify the surface features.
- Films were 60 unit cell size thick (above $t_c$ for all cooling rates)
- Rectangular features were observed with changing lateral size, distribution and thickness.
- Gwyddion, R-Studio, and ImageJ were used to explore the 3D topographic data where height is represented by pixel intensity.

## Histograms of Images:




- Histograms generated in R-Studio indicate bimodal height distribution at all cooling rates.
- Background indicated by first bin removed from further processing.
- Pixel intensity represents height in the AFM Images.
- Further analysis examines each "peak" of histogram separately.
- Second peak analysis is focused on "islands" identified as highest part of image.

Figure 1: AFM images of films at four cooling rates and associated histograms

See also: Elahe Farghadany's Presentation in S4: Post Thin Film Pulsed Laser Deposition Cooling Rates and The Effect on Critical Thickness

## Process for Analyzing Second Histogram Peak:

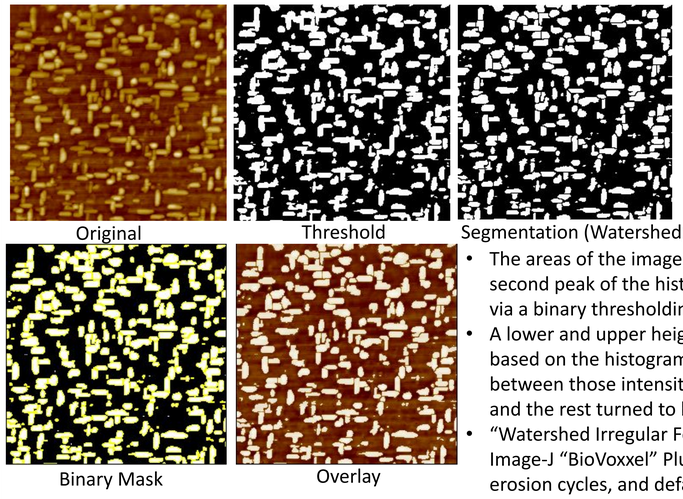
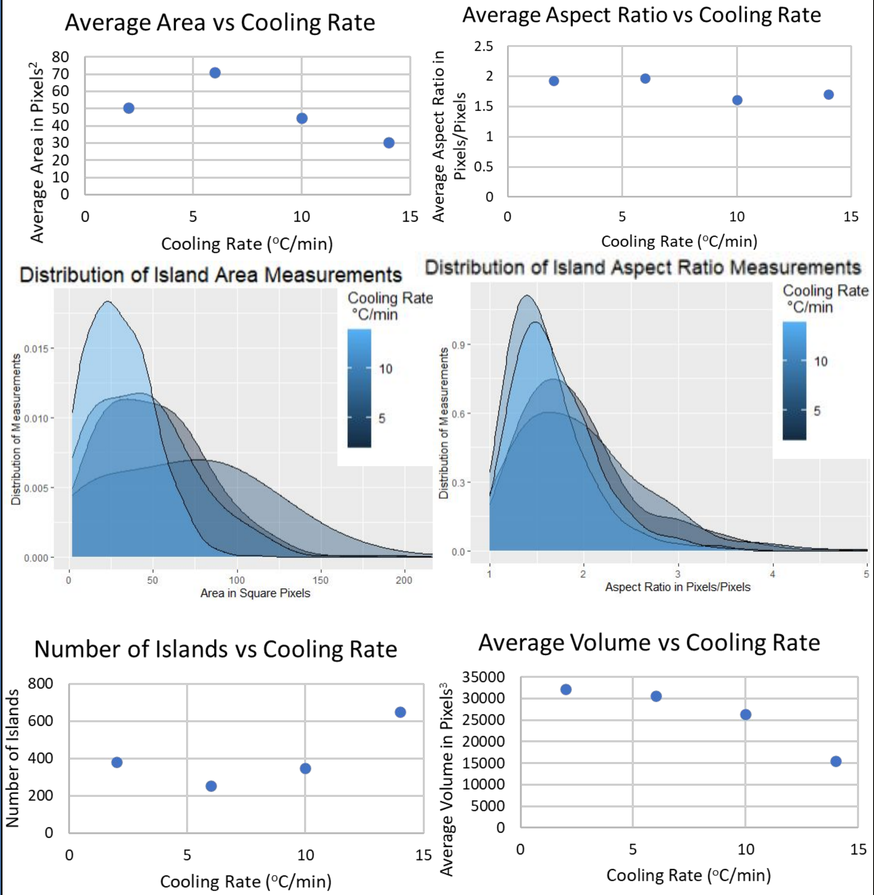



Figure 2: Process for Image Analysis of 2nd Peak of Histogram from 6°C/min Cooling Rate

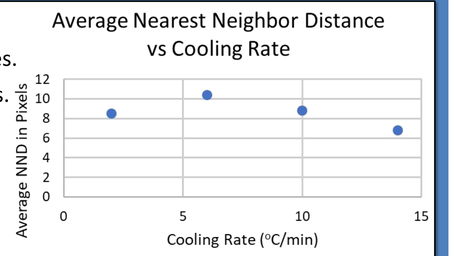
- The areas of the image represented by the second peak of the histogram were isolated via a binary thresholding process.
- A lower and upper height were selected based on the histogram, with pixels falling between those intensities turned to white, and the rest turned to black using R-Studio.
- "Watershed Irregular Features" from Image-J "BioVoxxel" Plugin was applied w/ 5 erosion cycles, and defaults options.
- "Analyze Particles" under the "Analyze" tab was used to detect individual islands and add them to Region of Interest Manager.
- ROI's were overlayed on original (not binary image) as a mask to select areas of image
- Automatic measurements performed on selected islands in Image-J.

## Results of Second Peak Analysis:




## Voronoi Analysis:

- Done on binary "second peak" images.
- Partitions plane into convex polygons.
- Pixel intensity indicates separation between islands.
- Affected by whether image was segmented.



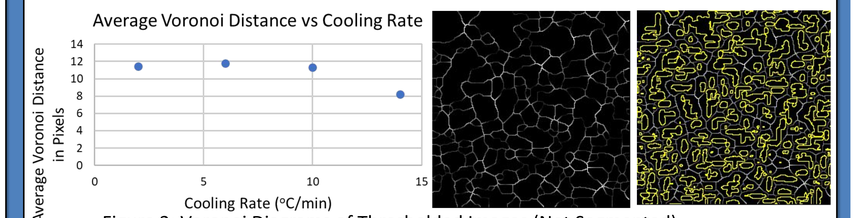




Figure 3: Voronoi Diagrams of Thresholded Images (Not Segmented)

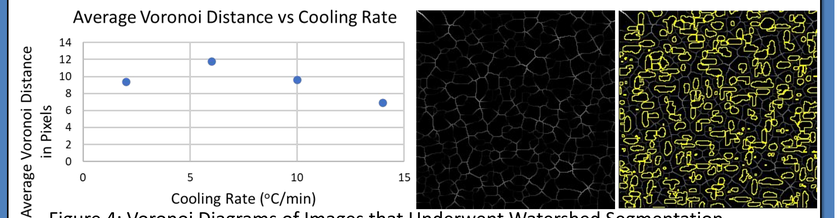



Figure 4: Voronoi Diagrams of Images that Underwent Watershed Segmentation

## Investigation of First Histogram Peak:

Figure 5: Binary Image Showing First Bin of 6°C/min Cooling Rate in Black

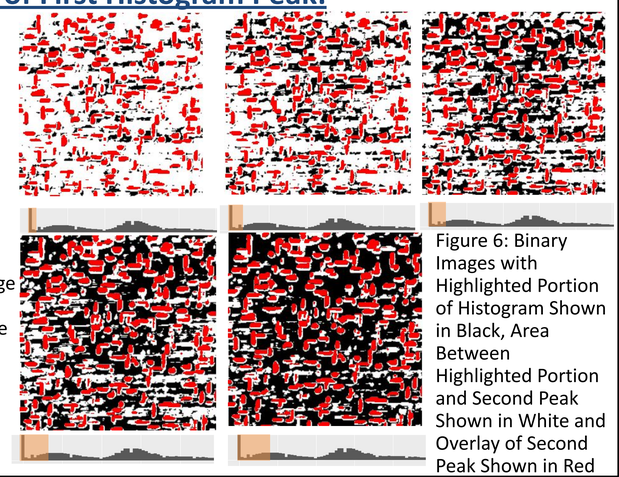


Figure 6: Binary Images with Highlighted Portion of Histogram Shown in Black, Area Between Highlighted Portion and Second Peak Shown in White and Overlay of Second Peak Shown in Red

## Future Work:

- Analysis of more images.
- Quantification of effect of segmenting versus not segmenting images.
- Analysis of first peak: machine-learning approach to examine change in particle distribution at individual height levels.

## Conclusions:

- 6 °C/min cooling rate maximizes area, aspect ratio, and average Voronoi distance of second peak islands and has fewer islands.
- Longer cooling rates results in increased number of small, more closely packed islands.
- First peak is mix of new features and of sloping from highest islands.