Linking surface morphology, microstructure, and superconducting properties in YBCO thin films using image analysis and artificial intelligence

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Introduction

The superconducting properties of $REBa_2Cu_3O_y$ (REBCO) conductors are determined not only by the choice of constituent materials but also by the fabrication conditions. During the fabrication of thin films, various deposition parameters dictate the resulting microstructure. For the REBCO matrix, these microstructural features strongly influence the critical temperature (T_c), the self-field, and the in-field critical current density (J_c). Thus, deposition parameters are indispensable for producing high-performance REBCO conductors. Atomic Force Microscopy (AFM), a technique for analyzing surface topography, can be used to evaluate the growth environment during epitaxial deposition. Given that the superconducting performance of REBCO thin films depends on their microstructure, which in turn depends on deposition conditions, AFM analysis provides a potential means to relate surface morphology to both crystal structure and superconducting properties [1, 2]. While fabrication conditions naturally correlate with superconducting performance, deposition of the thin film inevitably involves non-quantifiable factors that can introduce variations. AFM is a non-destructive method for evaluating the deposition environment of actual samples. It may be possible to compensate for such variations through surface morphology analysis, and even to predict microstructural features on scales ranging from hundreds of nanometers to several tens of micrometers. In this study, we employed AFM to comprehensively analyze the deposition conditions, surface morphology, crystal structure, and superconducting properties of YBCO thin films using image analysis and artificial intelligence (AI). By investigating correlations among these parameters, we aim to assess whether surface morphology measurements, as a non-destructive and localized evaluation method, can be established as a reliable characterization approach.

Experimental method

YBCO thin films were fabricated on $SrTiO_3$ (100) single-crystal substrates using the Pulsed Laser Deposition (PLD) method, with the deposition temperature and deposition frequency systematically varied. For each fabricated sample, more than 20 surface morphology datasets were acquired using AFM. Figure 1 presents a schematic overview of the constructed model. The phase images obtained from AFM measurements, labeled according to deposition temperature and deposition frequency, were used as the model inputs. To enhance the dataset and improve model accuracy, each input image was augmented by flipping it vertically and horizontally. Additionally, edge enhancement and noise reduction were applied to the images before training. A convolutional neural network (CNN) was then trained to classify each input image according to the corresponding fabrication conditions, thereby constructing a model capable of predicting the deposition parameters from AFM data.

Results and discussion

Figure 2 shows the loss functions and accuracies of both the training and validation datasets for each epoch of the constructed model. After 100 epochs of training, the loss functions converged for both datasets. Moreover, the accuracy approached nearly unity, indicating that the classification model effectively distinguished deposition conditions based on AFM surface morphology images.

It should be noted, however, that the present model discretizes inherently continuous deposition parameters, and thus its applicability is limited to specific experimental conditions. In future work, we aim to extend this approach by incorporating more refined classification and regression models, thereby enabling a comprehensive analysis of the correlations among AFM-based surface morphology measurements, microstructural features, and superconducting properties in YBCO thin films. On the day of the presentation, we will explain the perspectives on the correlations among surface morphology, microstructure, and superconducting properties, using both image analysis and AI-based approaches.

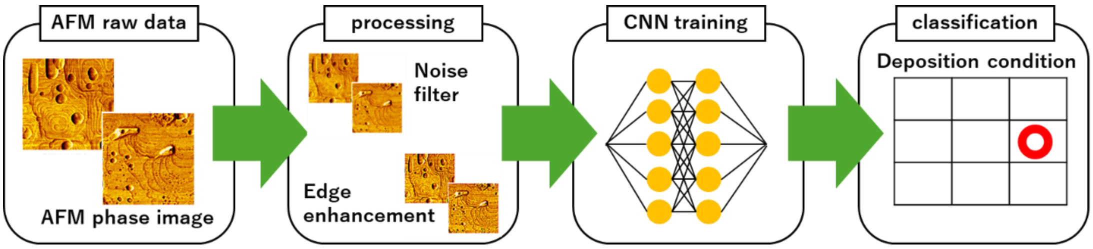

Figure 1 Schematic diagram of CNN classification model.

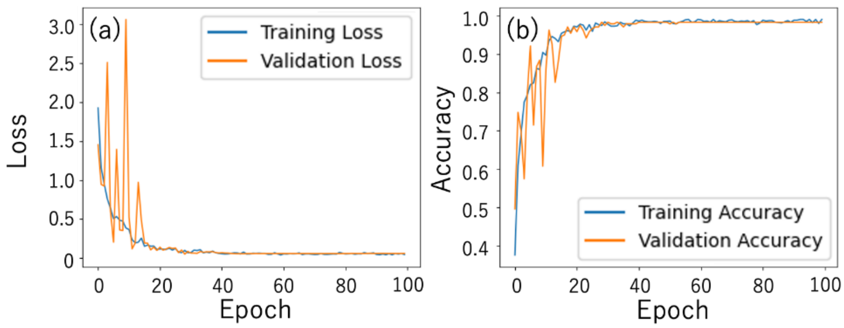

Figure 2 The results for the classification model over epochs; (a) loss function, (b) accuracy.

References

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