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Quantitative misfit dislocation characterization with electron channeling contrast imaging

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Electron channeling contrast imaging (ECCI), a diffraction-based technique in the scanning electron microscope (SEM), has become an increasingly popular tool for characterization of defects in epitaxial heterostructures, especially in cases of lattice-mismatched growth. As an SEM-based measurement, ECCI is an attractive option compared to defect imaging in the transmission electron microscope: it is inherently non-destructive for plan-view measurements (no specimen thinning needed) and is able to probe large areas of material in a very short time [1]. Although this technique is regularly employed for qualitative characterization, its potential for accurate and statistically relevant quantitative characterization (beyond simple enumeration of threading dislocation density, TDD) is highly enticing.

In lattice-mismatched heterostructures, if the epilayer is sufficiently thin (< 200 nm), the strain-induced misfit dislocations (MDs) can be readily observed via ECCI [1]–[3]. Appearing in ECCI micrographs as straight lines with bright or dark contrast related to their specific Burgers vectors, MDs are easily segmented from the background using image processing software like MIPAR [4]. Using batch processing, such analysis can be done in a semi-automated fashion, although human intervention is often required to ensure high accuracy. However, recent developments in the use of machine learning for image analysis, including the addition of a deep learning toolkit in MIPAR, have allowed us to expand to a more practical, fully-automated image segmentation process (given an adequately-trained model). Figure 1 presents an example of such automated segmentation of an ECCI micrograph, targeting a specific set of MDs, from which a variety of quantitative descriptors can be determined. This approach enables rapid extraction of large and statistically relevant datasets containing a wide range of useful microstructural information, including dislocation line direction, line lengths, distribution/density, Burgers vectors, and so forth. Figure 2 shows examples in which a line length distribution and line densities of MDs are pulled from a segmented ECCI micrograph. Extracted values may then be used to directly calculate metrics such as direction-resolved strain state/relaxation and epilayer tilt [5], [6]. An imbalance between MD Burgers vector populations, as seen in Figure 2(c) for the $\mathbf{g} = [220]$ set, is the direct cause of epilayer tilt (consistent with XRD measurements on the same sample) and a clear example of the quantitative, microstructure-resolved potential of ECCI. In fact, these results are in good agreement with tilt values taken from x-ray diffraction (XRD) measurements of the same sample. Thus, this approach can be thought of as a highly-localized method to probe information similar to what can be extracted from XRD measurements, while also providing specific defect/microstructure detail. Going further, combined with careful sample design, this additional detail can be used to provide insight into critical dislocation dynamics, such as dislocation reactions, nucleation rates, and glide velocities.

In this work, we explore the efficacy of ECCI as a tool for rapid, highly quantitative characterization of MDs in epitaxial heterostructures, as well as demonstrate the use of automated image processing to further improve throughput. In particular, we focus here on an example material system, GaP/Si, grown via metal organic chemical vapor deposition. Relaxation and tilt information obtained via ECCI show excellent agreement with XRD results. In addition, approximate glide velocities were extracted and found to be in good agreement with previously published glide velocities of similar material systems collected using conventional bulk deformation techniques.

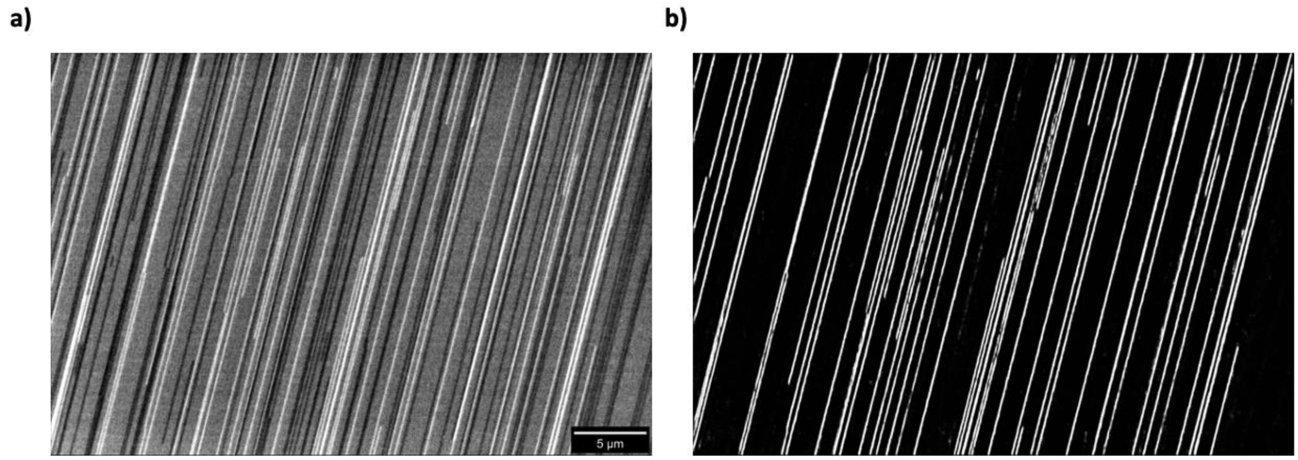

Figure 1. Representative examples of an (a) as-captured ECCI image from a 100 nm thick, partially-relaxed GaP/Si epilayer, and (b) fully automated segmentation of the bright-contrast MDs in (a) performed using the machine learning tool in MIPAR.

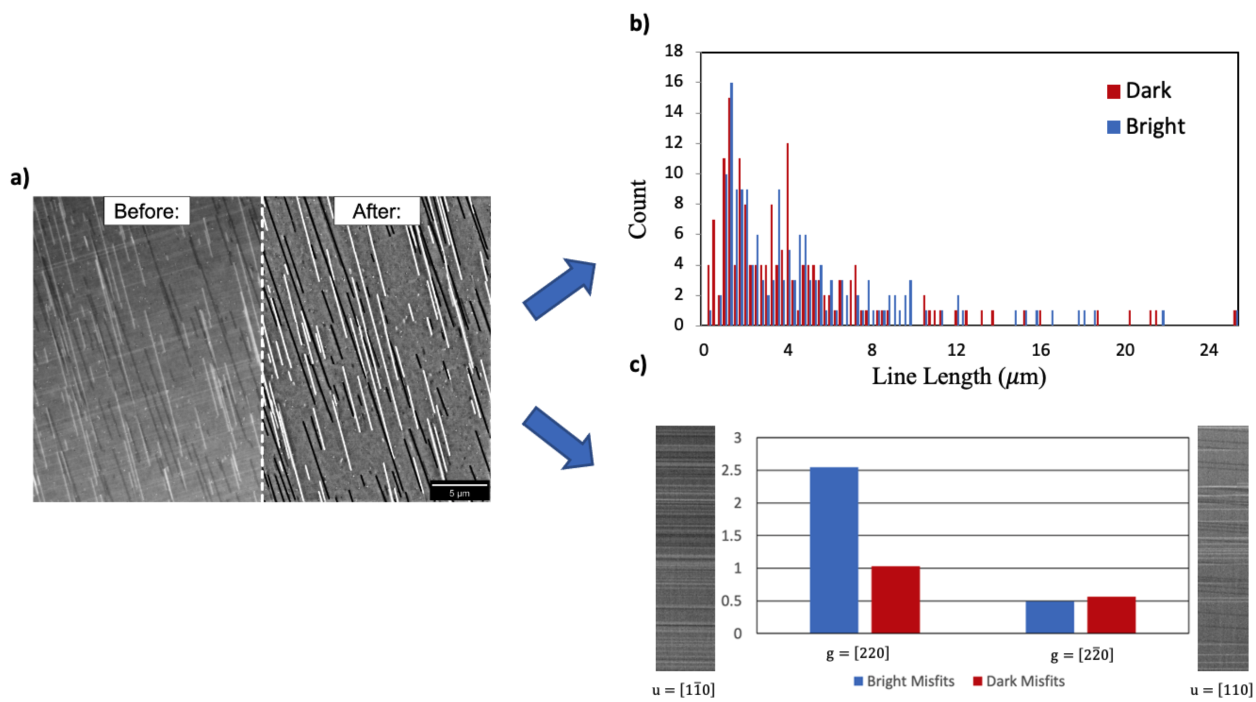

Figure 2. (a) ECCI micrographs of 100 nm GaP/Si before and after segmentation, (b) extracted misfit dislocation line length distribution, and (c) extracted misfit dislocation line densities of perpendicular line directions, showing evidence of tilt in the direction, consistent with XRD tilt measurements of the same sample

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