Methodology to Improve Strain Measurement in III–V Semiconductors Materials

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Geometric phase analysis (GPA), a fast and simple Fourier space method for strain analysis, can give useful information on accumulated strain and defect propagation in multiple layers of InAs/GaAs quantum dot (QD) materials. In this work, GPA has been applied to both high-resolution transmission electron microscopy (HRTEM) and high angular annular dark field scanning transmission electron microscopy (HAADF STEM) images. Strain maps determined from these images have been compared to each other, in order to analyze and assess the GPA technique in terms of accuracy. Ways to improve STEM data to get more reliable results are discussed.

GPA is a novel and straightforward technique that can be used for quantitative measurements of lattice strains in aberration corrected HRTEM and HAADF STEM images. The method is based on the assumption that there exists a constant spatial relationship between the intensity maxima and the location of atomic columns in the studied material [1]. This relationship appears in the form of a spatial shift of the intensity maxima positions with respect to the atomic columns. In aberration-corrected STEM, sub-Ångström resolution can be achieved, providing precise atomic-column positions and clear contrast to map the strain field. Nevertheless, in experimental images, additional precautions must be taken to avoid unwanted effects from the microscope or the specimen that can produce incorrect strains and also to which two **g** vectors to be chosen in the Fourier transform to create the strain maps [2].

In the present work, we study strain relaxation mechanisms during the growth process of III–V semiconductors. The GPA technique is applied to experimental HR(S)TEM images of InAs/GaAs QD based intermediate band solar cell (IBSC) materials. The IBSC utilizes multiple band gaps in order to increase the efficiency beyond the Shockley-Queisser limit [3]. A necessary but challenging step towards fabricating high efficiency QD based IBSCs is to provide accurate quantitative descriptions of the QD structures. The InAs/GaAs QD materials were grown by molecular beam epitaxy (MBE), in the Stranski-Krastanov growth mode. The growth mode relies on the lattice mismatch between two materials to create the QDs, and thus there is inherent strain. This strain can be a problem when growing multiple layers of QDs, due to formation of defects, which might act as recombination centers. To compensate for the inherent strain, one can introduce nitrogen in the spacer layers. The small N atoms is supposed to cancel out the strain introduced by large In atoms. All experimental HRTEM and HAADF-STEM images were taken using a double Cs aberration-corrected, coldFEG JEOL ARM-200CF microscope, operating at 200 kV.

The advantage of using HRTEM images is that they are captured in a very short time with no scanning, so that drift is not a problem. However, the phase contrast is dependent on the thickness of the TEM foil, microscope focus and chemical composition. In STEM mode, we spend longer time to acquire the image, providing significantly more systematic and random noise in the data due to the long recording time. Furthermore, the noise and drift contributions can differ significantly between the fast and the slow scan directions. A HAADF-STEM image and the corresponding GPA strain map are

shown in Fig. 1 a and d, respectively. A possible solution to reduce the noise is to acquire a video where we have used a very short pixel time, ending up with several tens of images, and then use the SmartAlign tool [4] to superposition this image stack into a single image. Moreover, in order to avoid the difference between the primary and the secondary scan directions, a 90° rotation between each image in the series has been used. Fig. 1(b) shows a HAADF-STEM image after applying SmartAlign, but with a fixed primary scan direction. Fig. 1(e) is the corresponding strain map. Much of the noise seen in the strain map from a single STEM image acquired with "normal" pixel time is now removed, but some horizontal, artificial strain lines are still present. These lines are related to the primary and the secondary scan directions. Fig.1(c) shows a HAADF-STEM image after applying SmartAlign with 90° rotation between every image in the stack. We observe in Fig. 1(f) that the systematic lines are removed from the strain map.

In conclusion, GPA provides errors in strain when applied to HRTEM images. The most credible results are obtained by using GPA on HAADF-STEM images where noise and artificial errors can be reduced by a smart and improved experimental design, and by careful choice of **g** vectors in the GPA procedure. The presentation will show examples of accumulated strain and defect formation and propagation through multiple layers of strained InAs/GaAs QD materials [5].

References:

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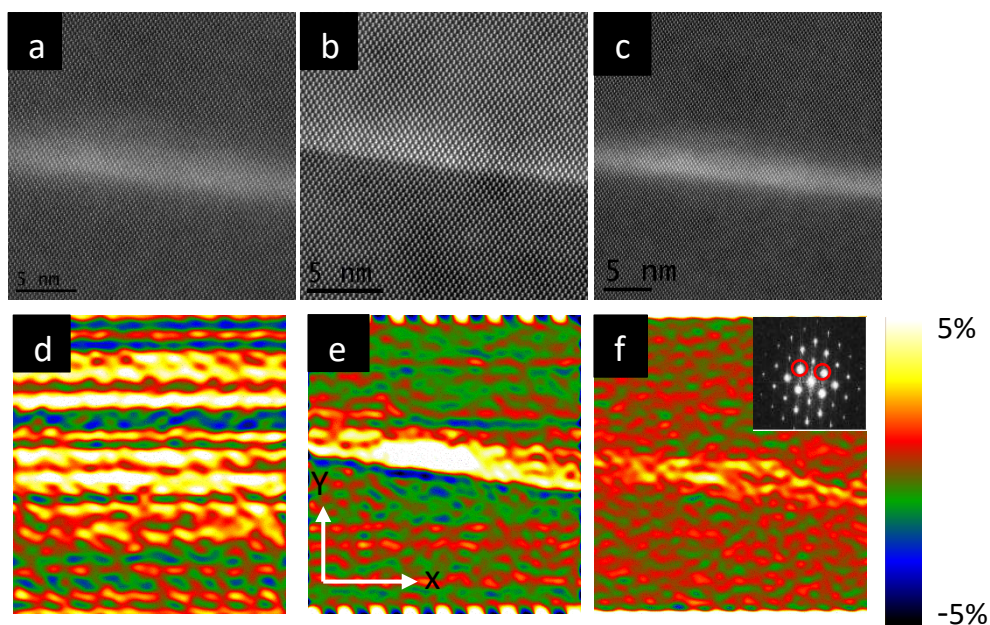
Figure 1. (a) HAADF-STEM image of InAs/GaAs QD, (b) HAADF-STEM image of InAs/GaAs QD after applying the SmartAlign without 90° rotation , (c) HAADF-STEM image of InAs/GaAs after applying the SmartAlign with 90° rotation (d) ε_{yy} strain measured from (a), (e) ε_{yy} strain measured from (b), (f) ε_{yy} strain measured from (c). The Bragg spots highlighted in the inset FFT in (f) are used to create strain maps.