Measuring strain using aberration corrected High Resolution Scanning Transmission Electron Microscopy

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CEA-Grenoble has been developing tools to measure strain at the nanoscale for several years, using different TEM techniques [1]. This presentation will focus on the use of the Geometrical Phase Analysis (GPA) [2-3] to measure strain from High Resolution Scanning Transmission Electron microscopy (HR-STEM) images. Indeed due to the developments of probe Cs-correctors and improvements in the stability of electron microscopes and software, HR-STEM is now an efficient and simple technique to measure strain at a near atomic scale.

In this work, HR-STEM images were acquired on two FEI Titan microscopes equipped with probe Cs-correctors and Fishione High Angle Annular Dark Field (HAADF) detectors to record Z-contrast images. The first used Titan, called Titan1, was one of the first Titan microscopes delivered by FEI. Installed in Sept 2005 without corrector, a Cs-probe corrector (Cescor) was retrofitted in our laboratory about 2 years later. The second Titan is an optimized Titan cube, called Titan Ultimate that has image and probe Cs-correctors (D-Corr), monochromator, X-FEG and digiscan. As presented in [4], HR-STEM images obtained with Titan1 without probe Cs-corrector could give some information. However the introduction of the probe Cs-corrector increased the sharpness of images and facilitated the analysis. For instance in [5,6], this allowed us to measure the strain field around threading dislocations in thick AlInN layers and point out the importance of In segregation around these dislocations. By comparison, we will show how the new Titan Ultimate column and corrector has greatly increased the quality of the measurements: (i) the cube and its remote control gives a better stability of the microscope, (ii) the new design of the probe-Cs-corrector improves the resolution and more importantly the sharpness of the HR-STEM images, (iii) improved software and electronics allows to acquire images greater than 2048x2048 pixels. The TIA software has an option for acquiring 4096x4096 images. The digiscan package from Gatan allows acquiring 8192x8192 images.

We improved our own GPA Digital Micrograph script to be able to analyse such large images. Now large fields of view (up to 500 nm) can be acquired while keeping atomic resolution. Such large field of view is important for the microelectronics industry to analyse a whole device in one picture (Fig. 1g). It is also required when a long and/or large (~200nm) nanowire is observed or when the region of interest is far from the reference region (Fig. 1a). Large images allow to have an overview of the sample (Fig. 1g) or to zoom on the atomic structure of a defect (Fig. 1f) whose structure can be determined and compared to atomistic simulations.

In this presentation, we will outline the main advantages of HR-STEM images over HR-TEM images: (i) patterns in HR-STEM do not change with thickness and chemical composition, (ii) thicker samples can be analysed and (iii) strain and composition can be simultaneously determined (Fig. 1c, 1f-h). It would have been more difficult, and may be impossible to use HR-TEM images for these strain measurements of devices and nanowires as HR-TEM is very sensitive to thickness variations. We will show that the scanning errors, more or less present in all HR-STEM images, do not cause significant problems. Either they can be partly corrected [6] (all strain maps of fig. 1 have been corrected) or partly biased by acquiring two sets of images with orthogonal scanning directions.

Strain variations as small as 0.2% (fig. 1e), i.e. lattice variations of about 0.5 pm and rotations as small as 0.16° were detected (in sample of Fig. 1a a miscut of 0.16° between the SiGe/Si layers and the Si substrate was measured). The trade-off between precision and lateral resolution will be also discussed.
Figure 1. (a) HR-STEM image of SiGe layers grown on a SOI substrate observed along [110]. At this scale the atomic columns are not visible. A magnified image will be similar, but noisier, to Fig. 1i. The three SiGe layers on the right part of the image have respectively a Ge content of 21, 34 and 45%. The larger field of view of the image (300 nm) allows to visualize both the Silicon substrate (on the right) and the SiGe layers although they are separated by 145nm of amorphous SiO2 insulator. The image has 8192x2048 pixels. (b) (002) lattice planes are separated by 8.2 pixels. (c) (002) strain map obtained with the GPA method using two {111} beams. (c) Superposition of the (002) strain profile (extracted from 1b) and HAADF intensity profile (extracted from 1a). Strain and chemical composition can be compared. (d) (002) strain map obtained from a HR-STEM image of a Si0.64Ge0.36 layer on top of Si after suppression of the scanning errors. (e) Strain profile extracted from d. A small negative strain (-0.2%) can be seen (black arrow) in Silicon. It is due to the stress relaxation in the thin TEM lamella and is a sign of the sensitivity of the technique. (f) HR-STEM image of a 60° dissociated dislocation observed on the device of fig. 1g. The atomic structure of the dislocation is directly determined and the step at the SiGe/Si interface introduced by the dislocation is clearly visible. (g) HR-STEM image of a transistor with Si0.64Ge0.36 source and drain. (h) (002) strain map obtained from the Z-constrast image f of the 60° dislocation. The reference of strain is taken in the SiGe layer. (i) (220) strain map of g. Here the reference is Si. Some dislocations can be seen. A black arrow points to one of them. (j) (002) strain map of g