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AUTOMATED STRAIN MEASUREMENT USING NANOBEAM DIFFRACTION COUPLED WITH PRECESSION

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INTRODUCTION

Measurement of strain with high spatial resolution and high precision in semiconductor devices is critical to monitor the designed strain distributions. For this purpose, spot diffraction patterns acquired using nanobeam illumination in the transmission electron microscope (TEM) have been used previously. Such patterns can be acquired at high spatial resolution compared to other strain measurement techniques, and the experiment is relatively straightforward to perform on most modern microscopes [1].

Previous studies using nanobeam diffraction have used the measurement of shift in individual diffraction spots to measure strain. In order to improve strain measurement precision, it is desirable to fit entire strained diffraction patterns to unstrained reference patterns. However, the presence of strong dynamical effects in electron diffraction makes such a fitting difficult. Because of the dynamical effects, spot intensity distributions are strongly dependent on local specimen thickness, so there is often little similarity between diffraction patterns from different areas. This particular challenge can be overcome by combining nanobeam diffraction with beam precession [2]. With precession, the incident beam is tilted and rotated at a high frequency (typically about 100 Hz) so that the acquired diffraction pattern is an average of all orientations within the precession cone. Dynamical effects are reduced as the incident beam is not exactly on axis and fewer beams are excited simultaneously. The use of precession also enables the collection of higher-order reflections, which are more sensitive than lower-order reflections to small changes in lattice parameters. The combination of these features makes nanobeam diffraction coupled with precession an attractive method for automated strain measurement.

METHODS

The electron microscopy was performed on a 200kV Zeiss Libra L200 TEM equipped with a field emission gun (FEG), operated in the Scanning TEM (STEM) mode. A NanoMEGAS DigiSTAR unit was used to produce precession and descanning of the electron beam. An AppFive TopSPIN data acquisition system was used to acquire electron diffraction patterns using a CCD camera while synchronously positioning the electron beam in various patterns on the specimen. A cross section sample of a blanket SiGe layer grown on a single-crystal Si substrate was prepared using Focused Ion Beam milling. The high angle annular dark field

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(HAADF) STEM image of the Si/SiGe cross section is shown in Fig. 1. Nanobeam diffraction profiles were acquired in both longitudinal (along the SiGe layer) and transverse (perpendicular to the Si/SiGe boundary) directions (Fig. 1).

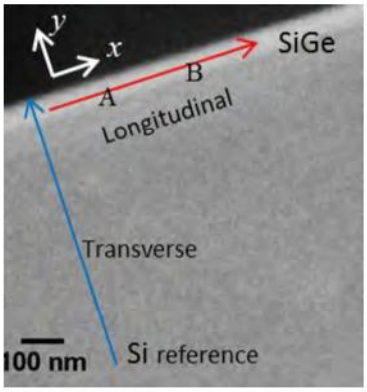

FIGURE 1. HAADF STEM image of the Si/SiGe multilayer.

A proprietary algorithm developed by AppFive was used to calculate the strain at each position of the electron beam. Diffraction patterns from strained regions of the specimen were numerically distorted in order to produce an optimum match with a reference diffraction pattern obtained from the unstrained Si region (see Fig. 1).

Results And Discussion

Diffraction patterns, with and without precession, from two points marked A and B in the STEM reference image (Fig. 1) are shown in Fig. 2. By comparing these patterns obtained from seemingly identical regions, one can see the improvement in the pattern quality when precession is included. The diffraction patterns without precession contain a small number of low-order spots that are not very sensitive to strain. Also, the spot intensities change dramatically at each position due to small changes in specimen thickness or bending. This causes problems for the automated processing algorithms, which can have significant systematic errors due to matching the wrong spots between different patterns. Additionally, less than one quarter the number of spots appear in the unprecessed diffraction patterns compared to the precessed patterns, which would lead to considerably higher statistical uncertainty in results calculated from unprecessed diffraction patterns.

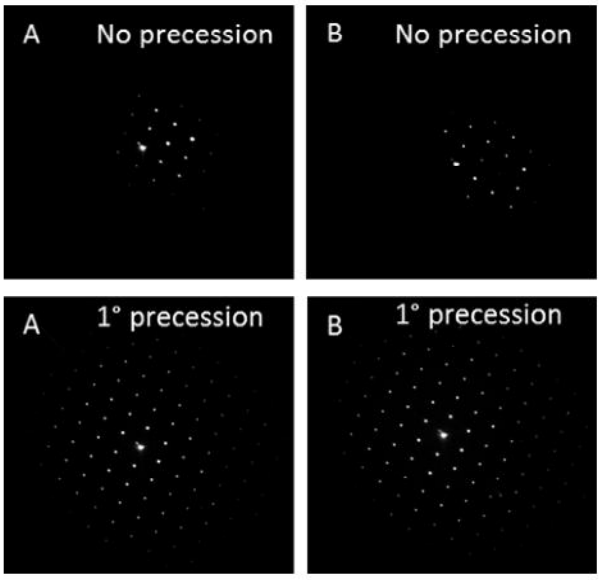

FIGURE 2. Diffraction patterns from points A and B in Fig. 1, without precession (top) and with 1° precession (bottom).

Figs. 3 and 4 show the strain profiles measured using diffraction patterns acquired with 1° precession. The transverse profile (normal to the Si/SiGe interface) was acquired with a step size of approximately 8 nm and a longitudinal profile (along the SiGe layer) was acquired with a step size of approximately 30 nm. The transverse profile shows that the Si layer far from the SiGe is unstrained and there is a sharp increase in tensile strain in the normal direction immediately inside the SiGe layer. On the other hand, strain in the longitudinal direction ε_{xx} is very small, which is consistent with the fact that the SiGe layer is coherent with the substrate. The longitudinal profile shows that the strain is relatively constant along the SiGe layer. The average normal strain ε_{yy} in the longitudinal profile was 1.22% and the standard deviation was 0.02%. It was not possible to obtain any physically meaningful results using the same automated algorithm for processing diffraction patterns acquired without precession,

due to the significant differences in the intensity distributions as shown in Fig. 2.

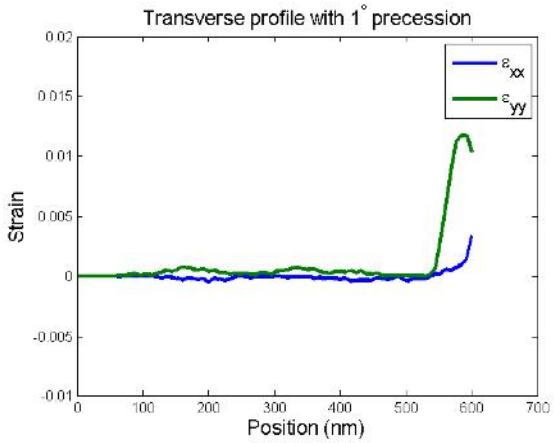

FIGURE 3. Transverse strain profile.

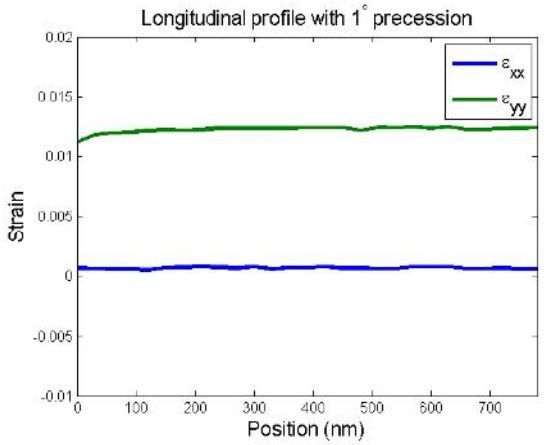

FIGURE 4. Longitudinal strain profile.

The spatial resolution of this method depends on the size of the electron probe. With most modern FEG TEMs, one can expect to produce an electron probe diameter smaller than 5 nm, although there are special compensations necessary to maintain that probe size with precession. Other precession nanobeam experiments in the TEM (for example, orientation mapping) have achieved a spatial resolution down to approximately 1 nm [3]. It is reasonable to expect similar spatial resolution with strain mapping using nanobeam diffraction.

Because of the insensitivity of precession electron diffraction (PED) towards small changes in specimen thickness, this method for strain measurement does not impose any stringent requirements on specimen preparation, as opposed to other TEM strain measurement techniques. Furthermore, spot intensities in PED do not vary with small local orientation changes in the crystal. These features make it possible to design computer algorithms that can measure strain using PED patterns with no manual input needed to identify the spots or to specify the principal strain directions.

CONCLUSION

We have demonstrated automated strain mapping using nanobeam electron diffraction coupled with precession. The analysis of the precession electron diffraction patterns to produce strain distributions required no user input. With this technique, we observed that the strain in the SiGe blanket layer was 1.22% in the direction perpendicular to the Si/SiGe interface. Strain along the direction parallel to the interface was close to zero, as expected in a coherent interface. The precision of strain measurements with this method was 0.02%. Without precession, automated strain determination from spot patterns was not possible with the current algorithm.

REFERENCES

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KEYWORDS

Strain measurement, TEM, nanobeam, electron diffraction, precession