NANOMEGAS USA

Topspin Strain Application Note

Introduction

Modern devices are based on FinFET transistors, where strain monitoring is critical for process development. Strain metrology on these devices demand a high degree of accuracy, precision and efficiency in data acquisition. At the scale of these devices, strain measurement using transmission electron microscope (TEM) is the only approach that can provide the adequate spatial resolution.

Existing TEM methods to measure strain include convergent beam electron diffraction (CBED), dark field electron holography, high resolution imaging and nanobeam diffraction (NBD). Although CBED is an accurate way to measure strain, the sample needs to be relatively thick (>150 nm) which limits its applicability to semiconductor devices. Dark field holography is another attractive approach although the experimental difficulties limits its application as a strain metrology technique. High resolution imaging offers the best spatial resolution for strain measurement. However, the sample needs to be ultra thin with uniform thickness and no bending. This stringent requirement along with limited field of view makes it difficult to use high resolution imaging for routine strain analysis. Of these techniques, NBD is the most practical approach with good spatial resolution and ease of implementation. Hence NBD has been adopted widely in the industry for strain metrology.

Strain measurement using NBD involves measurement of shift in individual diffraction spots. However, the presence of strong dynamical effects in electron diffraction is a serious limitation to achieve the desired precision. Since strain is measured using NBD patterns that are exactly on zone axis, the dynamical effects are exacerbated. Because of the dynamical effects, spot intensity distributions are strongly dependent on local specimen thickness and orientation. Although the technique is straightforward, it requires tedious specimen tilting to align specimen exactly at the zone axis. Fig. 1 compares two Si diffraction patterns from near by regions in the same specimen prepared by focused ion beam milling.

With the introduction of FinFETs, strain metrology has run into new challenges. In particular, strain measurement in FinFETs is difficult because:

- the gate wraps around the active region in the channel, it is difficult to prepare samples without any gate overlap. The diffraction patterns almost always are convoluted with the spots from the overlapping layers.
- the thickness of the fin is very small which results in TEM lamella that are less than 25 nm. At the specimen thickness, bending of the TEM lamella is unavoidable. This makes it very difficult to orient the sample close to zone axis, which is critical for accurate measurement of strain with NBD.

Topspin strain analysis is a novel approach to strain measurement that combines NBD with a technique known as precession electron diffraction to overcome the above mentioned limitations. Further, Topspin strain analysis uses a robust analysis algorithm for high accuracy and precision with the ability to handle overlapping patterns.

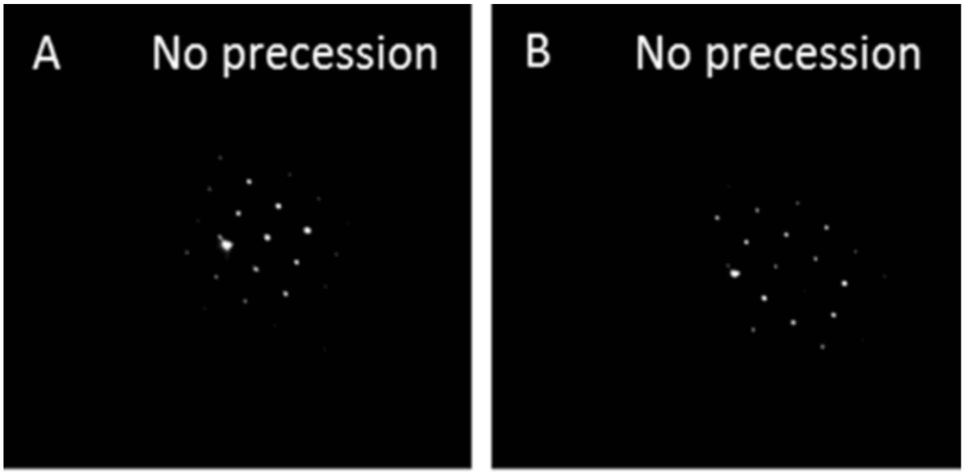

Fig. 1 Si <110> Diffraction patterns from two nearby regions in a FIB sample. Note the strong intensity variations due to dynamical effects

Precession electron diffraction

Precession is an effective way to mitigate the strong dynamical effects and improve the quality of diffraction patterns making them amenable for quantitative analysis.. With precession, the incident electron beam is rocked in a conical fashion above the specimen and a complimentary "de-scanning" is applied below the specimen to bring the beam back to optic axis (Fig. 2). In doing so, the acquired diffraction pattern is then an average of all the diffraction patterns within the precession cone. The complementary de-scanning below the specimen is required as a tilt in the beam causes a shift in the diffraction pattern. Without descanning, the pattern would consist of a number of rings centered on the diffraction spots with the radius corresponding to the precession angle. This combination of precessed illumination with a complimentary descanning below the specimen has the net effect of rocking the crystal while keeping the beam stationary, similar to rocking beam experiments in X-ray diffraction. Of course, in a TEM it is much easier to rock the electron beam which can be controlled electronically, compared with rocking the specimen where the mechanical tolerances limit the spatial resolution with precession.

Precession offers the following advantages for strain measurement:

- Dynamical effects are reduced even when the specimen is close to zone axis. Because of this diffraction patterns are less sensitive to changes in thickness

- The use of precession also enables the collection of higher order reflections which are more sensitive to small variations in strain
- Zone axis alignment is easier with precession as the averaging of diffraction patterns over different tilts results in a symmetric diffraction pattern even when the specimen is slightly off axis.
- Effect of specimen bending is mitigated with precession.

The effect of precession on the diffraction patterns shown in Fig. 1 is shown in Fig. 2, which shows the advantages of using precession.

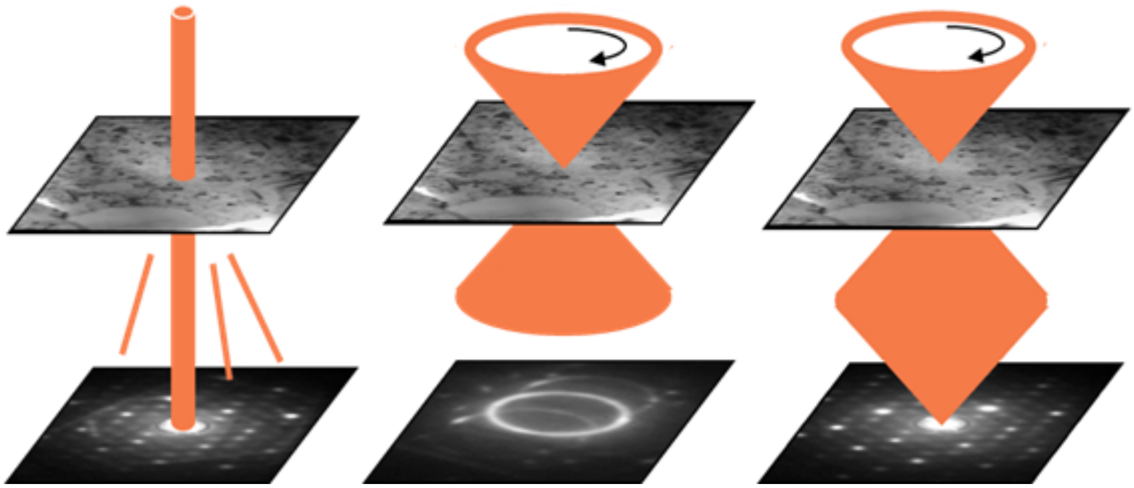

Fig. 2 (a) Conventional nanobeam illumination. (b) Precession illumination without complimentary descanning below specimen. (c) Precession combined with descanning below specimen.

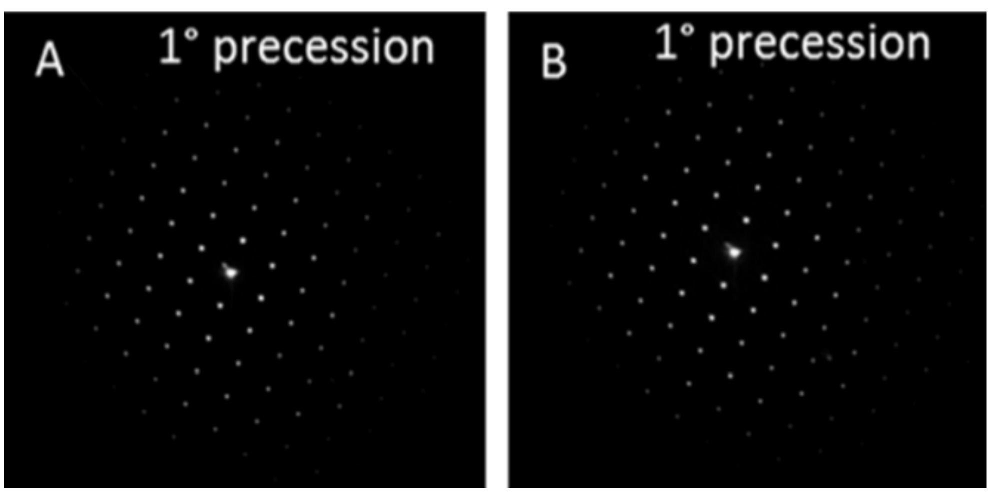

Fig. 3 Si <110> Diffraction patterns from the same region as shown in Fig. 1 with 1°precession.

Strain analysis

Topspin strain analysis uses a proprietary algorithm to identify all the spots from the crystal of interest with the desired orientation. For most Si devices, this is the <110> zone axis pattern of Si. The algorithm uses a model based approach to accurately find the spot positions for both the reference and the strain diffraction patterns. This approach has the important advantage of handling cases with overlapping patterns making it ideal for finFETs. Another important advantage of this approach is a high degree of reproducibility and minimal user input, both important requirements for a metrology tool. Fig. 4 shows an example of spot identification with Topspin strain analysis on a Si diffraction pattern with overlapping spots.

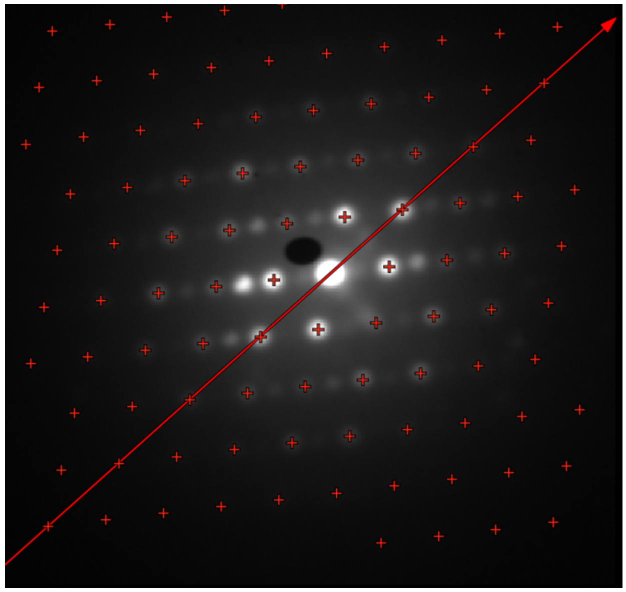

Fig. 4 Spot identification with Topspin strain analysis from a diffraction pattern with overlapping spots

Topspin set up

Topspin hardware consists of Digistar, which enables synchronized beam scanning with precession. A high frame rate optical CCD camera is used to acquire PED patterns synchronously with precession. Topspin system can be installed on most modern microscopes and it does not require a scanning unit to be present on the microscope (Fig. 5).

Typically, precession of the beam is performed at 100 hz and the aquisition time per PED pattern is 0.01 - 0.05 ms. Topspin has a streamlined workflow which makes it possible to acquire strain data sets with minimal time for set up. Apart from routine microscope alignments, which most users are familiar with, the advanced precession alignments are automated by a computer and does not require the user to have an intimate knowledge instrument optics and alignment.

Spatial resolution and sensitivity depend on the particular model of the TEM, beam current, beam convergence and sample quality. In a typical Topspin set up

- Use a precession angle of 1∘
- Acquisition time for 150 x 150 map is 5-10 min
- Typical analysis time is 5 to 10 min

- Strain sensitivity of the technique is 0.02%
- Practical spatial resolution at 1∘ precession angle : 1 to 5 nm

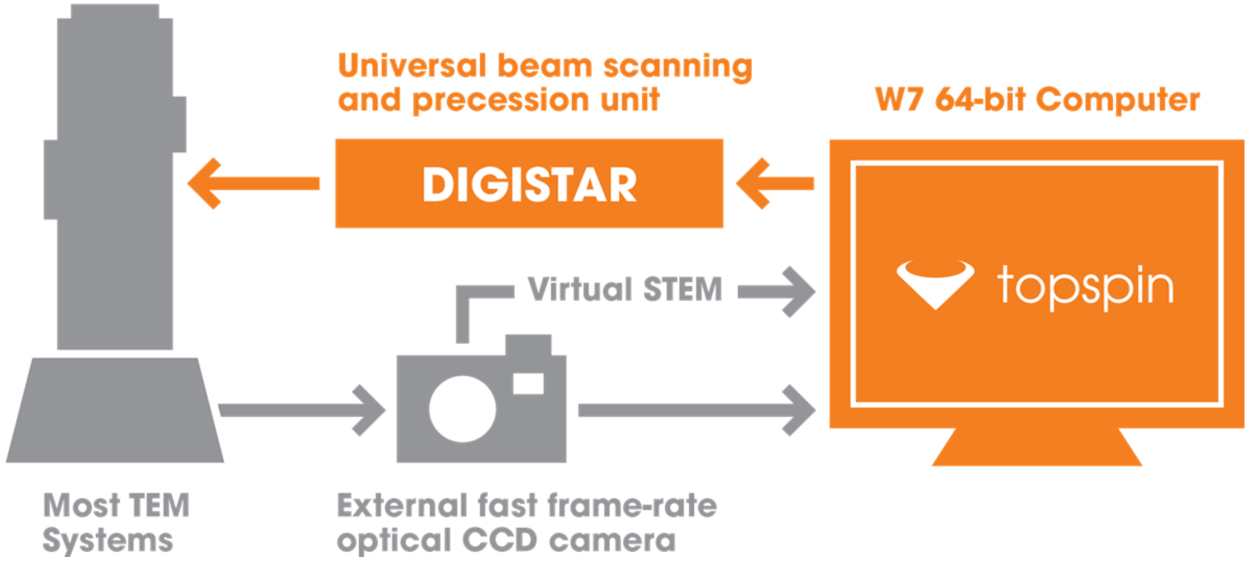

Fig. 5 Typical Topsin setup

Topspin strain analysis has been rigorously tested with a variety of standard structures including fin structures. Fig. 6 shows an example of a strain map from a p-FET device using Topspin Strain analysis installed on a JEOL ARM 200F TEM.The map was acquired with a step size of 3 nm and the acquisition time was under 5 minutes. A precession angle of 1∘was used to acquire the data.

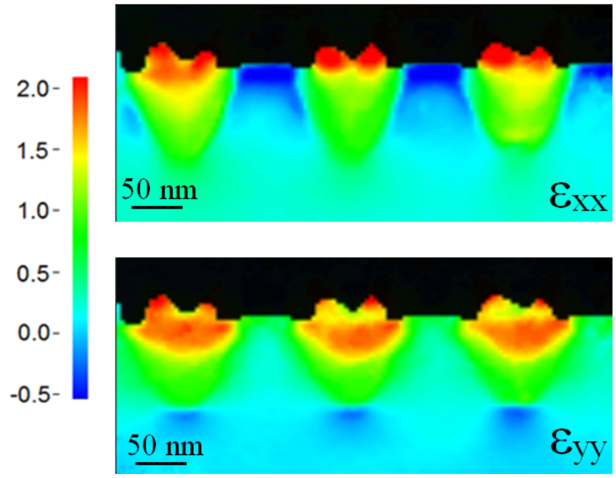

Fig. 6 Strain map from a p-FET device