TEM for Strain-engineered Devices

Dark-field Inline Holography for Nanoscale Strain Mapping

The performance of today's state of the art semiconductor electronic devices depends on charge transport within very small volumes of the active device regions. One means of optimizing the band structure of these small volumes of semiconductor material for carrier mobility is to tune its strain state.

Be it process-induced local strain, globally induced strain in thin strained silicon layers, strained SiGe or Ge channels, strain-inducing embedded SiGe or SiC in the source/drain, or the addition of stressed thin film silicon nitride liner layers over the top of the transistor, etc. [1] a large number of different ways of inducing strain in the channel region of MOSFET and DRAM structures are applied and investigated, all for enhancing the charge carrier mobility and thus the speed of the device. Being able to map strain with high spatial resolution and a large field of view is therefore crucial for developing modern microelectronic devices.

Nanometer-scale Strain Analysis Using TEM

Although strain can be measured with high sensitivity using X-ray diffraction or Raman spectroscopy, transmission electron microscopy (TEM) is still the only technique to offer the required spatial resolution to characterize today's strain engineered devices. TEM techniques can be divided into two main groups: Diffraction based techniques such as convergent beam electron diffraction (CBED) [2] and nano-beam electron diffraction (NBED) [3], and image based techniques such as high-resolution TEM (HRTEM) [4] and more recent methods which employ electron holography [5,6]. Here we will focus on image-based techniques as they are able to provide higher spatial resolution compared to diffraction based counter parts.

Specimen Requirements

Quantitative TEM requires the preparation of specimens of very high quality. Side specific preparation of thin lamella with well defined geometry is mainly obtained by means of focused ion beam (FIB) milling. Even though recent advances in FIB such as low energy milling or availability of noble gas ions like Xe have allowed preparation of thin sections with reduced side wall damage, it stays still as a
limiting factor if one uses HRTEM as a quantitative method.

In spite of being a delicate method, tripod polishing followed by broad beam low energy ion milling is a more suitable option to achieve large area cross-sections with uniform thickness as well as remarkable surface quality [7] (see figure 1 for an enlargement).

**Strain Mapping Using HRTEM**

HRTEM-based strain mapping relies on the assumption that every unit cell across the field of view has the same contrast, allowing distortions in the observed pattern to be interpreted as lattice distortions. Figure 2a shows the HRTEM image with uniform contrast across the active region of the transistor. For the p-MOSFET structures investigated here, only the longitudinal strain component, \( \varepsilon_{xx} \), along the \(<220>\) direction was of major interest because of its effect on the charge carrier mobility within the gate channel. Longitudinal strain, \( \varepsilon_{xx} \), calculated using geometric phase analysis (GPA) algorithm [4] is displayed in figure 2b as a color-coded 2-dimensional map.

Although HRTEM methods have proven the required accuracy at the nanometer scale, a larger field of view is generally required to include the distortion-free reference area and the strained channel in the same image. In addition, the low specimen thickness (max. 30 nm) necessary for high-quality HRTEM images may cause strain relaxation. To overcome these limitations, Hýtch and coworkers have combined GPA and dark-field off-axis holography (DOAH) and applied it to semiconductor structures [5].

**Dark-field Inline Holography**

Being inspired by the DOAH technique, we have recently applied dark-field inline holography (DIH) to map strain in semiconductors [6,8]. Unlike its off-axis counterpart, which requires a highly coherent electron source, an electrostatic bi-prism, as well as some kind of Lorentz lens, DIH relies on the reconstruction of the geometric phase from a focal series of zero-loss filtered dark-field images using an exit-wave reconstruction algorithm. Figure 3a shows the experimental setup and contrast mechanism that is being made use of in DIH. The electron beam is tilted in such a way that the desired reflection (e.g. the (220) beam) is aligned parallel to the optical axis of the microscope. A small (10 µm) objective aperture is used to block the undiffracted beam as well as all other reflections. The specimen is tilted to a two-beam diffraction condition to excite the reflection of interest. Figure 3b displays sub-areas of three differently focused and zero-loss filtered (220) dark-field
images of the p-MOSFET structure recorded on the Sub-Electron-Volt-Sub-Angstrom-Microscope (SESAM) [9].

The phase image shown in figure 3c is reconstructed from dark-field images using the FRWR algorithm [10]. This software automatically and self-consistently corrects for geometric distortions produced by large changes in the objective lens defocus. The spatial resolution of the reconstruction is limited to 0.8 nm, by the objective aperture. The phase of the diffracted beam gives direct access to displacements along its direction, in this case the displacement in (220) atomic planes. The longitudinal strain map, $\varepsilon_{xx}$, in figure 4 derived from the geometric phase combines high spatial resolution, better than 1 nm, with a field of view of about 1 µm in each dimension. The profiles extracted from the channel region indicated as dashed lines reveal compressive strain values reaching $1.0 \pm 0.1 \%$.

**Conclusion**

Quantitative TEM is a powerful tool for characterizing strain-engineered semiconductor devices. The dark-field inline holography method described here overcomes many of the limitations of HRTEM based techniques, such as GPA, and, at the same time, does not require a large area of perfect crystal adjacent to the strained region, nor a highly coherent electron source as is the case for dark-field off-axis holography. Unlike in HRTEM, where images are acquired in zone axis orientation, the specimen is oriented in a two-beam Bragg diffraction condition. The phase of the diffracted beam is therefore much less sensitive to thickness variations and local changes in specimen orientations. Non-necessity for imaging lattice fringes breaks the barrier of the limited field of view, while at the same time the low electron dose required for image formation reduces the electron-beam induced modification of the original structure [7]. Application of DIH on compressively strained p-MOS transistors shows that a 10 times larger field of view is achievable compared to HRTEM (typically 100 nm square) allowing simultaneous strain mapping on multiple transistor channels.

Its relatively simple experimental setup, excellent signal-to-noise properties and loose requirements on the spatial coherence are the main advantages of DIH. There is also no need for a large reference area of a well oriented crystal specimen, which makes it possible to characterize the strain state in more complicated structures in semiconductor devices.

**References**


Authors

Dr. V. Burak Özdöl (corresponding author via email button)

Prof. Dr. Peter van Aken
Max Planck Institute for Intelligent Systems
Stuttgart Center for Electron Microscopy
Stuttgart, Germany

Prof. Dr. Christoph T. Koch
Carl Zeiss Professor
Ulm University
Institute for Experimental Physics
Ulm, Germany
www.christophtkoch.com

Contact

MPI für Intelligente Systeme
Heisenbergstr. 3
70569 Stuttgart
Germany