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Strain mapping in MOSFETS by high-resolution electron microscopy and electron holography

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ABSTRACT

We present two methods for mapping strains in MOSFETs at the nanometer scale. Aberration-corrected high-resolution transmission electron microscopy (HRTEM) coupled with geometric phase analysis (GPA) provides sufficient signal-to-noise to accurately determine strain fields across the active regions of devices. Finite element method (FEM) simulations are used to confirm our measurements. The field of view is however limited to about 100 nm^2. To overcome this, we have developed a new technique called dark-field holography based on off-axis electron holography and dark-field imaging. This new technique provides us a better strain resolution than HRTEM, a spatial resolution of 4 nm and a field of view of 1 μm.

1. Introduction

Strained silicon is now an integral feature of the latest generation of transistors and electronic devices because of the associated enhancement in carrier mobility [1]. Tensile strain leads to a splitting of the degeneracy of the conduction band minima in the ⟨0 0 1⟩ direction resulting in reduced intervalley scattering. Electron mobility in biaxially strained-Si (s-Si) grown on virtual substrates of $Si_{1-x}Ge_x$ can be increased by a factor 2 for $x > 20\%$ [2]. Furthermore, strain lowers the energy of the heavy hole and spin-orbit bands relative to the light hole band. For $x > 40\%$ the hole mobility in s-Si can be increased by more than two [3]. Other techniques can also be used to introduce strain into the channel such as embedded SiGe or Si-C source and drain or with nitride stressors. These techniques lead to an improvement of the carrier mobility for both electrons and holes. Recent analysis showed that uniaxial strain is 3 times more efficient than biaxial strain [4].

With the continuous reduction in scale of devices, strain has become increasingly difficult to measure. Developing methods of strain measurement at the nanoscale has therefore been a major goal of recent years but has proven illusive in practice [5]. Raman spectroscopy or X-ray diffraction techniques can map strain only at the micron scale. At smaller scale, transmission electron microscopy (TEM) techniques such as convergent-beam electron diffraction (CBED) [6] and nano beam diffraction (NBD) [7] can be used. However, CBED can sometimes be too sensitive to foil bending in the highly strained areas typical of devices [8] and none of the techniques combine the necessary spatial resolution, precision and field of view.

An alternative method for measuring local strains is high-resolution transmission electron microscopy (HRTEM) combined with the image processing technique of geometric phase analysis (GPA) [9,10]. We have shown recently how strains can be mapped across an entire MOSFET including source, channel and drain region [11]. However, because of the relatively high magnifications necessary to image the atomic lattice, the field of view is limited. We will show an example of such HRTEM analysis followed by preliminary results for a new technique, based on electron holography, capable of circumventing all the problems currently plaguing strain characterisation [12].

2. Experimental methods

Lamellas of uniform thickness were prepared for TEM observations by mechanical polishing (tripod method) followed by focused-ion beam (FIB) using a Cross Beam XB 1540 (Zeiss): a scanning electron microscope (Gemini Zeiss) combined with a FIB column (Orsay Physics). Specimens are thinned to have the two surface normals parallel to the $[1\,\bar{1}\,0]$ zone axis and are typically 80 nm thick for HRTEM observations, and 200 nm thick for electron holography experiments.

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TEM experiments were performed on the SACTEM-Toulouse, a Tecnai F20 ST (FEI) fitted with an imaging aberration corrector (CEOS), 2048 × 2048 CCD camera (Gatan) and a rotatable electrostatic biprism (FEI). HRTEM images were obtained at the [1 $\bar{1}$ 0] zone axis in nominally zero spherical aberration conditions, and at relatively low magnification (×200,000) in order to maximize the field of view to about 100 nm square. For electron holography, specimens were oriented to a two-beam condition close to the [1 $\bar{1}$ 0] zone axis. The microscope was operated in Lorentz mode [13] at a nominal magnification ×20,000 to obtain a field of view of 1 μm. The voltage applied to the electron biprism was 80 V producing holographic fringes of 2 nm spacing and overlap width of 250 nm.

Images were analysed using a modified version of the software package GPA Phase 2.0 (HREM Research Inc.) a plug-in for DigitalMicrograph (Gatan). Image processing uses a mask in Fourier space which determines the real-space spatial resolution of the measurements: 5 nm for HRTEM measurements and 4 nm for electron holography. A detailed explanation of geometric phase analysis can be found in ref. [9]. Images were corrected for the geometrical distortions introduced by the CCD camera and the projector lenses of the microscope [14].

Strains were simulated in the p-MOSFET by the finite element method (FEM) based on linear anisotropic elastic theory. Domains of different chemical composition are distinguished by their elastic coefficients and lattice parameters (determined by applying Vergard's law to the bulk values for Si and Ge). The geometry of the model was based on the bright-field images of the observed structures. Epitaxy is treated as a thermal expansion problem [15]. Relaxation of the different domains is principally governed by the elastic tensor in each domain and the boundary conditions. Along the *x*-axis, in the source–drain direction, the lamella is considered to be infinite by using periodic boundary conditions. In the *z*-direction of growth, the lower boundary in the substrate is held fix and the upper surface treated as a free surface. For the bulk simulation, the y direction (electron beam direction) is infinite with periodic boundary conditions. Simulations were carried out for a 100 nm thick lamella with two free surfaces (corresponding to the TEM samples) and an infinitely thick sample (corresponding to the bulk structure).

3. Experimental results

3.1. High-resolution electron microscopy

An example of an HRTEM image of a p-MOSFET with a dummy gate and $Si_{80}Ge_{20}$ source and drain (schematically shown in Fig. 1a) is shown in Fig. 1b. The contrast is poor compared to typical HRTEM because of the thickness of the specimen and the damage layers caused by FIB preparation. Indeed without the aberration correction, the images would not have sufficient signal-to-noise to carry out meaningful analysis [11]. The 2-dimensional strain components were determined using GPA with the *x*-axis defined by the source–drain direction. The map of the ε_{xx} component (Fig. 1d) has a spatial resolution of 5 nm and a precision of 0.3% (determined by the standard deviation of the variations within the substrate). The reference used for the undeformed lattice was chosen in the substrate, as far from the gate as possible but still within the image. Any strain in this region will add a constant value to the measured

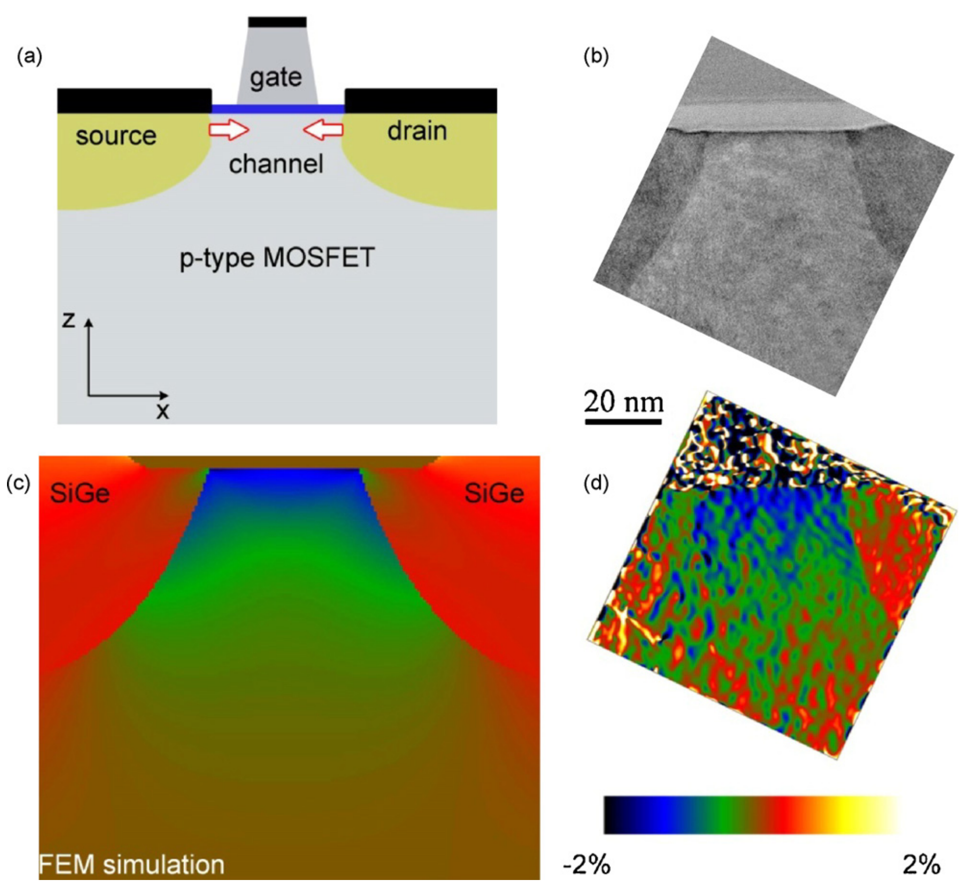

Fig. 1. HRTEM strain mapping of a uniaxial 45 nm strained silicon channel pinched between $Si_{80}Ge_{20}$ source (S) and drain (D): (a) schematic representation of the p-MOSFET device; (b) experimental HRTEM image; (c) finite element method (FEM) simulation for thick specimen of ε_{xx} strain component parallel to source–drain direction; (d) experimental ε_{xx} strain component.