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Strain Measurement of 3D Structured Nanodevices by EBSD

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Stress and strain effect the performance—mechanical and otherwise—of materials at all length scales. In semiconductors, strain has a strong influence on carrier mobility that is exploited by manufacturers to improve device characteristics including power efficiency. Strain engineered devices are now commonplace, but the strain metrology solutions with spatial resolution below 100 nm are limited, particularly so for 3-dimensional (3D) devices. Transmission Electron Microscopy (TEM) is capable of measuring strain with very high spatial resolution, but this offline metrology is slow, expensive, and the sample preparation alters the mechanical boundary conditions of the structures. As an alternative, strain measurement by Electron Backscattered Diffraction (EBSD) provides high spatial resolution and can be performed on a wafer inline during production without TEM sample preparation constraints.

EBSD is performed in a scanning electron microscope (SEM) with large sample tilt that allows backscattered electrons to form EBSD patterns (EBSPs) on a camera. These patterns contain Kikuchi bands that form at the intersection of the crystal planes and the camera (Figure 1(a)). Because strain (other than hydrostatic) causes small deviations in the relative position of crystal planes, EBSPs can be analyzed in a relative manner to determine the rotation and deviatoric strain tensor between two points.[1,2] This technique has been applied to semiconductor materials previously, but in this work we focus on applying it to 3D samples with feature dimensions below 100 nm.

Samples of epitaxial $Si_{0.76}Ge_{0.24}$ lines on a Si substrate were provided by an industrial collaborator and verified to be fully coherent by Raman and microspot x-ray diffraction (µXRD). These lines varied in width, but were 55 nm tall, including a 5 nm overetch beyond the SiGe:Si interface. Plan view SEM and a schematic are provided in Figure 1(b). Strain in this sample was measured using the Si region between SiGe lines as a zero strain reference, and the results from the 66 nm and 33 nm wide lines are shown in Figure 2a and 2b. In addition to the strains measured from the observed EBSPs, FEA calculated surface strains are plotted for reference. The strain along the SiGe line (ε_{22}) is expected to be the coherency strain from the heteroepitaxy (0.0091), and should be uniform in the SiGe region regardless of width of the SiGe line; however, the EBSD measured ε_{22} strain decreases with decreasing line width—a trend that begins at line widths below 5 µm (data not shown) and is not consistent with other strain measurement techniques applied to this sample.

To investigate this phenomenon, artificial EBSPs were generated by mixing patterns taken from large mesas of equibiaxially SiGe and unstrained Si, effectively simulating an EBSP that might be observed when backscattered electrons exit from both the SiGe and Si regions simultaneously. Performing strain analysis on an EBSP from mixed SiGe and Si yields strains that aren't representative of either region. Given that the device dimensions (line width, height, and pitch) are all small compared to the expected scattering length for 10 kV electrons in Si, the trajectory of electrons through these 3D structures could easily lead to EBSD signal from both unstrained Si and the SiGe line simultaneously when probing the SiGe line. Monte-Carlo simulations of electron trajectories were performed on the 3D structure of the sample to provide quantitative insight into fraction of electrons arriving at the EBSD camera from the

SiGe and Si regions of the sample as a function of the line width and beam position on the SiGe.[3] These simulations yield the fraction of EBSP intensity that comes from the SiGe and Si regions, which is a function of position on the EBSP (as well as line width and beam position), and allows a weight map, $w_{i,j}$, to be generated. The weight map indicates what fraction of the intensity in the observed EBSP comes from the desired region (SiGe), and what fraction is unwanted signal from the Si substrate that is predominantly strain free. By assuming a simple linear mixing of the two signals, the desired SiGe EBSP can be found from solving $Obs_{i,j} = SiGe_{i,j} \cdot w_{i,j} + Si_{i,j} \cdot (1 - w_{i,j})$ for $SiGe_{i,j}$.

Applying this procedure to the observed EBSPs that yielded the data in Figure 2(a) and 2(b), and then performing strain analysis on the SiGe EBSPs gives the strain data presented in Figure 2(c) and 2(d) respectively. Compared to 2(a) and 2(b), the data from 2(c) and 2(d) matches the expected strain values from FEA, which is also consistent with the Raman and µXRD data from these samples. This result indicates that understanding the scattering path of the electrons that form the EBSD signal is essential to interpreting the strain data from nanoscale devices, particularly those with 3D features.

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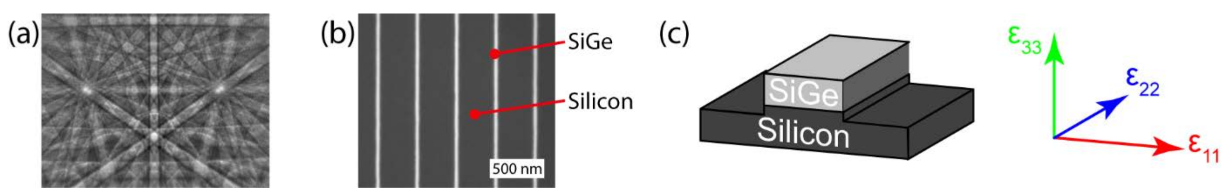

Figure 1. (a) typical Si EBSP, (b) a plan view SEM of the SiGe line structures, and (c) a schematic of the structure, including the direction convention used.

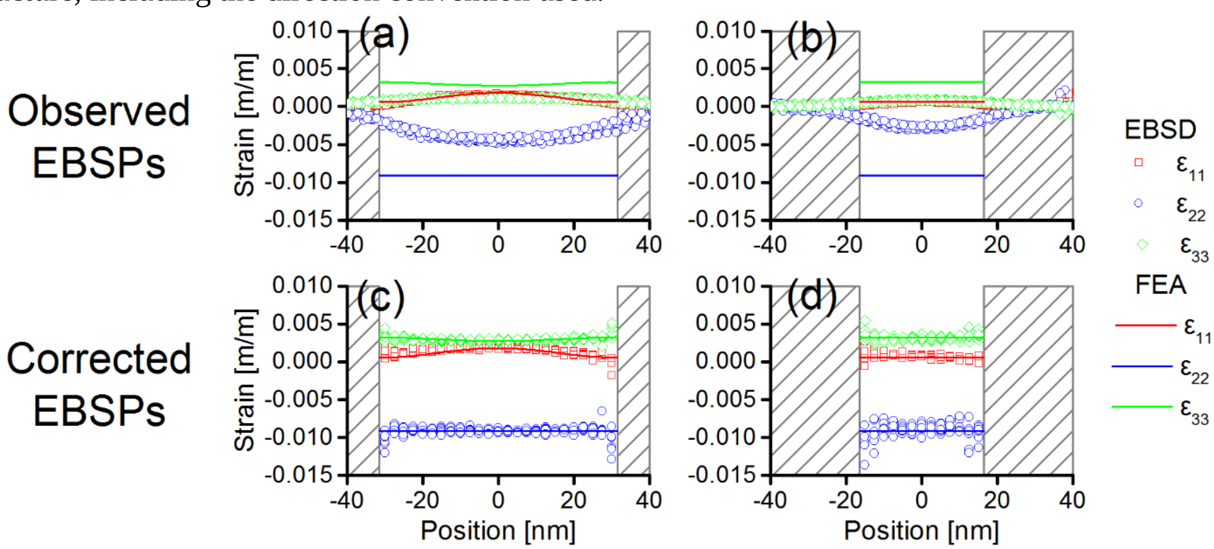

Figure 2. Strain results from the observed EBSPs of the 63 nm (a) and 33 nm (b) wide lines, and the same strain processing applied to the SiGe EBSPs (c) and (d). Strains from FEA simulation the surface values of the model and are plotted as reference for the expected strain of a fully strained SiGe line.

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