Electron Tomography of Gate-All-Around Nanowire Transistors

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Abstract. We present a study of gate-all-around (GAA) Si nanowire transistor structures using high angle annular dark field (HAADF) STEM tomography. Device structures have been prepared in needle shaped samples using a focused ion beam (FIB), in order to allow sample rotation to +/- 80°. Tomograms are presented, both from a full three channel device structure and also from a single wire test structure, without the hydrogen annealing step. It is observed that hydrogen annealing alters the rectangular cross section of the nanowires, narrowing them and smoothing the corners.

1. Introduction

Developments in transistor design have until recently involved scaling of the complementary metal oxide semiconductor (CMOS) architecture. However, as gate lengths are reduced below 50nm, short channel effects become increasingly significant, and high leakage currents become a problem. One promising solution to this is the gate-all-around (GAA) architecture [1]. The fabrication of these devices involves gate stack integration around semiconductor nanowires, as seen in figures 1 and 2. This design offers excellent electrostatic control combined with high $I_{ON}$ current and immunity from short channel effects.

The characterization of this new generation of devices presents fresh challenges in transmission electron microscopy (TEM). As the length scales of devices are reduced beyond TEM sample dimensions, 2D projections through devices are no longer sufficient. For this reason we present characterization of GAA device structures using electron tomography. This technique allows us to study our samples with a spatial resolution of ~2nm in all three dimensions [2]. The morphology of the nanowires in these devices has a significant effect on their electrical characteristics. With electron tomography we can study changes in morphology along the length of each channel, something which is not available from conventional TEM. To demonstrate this we have examined the effect of the hydrogen annealing step in device fabrication. It has been previously shown that this step rounds sharp corners and reduces roughness [3], which are both important steps towards improved device performance.

The overall aim of this work is to establish methods of sample preparation, data acquisition and treatment for successful and reliable 3D characterization of these samples.
2. Samples

The structures that have been studied in this project include a GAA three channel device and also single wire test structures. The GAA device is processed from a \((\text{Si}_{0.8}\text{Si}_{0.2}\text{Ge}_{0.2})\) superlattice, which is epitaxially grown on top of a silicon-on-insulator (SOI) substrate. Si/SiGe fins are formed by anisotropic plasma etching. The Si between the SiGe wires is then removed, the wires are annealed in \(\text{H}_2\) at 700°C and gate stack integration of 3nm HfO\(_2\) and 10nm TiN takes place. The resultant wire cross section is seen in figure 1. The single wire structures have the same gate stack integration, but have been prepared both with and without \(\text{H}_2\) annealing at 750°C.

3. Experimental Work

3.1. Sample Preparation

During initial studies these device structures were prepared for TEM examination inside parallel-sided lamellae, using standard lift-out techniques in the focused ion beam (FIB). It was found that although this type of sample preparation was sufficient to obtain high quality TEM images at zero tilt, several problems arose when using the same sample geometry for electron tomography. At high tilt angles, sample thicknesses became problematic, causing a degradation in image quality. Also, at these high angles shadowing from heavy element (Pt or W) capping layers caused images to be unusable. Both these problems limited the available tilt range and therefore increased distortions caused by the missing wedge. In this work, we have used needle shaped specimens [4], prepared using annular milling in the FIB. The end result is that the device is isolated inside a 350nm diameter needle (see figure 3). The preparation in this case is more specialized and therefore more time-consuming, but the final sample can be tilted over the full tilt range of the holder without issues of shadowing or thickness changes, as demonstrated in figure 4.

Figure 1. Cross section and 3D schematic of a three channel GAA transistor.

Figure 2. Schematic of GAA transistor showing three channels running from source to drain.

Figure 3. SEM image of needle shaped specimen, containing a GAA device, prepared in FIB.

Figure 4. Two HAADF images of a 350nm diameter needle shaped specimen, containing a GAA device, with nanowires indicated.
3.2. Electron Tomography
All the TEM characterisation on these samples has been carried out on the FEI Titan 300kV fitted with a probe Cs corrector, located at Minatec, CEA-Grenoble. To allow high tilt for tomography, a Fischione 2020 sample holder is used. All tilt series have been acquired using high angle annular dark field (HAADF) STEM imaging. Each tilt series consists of 151 images, acquired with 1° steps, between +/- 75°. The post-acquisition tilt series alignment and tomographic reconstruction was carried out using the FEI Inspect 3D software. The simultaneous iterative reconstruction technique (SIRT) algorithm, with 25 iterations, was used for the reconstruction. Visualisation and analysis has been carried out using the visualisation software suites Amira and Chimera.

4. Results

4.1. Three channel GAA device
Figures 5 and 6 demonstrate that the reconstruction from the GAA device has been successful. An isosurface representation of the tomogram is presented in figure 5. The threshold in this image is set at the intensity level of the TiN encapsulating layer. In this case, the SiGe wire is not directly represented, but the location of its boundary is inferred from the shape of the 3nm HfO$_2$ surround. In figure 6, two slices through the raw tomogram are shown. From the slice on the left, through the diameters of the wires, the anisotropic loss of resolution and associated distortion due to the missing wedge can be observed, as indicated. This presents an obstacle to a full characterization of the morphology of the wire. Ultimately the solution lies in the acquisition of data over the full 180° tilt range, using an appropriate sample holder. This is not a problem in the plane of the second slice, on the right of the figure. It can be seen that the 3 different layers present can be resolved easily, allowing analysis of changes in thickness and morphology.

![Figure 5. Isosurface representation of tomogram obtained from 3-channel GAA transistor.](image1)

![Figure 6. Two slices through tomogram from 3-channel GAA transistor. Orientation of second slice is indicated by red dashed line.](image2)

4.2. Effect of H$_2$ annealing
Figure 7 shows a zero degree HAADF image, and two volume representations of the reconstruction from the single wire sample without H$_2$ annealing. The location of the encapsulated Si nanowire is indicated in all three images. The HAADF image indicates that the shape of the wire is significantly different from that seen in the finished device structure, though it contains no information about the wire cross section. Figure 7 (c) has the tomogram tilted in order to show the Si wire in cross section. It can be seen that before the annealing stage of processing the nanowires have cross sections that are approximately rectangular. This can be compared to the cross sections we observe in figures 5 and 6.
from wires in the full device structure. It is seen that during the H\textsubscript{2} annealing step, the wires are significantly narrowed and the edges are rounded.

5. Conclusion
It has been demonstrated that electron tomography, combined with advanced FIB sample preparation offers a unique 3D characterization of novel GAA transistors. From our tomograms we are able to resolve the SiGe, HfO\textsubscript{2} and TiN layers in these samples. Due to the missing wedge, we currently do not have sufficient resolution to carry out this analysis in all three directions. This can be solved in future by combining the same method of sample preparation with a holder capable of 360° rotation.

By preparing a single wire test structure we have demonstrated the change in wire cross section induced by H\textsubscript{2} annealing during processing.

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