Materials characterization for process integration of multi-channel gate all around (GAA) devices

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ABSTRACT

Multi-channel gate all around (GAA) semiconductor devices march closer to becoming a reality in production as their maturity in development continues. From this development, an understanding of what physical parameters affecting the device has emerged. The importance of material property characterization relative to that of other physical parameters has continued to increase for GAA architecture when compared to its relative importance in earlier architectures. Among these materials properties are the concentration of Ge in SiGe channels and the strain in these channels and related films. But because these properties can be altered by many different process steps, each one adding its own variation to these parameters, their characterization and control at multiple steps in the process flow is crucial. This paper investigates the characterization of strain and Ge concentration, and the relationships between these properties, in the PFET SiGe channel material at the earliest stages of processing for GAA devices. Grown on a bulk Si substrate, multiple pairs of thin SiGe/Si layers that eventually form the basis of the PFET channel are measured and characterized in this study. Multiple measurement techniques are used to measure the material properties. In-line X-Ray Photoelectron Spectroscopy (XPS) and Low Energy X-Ray Fluorescence (LE-XRF) are used to characterize Ge content, while in-line High Resolution X-Ray Diffraction (HRXRD) is used to characterize strain. Because both patterned and un-patterned structures were investigated, scatterometry (also called optical critical dimension, or OCD) is used to provide valuable geometrical metrology.

Keywords: OCD, scatterometry, gate-all-around, GAA, XPS, XRF, strain, SiGe

1. INTRODUCTION

One key problem in continued scaling of semiconductors is the lack of control of electrostatic properties for conventional FinFETs below the 7nm nm node[1]. By using an architecture where the gate wraps around the channel, known as Gate All Around (GAA), there is improved control over current flowing through the channel. The device performance is a function of both the size of the channel and the surface area. By choosing a configuration of stacked nanosheets, one can maximize the surface area for improved control, while at the same time avoiding the problem of the channel being too small such that not enough current can flow through (as may be the case with nanowires). These are illustrated in Figure 1.

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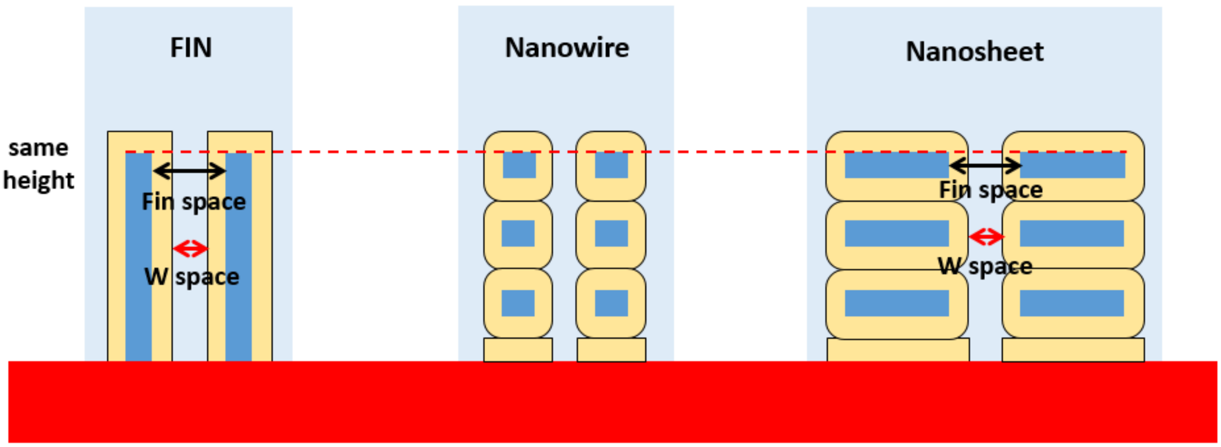

Figure 1: Comparing the Fin, Nanowire, and Nanosheet device structures.

In the manufacture of these devices, there are many key parameters that must be monitored and controlled to maximize performance and yield. The germanium concentration, as well as crystalline defectivity should be monitored. Other parameters of interest include the strain within each nanosheet, which affects the mobility of the electrons and holes, and the physical dimensions of the nanosheets before and after etching.

When the alternating layers of silicon and silicon germanium are deposited, the lattice mismatch between the two materials creates biaxial strain. After the blanket films are deposited, the structure is etched to produce uniaxially strained nanosheets (uniaxial because the etch allows the strain to be relaxed in one dimension)[2,3], as illustrated in Figure 2.

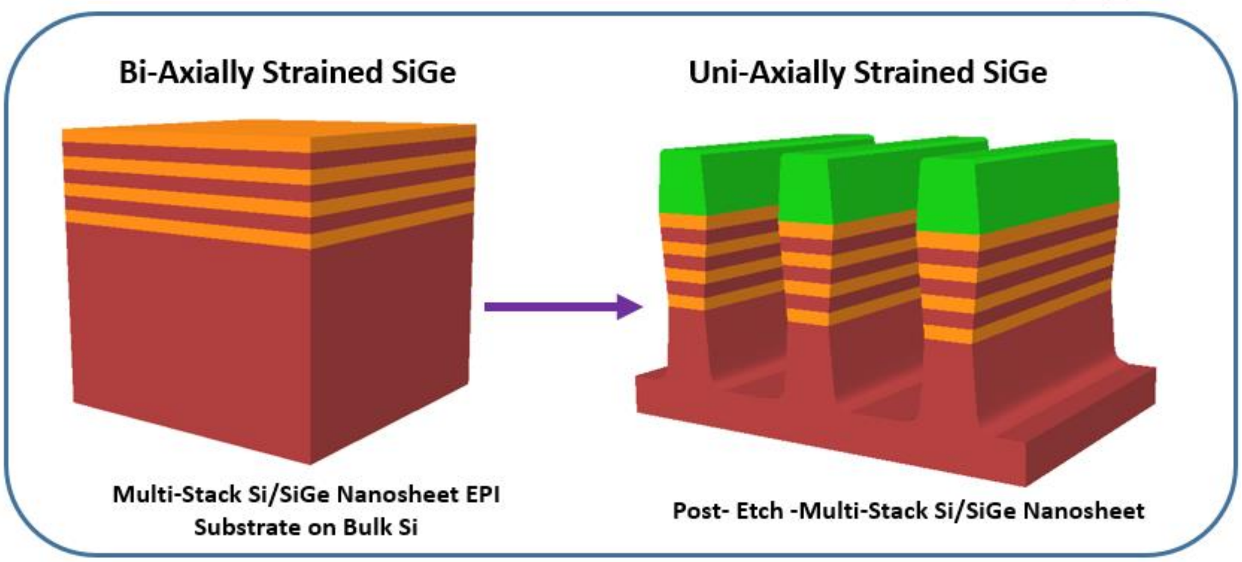

Figure 2: Left: blanket films have been deposited. Right: after etching.

2. DESIGN OF EXPERIMENT (DOE)

2.1 In-line Metrology Methods

Wafers were made containing three different SiGe concentrations to validate the ability to measure the SiGe concentrations and investigate the effect of strain. Measurements in this work are done using multiple metrology techniques. Scatterometry, also referred to as Optical Critical Dimension (OCD) is used, as are X-Ray Fluorescence (XRF), X-Ray Photoelectron Spectroscopy (XPS) and X-Ray Diffraction (XRD). Each measurement technique brings its own unique set of information to the table. OCD is an optical technique widely known for being a high-throughput technique capable of measuring geometrical and material information. XRF and XPS are often used in conjunction with each other, generating valuable thickness and composition information. In contrast to OCD, the XPS cannot extract information from much greater than 10nm below the surface, so this can only show the results for the top SiGe layer. XRD is valued for high accuracy thickness and compositional measurements of thin films.

2.2 Sampling

In this work, OCD is used to measure every die on every wafer at both the EPI deposition step and the etch step. XRF/XPS and XRD are also measured at both steps, with a lower sampling rate due to the longer measurement time, as shown in Figure 3.

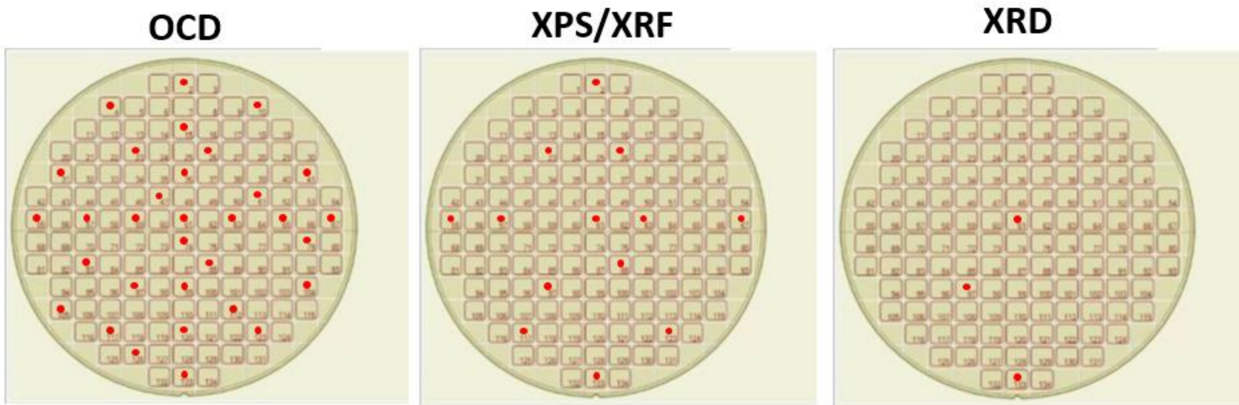

Figure 3: Sampling plans for different measurement tools.

3. RESULTS AND ANALYSIS

3.1 Epi Results

The alternating thin films of Si and SiGe are grown epitaxially. A schematic of them can be seen in Figure 4.

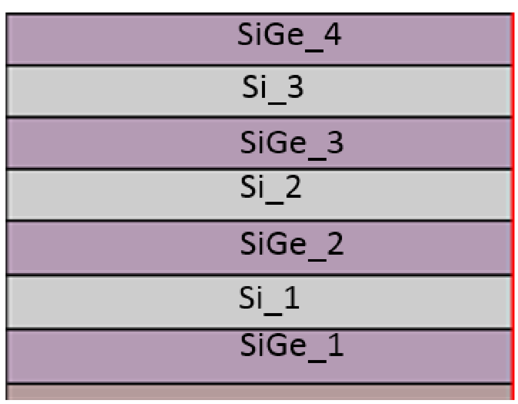

Figure 4: Schematic of alternating thin films.

3.1.1 OCD only

OCD is used to measure the films, and the results are shown in Figure 5. The differences in the germanium percent of the SiGe are easily identified. The germanium percentage concentration of the SiGe layers is a critical measurement parameter, and the OCD measurement is easily able to measure this (figure 5), thereby distinguishing the different DOE conditions across the wafers. Other measured parameters from the OCD measurement are also shown in figure 5, including the height of the top SiGe and Si layers, and the total height of the film stack.

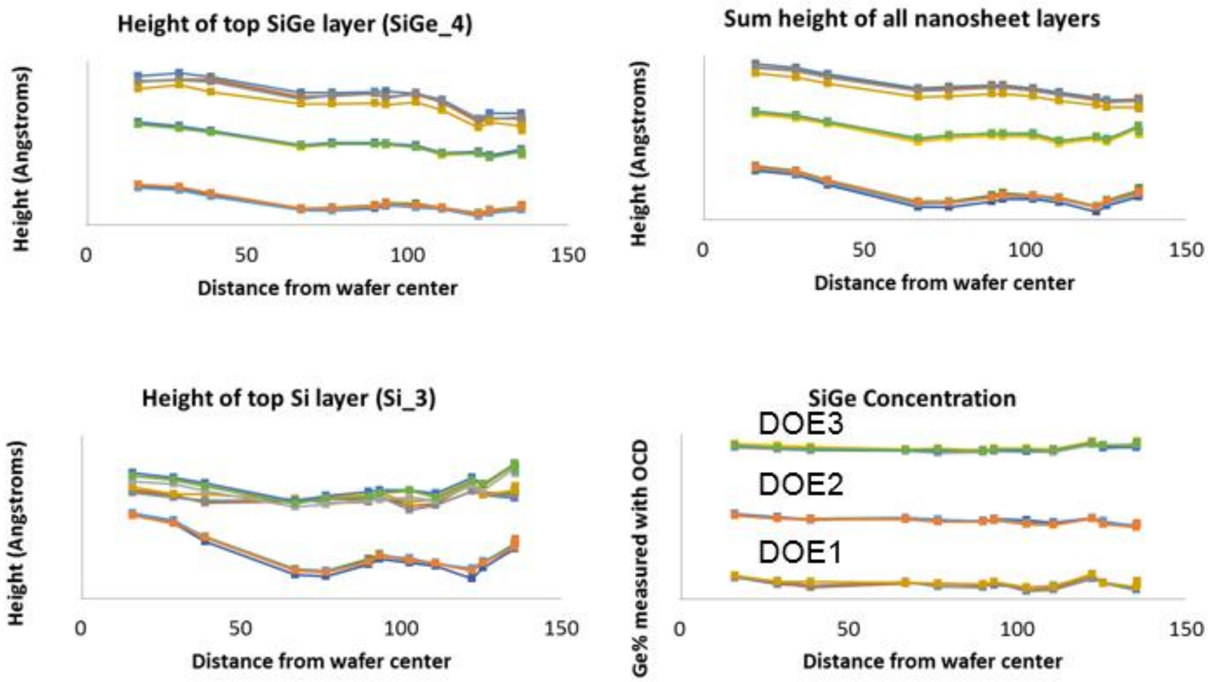

Figure 5: OCD results of epitaxial films after deposition.

3.1.2 XPS/XRF

Following the optical metrology measurements, XPS/XRF measurements are obtained, as shown in Figure 6. Similar to the OCD results, the split in the Ge% is easily identified. For this structure, the XPS is only sensitive to the top SiGe layer and part of the top Si layer. The model initially assumed that the top SiGe layer is ¼ of the total XRF signal, but after the XRD measurements became available, it was seen that there are differences in the thicknesses of the different SiGe layers. Because of this, the analysis was redone using the XRD measurement of the top SiGe layer as a reference, which improved the results of the Ge%, as is shown in Figure 7.

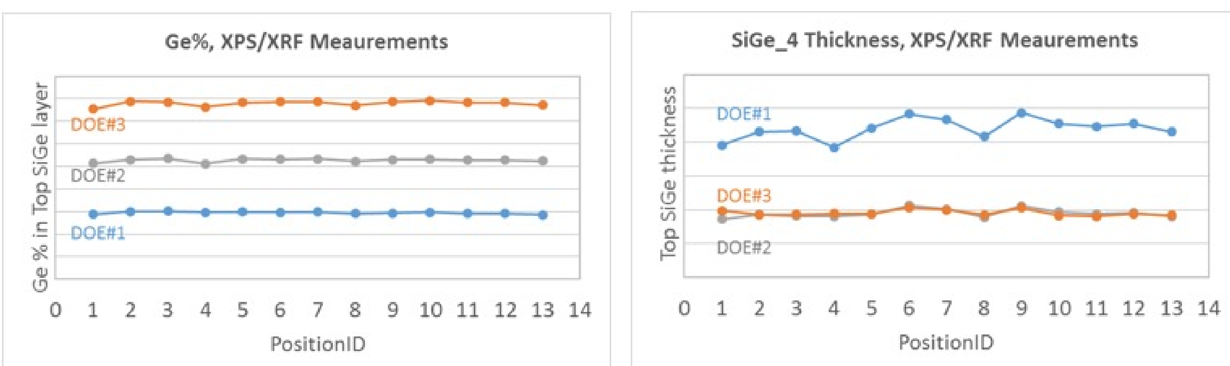

Figure 6: XPS/XRF results of epitaxial films after deposition.

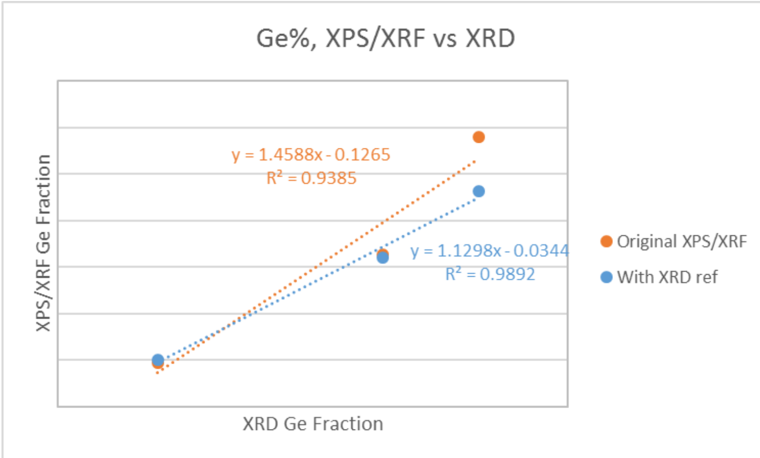

Figure 7: Comparing Ge% found with XPS/XRF to XRD.

3.1.3 OCD vs XRD

X-ray diffraction is used as an in-line reference to verify the other measurement techniques. Figure 8 shows good agreement between the OCD measurements of the sum of the nanosheet layers and the XRD result.

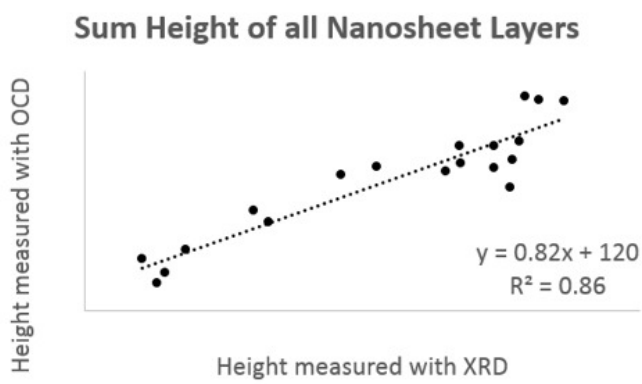

Figure 8: XRD results of epitaxial films after deposition.

3.2 Post Etch

After the alternating thin films are deposited, the wafers are etched to create fins, as shown in Figure 9.

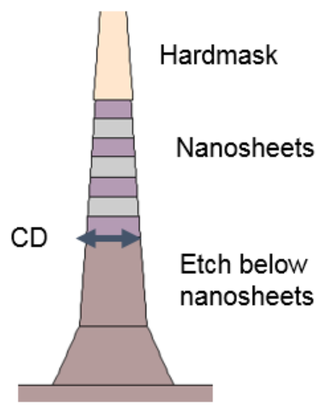

Figure 9: Post etch structure.

It is important to be able to measure several dimensions at this step for process control, including the remaining hard mask

(HM) height, the CD of the fin, and the total height of the fin (in this case, this is the sum of the heights of the alternating Si/SiGe layers plus the height of the etch into the bulk silicon below these layers). These results can be seen in Figure 10, and show a consistent behavior for all wafers.

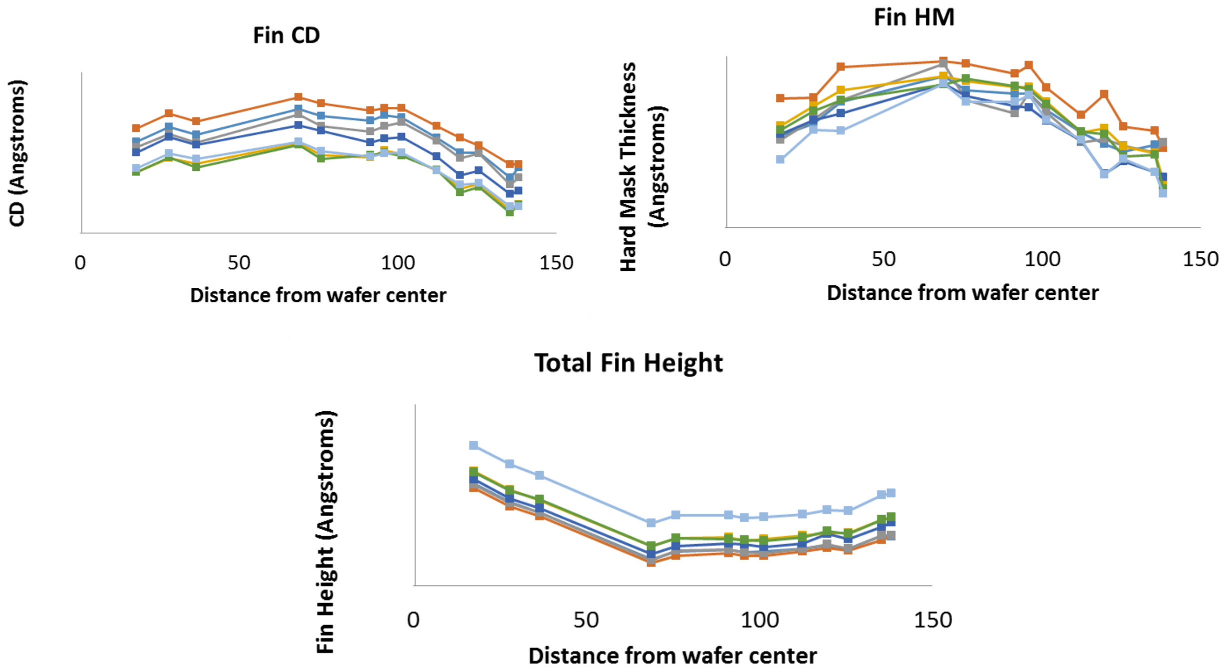

Figure 10: OCD results following etch.

3.3 Effects of process/strain on material properties

The information that OCD generates is based on both the geometry and the optical properties (refractive index n and extinction coefficient k) of the material. In the case of bulk materials, the optical properties typically do not change as a function of the geometry. However, in this work, we show that the n and k of the material change when the thin film layers are etched, as shown in Figure 11. This is because the n and k are affected by the strain of the material, and when the material is etched, the materials relax along the width of the channel[3,4]. As expected, a greater change was seen in the n and k for the SiGe with the highest concentration, which is shown in the RMS (root mean square) calculation results in Table 1.

Table 1: RMS (root mean square) calculation, showing change in the n and k for the different SiGe Concentrations. "DOE 1" has the lowest Ge concentration, while "DOE 3" has the highest.

RMS	delta_N	delta_K
DOE 1	0.068	0.068
DOE 2	0.102	0.101
DOE 3	0.138	0.135

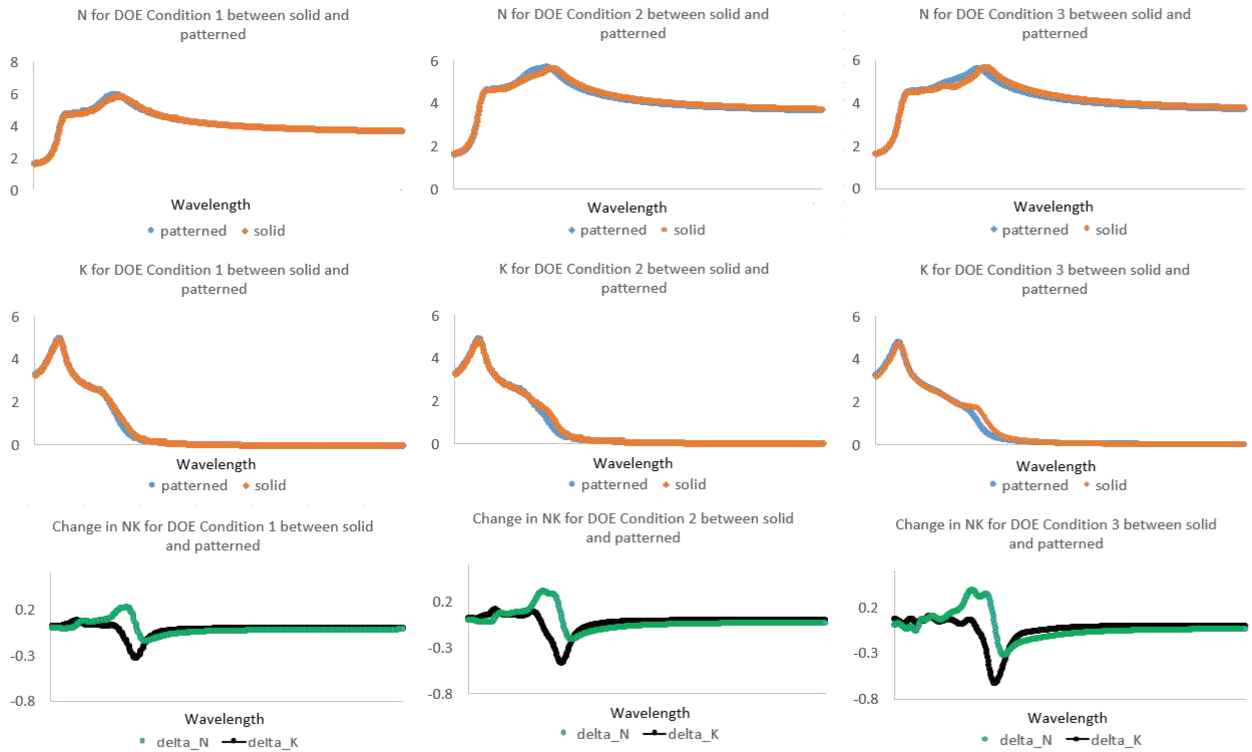

Figure 11: Change in n and k of SiGe between the solid and patterned structures for the three DOE conditions.

4. CONCLUSIONS

Through this work, we have developed advanced OCD, XPS, XRF, and XRD solutions for the measurement of early nanosheet fabrication steps. This includes the measurement of Ge%, total multi-stack thickness, and the thicknesses of the individual Si and SiGe layers. Good correlations between XRD and OCD of the total stack thickness, and between XRD and XPS/XRF of the Ge concentration, are demonstrated. It is also observed that OCD measurements after the etch step require optimization of the dielectric function of the SiGe layers to account for strain variation.

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REFERENCES

[1] Lauer, I., et al., "Si nanowire CMOS fabricated with minimal deviation from RMG FinFET technology showing record performance," 2015 Symposium on VLSI Technology (VLSI Technology), T140-T141 (2015).

[2] Muthinti, G. R., "Mueller based scatterometry measurement of nanoscale structures with anisotropic in-plane optical properties," Proc. SPIE 8681, 86810M (2013)

[3] Muthinti, R., Loubet, N., et al. "Advanced in-line optical metrology of sub-10nm structures for gate all around devices (GAA)," Proc. SPIE 9778, 977810 (2016).

[4] Muthinti, G. R., et al "Effects of stress on the dielectric function of strained pseudomorphic Si(1−x) Ge(x) alloys from 0 to 75% Ge grown on Si (001)," Journal of Applied Physics, 053519, 112 (2012).