Development of SiGe Indentation Process Control to Enable Stacked Nanosheet FET Technology

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Abstract— **The methodology of measuring the lateral etch, or indentation, of SiGe nanosheets by using optical scatterometry, x-ray fluorescence, and machine learning algorithms is presented and discussed. Stacked nanosheet device structures were fabricated with different etch conditions in order to induce variations in the indent. It was found that both scatterometry in conjunction with Spectral Interferometry and novel interpretation algorithms as well as TEM calibrated LE-XRF are suitable techniques to quantify the indent. Machine learning algorithms enabled an additional solution path by combining LE-XRF data with scatterometry spectra therefore avoiding the need for a full optical model.**

Keywords—nanosheet, scatterometry, x-ray fluorescence, metrology, machine learning.

I. Introduction

As compared to FinFETs, stacked nanosheet semiconductor devices require more measurements of critical parameters owed to the significant increase in process and device complexity. Also referred to as gate-all-around (GAA), stacked nanosheet FETs feature gates which wrap around the channels in order to improve electrostatic control. The additional complexities inherent in such an architecture combined with the ever-shrinking dimensions require precise process control for optimum device performance. One important process module in manufacturing nanosheet FETs is the inner spacer, which protects the channel from the source and drain region along with isolating the channels themselves [1,2,3,4]. A critical step prior to depositing the inner spacer is laterally etching the sacrificial SiGe nanosheet layers. The lateral etch step is alternatively known as a cavity etch or an indentation and a schematic depicting the structure after etch is shown in Figure 1.

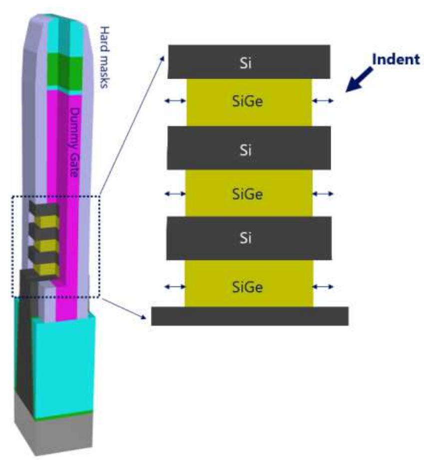

Fig. 1. Schematic drawing of a stacked nanosheet FET unit cell after SiGe indentation. The highlighted 2D section details the alternating Si and SiGe sheets with the lateral etch of the sacrifical SiGe.

Published studies discussing metrology solutions for process control related to the inner spacer of nanosheets have investigated the lateral etch on test structures with large and simplified features that do not include the complete device stack including dummy gates, for example, which is relevant for a metrology solution suitable for manufacturing [5,6].

It is very challenging to accurately measure the amount of the lateral etch with conventional metrology techniques for multiple reasons. In general, the volume change associated with the indent is very small, which usually results in very small signal changes of existing inline metrology techniques. Additionally, there are other possible structural and compositional variations within the complex 3D structure, which may lead to correlations and could impact the accuracy of the measurement.

This work demonstrates the development of inline metrology methodologies for accurately measuring dimensions of the indent for stacked nanosheet FET technology suitable for high volume manufacturing. Multiple methods to measure the lateral SiGe etch are explored with the primary metrology being optical scatterometry. Furthermore, low-energy x-ray fluorescence (LE-XRF) spectra are analyzed for Ge quantification as well as transmission electron microscopy (TEM) images acquired of selected samples for calibration purposes. The techniques bring different information content together and can be combined to measure the important dimensions in an accurate and precise manner. The use of machine learning algorithms to associate scatterometry spectra with LE-XRF results is also studied, which has the benefit of a fast time to solution without developing a full optical model.

II. Experiment

A. Design of Experiment

A set of patterned wafers with stacked nanosheet structures including dummy gate features are fabricated where the only intentional process variations are different amounts of lateral SiGe indentation, as shown in Table 1.

TABLE I: DESIGN OF EXPERIMENT

Wafer	Indent Etch
1-2	Etch 1 (shortest etch time)
3-4	Etch 2
5-6	Etch 3
7-8	Etch 4
9-10	Etch 5 (longest etch time)

B. Measurement Tools

The wafers are measured with advanced multichannel scatterometry (T600MMSR and NovaPRISM) and with Low Energy X-Ray Fluorescence (VeraFlexIII+). Scatterometry is used to obtain dimensional information. A location on the wafer is illuminated with a broad-band light source. The reflected light is collected across the entire wavelength range. Typically, a model is constructed based on the geometric parameters and optical properties of the measured features. An analytical technique such as rigorous coupled-wave analysis (RCWA) is used to calculate the diffraction from a periodic array of structures, and then interpret the measured data in order to obtain geometric and material information [7-9]. Spectral Interferometry, a unique channel of information introduced with the NovaPRISM scatterometry tool, is a novel method which provides exclusive information and increases the sensitivity to challenging structural parameters. LE-XRF is used in order to obtain elemental and compositional information. An x-ray photon collides with an atom and can eject an inner shell electron if it has sufficient energy. A second electron will then fall from a higher energy shell to fill the vacancy. The characteristic quantized energy loss of the second electron (x-ray photon) is used to identify which element is present in the sample [10]. Two TEM images from one wafer of each etch condition are analyzed to validate and calibrate the model results. Five wafers (one from each split condition) are measured with scatterometry and spectral interferometry, and all wafers are measured with conventional multichannel scatterometry and with LE-XRF. The optical scatterometry tools measured all full dies on the wafer, whereas the LE-XRF tool measured a subset of 10 dies per wafer.

III. Results and Discussion

A. Indent measured by scatterometry data modeling

In order to build an accurate scatterometry model, it is necessary to accommodate many degrees of freedom to account for potential process variations associated with the stacked nanosheet structure and employ strategies to optimize the sensitivity of the target measurement parameter while limiting correlations with other parameters.

The sensitivity to the SiGe indentation variation can be greatly enhanced by the use of Spectral Interferometry (SI) coupled with novel interpretation algorithms. An example of the sensitivity improvement when using SI to measure the indent parameter can be seen in the sensitivity plot in Figure 2. Theoretical spectra are calculated for two different indent values, which are 1 nm apart. The indent sensitivity, defined as the change in measured reflectivity for the specific geometry change, as a function of wavelength, is much greater with an SI channel as compared to a conventional scatterometry channel.

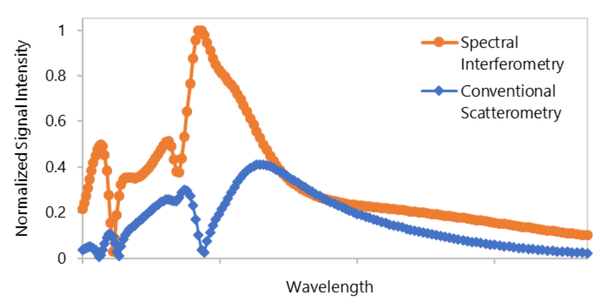

Fig. 2. Normalized signal intensity variation as a function of wavelength for conventional scatterometry and Spectral Interferometry channels when the SiGe indent parameter is varied by 1 nm.

The final scatterometry model solution utilizing spectra acquired only post indentation is able to directly measure the amount of the lateral etch. The accuracy of the results can be seen based on the comparison to ten TEM images, with an R^2 of 0.896, as shown in Figure 3.

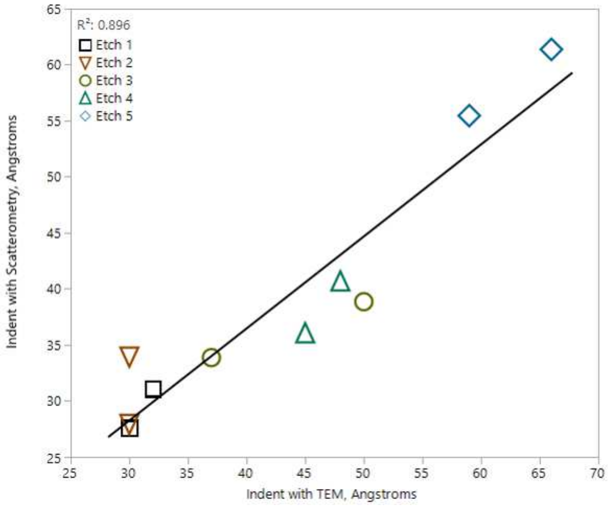

Fig. 3. Comparison of TEM and scatterometry results for the SiGe indentation design of experiments.

B. Indent measured by LE-XRF counts

Representative LE-XRF measurements for Etch1 and Etch5 are presented in Figure 4. The graphs show the normalized Ge Lα peak from a single die from two wafers, measured before and after the indentation process. Figure 4b illustrates that the shortest etch time (Etch1) results in lower Ge Lα counts as compared to the pre indentation measurement indicating the Ge and therefore SiGe has been removed. Furthermore, there is about a 30% difference in peak height between Etch1 and Etch5, which corresponds to approximately 3 nm indent variation, indicating that the LE-XRF is highly sensitive to minute amounts of Ge differences.

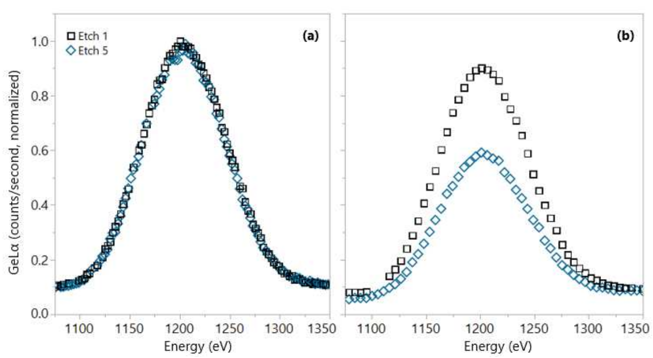

Fig. 4. Ge Lα counts as measured by LE -XRF, both (a) before and (b) after the indentation, for two of the different DOE conditions, Etch1 and Etch5.

However, in order to account for possible process variations related to the Ge fraction, the nanosheet thickness as well as the lateral dimension, only a count difference between pre and post indentation measurements can lead to most accurate

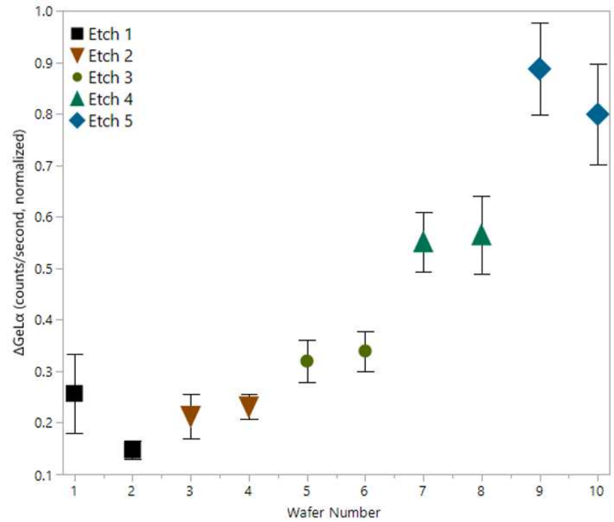

Fig. 5. Ge Lα count difference from pre and post indentation measurements as a function of wafer number. The individual data points are wafer averages and the error bars indicate the within wafer variation. An increasing ΔGe Lα corresponds to an increasing lateral SiGe etch.

indentiation measurements. Figure 5 shows the result after subtracting the Ge Lα counts measured after the etch from the counts measured before the etch, in order to determine the actual amount of Ge removed by the etch. The data presented here represent the average value per wafer. As expected, larger amounts of Ge are removed with increasing etch time. The wafer to wafer variations observed for shortest and longest etch times are due to non-optimized process conditions in these etch regimes.

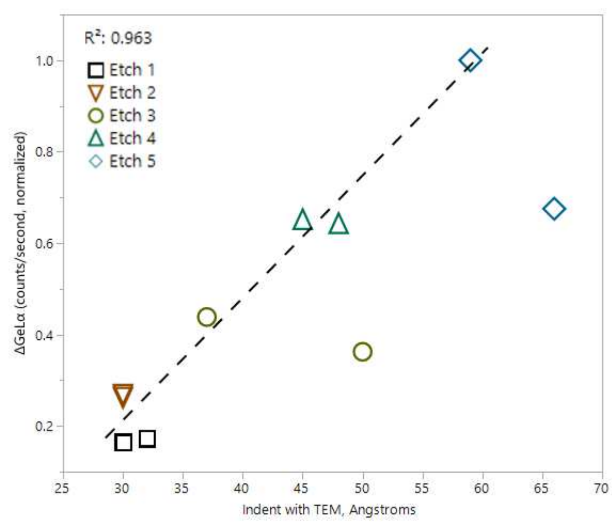

Fig. 6. Comparison of LE-XRF (ΔGe Lα) and TEM results for the indent. The dashed linear fit line is calculated without the two outliers (TEM = 50 Å and 66 Å).

In order to convert the XRF counts to the amount of laterally removed SiGe in nanometers, the data must be calibrated with measurements obtained from TEM images. As shown in Figure 6, overall a good correlation is observed between the

ΔGe Lα counts and the indent dimensions obtained from TEM image analyses. However, two outlier points are present, which originate from the edge of the wafer and are possibly related to processing and pattern recognition issues. If these points are removed, the correlation is excellent with an R^2 of 0.962. Calibration of the measured XRF counts to the TEM image analysis allows for accurate measurements of the indent parameter with two XRF metrology steps, one before and one after the SiGe etch process.

C. Indent measured by machine learning

A third indentation measurement procedure is presented, which uses machine learning to combine the two metrology techniques by directly relating the LE-XRF ΔGe Lα counts to the scatterometry spectra [11-15]. The trained machine learning model results using the scatterometry spectra post indentation in comparison to the actual LE-XRF data are shown in Figure 7.

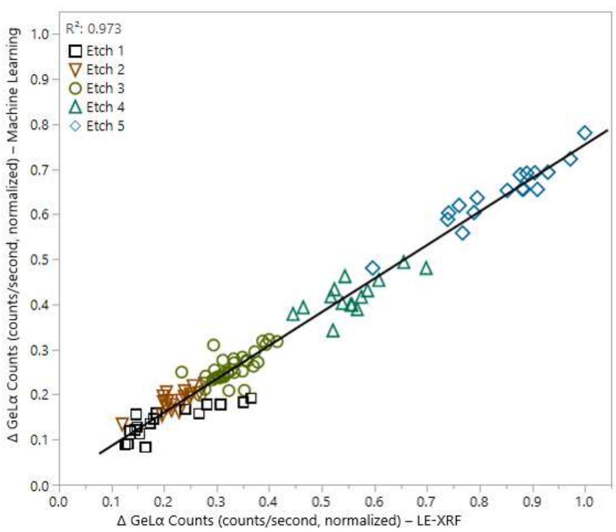

Fig. 7. Comparison of ΔGe Lα between machine learning based scatteromerty (post indent metrology only) and LE-XRF metrology (pre and post indent metrology).

Since the machine learning algorithm output is in the form of counts a conversion to a dimensional indentation parameter is required, which can be achieved based on TEM image calibration similar to what is shown in Figure 6. The results of the trained machine learning model with a dimensional output parameter in comparison to the TEM indentation values are presented in Figure 8. The accuracy of this methodology with respect to TEM image analysis is $R^2 = 0.872$, which is comparable to what was achieved with the full scatterometry model using NovaPRISM SI channels and novel interpretation algorithms. The machine learning solution combines the high-throughput of scatterometry metrology with the fast time to solution of LE-XRF analyses and has the additional advantaged that a traditional optical model is not required. Only a few TEM image analyses are needed for converting the counts to a quantifiable lateral indent in nanometers.

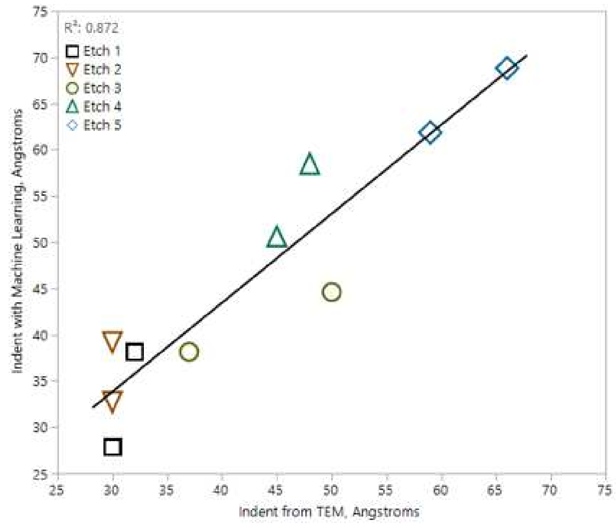

Fig. 8. Comparison of the dimensional indent as a result of the machine learning algorithm and the indent obtained from TEM image analyses.

CONCLUSIONS

We have demonstrated the ability to accurately measure the lateral SiGe etch at the critical indentation step prior to the inner spacer deposition. This is one of the most critical steps to monitor to ensure reliable and good nanosheet FET device performance. Three different approaches of quantifying the SiGe indentation were presented: a scatterometry model utilizing SI spectra and novel analysis algorithms, LE-XRF count differences calibrated by TEM, and machine learning using LE-XRF count differences and scatterometry spectra. Using a large DOE set, very good agreement between all three approaches and TEM image analyses was observed. The scatterometry model in conjunction with novel analysis algorithms yielded the best match to reference. The LE-XRF methodology is simple but requires a pre and post indentation metrology step for best accuracy. The machine learning based scatterometry model combines the fast time to solution of XRF with the fast throughput of optical spectra acquistion and does not require an often cumbersome three-dimensional optical model.

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