PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Full structure transistor process monitoring of boron and germanium in PFET EPI using in-line XPS

Jusang Lee, Ganesh Subramanian, Manasa Medikonda, Hossam Lazkani, Judson Holt, et al.

Jusang Lee, Ganesh Subramanian, Manasa Medikonda, Hossam Lazkani, Judson Holt, Churamani Gaire, Paul Isbester, Mark Klare, "Full structure transistor process monitoring of boron and germanium in PFET EPI using in-line XPS," Proc. SPIE 10959, Metrology, Inspection, and Process Control for Microlithography XXXIII, 109590N (23 May 2019); doi: 10.1117/12.2515266

SPIE.

Event: SPIE Advanced Lithography, 2019, San Jose, California, United States

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Sep 2019 Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

Full structure transistor process monitoring of boron and germanium in PFET EPI using in-line XPS

Jusang Lee [a], Ganesh Subramanian [a], Manasa Medikonda [a], Hossam Lazkani [a], Judson Holt [a], Churamani Gaire [a], Paul Isbester [b], Mark Klare [b]

[a] GLOBALFOUNDRIES, 400 Stonebreak Road Extension, Malta, NY 12020, USA
[b] Nova Measuring Instruments, Inc., 3090 Oakmead Village Drive, Santa Clara, CA 95051, USA

ABSTRACT

The epitaxial growth of source/drain structures demands a process with tight control of boron and germanium composition to ensure consistent device performance. However, in-line monitoring of the epitaxial composition in FINFET structures has been one of the most difficult challenges for both process development and manufacturing. Traditional in-line monitoring schemes have relied heavily on critical dimension (CD) measurements, with no composition information. Instead, composition information was provided by offline analysis techniques such as secondary ion mass spectrometry (SIMS), which is destructive and does not measure the composition directly on the FinFET device structure. In this paper, we present results from in-line X-Ray Photoelectron Spectroscopy (XPS) measurements on FinFET structures. This technique is not only sensitive to individual element abundance but also gives information related to the local chemical environment. For this application we monitored silicon, germanium, and boron concentrations in SiGeB EPI source/drain 3D structure without interference from other structural features in the logic device. The in-line XPS measurement of PFET EPI boron and germanium performed in this way on the full structure transistor has been demonstrated to correlate with CMOS device performance, thus significantly reducing time to detect epitaxial composition drift or excursion.

Keywords: In-line XPS, metrology, boron, process monitoring, Epi, germanium, SiGe, FinFETs.

1. INTRODUCTION

A basic field effect transistor (FET) as presented in figure 1 consists of a source, drain, and control gate. Doping silicon with Group III elements such as boron creates mobile holes in the valence band resulting in p-type semiconductor material. During epitaxial growth additional elements such as germanium are used to adjust lattice strain to further improve the electrical performance of the semiconductor device. For improved device performance many advance semiconductor nodes have moved from planar to FinFET device architecture, as shown[1] in figure 2. The source and drain in these FINFET structures are grown epitaxially into complex 3D geometries with specific tailored dopant and elemental composition to provide desired electrical performance in the final device. These 3D FINFET structures provide challenges to the in-line control of both the epitaxial structure and composition. Measuring structure with techniques such as optical critical dimension (OCD), critical dimension scanning electron microscopy (CDSEM) or other in-line techniques is effective for size control, but does not give any information about composition, which is critical for controlling electrical performance[2]. Instead, composition is typically measured on large planar pads using secondary ion mass spectroscopy (SIMS), X-Ray diffraction (XRD), X-Ray Fluorescence (XRF), XPS, ellipsometry, and resistivity. Although those techniques are sensitive to low level dopant concentrations, interpretation of those measurements is complicated by process loading effect differences between the large planar pads and device-like 3D structures[2]. As a result of these challenges, when evaluating 3D FINFET EPI device performance, problems related to dopant concentration are often only revealed after many process steps during electrical testing.

Metrology, Inspection, and Process Control for Microlithography XXXIII, edited by Vladimir A. Ukraintsev, Ofer Adan, Proc. of SPIE Vol. 10959, 109590N © 2019
SPIE · CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2515266

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Sep 2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

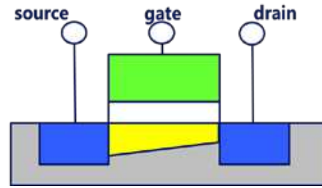

Figure 1: Planar transistor where electrical flow between epitaxially grown source and drain is governed by voltage applied to the gate

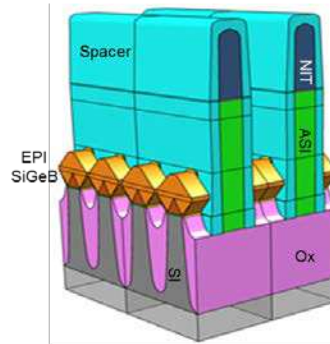

Figure 2: Representative FINFET 3D structure with diamond shaped SiGeB epitaxy.

2. BACKGROUND AND MOTIVATION

In-line metrology utilizing XPS provides several advantages over geometric or traditional material composition techniques in that the electron binding energy is directly related to not only the element of origin but also the local chemical environment. For the case of XPS measurements on complex 3D FINFET structures, the non-planar geometry is actually beneficial as it reduces undesirable plasmon peaks observed on blanket wafers. As shown in figure 3, the binding energy of boron at 188 eV overlaps with the significantly stronger Si2s resonance plasmon at 185 eV. Isolating the silicon into fins such as in 3D FINFET structures reduces the silicon lattice resonance and resulting plasmon signals, resulting in improved sensitivity for B1s peaks while also directly measuring the epitaxial composition in a device-like structure (figure 4).

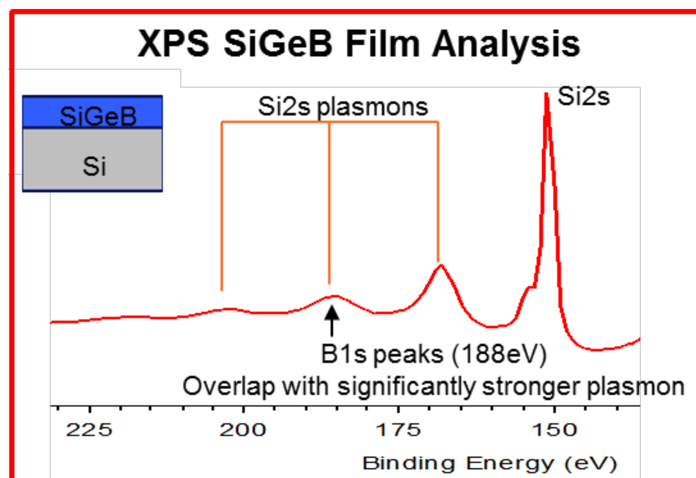

Figure 3: XPS spectrum of SiGeB on a blanket Si wafer showing strong Si2s resonance plasmons.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Sep 2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

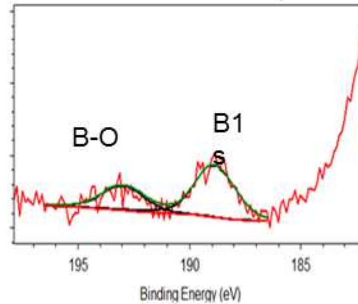

Figure 4: B1s spectrum from SiGeB epitaxy grown on a 3D FinFET structure which demonstrates the significant reduction of Si2s resonance plasmons to provide integrateable peaks (B1s and B-O) for determination of boron concentration in source/drain epitaxy.

As a result, in-line XPS allows for much tighter epitaxial process control, enabling tighter control of device performance. In this work, we will demonstrate a monitoring scheme that selectively monitors Si/Ge/B concentrations in a PFET structure using XPS. A set of full flow product wafers with various Si/Ge/B process conditions was analyzed in line with XPS, and the XPS results correlated to device electrical test results. Multiple experiment wafers were processed with varying epitaxial conditions, including different power and Ge and B precursor gas flows. Various techniques were used to characterize the completed process. These techniques included CD-SEM, Resistivity, XRD, OCD and in-line XPS. The full flow wafers were then advanced to electrical test (e-test) to compare device performance to inline metrology. The final results were tabulated, and all techniques were compared to e-test for all the varying process conditions. Each characterization technique was compared to e-test result, and ranked according to its correlation to critical parameters.

3. RESULTS

3.1 Comparison of in-line XPS to offline SIMS

For the assessment of dopant concentrations of EPI, offline SIMS provides a well calibrated depth-resolved measure of Boron concentration on solid pad sites. However, offline techniques result in significant delay between the time of EPI formation to the time of analysis, and can only be done on a small number of samples, both of which render unacceptable for statistical process control. In addition, SIMS is only able to characterize the composition on a representative solid measurement pad, in which may have elemental composition differences when compared to the composition in an actual device structure. In order to demonstrate the correlation between these measurement methods, source/drain epitaxy process with a series of different B2H6 precursor flows was grown on both FinFET production wafers (measured in-line with XPS) and blanket Si wafers (measured off-line with SIMS), and the results are shown in figure 5. We see comparable trends for boron dopant concentration with respect to B2H6 flow for each method. However, there are several points that should be mentioned. First, it is evident that the in-line XPS %B has a non-linear dependence on gas flow, compared to the linear response of the SIMS measurement. This is likely due to epitaxial dopant saturation in the device area, but it could also be due to an XPS measurement artifact. Second, the XPS reported value of the Boron concentration (between 10% - 20% B) is significantly higher than the SIMS value (between 1e20 – 2e20 atoms/cm^3). Part of that discrepancy is due to epi loading effect between blanket and patterned wafers, but even given that difference the XPS value is simply not physically possible. That is, any epitaxial film that contained >10% B would show high levels of defectivity, which are not observed. However, the fact that good correlation extends across a large process range validates the use of in-line XPS for statistical process control.

3.2 Comparison of in-line XPS to other in-line metrology

Wafers processed on different epitaxial chambers were evaluated by multiple in-line metrology tools such as XPS, CD-SEM, and OCD to assess response to variation in B_2H_6 flow, as shown in figure 6. Only XPS was able to differentiate healthy epitaxial chambers compared to those that required tuning. In addition to the device impact (discussed below), mismatched boron can also result in significantly higher defectivity. Figure 7 shows that elevated concentration of boron (as measured by in-line XPS) is directly correlated to higher on-wafer defectivity, in this case due to an epitaxial process tuning issue.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Sep 2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

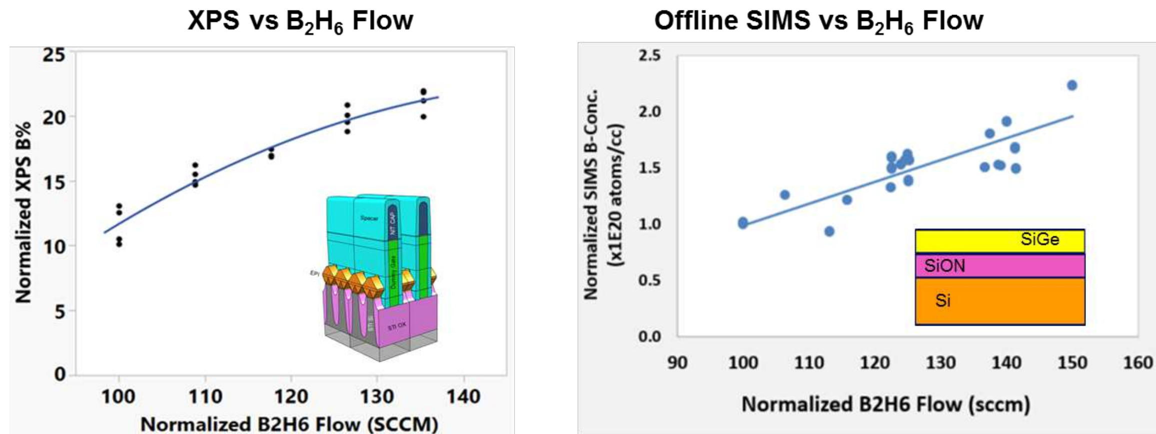

Figure 5: Offline SIMS analysis of epitaxial films on blanket Si utilized as reference metrology for boron concentration in source/drain EPI. Both SIMS and in-line XPS provide direct correlation of boron concentration to B_2H_6 flow but XPS measures on device-like 3D structure whereas SIMS evaluates EPI grown on a blanket Si wafer.

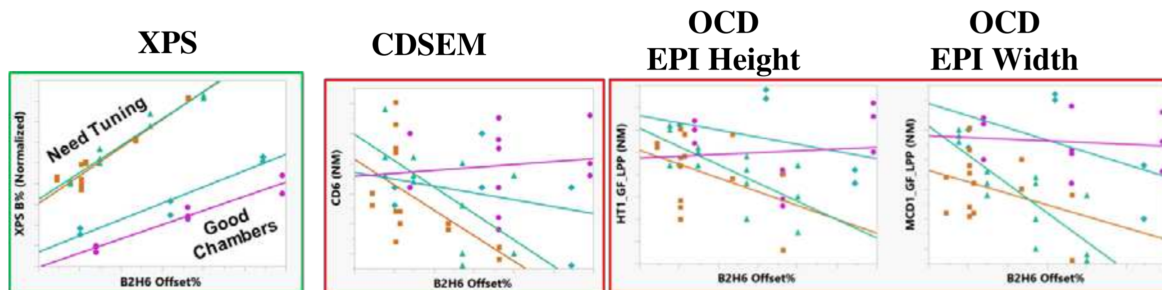

Figure 6: CDSEM, OCD, and XPS vs boron flow offset from multiple EPI chambers. Only in-line XPS was successful in identifying chambers which required tuning.

3.3 Effective electrical test

In-line device electrical test provides a direct measurement of device performance. Wafers measured with both in-line CDSEM (for EPI size) and XPS (for boron concentration) after source drain epitaxial growth were measured at electrical test. Figure 8 shows the correlation of device performance (as measured by Ieff) with both CDSEM epi size and XPS %B. Furthermore, to characterize the cross-device loading effect both 2 fin and 40 fin structures were tested. Compared to in-line CDEM, XPS boron % showed significantly clearer correlation with device performance, and especially good correlation to the ratio of the Ieff performance of the different devices measured (2FIN/40FIN).

4. CONCLUSION

In summary, we have demonstrated that in-line XPS compelling capability for in-line statistical process control of boron-doped source/drain epitaxy on FinFET structure, with good correlation to off-line SIMS, in-line defectivity, and device performance measured at electrical test. Being able to directly measure boron on the 3D FinFET structure also bypasses potential epitaxial loading effect differences that can be seen between blanket wafers and device structures. In-line XPS can be measured directly following epitaxial growth which decreases the turn-around time for identification of dopant concentration excursion or drift which can directly impact device electrical performance.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Sep 2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

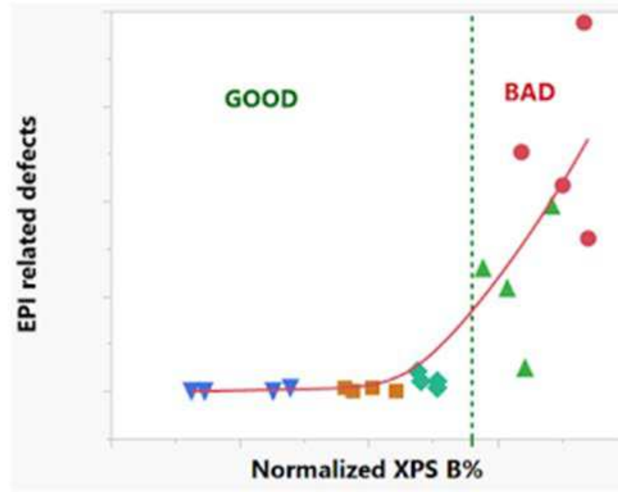

Figure 7: In-line defectivity vs. normalized XPS B% on patterened FinFET wafers.

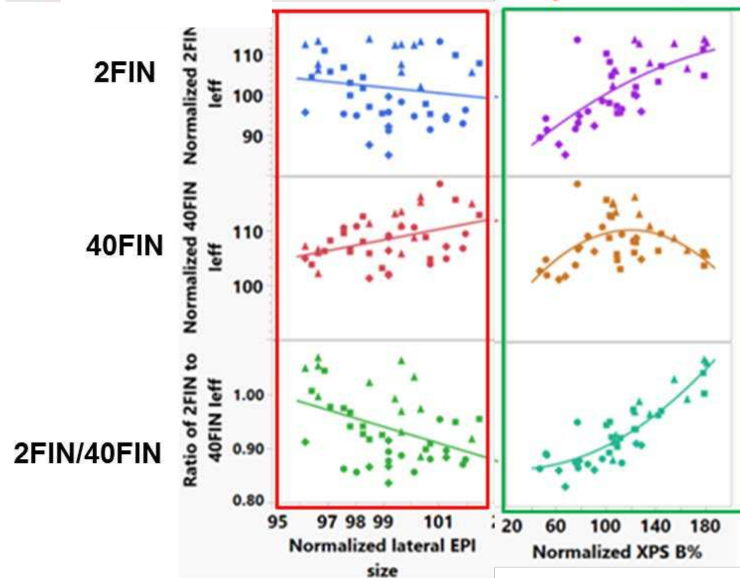

Figure 8: Correlation of effective device performance (Ieff) to epitaxial lateral dimension (as measured by CDSEM) and XPS B%. Device performance was measured on two different device structures (2FIN and 40FIN) and the ratio of the performance of those two stuctures is also shown.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Sep 2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

REFERENCES

[1] John F Watts, “X-ray photoelectron spectroscopy,” Elsevier Science Ltd, Vacuum, vol. 45, no. 6/7, pp. 653-671, 1994.

[2] C. Thomas Larson, Emir Gurer, and J. Kelly Truman, “Using an XPS-based metrology system to determine film thickness and composition,” Micro, Defect/Yield Analysis and Metrology, April 2005.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 09 Sep 2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use