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Analyzing the channel dopant profile in next-generation FinFETs via atom probe tomography

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ABSTRACT

Dopant analysis in next-generation semiconductor devices has become increasingly difficult for traditionally used analytical techniques. Atom probe tomography has been viewed by some as a possible solution to these challenges because of its three-dimensional capabilities, forcing the atom probe to mature at a rapid pace in this particular field. This work presents a well-rounded analysis of how APT can be used to examine B dopant diffusion into the channel of a next-generation FinFET, where the channel dimensions and the number of dopants atoms are significantly smaller than any devices measured by APT to date. Complimentary EELS analysis of the gate and channel provides a better understanding of how distortions and artifacts in the APT reconstruction affect the overall integrity of the dataset. Dopant measurements in the channel are confirmed through in-depth mass spectrum analysis and compared with values proposed by TCAD modeling.

1. Introduction

Measuring low atomic number dopant (*i.e.*, boron) distributions in advanced semiconductor devices continues to become a more and more complex task as device dimensions continue to shrink, following the International Technology Roadmap for Semiconductors (ITRS). Challenges to advanced analysis arise due to both structural and compositional complexity, which often go hand-in-hand for state-of-the-art fin field-effect transistors (FinFETs). The three-dimensional (3D) shape and extremely small critical dimensions of next-generation devices present structural challenges while simultaneously leaving a very small number of actual dopant atoms within the source/drain and channel regions to measure, making measurement efficiency and/or sensitivity increasingly important. Likewise, the complex arrangement of metals, semiconductors, and insulators in close proximity within these devices can obscure analysis via certain techniques, requiring meticulous sample preparation, and very careful interpretation of the data collected. For example, as device dimensions shrink, lamella thickness must follow suit to eliminate unwanted projection effects in transmission electron microscopy (TEM). Additionally, elemental analysis in actual devices (rather than planar test sites) by techniques such as secondary ion mass spectroscopy (SIMS) becomes exceedingly complicated due to the complex arrangement of materials with differing sputter rates, matrix effects, and extremely small device dimensions, requiring advanced methods for data interpretation.

Three-dimensional analysis via atom probe tomography (APT) is increasingly popular in microelectronics, [1–5] though certainly complicated to perform on FinFET devices compared to some commonly used imaging and elemental analysis techniques (*e.g.*, TEM and associated elemental analysis techniques). The major advantage of APT lies in its ability to perform both 3D structural and elemental analysis of not only surface but also buried features and to do so from any desired perspective. [6–8] For FinFETs, the dopant profile at the interface between the source/drain and the channel is crucial to device performance and, therefore, although this analysis is challenging for next-generation devices, it is critical for understanding and tailoring device properties. The atom probe's ability to measure low atomic number dopants [1,2,6–9] such as boron and map concentrations in 3D [9] with sub-nanometer resolution [10–12] makes it a unique candidate for FinFET analysis where structures are complex and critical dimensions are small. [6,9] While FinFETs in a very broad sense have been analyzed by APT going back to at least 2011, [7,8] those devices were extremely large in comparison to current-generation devices [6,9] (*i.e.*, those devices being currently manufactured by world-leading semiconductor companies) and particularly compared to next-generation devices as presented in this work (*i.e.*, those devices not yet implemented in today's products). This is significant because as the devices scale down to the dimensions of next-generation technology, the specific challenges change and become increasingly diffi-

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cult and more complex for all characterization techniques, including APT.

These very small device dimensions mean that elemental analysis within the channel of next-generation FinFETs requires measuring a very small number of dopant atoms, perhaps on the order of a few dopant atoms per 1000 nm^3! And the entire channel is less than 10x that volume for next-generation FinFETs! This small number of dopants represents those which have (unintentionally) diffused from the source/drain into the channel during subsequent annealing steps in the flow of device processing. While the required level of measurement sensitivity is generally not a problem for APT (approximately 0.01–0.1 at.%, 5×10^{18}–5×10^{19} cm^{-3}), in small analysis volumes, noise levels can be a significant problem. This is particularly true for dopant measurements within the channel of a FinFET due to the surrounding gate, which is comprised of a number of films with much higher evaporation field than that of the Si channel. These higher-field layers add to the noise level even if the mass spectrum from the actual analyzed volume (in this case the Si channel) is isolated from the surrounding gate.

High-field materials in the gate are expected to have a significant effect on the field-evaporation and reconstruction of the Si channel, [1,13–15] which is the primary area of interest in this work. The most significant distortion to the channel is expected to be normal to the plane of the fin due to the orientation of the gate films that wrap around the Si fin. For example, artificial compression of low-field regions (*i.e.*, the Si channel) and artificial expansion of higher-field regions (*e.g.*, the gate oxide) will cause distortions and artifacts in the reconstruction. Therefore, understanding distortions normal to the plane of the Si channel is critical. Due to the 3D nature of APT, analysis can be performed in any desired direction. Therefore, the same analysis volume used to examine the dopant profile in the channel can also be used to analyze distortion normal to the plane of the channel, providing a better understanding of how these anticipated distortions affect the integrity of dopant measurements in the channel.

To correct for some distortions, alignment with well-established, measured, critical dimensions or atomic density measurements (compared to theoretical values) can be used. [6] In these cases the dimensional integrity of the APT reconstruction can be strongly trusted. However, in some situations, some skewing of dimensions is still unavoidable. This is the case for the channel of a FinFET where the dimensional accuracy of the APT reconstruction cannot be fully corrected in every direction due to the complex arrangement of various films as just discussed. [9,13,14] This is particularly true normal to the plane of the fin where the Si channel is artificially “squeezed” by the higher-field materials in the gate, which wraps around it. [16] Furthermore, the difference in evaporation field between each of these gate films can result in overlapping trajectories of neighboring atoms creating a “blurry” interface between individual films in the structure. [17] Defining the different films within the gate by plotting elemental concentration measurements done by APT is also complicated due to the common use of certain elements in several of the films in the gate (*i.e.*, Ti, N, O). For these reasons, electron energy-loss spectroscopy (EELS) two-dimensional (2D) mapping can be used to provide perhaps not an ultimate standard, but at minimum a ruler by which to correlate APT measurements of the various films in the gate, and perhaps provide some information about the integrity of the Si channel itself. The dimensional accuracy supplied by TEM provides a metric by which to judge the dimensional accuracy of the APT reconstruction, and in return, APT provides actual concentrations for each layer in the gate where EELS does not (although the ultimate accuracy of the APT concentrations certainly contains some error, dependent on the particular layer and its neighboring films).

In this paper, we demonstrate how APT can be used to analyze boron dopants, which have diffused into the channel of a next-generation FinFET. First, compositional and structural analysis normal to the channel is presented and compared with complimentary EELS mapping to examine the integrity of the APT reconstruction in the direction most susceptible to significant distortion. Second, channel dopant measurements are presented and verified via in-depth mass spectrum analysis, and the APT data is compared to computer modeling of the dopant profile in the channel performed using Technology Computer Aided Design (TCAD).

2. Experimental procedure

APT analysis was performed on a wafer processed through the first metal wiring layer (M1), including annealing for dopant activation and electrical device testing in nearby test pads. The area selected for APT contained a series of devices processed identically to those in nearby electrically tested pads, but without metal contacts to the top of the source/drain or gate. Therefore, the properties of the channel and source/drain regions are expected to be representative of the electrically tested devices, but tungsten, which is typically used in the contacts and is notoriously difficult to field-evaporate in semiconductor devices, was avoided. The APT tip presented in this work was prepared for APT using a standard sample preparation method similar in fashion to that described by Thompson et al. [18] The tip was field-evaporated all the way through the shallow trench isolation (STI) regions on either side of the fin and into the Si substrate.

Field evaporation was performed in a Cameca FlexTAP 3D Atom Probe at 50 K under ultra-high vacuum conditions ($\sim 4 \times 10^{-11}$ Torr) using a 35 nJ (spot size ~20 µm) UV laser. Laser energy was decreased throughout evaporation to retain a Si^{++}: Si^{+} ratio of approximately 10:1. The laser frequency was 50 kHz and the detection rate was approximately 0.50%. The FlexTAP was operated using the largest diaphragm position of 30° (“cross-over” mode) in order to maximize the captured cross-section of the tip. The captured volume included the entire channel with more than a third of the SiGe source/drain on one side and a small portion of the SiGe source/drain on the opposing side. The data reconstruction and all APT analysis were performed using the Integrated Visualization and Analysis Software (IVAS). The shank angle method was found to provide the most accurate reconstruction. The detector efficiency value in IVAS was decreased in order to match the APT dimensions of key features to those of scanning electron microscopy (SEM) from the actual final APT tip and TEM from the same test site (presented in this work). A decrease in detector efficiency is expected for such a device due to the high evaporation-field of materials in the gate, surrounding the Si fin, and the insulating layers around the source/drain. STI height, shank angle and tip diameter at specific features were matched to SEM of the APT tip. Gate height and width and source/drain height were matched to TEM.

High angle annular dark field scanning transmission electron microscopy (HAADF STEM) imaging and EELS analysis of the gate materials were performed on a neighboring device to that analyzed by APT (*i.e.*, within a few microns of each other) to guarantee complementary analysis. The specimen for cross-sectional STEM analysis was prepared by traditional focused ion beam (FIB) technique where the lamella was thinned to ~50 nm. STEM imaging and EELS analysis were performed using a probe corrected high resolution FEI Titan TEM operated at 200 kV. The low loss EELS spectrum was acquired at 0.03 s and the high loss EELS spectrum was acquired at 0.2 s.