Cross-sectional atom probe tomography sample preparation for improved analysis of fins on SOI

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ABSTRACT

Sample preparation for atom probe tomography of 3D semiconductor devices has proven to significantly affect field evaporation and the reliability of reconstructed data. A cross-sectional preparation method is applied to state-of-the-art Si finFET technology on SOI. This preparation approach advantageously provides a conductive path for voltage and heat, offers analysis of many fins within a single tip, and improves resolution across interfaces of particular interest. Measured B and Ge profiles exhibit good correlation with SIMS and EDX and show no signs of B clustering or pile-up near the Si/SiGe interface of the fin.

1. Introduction

Atom probe tomography (APT) is rapidly becoming a highly desirable characterization technique for analyzing semiconductor devices, particularly, interfaces and light dopant profiles in source/drain areas of various planar and three-dimensional (3D) device structures [1–3]. Semiconductor devices continue to follow the International Technology Roadmap for Semiconductors, thus, demanding an attainable lateral shrink and driving the introduction of 3D shapes (vertical scaling) such as fin-shaped field-effect transistors (finFETs). These 3D devices pose characterization challenges and drive the development of new analytical techniques and capabilities. Transmission electron microscopy (TEM) and scanning TEM (STEM) have long been staples for semiconductor characterization due to their spatial resolution and the ability of electron energy loss spectroscopy (EELS) and energy dispersive X-ray spectroscopy (EDX) to provide elemental information on the nanoscale. Developments in electron (atomic number contrast and elemental) tomography have also proven significant in providing some level of 3D information [4,5], increasing the ability to characterize these complex structures. More detailed elemental composition with high sensitivity can be obtained by secondary ion mass spectroscopy (SIMS) [6], however, it is limited to large analysis areas and requires complex modeling to understand the details of 3D structures. APT, however, provides a unique combination of sub-nanometer spatial resolution and elemental information in three dimensions, making it uniquely suited for the analysis of 3D structures. But preparing samples for APT analysis can carry significant challenges depending on the desired area of interest and the materials and features present there. Semiconductor devices are by nature comprised of a combination of insulating, conducting, and semiconducting materials and may possibly even contain voids between certain features. Therefore, APT analysis of state-of-the-art 3D devices demands innovative sample preparation in order to avoid sample fracture during field evaporation and/or artifacts in the reconstructed APT data particularly at interfaces between dissimilar materials.

Focused ion beam (FIB) based sample preparation for APT has become a common preparation method for most semiconductor structures with advanced development allowing for site-specific sample preparation [3,4,7–9]. FETs and other semiconductor devices, however, remain challenging because they often contain some combination of metal, semiconductor, and insulator layers, all of which present different challenges in the FIB and/or during field evaporation. In particular, insulating layers, such as oxides, have been shown to create significant distortions when adjacent to metals or semiconductors [1,4,10] due to the large disparity in evaporation field between these materials. The increased ability to isolate structures containing various combinations of metal-semiconductor-insulator interfaces within an APT tip and to field evaporate them has increased the demand to understand the effects of such interfaces on the spatial resolution and elemental analysis of the reconstructed APT data. Computer simulated field evaporation of such structures has improved learning regarding...
tip shape dynamics [11–13] and interfacial effects [14] during field evaporation. An understanding of these phenomena can be used during sample preparation to deliberately align certain features in a particular way [15,16] or eliminate them completely [3] to avoid any negative impact on data quality. In this work, we present analysis of state-of-the-art Si fins with a diamond-shaped epitaxially-grown B-doped SiGe strain layer on a silicon on insulator (SOI) substrate prepared via cross-section, which eliminates data collection and reconstruction artifacts resulting from the presence of the buried oxide (BOX). A comparison of the APT data to that of TEM, SIMS, and EDX mapping done on the same wafer is also discussed.

2. Experimental procedure

The analysis utilized a specially designed array of Si fins with a known pitch and with length on the order of microns grown on an SOI substrate. Following the Si fin, an epitaxial Si layer was grown followed by a B-doped epitaxial SiGe layer. An oxide grew on the SiGe surface prior to encapsulation with an α-Si cap. A schematic of the structure is shown in Fig. 1. A fin-only (no gates) structure was used to eliminate additional distortions and/or artifacts that may be introduced by the presence of insulating layers used in the gates. This increases the ability to achieve accurate analysis of the Ge and B concentrations within the SiGe, which are of interest in this study. Specifically, the Ge concentration profile through the SiGe near the top of the fin (perpendicular to the Si/Ge interface), which will be referred to as the “shoulder” of the fin, and the degree of B clustering and/or interfacial pile-up at the Si/Ge interface are of highest interest in this work.

The sample was prepared using a cross-section method, which was first introduced over a decade ago [17] and has been implemented on various materials and structures [18–21]. This approach was favored over a standard preparation method because it is particularly advantageous for these structures for several reasons. First, it avoids positioning the BOX directly between the apex of the tip and the voltage source, providing a conductive pathway for both high voltage and heat from the laser through the conductive fins and α-Si cap rather than through the BOX. Although evaporation of semiconductor devices on an SOI substrate is possible using a standard, up-right approach (i.e., BOX oriented perpendicular to the tip axis) [1], the BOX presents numerous problems during field evaporation and significant distortion during data reconstruction due to the difference in evaporation field of the oxide as compared to the semiconductor layers above it, and avoiding it altogether is advantageous [2,3,15,21]. Second, with careful preparation, a cross-sectional approach allows the BOX to be completely recessed away from the tip while retaining nearly the entire fin, eliminating artifacts caused by simultaneous evaporation of the oxide and the fins. Finally, cross-sectional sample orientation allows for evaporation of many fins within a single APT volume whereas a standard preparation technique is likely limited to one or possibly two fins per tip. This is significant because it provides better statistical analysis of a given feature or interface by providing several fins, which can each be analyzed, within a single tip. Capturing multiple fins also allows the fin pitch, which is precisely fixed by lithography, to be used to assure a higher degree of accuracy in the data reconstruction. Sample preparation was further complicated by the presence of voids that ran parallel to the length of the fins just below the fin/BOX interface, which were formed during α-Si capping when access to the region between fins became prematurely pinched off at the side apexes of the SiGe layers of adjacent fins. The voids near the tip were removed from the analyzed volume altogether during tip shaping.

A cross-sectional sample preparation is also advantageous during analysis of the SiGe in these structures because the interface between the Si and SiGe is approximately 35° off the tip axis for cross-section preparation compared to 55° if prepared using a standard approach. It is well known that the spatial resolution of the atom probe is better parallel to the tip axis than perpendicular to it, [6,22,23] therefore, increasing the accuracy of dopant and SiGe concentrations profiles measured across the SiGe, perpendicular to the Si/Ge interface when using a cross-sectional orientation.

Atom probe sample preparation was performed in a dual beam FIB/SEM. Prior to sample liftout, a thin Ni cap was sputtered on top of the α-Si capping layer followed by a protective W layer. The cross-sectional preparation technique used in this study differs from the standard liftout procedure described by Thompson et al [7], in that a rather wide, straight-sided lamella, perhaps more typical of TEM sample preparation, was first created. In preparation for reorientation, the straight sidewall which would become the new top surface was cleaned with a lower current ion beam in order to remove some of the FIB damage caused by the initial cuts. After vertical side cuts, one end of the lamella was cut free and undercutts were made at 0° tilt. After liftout, the lamella was transferred from the liftout needle to the axial rotating manipulator (ARM) [16], which was used to rotate the lamella approximately 92°–94° as shown in Fig. 2a. A 2–4° rotation beyond 90° was used to more closely align the BOX/fins interface with the naturally-forming shank angle of the atom probe tip formed during tip shaping. This allowed the APT volume to capture a greater number of nearly complete fins (i.e., top-to-bottom of the fin) while simultaneously recessing the BOX from the tip. The additional rotation also aided in BOX removal during tip shaping by increasing the cross-section of the BOX exposed to the FIB.

After rotation, new wedge cuts were made at 40° to create the triangular wedge shown in Fig. 2b. The wedge cuts were purposely designed to center the point of the wedge in the conductive α-Si cap. Additionally, the width of the initial straight-sided lamella provided significant height for the final wedge-shaped lamella.

A number of tips were propagated from the lamella and welded onto W probe needles for tip shaping. Tip shaping was done in several steps with the intention of completely recessing the BOX from the top several fins while simultaneously recessing the Ni and original W cap along the opposite side of the tip. A 30 kV ion beam was used for initial milling down to a tip diameter of 0.3 µm. A 5 kV beam was used for final tip shaping and to completely recess the BOX and Ni away from the top several fins. Finally, a 2 kV beam was used to remove any remaining W cap and reduce any FIB damage near the surface of the tip. Complete removal of the BOX from the top several fins was found critical for achieving the

![Fig. 1. A schematic of the sample showing the APT tip orientation for traditional sample preparation (left) and for cross-sectional sample preparation (right).](image-url)
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