Toward atom probe tomography of microelectronic devices

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Summary: Atom probe tomography and scanning transmission electron microscopy has been used to analyze a commercial microelectronics device prepared by depackaging and focused ion beam milling. Chemical and morphological data are presented from the source, drain and channel regions, and part of the gate oxide region of an Intel® i5-650 p-FET device demonstrating feasibility in using these techniques to investigate commercial chips.

1. Introduction

Shrinking feature sizes continue to provide one of the main challenges for physical metrology methods. From the 2009 ITRS [1]: “To achieve desired device scaling, metrology tools must be capable of measurement of properties on atomic distances.” Atom probe tomography nominally has this capability and has been used in materials characterization and materials science for more than 40 years [2]. Although using a laser to assist field evaporation of materials in the atom probe was developed ~30 years ago [3], only recently has APT begun to see widespread usage in the areas of semiconductors [4-7] and ceramics [8-12]. Although APT has also recently been applied to transistor and FINFET-type structures [13-15], these structures usually have been stopped at some point in the semiconductor build process in order to accommodate the APT analysis. As it is a complex, multi-step task to analyze a fully processed microelectronic device using APT, we will take a step back and evaluate the three steps that are necessary to result in a successful APT analysis of any structure.

Number one is specimen preparation. For APT, the use of focused ion beam (FIB) instruments has revolutionized specimen preparation (for a recent review see [16]). For the case of microelectronic device analysis, FIB preparation to isolate <50nm heterogeneous devices in arbitrary XYZ orientations is critical. This occurs only after suitable deprocessing (may consist of depackaging, dry and wet electrochemistry for selective material etching, etc.) has been successfully achieved. Since a protective layer is needed if near-surface features are to be analyzed, proper “cap matching” becomes important. The important requirements are relatively low temperature deposition (to avoid inducing undesired diffusion), matching of evaporation field with target material (to minimize reconstruction artifacts) and good adhesion.

Number two is specimen yield during data collection. Even though a specimen may be prepared which contains the region of interest, specimen yield must be adequate (for the individual user’s purpose or specific laboratory environment). Clearly the details of specimen preparation are intricately related to yield, but data collection parameters may also have a significant effect on yield, and there is often a trade-off between yield and data quality (primarily mass spectral and background noise quality).
Number three is APT analysis data reconstruction, which is not discussed significantly in this document. Data may be collected with an adequate yield, but if the resulting data reconstruction is either not accurate or not precise enough, then the analysis may fail to meet requirements. The main problem with APT data reconstruction, from the perspective of devices, is that field evaporation of heterogeneous structures often leads to evaporated surfaces that are far from hemispherical [17] and a hemispherical end form is a fundamental assumption employed in the majority of current reconstruction algorithms.

This work presents the status of efforts to prepare, analyze, and reconstruct data from a commercial microelectronics device (32 nm node Intel® i5-650 nFET). This is a work in progress, and we acknowledge that satisfactory yield has not yet been obtained. Also, issues relating to APT data reconstruction of transistors are non-trivial and will not be discussed further herein.

2. Experimental

Specimen preparation was carried out in an FEI Novalab dual-beam focused ion beam instrument with an Omniprobe AP200 in-situ micromanipulator. STEM observations were performed along the [110] orientation of the Si substrate with a JEM ARM 200F operating at 200kV equipped with a Schottky field emission gun. APT data collection was performed on a LEAP® 4000XHR from Cameca Instruments Inc. The atom probe was operated in a 200 kHz pulsed laser mode with an energy of 100 pJ into an estimated spot size (four sigma) at the specimen of ~3 µm. The specimen temperature was 50K and the ion detection rate was 0.20% (1 ion detected in every 500 laser pulses).

The specimen examined in this work is a device from a commercial 32-nm technology chip (Intel® i5-650) which was purchased at a retail outlet. Following depackaging to (approximately) metal-1 [18], focused-ion-beam preparation [19] was used to create specimens. Figure 1 shows a sequence of images throughout the process from the initial surface of the wafer after depackaging (figure 1a) through to the final state of focused-ion-beam annular sharpening [20] of the tip (figure 1h).

3. Results and Discussion

The device structure analyzed with APT is shown in figure 2, which contains a bright-field, high-angle annular-dark-field pair of images. In figure 2a a multilayered gate oxide structure is clearly visible while in figure 2b the undercut and angled regions between the SiGeB source/drain regions and the channel become much more obvious.

The APT analysis obtained from a device in a region near the one shown in figure 2 is presented...
Figure 3. APT atom map containing As (large black spheres), B (small dark grey spheres), and HfO (small light grey spheres).

Figure 4. HfO complex molecule peaks detected in the 2+ charge state over the range of 95 to 99 Da. The inset table shows the comparison of expected isotopic abundances (using >0.2at.% only) to the detected abundances.

Figure 5. Superimposed STEM image and APT atom map containing B (small dark grey spheres), and carbon (large light grey spheres) atoms only. Note the indications of carbon atoms clustering together. (The APT data are 20nm in thickness into the page.)

This work demonstrates that a wealth of high quality information may be obtained in figure 3, which is an atom map containing As (large black spheres), B (small dark grey spheres), and HfO (small light grey spheres) together with a 12at.% Ge isoconcentration surface (arrowed). The Hf is detected entirely in HfO complex molecule peaks, shown in figure 4, which are detected in the 2+ charge state over the range of 95 to 99 Da. Measured at the peak at 98 Da, the mass resolving power is >1000 (FWHM) and >500 (FWTM), which demonstrates the capability to achieve good spectral resolution, even on very complicated heterogeneous structures. The Hf atoms are detected at the top of the image in figure 3, in a region estimated to have a composition of approximately 80at.% (Hf+O) and 20at.% Si. (Note that the apparent HfO molecules detected in the channel region are spectral noise due to the large number of mass ranges required for the HfO isotopes.) The maximum level of Ge (positioned along the left and right edges of the image shown in figure 3 is ~25at.%. The Ge isoconcentration surface shown in figure 3 (arrowed) delineates the source/drain regions from the channel region and has a shape which resembles the undercut shape of the channel region near the gate oxide shown in figure 2b.

This shape correlation may be used to create a composite image of the STEM and APT data, figure 5, in which the APT image was scaled to match the STEM image. Note the qualitative evidence of carbon atoms clustering together in the lower center portion of the image. The estimated concentration of carbon in the APT data is ~0.10at.%

Although these data are not from the same volume of material (something which has been done very few times to date in the literature [21]), the exercise is still useful. It provides us with information on the accuracy of the APT data reconstruction as well as perhaps a glimpse of the future of correlative microscopy. Indeed, TEM and APT are complementary techniques that will likely develop a closer relationship in the future where the spatial fidelity of TEM is combined with the analytical sensitivity and three dimensionality of APT. Instruments that combine these techniques into a single instrument are currently being pursued by adding a STEM to a LEAP [22] and a LEAP to a STEM [23].

This work demonstrates that a wealth of high quality information may be obtained...
from site-specific atom probe analysis of post-production microelectronic devices. Adequate yields (>50%) need to be realized and APT reconstruction methods improved going forward, but certainly at this time, feasibility has been shown.

Acknowledgements

The authors would like to thank our colleagues at Cameca Instruments Inc., who assisted in assembling the materials presented in this manuscript, including B. Geiser, J. Olson, J. Shepard, T. Payne, E. Strennen, E. Oltman, T. Gribb, D. Rauls, J. Watson and S. Gerstl (currently at Eidgenössische Technische Hochschule Zürich). We would especially like to thank P. Ronsheim (IBM) for helpful discussions.

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