Atom Probe and Electron Tomography for full 3D characterisation of semiconductor devices

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Semiconductor devices are now smaller than typical transmission electron microscope (TEM) sample dimensions (<100 nm) and three dimensional in nature, therefore conventional TEM images are no longer simple to interpret. Electron tomography using high angle annular dark field (HAADF) imaging modes in the scanning TEM (STEM) provides Z-contrast images and is well suited to characterize such 3D devices [1]. However, electron tomography in STEM-HAADF mode does not at this time give access to the 3D doping profile and to a quantitative distribution of the different chemical species present on the gate oxide.

Atom Probe Tomography is a powerful tool that can deliver high spatial resolution three-dimensional compositional information. Technical advances have made it possible to analyse semiconductors [2,3] and oxides which are difficult to evaporate. APT is now well established to identify the distribution of dopants inside semi-conducting materials [4], which is increasingly critical in the correct design of modern nanometre scale electronics. However, this technique suffers from reconstruction artefacts due to presence of materials with different evaporation fields making the use of this technique for full 3D structural characterization of semiconductor devices difficult. Here we combine STEM-HAADF electron tomography, to obtain information about the 3D structure and APT studies on the same sample to characterise the doping and metal gate stack distribution. Moreover, this combination can also be used to demonstrate and understand the artefacts due to reconstruction algorithms of such complex devices.

Sample preparation is one of the major obstacles to successful tomographic analysis of transistors and other types of devices structures. APT requires having the region of interest near the surface with an apex between 50 and 150 nm. These conditions are fulfilled when the sample is prepared with a needle shape by Focused Ion Beam (FIB). This type of preparation shown in Figure 1 is also suitable for electron tomography experiments.

Here we will present results obtained from a state-of-the-art 28-nm-gate MOSFET device. The STEM-HAADF projections were acquired on a FEI Titan Ultimate microscope operated at 200 kV using a Fischione 2050 specimen holder. This is adapted to examine specimens that are attached on APT specimen mounts. The series was acquired over -90° to +90° with a step of 1°. The images were aligned using cross-correlation algorithms and the volume was reconstructed using a Simultaneous Iterative Reconstruction Technique (SIRT). APT experiments were performed using a CAMECA FLEXTAP instrument equipped with flexible optics and provides variable fields of view (up to 165 nm diameter, high mass resolution (up to m/Δ3000) allowing the separation of Si^+ from $(N_2)^+$. The analysis was carried out at 72 K using a laser providing a 450 fs pulse duration and a 100 kHz repetition rate, at a wavelength of 343 nm using a 30 nJ/pulse energy.

Figure 2 shows the reconstructed volume of a p-MOS device which has been segmented. It emphasises width variations of the metal gate and the gate oxide. It highlights the need to perform atom probe and electron tomography on the same sample in order to understand how the dopant distribution and metal gate layers interact during devices processing. Figure 3 (a) shows the APT tip containing the same device analysed by electron tomography. Figure 3 (b) shows the 3D APT volume reconstructed according to the tip profile method around the Si-poly gate. In this figure, each dot corresponds to one atom and oxygen, silicon and arsenic atoms are shown in green, orange and red, respectively. Nevertheless, a reconstruction artefacts, due to the presence of materials with different evaporation fields and the 3D structure, lead to a strong deviation from the original structure. This leads to a deformed reconstructed morphology but doesn’t significantly interfere with element localization. Hence, despite the artefacts, APT has been able to observe the implantation of arsenic dopant atoms around the spacer regions.

In this presentation we will present the advances made in specimen preparation to be able to perform both APT and electron tomography on the same devices specimens. We will critically discuss the strengths and weaknesses of the different techniques. Finally we will present our latest results that have been obtained on these devices to show that combinations of APT and electron tomography can be used to obtain information about the device structure, dopant distributions and changes in the metal gate structure in 3D and is an indispensible tool for the future generations of semiconductor devices.

References

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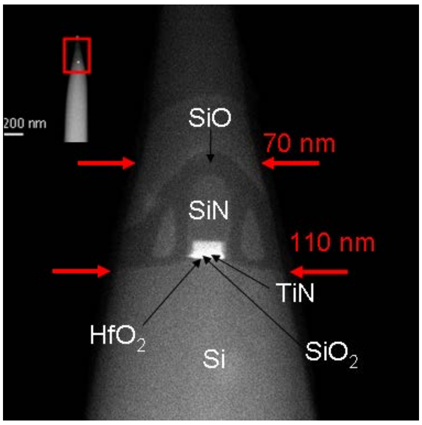

***Figure 1.** STEM-HAADF images of the needle prepared by FIB. On the right image is indicated all the materials which constitute the 28 nm - MOS device.*

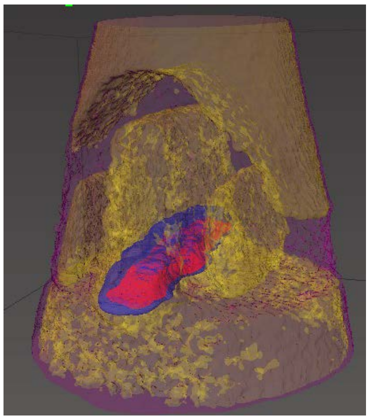

***Figure 2.** Reconstructed volume of a 28 nm p-MOS device. On the representation, the volume is segmented: the gate oxide is in red, the metal gate is in blue, the SiO_2 is in violet, the Si and the SiN are in yellow.*

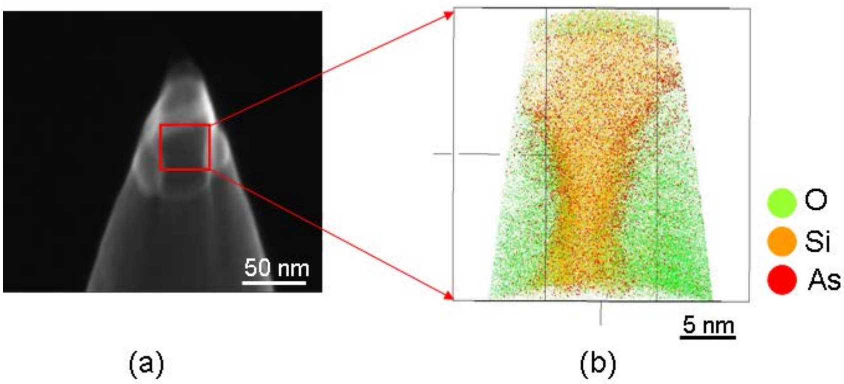

***Figure 3.** APT tip (a) containing the same device than ET analysis and APT 3D reconstructed volume around the top of the Si gate (b).*