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Atom probe tomography for advanced nanoelectronic devices: Current status and perspectives

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ABSTRACT

Atom probe tomography is unique in its ability to image in 3D at the atomic scale and measure composition in a semiconductor device with high sensitivity. However it suffers from many artefacts. The current state of the art of nanoelectronic device analysis by atom probe is addressed and the challenges in device analysis in the next ten years are laid out. Finally the improvements necessary in sample preparation, instrumentation and reconstruction procedures are discussed.

1. Introduction: the current status of atom probe tomography for nanoelectronic devices

The downscaling of "non-planar" MOSFET devices (FinFET, horizontal and vertical nanowires) for advanced technology nodes means creating a 3D–device with a growing diversity of materials whose dimensions are in the nm range only but nevertheless, need to be controlled tightly. As the related fabrication processes (and underlying physics) manifest themselves as size and feature dependent, the development of advanced CMOS devices has become increasingly reliant on analytical techniques capable of providing morphology, composition and dopant distributions at the device scale. Faced with the three-dimensional nature of these devices, 3D–spatial resolution has emerged as an essential specification for all metrology concepts involved.

Atom probe tomography (APT) has been successfully used in metallurgy for several decades for probing local compositional variations, precipitates etc. Early attempts to apply this technology to analyze semiconductors were not reproducible even when assisting the evaporation process with long laser pulses [1–4]. Successful semiconductor materials and devices analysis only has become really possible with APT through the availability of ultra-short laser pulses (~10^{-12} s or 10^{-15} s).

Analysis of devices remains nevertheless a challenging undertaking. Positioning a 3–5 nm device within the APT-tip during the sample preparation remains an art of its own as well, in particular when it is covered with a protective layer to avoid beam damage during the preparation. Some successful attempts are documented in the literature [5–7], but many of the failures are not! Nevertheless, the potential of APT to quantify chemical composition at the nanoscale and its 3D–resolving power in complex devices has led to its uptake by many semiconductor companies and research institutes.

Although the images produced by APT seem to contribute to our three-dimensional insight in many of the novel devices, they are often distorted and may contain severe artefacts and quantification inaccuracies. Correlative metrology whereby a complementary technique can be used on the same sample to verify the morphology or provide complementary information before APT analysis, can greatly facilitate the interpretation of the APT results. Whereas High angle annular dark field – (scanning) transmission electron microscopy (HAADF-(S)TEM) imaging can be used for planar devices, for devices of a three-dimensional nature, electron tomography (ET) becomes necessary. In such a case ET primary provides geometrical/structural information whereas APT delivers complementary information on low concentrations (e.g. dopants) which are not easily detectable in ET. The complementary information from ET (in particular geometrical info) can be used to steer the reconstruction of the APT data (which has many adjustable parameters) in the right direction. The ET/APT combination is particularly attractive as the tip sample preparation requirements and the spatial

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resolutions are comparable, thereby allowing to perform analysis on the same device and a minimization of the APT artefacts and inaccuracies in device analysis.

The example in Fig. 1(a) illustrates the application of this approach to the GAA (Gate-all-around) structure. These are the structures one expects to be analyzed routinely in the coming decade as vertically stacked GAA nanowires are viewed as a possible extension to FinFETs and a credible option for sub-7 nm nodes [8]. Its 3D–nature and ultrathin layer structure surrounding the vertical nanowires makes this a very difficult object to analyze whereby only APT and ET can provide some of the required 3D–information.

Fig. 1(b) presents a 3D iso-surface representation of the GAA device from ET, with a threshold for the iso-surface rendering set at the intensity level of the TiN encapsulating layer. In this case, the Si nanowire channel is not directly visible but the location of its boundary is inferred from the shape of the surrounding high-k layer. In essence ET probes here the extent of the combined silicon regions and silicon oxide interlayer as the average *Z*-numbers of the materials are too close to provide a discernable contrast. Nevertheless taking several slices along the Si nanowire leads to the measurement of an average radius for the Si + SiO_2 region. Different from "planar" TEM analysis the 3D–definition of these boundaries is less unique and some statistical fluctuations exist as a result of the limitations in the deconvolution process. These limit the observation of fine atomic scale details.

Fig. 1(c) shows the 3D APT elemental map of a similar GAA device reconstructed using the standard shank angle algorithm. All chemical species have been identified and the silicon oxide can be easily discriminated from the Si channel through the location of the oxygen atoms.

However the APT volume shows strong deviations from the shape observed by ET. The deviations are due to the difference between the evaporation field of the Si atoms of the nanowire and that of the surrounding materials. In such a case the Si region will evaporate easier than the surrounding regions causing the development of a non-hemispherical tip shape whereby ion trajectories are (de)focused (i.e. a higher/lower magnification), which induces a local reduction/enhancement of the measured atomic density and an expansion/compression of the lateral dimension of the surrounding oxide/core of the nanowire. This artefact leads to an under/overestimate of the densities of the Si in certain regions and hence to incorrect dimensions. As these processes are linked to the time dependent evolution of the tip shape, and as the resulting deformations are also related to the distance and tilt angle of the feature to the tip axis, their effect is non-stationary as a function of depth. This results in a distortion of the "square" GAA structure being distorted into the "S-shape" shown in Fig. 1(c).

These deformations can be understood by comparison with simulations of the evaporation of the atoms using a 3D numerical code taking into account the different evaporation fields in each layer. More details can be found in [9–11]. The simulations demonstrate the impact of a region with a higher evaporation field on the tip shape leading to trajectory compression and the local magnification effect.

In addition to non-homogeneities in evaporation field, local variations in temperature induce tip shape deformations. Basically the intent of the laser pulse is to induce a uniform heating across the tip apex thereby enhancing the evaporation probability equally at all sites. Unfortunately the latter is not necessarily true and the heating uniformity becomes among others a strong function of the laser wavelength and the heterogeneity of the sample. Indeed a non-uniform heating can be linked to the finite absorption length of the laser light versus the tip dimensions (for example one sided heating when using UV-light [12]) as well as to the different absorption probabilities (in the case of a Si/SiGe stack [13]) of the materials present in the various layers. Both phenomena lead to local differences in temperature which translate into

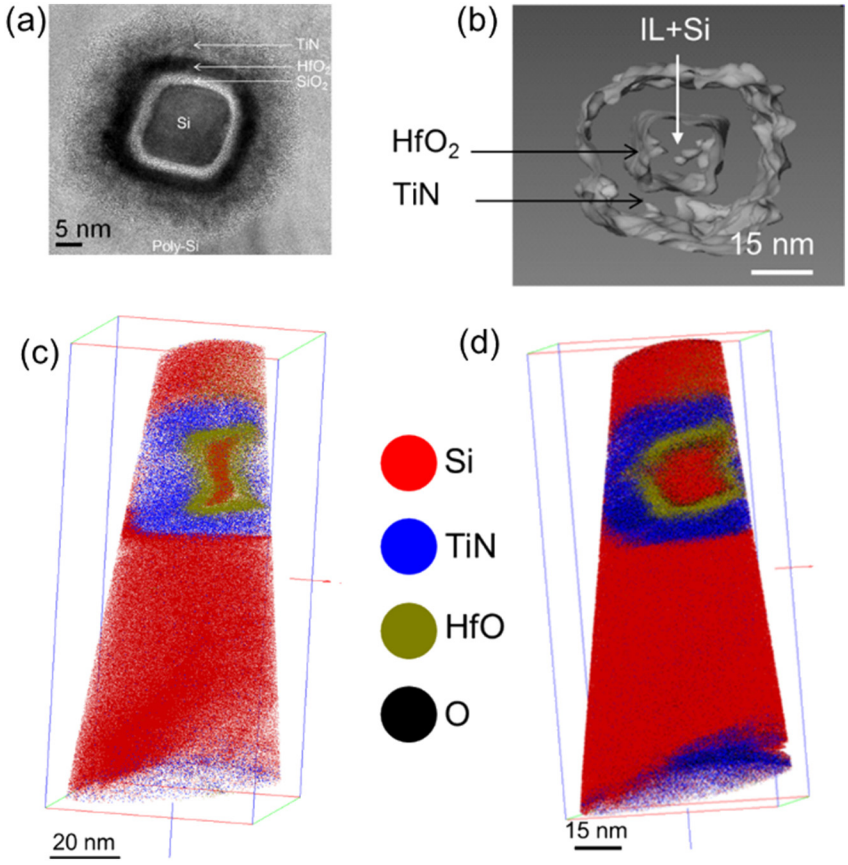

Fig. 1. (a) Cross-sectional TEM image, (b) isosurface rendering of ET, (c) 3D APT volume based on standard shank angle reconstruction algorithm and (d) improved after density correction of GAA device.

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