Field Mapping with 1 nm spatial resolution by off-axis electron holography.

D Cooper, T Denneulin, JL Rouviere[2], G Servanton[3], R Pantel[3], P Morin[3]
A Béché[4], D Delille[4] and RE Dunin-Borkowski[5]

1. CEA, LETI, Minatec Campus, 17 rue des Martyrs, 38054 Grenoble, Cedex - 9, France.
2. CEA, INAC, Minatec Campus, 17 rue des Martyrs, 38054 Grenoble, Cedex - 9, France.
3. ST Microelectronics, 850 rue Jean Monnet, 38926 Crolles, France
4. FEI France, Minatec Campus, 17 rue des Martyrs, 38054 Grenoble, Cedex - 9, France.
5. Ernst Ruska Centre, D-52425 Julich, Germany.

david.cooper@cea.fr
Keywords: Electron Holography, Dopant Profiling, Strain Mapping, Semiconductors.

The reduction in the dimensions of the latest generation of semiconductor devices combined with their complexity and the interplay between different materials that are present in a small volume can make the characterisation of the dopant and strain fields in these devices a daunting task. In this presentation, we will show that by taking advantage of the stability and versatility of the latest generation electron microscopes the dopant potentials and strain fields can now be measured with 1 nm spatial resolution. It is also now possible to obtain information about the structure and the composition from the same TEM specimen within a relatively short period of time.

We will start by presenting the state-of-the-art for "medium resolution" off-axis electron holography. We will critically evaluate the performance of electron holography when using our probe corrected FEI Titan which was delivered to CEA in 2006 [1]. This will then be compared to the performance of a double aberration corrected and monochromated FEI Titan Ultimate equipped with a latest generation high brightness electron source and aberration corrected Lorentz mode which was delivered in 2011. We will demonstrate how the stability of the microscopes allows electron holograms to be acquired for long time periods to provide field maps with an excellent sensitivity. In addition we will show that by using different lens settings, it is now possible to have the required flexibility between the hologram fringe spacing, sensitivity (contrast) and the field of view in order to bridge the gap between conventional "medium resolution" Lorentz mode electron holography and atomic resolution holography [2].

The second part of the presentation will demonstrate on how these latest generation electron microscopes have been used to perform electron holography to perform useful field mapping to solve real materials science problems. Figure 1(a) shows a potential map of a silicon specimen containing boron-doped delta layers each spaced by 3.5 nm. The map has been obtained by Lorentz mode off-axis electron holography with a spatial resolution of 6.6 nm. The potential map has been overlaid onto a high-resolution image to show the expected position of the delta layers and it is clear that the layers have not been resolved. Figure 1(b) shows a potential map of the same region acquired using free lens control to obtain a spatial resolution of 1 nm and the layers are now clearly resolved. Figure 1(c) shows profiles extracted from across the potential map and the high-resolution image and the position of the layers have been measured with an accuracy of 0.33 nm [3]. From these highly doped layers it was possible to quantitatively assess the active dopant concentration as the artefacts that are associated with dopant profiling become less important for the high dopant concentrations that are used in todays semiconductor devices.

Figure 2 illustrates the power of a modern TEM, showing how many techniques have been performed on the same TEM specimen both to build up a more complete understanding of how the structure, composition and fields interact with each other and to correctly interpret the phase maps that are generated by electron holography [4]. Figure 2(a) shows a HAADF STEM image of a 28 nm gate generation pMOS semiconductor device revealing the structure and (b) a C_s corrected TEM image used to accurately measure the thickness of the oxide layer. Figure 2(c) shows an EELS map revealing the position of the arsenic dopant atoms and (d) the electrical potential distribution from the active dopants obtained by electron holography. The strain fields can be quantitatively measured by using dark field electron holography and (e) and (f) show the maps of the deformation caused by the presence of a SiN stressor in the growth direction, ξ_{zz} and the in plane direction ξ_{xx} respectively. We will show that the small dimensions of semiconductor devices and the very high dopant concentrations that are now used are in fact advantageous for field mapping in the TEM. Finally, we will discuss the prospects of our ultimate aim, which is the detection of the electrostatic potential arising from single dopant atoms by electron holography.

This work has been performed in the frame of the IBM - ST Microelectronics - LETI alliance and has been performed on the characterisation platform on the Minatec Campus.

References

[1] D. Cooper *et al.* App. Phys. Lett. **91** 143501 (2007).
[2] D. Cooper *et al.* Appl. Phys. Lett. **99** 261911 (2011)
[3] D. Cooper *et al. In Preparation* Phys. Rev. Lett. (2012)
[4] D. Cooper *et al.* Nano Letters **11** 4585 (2011)

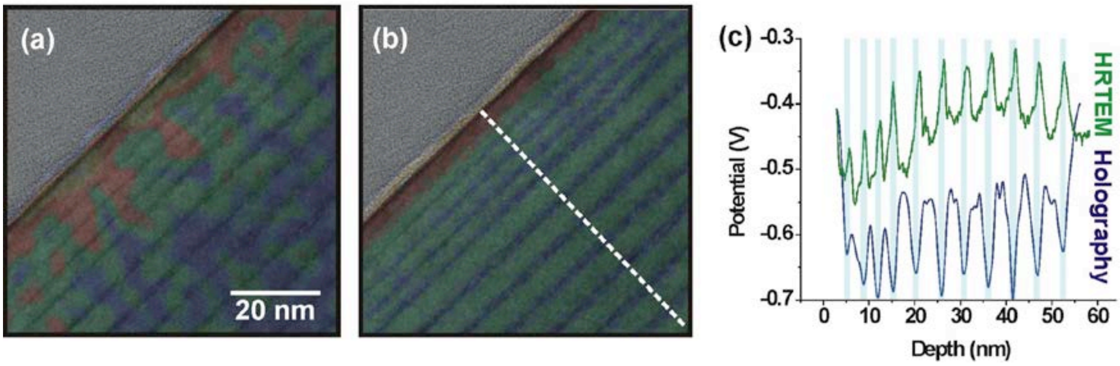

Figure 1. *(a) Potential map of 3.5 nm spaced boron doped delta layers overlaid onto a HRTEM image. The potential map was acquired using conventional Lorentz mode holography with a spatial resolution of 6.6 nm and the layers have not been resolved. (b) Potential map of the same region with a spatial resolution of 1.0 nm. (c) Profiles of the potential map and the HRTEM image are compared to show that the position of the layers have been measured by electron holography to an accuracy of +/- 0.33 nm.*

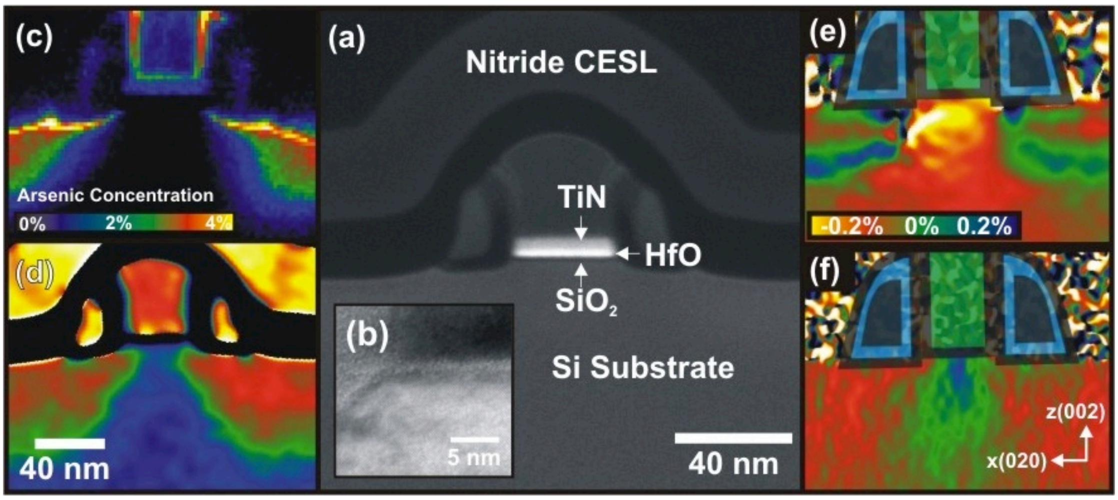

Figure 2. *(a) A STEM image of the nMOS specimen showing the structure and the different materials that are present. (b) A Cs corrected TEM image of the specimen focusing on the thickness of the SiO layer. (c) An arsenic map acquired by EELS. (d) A dopant potential map acquired by off-axis electron holography. (e) and (f) show strain maps that have been acquired by dark field electron holography for the ξ_{zz} and ξ_{xx} directions respectively. Figures (c-f) all use the same length scale.*