Improvement of off-axis electron holography on semiconductor device specimens using the FEI Titan transmission electron microscope.

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Résumé – Off-axis electron holography can in principle, quantitatively map dopants in semiconductor devices with nm-scale resolution. We will show our latest results performed on both Si calibration and MOSFET device specimens, demonstrating the low signal-to-noise and excellent phase resolution that is now possible due to the exceptional stability of our FEI Titan transmission electron microscope.

1. Introduction

Off-axis electron holography is a transmission electron (TEM) microscope based technique that promises to fulfil the requirements of the semiconductor industry for a quantitative 2D and 3D dopant profiling technique with nm-scale resolution. An electron biprism is used to interfere an electron wave that has passed through a specimen with one that has passed through only vacuum to form an interference pattern (or hologram) from which phase and amplitude images of the specimen can be reconstructed. In the absence of magnetic fields or diffraction contrast the phase change, $\Delta\varphi$ of an electron is related to the electrostatic potential of a specimen, V_0 by the relationship,

$$\Delta\phi = C_E \int V_0(x, y, z)dz$$

where C_E is a constant dependent on the energy of the electrons and dz is the direction of the electron beam [1]. Therefore in principle, quantitative information about the dopants in semiconductor specimens can be directly measured from the phase image.

Figure 1 shows a schematic of the experimental arrangement for off-axis electron holography. By increasing the voltage that is applied to the biprism, the virtual sources S_1 and S_2 are pushed further apart which has the effect of reducing the fringe spacing which increases the spatial resolution in the reconstructed images. The contrast of the holograms determines the resolution of the phase image [2]. From Figure 1, we can see that if the virtual sources are pushed further apart, then greater constraints are placed on the coherence of the electrons and the contrast of the hologram will deteriorate. There is a trade-off between spatial and phase resolution in the dopant maps acquired using electron holography.

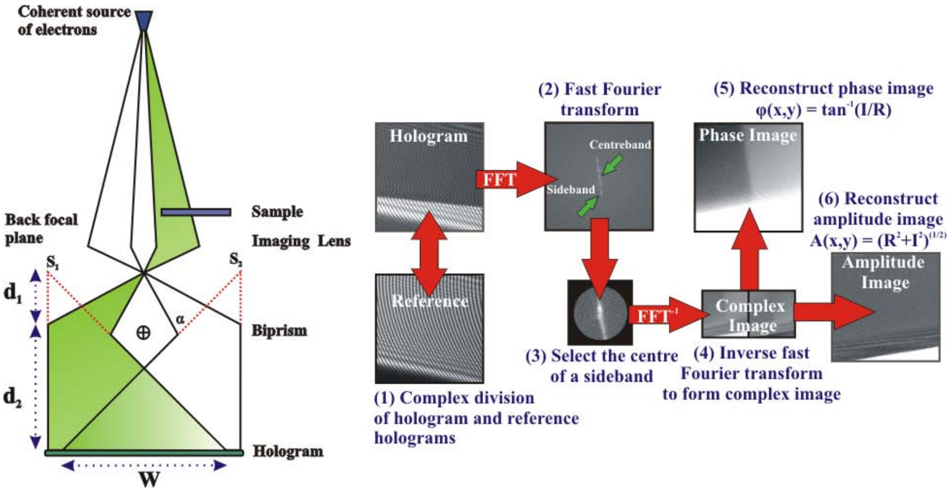

Figure 1. Shows schematic of arrangement for off-axis electron holography and procedure for reconstructing the phase and amplitude

It has been shown that semiconductor specimens can charge during examination in the TEM which influences the step in phase measured across electrical junctions [3]. To optimise the phase images for the examination of semiconductor devices with nm-scale resolution we need to form electron holograms with excellent contrast using a low electron beam intensity whilst ensuring that there are enough electrons collected for an adequate signal-to-noise ratio.

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2. Results

Si calibration specimens doped with differently doped layers of boron have been grown for examination using reduced pressure chemical vapour deposition (RPCVD) and specimens have been prepared using focused ion bem milling. The excellent stability of the Titan TEM allow holograms to be aquired for long time periods whilst preserving the contrast of the fringes. In addition the intensity of the electron beam can be reduced which will further improve the coherence of the beam whilst reducing the effects of specimen charging in the specimens.

Figure 2(a) shows phase images of a Si calibration specimen reconstructed from holograms acquired for 4, 16 and 64 seconds respectively. Figure 2(b) shows profiles extracted perpendicular to the doped layers and averaged over 100 nm. The improvement in the phase images and the profiles is clear. Typical hologram acquisition periods used for electron holography are 4 seconds with contrast levels of 20 %. Using the Titan we can acquire holograms for over one minute whilst maintaining contrast levels of more than 20 %. Now the dynamic range of our 16 bit CCD camera begins to limit the acquisition times that can be used.

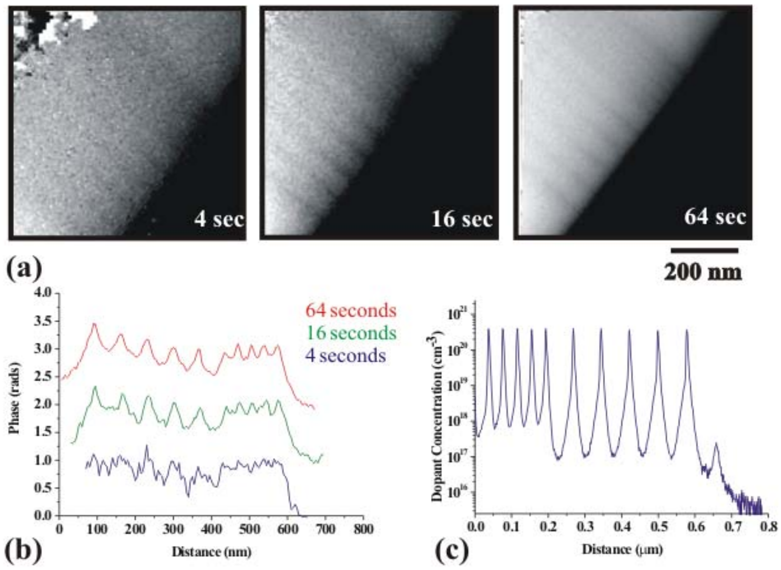

Figure 2(a) shows phase images reconstructed from holograms acquired for 4, 16 and 64 seconds respectively. (b) Profiles extracted from the phase images. (c) SIMS profile of the Si calbration specimen.

In this presentation we will show our latest results acquired from Si calibration specimens as well as from 65-nm-gate pMOS and nMOS devices. We will demonstrate the improvements in the phase resolution, the spatial resolution and the current limitations of the technique. We will also discuss the prospects of off-axis electron holography for quantitative dopant profiling.

3. Références

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