Mapping electromagnetic and strain fields by precession electron diffraction.

Cooper, D.[1], Boureau, V.[1], Haas, B.[2] and Rouviere, J.[2]

[1] Univ. Grenoble Alpes, CEA, LETI, 38000 Grenoble, France, [2] Univ. Grenoble Alpes, CEA, INAC, 38000 Grenoble, France

There is a need to make measurements of the internal fields such as the strain and electrostatic potentials in semiconductor materials. In this presentation we will show how electromagnetic and strain fields are today measured with nm-scale resolution using electron diffraction patterns that are locally recorded using fast CCD cameras. Quantitative measurements of the fields have been made on a range of different specimens and these results are compared to off-axis electron holography and simulations.

Precession electron diffraction is now used routinely to make accurate and precise measurements of the deformation in nanoscaled devices [1]. Figure 1(a) shows a HAADF STEM image of a SiGe/Si test specimen with different Ge concentrations. Precession electron diffraction has been applied to this specimen to provide deformation maps in the growth direction which have been compared to dark field electron holography and simulations. These techniques have also been applied to (b) nm-scale semiconductor devices and InGaN quantum well structures [2].

It is possible to measure the electromagnetic fields from the deflection of the transmitted beam [3]. In the past this was typically done using a segmented annular detector and was known as differential phase contrast. Today, this can be performed using fast CCD cameras. To assess the sensitivity and spatial resolution of the technique a simple silicon p-n junction has been studied. Figure 2(a) shows the p-n junction that is electrically connected to a Nanofactory biasing holder. Electron holography has been performed to measure the electrostatic potential (b) at zero bias voltage and (c) at 4 V reverse bias and (d) the electric field has been assessed. Equivalent measurements have been made using centre of mass (COM) measurements of the transmitted beam and Figure 2(e) shows an electric field map that has been calculated for the [001] direction for a specimen at 0 V bias voltage. The quantitative measurement of the field is shown in Figure (2)f. For simple specimens such as the Si p-n junction where there is limited dynamical diffraction contrast, it is possible to measure the field directly. However, for more complicated specimens such as an InGaN/GaN system where lattice plane bending will make measurements by COM techniques complex, precession diffraction can be used and the position of the transmitted beam is used for electric field measurements. By acquiring diffraction patterns containing the transmitted and diffracted beams, simultaneous measurements of both the electric fields and deformation are made. Figure 2(h) and (i) show electric field and deformation maps for the [0001] growth direction and quantitative measurements of these fields are shown in Figure 2(j) and (k).

In this presentation we will benchmark these field mapping techniques that have been developed on our double-aberration corrected FEI Titan Ultimate TEM equipped with a Gatan Oneview camera compared to electron holography. Spatial resolution and sensitivity will be discussed. We will assess the different methods of measuring the fields, using COM and by fitting for different materials with a focus on the effects on accuracy from the dynamical diffraction that is present in real specimens.

[1] D. Cooper et al, Nano Letters 15 (2015) 5289

[2] D. Cooper et al, Micron 80 (2016) 145

[3] M. Krajnak et al, Ultramicroscopy 165 (2016) 42

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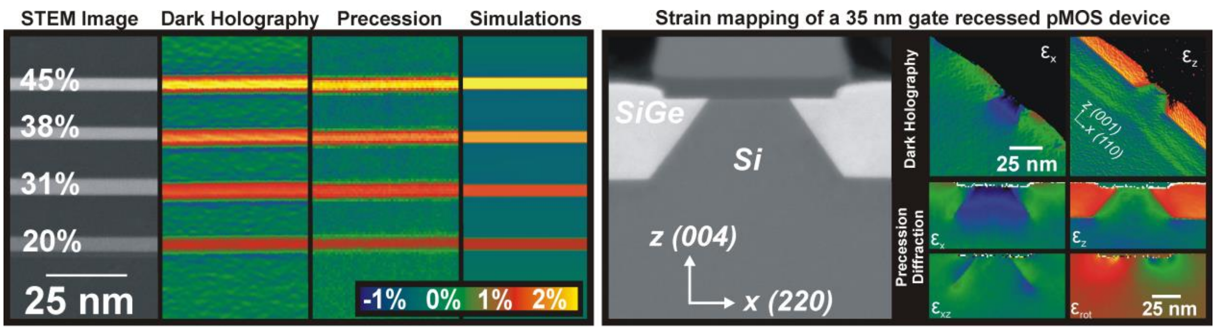

Figure 1: HAADF STEM image and deformation maps for the growth direction for a SiGe/Si multiayer specimen with different Ge concentrations. The experimental results obtained by dark holography and PED are consistent with simulations. Also shown is a HAADF STEM image of a SiGe pMOS device and deformation maps acquired by dark holography and PED.

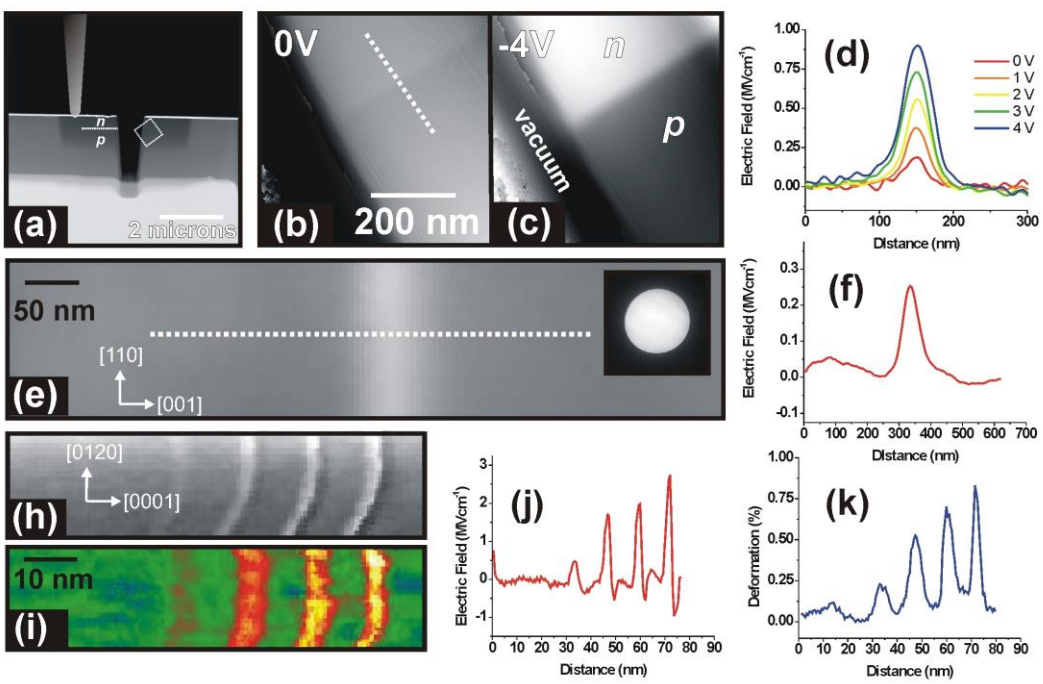

Figure 2.(a) A silicon p-n junction is connected to a Nanofactory biasing holder and (b), (c) potential maps have been acquired by off-axis electron holography at different reverse bias voltages to assess the sensitivity and (d) the electric field has been determined. (e) Shows an electric field map acquired using the shift of the transmitted beam in diffraction mode and (f) a quantitative measurement of the field. (h) Shows an electric field map and (i) deformation map acquired simultaneously from diffraction patterns of an InGaN/GaN superlattice acquired using PED and (j) quantitative measurements of the electric field and (k) deformation.