Characterizing electrical properties of semiconducting materials at nm length scales by Transmission Electron Microscopy

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Various transmission electron microscopy-based techniques have the potential for quantitative characterization of the electric properties of a material at nm length scales. For example, off axis electron holography enables measuring the phase change of the electron wave, that can be directly related to the projected electrostatic potential. Four-dimensional scanning transmission electron microscopy (4D-STEM) has gained in popularity rather recently, thanks to the development of fast pixelated detectors over the last years, enabling the assessment of internal electric fields with high spatial resolution [1,2] in experiments that would be too slow or noisy to be feasible in the past. However, the measurement of long range built-in electric fields present in semiconductor devices, for example p-n junctions, are typically three orders of magnitude smaller than atomic electric fields, making the 4D-STEM experiments in such systems challenging. The main difficulty for both methods is that the electrical information is combined with material contrast (for example due to chemical gradients, thickness gradients or diffraction contrast) and the challenge resides in reliably separating these two. One possibility to facilitate this task it to use in-situ biasing, in order to increase (decrease) only the electrical part of the signal, and allow subtraction of a reference measurement to remove all material related contrast, see Figure 1.

In this presentation we will show recent results we obtained using 4D STEM on semiconducting lamellae as well as nanowires containing a p-n junction. We will show a study on how the quantification, sensitivity and spatial resolution of electric field mapping in a silicon p-n junction are influenced by the acquisition parameters in a momentum resolved 4D-STEM experiment [3,4], also comparing two different TEM equipment's. It was observed that the electric field precision is improved decreasing the semi-convergence angle. The results were invariable even using an electron dose as low as 24 e-/A^2 and a detection limit as good as 0.01 MV/cm was possible. In addition, in-situ electrical biasing coupled to momentum resolved 4D-STEM measurements were performed, see Figure 2, allowing to study the junction abruptness, to asses phenomena like dopant segregation or interdiffusion [5]. Finally, recent results on a p-n junction in a Ge nanowire will be presented.

This work paves the way for the development of advanced STEM based techniques able to provide imaging and quantification of built-in electric fields, potentials and charge densities in semiconductor devices with high spatial resolution, providing crucial feedback to improve growth/device fabrication processes.

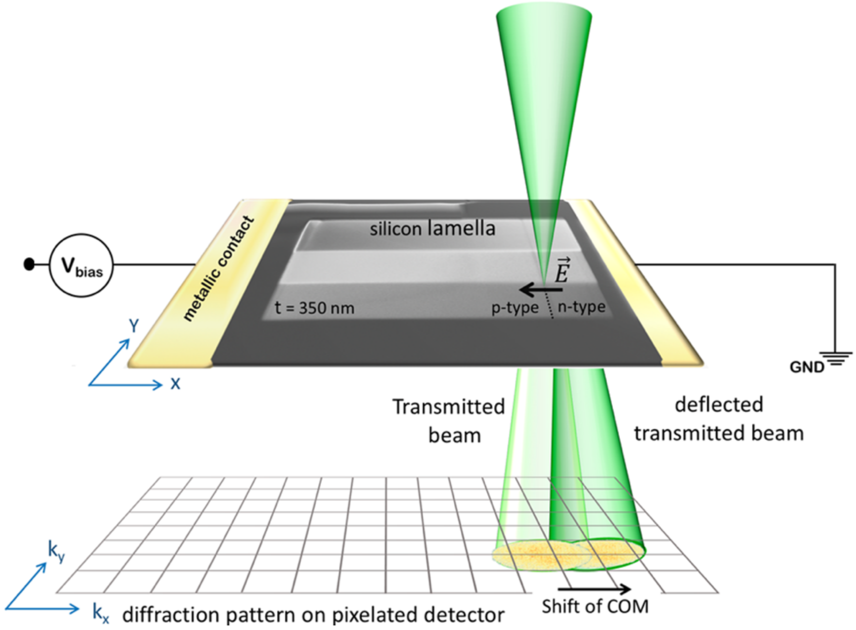

Figure 1 – Schematic of the momentum-resolved 4D-STEM experiment performed in a silicon *p-n* junction. Reverse bias is obtained by applying a negative bias ($-V_{bias}$) to the *p*-side while the *n*-side is grounded [5].

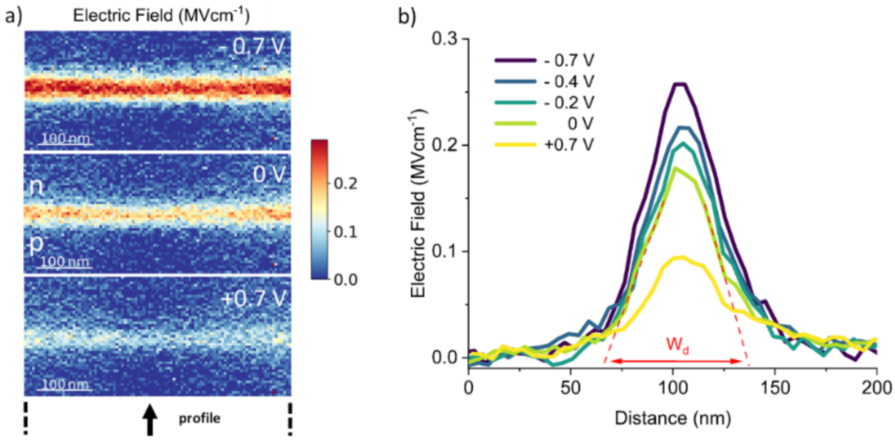

Figure 2 – In-situ biasing momentum resolved 4D-STEM electric field measurements in a silicon p-n junction [5].

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