Dopant engineering for the sub-28 nm nodes of CMOS technology is currently receiving a great deal of attention in the semiconductor industry. Indeed, the fluctuation of the position and the concentration of dopants is the main source of variability in the performance and may limit the ultimate dimensions of devices that can be achieved. Advanced characterization is thus required to study and optimize the doping process. Electron holography is the first characterization technique developed for mapping active dopants at the nanometer scale. This technique combined with a specimen preparation using FIB allows the positions of the junctions in a transistor to be measured in order to determine the effective channel length [1]. The total concentration of arsenic or phosphorus as dopants in silicon is also possible in a TEM using EELS or EDS [2]. Low loss EELS experiments also allow the detection of substitutional boron atoms in doped amorphous silicon layers used for photovoltaic applications [3]: the energy shift of the silicon volume plasmon peak is accurately measured and this shift is related to valence electronic density and varies linearly with dopant concentration. In this study, this technique is implemented successfully for the first time on crystalline silicon. The specimen analyzed in this study was grown on (001) silicon using RPCVD with closely spaced highly doped with boron nanometer layers (Fig. 1a). SIMS profile exhibits a maximum concentration of $2.5 \times 10^{21} \text{ at/cm}^3$ while $1 \times 10^{19} \text{ at/cm}^3$ is measured in the substrate (Fig. 2a). A 100 nm thick lamella was then prepared using a FEI Strata FIB at 8 kV to minimize damage. High resolution HAADF STEM image and low energy-loss spectra data cube were acquired at 80kV using a Cs image and probe corrected FEI Titan Ultimate microscope with a GATAN Quantum ER energy filter. The energy resolution reached with the monochromator and a dispersion of 0.025 eV/ch was less than 0.2 eV. A 520x80 pixels map (0.13 nm/pixel) was acquired with a 100 pA probe and a 0.7 ms exposure time for a total acquisition time of 70 seconds. Zero loss and silicon volume plasmon peak energy positions were determined for each spectrum using the Digital Micrograph NLLS fitting routine and subtracted to give the effective plasmon peak energy related to active boron concentration. A 70 meV offset is measured between highly doped layer and the silicon substrate (16.85 eV). Fig. 2b shows the good linearity between EELS and boron concentration (SIMS measurements). Figs. 1b to 1d illustrate how to improve the sensitivity by averaging.


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Fig. 1: a) STEM dark field image of the analyzed area (520x80 pixels), boron doped layers appear bright b) 16.85 eV silicon plasmon peak energy offset c) after binning by two the results (260x40 pixels) d) after binning by four the results (130x20 pixels)

Fig. 2: a) Boron concentration measured by SIMS and plasmon energy offset cumulated (80) profile for the seven first layers b) Linear relation between SIMS (logarithmic scale) and EELS using measurements starting from the substrate to the highest boron concentration of the first layer.