Quantitative determination of the dopant distribution in Si Ultra Shallow Junctions by TSADF-STEM

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In the last 20 years, the scaling down of the electronic devices has reduced the depth of the shallow junctions (SJ) by about one order of magnitude. These ultra shallow junctions (USJ) are located at a depth of a few nanometers from the sample surface that consequently assumes a critical role in determining the dopant distribution during solid phase epitaxy (SPE) and post-implantation annealing. To model the relative influence of each of the active phenomena on the observed surface dopant accumulation, as transient enhanced diffusion and SPE-based segregation, a more accurate quantitative experimental determination of the dopant distribution in these devices is mandatory.

In this work we explore, in the case of As in Si, the accuracy of the quantitative dopant distribution obtained with the recently proposed Tilted Sample Annular Dark Field Scanning Transmission Electron Microscopy (TSADF-STEM) technique [1]. The findings inferred from a comparison of the quantitative results with Secondary Ion Mass Spectroscopy (SIMS) results obtained on the same samples as well as with calculations based on a recently proposed new model for the As segregation [2] are reported and discussed.

Fig. 1 shows cross-sectional ADF-STEM images obtained from regions of equal thickness of about 100 nm, of samples implanted at 5 keV with $2x10^{15}$ As^{+}/cm^{2} : (a) and (b) refer to the as-implanted sample while (c) and (d) to the specimen annealed at 800 °C for 3 min in nitrogen atmosphere [1]. For each sample, two images obtained on the same region, corresponding to <110> zone axis ADF-STEM (Figs. 1a) and c)) and TSADF-STEM (Figs. 1b) and d)) imaging conditions are reported. The effectiveness of the TSADF-STEM sample tilt procedure is evident by comparing Figs. 1a) and b). In the latter image, an almost uniform background intensity has replaced the strong intensity variation observed in the former, at the a-c Si interface. This indicates that the strain contribution to the electron scattering present in the on-axis condition has been effectively filtered out leaving an image where intensity modulations closely follows compositional changes. Similarly, in the case of the annealed sample, Figs. 1c) and d), a compositional contrast is uniquely observed in the TSADF-STEM case as demonstrated by the presence of an extremely narrow bright region close to the sample surface: a feature that clearly shows the presence of segregated surface As.

In Fig. 2 are reported the contrast profiles (right ordinate axis) calculated from line profiles of Figs. 1b) and d) averaged over regions about 25 nm wide. To obtain a quantitative determination of the dopant distribution, the contrast scale expressed in arbitrary units in the depth profiles has been transformed into a concentration scale (left ordinate axis) assuming a linear relation between contrast and dopant concentration [4]. The contrast values have been multiplied by a suitable constant determined by matching the integral of the contrast profile to the total nominal As dose. The dopant concentration profiles have been compared with those obtained from accurate SIMS analyses [3].

An overall agreement among the two techniques on the shape of the dopant profiles is clearly seen and a sensitivity of the TSADF-STEM technique, slightly better than 1 at. %, is

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demonstrated in the case of As. The quantitative agreement with the ion beam technique appears to be excellent in the as-implanted case, within a precision of 10 %. In the case of the annealed sample the shape of the profiles is similar but the As surface accumulation in the TSADF-STEM profile appears clearly more confined in a surface peak, where about the 20% of the implantation dose appear segregated.

Beyond the surface dopant pile-up, a depletion region centered at a depth of 2-3 nm from the SiO_2/Si interface is observed in the TSADF-STEM profile. This feature is not visible in the corresponding SIMS profile, but it has recently been confirmed by high resolution Rutherford backscattering spectroscopy [5]. Moreover, the comparison with the As distribution obtained by means of the previously mentioned recently proposed analytical model for As segregation [2], reported with solid squares in Fig. 2b), confirms the TSADF-STEM results, indicating that the proposed technique is capable to describe quantitatively the As concentration profile with a higher depth resolution with respect to SIMS.

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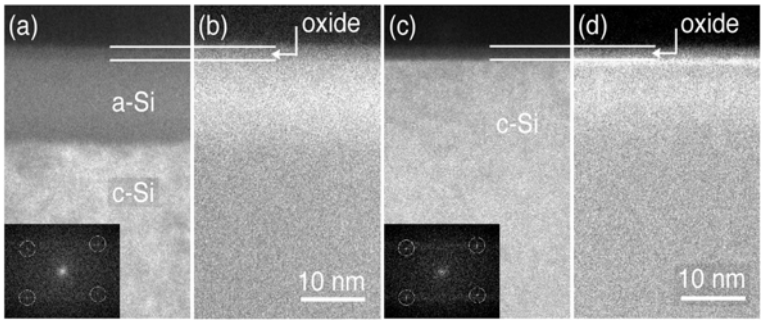

Figure 1. ADF-STEM analysis of 5 keV $2x10^{15}As^+/cm^2$ implanted samples before (a,b) and after annealing (c,d). The micrographs were obtained in <110> zone axis orientation (a,c) and in TSADF-STEM configuration (b,d). The diffractograms in the insets of (a) and (c), show {111} lattice fringes demonstrating an incident probe dimension smaller than the fringe spacing, i.e. < 0.314 nm.

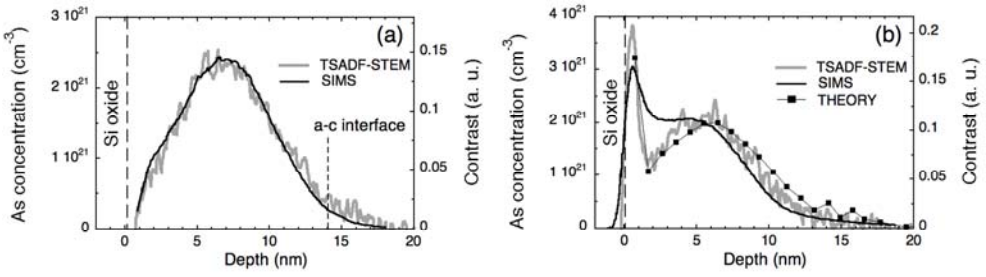

Figure 2. TSADF-STEM and SIMS dopant profiles obtained in 5 keV, $2x10^{15}As^+/cm^2$ implanted Si samples. (a) before and (b) after annealing at 800 °C for 3 min. The SIMS profiles in (a) and (b) have been shifted towards the bulk by 2.0 and 0.8 nm, respectively, in agreement with Ref. 3.