STEM EDX applications for arsenic dopant mapping in nanometer scale silicon devices

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Abstract. In this paper we evaluate sensitivity limits and applications of scanning transmission electron microscopy (STEM) energy-dispersive X-ray (EDX) spectroscopy technique for the mapping of arsenic dopant distribution in nanometer range silicon devices. First we show that lamella radiation damages, generated by the intense focused electron probe at 200 keV, are significantly reduced at 120 keV. This allows to use high electron doses and therefore to improve the EDX sensitivity. The analysis of 45nm nMOS transistor clearly shows the n doped areas and local segregation in gate and spacers.

1. Introduction
Highly doped shallow junctions are developed for short channel metal-oxide-semiconductor (MOS) transistors. The 2D mapping of dopants is critical to control their distribution and is also required for device improvements. In this paper, we evaluate the lamella radiation damages for primary beam energies ranging from 60 to 200 keV. Silicon knock-on damages is significantly reduced by lowering the primary energy to 120 keV. STEM EDX spectra can be integrated for longer acquisition times. The final work concentrates on STEM EDX 2D mapping arsenic distribution in a 45 nm complementary MOS (CMOS) device.

2. Experimental Set-Up
STEM EDX experiments are performed with a field-emission transmission electron microscope (FEG TEM) TECNAI F20. EDX spectra are acquired with an EDAX system. Samples are thinned using a focused ion beam (FIB) FEI HELIOS with a final cleaning at low energy (5 kV). Probe current is measured by the electron current on the phosphorous screen

\[ I(nA) = \frac{2.15 \times \text{emulsion}}{t(s)} \]

where \( t(s) \) is the exposure time in seconds. The lamella thickness is calculated using energy filtered TEM (EFTEM) imaging, with the formula:

\[ \frac{1}{\lambda} = \ln\left(\frac{I_{\text{Total}}}{I_{\text{Elastic}}}\right) \]

where \( t \) is the thickness and \( \lambda \) the inelastic mean free path.

3. Silicon radiation damage versus primary energy
FEG high brightness sources improve STEM EDX resolution and sensitivities but are susceptible to induce radiation damage in the silicon crystal. An example of STEM EDX line profile analysis with noticeable radiation damage at 200 keV is given in figure 1. These damages are undesirable because they can disturb the real arsenic distribution. Moreover structural defects inside silicon crystals (dislocations, grain boundaries, stacking faults) are susceptible to enhance dopant diffusion when radiation damage increases [1]. The first well known radiation phenomenon is the knock-on damage which is well documented [2, 3]. Nevertheless, this radiation effect is strongly energy dependant, in particular below a critical energy, the maximum electron momentum transferred to atoms is not high enough to displace silicon atoms. When the primary energy is below this threshold, the radiation damages become negligible.
Figure 1. TEM image showing silicon sputtering along a STEM EDX line profile with (1 nA × 40 s) dose on the left and (1 nA × 200 s) dose on the right.

We experimentally evaluate the radiation damage versus the electron dose for an intense probe focused on pure silicon. The analysis area is a fixed point from where the Si-K EDX emission signal is monitored to track the radiation damage. Figure 2(a) presents the EDX signal plotted versus radiation time for a 200 keV primary energy beam, 2.5 nA probe current and for various crystal thicknesses of 70 nm, 100 nm and 135 nm. As the specimen is locally etched, the EDX signal decreases and finally a hole is observed (see inset in figure 2). A 70 nm-thick lamella is completely sputtered for a (2.5 nA × 100 s) electron dose at 200 keV. The 100 nm and 135 nm thick lamellae are also totally sputtered after few minutes.

Figure 2(b) presents similar experiments obtained for various primary energies of 200, 160, 120 and 80 keV, in order to determine the critical energy below which no radiation damage will be observed. In this graph, all curves can be easily compared in dose since the recorded primary current is the same for both energies (2.5 nA). At 160 keV, Si etching still occurs but its rate is about five times lower than at 200 keV. Finally at 120 keV (and 80 keV), the relative EDX signal remains constant during the acquisition time. Radiation damages below 120 keV are not detectable.

Figure 2. (a) EDX signal plotted versus radiation time for a 200 keV primary energy beam, 2.5 nA probe current and for crystal thicknesses 70 nm, 100 nm and 135 nm. (b) 200 keV, 160 keV, 120 keV and 80 keV primary energy beam radiation damage kinetics versus the exposure time.
As a consequence, all our EDX analyses were performed at 120 keV. Figures 3 (a, b and c) show the influence of electron dose on the arsenic detection sensitivity in an EDX spectrum of a 0.7% As doped Si sample. Figure 3 (a), low dose (0.9 nA x 3 s), shows a very noisy EDX spectrum where the As-\(K_\alpha\) peak begins to be detectable but with a signal to noise ratio only about one. For higher doses (0.9 nA x 30 s in Fig. 3(b); 0.9 nA x 60 s in Fig. 3(c)), the As-\(K_\alpha\) peak is very distinct from the background. From Figure 3(a) to Figure 3(c), the signal to noise ratio is improved by a theoretical factor around \(\sqrt{20} \approx 4.5\). This points out that the key parameter in EDX analysis is the electron dose and this is the only way to lower the detection limits. This is possible at electron energy equal to or below 120 keV.

![Figure 3. EDX spectrum from a 0.7% As doped Si acquired during 3 seconds (a), 30 seconds (b) and 60 seconds (c). The platinum peaks surrounding the arsenic one come from the FIB capping deposition.](image)

4. STEM EDX quantitative arsenic mapping in a 45 nm SRAM device.
Dopant heterogeneities are undesirable since they can alter the transistor performances. The mapping of dopant segregation in nanometer scale devices is challenging regarding the low arsenic concentration to detect (less than 1%As in Si). Figure 4(a) shows a STEM image of a 45 nm nMOS transistor in SRAM. The regions of interest are indicated by white arrows and correspond to the arsenic low doped drain region (LDD). Applying optimization suggested in this paper, i.e. decreasing electron energy and increasing the dose, STEM EDX mapping at 120 keV (0.9 nA \(\times\) 5 s) is performed in figure 5(b) on a 45 nm CMOS transistor.

![Figure 4. (a) STEM image of the 45 nm SRAM under analysis showing the region of interest (arsenic low doped drain). (b) STEM EDX mapping performed at 120 keV with (0.9 nA \(\times\) 5 s) dose/pixel and for (37 \(\times\) 25) pixels with a drift correction procedure for each 10 spectra.](image)
The arsenic low doped drain regions (LDD), implanted at 2 keV energy and for 2.10^{15} \text{at. cm}^{-2} concentration, are detected and indicated by the white arrows in figure 4(b). After the implantation process, the spacers (Si_{3}N_{4}) were built and another dose of arsenic was implanted to create the source and drain doped pockets. This is why arsenic is clearly detected at the top of the spacers. Arsenic segregation under the NiSi, probably at point defects, is also shown (see figure 5(b)). Also it seems that at the bottom of the gate, arsenic segregates just above the thin SiO_{2} oxide. Arsenic segregation at SiO_{2}/Si interface is the subject of recent publications [4,5].

On figure 5(a), we present the result of several 120 keV EDX mappings that we recombined together as a global map to generate a more highly resolved zoom into the 45 nm SRAM. The different arsenic regions are detected and segregation at the oxide interface is also observed. Figure 5(b) presents a zoomed 120 keV EDX mapping of an n-doped silicided source/drain, showing the arsenic in the LDD but also arsenic segregation at the NiSi interface. This segregation occurs after the drain/source arsenic implantation and can be the place of NiSi encroachments [6].

![Figure 5](image_url)

**Figure 5.** (a) STEM EDX mapping zoomed on the spacer region. (b) STEM EDX mapping revealing arsenic segregation at point defects.

5. **Conclusion**

This study shows that STEM EDX allow arsenic dopant detection with low concentration at the nanometer scale. The application of this technique is very useful in particular in the microelectronic field to map the dopant distribution and to evaluate possible heterogeneities. Arsenic mapping on a 45 nm scale CMOS shows arsenic presence in the LDD, at the top of the spacers, at the SiO_{2}/Si interface at the bottom of the grid and also unexpected dopant segregation at point defects.

**References**

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