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The Influence of Beam Convergence Angle on Channeling Effect during STEM/EDS Quantification of SiGe Concentration

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Embedded SiGe in the source and drain region of the p-type metal–oxide–semiconductor field-effect transistor (p-MOSFET) has played a significant role in the modern complementary metal-oxide semiconductor (CMOS) technology as a stressor to improve the hole mobility in PMOS channel [1]. Due to the competing mechanisms between the stress generations from the lattice mismatch and strain relaxation because of stress induced crystal defects, a higher Ge concentration does not necessarily result in higher compressive stress in gate channel. However, an accurate Ge concentration measurement is still important to understand the device performance and to monitor the process stability in a modern Fab. Conventionally, this has been done by Auger electron spectroscopy (AES) and secondary ion mass spectrometry (SIMS). Both techniques can obtain an accurate measurement of Ge concentration. However, they suffer from poor spatial resolution and are not suitable for characterization of embedded SiGe in the start-of-art devices. Energy-dispersive X-ray spectroscopy (EDS) in scanning transmission electron microscope (STEM), on the contrary, can yield Ge concentration with atomic spatial resolution [2]. However, the quantification can be affected by several experimental factors, such as exposed electron doses [3], shadowing effect due to the mounting grid for the *in-situ* lift-out sample, and channeling effect [4]. Most EDS quantification of SiGe has been characterized by tilting the sample off the [110] zone-axis to avoid the strong electron beam-sample interaction due to channeling effect, which could adversely affect the spatial resolution of the EDS measurements. In this study, the state of art Titan G2 microscope equipped with the CEOS probe corrector enables a high electron beam convergence angle used for data collection. With higher electron beam convergence angle, it is still possible to collect SiGe EDS spectrum in the [110] zone axis orientation without incurring channeling effect. This is critical in the CMOS device to preserve the high spatial resolution of the analysis.

In Figure 1, the EDS quantification results are shown with two different collection convergence angles. The sample is a thin film with 29.8 at.% Ge content grown on Si substrate, whose Ge concentration has been characterized by AES and SIMS. The top of the thin film layer is amorphous due to the effect of ion implantation; the bottom of the SiGe layer is still crystalline. As seen from the Figure 1(b) and 1(c), a relatively higher Ge concentration is measured in the crystalline region as compared to the amorphous region with a convergence angle at 12.8 mrad. At the same time, there is almost no difference in Ge concentration between the crystalline region and the amorphous region if the data is acquired with the 29.8 mrad convergence angle. This result is summarized in Table 1.

In Figure 2, the STEM-EDS results of the monitoring pad and embedded SiGe between devices are presented. Interestingly, a thin Ge depletion layer is observed between the lower concentration L1 SiGe buffer layer and the L2 SiGe main layer for both structures (arrowed). To detect the concentration of such a thin interfacial layer, the analysis should be performed in the [110] zone axis orientation.

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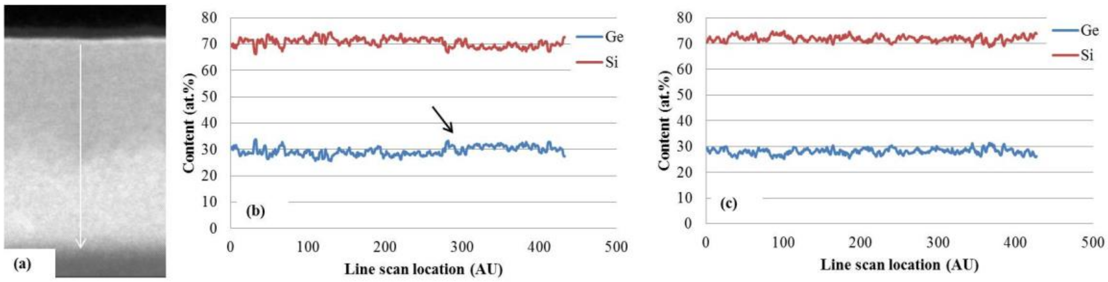

Figure 1. STEM image (a) of the SiGe sample with white arrow showing the line scan direction of (b) and (c). In the STEM image, the top layer is amorphous SiGe while the bottom is crystalline SiGe, grown on Si substrate. (b) is collected at 12.8 mrad convergence angle, showing a slight increase in measured Ge concentration at the crystalline SiGe layer. (c) is collected at 29.8 mrad convergence angle, showing no noticeable difference in Ge concentration between the amorphous and crystalline region.

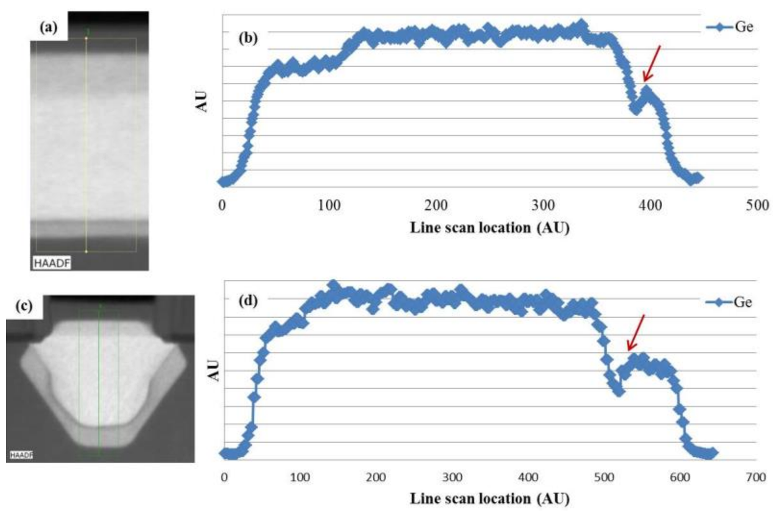

Figure 2. (a) STEM image of the monitoring pad; (b) Integrated EDS line scan of (a); (c) STEM image of the embedded SiGe in devices; (d) Integrated EDS line scan of (c). Notice the depletion layer between L1 and L2 layer (red arrowed). The standard error for the measurement is ~1.0 at.%.

Convergence angle (mrad)	**12.8**	**21.4**	**29.8**
In-zone (crystalline)	32.4	31.0	29.9
In-zone (amorphous)	29.9	29.3	29.4
Off-zone1 (crystalline)	29.3	28.6	28.9
Off-zone2 (crystalline)	29.0	28.8	28.9

Table 1. Summary of the measured Ge content of the standard SiGe sample (29.8 at.%) with different beam convergence angles and sample tilt angles. For "In-zone" measurements, the sample is oriented in [110] zone axis; for "off-zone1" measurement, the sample is tilted 2.5 degree in alpha from [110] zone axis; For "off-zone2" measurement, the sample is tilted -2.5 degree in alpha from [110] zone axis.