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Characterization and monitoring of silicon-on-insulator fabrication processes by high-resolution x-ray diffraction

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Abstract

High-resolution x-ray diffraction (HRXRD) was used to monitor silicon-on-insulator (SOI) processing steps. The use of HRXRD is attractive since it is non-destructive and can be applied directly to product wafers. We show the usefulness of this technique for the characterization of amorphizing implants for shallow junctions, solid phase re-crystallization of implanted junctions, cobalt-silicide formation, and oxidation; all are critical processes for CMOS fabrication on SOI.

Introduction

The idea behind the use of HRXRD to monitor SOI processing is straightforward. Oxidation, silicide formation and amorphizing implants reduce the single crystal SOI film thickness, which is easily and accurately measured by HRXRD [1]. For example, oxidation would convert the upper part of the SOI film into SiO_2. Similarly, silicidation reacts a metal (such as Co) with the top portion of the SOI film to form a silicide (such as CoSi and $CoSi_2$). The phase of the silicide that is formed can be determined from the amount of Si consumed. In the case of amorphizing implants, which are routinely used to form the source and drain region of a device [2], a portion of the SOI film is converted from single crystal silicon to amorphous silicon. Post-implant annealing, typically carried out by rapid thermal annealing (RTA), re-crystallizes the amorphous portion of the film and restores the SOI film thickness. Accurate measurement of the SOI film thickness is essential for tight monitoring of all these processes.

The change in the SOI layer thickness is not the only parameter obtained by HRXRD. The HRXRD data of amorphizing and non-amorphizing Ge, Si or boron implanted wafers, is further used to extract the strain profile and the implant damage profile in the SOI film. Moreover, in the case of boron-implanted wafers a change in the sign of the strain is recorded when the boron assumes a substitutional site following the RTA anneal.

Experiment

The x-ray diffraction measurements were carried out with a Philips materials research diffractometer (MRD), which is equipped with an asymmetrically cut four-crystal Ge(220) monochromator and mounted on a rotating Cu anode x-ray source. ω is the angle between the incident beam and the wafer surface and 2θ is the angle between the incident beam and the detector (reflected beam); therefore the angle of the incident or reflected beam with respect to the analyzed atomic planes, the Bragg angle, is $\theta_B = 2\theta/2$.

ϕ denotes a rotation in the plane of the wafer. The 004 reflections were measured in the triple-axis (TA) mode [4], i.e. by taking $\omega/2\theta$ scans with an analyzer crystal installed in front of the detector. The 113 reflections were measured using a large detector aperture and standard rocking curves (ω scans).

Figure 1 demonstrates how the cobalt silicide formation process is monitored on an SOI wafer. The process begins with a sputter deposition of a 7 nm thick cobalt layer over the SOI film. The cobalt layer is capped with a 20 nm thick TiN film to prevent the cobalt from oxidizing during annealing. A first anneal at a temperature of 520°C is performed to react all the cobalt with the underlying silicon to form the mono-silicide phase (CoSi). The TiN cap and unreacted cobalt on the regions of the wafer having no exposed Si (e.g. dielectric isolation regions) are then selectively etched off, and a second anneal at a temperature of 750°C is performed to form the disilicide phase ($CoSi_2$). Since the silicide reaction is self-limited, the nominal amount of silicon consumed from the SOI layer is known. The formation of the CoSi phase requires 1.82 nm of silicon per 1 nm of metal and the formation of the $CoSi_2$ phase takes 3.64 nm of silicon for each nanometer of metal [3]. By monitoring the change in the SOI thickness, which is equivalent to the amount of silicon reacted to form the silicide, it is possible to confirm the formation of the desired silicide phases.

We note that it is critical to form the lowest resistivity silicide phase for the manufacturing of high-speed devices. To reduce the parasitic resistance of a device the $CoSi_2$ phase is used since it exhibits a lower sheet resistance than CoSi. The lowest resistivity phase is not always the disilicide phase, however. For example, nickel mono-silicide (NiSi) has a lower resistivity than the disilicide $NiSi_2$.

Figure 1(a) shows a 004 triple-axes scan of the as-deposited cobalt on a bonded SOI wafer, where the diffraction peak of the SOI layer is offset from that of the substrate [1]. The trace is recorded with the incident angle, ω, centered at the SOI layer diffraction peak. The SOI layer thickness is accurately measured from the spacing in the Pendellosung fringes (also know as thickness fringes). Figure 1(b) shows a scan following the first anneal which forms the monosilicide phase, and figure 1(c) shows a scan following the second anneal which forms the disilicide phase. As is clearly seen, the fringe spacing increases when the silicide phase becomes more silicon rich. By measuring the change in the SOI thickness the silicide phase is identified as indicated on figures 1(b) and 1(c).

Ion implantation is another key process for semiconductor device fabrication. To obtain a shallow junction by implanting a light atom dopant such as boron, a pre-amorphizing implant of Ge is used. The amorphized surface prevents boron channeling, which would lead to a tail in the boron profile. The thickness of the amorphized portion of the SOI film is easily obtained by measuring the thickness of the remaining crystalline portion of the film.

To investigate amorphizing implants by HRXRD we implanted Ge into a SIMOX wafer using different implant conditions. For SIMOX wafers, the diffraction peak from the SOI layer overlaps that from the Si substrate. Figure 2 shows three rocking curves that correspond to the initial SOI wafer and two different implant conditions. The first trace (solid line) of figure 2 is a measurement of a region with no implant. The second trace (dashed line) corresponds to a Ge dose of $3x10^{14}$ cm^{-2} and implant energy of 15 keV, and the third trace (dash-dot line) corresponds to an implant with the same dose but a higher energy of 30 keV. The TEM images (not shown) confirm that the top portion of the SOI film is amorphized by the implant. A 15 keV implant resulted in a 20.5 nm thick amorphous layer, while the 30 keV-implant amorphized about 37.2 nm of single crystal silicon. The HRXRD measurements of figure 2 provide the same thickness data. The implanted samples show a larger fringe spacing than of the non-implanted sample, because the top portion of the single crystal SOI film was amorphized. The traces from the implanted samples also show an asymmetric spectrum, having pronounced thickness oscillations for negative ω and few fringes for positive ω. This asymmetry is due to the strain and damage introduced by the implant into the crystalline portion of the SOI, as explained below.

Figure 3 shows a rocking curve of a SOI film implanted with a Ge dose of $3x10^{13}$ cm^{-2} and energy of 50 keV, and figure 4 shows a TEM cross-section of the same sample. Due to the lower Ge dose, the implant does not amorphize the SOI film. Hence the fringe spacing is the same as that of the non-implanted SIMOX sample. To better explain the asymmetry in the rocking curve, we simulated the diffraction pattern using the wave summation approach outlined in reference 5. The Ge implant leads to strain and damage in the SOI film, which were incorporated into the simulation in the following way: The SOI film was sectioned into N laminae each having two parameters: strain and static atomic disorder. The strain distribution is represented by a set of coherently diffracting laminae. The laminae all have the same in-plane lattice parameter, but the out-of-plane lattice parameter of each one varies according to an assigned uniform strain value chosen to approximate the strain profile introduced by the implant. In addition to the coherent atomic displacements (strain), static random displacements (damage) are treated through their effect on the mean structure factor in each lamina [6]. The static atomic displacement factor is also known as the Debye-Waller factor, which accounts for the displacements of atoms from their lattice position. The higher the static atomic disorder value assigned to a lamina the less diffractive the lamina will be.

We further assumed that a Gaussian distribution could approximate the strain and damage profiles. Both the center position and width of each distribution were changed to obtain the best fit with the measured data. The maximum positions of the strain distribution and of the atomic disorder distribution obtained from simulation are in excellent agreement with the position of the maximum damage found by TEM. The simulated rocking curve, shown in Figure 3, predicts well all the features in the measured rocking curve. We note that the measured intensity is greater than the calculated intensity away from the center of the scan because of high background scattering when data is taken without a receiving slit to reduce the detector aperture. We also think that an improved prediction can be obtained by not fixing the distributions to an analytical form (such as a Gaussian distribution), but rather allowing the distribution to be calculated using a minimization procedure as discussed in [7].

Figures 5 and 6 demonstrate how HRXRD can be used to monitor RTA processing of implanted wafers. Figure 5 shows the rocking curves of a SIMOX sample that was implanted with a Si dose of 5×10^{14} cm^{-2} and energy of 23.8 keV and then annealed at 1000 °C for 2 seconds by RTA. The rocking curve clearly shows that the Si implant amorphized the top portion of the SOI film, and induces damage which cause the film to strain compressively, similarly to the observation made with Ge implants. During RTA the amorphous silicon film re-crystallizes by solid phase epitaxy and the thickness fringe spacing is restored to its pre-implant value (shown in figure 2 by the solid line). The post-RTA curve shows a slight asymmetry, which is due to residual damage that could not be removed by RTA.

Figure 6 shows the rocking curve of a sample that was implanted with a boron dose of 3×10^{14} cm^{-2} and energy of 3.8 keV. The thickness fringe spacing does not change since the light-mass boron atom does not amorphize the film. The rocking curve indicates that the post-implanted film is compressively strained, due to implant damage and the boron mostly assuming interstitial sites. Following an anneal at 1000 °C for 2 seconds by RTA, the boron atoms assume substitutional sites and the strain in the SOI film becomes tensile, since boron is a smaller atom than silicon.

Conclusion

We have demonstrated that HRXRD can be used to monitor critical SOI device fabrication steps. This technique is non-destructive and can, therefore, be applied to product wafers. While this method primarily provides the thickness change in the SOI film due to the processing, additional data such as the ion implantation damage and the strain distribution in the film was also obtained by simulating the x-ray diffraction spectrum.

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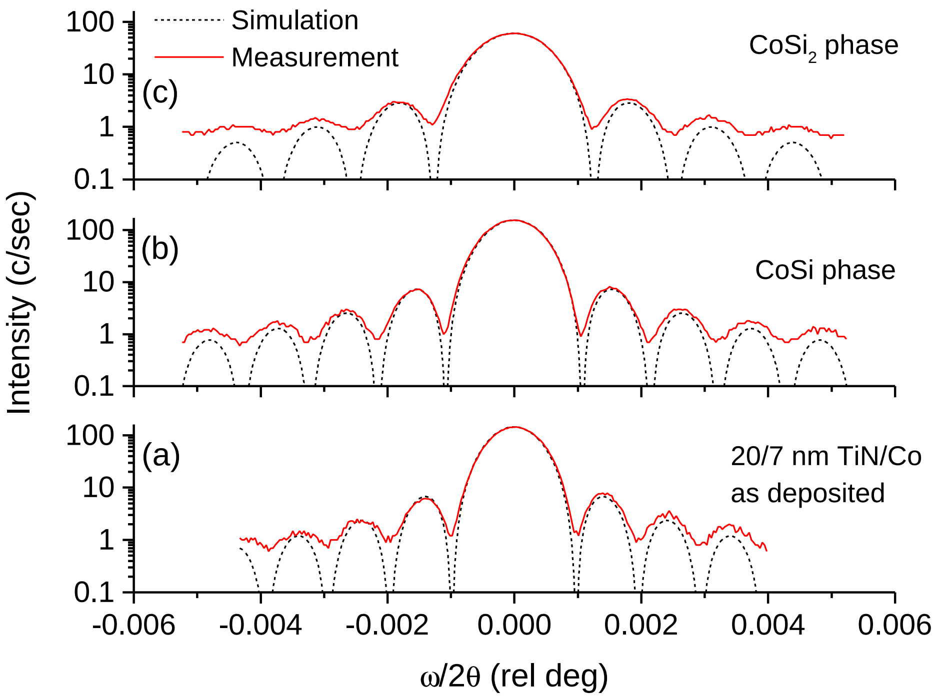

Figure 1: An 004 triple-axes scan of a bonded SOI wafer, showing only the diffraction pattern obtained from SOI film. (a) With as deposited cobalt. (b) After first RTA that forms cobalt monosilicide. (c) After second anneal that form the cobalt disilicide.

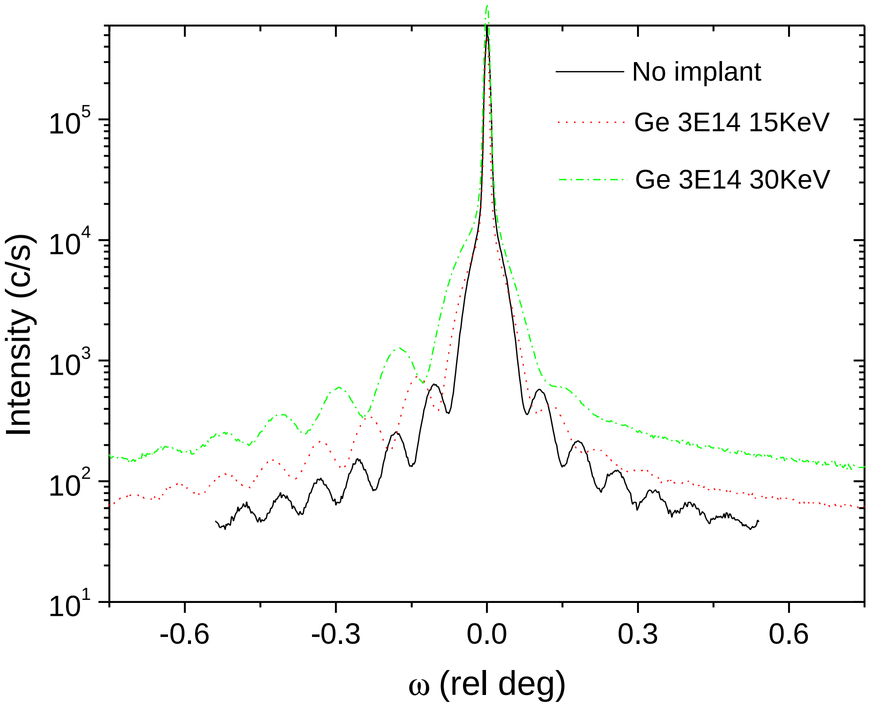

Figure 2: 113 rocking curves a SIMOX wafer. The solid line is a measurement of a region with no implant. The dashed line corresponds to a Ge dose of $3x10^{14}$ cm^{-2} and implant energy of 15 keV, and the dash-dot line corresponds to an implant with the same dose but a higher energy of 30 keV.

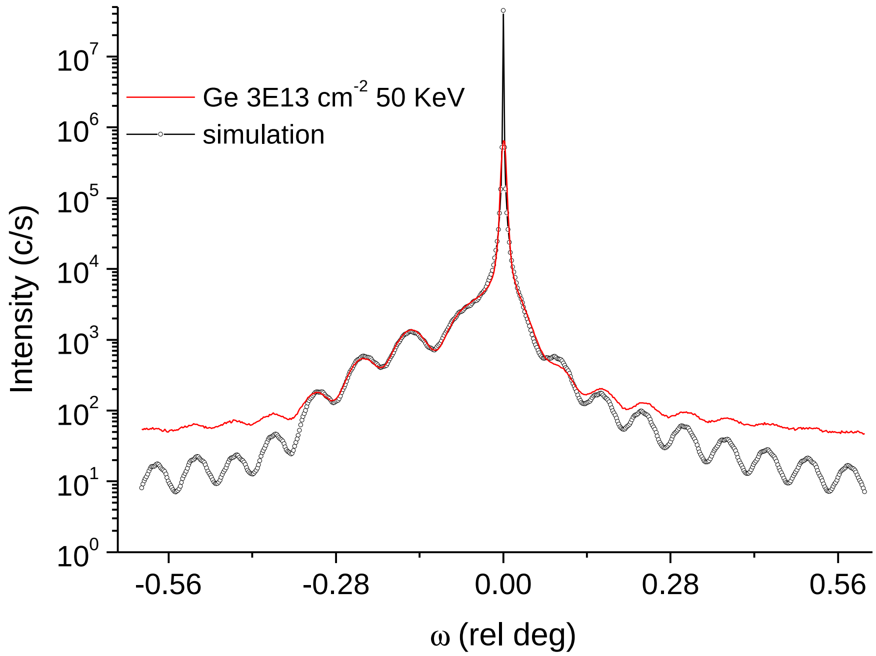

Figure 3: A 113 rocking curve of a SOI film implanted with a Ge dose of $3x10^{13}$ cm^{-2} and energy of 50 keV. The dash-dot line shows a simulation obtained by fitting the strain and damage distribution in the film.

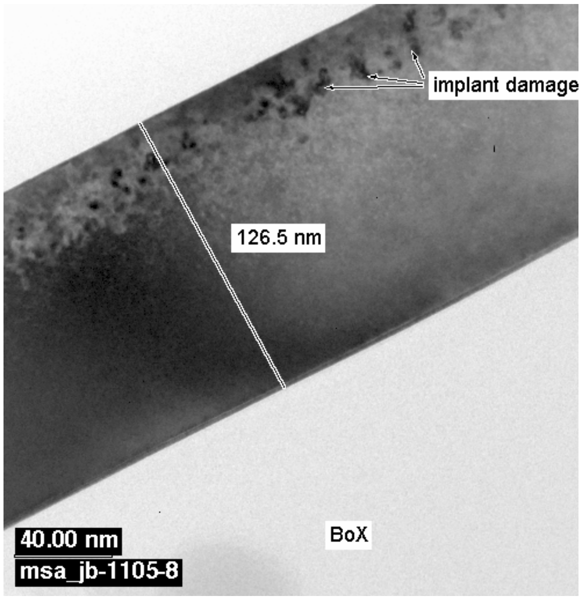

Figure 4: A TEM image of a SOI film implanted with a Ge dose of $3x10^{13}$ cm^{-2} and energy of 50 keV. Note the implant damage.

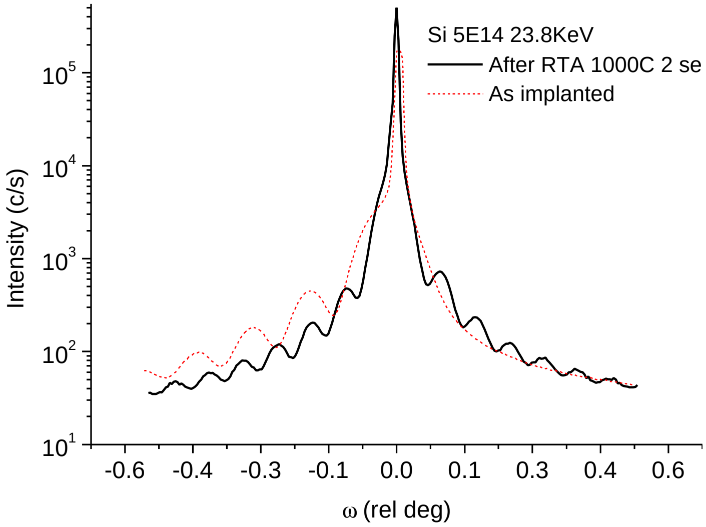

Figure 5: A 113 rocking curves of a SIMOX sample that was implanted with a Si dose of $5x10^{14}$ cm^{-2} and energy of 23.8 keV (dashed line) and then annealed at 1000 °C for 2 seconds by RTA (solid line).

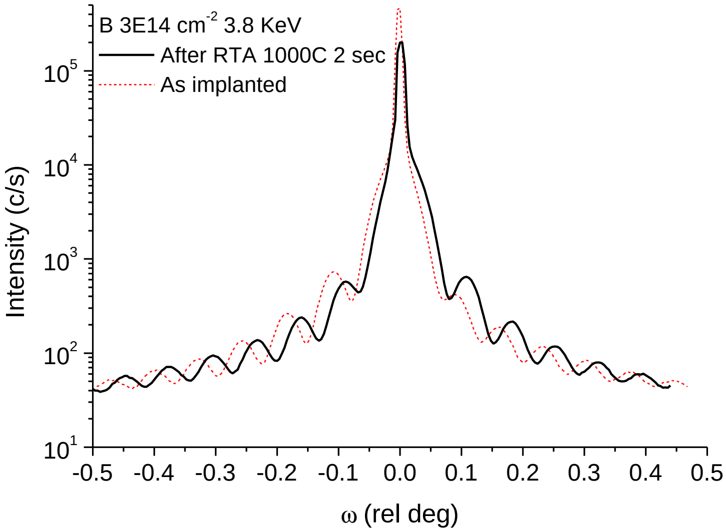

Figure 6: A 113 rocking curve of a sample that was implanted with a boron dose of $3x10^{14}$ cm^{-2} and energy of 3.8 keV (dashed line) and then annealed at 1000 °C for 2 seconds by RTA (solid line).