The Distribution of Boron and Arsenic in SOI wafers implementing SIMS

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***Abstract*—Silicon-on-Insulator (SOI) material is becoming increasingly more important for low-power, low-voltage applications. In this study, boron and arsenic implanted SOI wafers have been investigated using Secondary Ion Mass Spectrometry (SIMS). It is shown that efficient charge compensation in the oxide layer is required to obtain dose information at the active layer/oxide interface. A variety of implant energies and annealing conditions have been studied. The results show that there is considerable "pile-up" of boron at the interface between the active layer and buried oxide due to preferential migration to interfacial defects following implantation and annealing processes. This "pile-up" is shown to be dependant on the process parameters. A similar phenomenon is not apparent in the arsenic implanted wafers studied.**

INTRODUCTION

The development of Silicon-on-Insulator (SOI) technology has been dramatic in recent years, driven by the general acceptance of SOI materials for high-performance applications such as CMOS logic, RF-transceivers and the rapidly growing area of photonic and MEMS structures.

The speed advantage which can result in the use of SOI materials is a direct consequence of the insulating layer which provides isolation from the substrate, thereby decreasing capacitances for both devices and electrical interconnections.

SOI transistor applications require tight control of active layer thickness for consistent threshold voltage and sub-threshold leakage characteristics. This can be affected by the surface and interface roughness [1-3].

Another area of obvious importance is that of the electrical characteristics of the active top layer [4, 5]. Many of the challenges for CMOS transistors in bulk silicon are theoretically relaxed or removed when SOI wafers are used. For example, in bulk silicon, obtaining shallow junctions requires careful control of thermal annealing in order to limit both the vertical and lateral dopant diffusion. However, the buried oxide of SOI wafers plays an important role in the operation of electronic devices whereby the junction depth is determined by the active, top layer thickness, and dopant diffusion is restricted by the oxide layer.

In this study, SIMS is used to probe the active layer and oxide of SOI wafers of varying active layer thickness. Boron and arsenic implanted SOI and bulk silicon wafers with varying implant energies and annealing conditions have been analysed. Low energy electron flooding of the analysis sample is discussed, whereby efficient charge compensation may allow dopant distribution information through the active layer/oxide interface to be obtained in the SOI wafers. The effects of annealing and implant energy have been presented with respect to the distribution of the dopant material through the active layer and beyond and the results are compared with equivalent implant profiles in bulk silicon. Conclusions are made as to the efficiency of the oxide barrier and phenomena associated with restricting diffusion using such a passivating layer.

EXPERIMENTAL

All SIMS analyses were carried out using a Physical Electronics model Adept 1010 quadrupole based instrument. O_2^+ bombardment analyses were performed using a beam energy of 1.5 keV at 45º incidence with positive ion detection. Cs^+ bombardment analyses were performed using beam energies of 750 eV at 60º incidence with negative ion detection.

For arsenic dopant studies, a Cs^+ primary ion beam was implemented, with $^{103}SiAs^-$ and $^{75}As^-$ ions detected for arsenic profile measurements. $^{57}Si_2^-$ and $^{30}Si^-$ ions were detected as reference ions. For boron dopant studies, an O_2^+ primary ion beam was implemented, with $^{11}B^+$ ions detected for boron profile

measurements. $^{30}Si^+$ ions were detected as reference ions. Ion counts were converted to concentration using relative sensitivity factors (RSF) derived from the measurements of NIST traceable reference materials presently used by Cascade Scientific for the monitored species.

In order to compensate for charging of the sample during experiments, electron flooding was implemented.

The wafers analysed were supplied by Soitec (SOI wafers-Bernin, France) and Wacker (bulk Si wafers, Burghausen, Germany) whilst the boron and arsenic dopants were implanted (0.2 and 5 keV boron, 1 keV arsenic) by an Applied Materials LEAP ion implanter with certain wafers subjected to various annealing conditions. The central part of each blanket wafer was used for analysis.

Depth scale calibrations were performed using crater depths, which were measured with a Tencor Alpha Step-200 stylus profilometer. The pressure in the sample chamber was <5 x 10^{-9} Torr during analysis. The sputtering rate difference between Si and SiO_2 was accounted for.

RESULTS AND DISCUSSION

In order to investigate the implantation of dopant materials in SOI wafers it was first necessary to ensure that the dopant materials were not present to begin with in the fresh SOI wafers. Fig.1 shows the boron depth profile obtained from a fresh SOI wafer (active layer/oxide interface depth = 1100Å). Detection limits for boron were 1e15 atoms/cm3. It can be seen that before implanting the dopant species there is little or no boron present to this detection limit in either the active top layer of silicon or the oxide.

Critically, there is no dopant present at the active layer/oxide interface. A similar experiment was carried out implementing a Cs^+ primary ion beam whilst analysing for As species. The same result applied, with a background for As of 1e16 atoms/cm3 achieved.

An inherent problem of SOI wafers is their ability to build up charge due to the passivating oxide layer present. Following primary ion bombardment this effect is seen with the consequence that the secondary ion signal which is being detected tends to decay to zero.

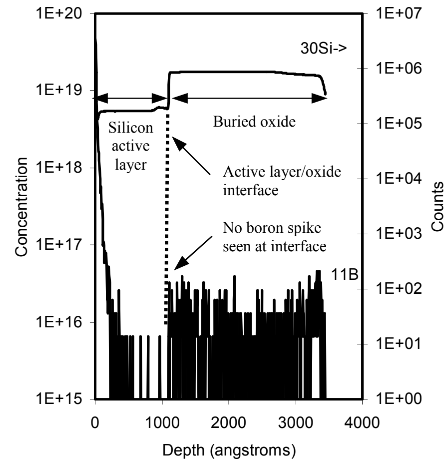

Figure 1. Boron SIMS Depth profile of fresh SOI wafer

To achieve adequate charge compensation to obtain a dopant depth profile beyond the active layer/oxide depth, tuning of the electron flooding must be carried out. Once the optimum reference signal is achieved by tuning of the focus and raster of the electron gun, a fresh area of the sample is then sputtered. The reference silicon signal in Fig. 1 shows that once this set-up procedure has been completed, the reference signal remains relatively constant in both the active layer and the oxide (the reference signal is enhanced in the oxide due to the greater sputtering yield of Si in SiO_2 with respect to pure Si) and hence the dopant profile obtained will be a true refection of the material present in the sample.

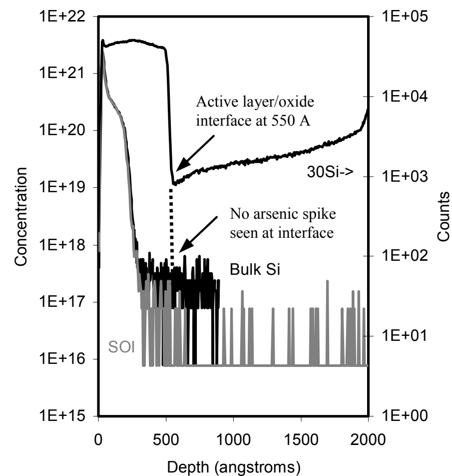

Figure 2. SIMS depth profile of 1 keV 1e15 atoms/cm^3 arsenic implanted and annealed in SOI and bulk silicon wafers

A similar set-up procedure is necessary to achieve adequate charge compensation when implementing a Cs^+ primary ion beam. Fig. 2 shows the arsenic depth profile obtained from an SOI wafer (active layer/oxide interface depth = 550 Å) implanted with a 1 keV 1e15 atom/cm^3 annealed arsenic implant along with an identical implant into a bulk silicon wafer. The silicon reference signal which was acquired from the SOI wafer scan decays somewhat at the active layer/oxide interface even following optimisation of the electron flooding to achieve charge compensation. However, this is expected, as the yield for $^{30}Si^-$ is lower in SiO_2 than in Si.

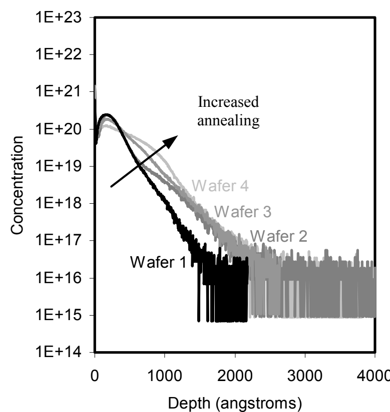

Figure 3. SIMS depth profiles of 4 differently treated boron implants (5 keV 1e15 atoms/cm^3) in bulk silicon wafers

Both arsenic implants extend to a depth of 350 Å, by which detection limits are reached, i.e. before the active layer/oxide interface at 550 Å in the SOI wafer. Although the arsenic ion signal from the SOI wafer will be expected to decay in a similar fashion to that seen for the reference silicon signal after the active layer/oxide interface is reached, the signal maintains its intensity right up to this interface, and it is apparent that there is no build up of arsenic towards this interface. In effect, the implant into the SOI wafer matches that seen for the same implant into the bulk silicon wafer and if pile-up of arsenic occurs at all in implanted SOI wafers, a more intense anneal procedure or thinner active layer would be necessary to show this with a 1e15 atom/cm^3 dose due to the low diffusion coefficient of arsenic (i.e. its large size).

Fig. 3 shows a set of boron depth profiles obtained from a range of boron implanted (5 keV, 1e15 atoms/cm^3) bulk silicon wafers. Wafer 1 is the as-implanted wafer, whilst wafers 2, 3 and 4 have been subjected to successively increased amounts of annealing. Replica implants in SOI wafers (active layer/oxide interface depth = 1100 Å) were also analysed and the results are displayed in Fig. 4. Detection limits for boron were 1e15 atoms/cm3.

The set of profiles in Fig. 3 show quite clearly that detection limits are not reached for this dopant species until ~2500 Å for the annealed samples, and ~1700 Å for the as-implanted sample.

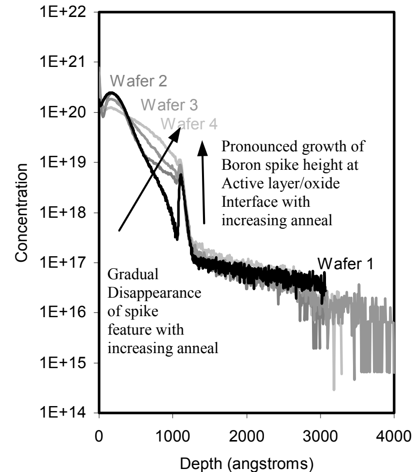

Figure 4. SIMS depth profiles of 4 differently treated boron implants (5 keV 1e15 atoms/cm^3) in SOI wafers

Fig. 4 suggests that the boron diffused beyond 1100 Å in the bulk silicon wafers can be found at interface between the active layer and the oxide in the SOI wafers. The peak height of the spike is seen to increase as annealing is increased, suggesting that more boron preferentially migrates to this interface following increased annealing. There is also a small amount of boron diffusion seen through the buried oxide layer from 1100 Å to ~ 3000 Å. This is indicated by the monotonic decrease in boron from ~1e17 atoms/cm3 to ~1e16 atoms/cm3 in all 4 wafers. Although only a fraction (~1/10,000) of the total dose of boron implanted into the wafers, this dopant diffusion must be taken into account when assessing the electrical characteristics of SOI devices and hence their efficiency.

The bar chart in Table 1 shows the boron dose values found in the bulk silicon wafers beyond 1100 Å compared to that found from the start of the boron spike seen in the SOI wafers to the end of the oxide. It is evident that the dose values for the annealed samples are very similar, and within experimental error, it can be suggested that they are equivalent.

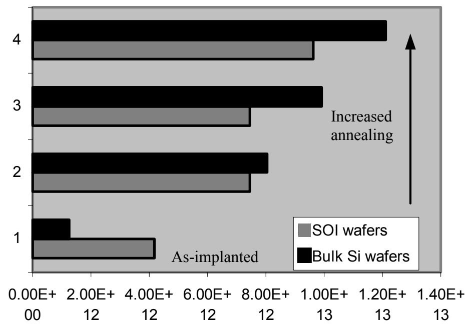

Table 1: Boron dose from spike leading edge in SOI wafers compared with dose in bulk Si from same depth

However, the boron dose found in the spike at the active layer/oxide interface and through the buried oxide layer in the as-implanted SOI wafer 1 is found to be much higher than the dose found beyond 1100 Å for the equivalent bulk silicon wafer. When the two depth profiles are seen overlaid (Fig. 5), we see that the boron concentration decreases more rapidly from 1000 Å towards the active layer/oxide interface of the SOI wafer with respect to the bulk silicon wafer suggesting preferential migration of boron to this interface, with dose intensity being lost in this region of the active layer to the interface.

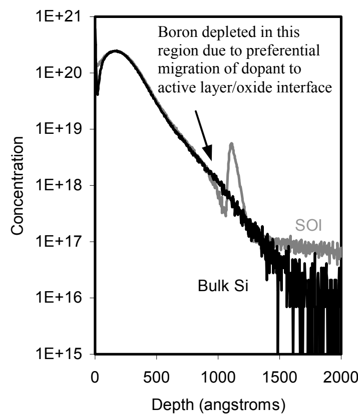

Figure 5. Comparison between the boron SIMS depth profiles obtained from an identical as-implanted boron implant (5 keV 1e15 atoms/cm^3) in bulk silicon and SOI wafers

For SOI wafers 2, 3 and 4, this defect-mediated boron accumulation at the active layer/oxide interface becomes outweighed by the conventional, yet more powerful effect of thermal annealing, and the boron doses found in the spike to the end of the oxide essentially become equivalent to the boron dose found in the bulk silicon wafer beyond 1100 Å.

In contrast to the arsenic results, similar depth profiles of *very low energy* (0.2 keV), and hence shallow, boron implants in SOI wafers (active layer/oxide interface depth = 1100Å) show a small amount of boron accumulating at the active layer/oxide interface, although the amount is obviously significantly lower (~18X) than that seen with the 5 keV as-implanted boron SOI wafer. Nevertheless, this result compounds the theory that this interface is a very favourable site for preferential migration of boron when implanted into SOI wafers.

SUMMARY

In summary, the results presented in this study have shown that SIMS is an excellent technique for the analysis of dopant implants in SOI wafers. Nevertheless, care must be taken to ensure that charge compensation factors are fully assessed when acquiring SIMS depth profiles.

From studying a limited number of arsenic implants in SOI material, it is suggested that arsenic does not preferentially migrate to the active layer/oxide interface and the implant profiles essentially mimic their bulk silicon counterparts.

The investigation of a range of boron implants in SOI and their comparison with bulk silicon equivalents, however, undoubtedly shows that when boron is implanted into SOI material a significant amount of the dose preferentially migrates to the active layer/oxide interface causing dopant "pile-up" at this interface, even for low energy implants. A small amount of diffusion in the oxide is also observed which may affect the electrical properties of SOI devices.

References

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