

OXIDATION INDUCED CRYSTALLINE DEFECTS IN BONDED SOI WAFERS

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ABSTRACT

This work investigates the role of interstitial oxygen content in CZ device wafers, and the effects of buried layer implants and thermal processing on the formation of crystalline defects in the surface of bonded SOI material. We found that unimplanted SOI material originating from Si with high oxygen levels ($>7.2 \text{ e}^{17}/\text{cm}^3$) were populated with heavy oxygen precipitation and related crystal defects, and were also characterized by low minority carrier lifetime values. However, a dramatic improvement was observed in the behavior of SOI with moderate oxygen levels, where the development of oxygen precipitation in the SOI layer was inhibited. Furthermore, wafers processed through deliberate oxygen precipitation cycles prior to bonding gave low lifetimes and high levels of defects, as revealed by Secco etching. Incorporation of a buried implant layer in the SOI gave a dramatic improvement in the lifetime of the material through a gettering effect.

INTRODUCTION

Bonded silicon-on-insulator (SOI) has become a proven, commercially viable substrate material. To accelerate this market acceptance, and extend the range of possible applications, it is vital to characterise the material in order to eliminate defects associated with crystal quality. The quality of the SOI layer depends on the crystalline quality of the starting Czochralski (CZ) silicon wafers and the high-temperature processing steps used for the buried oxide (BOX) layer formation and bonding. It is well known that CZ silicon contains grown-in microdefects, which are created during ingot formation, and in addition, process-induced defects such as oxide nuclei, precipitates and stacking faults (SF), which are formed during subsequent oxidation and device processing (1-4). The presence of these defects in the active region of the silicon wafer can have a detrimental effect on gate oxide integrity and minority carrier lifetime.

Grown-in microdefects are caused by intrinsic point defects (interstitials and vacancies) and can be classified in two categories: those associated with the agglomeration of vacancies, termed D defects or Crystal Originated Particles (COP), and those formed by clustering of interstitials, called A and B defects. The defect type, size, distribution and concentration depend primarily on the ratio between the pulling rate and thermal gradient in the growing crystal. Depending on this ratio, an oxidation induced stacking fault (OSF) ring is positioned near the edge of the wafer or disappears in the centre.

Oxygen is one of the most important impurities incorporated in the silicon, so that its behaviour has been the subject of extensive study. At commonly used processing temperatures, the presence of supersaturated interstitial oxygen leads to the formation of silicon oxide precipitates, the amount of which depends critically on the thermal history of the crystal (i.e. dwell time), vacancy concentration, interstitial oxygen concentration and post-growth thermal treatment. Precipitates can have both beneficial and harmful effects on the device performance. If they are located in the device active region, they can reduce the mechanical strength of the silicon wafer when their concentration becomes too high. On the other hand, they have a beneficial effect in gettering undesirable metallic impurities, provided they are confined far from the silicon surface. It is common practice to attempt to deplete the wafer of microprecipitates by dissociation at high temperatures and to create precipitate nuclei at lower temperatures. Thermal cycles which aim to lower the near-surface oxygen concentration and denude the surface zone of oxygen precipitates have been developed for bulk wafer processing. In this respect, high temperature processing steps involved in bonded wafer fabrication might cause dissolution of oxygen and related defects in the region close to the buried oxide and favour the formation of a defect-free SOI layer.

There is a continuing need for non-invasive, cost effective analysis of silicon material. Carrier lifetime is an excellent predictor of crystalline defects, whether such defects are metallic contaminants or structural imperfections (e.g. oxygen precipitates, SF and dislocations, etc.) (5). These defects are potential lifetime killers; thus, the lower the defect density, the higher the lifetime. After evaluating several techniques, we chose the Surface Charge Analyser (SCA) as a suitable commercial instrument for non-contact, non-destructive lifetime measurement. The salient feature of this measuring system is that it contains an insulating probe electrode, which when brought into contact with the oxidised silicon wafer automatically forms a MOS type capacitor structure. A beam of ac modulated light ($\lambda=560$ nm) passes through the transparent probe electrode onto the surface of the semiconductor, where it produces an induced ac photocurrent and a resulting ac photopotential. This ac photovoltage based technique can determine the carrier recombination lifetime of an oxidised silicon wafer without the formation of gate electrodes and substrate contacts.

Although there is a great deal of knowledge about the behaviour of crystalline defects in bulk silicon, very little information on crystalline- and process- induced defects in bonded SOI is available. The object of this work was to study the influence of interstitial oxygen concentration and buried implant dose on the micro-defect density of thermally processed SOI layers. SCA was used as an indirect way of evaluating the quality of the SOI. Moreover, the lifetime results have been correlated with the distribution of microdefects, as revealed by phase sensitive Nomarsky and atomic force microscopies after Secco etching.

EXPERIMENTAL

Starting materials were p (boron doped) and n (phosphorous doped) type (100) CZ silicon device wafers of 125 mm diameter, with resistivity of 3-5 ohm-cm. The oxygen concentration was varied between $5.9\text{-}7.2 \times 10^{17} \text{ cm}^{-3}$. To form an arsenic buried layer, device wafers were implanted before bonding with 40-80 keV As ions using doses of 3×10^{13} or 5×10^{15} As ions/cm². The fabrication process of the bonded SOI wafers is illustrated in Figure 1. A float zone (FZ) Si handle base wafer was oxidised at 1100 °C in wet O₂ before bonding to grow an oxide layer of 450 nm, which became the buried oxide in the SOI wafer. Bonding was carried out at a similar temperature. Thinning of the SOI layer to 20 µm was carried out by a grinding and chemical-mechanical polishing procedure. Bulk and SOI wafers were subsequently annealed at 1050 °C in wet O₂ for 1 hour to grow a 500 nm oxide.

Variations in the electrical and structural parameters were studied by an SCA minority carrier lifetime 9-point mapping method. The 9 points were located across and along the wafer surface. After SCA analysis, the wafers were stripped of the oxide and preferentially etched in Secco etch solution for 1 minute. Microscopic examination of the etched surface revealed the nature and density of crystalline imperfections present.

RESULTS AND DISCUSSION

Characterisation of p-type SOI as a function of oxygen concentration

Figures 2 and 3 show examples of Nomarsky and AFM imaged microdefects on etched p-type SOI, after growth of a 500 nm oxide layer at 1050 °C. The microdefects were characterised as oxide precipitates, dislocations, D defects and stacking faults. Secco etching delineates oxygen precipitates as protrusions, SF as rods and D defects or dislocations as etch pits. Lifetimes and average densities of microdefects determined by Nomarsky optical microscopy, are summarised in Table I. Each lifetime is the average of 9-point measurements taken on several wafers with exactly the same specification.

It is clearly seen that the interstitial oxygen concentration [Oi] in the bonding device wafer plays a major role in determining the microdefect content in these bonded SOI layers. The defect density increases with oxygen content, and strongly correlates with the measured minority carrier lifetime: the lower the lifetime, the higher the amount of observed defects. Almost no microdefects were found in SOI with oxygen levels below 6×10^{17} [Oi]/cm³. The results suggest that the high-temperature processing steps used for the bonding may cause the dissolution of oxygen related defects in the low-oxygen concentration SOI layer, and facilitate the formation of a defect-free zone of 20 µm. Furthermore, the creation of the defect-free zone may also be assisted by the buried oxide layer, which may act as a sink for diffusing oxygen during the high-temperature bonding process.

In contrast, for heavily oxygen-doped bonded wafers, the oversaturated oxygen in the Si layer is easily precipitated, giving rise to a highly defected surface, populated with precipitates and OSFs. To further demonstrate the elimination of oxidation-induced defects in low-oxygen content SOI, we carried out the same bonding and oxidation procedure using FZ Si as the device starting material, in which the oxygen level is two

orders of magnitude lower. As expected no defects could be observed, while a high minority carrier lifetime of around 200 μs was obtained.

Characterisation of n-type SOI as a function of oxygen content and As implant dose

The active n-type device wafers, having low and high oxygen contents were implanted with various doses of arsenic ions before bonding, and were subsequently processed as shown in Figure 1. To test for any gettering effects, the implanted SOI wafers were evaluated for OSFs, and the results compared with unimplanted SOI.

Results of minority carrier lifetime measurements and defect densities are summarised in Table II. The lifetime is seen to increase dramatically at the highest implant dose for both low and high oxygen contents, as shown in Figure 4 for the high oxygen material. This implies that the implant is acting as an internal getter of impurities in the SOI layer. Concerning defect generation, the unimplanted low-oxygen content SOI layer has a low defect density, while the unimplanted high-oxygen SOI has a much higher density of OSFs, which is consistent with the results found for p-type device wafers. Similar trends are seen with the 3×10^{13} As/cm² implanted samples, indicating that at this low dose the buried implant has little gettering ability. In contrast, at the higher dose of 5×10^{15} As/cm² both the low- and high- oxygen content samples show little or no OSF generation; i.e. a gettering effect is occurring at high dose. This is seen in Figure 5, which compares the defect density for high-oxygen samples with different implant doses.

In order to enhance the formation of oxygen precipitates, we subjected unimplanted and implanted n-type SOI device wafers to a standard low-temperature precipitate-nucleation anneal at 700 °C before bonding. An oxide layer of 100 nm was then grown at 1050 °C on the SOI after thinning, to assess defect generation and carrier lifetime. Table III compares the results for SOI samples prepared with or without the precipitation cycle. Defect densities are found to be much higher, while the lifetimes are lower, for the low-temperature processed SOI. It can be seen that the nuclei generated during the low-temperature anneal have led to substantial growth of oxygen precipitates during the subsequent high-temperature bond annealing. In this case, the gettering effect of the implant gives an improvement in lifetime, but appears to have little influence on defect generation.

CONCLUSIONS

We have investigated the role of interstitial oxygen content in CZ device wafers, and the effects of buried layer implants and thermal processing on the formation of crystalline defects in the surface of bonded SOI material. SCA was used to measure the carrier recombination lifetime of both implanted and unimplanted bonded SOI after high-temperature oxygen treatment, while Secco etching in conjunction with optical and atomic force microscopies has been used to assess the defect type and concentration. Defect-free SOI layers have been realised using low-oxygen content (6.0×10^{17} /cm³) starting material and by avoiding the use of low-temperature thermal processing. SOI layers originating from heavily oxygen-doped Si ($>7.2 \times 10^{17}$ /cm³) were populated with heavy oxygen precipitation and stacking faults, and were also characterized by low minority carrier lifetime values. Wafers processed through deliberate oxygen precipitation cycles

prior to bonding gave low lifetimes and high levels of defects, as revealed by Secco etching. The incorporation of a buried implanted arsenic layer in the SOI at the buried oxide interface gave a dramatic improvement in the lifetime of the material, and a reduction in defect generation in high-oxygen material, through an internal gettering effect.

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Table I: Lifetime and defect density versus oxygen content in p-type SOI layers after a 500 nm wet oxidation

SOI type	Oxygen concentration ($e17 [O_i] / \text{cm}^3$)	Average lifetime (μs)	Defect density (defects/ cm^2)
p-type CZ	6.0	144	1.5 e3
p-type CZ	6.6	112	3.2 e4
p-type CZ	7.0	90	8.7 e5
p-type CZ	7.2	82	9.5 e5

Table II: Lifetime and defect density in n-type SOI for various oxygen contents and arsenic implant doses, after a 500 nm wet oxidation

SOI type	Oxygen concentration ($e17 [O_i] / \text{cm}^3$)	As implant dose (atoms/ cm^2)	Average lifetime (μs)	Defect density (defects/ cm^2)
n-type CZ	6.0	0	71	8.0 e3
n-type CZ	7.0	0	54	9.1 e4
n-type CZ	5.9	3 e13	169	5.1 e3
n-type CZ	7.0	3 e13	131	1.4 e5
n-type CZ	5.9	5 e15	605	2.2 e3
n-type CZ	7.0	5 e15	717	1.5 e3

Table III: Lifetime and defect density in n-type CZ SOI processed with or without a pre-bond low-temperature oxygen precipitate nucleation cycle

Precipitation cycle	As implant dose (atoms/cm ²)	Average lifetime (μs)	Defect density (defects/cm ²)
without	0	130	2 e3
with	0	110	8 e4
without	5 e15	560	<1 e3
with	5 e15	420	9 e4

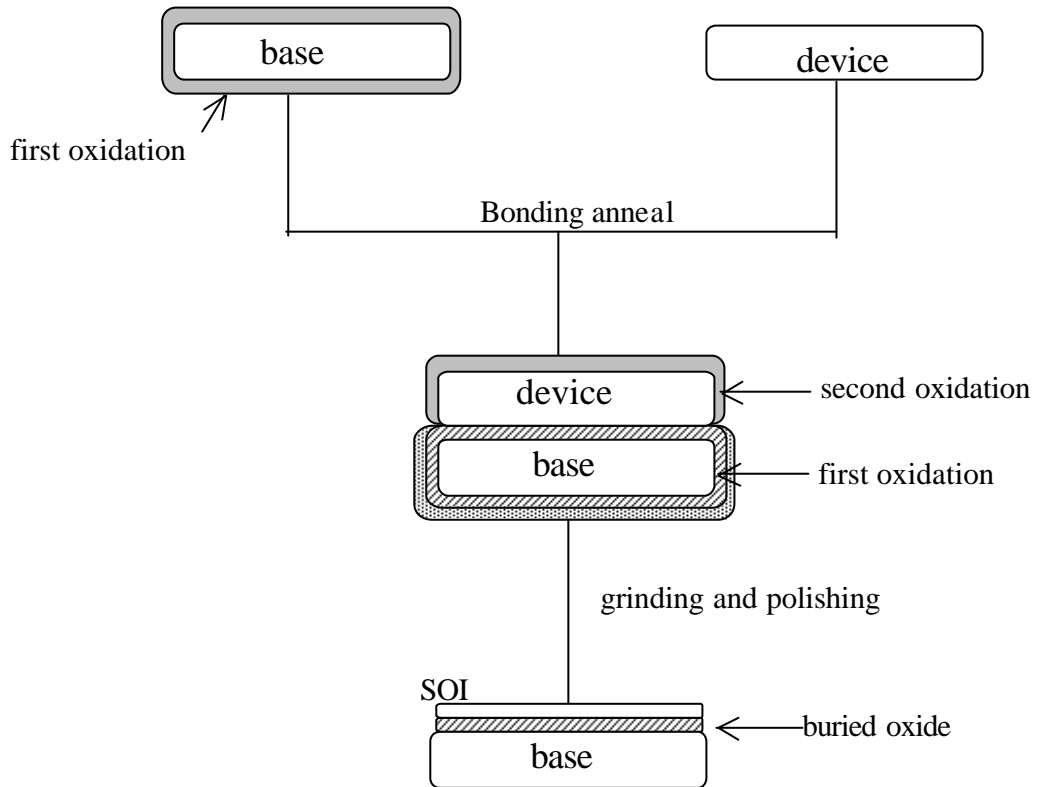


Fig. 1. Bonding procedure.