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The Status and Future of Low-Dose SIMOX Technology

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The status and future of silicon-on-insulator material synthesized by oxygen implantation with a dose of ~$4 \cdot 10^{17}$cm^{-2} (low-dose SIMOX) is reviewed. The present quality of low-dose SIMOX wafers and prospects for future developments are described.

1. Introduction

Separation by implanted oxygen (SIMOX) has become the leading technology for the production of industrial grade thin film silicon on insulator (TFSOI) substrates.[1-5] The SIMOX process involves implanting oxygen into a silicon substrate at a dose and energy sufficient to synthesize a buried oxide layer (BOX) below the Si surface during the subsequent thermal annealing at temperatures T>1300°C.

Depending on the oxygen implantation dose, two different types of SIMOX substrates can be produced. A high oxygen dose of about $2 \cdot 10^{18}$ atoms/cm^2 is used to fabricate so-called "conventional" SIMOX wafers, having the BOX thickness of about 400nm. At the moment, high-dose SIMOX substrates are mainly in use. Recently, however, interest is rapidly increasing in fabricating SIMOX using a low oxygen dose of about $4 \cdot 10^{17}$ atoms/cm^2. This is because the "low-dose approach" allows to increase significantly the production throughput of SIMOX wafers and also to reduce greatly the density of threading dislocations generated in the top Si layer.[3] Moreover, a thinner buried oxide layer formed by the low-dose implantation effectively suppresses the short-channel effect of MOSFET's.[6] Therefore, low-dose SIMOX technology is now considered as the most promising method to open the practical way for fabrication of ULSI's/SIMOX.

Low-dose SIMOX substrates were invented by NTT in 1990[5] and achieved the present quality through joint development work by Komatsu Electronic Metals and NTT Electronics Technology. This paper describes the status and future of low-dose SIMOX technology.

2. The status of low-dose SIMOX technology

At present, low-dose SIMOX wafers are produced using a 100-mA-class high-current oxygen implanter, NV-200.[7] Oxygen ions are implanted into (100) silicon wafers with a dose of about $4 \cdot 10^{17}$ atoms/cm^2. The acceleration energy and the beam current are kept at 180 keV and 70 mA, respectively. The wafer temperature during implantation is maintained at 550°C. The implanted wafers are annealed at T>1300°C for a few hours in an Ar-O_2 gas mixture. As a result, a uniform continuous buried oxide layer, about 84nm-thick, is synthesized beneath about 332nm-thick monocrystalline top Si film. The BOX layer has the breakdown voltage higher than 40 V, which is sufficiently high for ordinary LSI applications.[5] The threading dislocations with an extremely low density of <100 cm^{-2} are left in the top Si layer.

The quality of low-dose SIMOX wafers can be significantly improved by applying additional thermal treatment. In the low-dose SIMOX substrates, the high-temperature annealing results in the formation of rather thick top Si layer. Consequently, additional oxidation of the wafer surface is possible. Such oxidation treatment, performed at high temperature above 1300°C, greatly improves the quality of SIMOX wafers.[8,9] During the high-temperature oxidation the superficial thermal oxide grows on the wafer surface. Moreover, some oxygen atoms diffuse through the top Si layer and react with the silicon atoms at the BOX/Si interface. As a result, the thickness of the buried oxide increases (Figs. 1 and 2). The additional oxide layer formed due to Internal Thermal Oxidation is called ITOX, and this technique - ITOX technology.

The general specifications of low-dose SIMOX wafers are listed in Table 1. B-doped 20 Ωcm, 150 mm diameter, (100)-oriented CZ-Si wafers with mirror-polished front surfaces are used as substrates. Left column of Table 1 shows the parameters of the wafers fabricated without additional high temperature oxidation treatment, whereas right one - with an application of ITOX technology. As a result of internal thermal oxidation, the buried oxide layer becomes thicker, which obviously improves its insulating properties. Furthermore, the density of silicon pipes penetrating the BOX layer becomes significantly lower. Additional thermal oxidation improves also the surface morphology of low-dose SIMOX wafers. Moreover, the morphology of the interface between the top silicon and the buried oxide layers can be greatly improved due to the ITOX process, as it has been recently shown by Nakashima et al.[8] In both kinds of low-dose SIMOX wafers the surface concentrations of heavy metals are below $1 \cdot 10^{10}$ atoms/cm^2, whereas the densities of threading dislocations passing through the top Si layer are <100 cm^{-2}.

Fig. 3 shows the typical radial distributions of the top Si and BOX layer thicknesses in the low-dose SIMOX wafer, measured in two perpendicular directions by means of the spectroscopic ellipsometer. "On wafer" Si and BOX layer uniformity is excellent except for the region near the wafer edge. This issue will be discussed in the next section. "Wafer to wafer" uniformity of the top Si and BOX layer thicknesses is characterized in Fig. 4. Thickness distributions of both layers are narrow, indicating that the process conditions of ion implantation, such as an acceleration energy and the dose amount, are very stable.

An important parameter characterizing the quality of SIMOX wafers is the concentration of oxygen left in the top

Si layer after the SIMOX fabrication process. This is because the precipitation of supersaturated oxygen, which often occurs during the device process in thermally treated wafers, results in the generation of extended defects, such as oxide precipitates, dislocations and stacking faults. These microdefects, formed inside the device active region, may seriously affect the device performance. Recently we measured the oxygen concentration in the top Si layer of low-dose SIMOX wafers. It has been found that any oxide precipitates are not left in the top Si layer after the SIMOX fabrication process and that only interstitial oxygen atoms remain there. These oxygen interstitials diffuse out of the silicon layer during the cooling stage of the high temperature thermal treatment. Because of the low cooling rate and very small thickness of the superficial silicon film, oxygen concentration in the top Si layer of as-received low-dose SIMOX wafers has been found to be about $1 \cdot 10^{17}$ atoms/cm^3, which corresponds to the oxygen solubility in silicon at the final process temperature. Obviously, the oxygen atoms with such low concentration can not cause the formation of any extended defects in the device region.

Another important parameter of SIMOX wafers is the dopant concentration in the top Si layer. Recent measurements showed that the concentration of boron near the wafer surface is not significantly changed during the fabrication process of low-dose SIMOX wafers, thus having very similar value as in the starting silicon substrates.

An interesting feature of low-dose SIMOX wafers is related with their gettering properties.[10)] It has been found that numerous small tetrahedral stacking faults (SFT) are left just beneath the buried oxide layer during the standard low-dose SIMOX process. Such microdefects are hardly generated inside the top Si layer. It has been also found that the buried oxide does not prevent the diffusion of Cu and Ni impurities from the top Si layer into the bulk substrate at the temperatures ranged from 600 to 950°C. Moreover the effective gettering of Cu and Ni inside the region consisting of SFTs has been observed and explained as being due to the heterogeneous impurity precipitation at the stacking fault tetrahedra. It has been also shown that the observed gettering process remains stable during the thermal simulation of CMOS device process of new generation ICs with 0.25 µm feature size.[10)] Thus, the effective gettering of metallic impurities in low-dose SIMOX wafers can be expected during the modern low-temperature IC process.

3. The future of low-dose SIMOX technology

It has been pointed out in the previous section that the newly developed low-dose SIMOX wafers have the high thickness uniformity of the top silicon and buried oxide layers in the central part of the wafer, nearly defect-free thin top Si film, rather low density of silicon pipes penetrating the BOX layer, and they are virtually free from heavy metal contamination caused by implant and anneal procedures. However, the quality of low-dose SIMOX wafers must be more improved to meet the requirements laid on the silicon substrates used for ULSI applications. Namely, two parameters characterizing the quality of low-dose SIMOX wafers need to become better. They include "on wafer" uniformity of the top Si and BOX layers near the wafer edge as well as the density of Si pipes penetrating the BOX that should be at least 10 times lower.

Both mentioned problems originate from an unperfect implantation procedure. At present, low-dose SIMOX wafers are produced using the oxygen implanter designed for the substrates having the diameter of 100 mm. Thus, very uniform implantation of oxygen into the larger wafers is not possible. The density of silicon pipes penetrating the buried oxide layer depends on the implantation environment, since they are caused by the particles deposited on the wafer surface during the implantation, masking the oxygen flux. All these technical problems are expected to be solved with a new type fully-automated high-current oxygen implanter recently installed in the new SIMOX production line established in Komatsu Electronic Metals Co. This new line will supply low-dose SIMOX wafers with the diameter up to 200 mm.

4. Final remarks

Described material improvements and well-known advantages of TFSOI over bulk Si substrates make the low-dose SIMOX wafers one of the most promising substrates for advanced submicron CMOS circuit production. SIMOX wafers are especially suitable for low-power, low-voltage and high-speed device applications. However, to move low-dose SIMOX substrates into the mainstream, very close partnership between the wafer venders, device manufactures and equipment makers have to be established, allowing all the partners to get a suitable profit at each stage of SIMOX technology development.

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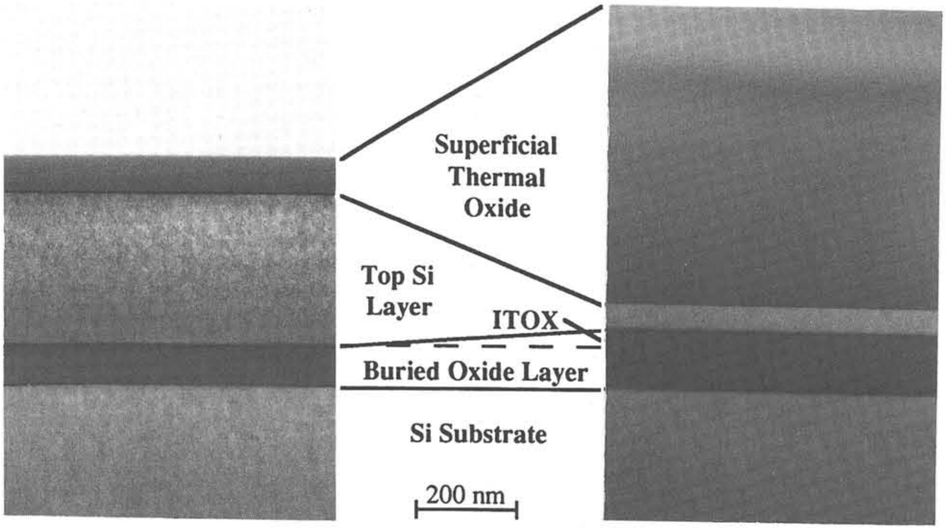

Fig. 1. XTEM micrographs of low-dose SIMOX wafers implanted with an oxygen dose of $4 \cdot 10^{17}$ at/cm^2 at 180 keV. Left: before high-temperature oxidation. Right: after high-temperature oxidation. (After Nakashima et al.[8])

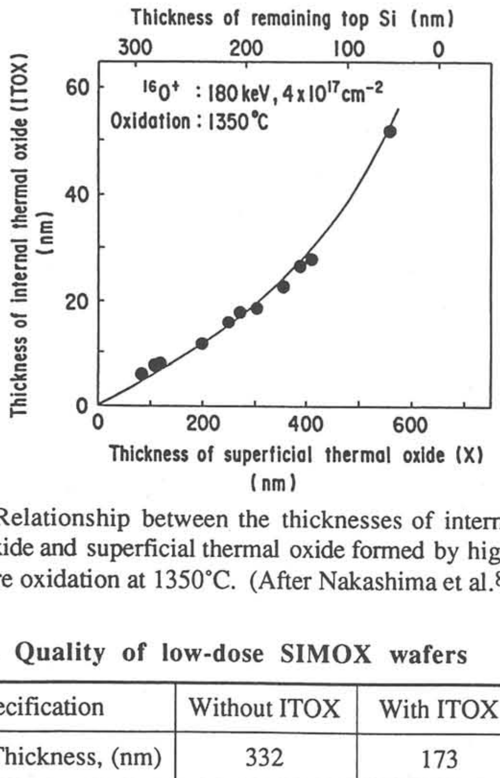

Fig. 2. Relationship between the thicknesses of internal thermal oxide and superficial thermal oxide formed by high-temperature oxidation at 1350°C. (After Nakashima et al.[8])

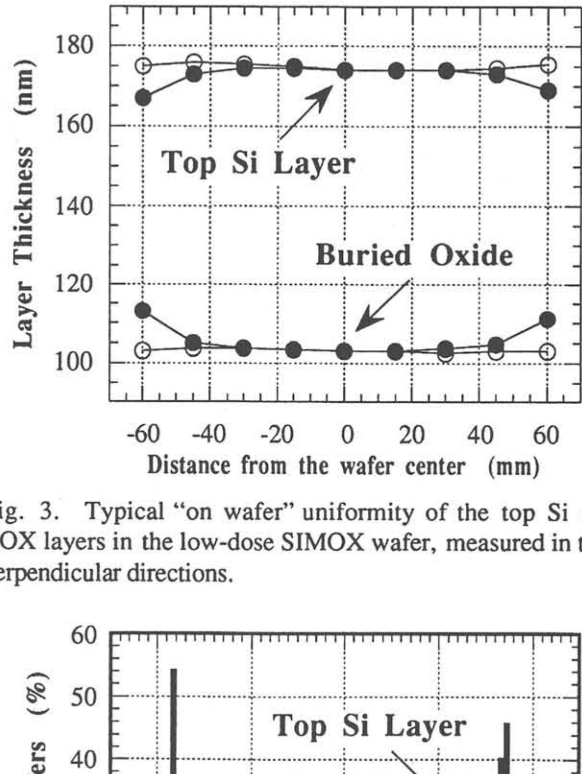

Fig. 3. Typical "on wafer" uniformity of the top Si and BOX layers in the low-dose SIMOX wafer, measured in two perpendicular directions.

Table 1. Quality of low-dose SIMOX wafers

Specification	Without ITOX	With ITOX
Top Si Thickness, (nm)	332	173
BOX Thickness, (nm)	84	104
Density of Si Pipes in the BOX, (cm^{-2})	> 30	< 5
Surface Morphology R_{ms}, (nm) (2µm*2µm)	0.38	0.16
Surface Cleanness; Heavy Metals, (at/cm^2)	$< 1 \cdot 10^{10}$	$< 1 \cdot 10^{10}$
Threading Dislocation Density, (cm^{-2}	< 100	<100

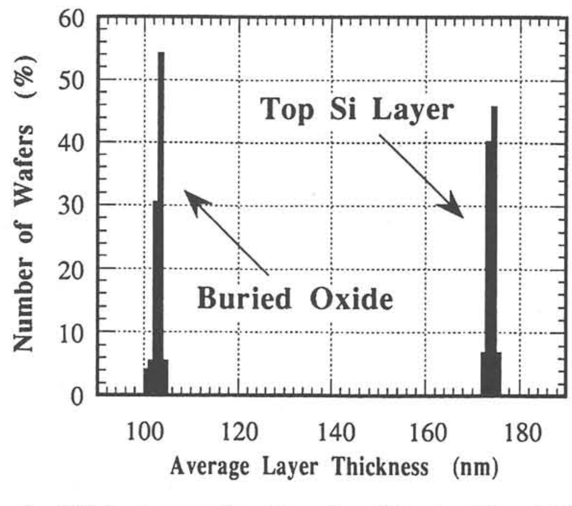

Fig. 4. "Wafer to wafer" uniformity of the top Si and BOX layers in the low-dose SIMOX wafers.