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Materials Science and Engineering B46 (1997) 8–13

MATERIALS SCIENCE & ENGINEERING B

Independent implant parameter effects on SIMOX SOI dislocation formation

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Abstract

Separation by implanted oxygen (SIMOX) material has proven to provide an extended temperature range (up to 500°C) of operation for partially depleted silicon-on-insulator (SOI) test structures and product circuits in both transportation and communication applications. Such high temperature use is possible due to the built-in dielectric isolation which eliminates the isolation junction and its associated leakage. In order to further improve high temperature performance, material quality must be ever improving. This study examines the independent implant parameter effects of implant energy, implant temperature, and beam current density on the silicon threading dislocation density in standard and thin buried oxide (BOX) SIMOX material. We have found that increased implant energies and a slightly lower beam current will improve the dislocation density by at least an order of magnitude. The kinetics of vacancy formation as it relates to the above parameters are presented. © 1997 Elsevier Science S.A.

Keywords: Dielectric isolation; High temperature; Silicon-on-insulator

1. Introduction

Automotive, aircraft, well logging, power plants, space systems, and other applications exist which benefit from high temperature integrated circuit solutions. However, device degradation at increased temperatures of operation due to exponential increase of leakage currents prohibits standard silicon circuitry from use in these high temperature environments. The junction leakage typically increases by six orders of magnitude from room temperature to 300°C device operation. In bulk silicon at high temperatures, the isolation junction forward turn-on voltage decreases, significantly increasing the sensitivity to latchup. Silicon-on-insulator (SOI) material solves this problem by providing dielectric isolation, eliminating the isolation junction and its leakage. The dielectric isolation also makes the IC latchup free. Thus, separation by implanted oxygen (SIMOX) SOI substrates provide a built in dielectric isolation which allows an extended temperature range for silicon circuitry in these applications.

The key feature of a SIMOX based process is the built-in dielectric of the substrate. While this allows extended temperature range operation for non fully depleted structures up to 500°C [1], a fundamental understanding and improvement of the material should further advance the performance of the substrates in all temperature ranges. The motivation and focus for the present paper is the fundamental understanding of the effect of the independent parameters of implantation on the microstructure of SIMOX SOI substrates.

Previous work on SIMOX SOI microstructures have been roughly divided into two categories: (1) the high current density regime (> 1 mA cm^{-2}) with coupled beam current and substrate temperature parameters and (2) the low current density regime (< 1 mA cm^{-2}) with independent variation of beam current and substrate temperatures made possible due to the insignificant beam current heating of the substrate [2–6]. The present work examines the decoupled parameters of substrate temperature, beam current, and beam energy for the high current density regime. This has been made possible for the first time with the advent of the Ibis 1000 implanter [7,8]. This implantation system has a unique magnetic scan capability with in-situ infrared heaters which effectively decouple the beam current

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PII S0921-5107(96)01922-8

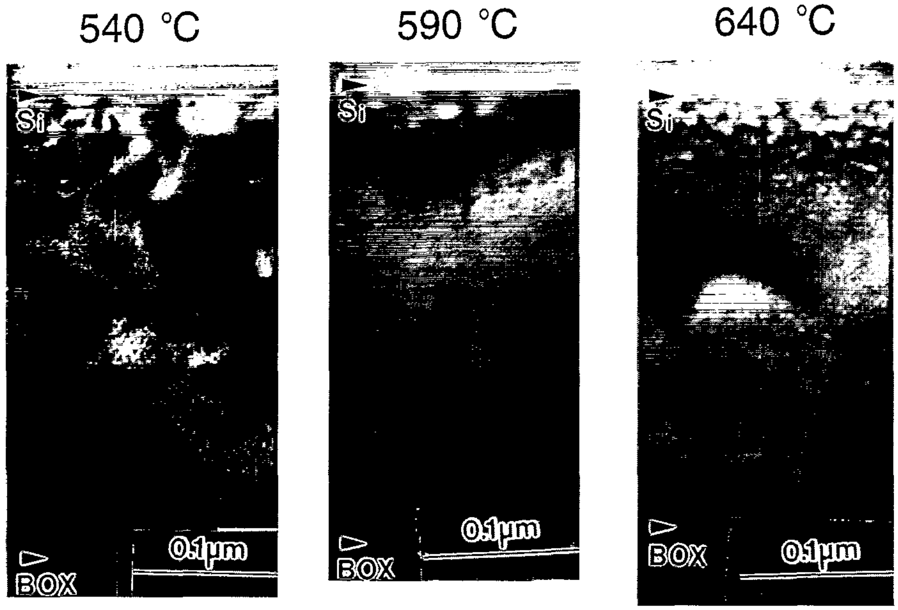

Fig. 1. TEM cross-sections of the Si layer for three different temperatures of implant.

from the substrate heating processes. In this paper, we examine the formation and evolution of silicon threading dislocations as they are influenced by independently assessed SIMOX formation parameters. We have found that the formation, density and size of vacancy cluster formations in the active silicon region, in addition to the dislocation half loops which are produced from the ion implant process, play a key role in the ultimate dislocation density of the material. The vacancy clusters appear to provide a critical stress relief mechanism for the dislocation half loops and oxide precipitates as the material undergoes the high temperature anneal stage. The morphology of the vacancy clusters have been found to track with the independent implant parameters of wafer temperature, beam current, and beam energy during the SIMOX fabrication process.

2. Experiment

The three variable matrix of wafer temperature, beam current, and beam energy was set up as a linear design of experiment. The first stage examined the temperature effect on the dislocation formation. Three implant lots using 540, 590, and 640°C substrate temperatures were fabricated, using 45 mA beam current and 175 keV implants, with all other implant and high temperature annealing parameters the same. The temperature was measured by a dual thermocouple attachment to the substrate. A variation of beam current matrix encompassed SIMOX substrate lots fabricated with beam currents of 45, 55, and 65 mA. Beam current was measured by a Faraday cup. A third set utilized implant energies of 155, 170, and 185 keV for different substrate lots. Beam energy is measured through the sum of the extraction and acceleration voltage settings. Each lot contained 17 wafers. Material characterization of the entire matrix included spectroscopic ellipsometry and reflective spectroscopy for measurement of annealed layer thicknesses (uniformity ±25 Å for all films measured), transmission electron microscopy (TEM) for analysis of dislocation formation mechanisms, diluted Secco etching of the surface for large area dislocation density analysis [9], as well as other applied layer cross-reference and analysis techniques. The as-implanted as well as the annealed substrates were examined.

3. Results

Two very important microscopic features became apparent as the results of the independent parameter analysis progressed. These are the presence of vacancy clusters and the presence of dislocation half loops in the as-implanted material. These vacancy clusters were noted prior to this study [10], with astute association to surface temperature of the wafers and their role in the formation of low dislocation material and good epilayer growth. The present results show that the vacancy clusters have a strong correlation with temperature as well as other independent implant parameters and interact with the presence of half loops to provide a dislocation reduction mechanism in the SIMOX SOI substrates. In addition, the temperature regime for the vacancy cluster formation has shifted from the previous referenced work, due to the independent parameter control given by the parallel magnetically scanned

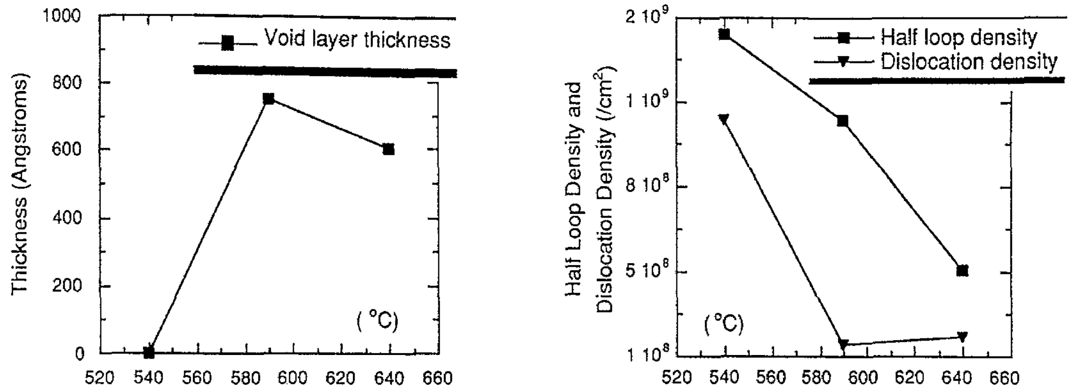

Fig. 2. Correlation of vacancy cluster formation depth at different substrate temperatures to ultimate threading dislocation density.

beam, the large increase in beam current, and the in-situ infrared heating configuration. The half loops are known to grow within the silicon layer during the anneal process. As they enlarge in diameter, the loop intersects the surface to form a threading dislocation 'pair' within the silicon layer in the after annealed state [4].

Fig. 1 shows the TEM cross sections for the as-implanted state of the SIMOX substrates for three different temperatures of implant. The white wavy 'stripe' in the images are bend contours from the thin TEM sample, and not an anomalous image from the sample itself. The silicon-to-buried oxide interface is shown at the bottom of each image, indicated with an arrow. Using a 175 keV beam energy, a beam current of 55 mA, and a total oxygen ion dose of $1.45 - 10^{18}$ cm^{-2}, the three implant lots were performed at 540, 590, and 640 °C, respectively. Dislocation half loops from the oxygen ion implants are present in all three temperature cases. However, in the case of the 540°C implant, there are no vacancy clusters observed in the TEM analysis. In the case of the 590°C implant, a plethora of small (15–20 nm), evenly distributed, high density vacancy clusters are formed. The vacancy clusters are observed at the top silicon surface and extend throughout the depth of the silicon film until they reach the buried oxide interface region. The vacancy clusters appear to be aligned perpendicular to the surface. This 90° implant to the wafer surface direction is also that of the oxygen ion beam due to the parallel magnetic scan capability of the Ibis 1000 implanter. In the case of the 640°C implant, the vacancy clusters were present, but were of larger size (20 nm) and lower density. Fig. 2 shows the correlation between the vacancy cluster presence (the thickness of the vacancy cluster layer) in the as-implanted state and the ultimate threading dislocation density found in the after-annealed SIMOX substrate. The half loop dislocation density in the as-implanted state has also been tracked in the figure. The data suggests that the presence of the vacancy clusters is required for a lower dislocation density silicon. The smaller size (2–5 nm diameter) vacancy clusters appear to be thermodynamically favored at the 590°C temperature of implant, and are observed to provide a more uniform stress relief mechanism for threading dislocation suppression in the silicon film.

The as-implanted microstructure for the variation in beam current is shown in Fig. 3. Using the 175 keV beam energy and the 'optimal' vacancy cluster temperature of 590°C, the implants were performed with beam currents of 45, 55, and 65 mA for three different implant lots. All of the beam current conditions examined contained both dislocation half loops and vacancy clusters in the as-implanted state. We speculate that, because the favored temperature of 590°C was used for each of the beam currents, all of the beam current variations examined contained vacancy cluster formations. The size and density of the clusters, however, varied with beam current. For the 45 mA case, the cluster formations extended from the surface nearly all the way through the silicon film to the buried oxide interface region. For this lower beam current, the vacancy clusters were observed to be of high density and small size (2–5 nm in diameter). For the 55 mA implant lot, the vacancy clusters were very similar in their high density and small size, but did not extend quite as far through the surface of the material. For the 65 mA case, the thickness of the vacancy cluster layer was very similar in appearance to the 45 and 55 mA case, but with approximately 10 nm shorter extension through the silicon layer. Fig. 4 summarizes the variation in beam current analysis regarding the vacancy cluster depth of presence and the strong correlation to the ultimate dislocation density of the material. The latter is indicated by the threading dislocation density. The half loop density has also been plotted, and shows a strong inverse relationship to the depth of the vacancy cluster presence.

The variation in beam energy was also analyzed. Using a 590 °C temperature of implant and a 45 mA

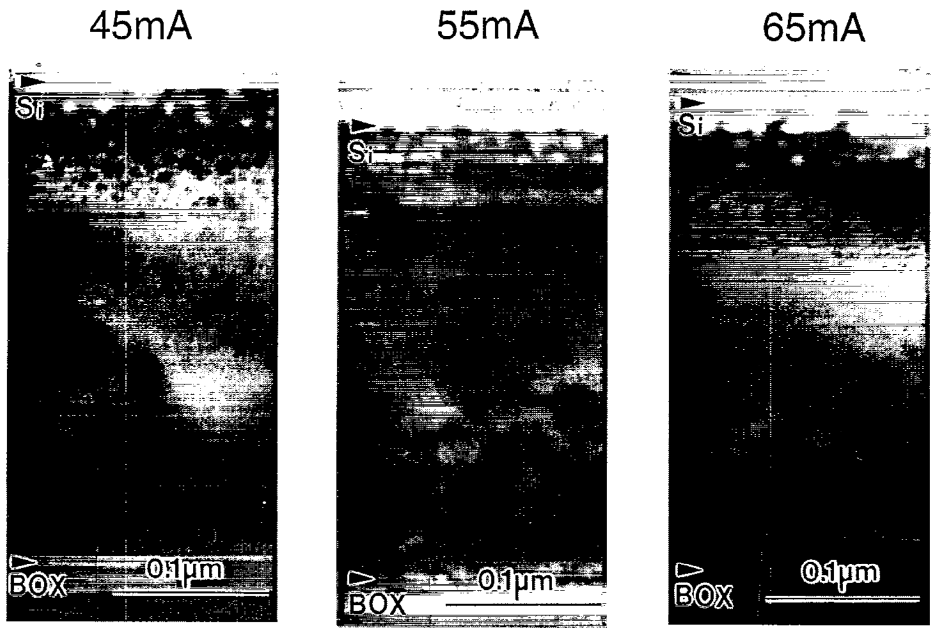

Fig. 3. TEM cross-sections of the Si layer for three different beam currents of implant.

beam current, the energy of implant was performed at 155, 170, and 185 keV. The results of the vacancy cluster formation and half loop evolution to threading dislocations are shown in Fig. 4. With an increase in the energy of implant from 150 to 185 keV, a two order of magnitude reduction in dislocation density was measured by both Secco etching and TEM analysis. This reduction in dislocation density is correlated with the small size (2–5 nm) vacancy clusters in high density throughout the film. As the energy of implant increases, the straggle of the implanted ions also increases and the buried oxide is actually less dense for a given dose. To avoid this confusion, the thickness of the buried oxide was maintained at approximately 360 nm for all beam energy cases. Thus, the analysis was performed at slightly higher doses as the energy increased, but with the same buried oxide thickness in the final SIMOX substrates. In fact, the dislocation density decreased as a function of decreased beam current, which correlated well with the thickness of the vacancy cluster presence.

4. Discussion

The microstructure of the silicon layer in SIMOX substrates as a function of the various independent implant parameters has been studied. The results show that the density, layer thickness, and morphology of the vacancy clusters as well as the presence of dislocation half loops in the as-implanted state play a key role in the ultimate dislocation density of the after annealed material. Using a model of nucleation and growth kinetics for irradiation induced voids in metals [10,11], a reasonable energy of formation and vacancy migration of 2 eV results, and is temperature dependent. This modeling will be presented in more detail elsewhere. However, a discussion of the presence and size of the vacancy clusters as they interact with the dislocation half loops is presented.

The first order dependency of the vacancy cluster presence to the substrate temperature can be seen from the data. At the lower temperature, vacancy formation is limited to a thermodynamically stable point defect phenomena. Migration of the vacancies to form clusters is not as favored as in the higher temperature cases. In fact the higher the temperature, the greater the average diameter of the vacancy clusters. However, as the temperature increases, the critical nucleus size of the vacancy clusters also increases, thus providing a mechanism for the dissolution of the smaller vacancies and their incorporation into the growing vacancy cluster nuclei. This simple process is consistent with the results of our study. For the 540°C case, there were no vacancy clusters present. For the 590°C case, the vacancy clusters were small in diameter and of high density. For the 640°C case, the size of the clusters had increased, but the density of the vacancy clusters had decreased.

The inverse relationship between the extended depth of the vacancy clusters and the ultimate dislocation density in the material is prevalent for all cases examined. Their presence appears to decrease the initial formation of the half loops during the implant. In addition, the clusters appear to provide a stress relief mechanism during the high temperature anneal process in SIMOX substrate formation through vacancy as-

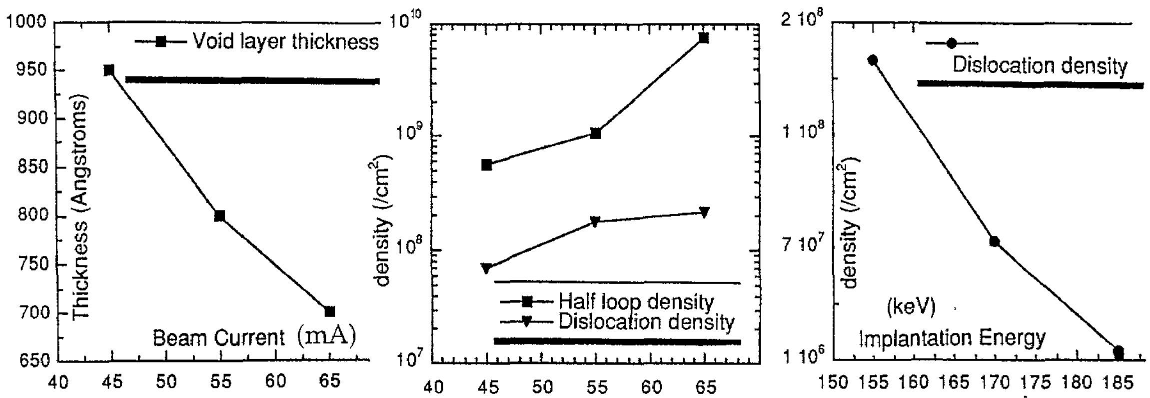

Fig. 4. Correlation of vacancy cluster formation. Dislocation depth at different beam currents (mA) with density for different ultimate threading dislocation density beam energies (keV).

sisted diffusion of excess oxygen (to material surfaces) and interstitial silicon in the silicon layer of SIMOX.

The beam current and beam energy portions of this study are more complex. With the present system configuration, minimal heating of the substrate is performed by the oxygen ion beam current [9]. This is largely due to the rapid rotation of the vertical wafers in the hub in combination with the rapid magnetic (parallel) beam scan system and the separate in-situ infra-red heaters. In fact, the resulting presence of the vacancy clusters did not vary greatly between the three beam current conditions. The extended depth of the vacancy clusters varied only by several hundred angstroms over 20 mA. The presence of the vacancy clusters has been attributed to the use of the 590°C temperature of implant, the latter considered as a first order effect. However, even this small depth difference of the vacancy clusters due to the beam current variation produced a corresponding inverse relation to the ultimate dislocation density in the silicon overlayer of the SIMOX substrates. As in the case of substrate temperature variations, the data suggests that the suppression of dislocation formation in the material was due to the stress relief mechanisms provided by the vacancy clusters during the oxygen implant process. The presence of the vacancy clusters appeared to prevent the half loops from forming. The deeper the clusters were found, the more effective the stress relief for the damaged silicon layer and fewer half loops evolved into threading dislocations. Similar arguments prevail for the case of beam energy variation. The presence of cavities lead to a significant reduction in the dislocation density of the higher beam energies employed. For nominally the same buried oxide thickness (the buried oxide varied by 6 nm between the three beam energies), the dislocation density was significantly reduced as the energy increased. The data suggests that the higher energy of implant resulted in a deeper formation of the vacancy clusters. We speculate that the combination of the depth of formation and their smaller average size at the higher implant beam energy provides a more uniformly distributed stress relief process during both the prolonged implant and high temperature anneal processes.

5. Conclusion

We have investigated the effects of the decoupled implant parameters of substrate temperature, beam current, and beam energy on the dislocation mechanisms in SIMOX SOI substrates. We have found that the formation of vacancy clusters during the implant process is a critical material phenomenon that provides for half loop suppression during the implant process and a stress relief mechanism during the high temperature anneal process. The depth and average size of the vacancy clusters play a critical role in the ultimate dislocation density of the silicon in SIMOX. By implementing the temperature, beam current, and energy which promotes small, high density vacancy clusters to form at extended depths, the resultant enhanced vacancy assisted diffusion of both silicon and oxygen atoms in the silicon layer promotes a low dislocation density SIMOX substrate.

Acknowledgements

The support of the Defense Nuclear Agency, Contract #DNA001-94-C-0043, and the helpful discussions with our contract monitor, Dr Les Palkuti, is gratefully acknowledged.

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