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ELECTRICAL CHARACTERISTICS OF SOI-LIKE STRUCTURES FORMED IN NITROGEN OR OXYGEN IMPLANTED SILICON TREATED UNDER HIGH PRESSURE

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Abstract Electrical parameters of SOI-like (silicon-on-insulator) structures formed in oxygen or nitrogen implanted silicon annealed at high temperature under atmospheric or enhanced hydrostatic pressure were compared and discussed. Based on current-voltage, capacitance-voltage, and cross-sectional transmission electron microscopy it was found that by application of pressure during post-implantation anneals one could change the defect distribution between the insulator layer and the silicon, the charges at the interfaces and the carrier concentration in the top silicon layer.

INTRODUCTION

Synthesis of SOI structures, based on the formation of buried insulator by high dose implantation of either oxygen or nitrogen ions into silicon has attracted the attention of the researchers in the recent years [1]. Implantation of oxygen is now a well-established and widely used technology in SIMOX wafer fabrication. The choice of silicon nitride or oxinitride over silicon dioxide as a buried insulating layer provides several potential advantages (a development of the radiation hardened materials, diffusion inhibition and impurity gettering) but there are still some unsolved problems (e.g. crystallization the nitride layer, large leakage current and non-uniform Si/Si_3N_4 interface) [2]. Completed removal of radiation defects is one of the main problems of all implantation based technologies due to the high fluences used. The application of high pressure during the high temperature post-implantation anneals is a promising way to control by transformation of the radiation defects. The electrical characteristics of SOI-like structures formed in silicon implanted with high fluence of oxygen or nitrogen ions and subsequently heat-treated under atmospheric or enhanced hydrostatic pressure were studied.

EXPERIMENT

(100) oriented Float-Zone (Fz-Si) and Czhochralski-grown (Cz-Si) silicon crystals both of p-type conductivity (~$2x10^{16}$ cm^{-3}) were implanted with oxygen and nitrogen ions. Details of the ion implantation and the ion projected ranges are given in Table1. Post-implantation anneals were performed in the temperature range of 800 – 1130°C under atmospheric and enhanced hydrostatic pressure up to 1.4 GPa, in argon atmosphere. Current-voltage (IV) and capacity–voltage (CV) measurements were carried

out for the characterization of the SOI-like structures formed after the annealing of the implanted silicon. High frequency (1 MHz) CV measurements were performed on the vertical capacitor structures consisting of the top Si layer, the buried oxide, and the substrate using a mercury probe (probe square of $3x10^{-4}$ cm^2). The estimation of the parameters of silicon or insulator layers of implanted and annealed samples was based on previously described procedure [3].

Table 1. Regimes of implantations, high temperature treatments, and type of SOI-like structures formed in implanted silicon.

Ion	sample	E, eV Rp, µm	F, cm^{-2}	Annealing regime	Type of SOI
N_2^+	N1	140 eV, 0.18 µm	$1x10^{17}$	1000°C, 5h, 10^{-4} GPa	n-Si/Si_3N_4/n-Si
				1000°C, 5h, 1.4 GPa	n-Si/Si_3N_4/n-Si
	N2		$8.5x10^{17}$	800°C, 5h, 10^{-4} GPa	-
				800°C, 5h, 1.1 GPa	n-Si/Si_3N_4/p-Si
	N3			1000°C, 5h, 10^{-4} GPa	p-Si/Si_3N_4/p-Si
				1000°C, 5h, 1.1 GPa	n-Si/Si_3N_4/p-Si
	N4			1130°C, 5h, 10^{-4} GPa	p-Si/Si_3N_4/p-Si
				1130°C, 5h, 10^{-2} GPa	p-Si/Si_3N_4/p-Si
				1130°C, 5h, 1.1 GPa	n-Si/Si_3N_4/p-Si
	N5		$1x10^{18}$	1000°C, 5h, 10^{-4} GPa	n-Si/Si_3N_4/p-Si
				1000°C, 5h, 1.1 GPa	p-Si/Si_3N_4/p-Si
N^+	N6	160 eV, 0.38 µm	$5x10^{17}$	1000°C, 5h, 10^{-4} GPa	n-Si/Si_3N_4/p-Si
				1000°C, 5h, 1.1 GPa	n-Si/Si_3N_4/p-Si
O^+	O1	170 eV, 0.35 µm	$6x10^{17}$	800°C, 5h, 10^{-4} GPa	n-Si/SiO_2/p-Si
				800°C, 5h, 1.2 GPa	n-Si/SiO_2/p-Si
	O2			960°C, 5h, 10^{-4} GPa	n-Si/SiO_2/p-Si
				960°C, 5h, 1.0 GPa	n-Si/SiO_2/p-Si
	O3			1130°C, 5h, 10^{-4} GPa	n-Si/SiO_2/p-Si
				1130°C, 5h, 0.1 GPa	n-Si/SiO_2/p-Si
				1130°C, 5h, 1.2 GPa	n-Si/SiO_2/p-Si

RESULTS AND DISCUSSION

CV characteristics for the structures treated at temperature $T \geq 800°C$ under different pressures show two voltage ranges when capacitance is modulated. The first voltage range corresponds to the formation of a depletion regime in the top Si layer and the second one is related to the formation of a depletion regime in the substrate. To understand the relation between the capacitance modulated areas and the depletion regimes either of the top silicon layer or the substrate, etching of the top silicon layer was made. Repeated CV measurements allowed us to determine the conductivity type of both silicon layers in the SOI-like structures. The results are given in Table 1. From the maximum values of the capacitance in the CV curves we can extract the effective thickness of the buried insulator. Other parameters extracted from the CV curves, are the fixed charges in the insulator near both interfaces: charge of the top Si / buried insulator interface, Q_f, and of the buried insulator / substrate interface, Q_s. The charge values were estimated with the use of the middle gap voltage, V_{mg}. The range of the capacitance modulation was used for the estimation of the carrier concentration in the top silicon layer or the substrate. For the carrier concentration in the top silicon layer, N_f, it was necessary to take into account the possibility that N_f was restricted by thickness of the top silicon layer.

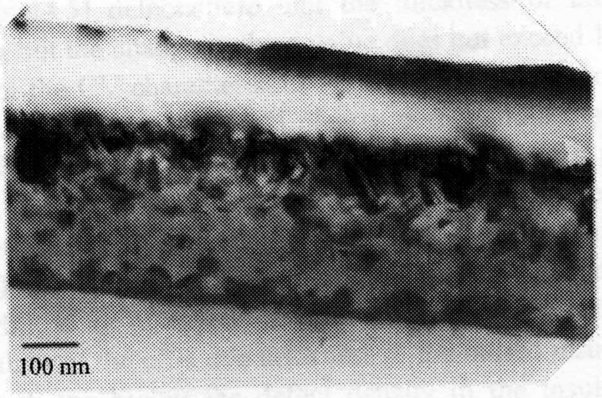

Figure 1 Cross-sectional TEM image for the sample O3 implanted with O^+ and post-treated at 1130°C, 1.0 GPa for 5 h.

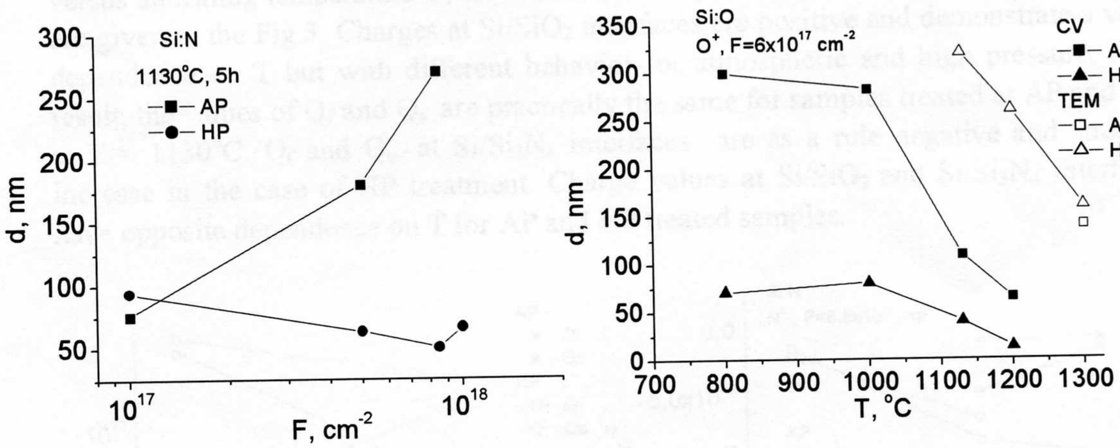

Figure 2 Effective thickness of the buried insulator extracted from maximum values of the capacitance of the CV curves (a) for the nitrogen implanted samples annealed at different pressures versus nitrogen fluence and (b) for the oxygen implanted samples annealed at different pressures versus treatment temperature. AP and HP correspond to atmospheric and high pressure (Table 1). TEM data [4,5] are given for comparison.

Cross-sectional TEM image of the sample O3 implanted with oxygen and annealed at high pressures are given in Fig,1. This figure demonstrates that SOI-like structures are formed in the implanted silicon not only after annealing at atmospheric pressure (AP), but also after high pressure (HP) treatment. Fig.2 shows the dependence of the effective thickness of the buried nitride and oxide extracted from CV characteristics for nitrogen and oxygen implanted samples correspondingly. In the case of AP annealed crystals, the nitride thickness d, increases with the nitrogen fluence, as expected. For the HP treated samples, d decreases with the fluence. The same effect (decrease of the effective thickness of the buried oxide with pressure) was observed for the oxygen implanted samples. The decrease of d with annealing temperature is connected with a partial dissolution of implanted impurity in silicon. IV measurements revealed an increase in the current through the insulator with a pressure both for the $Si/SiO_2/Si$ and $Si/Si_3N_4/Si$ structures. TEM results [4,5] demonstrate that the thickness of the buried insulator decreases with pressure, but the change in the d value does not exceed 10%. The effective thickness extracted from the CV characteristics for the HP-treated samples is essentially lower than that by TEM. TEM results [4,5] clearly demonstrate that application high hydrostatic pressure of ~1 GPa or higher leads to the creation of a perfect top silicon layer and a substrate, while a lot of defects are observed in the buried insulator. Application of low pressure during annealing of implanted samples (atmospheric pressure or pressure < 0.1 GPa) results in the formation of relatively low concentration of defects in the buried oxide, while a lot of defects are observed in the top silicon layer and the substrate. Thus, low values of the effective thickness of the buried insulator correspond to high defect density in it: the higher the defect density in the insulator the lower the effective thickness.

Fixed charges at both interfaces, Q_f and Q_s, extracted from the CV curves on V_{mg} versus annealing temperature T, for the samples implanted with oxygen or nitrogen ions, are given in the Fig.3. Charges at Si/SiO_2 interfaces are positive and demonstrate a weak dependence on T but with different behavior for atmospheric and high pressure. As a result, the values of Q_f and Q_s are practically the same for samples treated at AP and HP, at T = 1130°C. Q_f and Q_s at Si/Si_3N_4 interfaces are as a rule negative and strongly increase in the case of HP treatment. Charge values at Si/SiO_2 and Si/Si_3N_4 interfaces have opposite dependence on T for AP and HP treated samples.

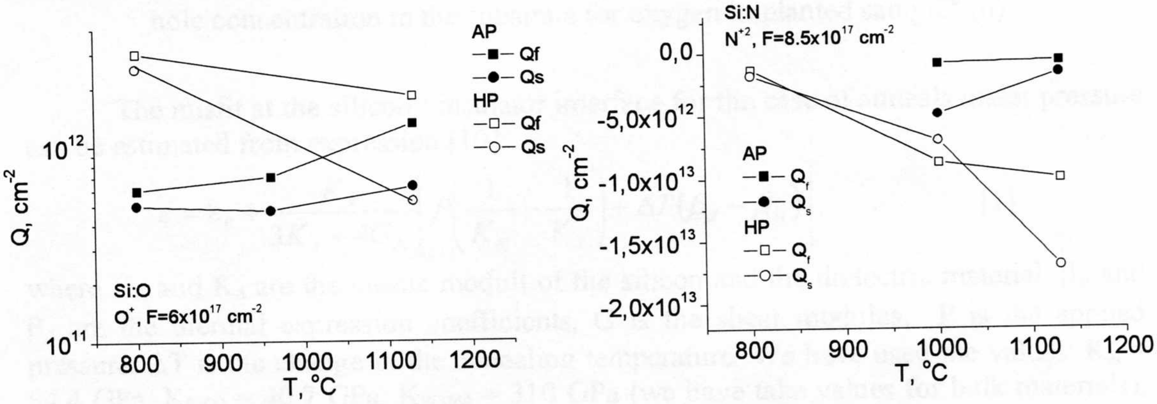

Figure 3 Fixed charges near the top Si / buried insulator interface, Q_f, and near the buried insulator / substrate interface, Q_s, extracted from CV curves on V_{mg} for samples N2-N4 and O1-O3 versus the annealing temperature.

For samples N1 (nitrogen implanted with the lowest fluence), n-type conductivity is found in the top silicon layer and the substrate. These donors are most likely related to the activity of nitrogen atoms [6]. As the implantation fluence increases (samples N2 –

N4) the n-type conductivity is observed only in the top silicon layer. Application of higher pressure results in higher electron concentration (see Table 1). The same effect (formation of donors) is also revealed in the oxygen implanted crystals (Fig. 4a). When the thickness of the buried oxide decreases with temperature, the thickness of the silicon layer increases (Fig.2). Moreover, the concentration in the top silicon layer is high enough not to be restricted by thickness of the top silicon layer. The origin of these donors is debatable, although the formation of donors is often observed in SIMOX or Smart-Cut SOI [7,8]. Formation of acceptor centers is observed in the top silicon layer of samples N6 (nitrogen implanted with the highest fluence) and also in the substrate of either the nitrogen or oxygen implanted samples, for doses of about 10^{18} cm^{-2}. This statement is based on the observed increase with the fluence or the annealing temperature of the hole concentration (Fig.4b).The origin of the acceptor centers is most likely connected with radiation-related defects [9] or process-induced acceptor impurities [8].

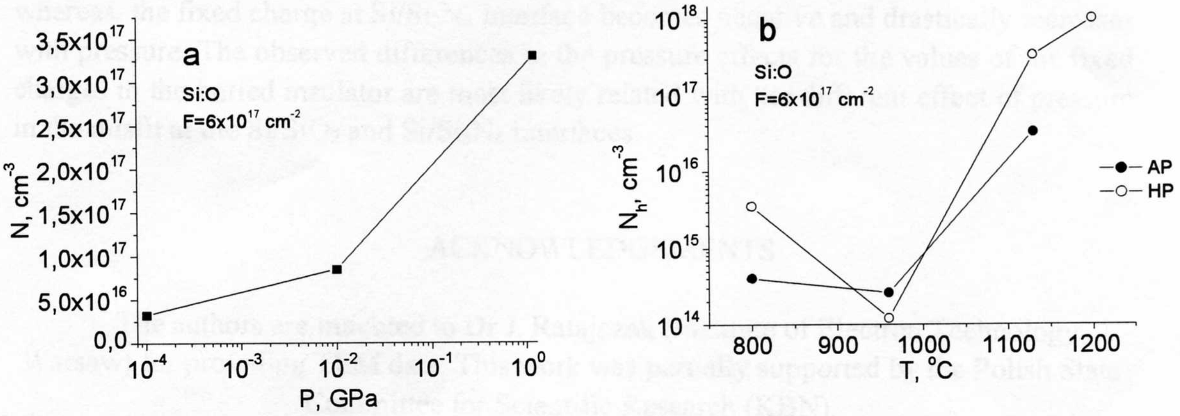

Figure 4 Electron concentration in the top silicon layer after annealing at 1130°C (a), and hole concentration in the substrate for oxygen implanted samples (b).

The misfit at the silicon / insulator interface for the case of anneals under pressure can be estimated from expression [10]:

$$\varepsilon = \varepsilon_0 + \frac{K_d}{3K_d + 4G_{Si}}\left[P\left(\frac{1}{K_{Si}} - \frac{1}{K_d}\right) + \Delta T(\beta_d - \beta_{Si})\right], \qquad [1]$$

where K_{si} and K_d are the elastic moduli of the silicon and the dielectric material, β_{si} and β_d are the thermal expression coefficients, G is the shear modulus, P is the applied pressure, ΔT is the change in the annealing temperature. We have used the values: K_{si} = 94.4 GPa, K_{SiO2} = 40.7 GPa, K_{Si3N4} = 310 GPa (we have take values for bulk materials), G = 79.9 GPa, $\beta_{si} = 1.6x10^{-6}$ K^{-1}, $\beta_{SiO2} = 1.3x10^{-5}$ K^{-1}, $\beta_{Si3N4} = 3.3x10^{-6}$ K^{-1}. The estimation of the change in the misfit ($\varepsilon - \varepsilon_0$) as a function of the applied pressure shows that in the case of the $Si/SiO_2/Si$ structures for P > 0.3 GPa and T > 1000°C an attractive elastic potential due to the highly reduced SiO_2 volume is formed. As a result, the Si/SiO_2 interface could serve as very effective getter for interstitial defects and impurities. The perfect top silicon layer in the samples treated at ~ 1 GPa is a result of interstitial defect gettering at the Si/SiO_2 interface. It is very interesting that in spite of this "dirty" interface in the case of HP treatments the interface charge values are very close for AP and HP treatments (Fig. 3). In the case of $Si/Si_3N_4/Si$ structures the change in misfit $(\varepsilon - \varepsilon_0)$ increases with pressure at the Si/Si_3N_4 interface. As a result, the interface charges strongly increase with pressure.

CONCLUSION

Strongly decrease of the effective thickness of the buried insulator with pressure applied during annealing (extracted from the CV characteristics) was observed for SOI-like structures formed by nitrogen or oxygen implantation. This effect was explained by the increase in the defect density in the buried insulator due to the defect gettering from the top silicon layer. As a result, a perfect top silicon layer formed. Opposite pressure effects are found for charges at Si/SiO_2 and Si/Si_3N_4 interfaces in SOI-like structures: a very weak pressure effect if revealed for the positive fixed charge at Si/SiO_2 interface, whereas, the fixed charge at Si/Si_3N_4 interface becomes negative and drastically increases with pressure. The observed differences in the pressure effects for the values of the fixed charges in the buried insulator are most likely related with the different effect of pressure in the misfit at the Si/SiO_2 and Si/Si_3N_4 interfaces.

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