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Pressure stimulated creation of oxygen-related defects in oxygen-implanted and neutron-irradiated silicon

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Abstract

The present work reports some experimental results based on capacitance measurements on float-zone silicon (Fz-Si) and Czochralski-grown silicon (Cz-Si) subjected to oxygen implantation, subsequent neutron irradiation and finally high-pressure thermal anneals. The purpose of this work was the study of the effect of irradiation on the formation of thermal acceptors and donors in silicon. We found that oxygen ion implantation followed by neutron irradiation results in shallow and deep level acceptor-like defects formation. Prolonged heat treatment leads to thermal donor generation as usual in Cz-Si annealed at 720 K. The most striking result of the study is finding that high-pressure thermal anneals result in extra donor formation even for low oxygen concentration. The effects mentioned above lead to changes in the type of conductivity (p-n junction formation) depending on oxygen content in the material, hydrostatic pressure and an extent of damage caused by the irradiation.
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1. Introduction

Oxygen implantation and radiation hardness of silicon are of great interest due to applications for instance in the SIMOX technology and silicon detectors (microstrip and pixel devices).

It is well known that oxygen-related centers formed in Czochralski silicon (Cz-Si) are responsible for thermal donors formation. The formation of thermal donors (TDs) and the transformation of oxygen-related complexes in irradiated silicon or germanium has been a matter of interest for a long time. It has been found that the TD formation was impeded in γ-irradiated silicon, while it was accelerated in electron-irradiated germanium as well as in γ-irradiated float zone-grown silicon. The application of increased hydrostatic pressure, in argon atmosphere, during heat treatment of Cz-Si samples, results in stress-induced creation of TDs [1].

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In addition to TDs, thermal acceptors (TAs) with a shallow level have been reported in irradiated silicon as well as were produced by heavy damage in oxygen-implanted Fz-Si material [2,3]. They form practically in the same temperature range (620–870 K) in which TDs are formed.

Neutron irradiation at room temperature introduces in Cz-Si various vacancy-oxygen complexes as for example the VO and the V_2O defects [4]. It also introduces divacancies and silicon di-interstitials (Si_I-Si_I) [5]. More complex vacancy-oxygen complexes form of the general type V_nO_m upon annealing [6]. Since TDs involve oxygen participation the neutron irradiation is expected to affect their formation. A motivation of this paper is the investigation of the effect of oxygen implantation followed by neutron irradiation and thermal anneals under pressure on the electrical characteristics of Si samples.

2. Experimental

Czochralski-grown silicon (Cz-Si) n-type samples with electron concentration $n = 1.2 \times 10^{15}$ cm^{-3} and floating zone silicon (Fz-Si) n-type samples with electron concentration $n = 4 \times 10^{13}$ cm^{-3} were used as initial crystals. The interstitial oxygen concentrations, c_o, were 8×10^{17} cm^{-3} and $<1 \times 10^{16}$ cm^{-3} for Cz-Si and Fz-Si, respectively. Oxygen implantation was carried out at 200 keV with doses of 1×10^{14}, 1×10^{15} and 1×10^{16} cm^{-2}. Projected range for O_2^+ ions is equal to 0.4 μm. After oxygen implantation the samples were neutron irradiated at 5 MeV with doses up to 5×10^{16} cm^{-2} and then pressure annealed up to 1 GPa at 720 K in argon ambient. The implanted and annealed samples were studied by measurements and numerical analysis of current–voltage (*I–V*) and capacitance–voltage (*C–V*) characteristics of Schottky barrier junction Hg–Si (mercury probe) using the measurement setup shown in Fig. 1 [7,8]. The measurement system was controlled via GPIB bus by PC with TestPoint environment and consisted of QuadTech 7600 admittance meter and Keithley 237 and 238 source measurement units. The QuadTech 7600 Precision LCR meter can measure capacitance in the wide band of test signal frequencies from 10 Hz to 2 MHz. Keithley 237 and 238 source measurement units provided bias voltage during measurements of *I–V* and *C–V* characteristics. Electrical measurements were done both on the top (implanted) surface and on the back (non-implanted) one.

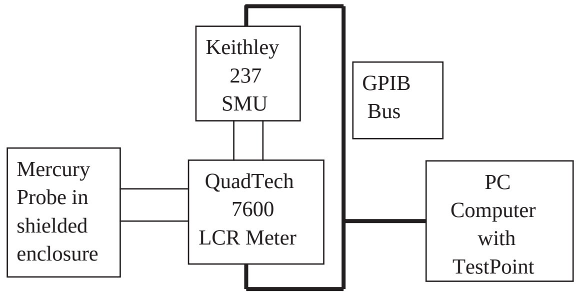

Fig. 1. Block diagram of the electrical measurement setup.

3. Results and discussion

Typical electron concentration profiles obtained from differentiation of the *C–V* characteristics measured at 300 K for as-implanted with doses 1×10^{14} and 1×10^{15}cm^{-2} non-irradiated Fz-Si and Cz-Si samples are presented in Fig. 2. From measurements of the as-implanted samples, both Fz-Si and Cz-Si, the result is that the initial type of conductivity has not changed after oxygen implantation and the projected range is in rather good agreement with theoretical calculations.

After neutron irradiation all samples are nearly compensated which indicates that deep-level defects with a very high concentration comparable, to the free-carrier concentration, are present in the irradiated samples [9,10]. The defects control the electrical characteristics and their impact on *C–V* dependence is meaningful for as-irradiated samples and annealed at high hydrostatic and normal pressure. The high concentration of the induced defects is confirmed by several facts. First of all, the Schottky barrier diodes have not exhibited rectifying properties in *I–V* characteristics if they have been formed on irradiated specimens, which have not been subjected to high temperature treatment and moreover, most of the as-irradiated

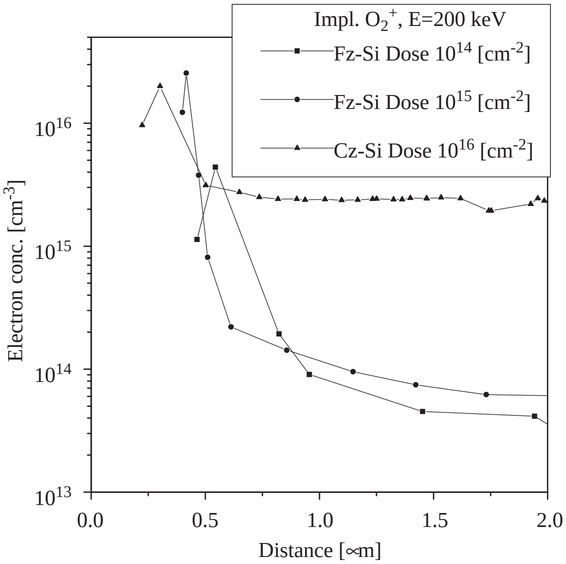

Fig. 2. Electron concentration in Fz-Si and Cz-Si surface layer oxygen implanted with the doses 10^{14}, 10^{15}, and $10^{16}\,cm^{-2}$ at $E = 200\,keV$.

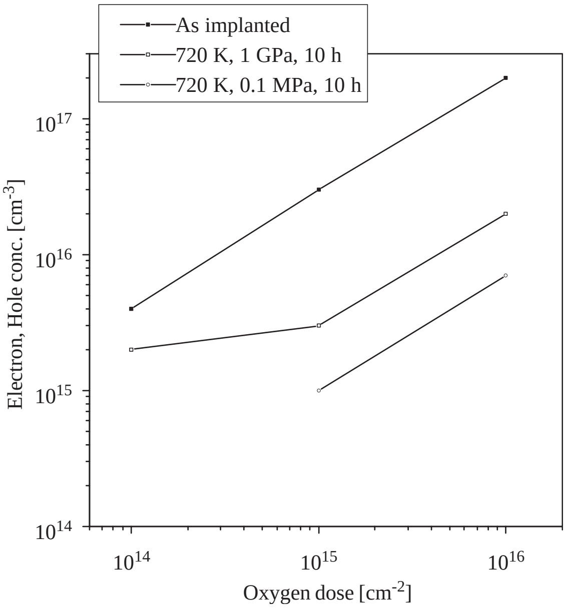

Fig. 3. Electron and hole concentration in the Fz-Si surface layer as a function of implanted dose.

samples exhibited surprisingly low capacitance. Irrespective of the recovery of the carrier concentration during annealing, the unexpected *C–V* characteristics were observed if specimens were annealed under high hydrostatic and normal pressure. It has occurred, that after annealing at 720 K under normal pressure for 10 h, the initial type of conductivity of Fz-Si samples has changed and p^+-p junction has been formed. Annealing at 720 K under high hydrostatic pressure of 1 GPa Fz-Si samples has resulted in p^+-n junction formation which means that high pressure annealing produced enough donor centers to compensate acceptor-like traps induced by neutron irradiation in the non-implanted part of samples. The calculated hole concentration in the surface-implanted layer and its dependence on oxygen implantation dose is presented in Figs. 3 and 4.

It is a well-known fact that the prolonged annealing of Cz-Si around 720 K leads to the generation of TDs [11]. On the basis of the results of our comparative study in as-grown and as-annealed Cz-Si specimens, it has been established that annealing at 720 K/10 h causes an increase in the electron concentration that is in a range of one order of magnitude. Let us note for comparison,

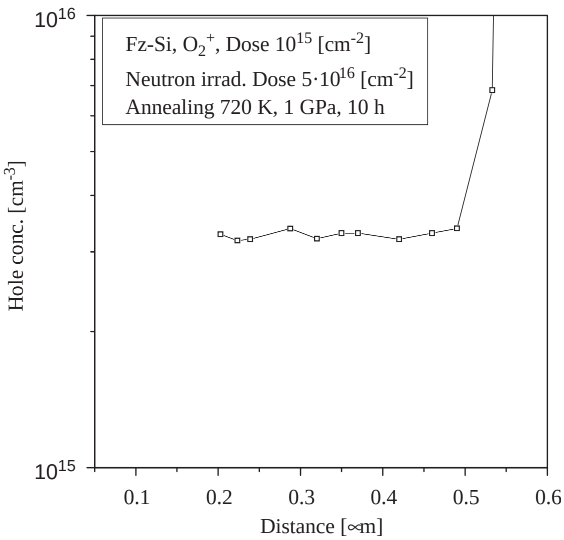

Fig. 4. Hole concentration in the oxygen-implanted Fz-Si surface layer after neutron irradiation and annealing at 720 K, 1 GPa for 10 h.

that decrease in the electron concentration to the value of about $7 \times 10^{14}\,cm^{-3}$ in the non-implanted part of the sample is observed, if irradiated with a dose of $5 \times 10^{16}\,n/cm^2$ Cz-Si samples are annealed at 720 K/10 h under normal pressure. Much better improvement in the electrical characteristics without changing the initial type of conductivity is observed in the implanted part if the irradiated Cz-Si specimens were annealed under high temperature/high hydrostatic pressure (HT/HP). It is attributed to extra donor formation under high-pressure conditions and higher concentration of electrons available in the specimens. The electron concentration in Cz-Si, subjected to oxygen implantation and neutron irradiation followed by HT/HP treatment, increased in a range of two orders of magnitude as shown in Fig. 5.

It is worth noting that it was more difficult to reach the electron concentration recovery as a result of the HT/HP treatment in neutron-irradiated Cz-Si that was not subjected to oxygen-ion implantation. In spite of 720 K/10 h/1 GPa treatment the electron concentration in the specimens remain on the level of concentration in the as-grown samples as shown in Fig. 5. This means that TAs are generated not only in irradiated Fz-Si but also in irradiated Cz-Si.

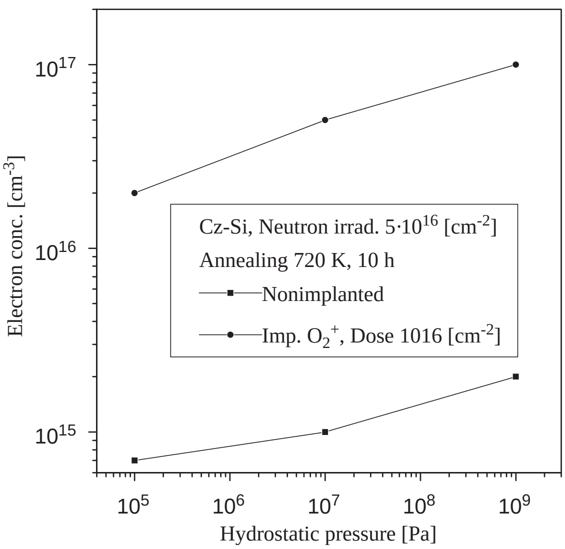

Fig. 5. Electron concentration in the oxygen-implanted and non-implanted Cz-Si surface layer after neutron irradiation as a function of hydrostatic pressure applied during annealing at 720 K for 10 h.

Ion implantation creates very high density of damage at the projected range depth. After annealing, the concentration of large defects increases due to transformation in the defect system. The interesting moment is that pressure stimulates the acceptor center formation. The retarding of the annihilation process between vacancy and interstitial defects can be the reason are the observed pressure-enhanced generation of acceptors [12]. The effect of p-layer formation in Fz-Si can be connected with lower initial electron concentration in the crystal. Probably some impurity atoms can activate the vacancy clusters to form acceptor centers.

4. Conclusions

On the basis of the results of the comparative study in Cz-Si and Fz-Si we conclude that oxygen-ion implantation followed by neutron irradiation results in formation of shallow acceptors and deep-level acceptor-like defects. Additional prolonged annealing at 720 K leads to thermal donor generation. As a result of the annealing at a high temperature under high hydrostatic pressure the free-electron concentration increases due to extra donor formation. We also postulate, that due to the combining of effects, there is a correlation between critical oxygen content in the samples and hydrostatic pressure applied during annealing on one hand, and the damage extent caused by irradiation on the other hand, at which the material of the n-type conductivity transforms to the p-type conductivity during annealing.

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