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Study of the defects in oxygen implanted silicon subjected to neutron irradiation and high pressure annealing

W. Jung[1,a], M. Kaniewska[1], A. Misiuk[1], and C. A. Londos[2]

[1] Institute of Electron Technology, 02-668 Warsaw, Poland
[2] The University of Athens, Solid State Physics Section, Panepistimiopolis Zografos 15784, Greece

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Abstract. This paper reports on capacitance measurements on Czochralski-grown and float-zone silicon 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 donors in silicon. The observed changes in the C-V characteristic curves and profiles are discussed. 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 450 °C. The most striking result of the study is finding that high pressure thermal anneals result in extra donor formation. The effects mentioned above may lead to changes in the type of conductivity depending on oxygen content in the material, hydrostatic pressure and an extent of damage caused by the irradiation.

PACS. 61.72.Tt Doping and impurity implantation in germanium and silicon – 61.80.Jh Ion radiation effects – 81.40.Rs Electrical and magnetic properties (related to treatment conditions)

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 centres 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 (FZ) 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].

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 silicon material [2,3]. They form practically in the same temperature range (350–600 °C) 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.

[a] e-mail: jung@ite.waw.pl

2 Experimental

Flow chart of experiment is presented in Figure 1. Czochralski grown silicon (Cz-Si) n-type samples with electron concentration $n = 2 \times 10^{15}$ cm^{-3} and floating

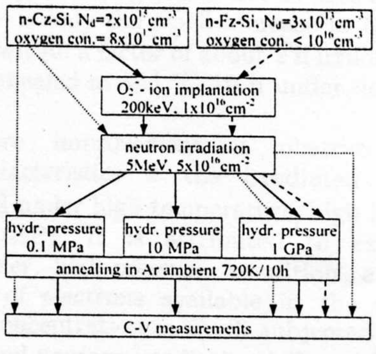

Fig. 1. Flow chart of experiment.

zone silicon (Fz-Si) n-type samples with electron concentration $n = 3 \times 10^{13}$ 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 dose of 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 450 °C in argon ambient. The majority carrier concentrations were determined from C-V characteristics of Hg-Si Schottky barrier junctions.

3 Results and discussion

Results of C-V measurements at 300 K for oxygen-implanted n-type Cz-Si subjected to neutron irradiation and prolong annealing at 450 °C under various hydrostatic pressures are presented in Figure 2. Figures 2(a)–(c) show C-V characteristics typical for a given hydrostatic pressure. Apparent carrier-concentration depth profiles obtained from differentiation of the C-V dependencies presented in the Figures 2(a)–(c) are shown in Figures 2(d)–(f).

The most striking feature of the C-V characteristics, seen in Figure 2(a), is that no appreciable changes in capacitance occur for small voltages for a specimen annealed under a pressure of 0.1 MPa. The flatness in the C-V characteristics has been already reported in Mg^+, Ni^+, and He-ion implanted Si [7–9] and it has been discussed by Giri and Mohapatra [10,11] for n-type Si irradiated with high dose of high energy Ar-ions. We have also found the effect for p-type Cz-Si implanted with H_2-ions and subjected to prolonged post-implant annealing at 450 °C [12]. So, the flat region in the C-V plot in Figure 2(a), in agreement with the results mentioned above, indicates the presence of a damaged region formed during the oxygen-ion implantation/neutron irradiation.

Usually, such flatness in the C-V curve is interpreted as a result of high resistance of specimens studied. Consequently, an increase of concentration, seen in Figure 2(d) that appears in the carrier profile near the surface might be assumed to be a result of an artifact of differentiation in the C-V profiling technique [13,14]. However, this is not the case for irradiated specimens, even if we deal with the heavily damaged region. The effect seems to be a consequence of the compensation that takes place in n-type Si because of the acceptor nature of the dominant traps induced in the region damaged by the processing steps [11].

Let us note that capacitance behaves like the depletion capacitance if the specimen annealed under the pressure of 0.1 MPa is polarised with bias higher than the maximal bias related to the flat region seen in Figure 2(a). As seen in Figure 2(d) the C-V profile concentration exhibits a smooth curve in the region of higher voltages. The electron concentration is on a level of about 5×10^{15} cm^{-3} as determined at a distance of about 1.35 μm from the surface and is slightly higher as compared to that of 2×10^{15} cm^{-3} determined for as-grown Cz-Si.

As seen in Figures 2(b) and (c) the capacitance of specimens annealed under increased hydrostatic pressure shows a substantial dependence on voltage. The capacitance monotonically decreases when increasing the negative voltage in a whole range of bias investigated. This indicates that the C-V characteristics for specimens annealed at the pressure of 10 MPa and 1 GPa is under a control of shallow levels. The carrier profiles corresponding to the C-V curves shown in Figure 2(b) and (c) are presented in Figure 2(e) and (f). The carrier concentration profiles show a clear trend to increase in the carrier concentration with the increase in distance from the semiconductor surface. The electron concentration determined from the carrier profiles corresponding to a distance of about 0.3 μm from the surface is on a level of 2×10^{17} cm^{-3} and 1×10^{17} cm^{-3} for specimens annealed under the pressure of 10 MPa and 1 GPa, respectively.

The basic trend in our results is a large decrease in specimens' capacitance at zero bias voltage, which consequently results in increase of the depletion layer width with decreasing hydrostatic pressure. This indicates that deep-level defects with a very high concentration comparable to the free-carrier concentration are present in irradiated samples. The defects control the electrical characteristics and their impact on the C-V dependence is meaningful for as-irradiated samples and annealed at normal pressure.

The high concentration of the induced defects is confirmed by several facts. First of all the Schottky barrier diodes did not exhibit rectifying properties in I-V characteristics if they were formed on specimens irradiated, which were not subjected to high temperature treatment. Most of the as-irradiated samples exhibited surprisingly low capacitance. Irrespective of the recovery of the electron concentration during annealing the featureless C-V characteristics were observed if specimens were annealed under normal pressure. It is a well-known fact that the prolonged annealing of Cz-Si around 450 °C leads to the generation of thermal donors [15]. On the basis of results of our comparative study in as-grown and as-annealed specimens it has been established that annealing at 450 °C/10 h causes an increase in the electron concentration that is in a range of one order of magnitude. Let us note for comparison that there is only the small increase in the electron concentration within a factor of about 2 if irradiated Cz-Si samples are annealed at 450 °C/10 h under normal pressure.

Much more improvement is observed in the electrical characteristics if the irradiated specimens were annealed under high temperature/high hydrostatic pressure (HT/HP). It is attributed to extra donor formation under high-pressure condition 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.

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

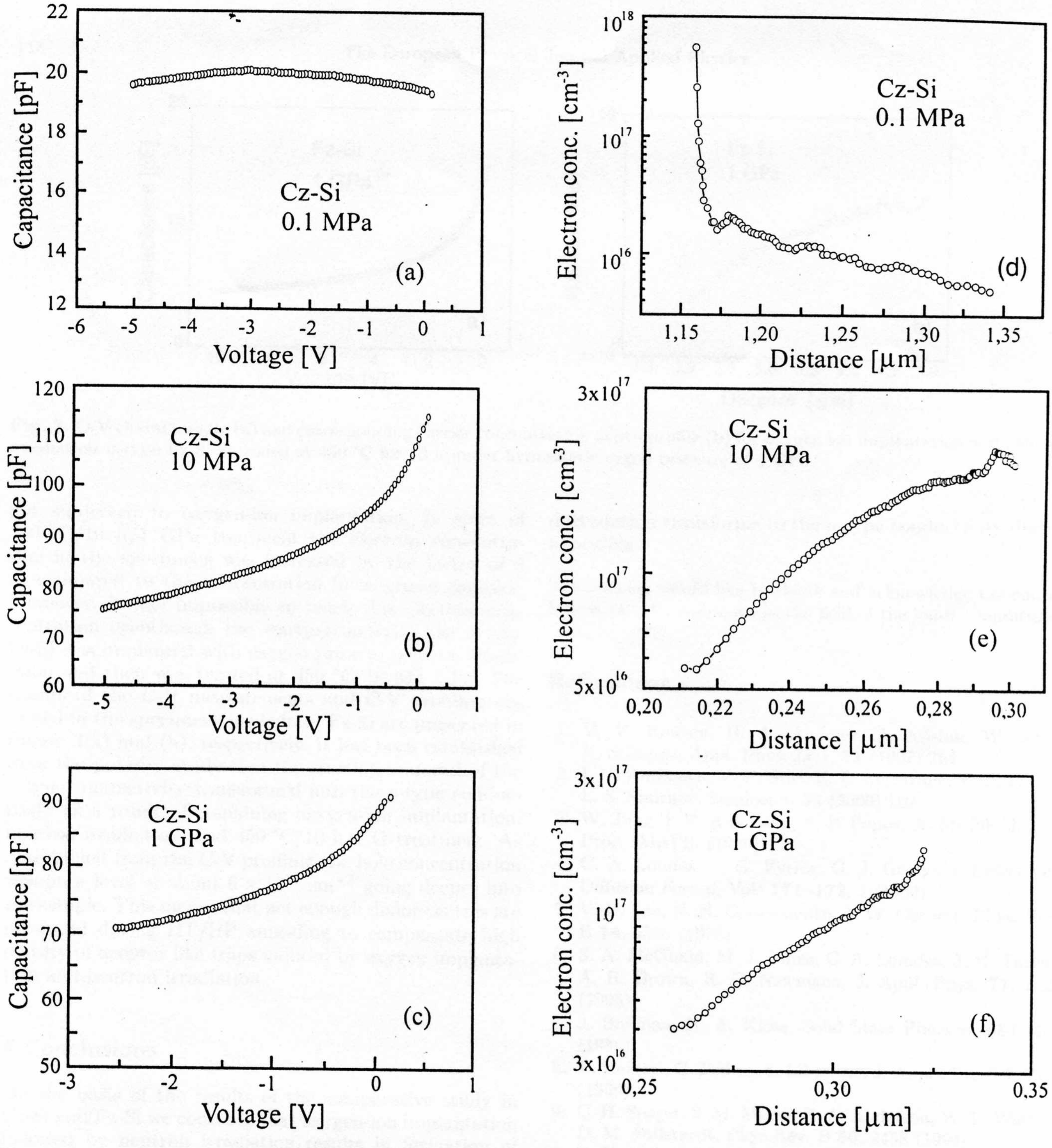

Fig. 2. C-V characteristics (a)–(c) and corresponding carrier concentration depth profiles (d)–(f) for oxygen ion implantation and neutron irradiation n-type Cz-Si annealed at 450 °C for 10 h under hydrostatic argon pressure of 0.1 MPa, 10 MPa and 1 GPa.

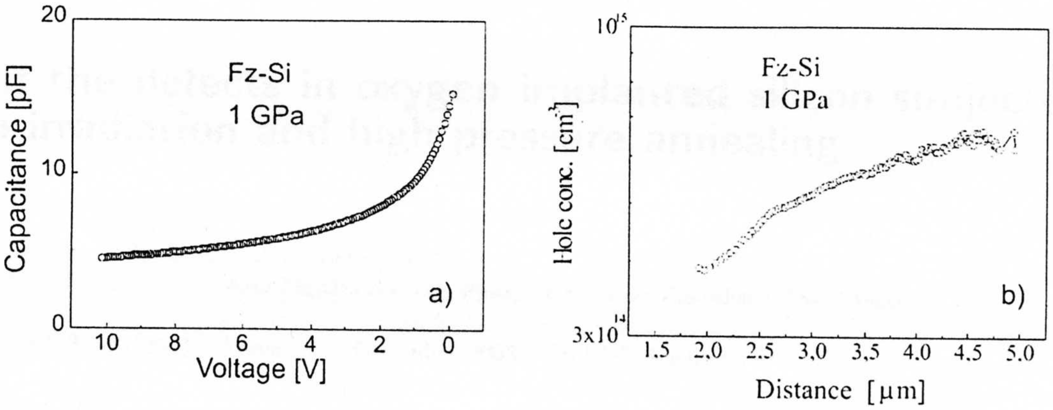

Fig. 3. C-V characteristic (a) and corresponding carrier concentration depth profile (b) for oxygen ion implantation and neutron irradiation n-type Fz-Si annealed at 450 °C for 10 h under hydrostatic argon pressure of 1 GPa.

not subjected to oxygen-ion implantation. In spite of 450 °C/10 h/1 GPa treatment the electron concentration in the specimens was increased by the factor of 5 as compared to the concentration in as-grown samples. Moreover, it was impossible to reach this electron concentration eventhough the starting material like n-type Fz-Si was implanted with oxygen prior to neutron irradiation and then was treated at 450 °C/10 h/1 GPa. The results of the C-V measurements and C-V profiling obtained in the specimens made from Fz-Si are presented in Figure 3(a) and (b), respectively. It has been established from the polarity study that the starting material of the n-type conductivity transformed into the p-type conductivity as a result of combining oxygen-ion implantation, neutron irradiation, and 450 °C/10 h/1 G treatment. As determined from the C-V profiling the hole concentration was on a level of about 6×10^{14} cm^{-3} going deeper into the sample. This means that not enough donor centres are produced during HT/HP annealing to compensate high density of acceptor like traps induced by oxygen implantation and neutron irradiation.

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 450 °C leads to thermal donor generation. As a result of the annealing at the 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 the effects there is a correlation between critical oxygen content in samples and hydrostatic pressure applied during annealing on one side and the damage extent caused by irradiation on the other side at which the material of the p-type conductivity resulted from degradation transforms to the n-type conductivity during annealing.

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