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Influence of high pressure annealing on electrical properties of surface layer of neutron irradiated or germanium-doped Czochralski-grown silicon

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The effect of annealing at 720–920 K under enhanced pressure (up to 1.1 GPa) in argon ambient on electrical properties of the surface layer of the Czochralski-grown silicon (Cz-Si) subjected to neutron irradiation (doses of up to 1×10^{17} cm^{-2}, E = 5 MeV) or germanium doping (doping level 7×10^{17} cm^{-3}) was investigated by electrical *C-V*, *I-V* and admittance method. The stress-induced decrease in electron concentration was observed in both *p*- and *n*-type samples after neutron irradiation and annealing under a pressure of 1.1 GPa at 720 K for 10 hours, while in the germanium doped samples an ascending dependence of the creation of thermal donors and lack of dependence of new donors on hydrostatic pressure was observed. The effects observed can be explained as resulting, among others, from the irradiation-induced defects (generation of thermal acceptors) and pressure stimulated creation of thermal donors in germanium-doped silicon.

Keywords: germanium-doped silicon, neutron-irradiated silicon, defects.

1. Introduction

Radiation hardness of silicon and germanium doping are of great interest due to applications in silicon detectors (microstrip and pixel devices) and advanced electronics and optoelectronics [1]. Germanium-doped silicon single crystals have greater mobility than silicon and can be produced with a band gap between those of silicon and germanium. SiGe single crystals are used in photodetectors, solar cells and other electronic and photonic devices. During single crystal growing by Czochralski method a large number of oxygen and carbon atoms are incorporated into the crystals due to chemical reaction between SiGe melt and quartz crucible. It is well known that oxygen related centres are responsible for the formation of thermal donors. It is also known that neutron irradiation and germanium doping induce silicon lattice extension, so annealing under compressive stress should change the surface layer properties. This paper describes our investigation of the electrical properties of surface layer of neutron irradiated and germanium doped Czochralski-grown silicon (Cz-Si) subjected to high pressure annealing.

2. Experimental

Boron doped *p*-type Cz-Si, ⟨100⟩ oriented with resistivity of about 16 Ωcm denoted as Si:*p*, phosphorus doped *n*-type Cz-Si ⟨111⟩ oriented with resistivity of about 18 Ωcm denoted as Si:*n* and boron doped *p*-type Cz-Si additionally doped with germanium (doping level about 7×10^{17} cm^{-3}) with resistivity of about 28 Ωcm made in China were used as initial crystals. The initial oxygen concentration was determined by Fourier transform infrared spectroscopy (FTIR) from the absorption band at 1107 cm^{-1} with a calibration factor of 3.14×10^{17} atom/cm^{-3} and the oxygen concentration was about 9.5×10^{17} cm^{-3}, 9×10^{17} cm^{-3} and 6.5×10^{17} cm^{-3} for Si:*p*, Si:*n* and germanium-doped samples, respectively. Some Si:*p* and Si:*n* samples were irradiated with neutrons of energy $E = 5$ MeV at room temperature to a dose of 1×10^{17} cm^{-3} n/cm^{-2} and then non-irradiated and irradiated Si:*p* and Si:*n* samples were annealed at a temperature of 720 K in argon ambient for 10 hours, some at atmospheric pressure (0.1 MPa) and some at hydrostatic pressure up to 1 GPa. Germanium-doped samples were subjected to annealing at 720 and 920 K in argon ambient for 10 hours for several different pressure values up to 1 GPa. The samples prepared were studied by electrical measurements of *C-V*, *I-V* and admittance characteristics of Schottky barrier junction Hg-Si (mercury probe) using the measurement setup shown in Fig. 1. Carrier

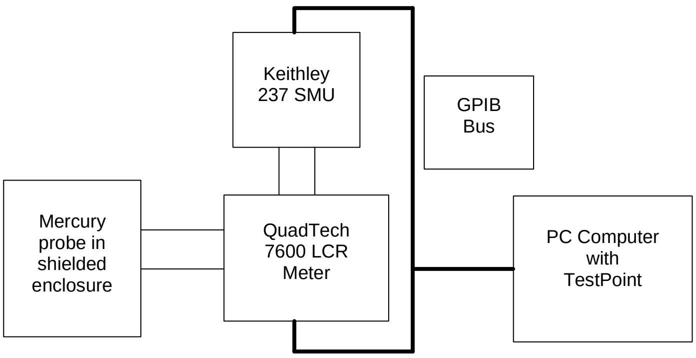

Fig. 1. Block diagram of the measuring system.

concentration profiles in the surface layer of the samples under study were determined by numerical analysis of *C-V* characteristics of Schottky barrier Hg-Si [2, 3].

3. Experimental results and discussion

Results of admittance measurements of neutron irradiated and non-irradiated Si:*p* and Si:*n* samples annealed at 720 K for 10 hours under atmospheric and high hydrostatic pressure of 1 GPa are shown in Fig. 2. There are no peaks on all loss tangent plots, so only shallow states are present in the samples investigated. Greater values of loss tangent observed for Si:*p* samples with higher oxygen concentration subjected to high pressure (HP) annealing or neutron irradiation and HP annealing, may result from structural defects formed due to oxygen precipitation [4].

Carrier concentrations calculated from *C-V* characteristics of Schottky barrier junction for Cz-Si samples Si:*p* and Si:*n* are presented in the Table. It is evident from the table that high hydrostatic pressure annealing at 720 K enhances the thermal donors creation both in the case of initially *p*- and *n*-type silicon and the concentration level depends on oxygen concentration. There are two kinds of explanation of this phenomena in literature. One of them says that an effect of HP can be explained as an activation of structural inhomogeneities creating nuclei for thermal donors formation and preventing them from dissolution with rising temperature [5]. The other one points out that the enhanced formation of thermal donors under high pressure is due to increasing diffusivity of oxygen atoms [6]. In the case of neutron irradiated samples

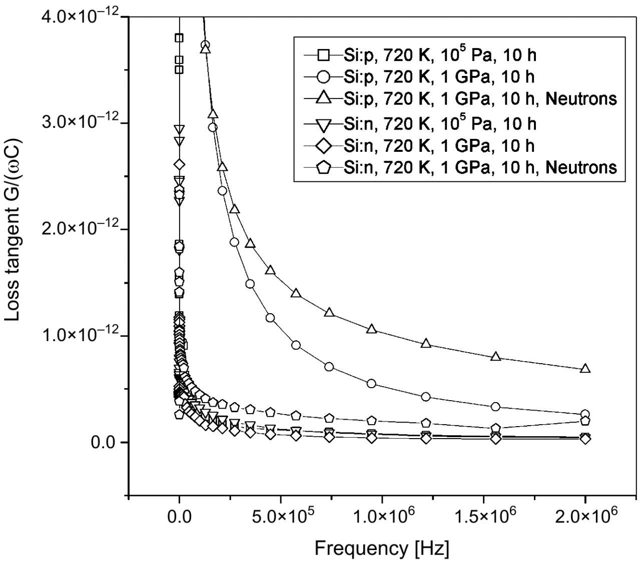

Fig. 2. Loss tangent as a function of test signal frequency for Cz-Si neutron irradiated and HP treated.

T a b l e. Carrier concentration and conductivity type of neutron irradiated and non-irradiated Cz-Si.

Si samples	Sample treatment	Carrier concentration [cm^{-3}] (type of conductivity)
Si:*p*	As grown	3×10^{14} (*p*)
Si:*p*	720 K, 10^5 Pa, 10 h	2×10^{15} (*n*)
Si:*p*	720 K, 1 GPa, 10 h	9.5×10^{15} (*n*)
Si:*p* neutron irradiated	720 K, 1 GPa, 10 h	4.5×10^{15} (*n*)
Si:*n*	As grown	2.5×10^{14} (*n*)
Si:*n*	720 K, 10^5 Pa, 10 h	1×10^{15} (*n*)
Si:*n*	720 K, 1 GPa, 10 h	3×10^{15} (*n*)
Si:*n* neutron irradiated	720 K, 1 GPa, 10 h	7×10^{14} (*n*)

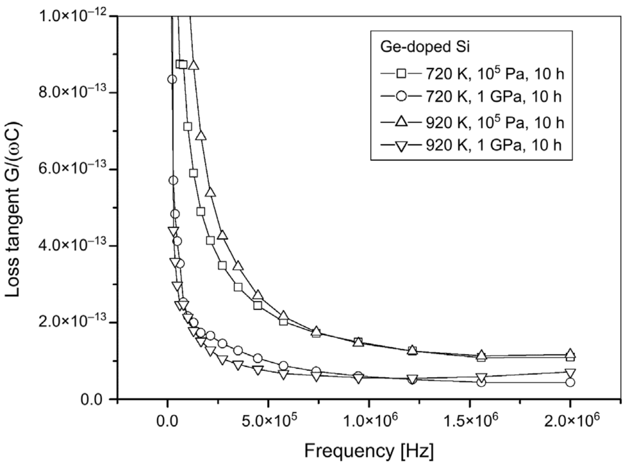

Fig. 3. Loss tangent as a function of test signal frequency for Ge-doped Cz-Si HP treated at 720 and 920 K.

a decrease in the electron concentration is observed. This phenomenon very important from the practical point of view may be explained as a generation of shallow thermal acceptors and increased oxygen precipitation.

Results of admittance measurements of germanium-doped Cz-Si annealed at 720 and 920 K under atmospheric and high hydrostatic pressure are presented in Fig. 3. Again no peaks are observed on all curves, so only shallow states exist in the samples under investigation. The fact of the values of loss tangent being lower in comparison with Si:*p* and Si:*n* samples follows from lower oxygen concentration and resulting lower density of structural defects.

Figure 4 shows carrier concentrations for germanium-doped Cz-Si, determined from *C-V* measurements of Hg-Si Schottky junction for different temperature – pressure conditions. Here, an ascending dependence of the concentration of thermal donors on hydrostatic pressure is noticed. Cz-Si annealing at a temperature of 920 K results in generation of new donors and annihilation of thermal donors [7]. In the case

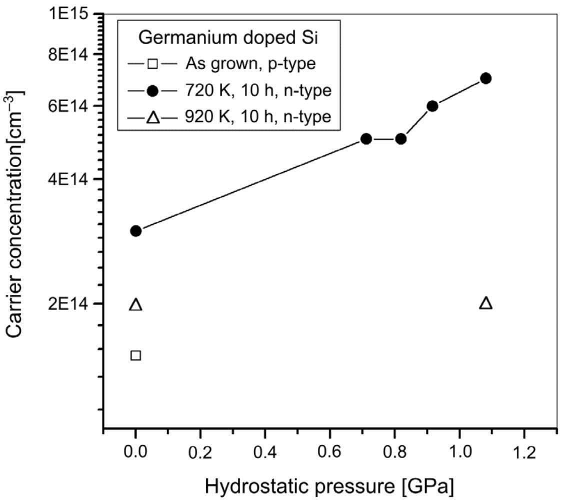

Fig. 4. Carrier concentration in Ge-doped Cz-Si surface layer as a function of hydrostatic pressure.

of germanium-doped Cz-Si generation of new donors at a temperature of 720 K is also observed (see Fig. 4), but no hydrostatic pressure dependence is noticed, contrarily to standard Cz-Si in which weak dependence of new donors generation on hydrostatic pressure is reported [8].

4. Conclusions

High pressure annealing of Cz-Si at 720 K results in enhanced formation of thermal donors due to increased diffusivity of oxygen atoms or HP-stimulated embryos for thermal donors creation.

High pressure annealing of neutron irradiated Cz-Si leads to a decrease in electron concentration compared to non-irradiated Cz-Si samples due to generation of irradiation induced defects (thermal acceptors) and enhanced oxygen precipitation.

Ascending dependence of thermal donors formation and no dependence of new donors creation on hydrostatic pressure in germanium-doped Cz-Si is observed.

Concentration of thermal donors depends on oxygen concentration in standard and germanium-doped Cz-Si.

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