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DEFECT FORMATION IN MIS STRUCTURES BASED ON SILICON WITH AN IMPURITY OF YTTERBIUM

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The characteristics of silicon MIS structures with ytterbium impurity are studied using non-stationary capacitance spectroscopy of deep levels. It is established that the presence of ytterbium atoms in the bulk of the silicon substrate leads to a shift in the capacitance-voltage characteristics towards positive bias voltages and a decrease in the density N_{ss} of the surface states of the MIS structures. It is shown that this effect depends on the concentration of ytterbium atoms in the silicon substrate of the studied structures. In MIS structures based on *Si<Yb>*, one deep level with an ionization energy E_c-0.32 eV is detected.

Key words: *Silicon; Substrate; Impurity; Rare Earth element; Diffusion; Doping; Ytterbium; MIS structure*
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INTRODUCTION

Currently, solid-state electronics devices are used in almost all areas of science and technology throughout the world. The scope of application of solid-state devices is constantly expanding, fundamentally new devices are created, stimulating the development of industry in new directions, which requires a significant increase in the perfection of the silicon structure - the main material of modern solid-state semiconductor electronics. Therefore, research aimed at studying the processes of defect formation in silicon doped with various impurities and establishing controlled methods for stabilizing the parameters of semiconductor devices are one of the important problems [1-10]. In connection with the search for semiconductor materials with special properties (increased thermal stability, radiation resistance, etc.), interest in silicon doped with rare earth elements has recently increased [5-13]. These specially introduced impurities enter into various interactions with structural defects and various uncontrolled impurities during technological processing, which is accompanied by almost any method of manufacturing semiconductor devices. Among all the rare earth elements in silicon, ytterbium is the least studied.

Analysis of the trends in the development of microelectronics worldwide today shows that in the future, the majority of manufactured microcircuits will be digital logic integrated circuits, the basic element of which is MIS (metal-insulator-semiconductor) structures. Charge-coupled devices (CCDs) are already widely used in digital and analog signal processing devices, and photosensitive CCDs, which are also based on MIS structures, are used as solid-state photodetectors [12-16].

However, with an increase in the degree of integration of microcircuits, when creating large and very large integrated circuits, surface and volume defects in multilayer silicon structures have an increasing impact on the operation of devices. This necessitates a more in-depth study of defects near the semiconductor-insulator boundary and in the volume of the semiconductor and determining their contribution to changes in the parameters of manufactured devices. The study of the interaction between impurity particles and defects in the semiconductor structure, the influence of the heterogeneity of the structure of the MIS structure on the redistribution of impurities opens up the possibility of increasing the stability of the operating parameters of microcircuits based on MIS structures [14-20].

It should be noted that the influence of various impurity atoms on the properties of MIS structures was studied using CV methods in [15-22], and the role of these impurities in the formation of the characteristics of multilayer structures was determined. The use of the *CC-DLTS* method allows scanning the DL both in the bulk of *Si* and SiO_2 and at the Si-SiO_2 interface and studying in detail the properties of each defect separately. There are no data in the literature on the influence of rare-earth element atoms introduced into the silicon substrate on the parameters of MIS structures. Therefore, this paper attempts to fill this gap and study in detail the properties of silicon MIS structures with impurities of rare-earth (non-traditional) elements.

EXPERIMENTAL PART

The aim of this work is to study the processes of defect formation in MIS structures with a silicon substrate doped with ytterbium impurity.

To study the effect of ytterbium atoms on the properties of the bulk and the interface of Si-SiO_2, we carried out complex studies using *CC-DLTS* and high-frequency capacitance-voltage characteristics (HF CV-characteristics). Doping of silicon with *Yb* was carried out by the diffusion method in the temperature range of 900÷1250°C for 5÷20 hours from a layer of metallic ytterbium deposited on

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the Si surface with different cooling rates of the samples after diffusion. Silicon wafers doped with ytterbium impurity during growth from the melt were also used. The method for fabricating MIS structures is described in our work [15]. After doping on Si plates with a specific resistance of ρ=15 Ω×cm, a layer of SiO_2 with a thickness of 650-700 Å was grown thermally at 900°C in an atmosphere of humid oxygen with the addition of trichloroethylene. Metallic electrodes on SiO_2 with an area of A=0.03 cm^2 and a thickness of 7000 Å were created by thermal spraying of aluminum.

The *CC-DLTS* spectra were measured in the temperature range of 77 - 300 K at different values of E_{FS} in the state of electron emission from the PS, where E_{FS} is the energy of the quasi-Fermi level for electrons on the Si surface, measured from the lower edge of the conduction band downwards [19]. E_{FS} is determined from the value of the constant capacitance C of the structure during emission and the position of the Fermi level in the neutral semiconductor depending on the temperature. The HF CV characteristics were measured at T = 280 K and a frequency of 150 kHz.

Measurements of the capacitance-voltage characteristics of MIS structures based on *Si<Yb>* showed that in the samples where the silicon substrate is doped with ytterbium during the Si growth process (Fig. 1, curve 2), they are shifted towards positive bias voltages compared to the control samples (Fig. 1, curve 1).

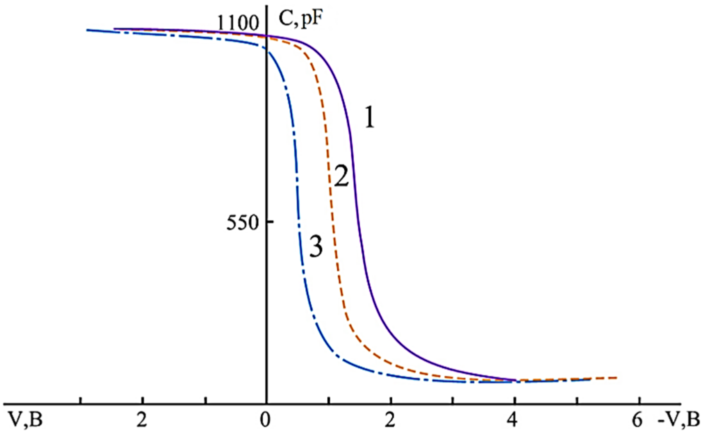

Figure 1. High-frequency capacitance-voltage characteristics of control MIS structures (1) and MIS structures based on *Si* with *Yb* (2 and 3)

Such a shift in the capacitance-voltage characteristics indicates that the presence of ytterbium impurity in the bulk of silicon leads to a decrease in the density of surface states of MIS structures and a decrease in the value of the positive charge at the Si-SiO_2 interface (relative to the control samples).

Analysis of the capacitance-voltage characteristics of MIS structures, where the silicon substrate is doped with ytterbium by the diffusion method (Fig. 1, curve 3) showed that an even greater shift towards positive bias voltages is observed compared to structures whose substrate is doped with ytterbium during melt growth (Fig. 1, curve 2).

Measurements of the *CC-DLTS* spectra in MIS structures based on *Si<Yb>* (Fig. 2, curve 2) and control MIS structures (Fig. 2, curve 1) showed that their spectra differ somewhat, since the value of N_{ss} decreases when ytterbium is introduced into the silicon substrate of the MIS structures. Analysis of the *CC-DLTS* spectra showed that this effect depends on the method of introducing the ytterbium impurity into the silicon substrate of the studied structures (by diffusion or during the growth process. A peak with a maximum at T=165 K is observed in the *CC-DLTS* spectra of MIS structures with a silicon substrate doped with ytterbium impurity by the diffusion method.

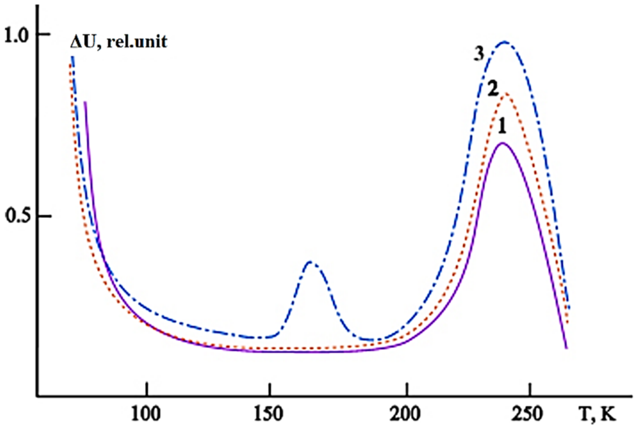

Figure 2. *CC-DLTS* spectra in control MIS structures (1) and MIS structures based on *Si<Yb>*, where *Yb* is introduced during growth (2) and diffusion (3)

Figure 2 shows the *CC-DLTS* spectra of the control MIS structures (curve 1) and MIS structures based on Si doped with *Yb* during growth (curve 2), measured at a depletion capacitance such that the quasi-Fermi level for electrons on the silicon surface EFS is approximately in the middle of the silicon band gap and a filling pulse $U_f=10\ V$ with a duration $t_f=1\ ms$, delay times $t_1=10\ ms$, $t_2=20\ ms$. The maximum at T=280 K (peak B) is associated with the recharging of surface states by minority current carriers, which we observed earlier [15]. Measurements of the *CC-DLTS* spectra of MIS structures based on Si diffusion-doped with *Yb* (Fig. 2, curve 3) showed that another peak with a maximum at a temperature of T_{max}=165 K (peak A) is observed in the spectra of the doped samples.

To determine the energy parameters of this defect caused by the ytterbium impurity in the studied MIS structures, the oxide layer was removed and Schottky barriers were fabricated on them. Measurements of the *CC-DLTS* spectra on the obtained barriers showed that in these samples, a recharge of one deep level in the upper half of the Si band gap with an ionization energy of E_c-0.32 eV is observed. The concentration of this level depends on the technological diffusion modes: the higher the diffusion temperature and the cooling rate of the samples after diffusion, the higher the concentration of the detected level E_c-0.32 eV. Analysis of the obtained results allows us to conclude that this level is caused by the introduction of an ytterbium impurity.

CONCLUSIONS

Thus, it has been established that the presence of ytterbium atoms in the bulk of the silicon substrate leads to a shift in the capacitance-voltage characteristics towards positive bias voltages and a decrease in the density of surface states N_{ss} of MIS structures.

Analysis of the *CC-DLTS* spectra showed that this effect depends on the method of introducing the ytterbium impurity into the silicon substrate of the studied structures (by diffusion or during the growth process).

From measurements of the CC-DLTS spectra on *Si<Yb>*-based Schottky barriers, it has been established that peak A at 165 K is due to a deep level in with an ionization energy of Ec-0.32 eV.

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ДЕФЕКТОУТВОРЕННЯ В МДП СТРУКТУРАХ НА ОСНОВІ КРЕМНІЮ З ДОМІШКОЮ ІТЕРБІЮ

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Методами нестаціонарної ємнісної спектроскопії глибоких рівнів досліджено характеристики кремнієвих МДП-структур з домішкою ітербію. Встановлено, що присутність атомів ітербію в об'ємі кремнієвої підкладки призводить до зсуву вольт-фарадних характеристик у бік позитивних напруг зміщення та зменшення густини N_{ss} поверхневих станів МДП-структур. Показано, що цей ефект залежить від концентрації атомів ітербію в кремнієвій підкладці досліджуваних структур. У МДП-структурах на основі Si<Yb> виявляється один глибокий рівень з енергією іонізації E_c-0,32 еВ.

Ключові слова: *кремній; підкладка; домішка; рідкоземельний елемент; дифузія; допінг; ітербій; МДП структура*