



ISSN: 2350-0328

International Journal of Advanced Research in Science,
Engineering and Technology

Vol. 6, Issue 12, December 2019

Electrophysical Properties of Cadmium and Sulfur-doped Silicon with Electronic Conductivity

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ABSTRACT: The paper presents the results of the study of peculiarities of inter-impurity interaction of cadmium and sulfur in silicon samples with electronic conductivity at $T = 1200^{\circ}\text{C}$. The starting material n-type silicon was initially doped with sulfur and then subsequently doped with cadmium impurity atoms and annealed at a temperature of 1200°C . The results of a study of the specific conductivity of silicon samples doped with cadmium and then sequentially doped with impurity atoms of sulfur, at temperature of 1200°C are also presented. In both cases, the control samples of Si <B, S> and Si <B, Cd> were annealed at a temperature of 1200°C for 45 minutes. The authors have shown the possibility of formation of impurity atom complexes at certain thermal annealing temperatures.

KEY WORDS: Resistivity, silicon, cadmium, sulfur, selenium, tellurium, complexes, semiconductor, impurity atoms, chemical bonding, diffusion

I. INTRODUCTION

As it well known, $A^{II}B^{VI}$ -type compounds mainly crystallize into crystal lattices and the form of a chemical bond from ranges from a purely ionic to covalent type depending on the technology of their preparation [1]. Recent studies have shown that $A^{II}B^{VI}$ compounds often crystallize in various polymorphic modifications and can belong to two main structural types: the cubic structure of zinc blende (sphalerite) and the hexagonal structure of wurtzite, which are characterized by a tetrahedral arrangement of atoms similar to that observed in semiconductors of IV group. In addition, they form a series of closely related polytypic forms, which are also characterized by a tetrahedral arrangement of atoms and are essentially derived structures of zinc blende and wurtzite [1].

In view of the abovementioned, the similarity of the tetrahedral arrangement of atoms in the $A^{II}B^{VI}$ lattice with the diamond structure, in which all atoms are of the same size, allows us to use the covalent bond model, which is inherent in the model of bonds in group IV semiconductors. In addition, it is known from chemistry that elements of the VI group of the periodic table exhibit exceptional chemical activity in relation to other elements.

These facts (the presence in nature of $A^{II}B^{VI}$ compounds obtained by technological methods, the similarity of tetrahedral bonds, the chemical activity of group VI elements) gives one the idea of the possibility of building and synthesis of these compounds in the bulk of a semiconductor material. In this case, the natural question arises: "will these compounds retain their original, at least qualitative, physical properties in the bulk of the semiconductor material?". Obtaining reliable data on the state of impurity atoms belonging to $A^{II}B^{VI}$ compounds would significantly expand the possibilities of using such compounds, as well as individually and the base semiconductor material. For successful resolve of this problem, thorough study and accumulation of material about the nature of chemical bonds and crystallization of II – VI compounds, in general, or the crystal lattice of another semiconductor material, and the nature of the chemical bonds in the base material will be required [2].

**II. SIGNIFICANCE OF THE SYSTEM**

The paper mainly focuses on hypothesis of how to extend the spectral sensitivity range of silicon photo-elements by building nanoscale structures—quantum dots based on the $\text{Si}_2\text{A}^n\text{B}^{8-n}$ binary elementary cells in the basic matrix and on surface of the samples. The study of literature survey is presented in section III, Methodology is explained in section IV, section V covers the experimental results of the study, section VI covers discussion, and section VII the Conclusion.

III. LITERATURE SURVEY

The fact that one cannot harness the extra photon energy $\Delta E = h\nu - E_g$, which transforms into heat due to thermalization and leads to the heating of photoelements and weakens their parameters is the main issue for modern solar power technology. As is known, with the heating of a photoelement by 1 deg above 25°C the open-circuit voltage of a photoelement deteriorates by 0.4% per degree. Thus, the main part of solar radiation in the UV and visible range, where $h\nu > E_g$, is also not effectively used and weakens the main parameters of the photoelement, which finally limits the efficiency of silicon photo-elements [3].

In photo-energetics, in order to reduce the effect of thermal generation and increase the absorption coefficient in the UV and visible solar ranges, multiple cascade photo-elements are developed based on $\text{A}^{\text{III}}\text{B}^{\text{V}}$ semiconductor compounds [4]. Regardless of their efficiency, multiple cascade photo-elements are subjected to quite a complicated technology for their fabrication and require expensive equipment, which finally determines their high cost. Apart from this, their widespread application in ground conditions is of particular difficulty.

In connection with this, the formation of impurity atoms in a Si cluster crystal lattice [5], particularly, binary clusters of impurity atoms, being a new $\text{Si}_2\text{A}^n\text{B}^{8-n}$ unit cell (where A and B are impurity atoms which substitute the adjacent sites in the Si lattice and n is the number of the valence electrons) are of particular interest [6,7].

IV. METHODOLOGY

In the present, it becomes relevant to search for the most optimal technological conditions for forming of $\text{A}^{\text{II}}\text{B}^{\text{VI}}$ compounds in the bulk of the base semiconductor material. The study of the electrical and physical, optical and chemical properties of such materials, as well as the analysis of experimental results, will allow us to make a reasonable conclusion about the possibility of engineering novel unique materials based on $\text{A}^{\text{II}}\text{B}^{\text{VI}}$ compounds in the basic matrix of a semiconductor material. This, in turn, will create new prospects for the design and development of unique materials that allow their widespread use in electronics, optoelectronics and photovoltaics.

V. EXPERIMENTAL RESULTS

To study how sulfur, selenium, tellurium and cadmium impurities interact with each in basic silicon matrix we have taken as a starting material the phosphor-doped silicon with resistivity $100 \Omega\text{-cm}$ sample that was doped with chalcogenides at $T = 1200^\circ\text{C}$, and then sequentially doped with cadmium impurity atoms at a temperature of 1200°C . On the other hand a starting material (the phosphor-doped silicon) with resistivity $100 \Omega\text{-cm}$ sample was initially doped with cadmium impurity atoms at $T = 1200^\circ\text{C}$, and then sequentially with sulfur, selenium and tellurium at the same temperature. At the same time, reference samples of Si <B, S>, Si <B, Se>, Si <B, Te> and Si <B, Cd> were annealed under the same doping conditions to determine the dynamics of changes in the specific conductivity of the initial silicon.

From the results of studies (Table 1), it was found that in Si<P> samples doped with Cd at temperatures of 1200°C , the resistivity (ρ) with respect to the starting material varies significantly, the sample remains relatively highly resistive with a resistivity of $\rho = 2967 \Omega\text{-cm}$, and the type of conductivity does not eventually change. These experimental results show that cadmium atoms in silicon act as a singly charged acceptor. These data demonstrate the exclusively acceptor nature of cadmium in silicon at a low concentration of its electroactive atoms, which confirms the bibliographic data [8].

The following samples Si <B, S>, Si <B, Se> Si <B, Te> doped with cadmium impurity atoms at T = 1200 °C manifest practically the same properties with specific resistance of $\rho = 36.4 \Omega \cdot cm$, $\rho = 112,5 \Omega \cdot cm$ and $\rho = 316 \Omega \cdot cm$, respectively, while remaining n-type in conductivity. These electro-physical parameters practical remain unchanged until the annealing temperature of T = 1200 °C.

VI.DISCUSSION

These research results can be explained by the transition of electroactive atoms of sulfur, selenium and tellurium to a neutral state with the transition of electrons of positively charged cadmium atoms in silicon. It was found that in samples of silicon doped with impurity atoms of selenium, the resistivity returns to its original value.

Table 1.

Phosphor-doped silicon $\rho = 100 \Omega \cdot cm$	Si<P,Cd>	Si<P,Cd,S>	Si<P,Cd> reference sample
type	n	n	n
R (Ω)	2967	36,4	265
Phosphor-doped silicon $\rho = 100 \Omega \cdot cm$	Si<P,Cd>	Si<P,Cd,Se>	Si<P,Cd> reference sample
type	n	n	n
R (Ω)	2967	112,5	178
Phosphor-doped silicon $\rho = 100 \Omega \cdot cm$	Si<P,Cd>	Si<P,Cd,Te>	Si<P,Cd> reference sample
type	n	n	n
R (Ω)	2967	316	178

The study of silicon samples initially doped with chalcogenides (S, Se, Te) at T = 1200⁰ C and then doped with cadmium atoms showed that in this case the change in the resistivity of the samples varies.

From the results of studies (Table 2), it can be seen that in the Si samples doped with S, Se, and Te, at a temperature of T = 1200⁰ C, the resistivity (ρ) with respect to the starting material changes quite significantly, i.e., the samples remain n-type with a resistivity of $\rho = 33 \Omega \cdot cm$, and $20 \Omega \cdot cm$ and $\rho = 19 \Omega \cdot cm$, respectively, which is caused by an intensive increase in the concentration of electroactive atoms. In control samples, a significant strong increase in resistivity is observed. From table 2 it is seen that the samples doped with tellurium become highly resistive with a specific resistance of $\rho = 3345 \Omega \cdot cm$.

After cadmium doping, the annealed samples doped with S, Se, and Te retained the type of conductivity, i.e., the samples remained n-type with a resistivity of $\rho = 188 \Omega \cdot cm$, $\rho = 310 \Omega \cdot cm$ and $\rho = 640 \Omega \cdot cm$. This is possibly due to occurrence of molecular formation between cadmium atoms and impurity chalcogenide atoms in silicon. In the case of samples doped with tellurium atoms, it is explained by the formation of diatomic and polyatomic molecules of tellurium, selenium, and partially sulfur atoms, which allows one to maintain a certain concentration of the formed electroactive monoatomic centers of these elements.

These results are consistent with the results of reports [9], where the effect of high-temperature annealing of diffusion doped silicon samples on the density of monoatomic sulfur centers S_1 is considered. The authors noted that the rare cooling of doped sulfur samples obtained at high temperature leads to an increase in the concentration of electrically neutral complexes formed by sulfur and cadmium atoms.

Table 2.

Phosphor-doped silicon $\rho = 100 \Omega \cdot cm$	Si<P,S>	Si<P,S,Cd>	Si<P,S> reference sample
Type	n	n	n
R (Ω)	33	188	68,4
Phosphor-doped silicon $\rho = 100 \Omega \cdot cm$	Si<P,Se>	Si<P,Se,Cd>	Si<P,Se> reference sample
type	n	n	n
R (Ω)	20	310	600
Phosphor-doped silicon $\rho = 100 \Omega \cdot cm$	Si<P,Te>	Si<P,Te,Cd>	Si<P,Te> reference sample
type	n	n	n
R (Ω)	19	640	3345

VII. CONCLUSION AND FUTURE WORK

It was determined that the optimal complex formation conditions under which almost all existing impurity atoms form electrically neutral chemically bound complexes occurs at 1200°C. In this case, impurity atoms of both sulfur and Cd are completely neutralized and the material acquires the electro-physical parameters of the material as the initial parameters.

The formation of such complexes is primarily associated with the further study of the bonding energy and structure of the studied silicon samples, as well as with the concentration of impurity atoms and diffusion conditions.

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