ANNOTATION

of dissertation for the Philosophy Doctor (PhD) degree on «6D071900 - Radio engineering electronics and telecommunications» specialty

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Development of high- sensitive detection system based on large- sized silicon lithium structures

The general characteristics of the study

The thesis is devoted to the development, research and application of spectrometric instruments for registration of X- ray radiation. Special attention was paid to the development of semiconductor detector and readout electronics for this. In the framework of this work, it was proposed a new method for double sided diffusion and double sided drift of lithium ions into a mono- crystalline silicon wafer for the further fabrication of Si (Li) p-i-n nuclear radiation detectors with a diameter of the sensitive area more than 110 mm and with a thickness of the sensitive region more than 4 mm. The theoretical assumptions and experimental characteristics of double sided diffusion are considered. To obtain the structure, dislocation-free p-type mono-crystal silicon grown by the Czochralski method and crystal silicon obtained by float-zone method were taken as the initial materials. Also, an optimized, fast-acting, low-noise read-out electronics was developed, an algorithm and a block diagram of the detecting system were proposed.

Actuality of the study

Today, silicon detection systems are widely used in the field of registration of various types of particles and radiations. One of the main advantages of this kind of detector systems is low energy, high efficiency of statistics collection, good radiation resistance. Due to such characteristics, silicon detection systems are the object of research and products of various laboratories from around the world. One of them is CANBERRA - which develops and manufactures silicon detectors and spectrometers for research and industrial needs. One of the leaders in the design and production of ionizing radiation detection systems is the industrial organization ORTEC. There are many worldwide laboratories, such as the Brookhaven National Laboratory, the laboratory of semiconductor detectors of the Institute of High Energy Physics, etc. who are engaged in research and development of semiconductor detectors and spectrometers.

At the same time, the registration of various types of particles and radiation continues to be a special task of science and technology. Among them, a special place is occupied by detection systems, based on nuclear radiation with high energy, good positional resolutions, signal linearity in a wide range of energy for various types of ionizing particles. One of the important technological, scientific and technical stages of obtaining highly efficient detection systems is the correct understanding of physical, technological and structural solutions. As the detector is an integral part of spectrometric systems, the process of formation of detector structures, plays very important role in development of spectrometric systems. The high energy resolution of the detector, the linearity of the output signal and the high operating ability of the detector ensures the successful operation of the whole system. In this matter, a special place is occupied by the quality of the initial crystal material for the detectors. In our study, monocrystalline silicon was chosen as the initial material. Comparing with other materials Silicon meets all of the above requirements.

It is well known that the Ge-detectors have the highest functional characteristics, but they work under temperature $T \leq 77K$, so they need cooling system with liquid nitrogen during the work process. The technologies of production of monocrystals, such as - GaAs, CdTe and CdZnTe, as initial material for detector manufacturing have low efficiency of detection and small energy resolution.

Nowadays, in the world practice detectors with relative small size are well developed. Simultaneously, the development of silicon detectors with big size is necessary. In comparison with other semiconductor devices, such as diodes, transistors, thyristors and etc., the structures of detector should correspond with high requirements related to their current, charge, capacitance, noise, spectrometric and time characteristics, also with the sameness of identification of ionizing radiation regardless of its contact with any part of the sensitive area of the detector. In this regard, it is important to study the technological issues caused by effects of big size semiconductor crystals for forming required detector structures with p-n and p-i-n junctions.

There is a need to increase the information taken from the spectrometer, both about the particle itself and about the processes occurring in the detector at the time of its registration. This statement is trivial, but its implementation by analog electronic methods is very problematic, since almost all the available resources are already involved. With the digital method of signal analysis, it becomes possible to use powerful mathematical methods inaccessible to analog electronics. This allows a new level to analyze the pulse shape and extract additional information from it.

The properties of electronic components that make up analog spectrometers vary with environmental conditions (temperature, humidity, mains voltage, etc.). Despite the widely developed systems of stabilization and compensation, the problem remains relevant for almost any experiments. In digital signal processing, much of the work done by electronic modules is transferred to computer programs. Therefore, the stability of the entire system increases.

The task of improving the resolution of the spectrometer is always relevant. There are known effects that interfere with its improvement (ballistic defect, non-optimal filtering of signals, etc.); however, this is difficult to implement using analog electronics. Means of digital signal processing can restore the signals and thereby reduce the effects of a ballistic defect. In addition, it is possible, before starting processing a particular signal, taking into account the peculiarities of its shape, to design an individual filter that optimally matches this signal.

The purpose of research - in order to construct high efficient, low cost spectrometer for X – ray radiation it is needed to develop technology of manufacturing of Si(Li) p-i-n detectors of large size and create suitable electronics for these detectors.

To achieve this purpose, the following tasks were set:

-To chose suitable initial materials for detectors.

-To study experimentally electro-physical characteristics of initial material for detectors.

-To develop the technological modes of double-sided diffusion of lithium atoms in silicon wafers of large sizes;

- To develop the technological modes of double-sided drift of lithium ions in silicon wafers of large sizes;

-To develop suitable and high efficient readout electronics for large size Si(Li) p-i-n detectors;

-Hardware implementation for highly efficient spectrometric system based on large size Si(Li) p-i-n detectors;

Objects of research:

Object is a highly sensitive X-ray detection system and Si (Li) p-i-n structured detectors.

Subject of study

Subjects of the research is the physical mechanisms and technology for the development of both detectors and detection systems.

The main provision for the defense

- The optimal regime for lithium diffusion into large-diameter silicon (≥110 mm) with a thickness of the sensitive region W ≥ 4 mm is at a temperature T = (450 ± 20) ^{0}C, t = 3 min, h_{Li} = (300 ± 10) µm.

- The method of conducting a double sided drift of lithium ions into a silicon monocrystal is performed by a synchronous stepwise increase in temperature from 55 ^{0}C to 100 ^{0}C and a reverse bias voltage from 70V to 200V.

- The technology of double-sided drift of lithium ions into a silicon monocrystal improves spectrometric characteristics, increases the efficiency of the detection system and reduces the time to manufacture the detector.

- The charge-sensitive preamps for silicon detectors have high speed (rise time no more than 5 ns), low sensitivity to the input capacitance, which ensures, as a result, a low-noise amplifier with a level of 0.45 nV/Hz$^{1/2}$ and its stability, and the possibility of matching the impedance of the connected line and the input of the amplifier.

Scientific novelty

- Experimentally, it was found the regimes of diffusion of lithium atoms in a silicon single crystal were detected, for the manufacture of a detector with a sensitive area greater than 110 mm^2 and a thickness of 4 mm.

-Technological regimes of double-sided drift of lithium ions into monocrystalline silicon were experimentally determined, including a synchronous step change in temperature and reverse bias voltage leading to a reduction in the drift path of penetration of lithium ions and to a more homogeneous detector structure, thereby reducing the energy resolution of the detector for beta particles by 5 keV and for alpha particles at 7 keV.

- Theoretical calculations and experimental data showed that the technology of double-sided drift reduces the manufacturing time of the Si (Li) p-i-n structure by four times.

- The developed charge-sensitive preamplifier for a Si (Li) p-i-n structured detector showed a low noise level; for detectors with an output capacitance of 300 pF, the mean square deviation of the noise current is 45 nA and the minimum delay time is up to 8 ns. Also, it is established that the preamplifier is fully compatible with other, alternative, silicon detectors with an output capacitance from 10 to 1300 pF.

Method of research

The Si (Li) p-i-n detector structure was obtained by the method of double-sided diffusion and drift of lithium ions on a silicon wafer. The determination of the electro-physical characteristics of the detector and the entire detection system was carried out by theoretical calculation and then experimental measurements. The electronic part of the system was built by modeling, theoretical calculation, then by an experimental method.

Scientific and practical significance of the work

In the dissertation work, new theoretical and experimental features of the formation of large sized Si (Li) p-i-n structures are considered. The creation of such detector structures is associated with a more detailed and in-depth understanding of the electrical properties of the original silicon of large diameter, and the establishment of their relationship with the requirements for obtaining high-performance Si (Li) p-i-n structures. These scientific results are important for understanding the physical processes for various large-sized semiconductor devices, as well as practical implications for improving their characteristics.

Development of unique spectrometers based on Si (Li) p-i-n detectors of large sizes opens up new opportunities to conduct research in the field of science and technology to study the physics-chemical properties of environmental objects. This development will open new perspectives in the development of science and industry in improving the quality of information processing of radioactive radiation, which further allows its use in seismology, geology, medicine and. etc.

Consequently, to complete these requirements in this work it was developed digital electronics for large sized Si(Li) p-i-n structured detectors. Also, algorithm for reading digital electronics of the detecting system has been created with respect to electro-physical and radiometric characteristics of the detecting system.

Personal contribution of the author is that the author was directly involved in obtaining the main scientific results. All the results of a physical experiment, theoretical calculations, numerical analysis of models, the assembly of the detecting system were obtained personally by the author. The setting of tasks and the development of ideas were carried out in collaboration with scientific consultants. All publications on the topic of the thesis were prepared with his direct participation.

Reliability of results

-The theoretical part described in this paper is a continuation of the well-known scientific works in the field of electronics and semiconductor electronics. The results obtained are associated with the works of previous research and their logical continuation.

- The experimental and theoretical results given in the paper are in good agreement.

- The developed X-ray detection system is fully functional.

Approbation testing of thesis

The main results of the thesis were presented and discussed at the seminars of the Physics and Technology Faculty of the Al-Farabi Kazakh National University, as well as at the following international conferences:

- Fourth International Conference on Radiation and Application in Various Fields of Research (2016, Niš, Serbia);
- International scientific conference of students and young scientists "Farabi alemi" (2018, Almaty, Kazakhstan);
- The results of dissertation was implemented in household activity of LTD «Scientia Kazakhstan», for determination of radiation level of equipment.

Publications

According to the materials of the dissertational work, 11 publications were published. From which 8 are articles, 2 in an international scientific publication, having citations in Thomson Reuters database (ISI Web of Knowledge, Thomson Reuters), which is also included in the Scopus database, 6 articles in scientific publications recommended by the Committee on the Control of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan, 1 report at an international conference abroad and 2 reports at local international conference.

Structure and volume of the dissertation

The dissertation consists of an introduction, four chapters, conclusions and a list of references. It is presented on 114 pages of typewritten text, contains 56 figures, 4 tables, 148 references.