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SILICON-LITHIUM NUCLEAR RADIATION DETECTORS WITH A LARGE SURFACE OF SENSITIVE AREA

R.A. Muminov[1], S.A. Radzhapov[1], Yo.K. Toshmurodov[1], S. Bekbaev[2]

[1]Physical-Technical Institute of AS RUz, Tashkent, Uzbekistan, detector@uzsci.net
[2]International Kazakh-Turkish Universitet names. H.A.Yasaui, Turkestan, Kazakhstan
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Мақолада қалинлиги $W > 2$ мм бўлган сезгирлик соҳасидаги ва катта юзадаги ($S \geq 60$ см^2) кремний-литийли ядровий нурланиш детекторларини ишлаб чиқишнинг ўзига хос хусусиятлари кўриб чиқилган. Катта ўлчамли *p-i-n* структурали юқори эффективли Si(Li) шакллантириш учун литий ионлар дрейфи ва диффузия технологиясининг ўзига хос хусусиятлари кўрсатилган. Акустостимуляция таъсири йўли билан кремний кристалл панжарасида термодинамик ҳолат ўзгариши натижасида кристалл ҳажмида бир жинслилик таминланиши аниқланди.

В статье рассмотрены особенности разработки кремний-литиевых детекторов ядерного излучения больших площадей ($S \geq 60$ см^2) и толщин ($W > 2$ мм) чувствительной области. Показаны особенности технологии диффузии и дрейфа ионов лития для формирования высокоэффективный Si(Li) *p-i-n* структур больших размеров. Установлена возможность изменения термодинамического состояния кристаллической решетки кремния путем акустостимулированного воздействия, в результате которого обеспечивается однородность объема кристалла.

The peculiarities of the development of Si-Li nuclear radiation detectors of large size ($S \geq 60$ cm^2) and the sensitive area thickness of $W > 2$ mm are considered in the article. Peculiarities of diffusion technology and lithium ions drift for formation of highly effective Si(Li) *p-i-n* structures of large sizes were shown. Possibility of changing the thermodynamic state of the silicon crystal lattice by means of acoustic stimulated impact is established, as the result the uniformity of crystal bulk can be provide.

I. INTRODUCTION

Registration of various types of ionizing radiation is one of the important tasks of the modern development of science and technology. The solution of the above problem is quite complex and far challenging. This is mainly due to the high devands to development of large size semiconductor nuclear radiation detectors, in particular with regard to the possibility to develop radiation detectors with sensitive surface up to the maximal possible in terms of diameter of the original single crystal silicon, up to 100–110 mm. Another factor is related to the thickness of the sensitive area which sometimes can be relatively huge, i.e. $W \geq 2$ mm.

Silicon-lithium radiation detectors are quite widespread among the large class of detectors based on semiconductor crystals. Currently, semiconductor detectors (SCD) of relatively small size are well studied and widespread [1]. At the same time, there is an urgent need for the development of large size semiconductor detectors. However, in the course of their development and design, scientists are facing multiple difficulties related to physical, technical and technological problems. Those are manifestation of the effects stemming from the relationships between the parameters of the original crystal with large diameters and the necessity to design effective radiation detectors based on them. In particular, this is related with the necessity to ensure high-quality detector structures of *p-n* or *p-i-n* type on large size crystals. In order to be able to develop such, one has to have a proper understanding of physical processes taking place in semiconductor crystal of large dimensions. One has to have the ability to deliberately manipulate the physical processes during complex industrial processes, in particular, when it comes to diffusion, drift, chemical and mechanical treatments, ensuring sharp plane parallel *p-n* or *p-i*, *i-n* transitions over the entire area of the crystal, obtaining thin highly efficient current collecting contacts and so on [2]. Ultimately, *p-n* or *p-i-n* detector structures must be characterized by optimal current, capacitive, noise characteristics and must have effective radiometric characteristics (energy resolution, high-quality amplitude signals, high sensitivity, thin entrance windows (i.e. "dead layer" and so on).

II. METHODOLOGY AND TECHNOLOGY OF FORMATION OF DETECTOR STRUCTURES

To ensure detector structures on crystals of large diameter with the above mention requirements, it is necessary to study the peculiarities of emerging processes symbolic to large dimensions and to find optimal physical, technical, design and technological solutions, such as:

– design and development of silicon lithium nuclear radiation detector on a single monocrystalline wafer (diameter up to 100–110 mm);

– development of novel technological methods of producing high-quality *p-n* and *p-i-n* structures on large area's silicon wafers;

– since the equation for fluctuation of charge collection in semiconductor radiation detectors is determined by multiplication of two components – average losses of charge and their degree of uniformity, then direct analysis of the parameters of the original material is required.

At whatever technique (be it a Czochralski method, zone melting and so on) used for manufacturing of silicon monocrystals, they always contain certain defects of structures and composition. Ability to control them and manage their concentrations is essential in the development of highly efficient radiation detectors, since they are the factors that will ultimately determine measuring and spectrometric characteristics of these devices. All this is particularly important for crystals of large diameter, since during growth of large diameter crystal one has to anticipate significant fluctuations in technological conditions (temperature field, the crystallization front, stress, etc.)

One of the ways to influence the processes in large-diameter silicon wafers is related to the possibility to use ultrasound waves which can improve the properties of the original crystal.

Ultrasonic treatment is based on acoustically stimulated phenomena in semiconductors. We have pioneered the development of the technique of improving properties of crystal bulk for the sake of the development of semiconductor detectors of nuclear radiation on silicon wafers of small size [3]. Similar technique was developed for large crystals eventually.

The specific characteristic of the ultrasonic wave as a carrier of energy in this case permits us to effectively manipulate the thermodynamic state of the semiconductor crystal. In addition, the spectral composition of the ultrasonic wave (frequency and harmonics) selectively determines the effectiveness of their interactions with single impurity atoms and their clusters, dislocations. These properties of ultrasonic treatment to alter bulk and surface properties of the crystal and allowing to observe the processes of diffusion and drift of impurity atoms, decay of impurity clusters and complexes at low (ambient) temperatures, allow us to utilize this technique for solving scientific, technical and technological challenges related to the development of large size semiconductor radiation detectors.

The problems of technical nature include mechanical and chemical processing of silicon wafers of large diameters. The formation of *p-n* or *p-i-n* structures on wafers of large diameters with the necessity to ensure precious flatness of the surface requires resolving of a number of technical problems related with mechanical and chemical treatment [4]. We have developed special tools to bring crystals of large diameter to technological processes of diffusion and drift of impurity atoms and formation of sharp edges on *p-n* junctions on strict parallel wafers. Also, we have developed technical and design techniques for efficient current collector contacts. We have found also efficient designs of cases that allow convenient operation and storing them for a long time without degradation of their performance [3].

Technological problems facing the development of radiation detectors are quite complex, whereas when it comes to the development of large size detectors these complexities increase in magnitude. In comparison to other semiconductor apparatus, such as diodes, transistors, thyristors, etc., designing detector structures has to satisfy the stringent requirements related to their current, charge, capacitance, noise, spectrometric, timing characteristics, and the necessity of uniform identification of ionizing radiation regardless of falling of radiation on any sensitive area spot of the radiation detector. In this regard, extensive investigations of technological processes stemming from the large dimension effects of semiconductor crystals are required for the design of detector structures of *p-n* and *p-i-n* types. It is well known that for detector structures, the rear *p-n* junction must be sharp and locates close to the surface layer to ensure thin entrance window (i.e. thin "dead layer"). Base *i*-region should have a very high specific resistivity to ensure its complete depletion at reverse bias voltage applied to the *p-i-n* structure. During formation of *p-i-n* structures on large diameter monocrystalline silicon one needs to take into account physical processes of diffusion, drift, and contact phenomena, which need to studied. Technological methods of their control also need to be developed. Of particular difficulty is the protection (passivation) of the surface of the crystal, mounted in the frame and sealing. Another important process is the deposition of gold collector contact over the detector surface, so that the losses due to the absorption of ionizing radiation on it should be minimal whereas transmission of current shall be maximal. The thickness of the gold layer over the large area of the detector should be uniform.

III. RESULTS OF SCIENTIFIC-TECHNOLOGICAL DATA

Summarizing the above mentioned we have developed a technological route (Fig. 1) for the development of radiation detectors of large size, in particular:

1. Dynamic rotational methods of etching of silicon wafers up to 110 mm are developed to ensure their flatness and parallel to ± 1–2%.

2. Methods for lithium diffusion on monocrystalline silicon wafers of large size are developed to provide a sharp drop in the distribution of their concentration after a certain pre-set depth of penetration.

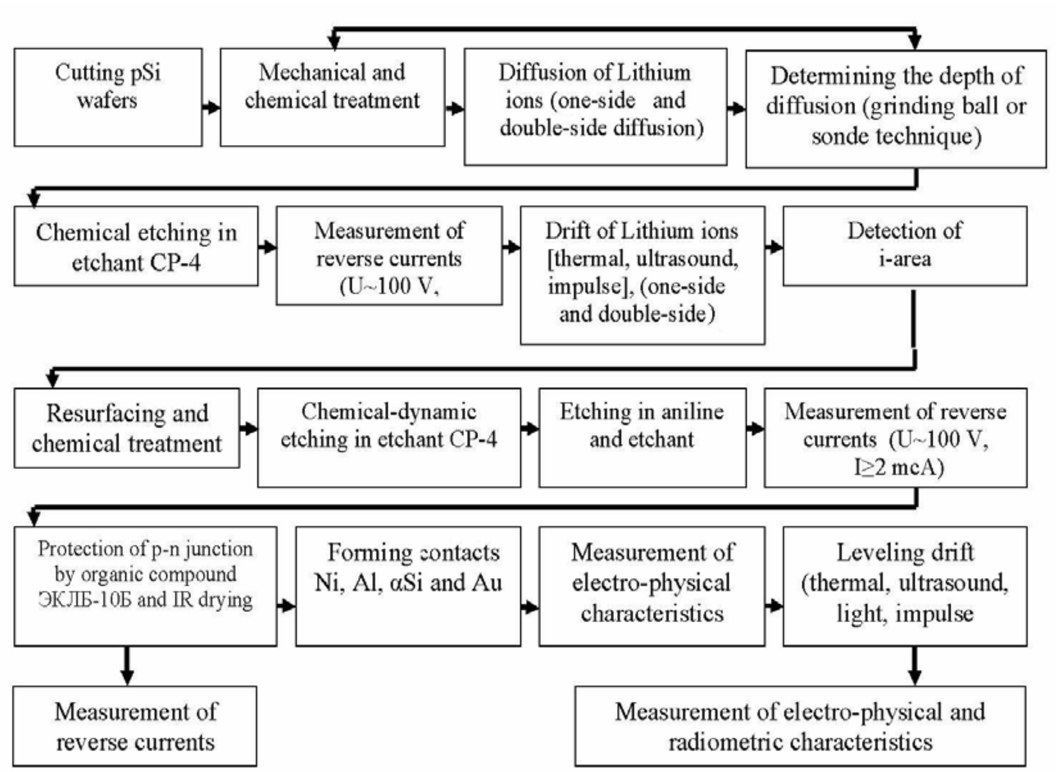


Fig. 1. Technological route of the development of Si (Li) detectors.

3. Multi-stage process of lithium ion's drift onto silicon wafers with diameters up to 110 mm to ensure high uniformity of compensation of sensitive area of the detector has been developed.

4. Scientifically-based methods of acoustically stimulated processes to optimize the performance of silicon-lithium radiation detectors with a large area of the sensitive area have been developed.

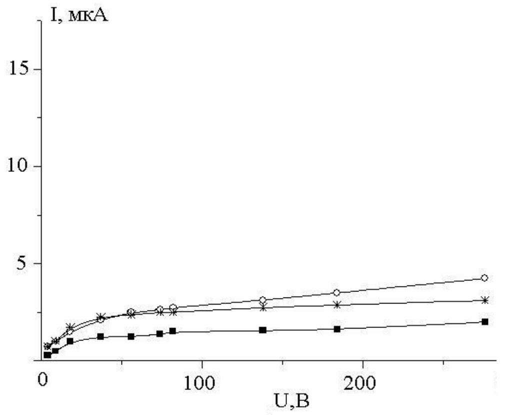
5. Highly efficient silicon-lithium detectors each with an area of not less than 60 cm^2 with the following parameters: $U_{reverse} \approx$ 50–200 V, dark current $I_{dark} \approx$ 1–4 mA, the capacitance C = 200–1000 nF, detection efficiency 30–35%, noise factor $E_n \approx$ 30–50 keV, energy resolution as per internal conversion electrons ^{207}Bi, R_β = 40–90 keV, have been manufactured.

The current-voltage characteristics and the capacitance-voltage one and the noise-voltage characteristics of developed detectors are presented in Fig. 2. Also, and amplitude spectra of developed silicon-lithium *p-i-n*-detectors are presented in Fig. 3.

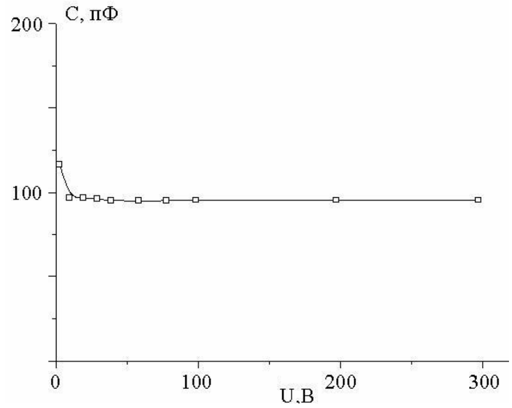
As seen, the characteristics obtained for detectors with large area of the sensitive region do not differ from analogous characteristics of the small area detectors (Fig. 2, 3).

Thus, we have developed technology for manufacturing large area Si(Li) *p-i-n* detectors. On the basis of that technology we have designed and manufactured a number of apparatus, in particular radon radiometer.

a



b



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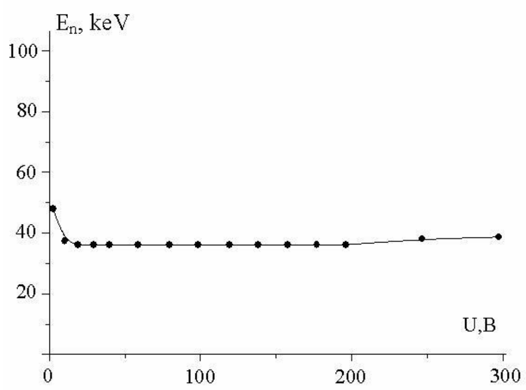
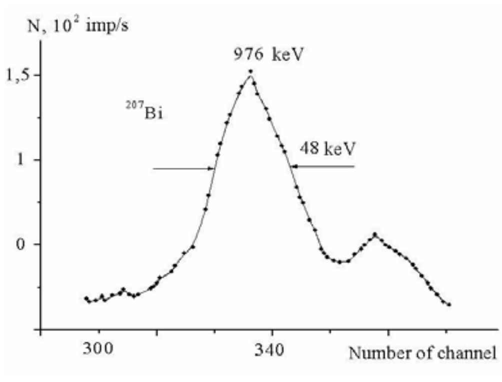


Fig. 2. The current-voltage (*a*), the capacitance-voltage (*b*) and noise-voltage characteristics of Si(Li) detectors with a large area of the sensitive area.

a



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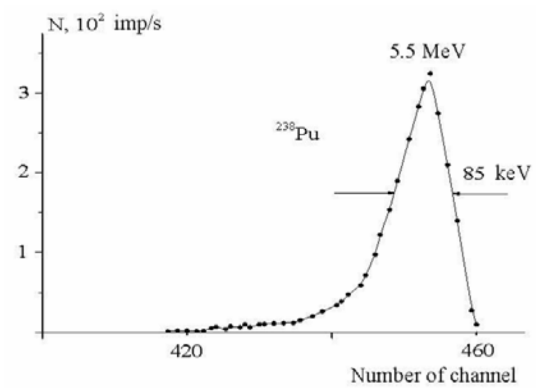

Fig. 3. The amplitude spectra of Si(Li) *p*-*i*-*n*-detectors with a large area of the sensitive area (Ø*i* = 110 mm, *W* = 4 mm); a) registration of β-particles ^{207}Bi (E_β = 976 keV) at *U* = 200 V; b) registration of α-particles ^{238}Pu (E_α = 5.5 MeV) at *U* = 200 V.

Radon is a naturally occurring radioactive gas generated through earth. Its concentration is higher in seismically active regions. Measurement of concentration of radon is essential for the sake of health prevention, environmental protection and forecasting of earthquakes [5].

Radon radiometer is designed for measurement of volume activity of Radon-222 and quantity of распадов ^{216}Po in the air in households and office areas, as well as in open air within the operational parameters of radiometer.

The instrument can be applied in geophysical studies. Additionally, the radiometer can control ambient temperature. Semiconductor radiation detector performs detective functions in the radiometer (Fig. 4).

Fig. 4. The appearance of Radon radiometer.

Performance specifications: Measurement range of volume activity Radon-222 (Becquerel) – from 20 to 2.0×10^{4} Bc·m^{-3}. Measurement range of ^{216}Po (ThA), distr. – from 0 to 10^{3}. Sensitivity of radiometer not less than 1.4×10^{-4} c^{-1}Bc^{-1}m^{-3}. Temperature measurement range – 5–50°C.

Operational conditions: ambient temperature – from +5°C to +35°C; relative humidity at ambient temperature +25°C – to 80%; atmospheric pressure – from 700–820 mm of mercury column.

Accumulator as an autonomous source of power is used for powering radiometer. Radiometer is designed as portable unit with autonomous battery.

It has following core elements: measurement camera with filter and Si(Li)-radiation detector; charge-sensitive preliminary amplifier; spectrometric amplifier and the circuit for obtaining of useful information; high-voltage power supply unit; stand-alone power supply; control unit, display and computer interface.

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