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Application of Additional Leveling Drift Process to Improve the Electrophysical Parameters of Large Sized Si (Li) *p-i-n* Structures

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The development of large sized Si (Li) detectors (with a sensitive region diameter more than 110 mm), with high energy and positional resolutions, signal linearity over a wide energy range, for alpha, beta and gamma particles is still a rather difficult technological task. This work proposes a technology to improve manufacturing procedure of *p-i-n* structured Si(Li) detectors. We consider a method of additional "leveling" drift to already prepared Si (Li) detectors to reach a uniformly compensated sensitive region throughout the entire volume, and to smooth out local areas of uncompensated detector regions at a certain temperature and electric field. Experimentally obtained results show that conducting an additional "leveling" drift process ensures uniform distribution of lithium ions in silicon and is one of the main technological operations. The choice of the temperature-time regime of the "leveling" drift depends on the specific resistance of the initial material. Therefore, an additional "leveling" drift was carried out on detectors obtained by *p*-type monocrystalline silicon with high resistance (obtained by the float-zone method) and with low resistance (obtained by the Czochralski method), and their electrophysical responses were compared. Consequently, it was determined that for low-resistance materials, "leveling" drift is more effective.

Keywords: Li diffusion, Si (Li) *p-i-n* structures, Li drift, Additional drift, Si (Li) *p-i-n* detectors.

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1. INTRODUCTION

Silicon-lithium detectors are a key element of semiconductor systems for X-ray, alpha, beta and gamma spectroscopy and are the subject of much research and the main tool of spectrometric apparatus in various fields of science and modern technology. Such detectors have a structure with a *p-i-n* junction formed by diffusion and drift of lithium in a *p*-type semiconductor silicon wafer. The scope of Si (Li)-detectors covers the energy range from several hundred eV to 50 keV and more.

The operating conditions of the detection systems mainly depend on the temperature of the silicon detector itself. In practice, the full width at half maximum (FWHM) value of spectrum and the percentage ratio of effectively detected particles are often determined and reported for evaluating the efficiency of the detector. To obtain the most effective radiation detection, the detector should be located at a temperature closer to the temperature of liquid nitrogen. The FWHM value for the detectors with cooling system is up to 10 keV at an α-particle energy of 6 MeV [1].

However, in practice, the use of silicon detectors without cooling system is not excluded. In the work [3], it was compared with the main characteristics (such as sensitivity and energy resolution) of conventional (without cooling system) Si (Li) detectors with thermoelectrically cooled detectors. Here it says that despite of good energy resolution of thermoelectrically cooled detectors, the work is restricted out of the laboratory application, where cooling system is not appropriate. Also, here X-ray energy range from 4.5 keV ($Z = 22$) to 17.5 keV ($Z = 42$) is investigated. Comparing the results from various research works, they conclude that cooled detectors have low sensitivity to higher Z elements.

On the basis of silicon detectors, inexpensive, efficient conventional spectrometers (without cooling system) can be constructed for many purposes. In particular, for X-ray telescopes [1], ionizing particle detection systems [2], in medicine [4], and in outdoor operation, for example, to determine the contamination of soil with radionuclides [5].

Increasing efficiency of such detectors is a matter of time and technology. It is possible to increase the efficiency of conventional detection systems by increasing the thickness and sensitive region of the detectors [2, 3].

Particularly, important parameters of the detectors are the size of the sensitive surface and their radiometric characteristics. Providing a large sensitive surface of a semiconductor detector in combination with high energy resolution is still a rather difficult task [6, 7]. This is due to a group of problems encountered in the development of the detector. First of all, this is due to the special requirements for the technology for growing semiconductor materials for detectors. Secondly, the process of diffusion and drift of lithium ions into silicon requires special attention. Since achieving a uniform distribution of charge carriers is complicated by increasing surface of the sensitive region of the detector [8]. Its complexity is determined by the needs to create sufficiently extended, uniformly alloyed with lithium diffusion regions. Usually, empirically selected technology for *p*-Si volume compensation by lithium implies introducing a known greater value of lithium to silicon crystal than its necessary value for accurate

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compensation, through one of the surfaces of the silicon matrix to a depth of 10 % of the total thickness, followed by the drift of lithium ions in the electric field to the remaining depth. Moreover, to obtain the desired characteristics of the detector, such parameters as the temperature and time of diffusion annealing, as well as time, voltage value and the method of drift are essential. The papers [9, 10] are devoted to search for the optimal p-Si crystal manufacturing technology. Earlier, in the work [11] it was described, in detail, the new double-sided technology of diffusion of lithium atoms into silicon crystal. In the work [12], it was proposed manufacturing technology of large sized Si (Li) detectors by double-sided diffusion and drift of lithium ions into silicon crystal.

The aim of this work is to improve the electrophysical parameters and modify manufacturing process of conventional large sized Si (Li) *p-i-n* detectors by obtaining a uniformly compensated sensitive region throughout the entire volume, and to smooth out local areas of uncompensated detector regions by conducting an additional “leveling” drift (from both flat surface side of detector) at a certain temperature and in certain electric field.

2. MATERIALS AND METHODS

Fabrication of the detector structures consists of several stages, these are mechanical and chemical processing of crystals, the process of diffusion of lithium atoms into a silicon crystal, the drift of lithium ions in an electric field, and the final stage is deposition of metal contacts on detector surface [12]. The main aim of “leveling” drift is to carry out the additional drift to prefabricated detector structures to achieve a more uniform distribution of lithium ions in whole volume of monocrystalline silicon. In this work, we considered detector structures without metal contacts obtained by lithium diffusion mode at a temperature $T = 450 \pm 20$ °C, at a time $t = 3$ min, and to a depth $h_{\mathrm{Li}} = 300 \pm 10$ μm from both surfaces of the p-type Si crystal. The method of conducting double-sided drift of lithium ions, into a silicon single crystal, for these detectors was carried out by synchronously stepwise increasing the temperature from 55 °C to 100 °C and the reverse bias voltage from 70 V to 200 V. As initial materials we have chosen: a) p-type silicon crystal obtained by the float-zone method (with a diameter of 110 mm, a thickness of 8-10 mm, resistivity $\rho = 1000$-10000 Ohm·cm and with life time $\tau \geq 500$ μs), b) p-type silicon crystal (with a diameter of 110 mm, with a resistivity $\rho = 10$-12 Ohm·cm, lifetime $\tau \geq 50$ μs, grown in an argon atmosphere) obtained by the Czochralski method.

The optimal mode of “leveling” drift was selected at a temperature $T = 65$-70 °C with a reverse bias voltage $U_{\mathrm{rev}} = 150$-300 V for 15-40 hours. Temperature and electric field regimes were determined experimentally by comparing best electrophysical parameters of detector with applying temperature and electric field modes. In practice, ordinary drift completion moment is fixed by a sharp increase of reverse current. Sometimes, electrophysical characteristics of detectors, measured just after conventional drift process, show the existence of uncompensated regions. It can be seen from great value of inverse current and from fluctuations in *I-V* characteristics of detectors. Applying additional “leveling” drift helps to provide uniformly compensated sensitive region.

3. RESULTS AND DISCUSSION

The compensation accuracy of the initial semiconductor is the most important quality criterion for Si (Li) *p-i-n* structures intended for the manufacture of spectrometric detectors [13]. The deviation of the local lithium concentration during its drift, at any separate (local) points from the concentration of their acceptors, leads to fluctuations in the electric potential, and, as a consequence, to deterioration of the radiometric characteristics of the detector [14]. For this reason, temperature and field drift conditions are subject to particularly stringent requirements. At the same time, the increased thermal generation of carriers at the drift temperature and the presence of local inhomogeneities in the distribution of the acceptor impurity do not allow uniform compensation in the entire volume of the sensitive region of the detector [15].

According to the principle of self-compensation, at a drift temperature, the lithium concentration at a given point is determined by the concentration of the acceptor impurity $N_A(x)$ and thermally generated carriers $N_T(x)$:

$$N_{Li}(x) = N_A(x) + N_T(x)\,. \tag{1}$$

The coordinate dependence of $N_A(x)$ mainly has a growing character. Compensation features of local fluctuations of acceptor impurity concentrations were considered in [16, 17], where it was shown that the accuracy of the compensation substantially depends on the drift voltage. The dipole moments of the space charge systems formed in this case are nonzero at all bias voltages [18]. Thus, after the end of the drift process, the localized areas of the space charge remain in the compensated i-region due to the relative shift in the distribution of acceptor and donor impurities.

The coordinate dependence of the concentration of free electrons and holes at the drift temperature, as was shown in the work of Lauber [18], has the form:

$$n(x) = \frac{\dfrac{2n_i}{\sqrt{q_n}}\, tg\left(\dfrac{(L-x)\sqrt{q_n}}{2\lambda_n}\right)}{\left[1 + \dfrac{L_e}{\lambda_p\sqrt{q_n}}\, tg\left(\dfrac{(L-x)\sqrt{q_n}}{2\lambda_n}\right)\right]}; \tag{2}$$

$$p(x) = \frac{\dfrac{2n_i}{\sqrt{q_p}}\, tg\left(\dfrac{(L-x)\sqrt{q_p}}{2\lambda_p}\right)}{\left[1 + \dfrac{L_e}{\lambda_n\sqrt{q_p}}\, tg\left(\dfrac{(L-x)\sqrt{q_p}}{2\lambda_p}\right)\right]}, \tag{3}$$

where

$$\lambda_n = 2\mu_n\tau_n E,\ \lambda_p = 2\mu_p\tau_p E,\ s = {}^{np}\!/_{n^2}, \tag{4}$$

$$\int_0^L (1-s)\,dx.\ \int_0^L (1-s)dx\cdot \tag{5}$$

If we denote $M = \dfrac{L_e}{2\sqrt{\lambda_n \lambda_p}}$, then

$$q_n = 4\cdot\frac{\mu_n}{\mu_p}\left[1-M^2\right], \tag{6}$$

$$q_p = 4\cdot\frac{\mu_p}{\mu_n}\left[1-M^2\right], \tag{7}$$

L is the width of the compensated area. Other designations are generally accepted designations.

In practice, silicon for detector manufacturing has a large value of the lifetime. In this case, the inequality $L \ll \sqrt{(\lambda_n\lambda_p)}$ takes place, hence it follows:

$$L_e \approx L,\ {}_p\approx 4\frac{\mu_p}{\mu_n},\ q_n \approx 4\frac{\mu_n}{\mu_p}.$$

Then, instead of (2) and (3) we have the form:

$$n(x) = n_i\frac{L-x}{2\mu_n\tau_n E},$$

$$n(x) = n_i\frac{L-x}{2\mu_n\tau_n E},\ p(x) = n_i\frac{x}{2\mu_p\tau_p E}, \tag{8}$$

Therefore, the concentration gradient of lithium "*Q*", determined by the coordinate dependence of free carriers, can be calculated by the formulas:

$$N_{Li}(x) = N_A + n(x) - p(x) = N_A - \frac{n_i}{2\mu_n\tau_n E}(2x-L), \tag{9}$$

$$Q = \frac{d}{dx}\cdot N_{Li}(x) = -\frac{n_i}{\mu_n\tau_n E}. \tag{10}$$

Due to the distortion of the initial field, lithium ions will be tuned up until the distribution of lithium compensates the spatial charge of mobile carriers. After cooling the transition to room temperature, the space charge created by mobile carriers will become negligible, therefore, only the space charge due to the distribution of lithium ions will remain. The lithium distribution will therefore reflect the spatial charge distribution of mobile carriers at higher temperatures.

Thus, at the stages of "leveling" drift at low temperatures (≈ 60 ^{0}C), the voltage drop mainly occurs in local areas separated by a space charge of the opposite sign, due to fluctuations in acceptor concentrations in the initial semiconductor, as well as the gradient of thermally generated carriers. The effectiveness of the "leveling" drift in low-resistant *p*-Si is due to the fact that the "substitution" of the excess or missing lithium concentration for the acceptor concentration occurs according to the law [18]:

$$N_{Li}(t) = \frac{N_A}{1+\left(\dfrac{N_A}{N'}-1\right)\exp\left(-\dfrac{t-t_0}{\tau}\right)} \tag{11}$$

with characteristic time

$$\tau = \frac{\varepsilon\varepsilon_0}{2\mu_{Li}\cdot N_A}, \tag{12}$$

where N_A is the distribution of lithium before "leveling". Therefore, the lower the resistance, the faster the "leveling". For example, $\mu_{\text{Li}} = 0.5\cdot 10^{-10}$ cm^2/B for $T_{\text{dr}} = 60$ °C and a characteristic time $\tau \approx 7$ min. On the other hand, a large voltage at local *p*-*n* junctions (since the rest of the compensated region has relatively low-resistance) quickly eliminates the space charge by moving lithium ions a short distance.

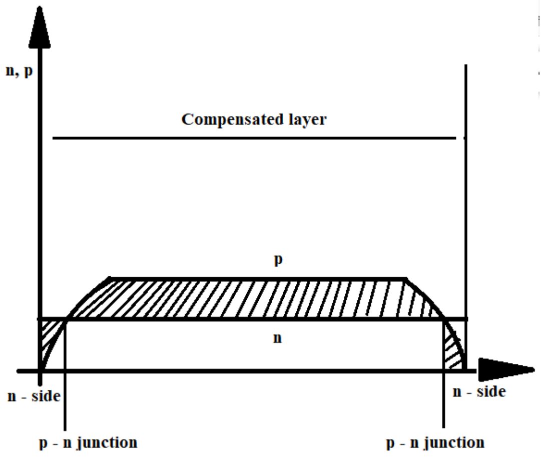

Fig. 1 – Ideal space charge distribution in Si (Li) *p*-*i*-*n* structure

Fig. 1 shows cross-section of ideally compensated Si (Li) *p*-*i*-*n* structures, which can be obtained by double-sided technology.

Furthermore, Volt-Farad and Volt-Noise characteristics of prepared Si (Li) *p*-*i*-*n* detector structures were measured.

The capacitance of Si (Li) *p*-*i*-*n* structured detectors is mainly connected with size (thickness) of the depletion layer and with a specific resistance of initial material. Correspondingly, by measuring Voltage-Farad characteristics, it is possible to determine the specific resistance of compensated region of silicon in the prepared structure and estimate the values of maximum energy of charged particle under the conditions of its total absorption in the depletion layer [6].

Fig. 2 and Fig. 3 show that the "leveling" drift leads to a significant improvement in the degree of compensation of the detector obtained by Czochralski method compared with detector obtained by float-zone method. This is explained by the fact that in the initial high-resistance Si crystal obtained by float-zone method there are more effective sizes of local inhomogeneities in comparison with the low-resistance Si crystal obtained by Czochralski method, which determine the appearance of large dipole formations at the drift stage.

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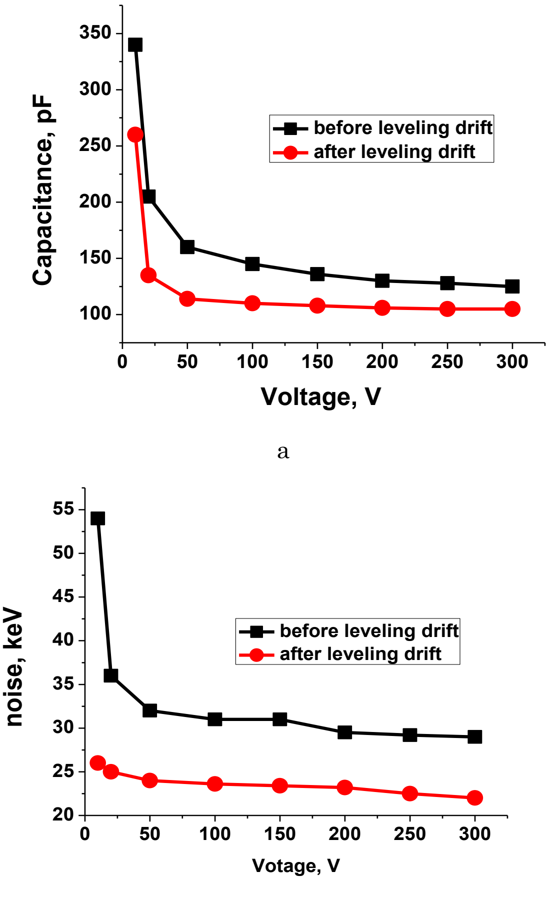
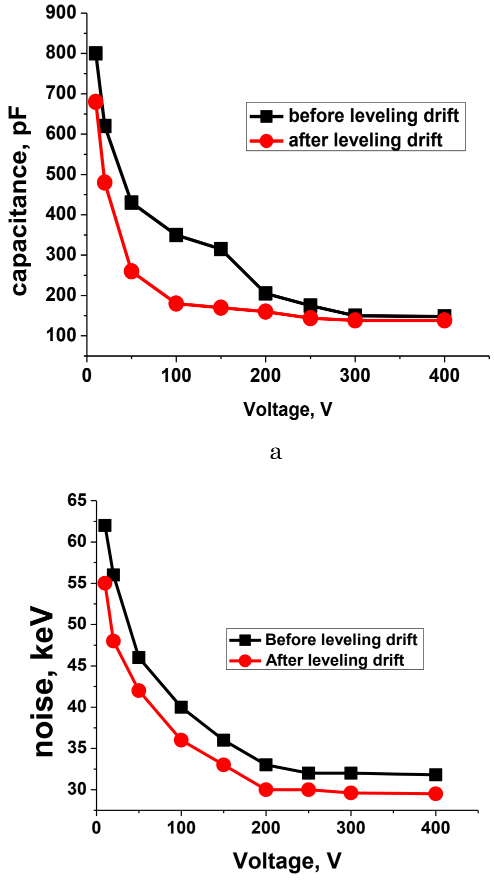


a

b

Fig. 2 – Change of the Voltage-Farad and Voltage-Noise characteristics of the detector obtained by Czochralski method with the diameter $D = 110$ cm^2 and thickness Wi = 4 mm. Before and after "leveling" drift under temperature $T = 65$-70 °C with a reverse bias voltage $U_{\text{rev}} = 150$-300 V for 15-40 hours



a

b

Fig. 3 – Change of the Voltage-Farad and Voltage-Noise characteristics of the detector obtained by float-zone method with the diameter $D = 110$ cm^2 and thickness Wi = 4 mm. Before and after "leveling" drift under temperature $T = 65$-70 °C with a reverse bias voltage $U_{\text{rev}} = 150$-300 V for 15-40 hours

are more effective sizes of local inhomogeneities in comparison with the low-resistance Si crystal obtained by Czochralski method, which determine the appearance of large dipole formations at the drift stage.

4. CONCLUSIONS

In conclusion, the creation of Si (Li) *p-i-n* structures with a diameter of more than 30 mm and a thickness of problem. Its complexity is determined, in particular, by the sensitive region ≥ 4 mm is a difficult technological the need to create sufficiently extended, uniformly alloyed with lithium, diffusion regions. In industrial silicon of large diameter, there is a significant concentration of micro defects distributed nonuniformly in the entire volume, which increase the fluctuation of the leakage current and the time of charge collection and impair the energy resolution of the detectors. Therefore, to obtain the desired characteristics of the detector, such parameters as the temperature and time of diffusion annealing, as well as temperature, time, voltage value and the method of drift are essential. As we realize from the results of work [19], after completing the drift process, lithium ions in the compensated region do not provide a sufficiently high resistivity, which is due to the presence of local inhomogeneities in the distribution of the initial acceptor impurity, as well as thermally generated carriers [20, 21]. Therefore, conduction of "leveling" drift, providing a sufficient degree of compensation, is a mandatory technological operation. Here, the choice of the temperature-time regime of the "leveling" drift depends on the specific resistance of the initial materials. It follows that, for low-resistance material, "leveling" drift is more effective. For our chosen samples, the optimal mode of "leveling" drift was selected at a temperature $T = 65$-70 °C with a reverse bias voltage $U_{\text{rev}} = 150$-300 V for 15-40 hours.

The results of this work can help to improve a technology of manufacturing large sized *p-i-n* structured Si (Li) detectors.

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Застосування додаткового процесу згладжування дрейфу для поліпшення електрофізичних параметрів *p-i-n* структур Si (Li) великих розмірів

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Розробка детекторів Si (Li) великих розмірів (з діаметром чутливої області більше 110 мм), з високою енергією та точністю позиціонування, лінійністю сигналів у широкому енергетичному діапазоні для альфа, бета та гамма-частинок все ще залишається досить складною проблемою. У роботі пропонується технологія вдосконалення процедури виготовлення структурованих *p-i-n* детекторів Si (Li). Ми розглядаємо метод додаткового «згладжування» дрейфу до вже підготовлених детекторів Si (Li), щоб досягти рівномірно скомпенсованої чутливої області по всьому об'єму та згладити локальні ділянки нескомпенсованих областей детекторів при певній температурі та електричному полі. Отримані експериментальні результати показують, що проведення додаткового процесу «згладжування» дрейфу забезпечує рівномірний розподіл іонів літію в кремнії і є однією з основних технологічних операцій. Вибір температурно-часового режиму «згладжування» дрейфу залежить від питомого опору вихідного матеріалу. Тому для детекторів, отриманих на основі монокристалічного кремнію *p*-типу з високим опором (отриманим методом поплавкової зони) та низьким опором (отриманим методом Чохральського), було проведено додаткове «згладжування» дрейфу та порівняно їх електрофізичні реакції. Отже, було визначено, що для матеріалів з низьким опором «згладжування» дрейфу є більш ефективним.

Ключові слова: Дифузія Li, *p-i-n* структури Si (Li), Дрейф Li, Додатковий дрейф, *p-i-n* детектори Si (Li).