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Physics

Development of Technological Conditions of Ion Implantation of Silicon by Boron for Ion Implanted Neutron Sensors

Anzor Guldamashvili*, Guram Bokuchava*, Giorgi Archuadze*, Yuri Nardaia*, Tsira Nebieridze*, Avtandil Sichinava*, Revaz Melkadze, Nodar Gapishvili***

*Ilia Vekua Sukhumi Institute of Physics and Technology,Tbilisi, Georgia
**Institute of Micro and Nano Electronics, Tbilisi, Georgia

(Presented by Academy Member Elguja Medzmariashvili)

ABSTRACT. The ion implanted silicon planar diode with p-n junction for neutron detection was studied and created. The p-layer of diode is the converter of neutrons simultaneously. High cross section ^{10}B nuclides for neutrons capture are used as converters. Neutron registration is conducted by the registration of products (^{4}He; ^{7}Li) of nuclear decay reaction ^{10}B(n,α)^{7}Li. The diode with the inversion layer of hole conductivity will be created by high fluence ^{10}B ion implantation of monocrystalline n-Si. The absence of independent converter in planar detector will simplify its manufacturing, exploitation and will decrease its cost. To determine the parameters of the converter the calculations of ^{4}He and ^{7}Li ions ranges and spatial distribution of their ionization losses in silicon are provided. To obtain a wider active layer of ^{10}B necessary to enhance the effectiveness of the sensor the TRIM-2013 code were used. Sequential step ion implantation mode for 20, 35, 65, 80 and 100 keV energy ^{10}B ions were chosen from this simulation. The ion current density, ion source, ion fluence and temperature regime of ion implantation were established. Laboratory samples of ionimplanted diodes were obtained and their IV characteristics were established. *2018 Bull. Georg. Natl. Acad. Sci.*

Key words: detector, neutron, ion implantation, silicon, p-n junction

Radiation security in modern conditions requires the creation and development of high-performance and low-budget detectors of various types of radiation as industrial, technological and scientific directions, as well as for wide consumption. For this purpose, leading international companies produce a wide range of radiation detectors [1], including semiconductor neutron counters, where the method of detection of neutrons by a semiconductor diode is used. Direct detection of neutrons does not occur. It occurs by recording charged particles, the products of nuclei decay caused by the interaction of neutrons with the converter the active part of the detector [2]. The nuclei with a high cross section for neutrons capture ^{3}He, ^{10}B, ^{6}Li, ^{157}Cd, ^{235}U, ^{239}Pu are used as an active material of converters. Independent converters of neutrons created by different technologies are used in existing detectors. An independent converter is usually between the detector and the source of the neutrons, or between the two sensors (the so-called "sandwich"). Both combinations of both methods are also used [3, 4]. In microstructured or perforated neutron detectors, the active material is placed in channels/holes of the semiconductor [5, 6]. To produce independent converters, sophisticated technological processes are used, which increases the cost of the product. It is also known a detector in which the inversion layer of electronic or hole conductivity simultaneously represents a neutron absorber. They are made of silicon by boron or lithium diffusion [7]. The efficiency of such detectors is low and limited by the limiting solubility of the doping element. Significant degradation of the parameters of silicon occurs at high temperature, which limits the use of this method. Ion implantation is free from the limitations of equilibrium thermodynamics. Therefore, among alternative methods of effective neutron flux control ion implantation is promising [8].

The purpose of this article is to create an ion-implanted semiconductor neutron detector. The proposed detector is a silicon planar diode with a p-n junction in which the inversion p-layer of the hole conductivity simultaneously represents a neutron converter (Fig.1).

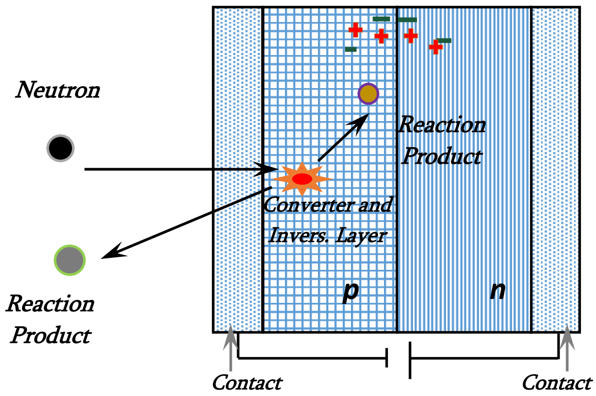


Fig. 1. The scheme of the proposed detector.

In the consumer market there is no ion implanted detector. In its analogs, other designs and technologies are used. The creation of a neutron converter is carried out by high-dose ion irradiation of n-type single-crystal silicon. Determination of neutrons is carried out by the registration the products of nuclear reaction decay ^{10}B (n, α):

10B+n → 4He (1471 keV) + 7Li (839.0 keV) + γ (471 keV) 93%

10B+n → 4He (1777 keV) + 7Li (1010 keV) 7%

The absence of an independent converter and a radiation insensitive part in the detector design will increase the neutron detection efficiency, the reliability and vibration resistance of the detector, will simplify its production, operation and reduce its cost. Neutron registration will be performed by a microprocessor with programmable logic that will provide miniaturization, energy efficiency and detector autonomy. Detectors and electronic schemes are designed using different software. The proposed work is a continuation of the long-term work of the authors in SIPT [9-12]. This corresponds to the current stage in the development of ion implantation and problems of national security.

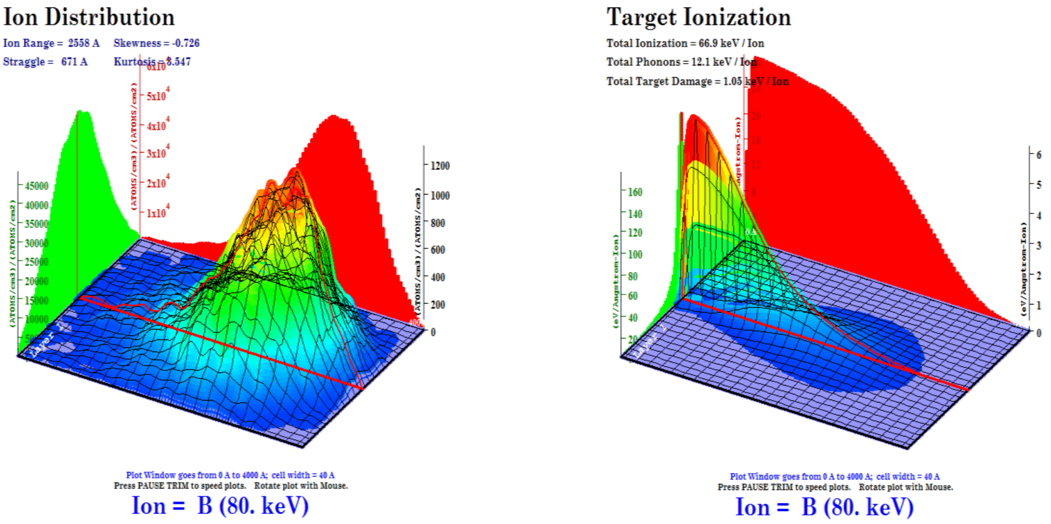
Materials and Methods

For the choice of the technology of ion implantation of semiconductor materials, interpretation of their electrophysical characteristics and parameters of the diodes and the detectors created on their basis, the characteristics of bombarding particles were calculated. The ranges of 20, 35, 65, 80 and 100 keV energy ions of ^{10}B in silicon, the spatial distribution of displaced atoms, the ranges of the products of the reaction $^{10}B(n,\alpha)^{7}Li$: ^{4}He(1.5 MeV), ^{4}He(1.78 MeV), ^{7}Li(839.0 keV), ^{7}Li(1.01 MeV) and the spatial distribution of ionization losses in Si are chosen as parameters. Calculations were carried out by TRIM-2013 code [13]. Ion-atom interaction is considered in the binary model of collisions with target atoms. The calculations of the parameters of ^{10}B ions interaction with silicon atoms conducted in the mode "Detailed Calculation with Full Damage Cascades"[13]. The interaction of the products of $^{10}B(n, \alpha)^{7}Li$ reaction with target atoms was carried out by the method of successive collisions in monolayers. The evolutions of radiation point defects generated during the elastic collisions of ions are not considered. The inversion p-layer of the acceptor conductivity (converter) is created by high fluence ion implantation ($1{\cdot}10^{17}cm^{-2}$) of ^{10}B ions in monocrystalline n- Si. The results of calculation are presented in the form of Tables and graphs:

Table 1. Radiation characteristics of the interaction of ^{10}B ions of different energy with Si atoms

E, keV	R_P, nm	ΔR_P, nm	Energy Loss, keV/Ion			Displacements/Ion		
			Ionization	Phonons	Displaced	Displaced	Vacancies	Replaced
30	111.9	40.6	21.7	7.7	0.67	365	336	28
80	260.2	69.4	66.9	12.1	1.05	572	528	45
100	308.2	74.3	85.6	13.2	1.15	627	578	49

Where: E – Ion Energy, keV; R_P – Projective Range, nm; ΔR_P – Straggling, nm.



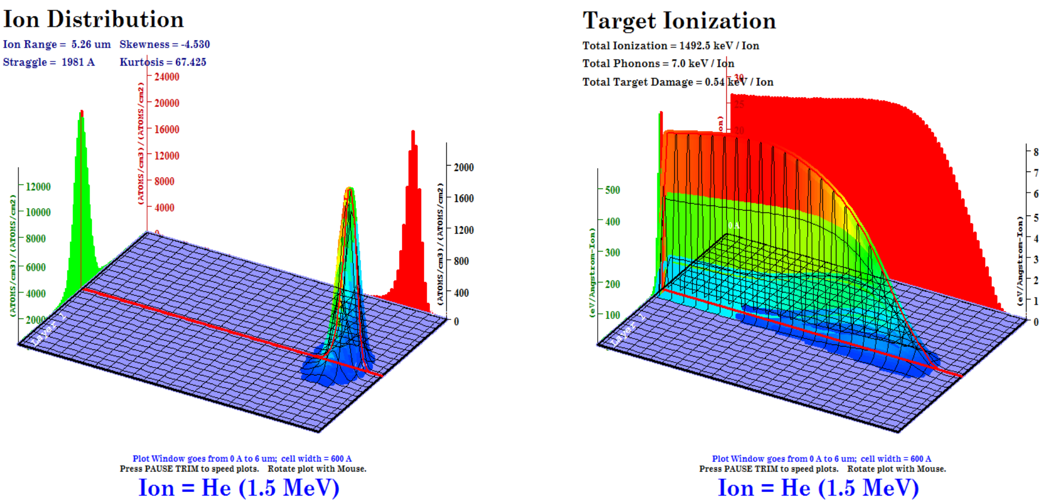
a) b)

Fig. 2. The range distribution of 80 keV energy ^{10}B ions in Si; b) 80 keV energy ^{10}B ions ionization losses in Si.

Table 2. Radiation characteristics of the interaction of products (^{4}He (1.5 MeV) and ^{4}He (1.77 MeV)) of the decay reaction $^{10}B(n,\alpha)^{7}Li$ with Si atoms.

E, MeV	R_P, μm	ΔR_P, μm	Energy Loss, keV/Ion			Displacements/Ion		
			Ionization	Phonons	Displaced	Displaced	Vacancies	Replaced
1.5	5.26	0.198	1492.5	7.0	0.54	293	271	22
1.77	6.33	0.198	1768.3	8.2	0.55	301	278	23

Where: E – Ion Energy, MeV; R_P – Projective Range, μm; ΔR_P – Straggling, μm.



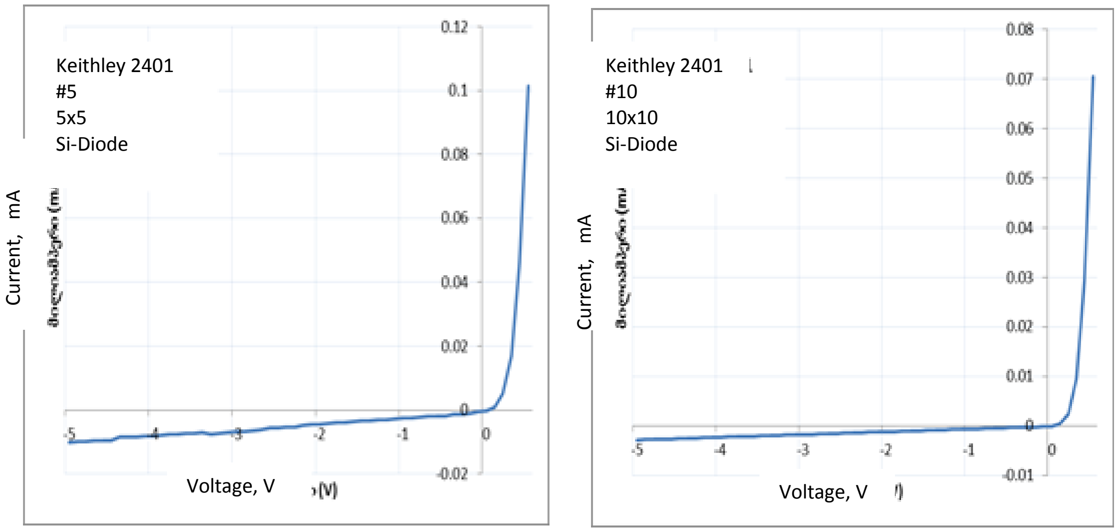
a) b)

Fig. 3. a) The range distribution of 1.5 MeV energy ^{4}He ions in Si; b) Ionization losses of 1.5 MeV energy ^{4}He ions in Si.

The evolution of point defects generated during the elastic collisions of bombarding ions with the target atoms in the calculations is not provided. The value of vacancies and displaced atoms calculated with this approach is the ability of bombarding ions to create point radiation defects. Taking into account the calculated parameters, a technological mode for obtaining modified materials by ion implantation was developed.

As initial material monocrystalline n- Si substrates with: <100> ± 0.50 orientation, 500 ± 15 µm thickness, 50.8 ± 0.2 mm diameter, 6·103 Ohm·cm resistivity, 1540 cm2·V-1·s-1 mobility and 800 µs minor charge carriers lifetime grown by Czochralski method were selected. To eliminate overheating of Si samples ion current density ~ 10 µA/cm2 was chosen. Ion implantation was performed on “VEZUVI-3M” plant in conditions: ions 10B (ion source gaseous 10BF3), energy 20, 35, 65, 80 and 100 keV, fluence Φ=1017cm-2, ion current density ~ 10 µA·cm-2, temperature interval T=300-330 K.

The laboratory samples of diodes 5×5 mm2 and 10×10 mm2 area are made. Fig 4. represents the results of IV measurements of obtained laboratory diodes conducted on Keithley 2401. Ion implantation of n- Si was conducted by 100 keV 10B ions with ion fluence Φ=1·1017cm-2 in temperature interval of T=300-330 K.



a) b)

Fig. 4. IV characteristics of 0.25 cm2 (a) and 1 cm2 (b) area diodes obtained by 100 keV 10B ion implantation (fluence Φ=1·1017cm-2) of <100> n-type Si.

The absence of an independent converter in planar detector simplifies its production, exploitation and will reduce its cost.

Conclusion

1. Calculations of the ranges of 10B ions with energies of 20, 35, 65, 80 and 100 keV and the ranges of 4He and 7Li ions and the spatial distribution of ionization losses in Si have been carried out.

2. The technological conditions to implement ion implantation: ion energy, fluence and temperature has been chosen.

3. The laboratory samples of 0.25 and 1 cm2 area diodes are obtained and their IV characteristics were measured.

4. The technology of high fluence ion implantation of high resistivity monocrystalline silicon with 10B ions has been developed.

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ფიზიკა

სილიციუმის ბორის იონებით იმპლანტაციის ტექნოლოგიური პროცესების დამუშავება იონ-იმპლანტაციური ნეიტრონების სენსორებისათვის

ა. გულდამაშვილი*, გ. ბოკუჩავა*, გ. არჩუაძე*, ი. ნარდაია*, ც. ნებიერიძე*, ა. სიჭინავა*, რ. მელქაძე, ნ. გაფიშვილი*

**სოხუმის ილია ვეკუას ფიზიკა-ტექნიკის ინსტიტუტი, თბილისი, საქართველო*
***მიკრო და ნანოელექტრონიკის ინსტიტუტი, თბილისი, საქართველო*

(წარმოდგენილია აკადემიის წევრის ე. მემმარიაშვილის მიერ)

ნეიტრონების დეტექტირებისათვის შექმნილი და შესწავლილია სილიციუმის იონ-იმპლანტაციური **p-n** გადასასვლელიანი პლანარული დიოდი. დიოდის **p**-ფენა ერთდროულად ნეიტრონების კონვერტერს წარმოადგენს. კონვერტერად ნეიტრონების მაღალი შთანთქმის კვეთის ^{10}**B** ნუკლიდებია გამოყენებული. ნეიტრონების რეგისტრაცია ბირთვული რეაქციის ^{10}**B(n,α)**^{7}**Li** დაშლის პროდუქტების (^{4}**He;** ^{7}**Li)** აღრიცხვით წარმოებს. მონოკრისტალურ **n- Si**-ში მაღალი ფლუენსის ^{10}**B** იონების დასხივებით შექმნილია დიოდის ხვრელური გამტარობის ინვერსიული ფენა. პლანარულ დეტექტორში დამოუკიდებელი კონვერტერის არარსებობა გაამარტივებს მის წარმოებას, ექსპლუატაციას და შეამცირებს ღირებულებას. კონვერტერის პარამეტრების დასადგენად გამოთვლილია ^{4}**He** და ^{7}**Li** განარბენებისა და იონიზაციური კარგვების სივრცული განაწილება Si-ში. სენსორის ეფექტურობის ასამაღლებლად აუცილებელი განიერი აქტიური ^{10}**B** შრის მისაღებად გამოყენებულია პროგრამა **TRIM-2013**. ჩატარებული მოდელირების შედეგად შერჩეულია 20, 35, 65, 80 და 100 კევ ენერგიის ^{10}**B** იონების თანმიმდევრული საფეხურებრივი იონური იმპლანტაციის რეჟიმი. დადგენილია იონური დენის სიმკვრივე, ფლუენსი, იონების წყარო და ტემპერატურული რეჟიმი. მიღებულია იონიმპლანტაციური დიოდების ლაბორატორიული ნიმუშები და დადგენილია მათი ვოლტ-ამპერული მახასიათებლები.

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