MODULE FOR THERMAL NEUTRONS REGISTRATION BASED ON UNCOOLED SILICON DETECTOR AND METAL GADOLINIUM CONVERTER

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Compact design of the single-channel thermal neutron detection module based on planar silicon detector (PSD) and the metal gadolinium converter developed. PSD of 300 microns thick with a working area of 2×2 and 5×5 mm arranged in a module housing in a special holder perpendicular to the base that allows access of the radiation from all detector sides. In order to improve the performance stability the module designed sealed, and the sealing process is carried out in a controlled atmosphere with a reduced content of water vapor. Test registration of electrons and low energy radiation was conducted that provides a measure of the conversion electrons and characteristic X-rays from the reaction of Gd(n, $\gamma + e^-$)Gd. Background measurements were conducted by two modules samples with the size of the working area of 2×2 and 5×5 mm. Detection modules have a low noise level (about 100 counts per day).

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INTRODUCTION

Neutron spectrometry weak intense fluxes of slow neutrons is of great importance for modern medicine, radiation dosimetry, experimental physics and many other applications. Thermal neutrons are dangerous to the human body, causing the need for accurate registration of the intensity of the neutron flux. Nowadays, the detectors on the base of scintillators, ball detectors, ^{10}B using counters, ^{3}He cameras, et al. and photo type detectors (image plate, scintillators + CCD) are used for neutron registration.

Systems based on metallic converters with a large thermal neutron capture cross-section, which are located close to the surface of the semiconductor detector are used in global scientific centers for neutron detection. These systems have shown high reliability, durability, accuracy and reliability of the results. There are a number of foreign publications on the use of various converters, including gadolinium (Gd), in conjunction with the planar silicon detectors (PSD) [1 - 5], but works on specified subject have not been identified in Ukraine.

Using PSD with high energy resolution, being developed at NSC KIPT, and converter of metal gadolinium, which has a record high thermal neutron capture cross-section, is the basis for this work.

Gd undergoes the following radiative capture (n,γ) reactions with neutrons: $n + {}^{155}Gd \rightarrow {}^{156}Gd^* \rightarrow {}^{156}Gd + \gamma$-rays + Gd characteristic X-rays + internal conversion electrons (39…199 keV); $n + {}^{157}Gd \rightarrow {}^{158}Gd^* \rightarrow {}^{158}Gd + \gamma$-rays + Gd characteristic X-rays + internal conversion electrons (29…182 keV).

Characteristic X-ray (CXR) and conversion electrons registration performed by PSD with gadolinium converter without the use of scintillation materials.

1. MODULE DEVELOPMENT AND MANUFACTUIRNG

As a module detection element the unpackaged uncooled PSD with the size of the active area of 2×2 and 5×5 mm, that was developed at NSC KIPT, used [6 - 10]. Their images are shown on Fig. 1. Depending on the type of detector the physical sizes of the crystals are 4.2×4.2 or 7.1×7.1 mm, thickness of silicone is 300 um.

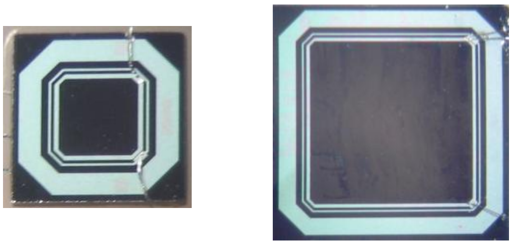
a *b*

Fig. 1. The planar silicon detectors with an active area of 2×2 mm (a) and 5×5 mm (b)

A special feature of the detectors, developed at NSC KIPT, is the presence of a protective ring surrounding the active region, thus allowing to obtain the excellent values of the energy resolution (0.9 keV for 2×2 mm detector and about 1.2 keV for 5×5 mm detector) at the absence of specific cooling. Fig. 2 shows a cross-sectional structure of PSD, a detailed description of which is given in [6].

Converter of gadolinium in the form of a polished metal plate with thickness of 300 um that is fixed on the surface of the silicon detector with an adhesive.

Laboratory module operating conditions for the registration of thermal neutrons in enclosed spaces allow increasing humidity of the surrounding atmosphere to 85%, what is unacceptable for unpackaged PSD. It is known that an increase of the humidity more than 50% leads to increasing of the detector leakage current and deteriorating of the energy resolution [7]. Therefore, a key requirement for the module design is the need to ensure the continued operation of the PSD with the low humidity of the surrounding atmosphere, i.e. the need for sealing the module.

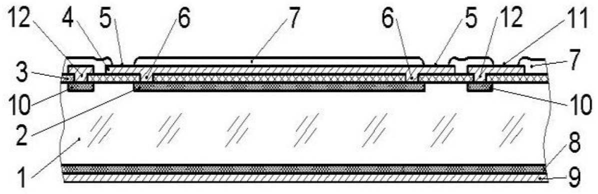

Fig. 2. PSD cross-sectional structure:
1 – silicon wafer; 2 – doped layer of detecting element p/n junction; 3 – oxide layer SiO_2; 4 – contact layer Al; 5 – pad on the oxide layer; 6 – the contact hole to the detecting element p/n junction, 7 – protective oxide layer; 8 – doped ohmic contact n+ layer; 9 – Al contact layer on the back side of the detector; 10 – protective ring of p/n junction; 11 – guard ring of contact pad; 12 – a contact hole to the guard ring p/n junction

Schematic drawing of a module with sliced housing is shown on Fig. 3.

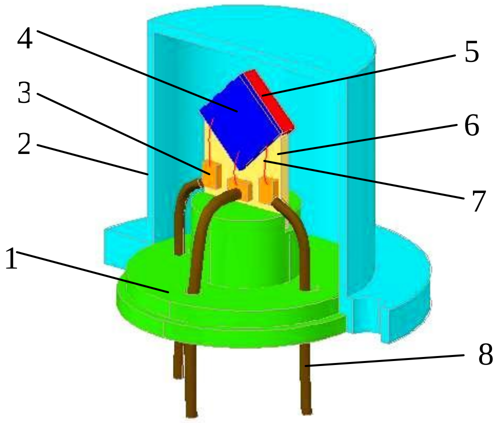

Fig. 3. Schematic drawing of the sealed module for thermal neutrons detection: 1 – a metal base; 2 – metal housing; 3 – an intermediate terminals; 4 – PSD; 5 – gadolinium converter; 6 – dielectric holder of a detector; 7 – aluminum wire jumper; 8 – external terminals

The module housing and a base with a dielectric detector holder made of aluminum alloy D16. This alloy ensures the required mechanical strength of the structure and its leaktightness, as well as minimizing the obstacles to the detected particles thanks to the big radiation length, which for aluminum is 8.9 cm.

As a dielectric holder the substrate of the glass-ceramic CT 50-1 0.6 mm thick used. Holder with a detector arranged perpendicular to the base that allows access of the radiation from all detector sides. The size of the holder depends on the detector type.

Attaching construction elements with each other (a base, housing, holder, detector converter, intermediate and outer terminals) performed by using different adhesives. A number of design and process requirements takes into account when adhesive materials select. The basic requirements are the purity, minimum ionic impurities, corrosion inactivity on the module components, the minimum of outgassing during the polymerization process and in operation.

Due to the high mechanical strength and the absence of direct contact with the silicon detector, which is most sensitive to the contaminations, the dielectric epoxy adhesive Araldite Standard of company Huntsman was used for attaching the intermediate terminals to the holder and the holder to the base [11].

The fragments of standard integrated circuit lead-frame are used as intermediate terminals, they are made of nickel with gold coating to improve the welding.

For gluing the other components that are in direct contact with the silicon detector (holder, converter, aluminum wires), for the housing sealing and for filling the holes in the base with external terminals the elastic two-component silicone adhesive Wacker Silicone G690 was used [12]. This adhesive has a high volume resistivity that does not affect on increasing the leakage current and, accordingly, does not lead to deterioration of the detector energy resolution. In addition, the adhesive Wacker Silicone G690 has a very low outgassing parameter (CVCM <0.1%), what is especially important for sealed devices with sensitive components.

The low adhesion of the silicone adhesive is increased by pre-coating the gluing surfaces by the primer Wacker Silicone G790 [12].

Electrical commutation between detector aluminum pads and the intermediate terminals made by a 25 um diameter jumper wire of alloy Al-1% Si series TABN of company Tanaka [13]. Attaching of the jumpers performed by US (ultrasonic) welding on the bonder Delvotec 5330 using a welding tool FP45A-1515-L-CM VR Set "C" of company Small Precision Tools [14, 15].

The modules used the gadolinium converter in the form of polished square plate of 0.3 mm thick with the dimensions of 2×2 and 5×5 mm. In order to minimize the distance between the detector and the converter, the latter firmly mounted on the surface of the detector and the top is covered by adhesive (Fig. 4). The adhesive between the detector and the converter is absent.

Fig. 4. The base unit with mounted detector of 5×5 mm (view on the front side of detector)

Sealing is accomplished by installing a module base with the mounted detector in the housing and filling a gap between the base and the housing by adhesive Wacker Silicone S690 in a special chamber filled with dry nitrogen, followed by thermal treatment of the module in order to cure the adhesive.

Thus, the research modules for detection of thermal neutrons, based on uncooled PSD having active areas of 2×2 and 5×5 mm and metal gadolinium converters, were manufactured.

Fig. 5 shows a photograph of the assembled module for detection of thermal neutrons in an aluminum housing which has a maximum diameter of 20 mm and a height of 20 mm.

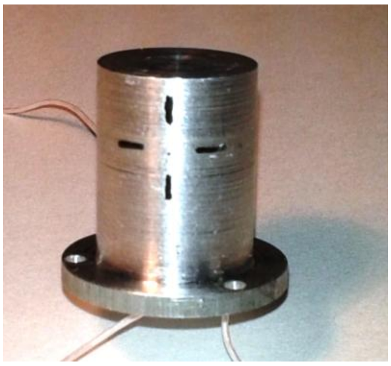

Fig. 5. A sealed module for detection of thermal neutrons on the basis of uncooled PSD (5×5 mm) and a metal gadolinium converter in an aluminum housing

2. RESEARCH OF MODULE CHARACTERISTICS

During manufacturing of the research samples modules for detection of thermal neutrons, PSD static characteristics were conducted, i.e. current-voltage characteristics (IV characteristics) of the detector active region and the protective ring were measured. The measurements were performed on a dedicated manual probe workstation (Fig. 6), which includes a light-blocking box, microscope with illumination, translation stage, microposition probes [16]. For measuring IV-characteristics picoampermeter Keithley Model 6487 with built-in power supply up to 500 V was used [17].

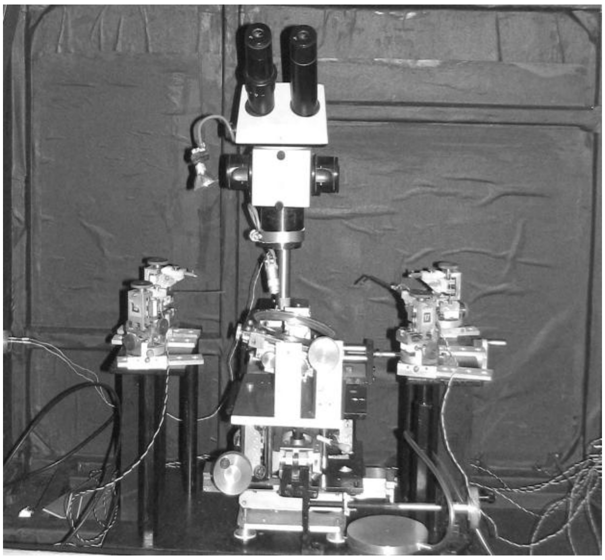

Fig. 6. Manual probe workstation for IV-characteristics measuring

Fig. 7 shows the IV-characteristics of active region and protective ring of the detector with the active area size of 2×2 mm. At 40 V depletion voltage the current of the active region is less than 0.18 nA and the protection ring current is 0.25 nA, what characterizes high quality of the detector.

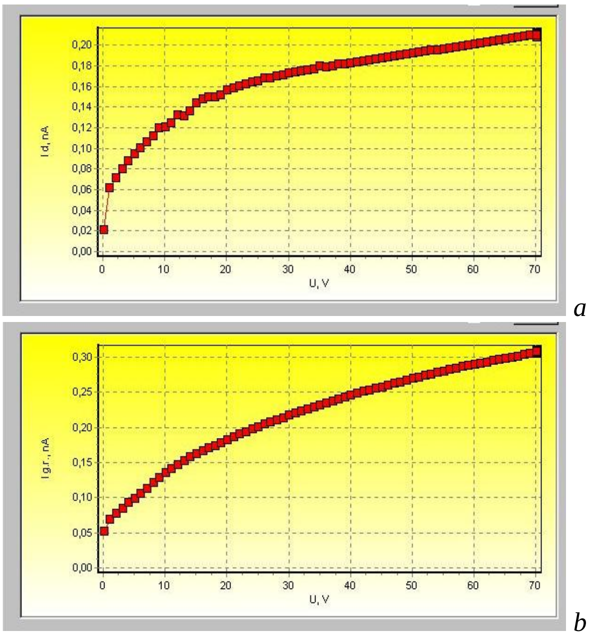

Fig. 7. The current-voltage characteristics of the detector with an active area of 2×2 mm; a – active region; b – protective ring

In order to register the nuclear reaction yield Gd(n, γ + e$^-$)Gd it is supposed to use gadolinium characteristic X-ray lines with the energy of 42.99 and 49.69 keV and internal conversion electrons in the energy range 29…200 keV.

In order to test the dynamic characteristics of the detectors with metal gadolinium converters measurement of gamma and electron radiation have been held for two detector sizes 2×2 and 5×5 mm. Measurements were made before mounting the gadolinium converter (i.e. in a variant of the standard PSD) and after mounting the converter.

Fig. 8 shows the experimental radiation spectra of ^{241}Am and ^{57}Co sources before mounting the converter.

Spectrometric electronics developed at NSC KIPT for an uncooled PSD with thickness of 300 microns provides radiation detection in the energy range Eγ = 5...150 keV with an energy resolution FWHM = 0.9…1.2 keV.

Fig. 9 shows the experimental spectra of electrons measured by PSD for ^{90}Sr-^{90}Y sources (groups of electrons with boundary energies of 546 and 2280 keV) and ^{137}Cs (groups of electrons with boundary energies 514 and 1176 keV) before mounting the converter. Dedicated energy spectra have a characteristic appearance of Landau distribution [8]. There are also lines of barium characteristic X-ray on Fig. 9,b.

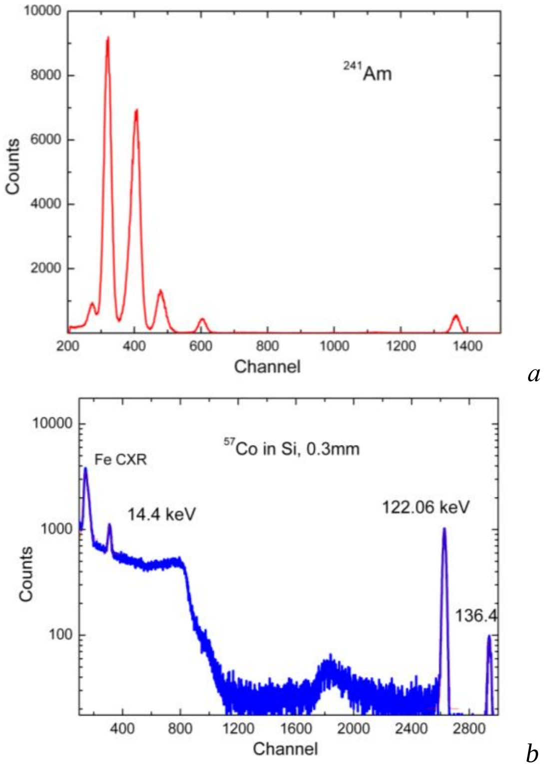

Fig. 8. Experimental radiation spectra of ^{241}Am (a) and ^{57}Co (b) sources for a detector size of 2×2 mm

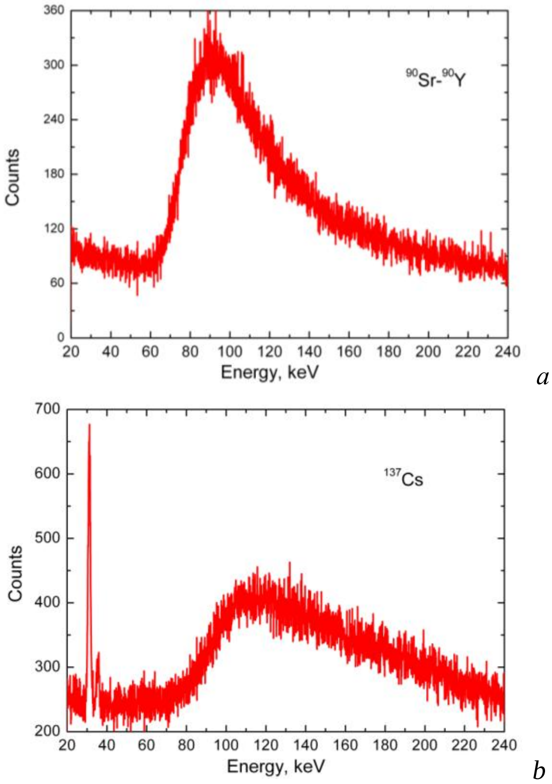

Fig. 9. Experimental electron spectra measured by PSD for radiation sources ^{90}Sr-^{90}Y (a) and ^{137}Cs – (b) for the detector size of 5×5 mm

Fig. 10 shows the experimental spectrum of the radiation source ^{241}Am for 5×5 mm detector after gadolinium converter mounting. The lines of energy 26.35 and 59.54 keV for ^{241}Am are clearly visible in the spectrum, as well as CXR gadolinium lines with energies 42.99 and 49.69 keV. The energy resolution and radiation detection efficiency has not changed.

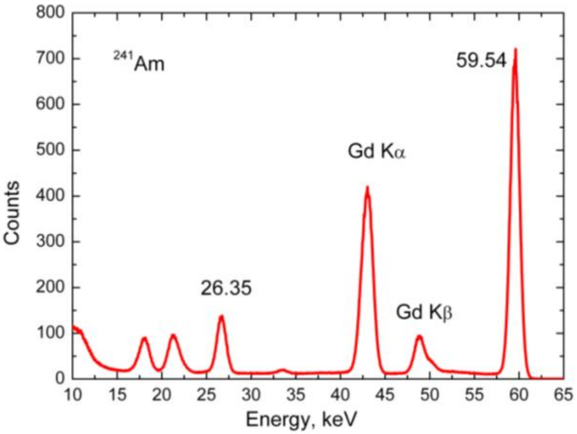

Fig. 10. The spectrum of gamma radiation from ^{241}Am source for 5×5 mm detector after gadolinium converter mounting

Thus, the possibility of use the PSD for registration electrons and gamma rays was experimentally proved. Energy range, which is available to measure, completely covers the energy diapason, typical for conversion electrons and X-rays of nuclear reaction Gd(n, $\gamma + e^-$)Gd.

The background flux value has a big importance in experimental studies at low neutron fluxes. This background flux may be detected by both types of detection modules in the energy range of 20…200 keV, in which there are peaks of the conversion electrons and the CXR quanta.

Background flux measurements for two sizes 2×2 and 5×5 mm PSD were performed. Fig. 11 shows the spectrum of 5×5 mm detector with gadolinium converter measured at the absence of the radiation source.

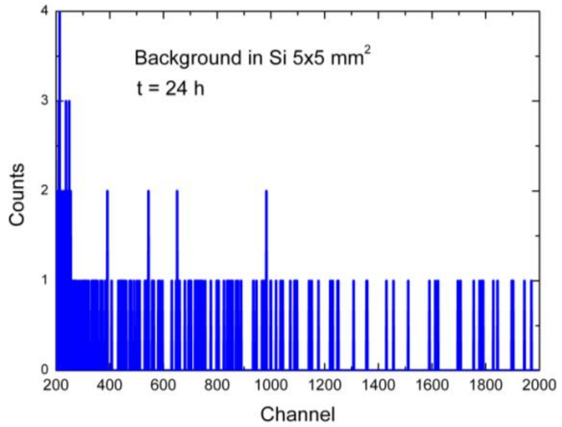

Fig. 11. The background spectrum for 5×5 mm detector with gadolinium converter measured at the absence of the radiation source

The sum of counts in the channels from 200 to 2000, which corresponds to the energy range ~ 20…200 keV for the 24-hour time period did not exceed 85 counts for 2×2 mm size detector and 200 counts for 5×5 mm detector.

It was stated experimentally that the investigated detecting systems have low noise and can be used in the registration of low thermal neutron fluxes [18].

CONCLUSIONS

The studies proved that the use of the PSD with the metal gadolinium converter that has a record high thermal neutron capture cross section is a promising direction of researches.

Development, manufacture and research of the hermetic modules for thermal neutrons detection on the base of PSD with a thickness of 300 microns with the size of the working area of 2×2 and 5×5 mm and metal gadolinium converters have been done.

The static characteristics of the modules were measured, emission spectra of the sources ^{241}Am, ^{57}Co, ^{90}Sr-^{90}Y and ^{137}Cs, as well as the background measurement were investigated. Energy range which is available for measurements by the PSD with a thickness of 300 microns and the size of the working area of 2×2 and 5×5 mm with Gd converters completely covers the area of the energy of conversion electrons and X-rays of nuclear reaction $Gd(n, \gamma + e^-)Gd$.

The possibility of using these modules for thermal neutrons detection as the components of the promising devices for the medical and nuclear physics detection systems was shown.

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МОДУЛЬ ДЛЯ РЕГИСТРАЦИИ ТЕПЛОВЫХ НЕЙТРОНОВ НА ОСНОВЕ НЕОХЛАЖДАЕМОГО КРЕМНИЕВОГО ДЕТЕКТОРА И МЕТАЛЛИЧЕСКОГО ГАДОЛИНИЕВОГО КОНВЕРТЕРА

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Выполнено проектирование малогабаритного одноканального детектирующего модуля тепловых нейтронов на основе планарного кремниевого детектора (ПКД) и конвертера из металлического гадолиния. ПКД толщиной 300 мкм и рабочей площадью 2×2 и 5×5 мм располагается в корпусе модуля на специальном держателе перпендикулярно основанию, что обеспечивает доступ излучения со всех сторон детектора. Для повышения стабильности показателей модуля его конструкция спроектирована герметичной, а процесс герметизации проводится в условиях контролируемой атмосферы со сниженным содержанием водяных паров. Протестирована регистрация электронов и излучения низкой энергии, что обеспечивает измерение конверсионных электронов и характеристического рентгеновского излучения из реакции Gd $(n, \gamma + e^-)$Gd. Проведены фоновые измерения для двух размеров исследовательских образцов модулей с размером рабочей площади детекторов 2×2 и 5×5 мм. Установлено, что детектирующие модули имеют низкий уровень шумов (~ 100 счётов в сутки).

МОДУЛЬ ДЛЯ РЕЄСТРАЦІЇ ТЕПЛОВИХ НЕЙТРОНІВ НА ОСНОВІ НЕОХОЛОДЖУВАНОГО КРЕМНІЄВОГО ДЕТЕКТОРА І МЕТАЛЕВОГО ГАДОЛИНИЕВОЙ КОНВЕРТОРА

Г.П. Васильєв, О.С. Деєв, О.А. Каплій, С.К. Кіпріч, М.І. Маслов, В.Д. Овчинник, С.М. Потін, М.Ю. Шуліка, В.І. Яловенко

Виконано проектування малогабаритного одноканального детектуючого модуля теплових нейтронів на основі планарного кремнієвого детектора (ПКД) і конвертора з металевого гадолінію. ПКД товщиною 300 мкм і робочою площею 2×2 і 5×5 мм розташовуються в корпусі модуля на спеціальному утримувачі перпендикулярно основи, що забезпечує доступ випромінювання з усіх боків детектора. Для підвищення стабільності показників модуля його конструкція спроектована герметичною, а процес герметизації проводиться в умовах контрольованої атмосфери зі зниженим вмістом водяної пари. Протестована реєстрація електронів і випромінювання низької енергії, що забезпечує вимірювання конверсійних електронів і характеристичного рентгенівського випромінювання з реакції Gd (n, γ + e-) Gd напівпровідниковими ПКД. Проведено фонові вимірювання для двох розмірів дослідних зразків модулів з розміром робочої площі детекторів 2×2 і 5×5 мм. Встановлено, що детектуючі модулі мають низький рівень шумів (~ 100 рахунків на добу).