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RESPONSE OF THE TIMEPIX DETECTOR WITH GaAs:Cr AND Si SENSORS TO HEAVY IONS

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The response of the Timepix detector to ^{22}Ne ions with kinetic energies of 77 and 158.4 MeV has been studied at the cyclotron U400M of the JINR Flerov Laboratory of Nuclear Reactions. Semiconductor sensors produced from gallium arsenide compensated by chromium (GaAs:Cr) and from silicon (Si) are used for these measurements. While in the Timepix detector with Si sensor the so-called "volcano effect" was observed, in the Timepix detector with GaAs:Cr sensor such an effect was completely absent. In the work, the behavior of the Timepix detector with GaAs:Cr sensor under irradiation with heavy ions is described in comparison with the detector based on Si sensor. Also, the possible reason for absence of the "volcano effect" in GaAs:Cr detector is proposed.

На циклотроне У400М Лаборатории ядерных реакций ОИЯИ изучался отклик пиксельного детектора Timepix на ионы ^{22}Ne с энергией 77 и 158,4 МэВ. В этих измерениях использовались детекторы с полупроводниковыми сенсорами из арсенида галлия, компенсированного хромом (GaAs:Cr), и из кремния (Si). В детекторе с сенсором Si наблюдался так называемый «вулкан-эффект», тогда как в детекторе с сенсором GaAs:Cr данный эффект полностью отсутствовал. В статье представлены результаты отклика детектора Timepix с сенсором GaAs:Cr при облучении тяжелыми ионами в сравнении с аналогичным детектором на основе сенсора Si. Также объясняется причина отсутствия «вулкан-эффекта» в детекторе GaAs:Cr.

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INTRODUCTION

The manifest interest in the introduction of the advanced chromium-compensated gallium arsenide (GaAs:Cr) semiconductor, developed at the Tomsk State University [1], for radiation detection continuously grows. This is a consequence of its numerous advantages [1–3] converting GaAs:Cr into a very promising material for the development of sensors for applications ranging from medical imaging to high-energy physics.

The JINR Dzhelepov Laboratory of Nuclear Problems in cooperation with other institutions such as Medipix international collaboration (CERN), Institute of Experimental and Applied Physics of the Czech Technical University (Prague), and the Tomsk State University investigates the convenience of using the GaAs:Cr as integrated sensor in hybrid pixel detectors based on the Timepix readout chip [4].

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Obtained to date results on the detection of photons using the Timepix detector with GaAs:Cr sensor are very promising, and, besides being published [5], a prominent practical result was reached when the implementation of this hybrid pixel detector in a fully operational CT scanner was achieved [6].

The investigations continue today, and the response of the device to other types of radiation such as heavy-ion beams is evaluated. In this research process a useful complementary method is the comparison between the results obtained by the Timepix detector based on GaAs:Cr sensor and those obtained by a similar detector but made using a silicon sensor. This procedure allows testing the behavior of the former comparing it with the considered as classic silicon sensor. Also, let studying the characteristics and behavior of the Timepix with Si sensor, that is still in development and improvement.

The main goal of this work is the investigation of the response of Timepix detectors with GaAs:Cr to heavy ions. While the Timepix detector with Si sensor was irradiated by heavy ions by several research groups [7, 8], there was no any information about similar results with the GaAs:Cr Timepix detector so far; therefore, this objective seems an interesting problem.

1. MATERIALS AND METHODS

The Timepix detector is a hybrid detector which consists of a pixelated semiconductor sensor bump-bonded to a readout electronics with matrix of 256×256 independent channels (pixels) with pitch of 55 μm. Each channel with respective preamplifier, discriminator and digital counter can independently work in one of three modes: Medipix mode (the counter counts the number of detected particles), Timepix mode (the counter measures the time between the moment the particle is detected and the end of the frame), and Time-over-Threshold (TOT) mode (the counter is used as a Wilkinson-type ADC allowing direct energy measurement in each pixel).

In this work, we used two Timepix detectors based on Si and GaAs:Cr sensors and operated in TOT mode. Table 1 shows the main characteristics of these detectors. Whereas the Timepix contains 65536 independent channels and their response can never be identical, it is necessary to perform an energy calibration for each pixel. Such a calibration was done with characteristic X-ray radiation [9].

The irradiation process took place in one of the output channels of cyclotron U400M of the JINR Flerov Laboratory of Nuclear Reactions where ^{22}Ne ions were accelerated to energies of 77 and 158.4 MeV. The detectors were irradiated simultaneously placing side by side in the vacuum chamber as shown in Figs. 1 and 2. The distance between the centers of both sensitive detector areas was 3 cm. The temperature conditions in the chamber were about 27°C. The ion beam cross section was larger than the area occupied by both sensors,

Table 1. **The main detector characteristics and the used biased voltage intervals**

Sensor material	Sensor thickness, μm	Readout chip	USB interface	U_{bias}, V
Si	300	Timepix DO5	FitPix	From +5 to +100
GaAs:Cr	300	Timepix SO2	FitPix	From −5 to −200

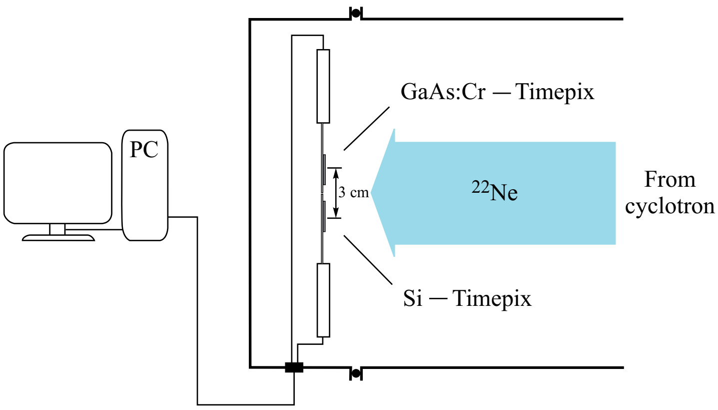

Fig. 1. General schema of the experiment showing the location of the two detectors relative to the incident ion beam inside the irradiation chamber

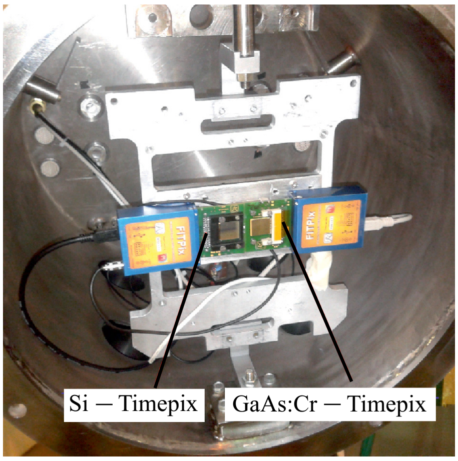

Fig. 2. Photo of the vacuum chamber where the two Timepix detectors are visible with readout electronics FitPix

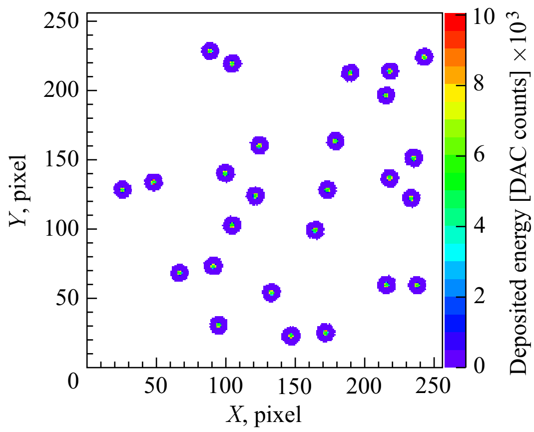

Fig. 3. Typical frame recorded by the Timepix detector with clusters created by heavy ions

and sufficiently homogeneous to consider that the detectors were under the same irradiation conditions.

The energy deposited by a charged particle in the semiconductor sensor results in an induced charge in adjacent pixels, the signals of which form a cluster (Fig. 3). The full deposited energy by the particle is defined as the sum of the energies of all pixels in the cluster. Due to a spatial resolution and single-event counting possibility of the Timepix, each individual ion can be observed together with clusters from other particles presented in the irradiation chamber. A correlation between specific types of ionizing radiation and the obtained cluster shapes, as well as the possibility to differentiate different types of irradiation by the pattern they introduce in Medipix2 detectors, was described in [10, 11]. With this capability in our analysis for obtaining the best results, we selected only clusters produced by single ion and excluded the clusters formed by pile-up of several clusters from ions or clusters from other particles presented in the beam.

Recording of the data from both detectors was done with USB interface FitPix [12] and the Pixelman software package [13]. All data processing was carried out in the ROOT data analysis framework [14].

2. RESULTS AND DISCUSSION

2.1. The Response of the Timepix Detector with Si Sensor. Using the code system SRIM-2013 [15], the range of ^{22}Ne ions in silicon for the two energies was calculated, resulting in 41.8 μm for 77 MeV, and in 112 μm for 158.4 MeV. This confirms that the silicon sensor with a thickness of 300 μm is able to stop 100% of the ions to come to it; i. e., all the incident ions will interact and deposit all their energy into the sensor. More than 99.7% of the deposited energy is lost in processes associated with the ionization, as can be seen in Table 2.

Figures 4 and 5 show the energy spectra and the average cluster profiles, respectively, for different bias voltage values obtained for different values of bias voltage and two incident ion energies. The average cluster profile corresponds to profile of generalized cluster (10000 typical clusters are superposed on each other in their geometrical center and are normalized).

Analyzing the response of the detector to 77-MeV ions, it can be seen that for the bias voltage +5 V the mean energy in cluster is about 62 MeV. This value is lower than the expected one of 77 MeV, which, according to the simulation, should have been deposited in the sensor. At this bias voltage it is related to the incomplete charge collection and incomplete depletion volume of silicon sensor [16] due to the insufficient electric field applied to the sensor work volume. However, in this case, the average cluster profile has a typical Gaussian-like shape.

Table 2. **The ion ranges and energy losses of ^{22}Ne ions interacting with the sensor materials for the two studied energies**

Parameter	Si (Ne, 77 MeV)	Si (Ne, 158.4 MeV)	GaAs:Cr (Ne, 77 MeV)	GaAs:Cr (Ne, 158.4 MeV)
Longitudinal ion range, μm	41.8	112	26.3	67.1
Radial ion range, μm	0.93	1.58	1.06	1.66
Total ionization energy loss, keV/ion	76829.2 (99.77%)	157806.0 (99.877%)	76759.7 (99.688%)	157728.3 (99.828%)
Total phonon energy loss, keV/ion	160.1 (0.20%)	182.0 (0.115%)	229.3 (0.298%)	259.4 (0.164%)
Total target damage energy loss, keV/ion	10.72 (0.01%)	12.04 (0.008%)	10.99 (0.014%)	12.28 (0.008%)

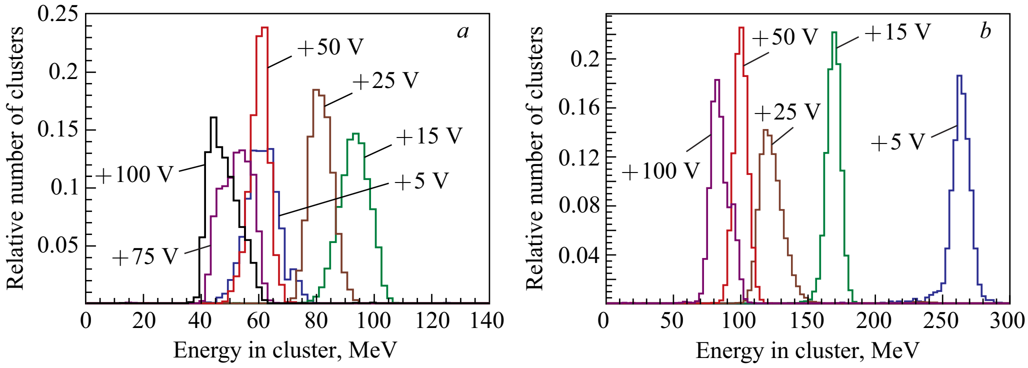

Fig. 4. Energy spectra registered by the Timepix detector with Si sensor for different bias voltages and ion energies of 77 MeV (*a*) and 158.4 MeV (*b*)

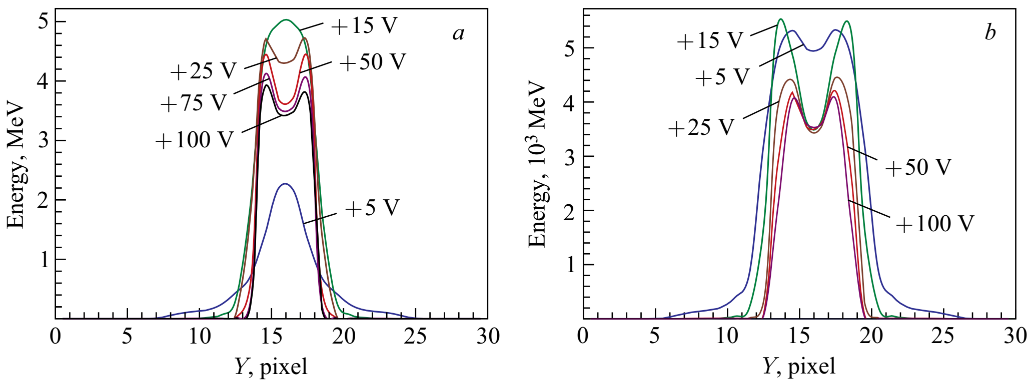

Fig. 5. Average cluster profiles registered by the Timepix detector with Si sensor for different bias voltages and ion energies of 77 MeV (*a*) and 158.4 MeV (*b*)

When the bias voltage is increasing to +15 and +20 V, the responses are characterized by the high values of mean energy in cluster, exceeding 77 MeV, probably as a consequence of the nonlinearity in the used energy calibration at high energies [7, 17]. But it is interesting that even though both profiles increased their height, in +15 V a deformation starts to appear in the shape of the peak top. For +20 V this deformation has become in an evident unusual depression, called the "volcano effect" because of its profile [7, 8].

For higher bias voltages the mean energy in cluster is always less than 77 MeV, but the "volcano effect" is enhanced significantly.

Analyzing the detector response to 158.4-MeV ^{22}Ne ions (see plots *b* in Figs. 4 and 5), it is observed that the previous behaviors are repeated, but now the "volcano effect" appears from the lowest biasing values.

Figure 6 shows the dependence of the mean energy in the cluster geometrical center with the bias voltages in the Timepix detector with Si sensor for the two ion energies. This supplementary information was obtained from the average cluster profiles shown in Fig. 5

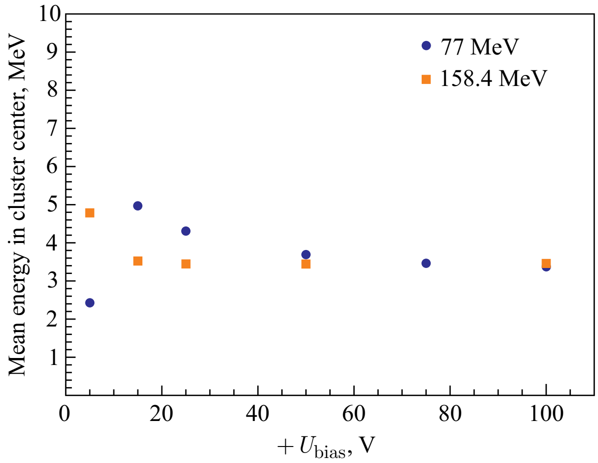

Fig. 6. Dependence of the mean energy in the geometrical center of cluster with the bias voltage for 77 and 158.4 MeV ion energies (for the Timepix detector with Si sensor)

and allows us to clearly see how with increasing bias voltage there takes place a process of signal saturation to the same level for both ion energies. This behavior is consistent with the saturation of the preamplifier in each channel of the Timepix electronics.

2.2. The Response of the Timepix Detector with GaAs:Cr Sensor. Whereas the response of the Timepix detector with Si sensor to heavy ions was already investigated by several groups from all over the world (see, e.g., [7, 8]), there were no articles about the irradiation of the Timepix with GaAs:Cr sensor with heavy ions so far.

As shown in Table 2, the 77- and 158.4-MeV ^{22}Ne ions also deposit all their energy into the volume of the 300-μm GaAs:Cr sensor, and losses by ionization are still the dominant processes.

The energy spectra obtained using the Timepix detector with GaAs:Cr sensor for different bias voltages are shown in Fig. 7, while Fig. 8 shows the average cluster profiles also for certain values of biasing values. As one can see from Fig. 7, the mean energy in cluster is

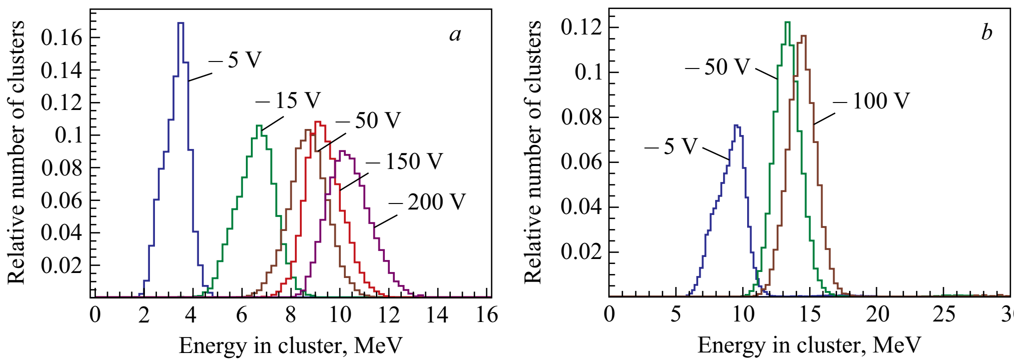

Fig. 7. Energy spectra registered by the Timepix detector with GaAs:Cr sensor for different bias voltages and ion energies of 77 MeV (*a*) and 158.4 MeV (*b*)

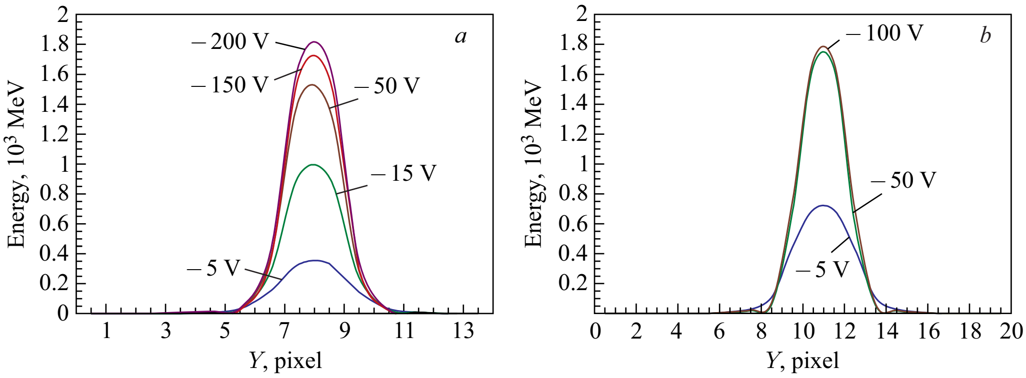

Fig. 8. Average cluster profile registered by the Timepix detector with GaAs:Cr sensor for different bias voltages and ion energies of 77 MeV (*a*) and 158.4 MeV (*b*)

much lower than the expected ones of 77 and 158.4 MeV, that indicates that the used energy calibration is incorrect for heavy-ion detection.

The first remarkable fact observed in these figures is that a significant reduction in the charge collection efficiency takes place for both ion energies, compared with the experiment where the silicon sensor was used. However, the observed before "volcano effect" now has completely disappeared.

Figure 9 shows how the doubling of the ions energy led to increase of the mean energy in the geometrical cluster center twofold only for low bias voltage at which there is incomplete charge collection and consequently input charge for preamplifier is small. At higher bias voltages, as observed before for the Si sensor, the maximum signal in cluster significantly reduces their growth to become practically imperceptible, indicating that the input charge is high enough to produce the preamplifier saturation.

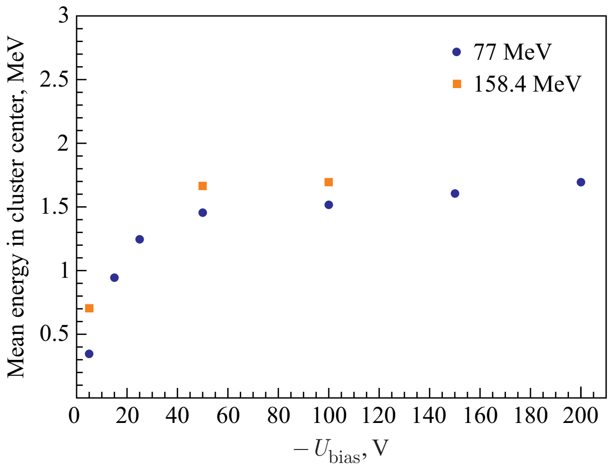

Fig. 9. Dependence of the mean energy in the cluster geometrical center with the bias voltage for 77 and 158.4 MeV ion energies

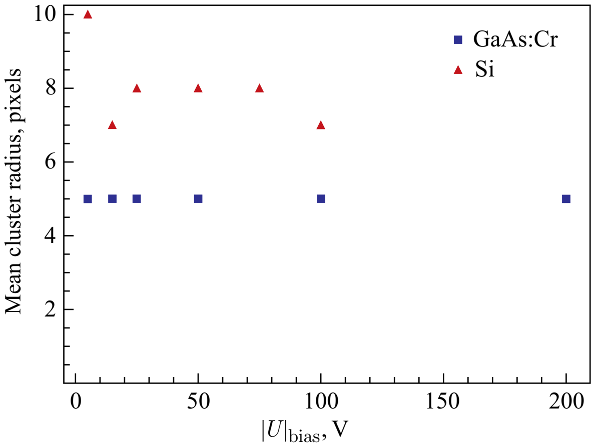

Fig. 10. Dependence of the mean cluster radius with the bias voltage for the two sensors

The manifestation of the "volcano effect" is compatible with the fact that the Timepix readout chip is equipped with an internal protection circuit for very high input charges that is active only for hole collection mode (for electron collection mode the internal protection circuit is not provided). The ^{22}Ne ions with kinetic energies of 77 and 158.4 MeV generate very high numbers of electron-hole pairs in the sensor (Table 2), and for the Timepix with np-type Si sensor it triggers the chip overload protection system to limit the portion of the signal which exceeds the predetermined threshold that is expressed in the reduction of signal from pixels with high input charges (usually in the center of cluster). Thus, as was shown, the "volcano effect" is present in the Timepix with Si sensor, but absolutely absent in the Timepix with GaAs:Cr sensor.

Finally, Fig. 10 shows the dependence of the mean cluster radius with the bias voltage for both studied Timepix detectors irradiated with 77-MeV ^{22}Ne ions.

According to the results obtained from the simulation with SRIM-2013, the approximate dimensions of the primary electron-hole cloud generated by 77-MeV ions in Si are 41.8 μm long and 0.93 μm wide, whereas the same ions in GaAs:Cr create an electron-hole cloud of 26.3 μm long and 1.06 μm wide. As noted, the two charge carrier clouds have approximately the same radius both in silicon and in gallium. From Fig. 10 one can observe that the Timepix clusters have in average a radius of 450 μm for Si and of 250 μm for GaAs:Cr (pixel size is 55 μm). This means that the cluster radius ratio between Si and GaAs:Cr is in the range of 1.5–2 pixels. The observed difference of this relationship and the one existing between the radius of the electron-hole clouds at the initial collection moment is the result of the multiple differences in the intrinsic properties of the two sensor materials, decisive in the charge transport and collection processes.

CONCLUSIONS

It was shown that the Timepix detector with GaAs:Cr sensor can register heavy ion in the energy range of 77–158.4 MeV as well as the Timepix with Si. The used energy calibration with characteristic X-rays is incorrect for heavy-ion detection due to the pixel signal which deviates at energy of about 1 MeV per pixel [7, 17]. During investigation in the current work it was confirmed that the "volcano effect" is present in the Timepix with Si sensor (np-type), but absolutely absent in the Timepix with GaAs:Cr sensor. The possible explanation of this fact connected with an internal protection circuit for very high input charges in hole collection mode is given.

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