

Design and properties of silicon charged-particle detectors developed at the Institute of Electron Technology (ITE)

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ABSTRACT

The paper discusses the design of charged-particle detectors commissioned and developed at the Institute of Electron Technology (ITE) in collaboration with foreign partners, used in international research on transactinide elements and to build personal radiation protection devices in Germany. Properties of these detectors and the results obtained using the devices are also presented. The design of the following epiplanar detector structures is discussed:

- 64-element chromatographic arrays for the COMPACT (Cryo On-line Multidetector for Physics And Chemistry of Transactinides) detection system used at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt (GSI) for research on Hassium, Copernicium and Flerovium, as well as elements 119 and 120,
- 2-element flow detectors for the COLD (Cryo On-Line Detector) system used for research on Copernicium and Flerovium at the Joint Institute for Nuclear Research, Dubna,
- detectors for a radon exposimeter and sensors for a neutron dosimeter developed at the Institut für Strahlenschutz, Helmholtz Zentrum München.

The design of planar detectors – single-sided and double-sided strip detectors for the Focal Plane Detector Box used at GSI for research on Flerovium and elements 119 and 120 is also discussed.

Keywords: Silicon PIN diode, silicon detector, strip detector

1. INTRODUCTION

A range of specialised silicon charged-particle detectors were developed at the Institute of Electron Technology (ITE) in the period 2004 ÷ 2012. Four types of 64-element chromatographic arrays (64 x 1 cm²) for the COMPACT (Cryo On-line Multidetector for Physics And Chemistry of Transactinides) detection system developed at the Institut für Radiochemie, Technische Universität München (IR TUM) and used at the GSI Helmholtzzentrum für Schwerionenforschung GmbH (GSI) for research on Hassium (TUM1/Al, TUM1/Au, TUM2/SiO₂ and TUM2/Au arrays) were commissioned and developed in collaboration with IR TUM. TUM4/SiO₂ and TUM4/Au arrays for research on Flerovium and elements 119 and 120 were developed in collaboration with GSI.

Three types of 2-element flow detectors (2 x 1 cm²) for the COLD (Cryo On-Line Detector) system were commissioned and developed in collaboration with the Paul Scherrer Institut (PSI). The COLD system, developed at PSI, consists of 32 detectors forming a 64-element chromatographic array. PSI1 detectors were used in research on Copernicium, and PSI2 and PSI3 in research on Flerovium conducted at the Joint Institute for Nuclear Research, Dubna (JINR).

Detectors for a radon exposimeter and sensors for a neutron dosimeter were commissioned and developed in collaboration with the Institut für Strahlenschutz, Helmholtz Zentrum München, GmbH (HZM).

A set of strip detectors for the Focal Plane Detector Box (FPDB) for the TASCA (TransActinide Separator and Chemistry Apparatus) separator, developed at IR TUM and GSI, used at GSI for research on Flerovium and elements 119 and 120, was commissioned and developed in collaboration with IR TUM. The FPDB consists of a double-sided

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strip detector DSSSD (144 x 48 strips) with an active area of 144 x 48 mm, which acts as a “stop detector”, eight double-sided strip detectors DSSSD (16x16) forming a “backward array” and two single-sided strip detectors SSSSD forming a “veto detector”.

While the design and technology of the detector structures are based on common, basic design and technological ideas, in order to obtain the required extreme detector parameters (very low dark current densities, low depletion voltage) both the design and technology¹ need to be separately developed and optimised, taking into account the type of particles and their energy, detector operating conditions and highly specific requirements resulting from applications.

Due to the unique design of the detector structures (high-resistivity starting material, very large active areas, small “dead” area) and due to their specific applications and resultant requirements for detectors, it was necessary to develop special detector cases and non-standard assembly techniques.

2. TUM CHROMATOGRAPHIC ARRAYS

2.1 Principle of construction

The array consists of two connected panels made of invar®. 32 detector structures forming a power system with a common cathode are mounted on each panel. Anodes of each of the 32 detectors are carried outside through vacuum-tight feedthroughs. The panels are fastened by screws, creating a vacuum-tight gas pipe of 10x0.6 mm cross-section and 320 mm length “lined” with detector structures. The case is sealed by pressing an indium seal mounted in a special channel of one of the panels. The array remains vacuum-tight both when one end is cooled to liquid nitrogen temperature (operation under temperature gradient, the other end at room temperature), and when the whole detector is cooled to liquid nitrogen temperature.

The principle of construction of the array is shown in Fig. 1.

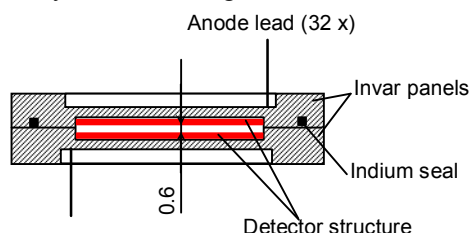


Figure 1. Principle of construction of the TUM array.

2.2 Detector structures

Sixty four discrete, epiplanar p^+-v-n^+ structures with an area of 1 cm^2 were used in TUM1 arrays, while in TUM2 and TUM4 arrays, eight p^+-v-n^+ 4-detector structures were mounted on one panel, and seven 4-detector and two 2-detector structures were mounted on the other. The 2-detector structures were mounted at the ends of the panel. The use of multi-detector structures allowed to increase the active area from 78% in the TUM1 array to 93% in the TUM2 and TUM4 arrays. The thickness of the active layer (v) was optimised for the detection of α -particles with energy up to 12 MeV (100 mm, TUM1 and TUM2) and up to 16 MeV (150 mm, TUM4). Silicon wafers with a high-resistivity epitaxial layer v/n^+ were used as the starting material. The p^+-v junctions were formed by selective boron diffusion. Contacts to the n^+ and p^+ regions were made of aluminium – the contact to the n^+ region over the entire surface, the contact to the p^+ region was shaped like a frame encircling the junction. The active area of the detectors was covered with a very thin (5 nm) aluminium layer (TUM1/Al arrays), a thin (150 nm) SiO_2 layer (TUM/ SiO_2 arrays), or a very thin (5 ÷ 35 nm) gold layer (TUM/Au arrays). The basic design parameters of the detector structures are shown in Table 1.

Table 1. Basic design parameters of the detector structures of the chromatographic arrays

Parameter	TUM1		TUM2-4		TUM2-2		TUM4-4		TUM4-2		
Structure dimensions	10x10 mm		40x10 mm		20x10 mm		40x10 mm		20x10 mm		
Number of p ⁺ -v junctions	1		4		2		4		2		
p ⁺ -v junction dimensions	8.8x8.8 mm		9.6x8.8 mm 9.2x8.8 mm		9.2x8.8 mm		9.6x8.8 mm 9.2x8.8 mm		9.2x8.8 mm		
p+-v junction depth	0.5±0.1 μm		0.6±0.1 μm								
Active layer (v) thickness	100 μm		100 μm		100 μm		150 μm		150 μm		
Active layer (v) resistivity	Min 3 kΩcm										
n ⁺ layer resistivity	Max 0.02 Ωcm										
Total thickness	0.3±0.02 mm		0.5±0.02 mm								
Active surface covering	Au	Al	Au	SiO ₂	Au	SiO ₂	Au	SiO ₂	Au	SiO ₂	
Active surface covering thickness	5 nm	5 nm	15 nm	175 nm	15 nm	175 nm	35 nm	175 nm	35 nm	175 nm	

2.3 TUM4 arrays

Fig. 2 shows a photograph of the TUM4 array. The basic electrical parameters are shown in Table 2.



Figure 2. TUM4/Au array - inside of the array and the assembled array

Table 2. Basic electrical parameters of the TUM4 array (for 1 element)

Parameter		Value	
		typical	max/min
Breakdown voltage ($I_0 = 100 \mu\text{A}$)	[V]	> 200	min. 100
Dark current ($V_R = 15 \text{ V}$)	[nA]	12	max 25
Depletion voltage	[V]	10	max 15
Series resistance ($I_F = 10 \text{ mA}$)	[Ω]	9	max 15

3. FLOW DETECTORS

The flow detectors consist of two epiplanar p^+-v-n^+ structures (11.25x11.25 mm) placed opposite to one another in a special ceramic case mounted on a laminate substrate. As in the case of the TUM arrays, the flow detectors mounted in the COLD system form a gas channel of 11.6x1.5 mm cross-section and 361.6 mm length. In PSI1 and PSI2 detectors, the upper structure was covered with a thin (~40 nm) gold layer, and the lower one with a SiO_2 layer with a thickness of 150 nm. In PSI3 detectors, both structures are covered with a gold layer. In the PSI1 detectors, the thickness of the active layer v was optimised for the detection of α -particles with energy up to 14 MeV and amounted to 120 μm , while the PSI2 and PSI3 were designed for the detection of α -particles with energy up to 16 MeV, and the active layer thickness was 150 μm . The p^+-v junction is 10x10 mm in size and has a depth of 0.6 μm . Fig. 3 shows photographs of the PSI3 detectors. Table 3 shows the basic electrical parameters of the detectors.

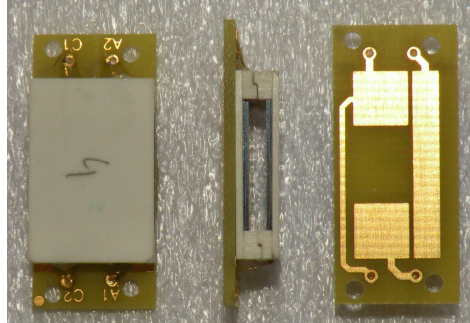


Figure. 3. PSI3 detectors: top view, side view and bottom view

Table 3. Basic electrical parameters of the PSI3 detectors (for 1 element)

Parameter		Value	
		typical	max/min
Breakdown voltage ($I_0 = 100 \mu A$)	[V]	> 200	min. 100
Dark current ($V_R = 15 V$)	[nA]	11	max 25
Depletion voltage	[V]	10	max 15
Series resistance ($I_F = 10 mA$)	[Ω]	27	max 50

4. DETECTORS FOR RADON EXPOSIMETER (^{222}RN)

The detectors for the radon exposimeter, called GSF3, consist of four parallelly connected silicon epiplanar p^+-v-n^+ structures with an active area of 1.2 cm^2 each, mounted on a ceramic substrate. Table 4 shows the basic design parameters of the GSF3 structures. Fig. 4 shows photographs of a GSF3 detector. Table 5 shows the basic electrical parameters of these detectors.

Table 4. Basic design parameters of GSF3 structures

Parameter	Value	Parameter	Value
Active layer (v) thickness	$110 \pm 10 \mu m$	p^+-v junction dimensions	$10.8 \times 10.8 mm$
v layer resistivity	min 3 $k\Omega cm$	p^+-v junction depth	$0.6 \pm 0.05 \mu m$
n^+ layer resistivity	max 0.02 Ωcm	Surface concentration of B in the p^+ region	min $10^{19} cm^{-3}$
Structure dimensions	$12.4 \times 12.4 mm$	Active surface covering (Al) thickness	400 nm

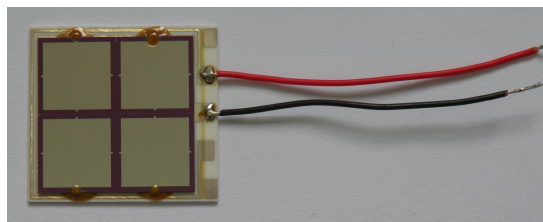


Figure 4. Detector GSF3

Table 5. Basic electrical parameters of the GSF3 detectors

Parameter		Value	
		typical	max/min
Breakdown voltage ($I_0 = 100 \mu\text{A}$)	[V]	>100	min 80
Dark current ($V_R = 15 \text{ V}$)	[nA]	9	max 12
Depletion voltage	[V]	35	max 100
Series resistance ($I_F = 10 \text{ mA}$)	[Ω]	4.1	max 5

5. NEUTRON SENSORS

5.1 Principle of operation

In neutron sensors, neutrons generate charged particles (α , ^3H or protons) in converters. The particles then interact with a semiconductor detector. In sensors developed at ITE, a thin ^6LiF layer coated over the active surface of a $\text{p}^+\text{-v-n}^+$ diode was used as a thermal and epithermal neutron converter (neutrons with energies from 0.025 eV to 10 keV) (HZ1/50-Cd sensors). In fast-neutron sensors (energies from 1 MeV to 20 MeV), cases are filled with synthetic wax (HZ1/50-Pb sensors). The same type of epiplanar ($\text{p}^+\text{-v-n}^+$) silicon structures (called HZ1/50) with active layer (v) thickness of 55 μm , selected in such a way as to effectively detect only particles with particular energies (α up to 8 MeV, protons and ^3H up to 3 MeV) is used in both types of sensors. In order to ensure selective detection, cadmium cases with a calibrated opening were used in thermal in epithermal neutron sensors. A lead case was used in fast-neutron sensors.

5.2 HZ1/50 detector

The HZ1/50 detector consists of an epiplanar $\text{p}^+\text{-v-n}^+$ structure with an area of 2 cm^2 , mounted on a ceramic substrate. Table 6 shows the basic design parameters of HZ1/50 structures. Fig. 5 shows a photograph of a HZ1/50 detector.

Table 6. Basic design parameters of the HZ1/50 detector structure

Parameter	Value
Active layer (v) thickness	$55 \pm 5 \mu\text{m}$
Active layer (v) resistivity	Min 3 $\text{k}\Omega\text{cm}$
n^+ layer resistivity	Max 0.02 Ωcm
Structure dimensions	16.6 x 14.6 mm
$\text{p}^+\text{-v}$ junction dimensions	15.2 x 13.2 mm
$\text{p}^+\text{-v}$ junction depth	$0.55 \pm 0.05 \mu\text{m}$
Surface concentration of boron in the p^+ region	min 10^{19} cm^{-3}
Active surface covering (SiO_2) thickness	150 nm

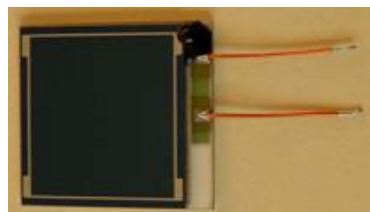


Figure 5. HZ1/50 detector

5.3 HZ1/50-Cd and HZ1/50-Pb neutron sensors

Detectors destined for assembling in cadmium cases are covered with a thin ^6LiF layer. Then the detectors are placed in cadmium or lead cases according to their destination. Lead cases are filled with wax. Openings in cases used for leads and for filling lead cases with wax are sealed with epoxide including BN powder. The principle of the detector cases is shown in Fig. 6. Figs. 7 and 8 show photographs of the assembled sensors.

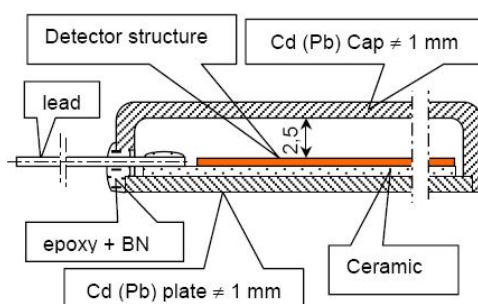


Figure 6. Principle of the detector case (cross-section in the cutting plane of the cathode lead)



Figure 7. Photograph of HZ1/50-Cd sensors

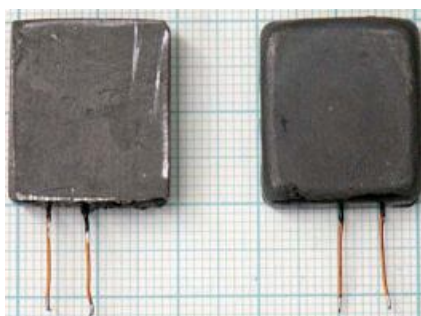


Figure 8. Photograph of HZ1/50-Pb sensors

The basic electrical parameters of HZ1/50 neutron sensors are shown in Table 7.

Table 7. Basic electrical parameters of HZ1/50 neutron sensors

Parameter	Value	
	typical	max/min
Breakdown voltage ($I_0 = 100 \mu\text{A}$) [V]	> 200	min 50
Depletion voltage [V]	8.9	max 12
Capacitance ($V_R = 9 \text{ V}$) [pF]	430	
Dark current ($V_R = 15 \text{ V}$) [nA]	3.7	max 25
Series resistance ($I_F = 10 \text{ mA}$) [Ω]		max 5

6. STRIP DETECTORS FOR FPDB

6.1 FPDB design

A schematic design of the TASCA FPDB is shown in Fig. 9.

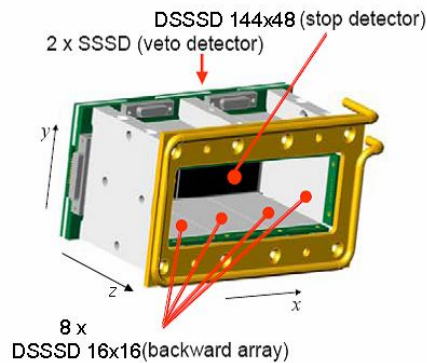


Figure 9. Configuration of detectors in the new TASCA FPDB

The FPDB consists of a double-sided strip detector DSSSD (144 x 48 strips) with an active area of 144 x 48 mm, which acts as a “stop detector”, eight double-sided strip detectors DSSSD (16 x 16) forming a “backward array” and two single-sided strip detectors SSSSD forming a “veto detector”.

6.2 Double-sided strip detector DSSSD 144x48

The DSSSD 144x48 detector consists of two planar multi-junction silicon p^+-v-n^+ structures. On the top surface, each of the structures contains seventy two p^+-v junctions shaped like strips with the dimensions 0.9 x 48 mm, distributed every 0.1 mm, formed by selective boron diffusion. On the bottom surface, each structure contains forty eight perpendicularly placed n^+-v junctions with the dimensions 72 x 0.5 mm, distributed every 0.5 mm, formed by selective phosphorus diffusion. A p-type region with the width 0.3 mm is formed around the n^+ strips by selective boron diffusion. The thickness of the detector (v layer) is 300 μm , and the depth of the p^+-v junctions on the top surface, and p-v and n^+-v junctions on the bottom surface is 0.5 μm , 2.5 μm and 3 μm respectively. The v layer resistivity is $5 \div 7 \text{ k}\Omega\text{cm}$. Aluminium contacts of thickness 400 nm were used both for p^+ regions and for n^+ regions.

Structures, after cutting from a wafer, are glued using an elastic glue to the special PCB substrate. Next, wire connections are made by ultracompression using aluminium wire of diameter 25 μm (2 connections to each contact). Photographs of the assembled DSSSD 144x48 detector are shown in Figs. 10 and 11.

Examples of measured electrical parameters are presented in table 8. Measurements of the p^+-v junctions breakdown voltage were carried out separately for each strip, with other strips not connected. Dark current for particular strips was measured with supply voltage for all strips 28 V, equal to the calculated full depletion voltage.

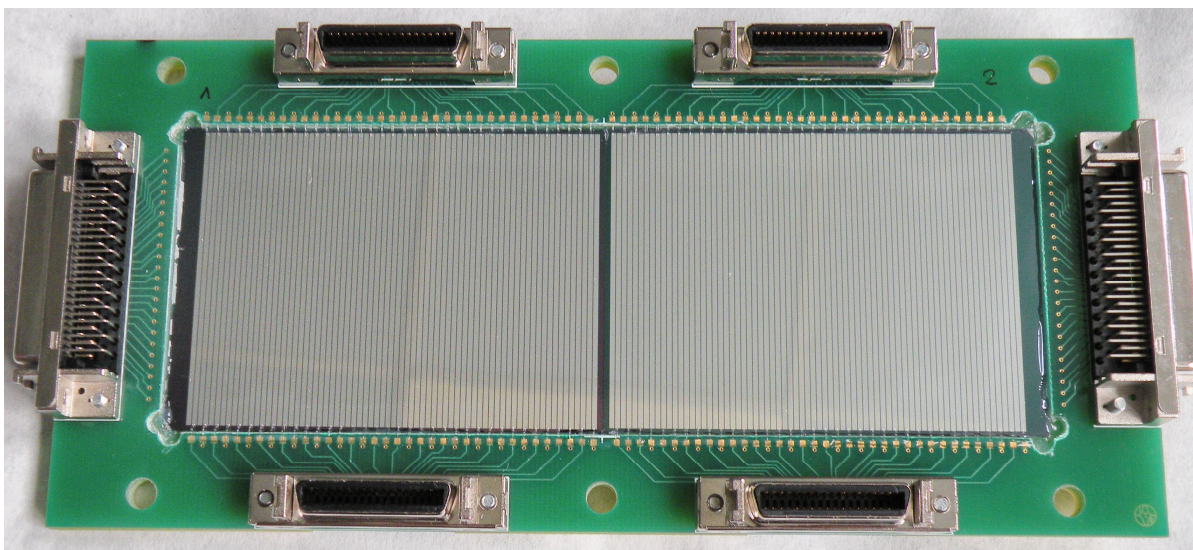


Figure 10. DSSSD 144x48 detector – top side (p^+)

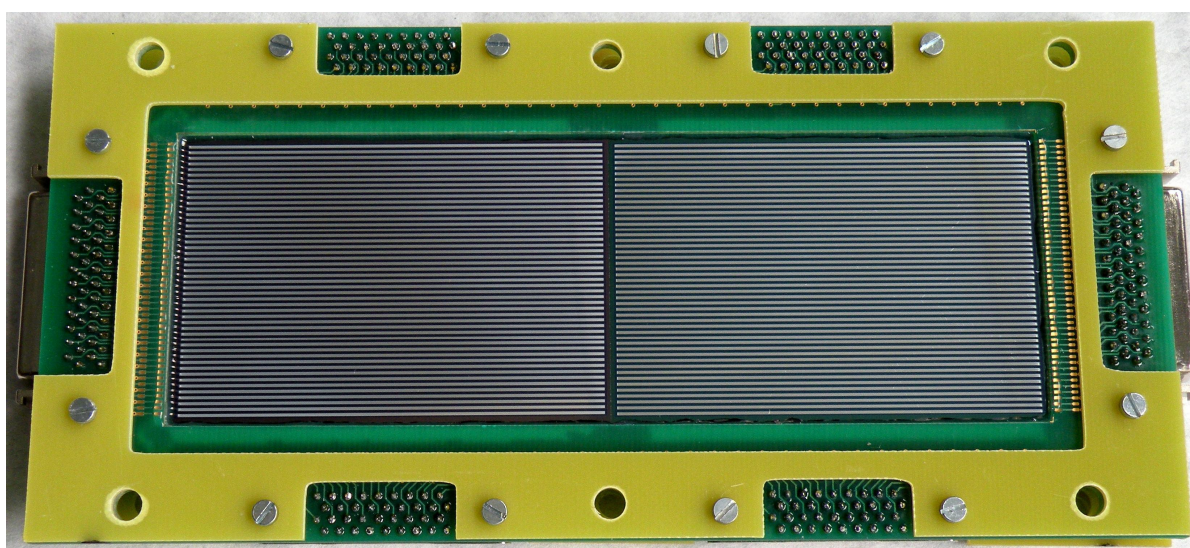


Figure 11. DSSSD 144x48 detector – bottom side (n^+)

Table 8. Electrical parameters of the DSSSD 144x48 detector

Parameter	Value		
	Min.	Av.	Max.
Breakdown voltage [V]	60		> 100
Dark current (VR = 28 V) [nA]	12.2	35	561 *)
*) There was one p^+ -v junction with dark current greater than 100 nA (561 nA, strip 26)			

6.3 Double-sided strip detector DSSSD 16x16

The DSSSD 16x16 detector consists of a planar multi-junction silicon p^+-v-n^+ structure. On the top surface, the structure contains sixteen p^+-v junctions shaped like strips with the dimensions 2.75 x 71.5 mm, distributed every 0.1 mm, formed by selective boron diffusion. On the bottom surface, the structure contains sixteen perpendicularly placed n^+-v junctions with the dimensions 46 x 4 mm, distributed every 0.88 mm, formed by selective phosphorus diffusion. A p-type region with the width 0.16 mm is formed around the n^+ strips by selective boron diffusion. The thickness of the detector (v layer) is 500 μm , and the depth of the p^+-v junctions on the top surface, and p-v and n^+-v junctions on the bottom surface is 0.5 μm , 2.5 μm and 3 μm respectively. The v layer resistivity is $5 \div 7 \text{ k}\Omega\text{cm}$. Contacts for both sides are made of aluminium – for p^+ regions their thickness is 400 nm, for n^+ regions – 1200 nm. Structures are glued using an elastic glue to the special PCB substrate. Next, wire connections are made by ultracompression using aluminium wire of diameter 25 μm (2 connections to each contact). Photographs of the assembled DSSSD 16x16 detector are shown in Figs. 12 and 13. Examples of measured electrical parameters are presented in Table 9. Measurements of the p^+-v junctions breakdown voltage were carried out separately for each strip, with other strips not connected. Dark current for particular strips was measured with supply voltage for all strips 80 V, equal to the full depletion voltage determined from the C-V curve.

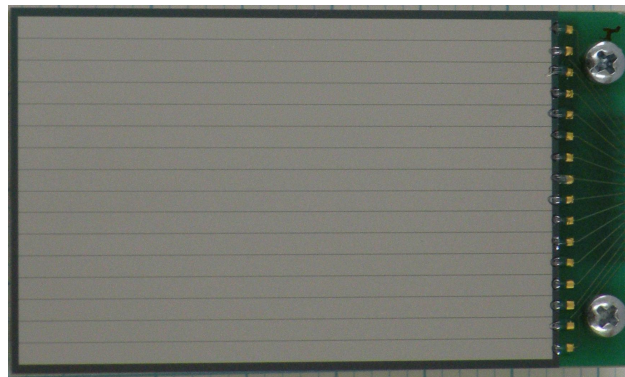


Figure 12. DSSSD 16x16 detector – top side (p^+)

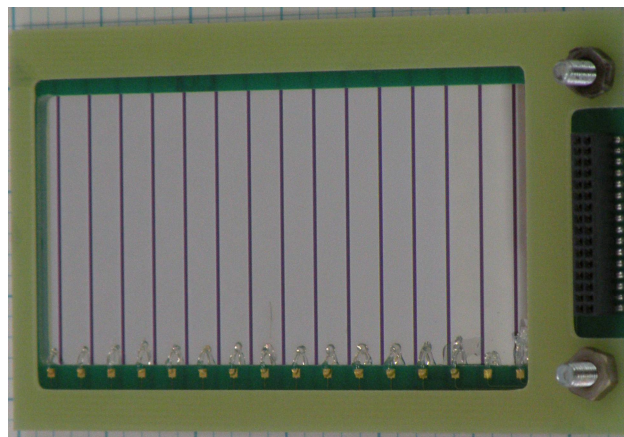


Figure 13. DSSSD 16x16 detector – bottom side (n^+)

Table 9. Electrical parameters of the DSSSD 16x16 detector

Parameter	Value		
	Min.	Av.	Max.
Breakdown voltage [V]	Min 100		
Dark current ($V_R = 80 \text{ V}$) [nA]	21	30	48

6.4 SSSSD detector

The SSSSD detector structure is an onesided planar eight-junction p^+-v-n^+ structure with a very large area (72 x 48 mm active area). The structure's active region (v) thickness is 500 μm . This structure contains eight p^+ strips of dimensions 5.6 x 72 mm, evenly distributed every 0.1 mm on the top side of the wafer. The p^+ stripes are formed by selective boron diffusion. The n^+ region is formed on the whole bottom surface of the wafer by phosphorus diffusion. Contacts for both sides are made of aluminium – for p^+ regions their thickness is 400 nm, for n^+ regions – 1200 nm.

Structures are assembled on ceramic (Al_2O_3) substrates by gluing using a silver epoxy. Strip p^+ wire connections are formed by ultracompression using aluminium wire (ϕ 25 μm). Fig. 14 shows a photograph of the assembled SSSSD detectors. Examples of measured electrical parameters are presented in Table 10. Measurements of the p^+-v junction breakdown voltage were carried out separately for each strip, with other strips not connected. Dark current for particular strips was measured with supply voltage for all strips 40 V, equal to the full depletion voltage determined from the C-V curve.

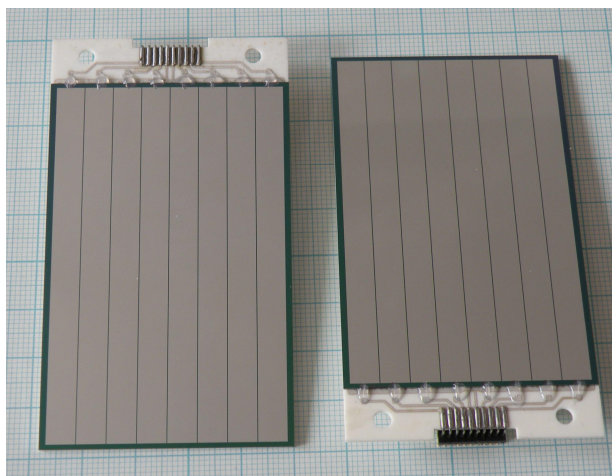


Figure 14. SSSSD detectors

Table 10. Electrical parameters of SSSSD detectors

Parameter	Value		
	Min.	Av.	Max.
Breakdown voltage [V]	> 100		
Dark current ($V_R=40$ V) [nA]	34	65.3	89

7. SUMMARY

The specialised charged-particle detectors developed and fabricated at ITE are characterised by excellent parameters – low dark current ($I_0 < 25$ nA/cm²), low depletion voltage ($V_D < 15$ V for epiplanar detectors and $V_D < 50$ V for planar detectors with v layer thickness of 500 μm), p^+-v junction breakdown voltage much higher than depletion voltage (in general $V_{BR} > 200$ V). Low dark currents make it possible to obtain good energy resolution (better than 20 keV and 30 keV for epiplanar and planar detectors respectively). Low dark currents and low depletion voltages also enable battery power supply of dosimetric devices which use the epiplanar detectors. One battery provides 6 months of continuous operation. The detectors are also characterised by very high radiation resistance, and can therefore be used in experiments lasting several months.

The chromatographic arrays, flow detectors and strip detectors are used in international research on transactinide elements conducted in such scientific centres as GSI, PSI and JINR, where experiments carried out using the detectors led to significant scientific discoveries, such as the discovery of four new nuclides – ^{270}Hs ², ^{271}Hs ³, ^{283}Cn ⁴ and ^{277}Hs ⁵. Some of the physical and chemical properties of elements Hs, Cn and Fl^{2,4,6,7,8,9} were also determined as a result of the

research. Thirteen full decay chains of two isotopes, $^{288,289}\text{Fl}$, were observed in one of the experiments conducted at GSI - the best result obtained to date ⁶.

The GSF3 detectors and neutron sensors are used in radon exposimeters and neutron dosimeters fabricated in Germany.

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