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CERN LARGE HADRON COLLIDER PROJECTS TO IMPROVE THE RADIATION HARDNESS OF IONIZING RADIATION DETECTORS: THE ROLE AND CONTROL OF DEFECTS IN Si AND POTENTIAL OF GaN

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We review recent contributions of Vilnius University teams in collaboration with others participating in the CERN RD39 and RD50 collaborations. These address detector technologies suitable for the proposed Super-LHC facility, capable of withstanding radiation levels arising from a luminosity of 10^{35} cm^{-2}·s^{-1} which will present severe challenges to current tracking detector technologies. Candidates among those technologies for use as particle tracking detectors are cryogenic operation and/or defect engineering of Si detectors and GaN – a new semiconductor material for use as a particle tracking detector. The use of advanced methods for material characterization and the investigation of semi-insulating GaN are described in this paper. Peculiarities related to trap recognition in the temperature dependence of photoconductivity kinetics and recombination parameters in highly irradiated Si are presented, together with an overview of the promise of GaN as a radiation hard material.

Keywords: recombination and trapping of charge carriers, III–V semiconductors, GaN photoluminescence, interaction of particles and radiation with semiconductors, methods of materials testing and analysis

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1. Introduction

The Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) will start work only in 2007 but studies have already begun of the physics potential and the experimental challenges which would be presented by an upgrade of the LHC to a 10 times higher luminosity of 10^{35} cm^{-2}·s^{-1}. The clear gain in physics potential identified requires the setting up as soon as possible of an intensive R&D program for detectors to match the more stringent requirements of the Super-LHC, namely the increased track density and radiation levels and the probable reduction in the interval between proton bunch crossing times (from 25 ns to the order of 10 ns). The inner tracking detectors have to survive fluences of fast hadrons up to $1.6\cdot10^{16}$ cm^{-2} assuming 5 years of operation accumulating an integrated luminosity of 2500 fb^{-1}. This is a 10 times higher radiation level than predicted for the present LHC detectors and it is more or less evident that the present detector technology can survive in this initial radiation environment. The reduced bunch crossing time will demand faster electronics and detectors that deliver their signals within 10 ns [1, 2].

A number of R&D collaborations were formed to address the Super-LHC problems. They are concentrating, respectively, on the possibility of improving the performance of detector material by cooling (CERN RD39 collaboration "Cryogenic detectors" [3]), creating a new type of detector based on diamond as a radiation hard material (CERN RD42 collaboration "Diamond radiation detectors" [4]), and investigating different ways to improve material, detector, and full system properties (CERN RD50 collaboration "Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders" [5]). The RD39 collaboration, presently consisting of 18 institutes with about 59 members, concentrates on the investigation of the improvement of detector parameters by using different types of Si crystalline material and

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on the investigation of defect evolution. The RD50 collaboration has 52 participating institutes with about 270 members. Special emphasis is put on the development of radiation tolerant defect engineered silicon and new semiconductor materials for radiation detectors, such as Czochralski (Cz) or magnetic Czochralski (MCz), epitaxial (EPI), and oxygen enriched (DOFZ) silicon, SiC, and GaN. New detector concepts such as "3D" and "Semi-3D" detectors, as well as thinned detectors are also under evaluation and cost effective radiation tolerant devices are under development. Furthermore, the collaboration concentrates on the identification and understanding of the microscopic radiation-induced defects that lead to the macroscopic degradation of detector properties.

Since 2002 Vilnius University research groups have been involved in the RD39 and RD50 collaborations, participating mostly in projects related to new material research and design and the use of different methods of semiconductor parameter measurement by non-equilibrium conductivity. During an earlier period (1996–2001) our participation in the CERN-supported RD8 collaboration and the U.K. Royal Society programs covered the analysis of the properties of highly irradiated GaAs and Si [6, 7]. A complex behaviour of traps and microinhomogeneities was demonstrated that led to the dependence of trap thermal activation energy on the emptying or other traps in GaAs [8] and a significant decrease of the lifetime in Si irradiated by high energy particles and ions [9, 10]. Also a new type of ionizing radiation detector was proposed, based on converting non-equilibrium carriers, concentrated at one detector surface by an internal electric field, into a luminescence response [11]. At this time GaN was also proposed as a potentially suitable material for ionizing radiation detectors [12] and during the period of work in the RD50 collaboration the radiation hardness of this material has been investigated [13–15].

This paper presents our latest contributions to local level parameter measurement technology in Si and achievements in the analysis of the radiation hardness of epitaxial GaN.

2. GaN as a radiation hard material for the ionizing radiation detectors

GaN samples were grown by MOCVD in Tokushima University and Lumilog, Ltd. The semi-insulating material was grown on a high conductivity substrate cap layer by a change of trimethyl-gallium flow rate [16].

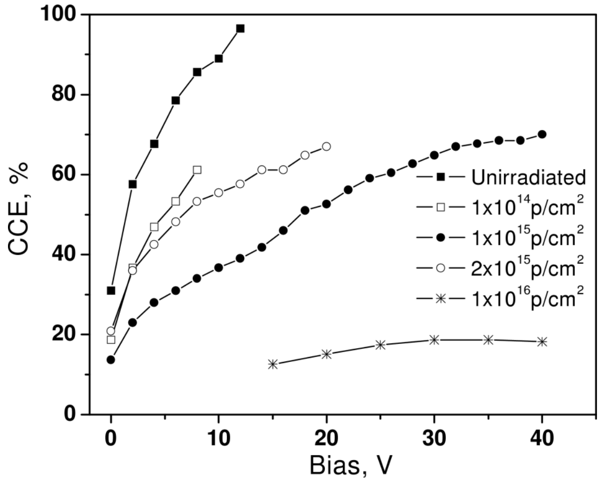


Fig. 1. Charge collection efficiency in GaN (epi-layer of 2 μm thickness) irradiated by 24 GeV protons.

Pad detectors were fabricated and their charge collection efficiency (CCE) was used to characterize the devices. An ^{241}Am radioactive source which emits 5.48 MeV α particles was used for excitation of non-equilibrium carriers. These were detected using a standard pulse height analysis setup, comprising charge sensitive pre-amplifier, shaper amplifier with a shaping time of 1 μs, and multichannel pulse height analyser. The detector and source were housed in a vacuum chamber. The samples were tested before and after irradiation by an X-ray dose of 600 MRad and by electrons, protons, and neutrons up to fluences of 10^{16} cm^{-2}.

The CCE in the non-irradiated and X-ray irradiated samples was in the range 80–100%, depending on the sample thickness. The CCE decreased to 19% in the samples irradiated by protons to a fluence of 10^{16} cm^{-2}, and to 5% in the samples irradiated by neutrons to a fluence of 10^{16} cm^{-2}. These data were obtained in the samples (1.8–2.5 μm) in which substrate induced defects play a significant role. An example of the CCE bias dependence is given in Fig. 1. The CCE in a 12 μm thick layer was up to 30% in the samples irradiated by 24 GeV protons to a fluence of $1.15 \cdot 10^{16}$ cm^{-2}, indicating the promise of this material but also the need for improvement of material growth technology.

The quality of the epi-layers and the influence of the irradiation was characterized by photoluminescence. Some results are presented in Fig. 2. The quality of the samples was rather good, as indicated by the exciton peak shape (Fig. 2(b)). If the results are normalized to the exciton peak value then the impurity band intensity is lowest in the thick epi-layer sample. The irradiation quenches the exciton luminescence more than in the impurity bands, therefore it can be proposed that the irradiation introduces additional fast recombination centres that are not seen in the luminescence spectra.

The irradiation of GaN significantly changes the defect structure in the sample, as seen in the current versus bias dependences that show a significant change of the material bulk resistivity. It remains high enough, however, to meet the detector requirements. Systematic analysis of the rear contact properties by Van der Pauw and capacitance methods identified problems related to contacting the semi-insulating GaN layer and to the origin of noise and instability of the samples. The complicated trap spectra were analysed by the thermally stimulated current (TSC) method. Two examples are presented in Fig. 3. A decrease of TSC activation energy during multiple annealing was observed in a

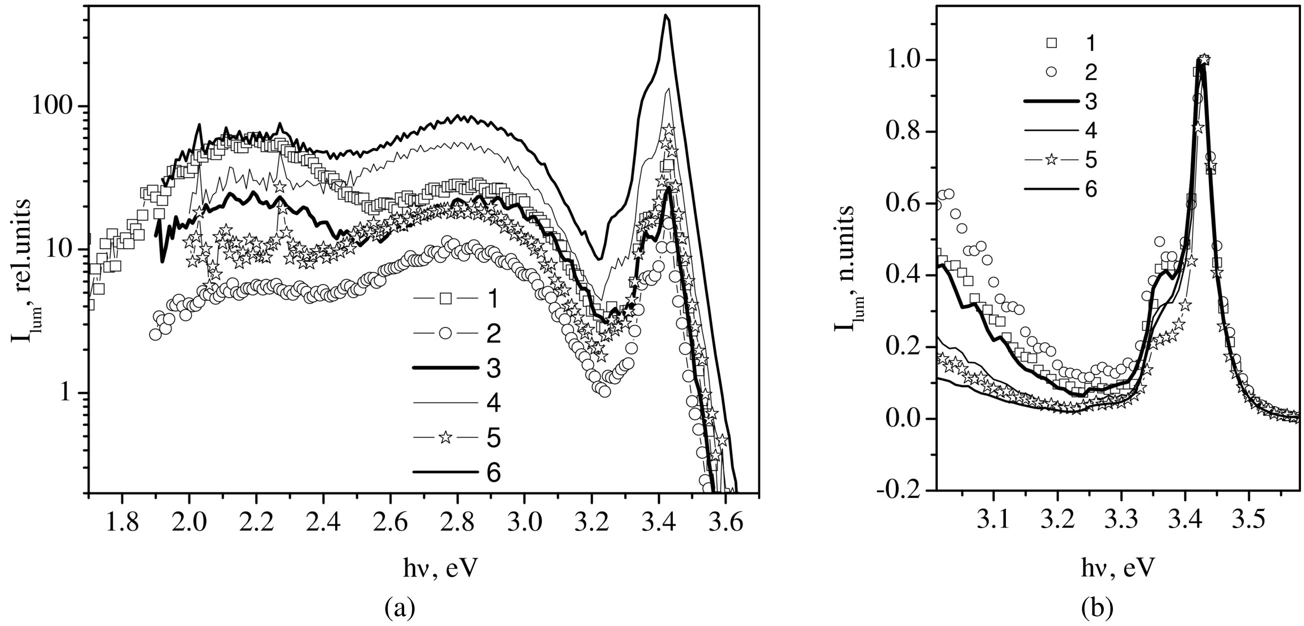


Fig. 2. Luminescence spectra in epitaxial GaN as-grown (*1*, *6*), irradiated by a 600 Mrad X-ray dose (*2*), irradiated by 100 keV neutrons to a fluence of $5\cdot10^{14}$ cm^{-2} (*3*), irradiated by 24 GeV protons to a fluence of $1.15\cdot10^{14}$ cm^{-2} (*4*), irradiated by 24 GeV protons to a fluence of $1.8\cdot10^{15}$ cm^{-2} (*5*); epi-layer thickness 2 μm (*1–3*) and 12 μm (*4–6*). (a) Absolute values of luminescence excited by laser intensity $\sim$3 W/cm^2, (b) the same normalized to the exciton peak value. If the intensity of luminescence in 2 μm thick as-grown sample is taken as 1.0, the intensity for curve *2* is 0.69, for *3* it is 0.4, for *4* – 3.4, for *5* – 1.75, and for *6* – 11.1, respectively.

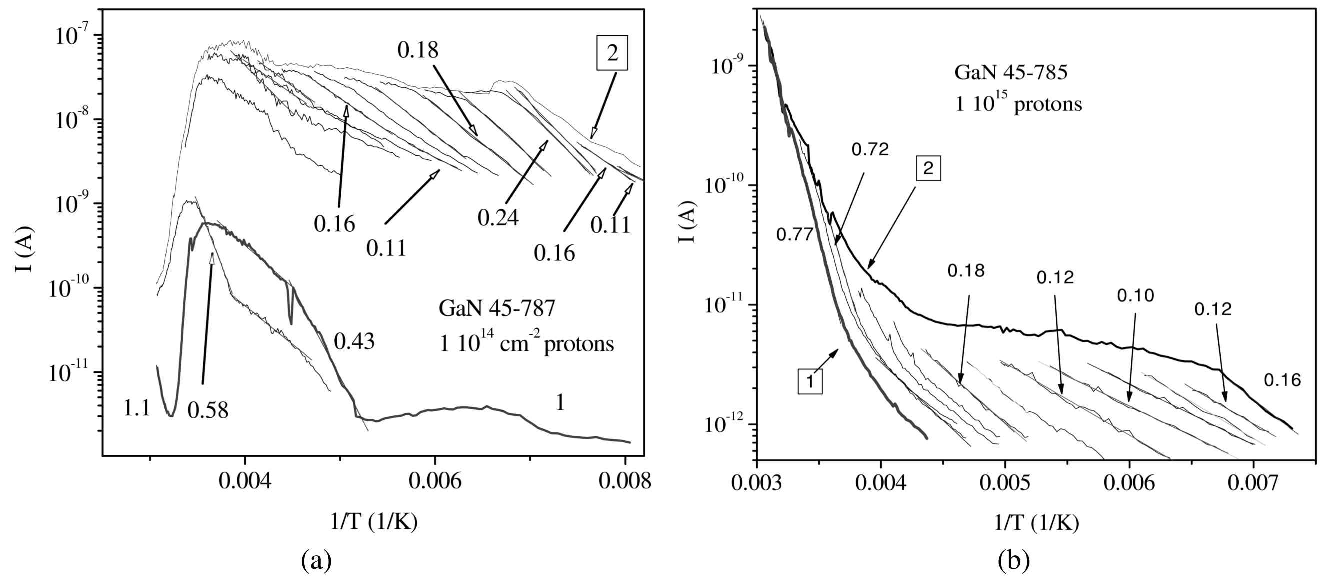


Fig. 3. Thermally stimulated current in GaN irradiated by 24 GeV proton fluences (given in the inserts). *1* – dark current, *2* – current after excitation at low temperature, the rest – current measured during multiple heating after excitation at low temperature. The numbers on the curves are the thermal activation energies in eV.

certain temperature range, as previously observed in GaAs in [8]. It indicates the simultaneous release of carriers from traps and local levels in the drift barrier regions.

The increase of the dark conductivity is shown in Fig. 3(a, b), as well as the influence of deep levels on the dark current (Fig. 1(a), curve *1*). An activation with an activation energy 0.43 eV that appeared without excitation of the sample shows that the level filling was non-equilibrium at room temperature.

The measured activation energies in differently irradiated samples do not allow the identification of the radiation induced defects, but it can be concluded that at least three families of traps change their role in the irradiated samples.

3. New challenges of lifetime measurement in the investigation of defect properties

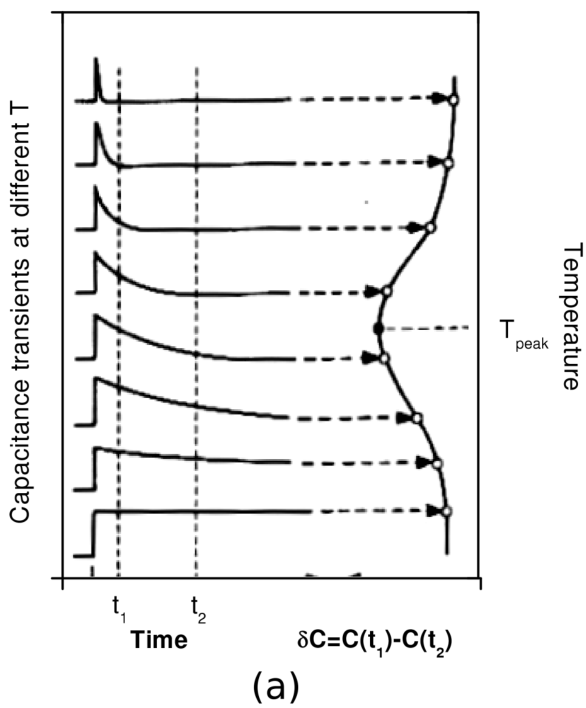
Deep level transient spectroscopy (DLTS) could now be cited as the main method for deep level investigation [17]. With this method it is difficult to recognize the centres that play the main role in the temporal dependence of non-equilibrium carrier concentration, however, as the peak signal of DLTS appears at the temperature when the trap changes from multi-trapping to single trapping. A schematic correspondence of this behaviour in DLTS and in photoconductivity decay is shown in Fig. 4. In general, the characters of fast and slow components of photoconductivity can be different, as analyzed in our rather old paper [18].

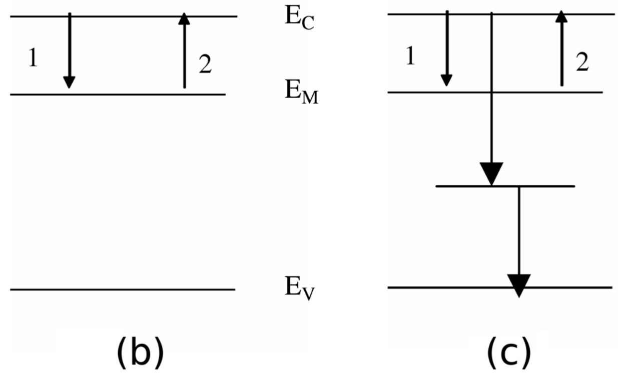
In the inset the decay time constants are given in terms of the following parameters: $\gamma_{n\mathrm{M}}$ and $\gamma_{n\mathrm{R}}$ are the capture coefficients of trap (M) and recombination (R) centres, respectively; M and R, m, r, and n are the concentrations of traps and recombination centres, electrons in traps, recombination centres, and the conduction band, respectively; N_{CM} is the effective density of states in the conduction band corresponding to the trap level.

A detailed analysis of the temperature dependence of the free carrier lifetime, measured by microwave absorption induced in by a short light pulse [19], shows peculiarities in the environment of the DLTS peak temperature (Fig. 5 and Table 1). This correlation needs a more systematic approach that will be presented elsewhere.

4. Demonstration of the role of deep centres by the transient grating method

The transient grating method [20] permits the measurement of the free carrier lifetime and diffusivity as well as the analysis of the optical transition type in the material. This method was applied to irradiated silicon and a great decrease of free carrier lifetime was





1 $\tau_M=1/\gamma_{nM}(M-m)$

2 $\tau_N=1/\gamma_{nM}N_{CM}$

3 $\tau_{rec}=1/\gamma_{nR}(R-r)$ or $\tau_{asimp}=\Theta_I=1/[\gamma_{nM}N_{CM}]$

or $=\Theta_{II}=\tau_{rec}[1+(M-m)/(N_{CM}+n)]$

(d)

Fig. 4. (a) Schematic presentation of DLTS measurement [17], electron transition model in the case of (b) DLTS and (c) photoconductivity, and (d) photoconductivity decay asymptotic time constants.

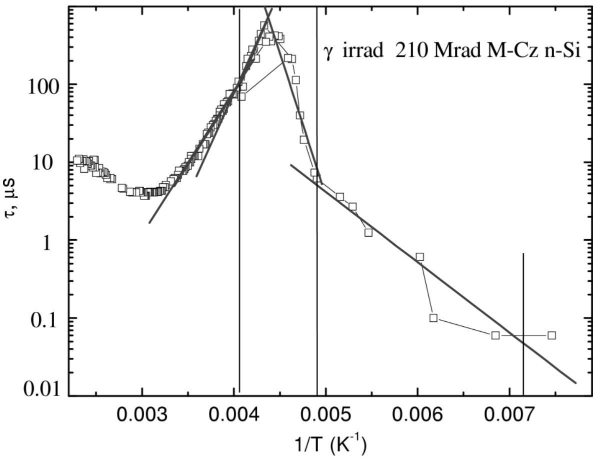


Fig. 5. Temperature dependence o the free carrier decay asymptotic time constant, τ, in Si irradiated by a γ ray dose of 210 Mrad. The vertical bars show the DLTS peak temperatures.

Table 1. The DLTS peak temperature, τ thermal activation energy and its interval of temperature, and the change of activation energy at the DLTS peak position (Fig. 5).

DLTS	MCz n-Si		
T, K	ΔT	ΔE, eV	δ, eV
246	290–246	0.368±0.005	−0.17
	246–229	0.556±0.079	
205	225–205	0.635±0.004	0.42
	205–140	0.218±0.026	
140	205–140	0.218±0.026	0.22
	<140	0 (???)	

observed. In non-irradiated material a lifetime of up to a few hundred microseconds was observed, and in the material irradiated by protons to a fluence of 10^{15} cm^{-2} the lifetime decreased to a few nanoseconds. In a measurement of the light induced diffraction efficiency versus temperature, it was observed (Fig. 6) that the diffraction efficiency decreases with temperature in the non-irradiated samples but not in the irradiated sample. This can be understood in terms of optical transitions via radiation induced deep levels that can be excited by 1.06 eV light quanta from the valence band to the deep level and from the level to the conduction band. At low temperature the intrinsic absorption edge shifts to higher energy and these light quanta can no longer excite free carrier pairs in the non-irradiated material [21].

5. Summary

1. The application of characterization methods which depend on non-equilibrium free carrier concentration kinetics allows a deeper understanding of the roles of traps and deep centres in semiconductor radiation detectors.
2. GaN promises to be a useful material for radiation hard detectors. An increase of the epi-layer thickness improves the material quality and its radiation hardness.

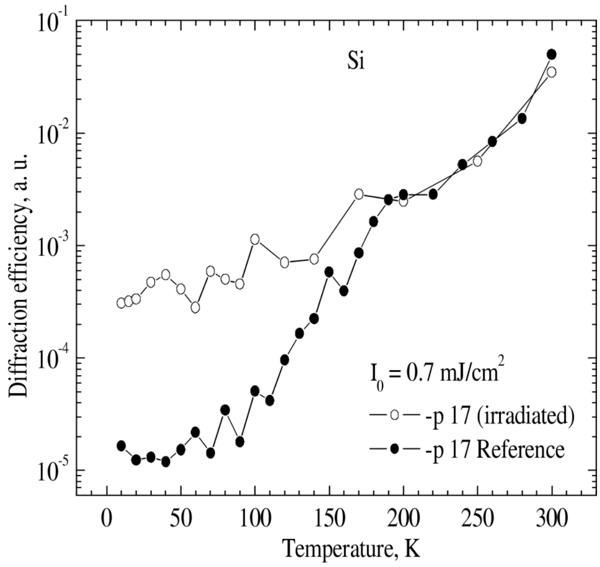


Fig. 6. Diffraction efficiency versus temperature in the reference (bold dots) and heavily irradiated (open dots) Si samples.

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CERN'O DIDŽIOJO HADRONŲ KOLAIDERIO PROJEKTAI, SIEKIANT PAGERINTI JONIZUOJANČIOS SPINDULIUOTĖS DETEKTORIŲ RADIACINĮ ATSPARUMĄ: DEFEKTŲ SILICIO KRISTALUOSE VAIDMUO BEI JO KONTROLĖ IR GaN – NAUJA MEDŽIAGA DETEKTORIAMS

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Santrauka

Apžvelgiamas pastarųjų metų Vilniaus universiteto mokslininkų indėlis į tarptautinio bendradarbiavimo programas, skirtas Didžiojo hadronų kolaiderio (LHC) modifikavimo problemoms spręsti. Tai Europos branduolinių tyrimų centro CERN programos: kriogeniniai spinduliuotės detektoriai (CERN-RD39) ir spinduliuotei atsparūs detektoriai didelio šviesingumo kolaideriams (CERN-RD50). Kuriami detektoriai turi patenkinti naujos kartos kolaiderio Super-LHC reikalavimus, numatančius galimybę dirbti didelės radiacijos, kurią iššauks didelės energijos dalelių srautas, siekiantis 10^{35} $cm^{-2}s^{-1}$, fone. Šiandieninės technologijos detektoriams tai kol kas neįmanoma. Si detektoriai žemoje temperatūroje, detektoriai, pagaminti panaudojant defektų reakcijas Si kristaluose ir naujos medžiagos – GaN pritaikymas jonizuojančios spinduliuotės detektoriams yra keliai, kuriais ieškomi būdai sukurti tinkamus eksperimentams detektorius. Pateikiami modernizuoti puslaidininkių charakterizavimo metodai, pagrįsti nepusiausvirių krūvininkų relaksacijos tyrimu, ir nauji rezultatai, gauti tiriant pusiau izoliuojantį GaN. Krūvininkų prilipimo ir rekombinacijos ypatumai aptikti, tiriant temperatūrines fotolaidumo kinetikos priklausomybes, bei ištirta krūvininkų gyvavimo trukmė stipriai apšvitintame Si. Apžvelgta dabartinė būklė ir perspektyva sukurti spinduliuotei atsparius GaN detektorius.