Radiation hardness of semiconductor avalanche detectors for calorimeters in future HEP experiments

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Abstract. During the last years, semiconductor avalanche detectors are being widely used as the replacement of classical PMTs in calorimeters for many HEP experiments. In this report, basic selection criteria for replacement of PMTs by solid state devices and specific problems in the investigation of detectors radiation hardness are discussed. The design and performance of the hadron calorimeters developed for the future high energy nuclear physics experiments at FAIR, NICA, and CERN are discussed. The Projectile Spectator Detector (PSD) for the CBM experiment at the future FAIR facility, the Forward Calorimeter for the NA61 experiment at CERN and the Multi Purpose Detector at the future NICA facility are reviewed. Moreover, new methods of data analysis and results interpretation for radiation experiments are described. Specific problems of development of detectors control systems and possibilities of reliability improvement of multi-channel detectors systems are shortly overviewed. All experimental material is based on the investigation of SiPM and MPPC at the neutron source in NPI Rez.

1. Introduction
The use of modern semiconductor devices as the replacement of traditionally used photomultipliers has three main reasons – cost, insensitivity to magnetic fields and small size. Also it is important to note that the power supply voltage for semiconductor analogues of photomultipliers is 30-100 V in contrary to voltage level of kilovolts required for photomultipliers. Moreover, one can simply place a pre-amplifier near to the photodetector, which together with its small size allows the construction of calorimeters with a high degree of granularity. It gives an opportunity to extend the tracking system up to the sophisticated detector module itself and improve tracking and energy resolution.

On the other hand, one cannot forget about the shortcomings inherent in modern solid-state semiconductor photodetectors with internal gain. Firstly, this kind of apparatus has sensitivity to the detector’s external temperature changes. It leads to the need of the additional compensation of detector’s operating point voltage to stabilize the detector gain and to minimize its own noise caused by the dark current.

The second drawback is connected to the operating principle of all modern Solid-State Photomultipliers (SSPM). Despite the fact that the market is saturated with a variety of devices, all of them are built on a similar principle. The phenomenon of microplasma breakdown in the heterogeneity...
known since the 60's of the last century. The basis of any SSPM is a microscopic cell with mesh size of 3-50 µm representing the PN junction with artificially created inhomogeneity in the centre of the junction, which is the hub of the high electric field in the avalanche region.

Parameters of the material around the heterogeneity are chosen so that at the operating voltage the probability of the beginning of microplasma breakdown caused by carriers thermogenerated in region of high-field is very small. In other words, there is a certain threshold number for nonequilibrium charge carriers in the depletion region, starting from which the microplasma breakdown occurs with a probability close to 1. The resulting microplasma must have the property of self-extinguishing, i.e. once created it changes the shape and magnitude of the electrostatic field so that avalanche multiplication stops. Various methods can be applied for this purpose, such as connection of a high resistance sequentially to the PN junction, which acts as a voltage divider decreasing the junction voltage with the increase of its current. Method that is more complex is to select the material properties of the cell so that an avalanche does not develop any further due to the depletion of ionisable impurities in the high-field region.

Based on the description of physical processes, one can see that all SSPM have essentially the same principle of operation – they cannot amplify photons falling on the photodetector, but can amplify photo generated carriers inside silicon. Moreover, the range of SSPM linearity is sufficiently narrow. On the other hand, it is known that the microplasma breakdown areas are the source of wide range spectrum of photons [13], which in turn triggers the neighbouring cells called the phenomenon of after-response or crosstalk.

Still the most significant drawback of SSPM is a quite low radiation hardness compared with photomultipliers, which leads to the need for further study of these devices prior to their use in experiments. However, in cases where the detector loads are low and there are no strict requirements for the material budget the use of these detectors is justified. Commonly, detectors of this kind are zero-angle calorimeter and similar, i.e. detectors placed outside the main detector system and applied for the measurement of the energy distribution of the very forward going projectile nucleons and nuclei fragments. Several examples of such detectors already existing and being constructed for future experiments are further overviewed.

2. Calorimeters NA49, NA61/CERN, FAIR and NIKA

The NA49 is one of the first experiments, where a calorimeter designed with SSPM was applied [1]. Many ideas of construction such a detectors were piloted there further widely used in the construction of new ones. Originally, the NA49 had a Ring Calorimeter and a Veto Calorimeter, designed to measure the energy flow due to the particles produced in nucleus-nucleus collisions. Both calorimeters were of the sampling type composed of sandwiched layers of lead or iron absorber and scintillator plates. The summed light signal from the scintillator plates is proportional to the energy of the particles absorbed in the calorimeter. The device had a cylindrical structure, coaxial with the incident beam, and its sensitive area is circular with an outer diameter of 3.0 m and a 56 cm central hole. It is segmented into 240 cells, 24 sectors in azimuth and 10 rings radially.

During the further upgrades leading to the new being operated nowadays NA61 experiment, the two original forward calorimeters were replaced by the single Projectile Spectator Detector [2]. The PSD calorimeter consists of 44 modules which cover a transverse area of 120 × 120 cm². The central part of the PSD consists of 16 small modules with transverse dimension of 10 × 10 cm², the outer part consists of 28 large 20 × 20 cm² modules. Each module consists of 60 pairs of alternating lead plates and scintillator tiles with 16mm and 4mm thickness, respectively. The stack of plates is tied together with 0.5 mm thick steel tape and placed in a box made of 0.5 mm thick steel. Steel tape and box are spot-welded together providing appropriate mechanical rigidity. The full length of the modules corresponds to 5.7 nuclear interaction lengths. The scintillation light is read out via wavelength shifting fibers by SSPM Avalanche Photo-Diodes (APD). This layout is enough to provide fine granularity corresponding to the beam intensity up to 2 × 10⁵ ions/sec and beam energy up to 150 AGeV.

The Projectile Spectator Detector (PSD) at the Compressed Baryonic Matter experiment of FAIR being built nowadays is a very similar machine with a few minor changes [3]. The calorimeter
comprises 44 individual modules, each consisting of 60 lead/scintillator layers with a surface of $20 \times 20$ cm². Combined with the small beam hole of 6cm diameter it compensates for the very high beam intensity up to $10^9$ ions/sec and energy up to 35 AGeV. The Zero Degree Calorimeter at MPD detector within currently being developed NICA collider is quite similar as well [4]. The prior difference is the number of the modules – 84 pieces and its sizes of $5 \times 5 \times 120$ cm³, as well as the increased beam hole in center of $10 \times 10$ cm² size. This change provides suitable occupancy of the detected particles and therefore transverse segmentation to fit the experimental conditions of beam intensity up to $1 \times 10^9$ ions/sec and energy up to 63 AGeV. The individual geometry of the modules except its transverse sizes for both described detectors is the same as for the NA61 PSD detector.

All afore described detectors are intended to measure the non-interacting nucleons and fragments emitted at very low polar angles in forward direction in nucleus-nucleus collisions. It is used to determine the collision centrality and the orientation of an event plane. Moreover, the precise event-by-event measurement of the energy carried by projectile spectators enables the extraction of the number of interacting nucleons from the projectile with the precision of one nucleon. The high energy resolution of the PSD is important for the study of fluctuations in nucleus-nucleus collisions which are expected to be sensitive to properties of the phase transition between the quark-gluon plasma and hadron-resonance matter. Namely, the PSD provides the precise control over fluctuations caused by the variation of the number of interacting nucleons and thus excludes the "trivial" fluctuations caused by variation of the collision geometry.

For selection SSPM we can use next criteria. Area $S_1$ of SSPM must be selected for maximal load. It is possible in experiment and for linearity of response what we need. For pixel area $A$ and fluence of photons in the bunch $N_{ph}$ from scintillator we must be select $S_1$ from relation $S_1/A > K \cdot N_{ph}$ for number of events $K$. The sensitivity of SSPM must be higher compared with scintillator output. For prototype of CBM module 1MIP produces about 20 photons. From this point of view we can estimate what maximal number of event we can register for SSPM with active area $3 \text{ mm}^2$ for size of the cell $10 \mu \text{m}$ we can obtain $1.5 \times 10^3$ and for other size of $50 \mu \text{m} - 600$ events. Next important parameter is dead-time $T_d$. The dead-time defines the maximal frequencies of events $F_{max} < 1/T_d$. We can not increase area of SSPM in arbitrary way because of noise and increased after-pulsing. All criteria must be applied to select SSPM with respect to irradiation environment.

### 3. Investigation of radiation hardness of SiPM and MPPC

The radiation loads for SSPM were quite small in the first experiments. It seems that the passage of charged particles and gamma radiation will not lead to any substantial problems. The simulation by FLUKA for two months of run shown that the neutron absorbed dose reaches the $10^{13}$ n/cm² [5]. The magnitude of absorbed dose is of the order comparable with the concentrations of impurities in the semiconductor detectors. Therefore, one must consider at least an increase of the detector intrinsic noise. For the optimal detector operation, it is important to know how the noise spectrum changes, since then one can theoretically correct the signal bandwidth of the amplifier and cut off the spectrum parts corresponding to noise. Those considerations are leading to the understanding that the method of processing SSPM signal should be different from the conventional processing techniques of other detectors.

Two additional SSPM investigation procedures were developed within our group, namely measurement and analysis of the Capacitance Frequency Characteristics (CF) and study of transient process of switching the PN junction from an open to a closed state in the detector. Results of CF measurement are processed with help of a simplified model, where the ratio of the average lifetime of minority carriers to their average concentration is the main parameter characterizing the change in the junction after irradiation. This parameter provides a qualitative picture of the processes dynamics of the traps generation in silicon. The second technique based on the switching charge measurement gives an information about the lifetime of minority carriers in the base of PN junction.

Investigated APDs were irradiated at the Cyclotron facility of NPI Řež using quasi-monoenergetic 35 MeV secondary neutron beam with doses indicated at corresponding measurement figures [6]. Doses here are measured by the special PIN diode calibrated for a 1 MeV neutrons equivalent dose; the temperature during the irradiation and measurements was $22 \pm 0.5 \degree C$ [7].
The I-V characteristics of all Ketek PM3375 [8], Zecotek MAPD-3N [9] and Hamamatsu S12572-010P [10] APDs show the increase of the dark current \( I_{\text{dark}} \) in \( \sim 10^3 \) times right after irradiation by dose of \( 10^{13} \) n/cm\(^2\) (figure 1) [8]. Due to self-annealing \( I_{\text{dark}} \) of Zecotek APD increased a bit, but \( I_{\text{dark}} \) of Ketek APD decreased a bit on the contrary. Hamamatsu APD was initially irradiated with a much smaller dose of \( 10^{10} \) n/cm\(^2\) leading to the increase of \( I_{\text{dark}} \) in \( \sim 10 \) times near the operating voltage, which is still a significant change (figure 2).

\[
\tau \frac{\partial n}{\partial t} = \frac{1}{e} \frac{\partial J_n}{\partial x} + \frac{\Delta n}{\tau},
\]

where \( e \) is elementary charge and \( J_n \) is the current through p-n junction.

Based on this, by applying simple substitutions one can achieve:

\[
\frac{1}{C(f)} = \frac{1}{e} \langle \tau \rangle \frac{\Delta \phi}{N_i} \cdot f,
\]

where \( N_i \) is traps levels concentration, \( \Delta \phi \) - voltage modulation applied to p-n junction at frequency \( f \).

Achieved equation (2) is describing the dependence of traps' levels in semiconductor volume on the capacitance of p-n junction and can be extremely useful for the C-F characteristics analysis [12].

C-F characteristics of both Zecotek and Ketek APDs are showing the capacitance increase for high frequencies and the capacitance decrease for low frequencies after irradiation (figure 3a,b). Considering the \( I/C \sim f \) model, this effect can be related respectively to the increase of short-living traps amount and the decrease of long-living traps amount. The delimiting value of traps lifetime to be
considered as short- or long-living is 0.5 µs for Zecotek and 2.5 µs for Ketek. Situation for Hamamatsu APD is different, probably due to its very complicated internal structure. Capacitance and therefore traps amount increased significant for whole frequency range right after the first irradiation with dose of \(10^{10}\) n/cm\(^2\), while no big impact was observed after increase of the dose by roughly two orders of magnitude (figure 4a). A characteristic point can be found corresponding to traps lifetime of 1.8 µs separating the long-living traps having the stable average \(N_t\) with many peaks from the short-living traps having the \(N_t\) increasing with frequency in a stable fashion (figure 4b).

![Figure 3](image1.png)

**Figure 3.** C-F characteristics of APDs before and after irradiation: a) Ketek; b) Zecotek.

![Figure 4](image2.png)

**Figure 4.** Full C-F (a) and relative C-F (b) of Hamamatsu APD before and after irradiation.

4. Conclusion

The conducted investigation shows that the replacement of PMTs by SSPM can be very prominent solution. Still is not clear whether it is possible to apply SSPM as core of tracking detectors near the beam axis in a high granularity systems probably requiring the core detector structure changes. It is necessary to apply more recourses to provide a stable detector operation. For modern detectors operating in high intensity neutron fields it is important to conduct accurate radiation hardness investigations. The main purpose of those studies should be minimization of the detector noise after irradiation caused by partial deterioration of its parameters due to change of detectors internal structure. Study of the CF characteristics shows that the SSPM noise characteristics depend heavily on the production technology. Controlling the bandwidth of readout electronics is one of the ways to improve signal to noise ratio of the detector. Comparing the Ketek, Zecotek and Hamamatsu SSPMs one can conclude that each of them has specific properties, which allows to optimize its operation by combination of various control methods: control of detector's conditions, bandwidth control and signal filtering. Direct measurement of the SSPM noise spectrum is currently under development and will
allow us to specify the further investigation approach to improve detectors parameters during irradiation.

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References
[1] Large Acceptance Hadron Detector for an Investigation of Pb-induced Reactions at the CERN SPS (http://na49info.web.cern.ch/)
[2] NA61/SHINE experiment at the CERN SPS (http://shine.web.cern.ch/)
[3] The CBM experiment at FAIR facility (http://www.fair-center.eu/public/experiment-program/nuclear-matter-physics/cbm.html)
[4] Kekelidze V D et al. (NICA Collaboration) Design and Construction of Nuclotron-based Ion Collider fAcility (NICA) Conceptual Design Report (http://nica.jinr.ru)
[5] Böhlen T T et al. 2014 The FLUKA Code: Developments and Challenges for High Energy and Medical Applications Nuclear Data Sheets 120 211–4
[6] Stefanik M et al. 2014 Neutron Spectrum Determination of the p (35 MeV) - Be Source Reaction by the Dosimetry Foils Method Nuclear Data Sheets 119 422
[7] Kushpil V, Kushpil S and Huna Z 2012 A simple device for the measurement of kerma based on commercial PIN photo diodes EPJ Web of Conferences 24 07008
[8] Ketek PM3350 Datasheet (http://www.ketek.net/products/sipm/pm3350/)
[9] Zecotek WHITE PAPER MAPD Photo-Detectors (http://www.zecotek.com/media/MAPD-WhitePaper-March-2011.pdf)
[10] Hamamatsu S12572-010P Datasheet (http://www.hamamatsu.com/jp/en/S12572-010P.html)
[11] Schibli E and Milnes A G 1968 Effects of deep impurities on n+p junction reverse-biased small-signal capacitance Solid-State Electronics 11 323–34
[12] Kushpil V et al. 2015 Radiation hardness investigation of avalanche photodiodes for the Projectile Spectator Detector readout at the Compressed Baryonic Matter experiment Nucl. Instrum. Meth. A 787 117–20
[13] Mirzoyan R, Kosyra R and Moser H-G 2009 Light emission in Si avalanches Nucl. Instrum. Meth. A 610(1) 98–100