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ScienceDirect

Physics Procedia 74 (2015) 390 – 393

Physics Procedia

Conference of Fundamental Research and Particle Physics, 18-20 February 2015, Moscow, Russian Federation

# The application of SensL silicon photomultipliers in GAMMA-400 satellite project

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**Abstract**

Scientific project GAMMA-400 (Gamma-Astronomy Multifunction Modules Apparatus) relates to the new generation of space observatories for investigation of cosmic $\gamma$-emission in the energy band from ~20 MeV up to several TeV, electron/positron fluxes from ~1 GeV up to ~10 TeV and cosmic-ray nuclei fluxes with energies up to ~$10^{15}$ eV. The core of the scientific complex is gamma-telescope GAMMA-400. It contains a set of detecting systems using so-called "segmentation" principle and consists of a large amount of scintillation elements (~1200 by current apparatus design). The utilization of vacuum PMT as the light sensors for scintillation elements arouses a number of serious problems connected with the apparatus weight and dimensions restrictions, power consumption, reliability requirements and so on. An alternative solution – the application of silicon photomultipliers as the light sensors for scintillation detectors is considered.
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Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)

*Keywords:* GAMMA-400; gamma-telescope; scintillation detector; silicon photomultiplier; SiPM; space project

## 1. Introduction

Space project GAMMA-400 [1-3] is intended for measurements of characteristics of cosmic gamma-emission in the energy band from ~20 MeV up to several TeV, electron/positron fluxes from ~1 GeV up to ~10 TeV and cosmic-ray nuclei fluxes with energies up to ~$10^{15}$ eV by means of GAMMA-400 gamma-telescope [4-6] represents

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doi:10.1016/j.phpro.2015.09.205

the core of the scientific complex. For γ-rays in the energy region from 10 to 100 GeV expected energy resolution changes from ~3% to ~1% and angular resolution from ~0.1% to ~ 0.01% respectively, γ/protons rejection factor is $\sim 5 \cdot 10^5$.

The GAMMA-400 space observatory will be launched on the NAVIGATOR service platform designed by Lavochkin Association at the beginning of the next decade on the high apogee orbit with following initial parameters: apogee altitude ~300000 km, perigee altitude ~500 km, rotation period ~7 days, inclination to the equator plane 51.4º. After approximately half a year the orbit will evolve into an almost circular orbit with radius of ~150000 km, i.e. the observatory will fully leave the Earth's radiation belts. The expected lifetime will be more then 7 years. The planned scientific complex main technical parameters are: total weight ~4100 kg, power consumption ~2000 W, information quote ~100 GByte/day.

## 2. The distinctive features of gamma-telescope GAMMA-400 construction

The core of the scientific complex is the gamma-telescope GAMMA-400 [4-6] contains a set of scintillation detecting systems including:

- anticoincidence system AC and LD (ACtop – top detector, four lateral detectors AClat1–AClat4 and four lateral calorimeter detectors LD1–LD4);
- time-of-flight system TOF (two detectors S1, S2);
- scintillation detectors of calorimeter SDC (two detectors S3, S4);
- position-sensitive calorimeter CC (position-sensitive converter-calorimeter CC1 and total-absorption calorimeter CC2);
- neutron detector ND.

The gamma-telescope detecting systems use so-called "segmentation" principle and consist of a large amount of scintillation elements (~1200 by current apparatus design). The utilization of vacuum PMT as light sensors for scintillation elements arouses a number of serious problems connected with the apparatus weight and dimensions restrictions, power consumption, reliability requirements and so on. Therefore, the application of silicon photomultipliers (SiPM) as light sensors for scintillation detectors is the reasonable approach. Total amount of scintillation sensors in detecting systems of the gamma-telescope GAMMA-400 exceeds several thousands pieces (see Table 1) and the requirements of the highest sensor performance, uniformity, and reliability combined with the lowest-cost are very important. That is the reason we have chosen the SiPM sensors from SensL (Cork, Ireland) as a fully complied with these requirements for high-volume applications [7].

Table 1. The light sensors amount for scintillation detecting systems of GAMMA-400 telescope (by current apparatus design).

| Detecting System | Scintillator | Wavelength of maximum emission | Scintillation elements number | SiPM number |
|---|---|---|---|---|
| AC, LD, TOF, SDC | BC-408 | 425 nm | 260 | 3120 |
| CC | CsI(Tl) | 550 nm | 904 | 7232 |
| ND | $ZnS(Ag)+^6LiF$ | 450 nm | 20 | 400 |

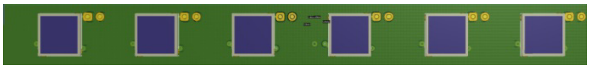
The construction of ACtop, AClat1-AClat4, LD1-LD4 and S1-S4 detectors is similar. Each of them consists of two layers of scintillator paddles made of a 10 mm thick polyvinyltoluene scintillator BC-408. The paddles in neighbor layers are parallel oriented and slightly shifted relative to each other providing the overlapping of construction slits, to avoid geometrical inefficiencies. The dimensions of paddles are 1200x120 $mm^2$ for ACtop (20 paddles total), 544x120 $mm^2$ for AClat1-AClat4 (80 paddles total), 1060x120 $mm^2$ for LD1-LD4 (80 paddles total) and 1000x100 $mm^2$ for S1-S4 (80 paddles total). Each paddle is viewed from both opposite shortest ends by six silicon photomultipliers mounted on four-layer printed circuits boards (PCB).

The position-sensitive calorimeter CC consists of two layers of CsI(Tl) scintillation crystals with dimensions of 333×50×20 $mm^3$ (position-sensitive converter-calorimeter CC1, 120 scintillation crystals) and a block of

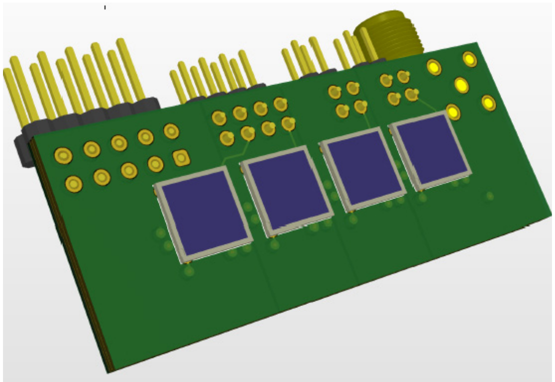
36×36×430 $mm^3$ CsI(Tl) scintillation crystals (total-absorption calorimeter CC2, 784 crystals). All scintillators are viewed by mounted on PCB four silicon photomultipliers from both opposite shortest ends of scintillation crystals.

The neutron detector ND consists of three layers of polyethylene neutrons moderator interleaved with two layers of 0.45 mm (ZnS(Ag)+$^6$LiF) scintillation screen foil, each situated between two polymethyl methacrylate (PMMA) light guides with dimensions of 1000×100×15 $mm^3$ (20 scintillation blocks). Each scintillation block is viewed by ten silicon photomultipliers from both opposite shortest ends.

The signals from SiPM modules arrive to the set of front-end electronics for subsequent processing. The energy thresholds and a number of other electronics parameters can be changed by means of program control commands. The front-end electronics of SiPM blocks includes temperature compensation circuits to adjust for the change in overbias with changing temperature. Fig. 1. shows the example of SiPM moduless for two types of gamma-telescope scintillation sensors.



a)



b)

Fig. 1. The example of SiPM modules manufactured for scintillation sensors prototypes a) AC, LD, TOF, SDC; b) CC1.

The most important parameters for selection of optimum light sensors for space gamma-telescope scintillation detectors are: wide operating temperature range; reliability and radiation tolerance; photon detection efficiency (PDE) at wavelength of maximum scintillator emission (λe) and peak wavelength (λp); gain; crosstalk and afterpulsing level; dark count rate (DCR); rise and recovery time of SiPM microcell; number of microcells and microcell fill factor effected on the sensor dynamic range.

For SensL SiPM in SMT, MLP and TSV packages (see [9-11] for details) the operating temperature range is -40°C to +85°C that satisfy the orbital conditions of the GAMMA-400 apparatus.

SensL follows industry standard reliability test flows designed for integrated circuits modified as needed to suit the SiPM sensor. The test flows [7] are performed on multiple wafer production and package assembly batches for each product type. All stress and test steps carry out as per JEDEC (JESD22-A108D) standard conditions. The value MTTF=$0.9 \cdot 10^9$ hours is declared by SensL producers for MicroFB and MicroFC SMT devices (private communications). This value is quite enough for reliability requirements compliance.

In accordance with the data of radiation hardness tests of SensL products [8] one can make following conclusions. Single event type occurrences are not applicable to SiPM devices. Only a moderate increase in dark current occurred below breakdown at list up to 150 krad of total ionization dose (TID) for gamma-irradiation and therefore the effects of TID on SiPM sensors is negligible. For proton and neutron irradiation due to displacement damage, the dark current increase with the fluence. At fluence below ~$10^8$ p(n)/$cm^2$ the effect is very small, at $3.7 \cdot 10^9$ p(n)/$cm^2$ the dark current increases by factor of ~10 and the output amplitude dropped by about 10%, and at ~$10^{12}$ p(n)/$cm^2$ the dark current increase by factor of ~$10^3$. After 50 days of annealing at room temperature, the dark count level is recovered by 50%. All these factors restrict the operating time of GAMMA-400 apparatus in radiation conditions of the high apogee orbit by about 10-15 years.

The values of other most important parameters of SensL silicon photomultipliers that satisfy the requirements of detecting systems of GAMMA-400 gamma-telescope are listed in Table 2.

Table 2. The basic parameters of SensL SiPM most suitable for scintillation detecting systems of GAMMA-400 telescope ($V_{br}$=24.5V is the recommended breakdown voltage; all data correspond to $V_{br}$+2.5V except separately specified cases).

| Parameter | MicroFC-60035-SMT (6x6 mm$^2$) [9] | MicroFJ-60035-TSV (6x6 mm$^2$) [10] | MicroFR-10035-MLP (1x1 mm$^2$) [11] |
|---|---|---|---|
| Peak wavelength λp (nm) | 420 | 420 | 635 |
| PDE at λp/or 550 nm (%) | 31/15 at $V_{br}$+2.5V<br>41/21 at $V_{br}$+5.0V | 37/- at $V_{br}$+2.5V<br>51/26 at $V_{br}$+5.0V | -/- at $V_{br}$+2.5V<br>47/47 at $V_{br}$+5.0V (~40 at 425 nm) |
| Gain, anode to cathode readout | $3\cdot10^6$ | $3\cdot10^6$ | $3\cdot10^6$ |
| Gain, fast output readout | $4.3\cdot10^6$ | - | - |
| Rise time, fast output (ns) | 1 | 0.36 | 0.3 |
| Pulse width, fast output (FWHM) (ns) | 3.2 | - | - |
| Microcell recovery time (ns) | 210 | 108 | 108 |
| Crosstalk (%) | 7 | 7.5 | - |
| Afterpulsing (%) | 0.2 | 0.2 | - |
| DCR (kHz/mm$^2$) | 35 | 35 | 35 |
| No. of microcells (fill factor) | 18980 (64%) | 22300 (76%) | 622 (76%) |

In accordance with Table 1, 2 all three listed SensL light sensors are suitable. However, the most suitable sensors for BC-408 and (ZnS(Ag)+$^6$LiF) based devices are MicroFJ-60035-TSV or MicroFC-60035-SMT and for CsI(Tl) based devices - MicroFJ-60035-TSV or MicroFR-10035-MLP if the area of last one can be enlarged up to 6x6 mm$^2$.

## 3. Conclusions

The silicon photomultipliers manufactured by SensL were implemented as the light sensors for scintillation detectors of GAMMA-400 gamma-telescope. The measurements were carried out at the prototype [12] of the gamma-telescope for investigation of the efficiency, amplitude and temporal properties of fast plastic BC-408 based large area scintillation detectors, calorimeter detectors based on CsI(Tl) scintillation crystals and (ZnS(Ag)+$^6$LiF) based neutron detector. The correspondence of measuring characteristics to the requirements of detecting systems of gamma-telescope was obtained.

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