The investigation of the internal structure of SiPM from KETEK, ZECOTEK, HAMAMATSU and SENSL manufacturers after the neutron irradiation.

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Introduction

Modern avalanche photodiodes (APDs or SiPMs) with high gain are excellent device candidates for the light readout from detectors used for the high energy physics experiments. The SiPMs are proposed as a main option for the light readout for Forward Wall Detector (FWD) at the BM@N [1] in the heavy-ion program at NICA [2]. Another application of SiPMs is the Projectile Spectator Detector (PSD) for the Compressed Baryonic Matter (CBM) project experimental program [3] for fixed target heavy ion collisions at FAIR in future.

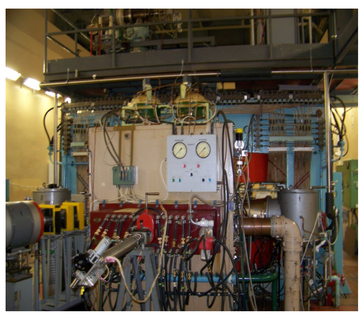
The main advantages of SiPMs are very compact sizes, low bias voltage, gain comparable to that for standard photo-multiplier tubes (PMTs), relatively low price, insensitivity to magnetic field and absence of nuclear counter effect (due to the pixel structure). SiPMs have the following typical properties: pixel density about 10^4 - $2x10^4$ / mm^2 , size of 3×3 mm^2, high dynamical range of 5–15000 ph.e., photon detection efficiency of ∼15%, high counting rate of 10^7 Hz. The radiation hardness of SiPMs, especially to neutrons, plays a significant role for the the detectors placed in the forward direction. For instance, according to FLUKA simulation [4] neutron flux near the beam hole might achieve 10^{12} neutrons/cm^2 for beam energy 4 A·GeV and 2 months of CBM run at the beam rate 10^8 ions per second [5] We report the results of the SiPMs radiation hardness study.

Four types of SiPM produced by Zecotec [6], Ketek [7], Hamamatsu [8], SENSL [9] were investigated to understand dependences of SiPMs radiation hardness on the manufacturing technology. The operational voltage and neutron fluence equivalent to neutrons with energy of 1 MeV for these types of SiPMs are given in table 1.

SiPM type	V_{bias}, V	Neutron fluence (1Mev), n/cm2	Density impurities produced in W_{depl}, 1/cm^3	Temperature during irradiation, ^{0}C
Zecotek MSiPM-3N	88.5	$3.4 \pm 0.2 \cdot 10^{12}$	$2.47 \pm 0.65 \cdot 10^{10}$	22 ± 0.5
Ketek PM3350	23.5	$2.5 \pm 0.2 \cdot 10^{12}$	$1.31 \pm 0.43 \cdot 10^{11}$	22 ± 0.5
Hamamatsu S12572-010P	69.2	$3.9 \pm 0.5 \cdot 10^{12}$	$1.12 \pm 0.16 \cdot 10^{12}$	22 ± 0.5
SENSl uF B30020	25.0	$4.2 \pm 0.2 \cdot 10^{8}$	$4.49 \pm 0.12 \cdot 10^{11}$	23.1 ± 0.2

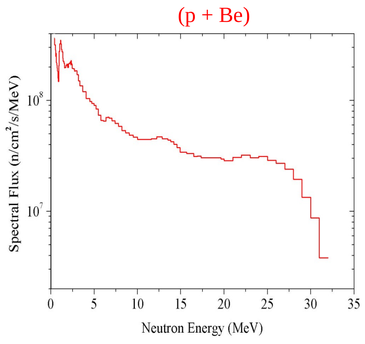
Cyclotron U120M facility

The SiPMs were irradiated using quasi-monoenergetic 35 MeV and “white-spectrum” secondary neutron beams from cyclotron facility U120M at NPI of ASCR, Řež. The setup for the beam fluence control and measurements of the irradiated SiPMs properties is described in [10].

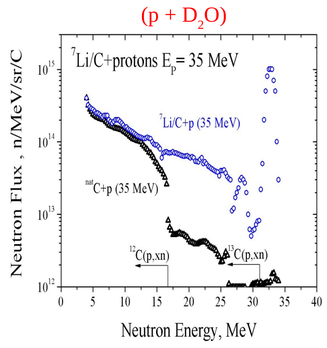


accelerated ions	energy [MeV]	extracted currents [μA]
H^-	6 - 38	15 - 35
H^+	6 - 38	3
d^+	11 - 20	3
$^3He^{2+}$	16 - 55	3
$^4He^{2+}$	22 - 40	3

(p + Be)



(p + D_2O)



Mono-energetic 20-37 MeV

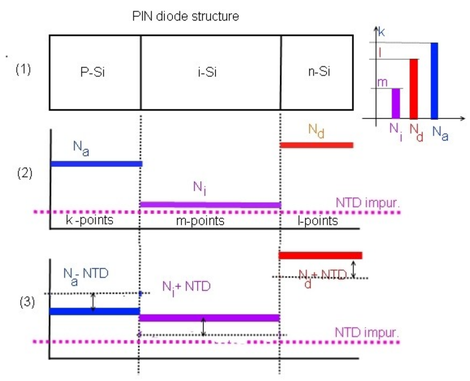
(p+^{7}Li) source: 3 x10^9 [n/cm²/s]

Maximal flux:

(p + Be) source: ~ 10^8 - 10^9 [n/cm²/s]

(p + D_2O) source: ~10^{11} [n/cm²/s]

Change of Si doping by neutrons



It is based on the conversion of the Si-30 isotope into phosphorus atom by neutron absorption:

30Si(n,γ) 31Si → 31P + β- (T½ =2.62h)

Neutrons continue to pass through the silicon, more and more phosphorus atoms are produced by transmutation, therefore, the doping becomes more and more strongly n-type.

HAMAMATSU

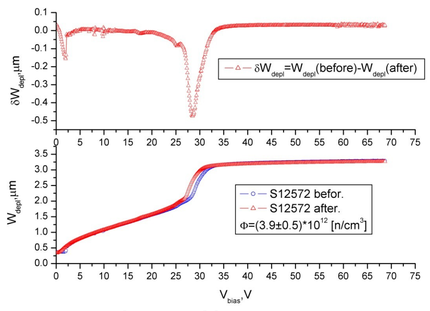


Fig. 1.1 Depletion width vs. V_{bias}

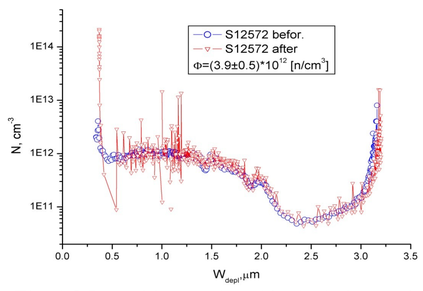


Fig. 1.2 Impurities produced in depletion region

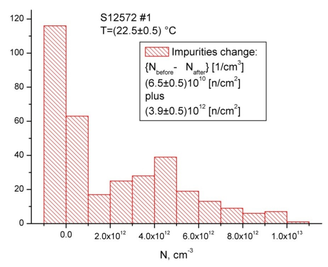


Fig. 1.3 The change of impurities after irradiation

Internal structure of HAMAMATSU changed more near surface, that can decrease sensitivity for blue light. Moreover, after irradiation detector is depleted for higher voltages. It can decrease sensitivity for light of long wavelength.

After first irradiation fife of tine to concentration ratio change not so strong as from beginning. Specific region from f_1 to f_2 was observed, where noise increase more than for other frequencies.

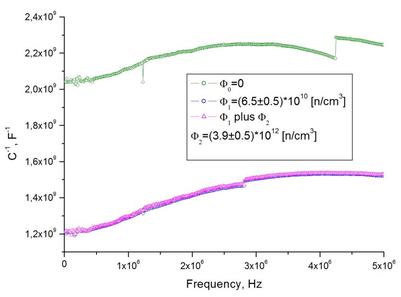


Fig. 1.4 Capacitance versus frequency

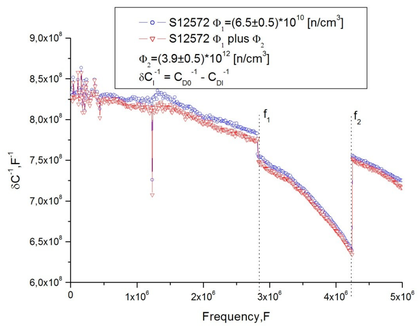


Fig. 1.5 Variation of capacitance before and after irradiation

KETEK

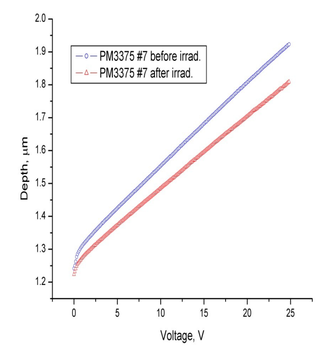


Fig. 2.1 Depletion width vs. V_{bias}

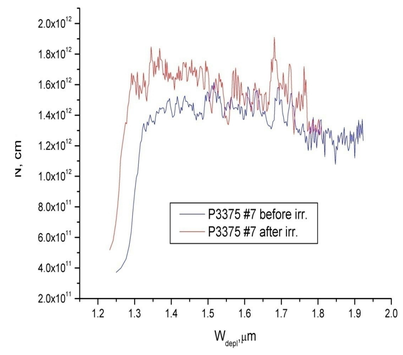


Fig. 2.2 Impurities produced in depletion region

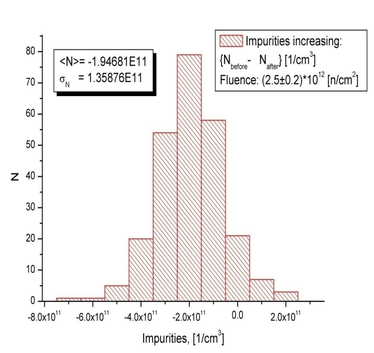


Fig. 2.3 The change of impurities after irradiation

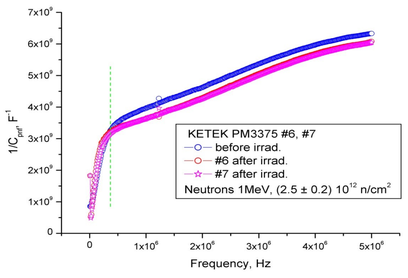


Fig. 2.4 Capacitance versus frequency

Internal resistance of KETEK SiPM decreases after irradiation that can be observed on Fig. 2.1 as depletion region shortening for the same voltages as before irradiation.

Generation–recombination noise $\delta<N_t^2>$ depends on characteristics in Fig.2.4 *$\delta<N_t^2>/N_t \sim (4\tau_n/(1+(\omega\tau_n)))$; $\tau_n/N_t \sim 1/C(\omega)$; where Nt - average number of carriers from traps, τ_n — carrier lifetime; $\omega=2\pi f$; f - frequency [12,13].*

Generation–recombination noise decreases for low frequency, but increases for high frequency.

We use KETEK SiPM for readout scintillator’s hodoscopes during neutron beam test. Decrease of gain and increase of internal noise due to neutrons were observed. Hodoscope system was developed in JINR for position monitoring of neutron beam for Cyclotron U120 in NPI Rez.

ZECOTEK

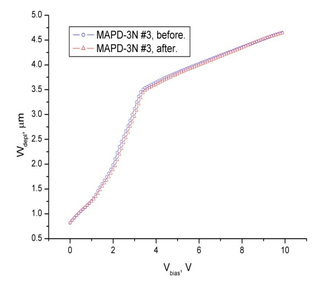


Fig. 3.1 Depletion width vs. V_{bias}

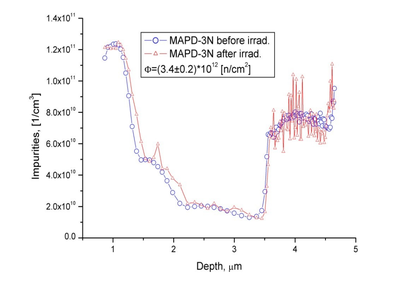


Fig. 3.2 Impurities produced in depletion region

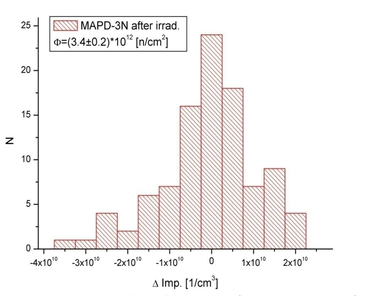


Fig. 3.3 The change of impurities after irradiation

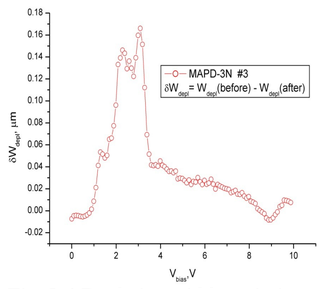


Fig. 3.4 Depletion width variation vs. V_{bias}

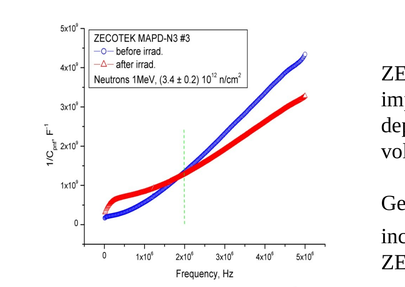


Fig. 3.5 Capacitance versus frequency

ZECOTEC has more symmetric change of impurities in depletion region. As a result, depletion region is more stable versus biasing voltage.

Generation–recombination noise $\delta<N_t^2>$ increases for more high frequencies for ZECOTEK compared to KETEK.

SENSL SIPM

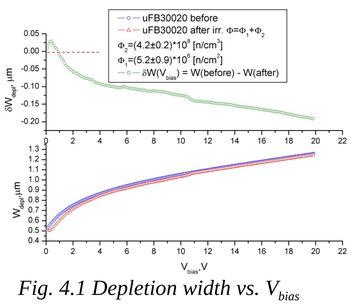


Fig. 4.1 Depletion width vs. V_{bias}

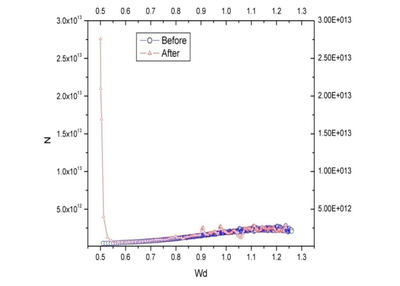


Fig. 4.2 Impurities produced in depletion region

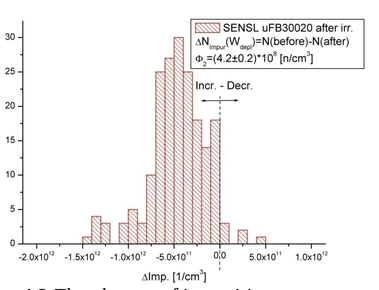


Fig. 4.3 The change of impurities after irradiation

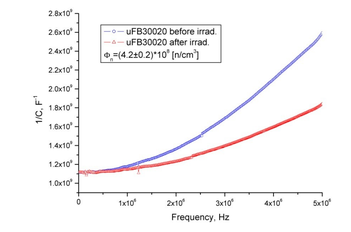


Fig. 4.4 Capacitance versus frequency

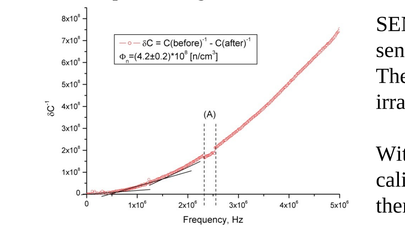


Fig. 4.5 Variation of capacitance before and after irradiation

SENSL compared to HAMAMATSU is more sensitive to irradiation in region near surface. Thermal neutrons flux was higher during irradiation of SENSL.

With help of neutron monitoring system calibrated for 1MeV neutrons, the part of thermal neutrons flux can be estimated.

Detector developed in JINR, Dubna was used for neutron monitoring. Generation–recombination noise increases homogeneity for all frequencies.

SUMMARY

- Influence of neutron irradiation on change of the concentration of internal doping inside Si active region was observed for all investigated detectors;
- Depending on internal topology of detectors we observe two kinds of behavior after irradiation: 1) Detectors with simple topology such as KETEK and SENSL; 2) Detectors with more complex topology - HAMAMATSU and ZECOTEK;
- Histograms of concentration show that HAMAMATSU, KETEK, SENSL SiPMs have more asymmetrical topology than ZECOTEK;
- Ratio of lifetime to concentration of minority carriers (Tau/N) demonstrates different behaviors of recombination-generation processes after irradiation;
- Difference in neutron fluence and number of generated impurities in active region for SENSL (Table 1) can be explained as result of higher fluxes of thermal neutrons during last irradiation;

Conclusion: We detect influence of neutron flux level on detector doping material. Different behavior of Tau/N ratio was observed, it can be detected independently by comparison of intrinsic noise spectrum of detectors after and before irradiation. It can be useful for development of readout electronics and improvement of detector technology.

Acknowledgments & References

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