AlGaN photocathodes and Schottky diode for BaF_2 scintillator detectors

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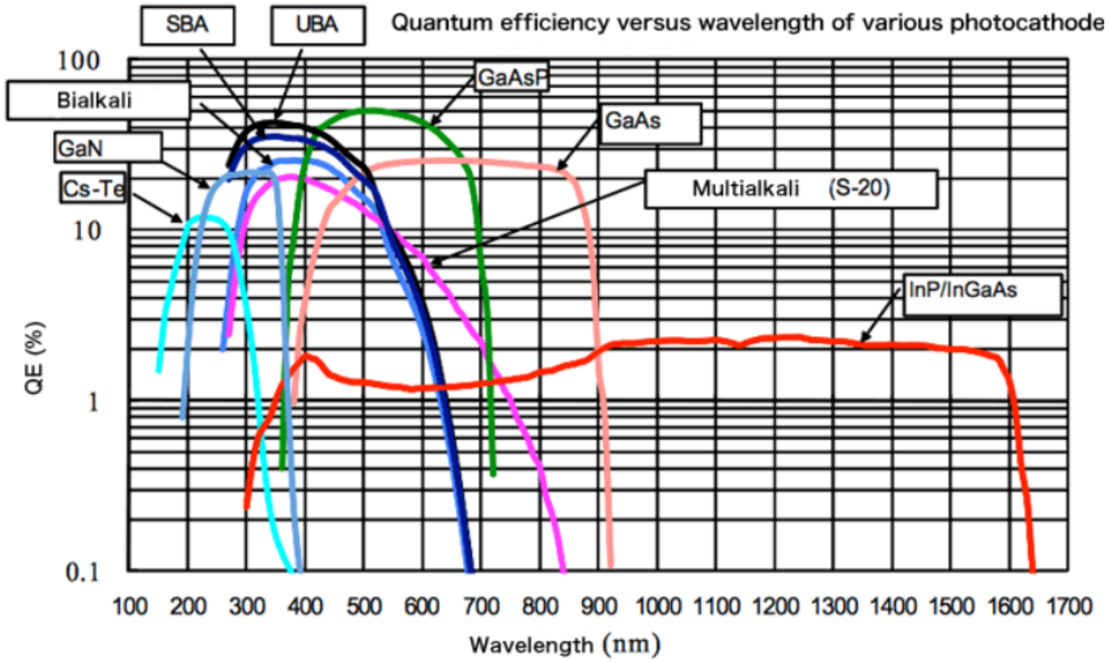
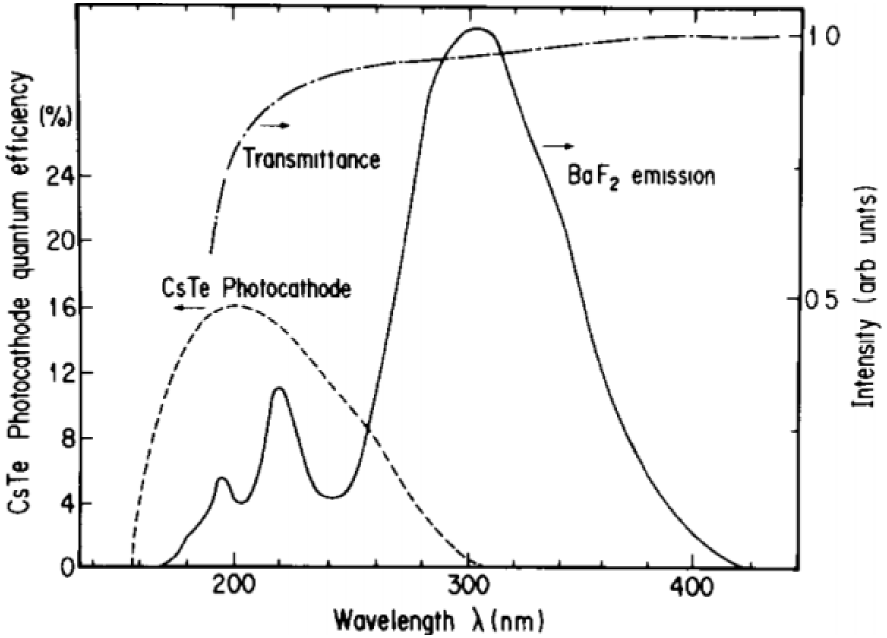
Outline

1. Introduction
2. AlGaN as a material for BaF_2 fast component selection
3. AlGaN heterostructures for photocathodes description
4. MCP PMT+ BaF_2 detector. Cosmic ray measurements setup
5. Cosmic ray energy spectrum measurements
6. BaF_2 + photodetector signal model
7. Schottky diodes for BaF_2 fast component

Photocathode material selection for UVC range



Hamamatsu. Photomultiplier tubes

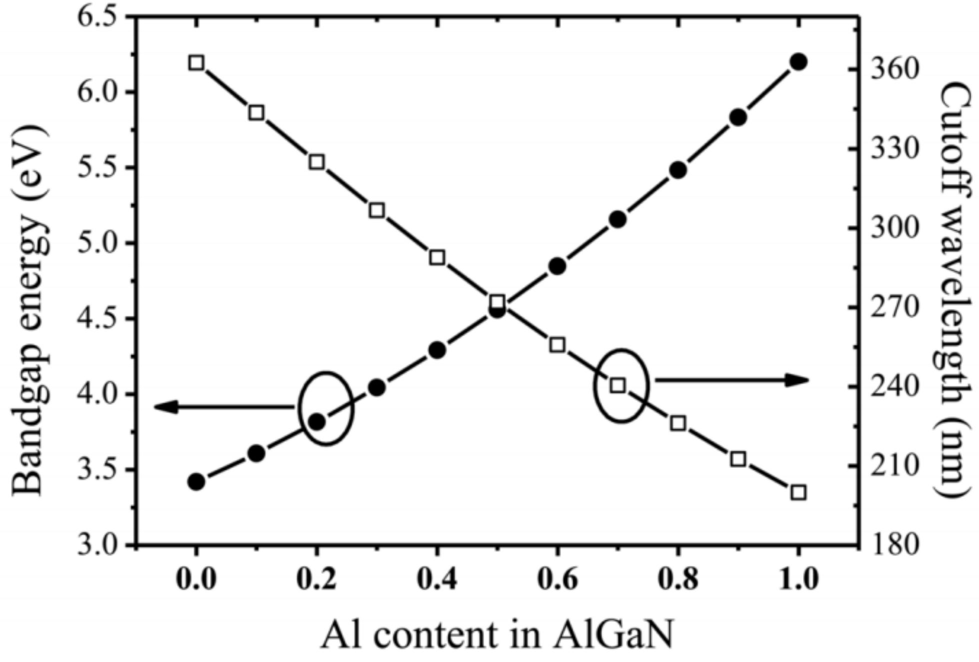


M. Kobayashi et al., *Nucl. Instrum. Meth. A*, **270**, 106 (1988)

CsTe, GaN/AlGaN, bi-alkali photocathodes are suited for BaF_2 fast emission component detection.

Solar-blind photocathode with threshold wavelength ~300 nm allows us to get slow to fast emission components ratio ~1.

Wide-bandgap semiconductor alloy $Al_xGa_{1-x}N$ with bandgap control



L.Sang et al., Sensors 2013, 13, 10482-10518

Threshold wavelength in semiconductor layer is determined by bandgap width.

A bandgap width as a function of Al mass fraction in AlxGa1-xN alloy. Al mass fraction should excess 40% to work in UVC range.

$$Eg = (1 - x)*Eg(GaN) + x*Eg(AlN) - b*x*(1 - x)$$

Quality of AlGaN layers is the key parameter for photodetector performance. Typical dislocations value for AlGaN layers grown on cheap sapphire substrate is 10^9-10^{10} cm^{-2} => photodetector QE decreases

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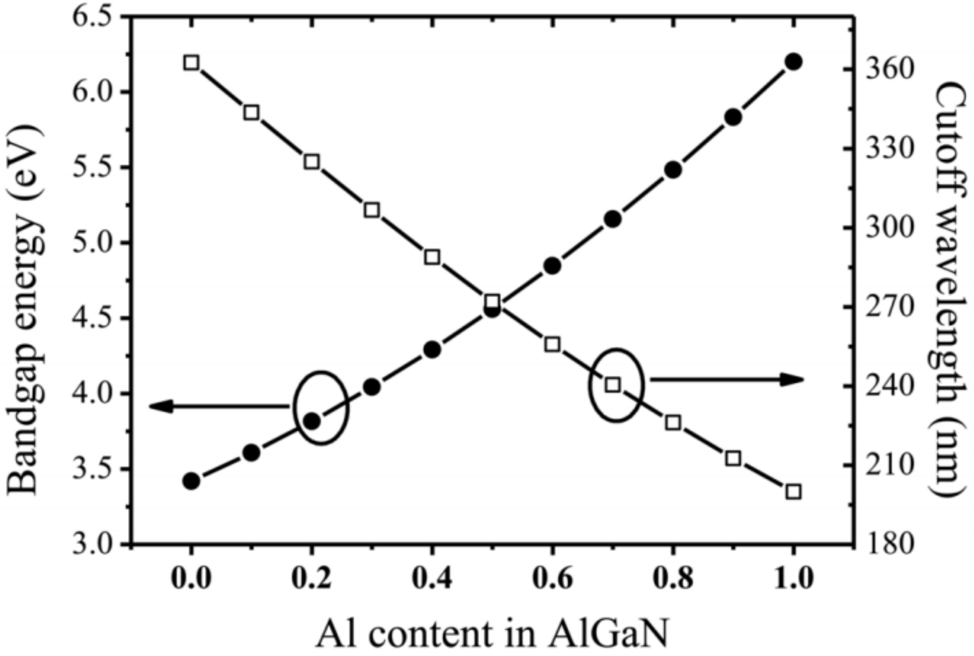

L.Sang et al., Sensors 2013, 13, 10482-10518

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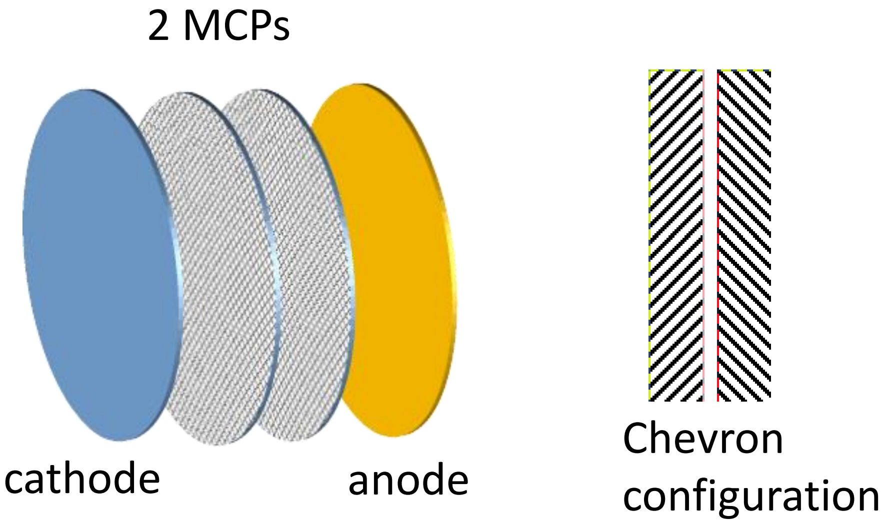
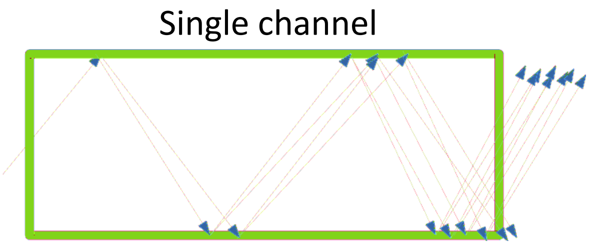
$$E_g = (1 - x)*E_g(GaN) + x*E_g(AlN) - b*x*(1 - x)$$

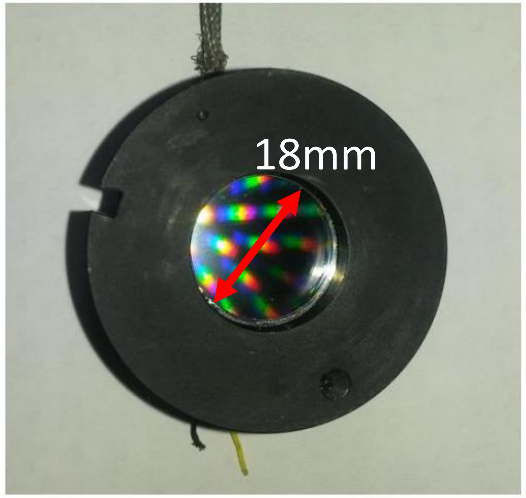
Fortunately, GaN is direct bandgap semiconductor => electron transition probability increases => higher photodetector QE even with high dislocations density.

Photomultiplier with microchannel plates and AlGaN cathode



- gain 10^6

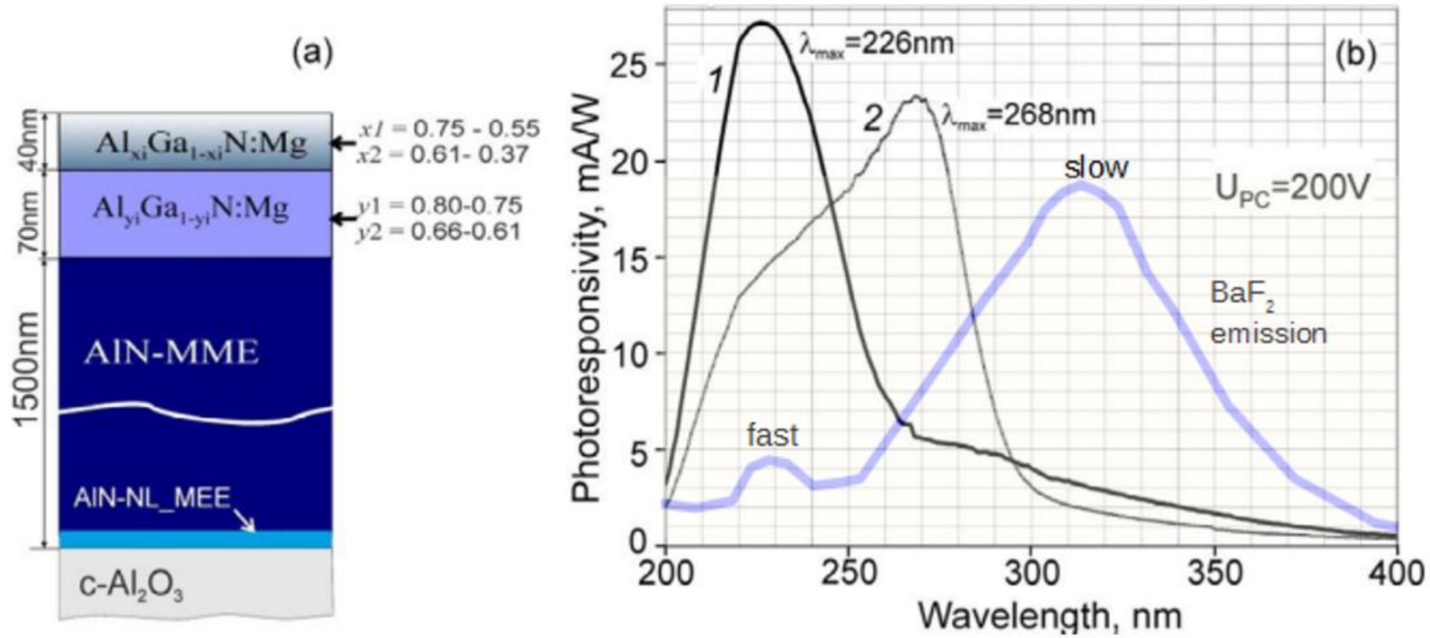




MCP consist of 2-D array of microscopic 30 um diameter lead glass capillaries placed on thin substrate. Electron from cathode goes to channel and produces secondary electrons by interacting with channel walls.

AlGaN cathodes with cut at 260 and 280 nm were assembled with 2 MCPs and anode in metal package to produce device which has 18 mm input window.

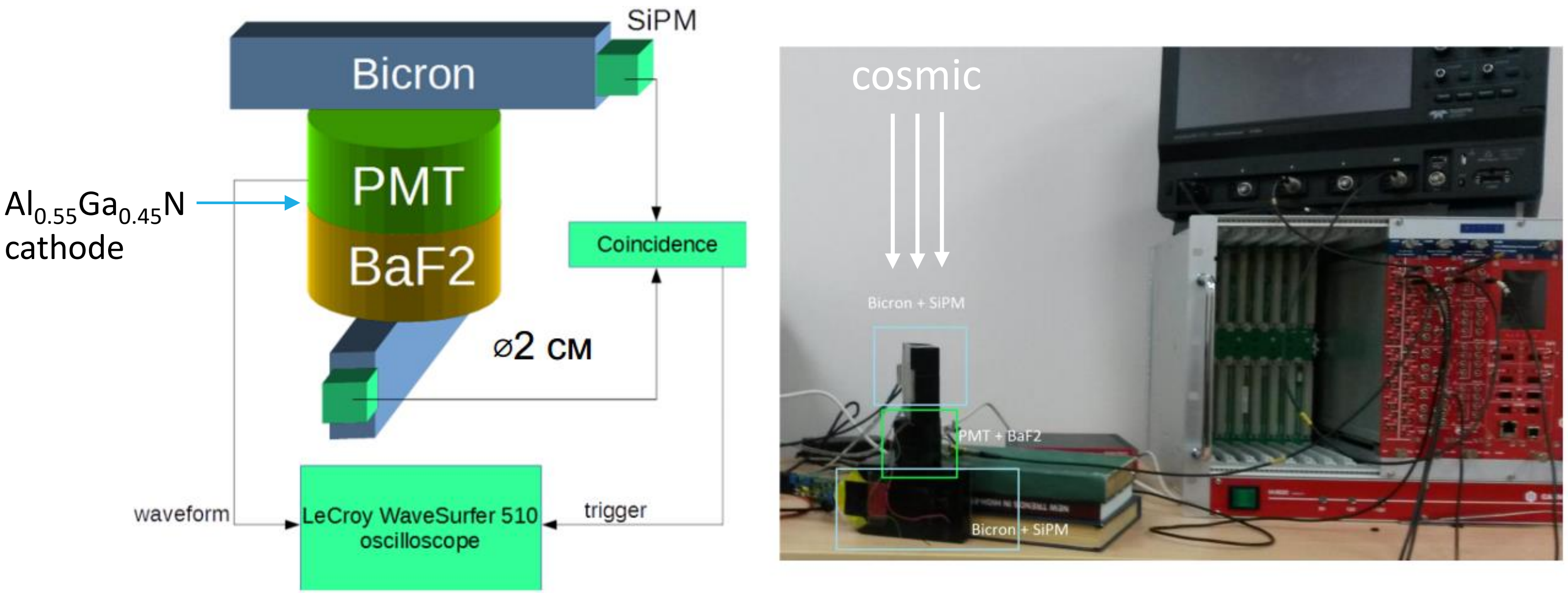
Photomultiplier with microchannel plates and AlGaN cathode



Dark current	~1uA at 23°C
	~1nA at -5°C

Scheme of AlGaN-structures used to produce photocathodes (a) and MCP device sensitivity spectrum on BaF2 emission spectrum background (b). There are conductive p-type layers $Al_xGa_{1-x}N:Mg$ with Al fraction x>0.5, grown with polarization doping and linear gradient of Al mass fraction: from 0.8 to 0.55 (b,1) and from 0.66 to 0.37 (b,2).

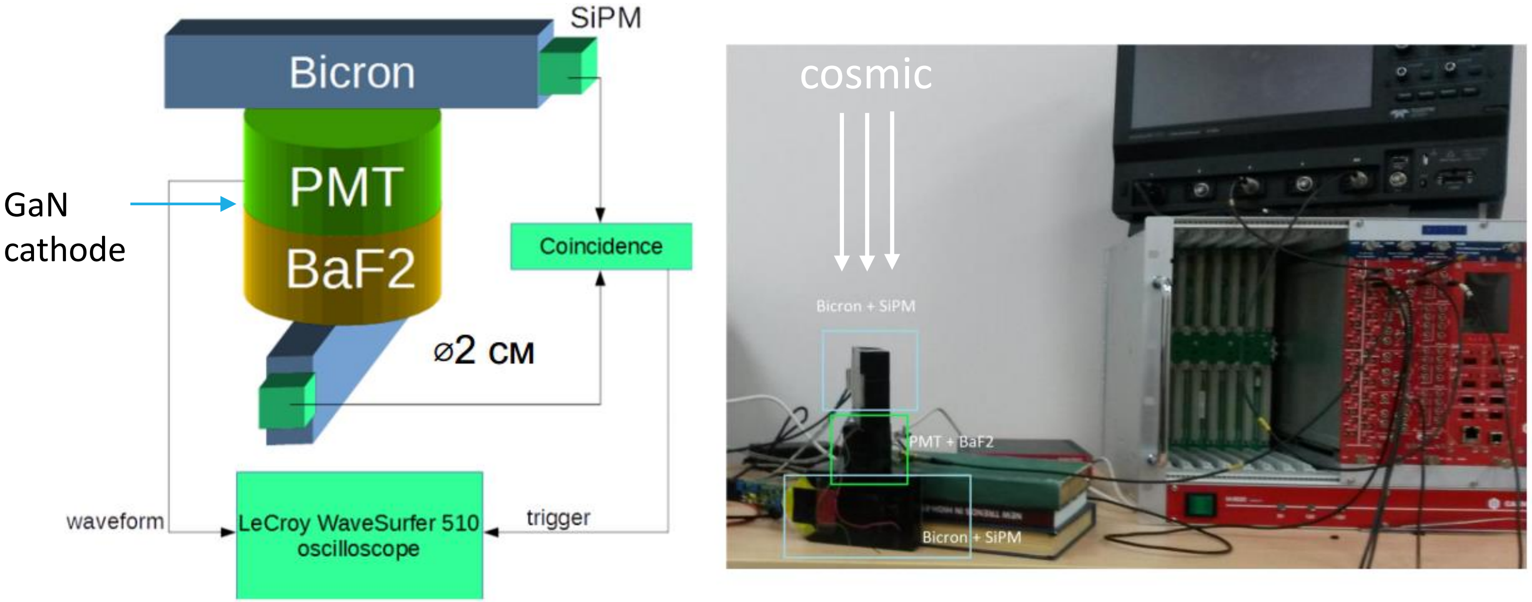
Cosmic ray test with BaF_2 scintillator



Experimental setup to measure energy losses spectrum for zenith cosmic rays.

MCP device with the most short-wavelength cathode (peak at 226 nm) was used to create scintillation detector with BaF_2 crystal. Cylindrical crystal with height of 1 cm and 2 cm diameter was connected with photomultiplier and wrapped with Teflon tape.

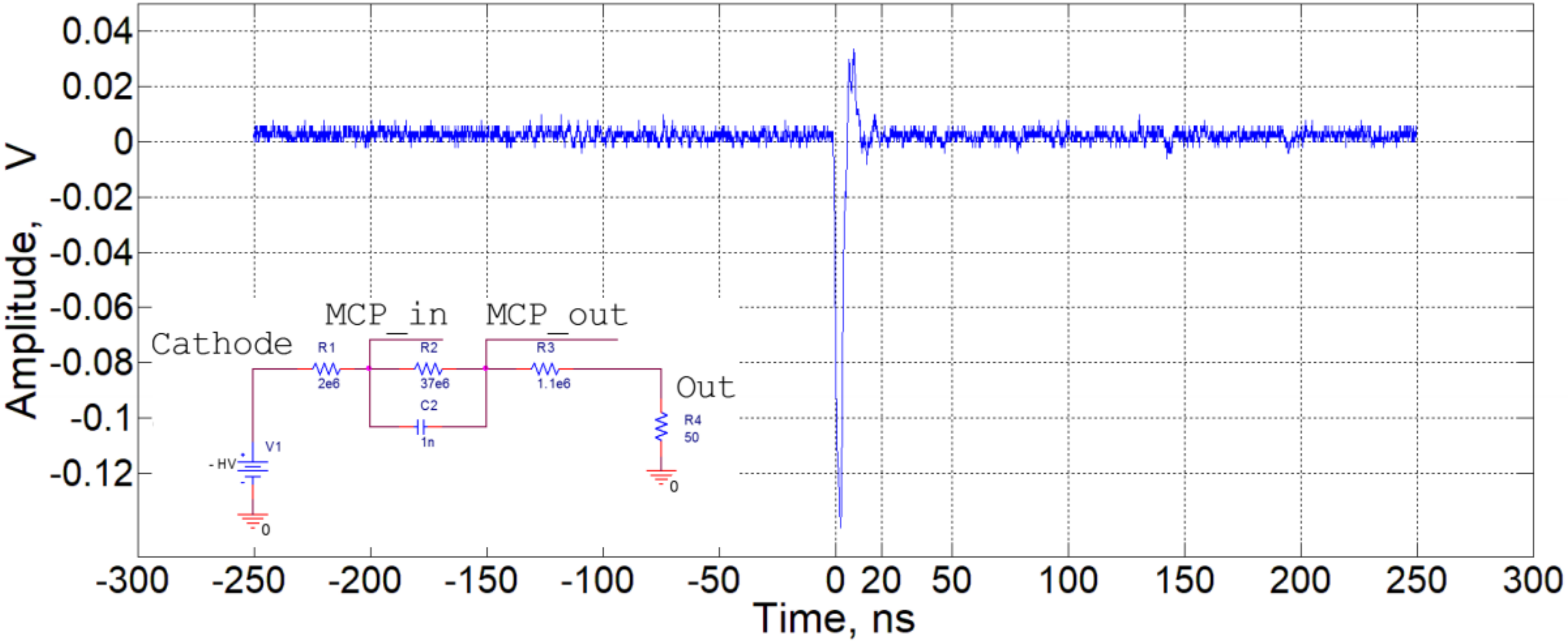
Cosmic ray test with BaF_2 scintillator



Experimental setup to measure energy losses spectrum for zenith cosmic rays.

To compare measurement results we used similar commercially available MCP PMT with GaN cathode (in fact $Al_xGa_{1-x}N$ with small Al mass fraction x<0.1)

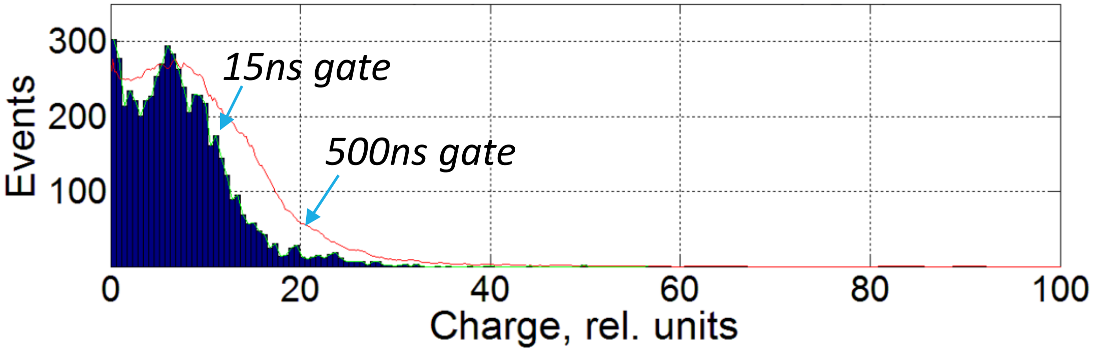
Cosmic ray test with BaF$_2$ scintillator. Typical response



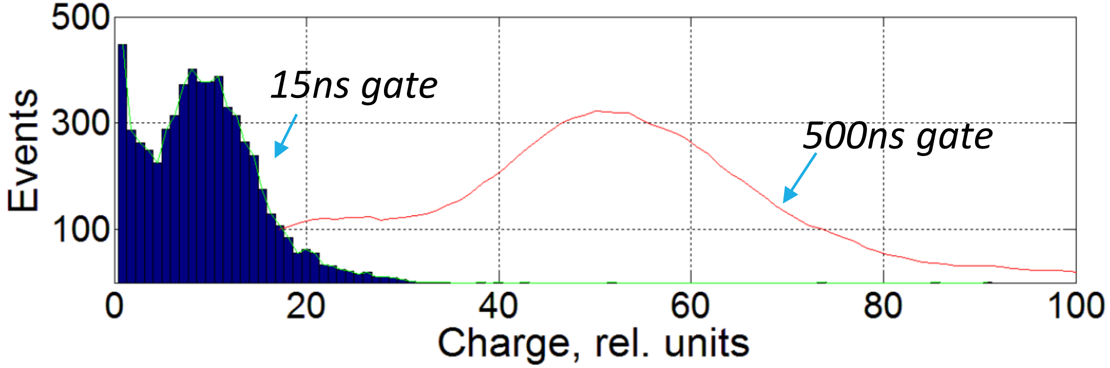
Typical response of BaF$_2$ + MCP device with Al$_{0.55}$Ga$_{0.45}$N:Mg cathode for zenith cosmic rays. One can see sharp fast component response, and slow component signal for time less than 20 ns goes to noise level.

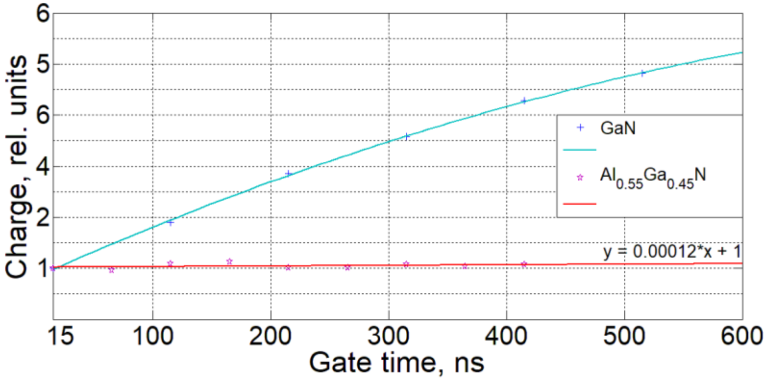
Cosmic ray test with BaF_2 scintillator. Charge spectrum

with $Al_{0.55}Ga_{0.45}N:Mg$ cathode



with GaN cathode





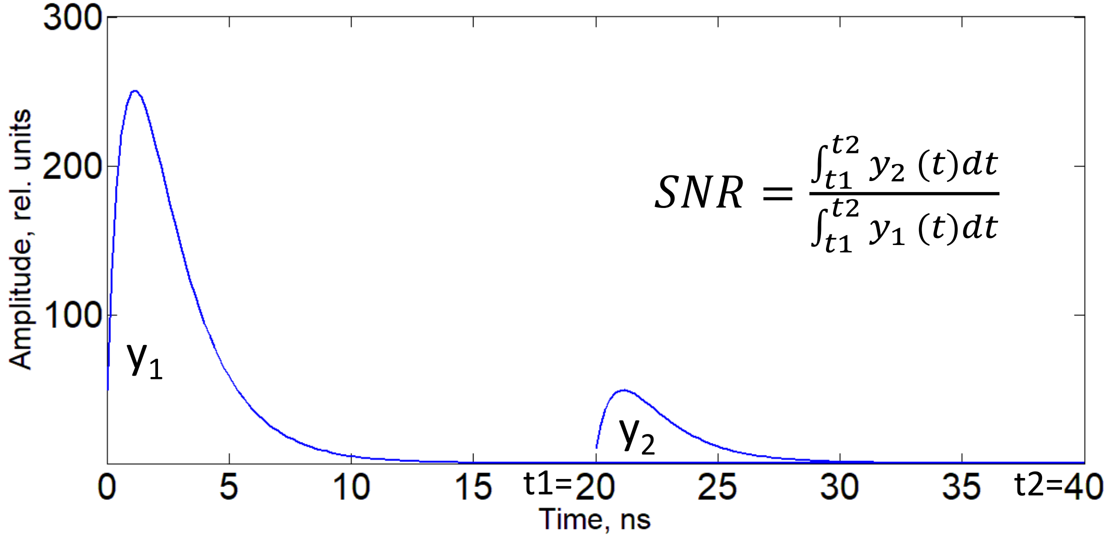
Relation to 15ns charge (≈ fast charge) vs. gate time

For $Al_{0.55}Ga_{0.45}N$ cathode gate time increasing doesn't affect restored charge value dramatically, while for GaN cathode the charge changes significally.

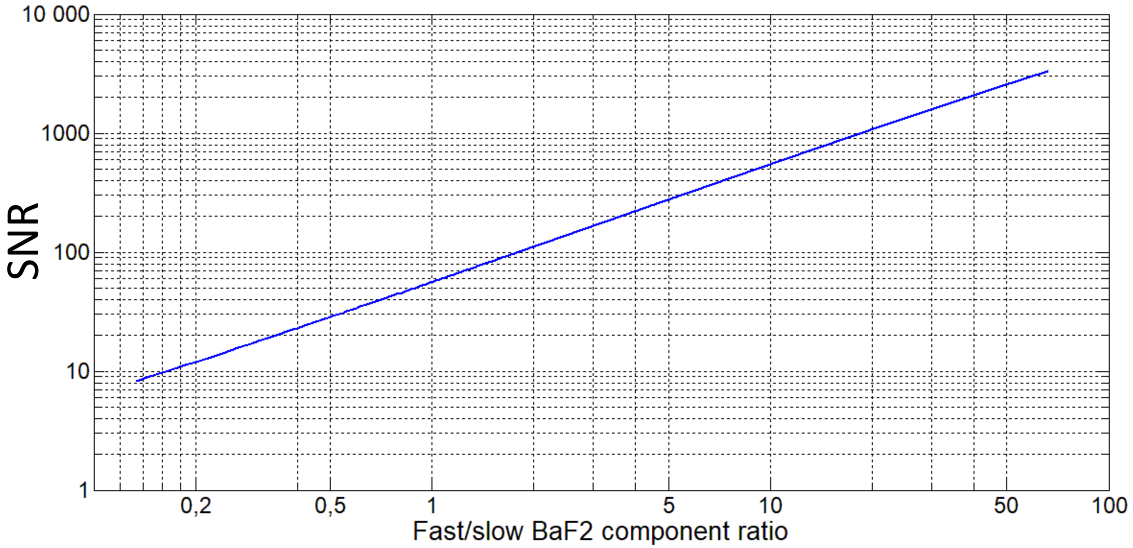
So for 600 ns gate registered slow/fast ratio ≈ 1/14

BaF$_2$ + detector signal model

The better we suppress slow component the lower a «noise» pedestal is, SNR is growing



$$SNR = \frac{\int_{t1}^{t2} y_2(t)dt}{\int_{t1}^{t2} y_1(t)dt}$$



For bandwidth f0 = 80 MHz

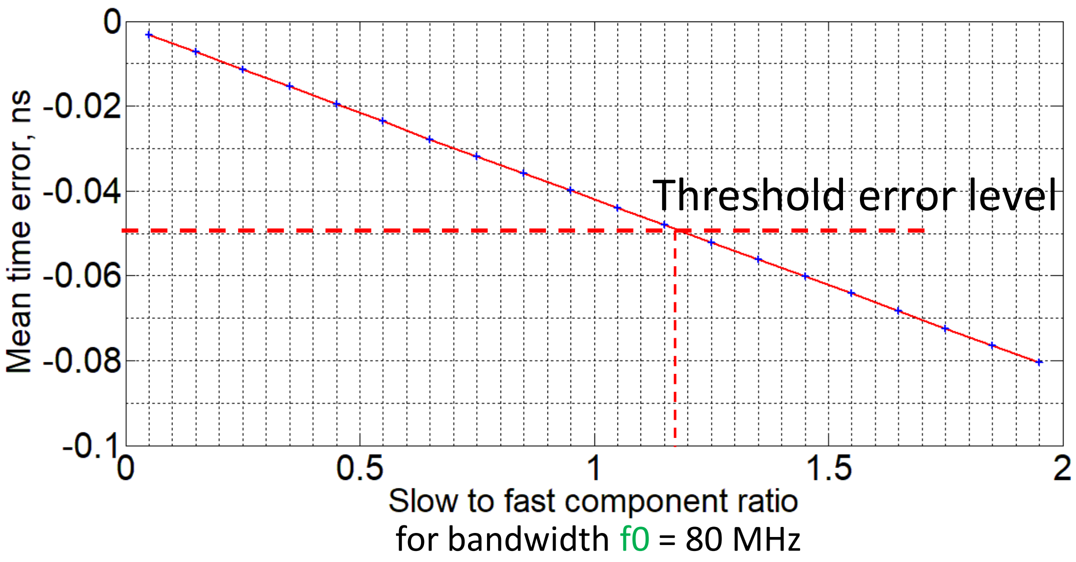
$$\begin{cases} J(t) = Ae^{-\frac{t}{\tau_{fast}}} + Be^{-\frac{t}{\tau_{slow}}}, \\ y(t) = \int_{-\infty}^{+\infty} h(\tau)J(t-\tau)d\tau = \int_{-\infty}^{+\infty} a_0 e^{-2\pi f_0 \tau}\left(Ae^{-\frac{t-\tau}{\tau_{fast}}} + Be^{-\frac{t-\tau}{\tau_{slow}}}\right)d\tau; \end{cases}$$

and

$$Q = Q_{signal} + Q_{noise} \sim \int_{t1}^{t2} [J_1(t) + J_{1\_noise}(t)]dt \sim \int_{t1}^{t2} y(t)dt$$

f_0 – shaper bandwidth

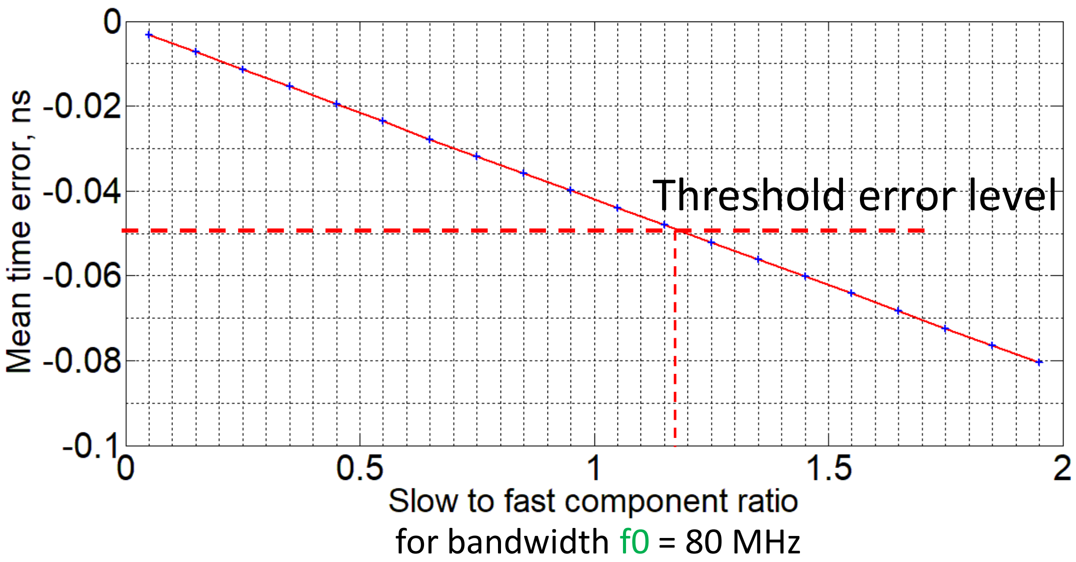
BaF$_2$ + detector signal model

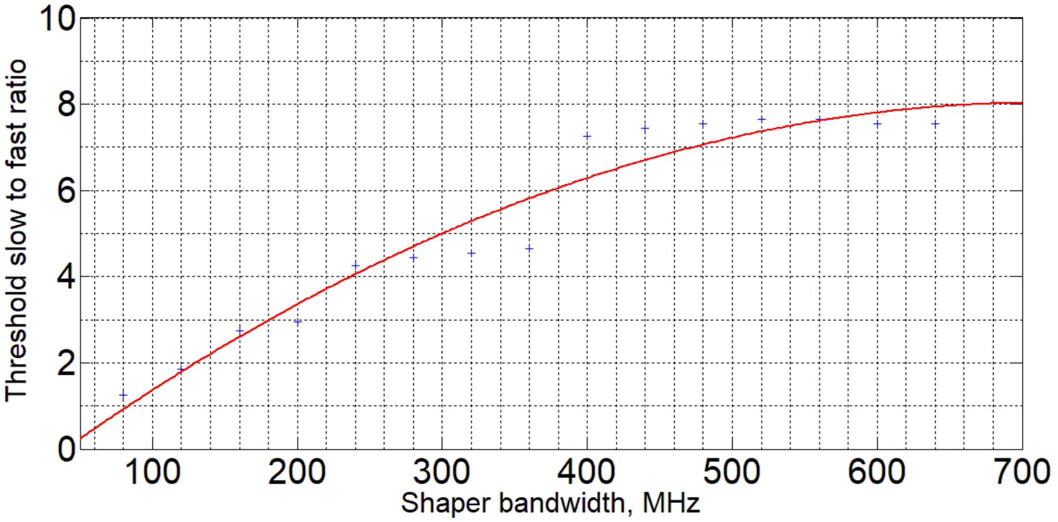


Let’s estimate an error level that lead us to additional time measurement error 50 ps (further “threshold error level”), 10% of current time resolution requirement for Mu2e electromagnetic calorimeter

Time stamp is set based on constant fraction = 5% criterion

BaF_2 + detector signal model

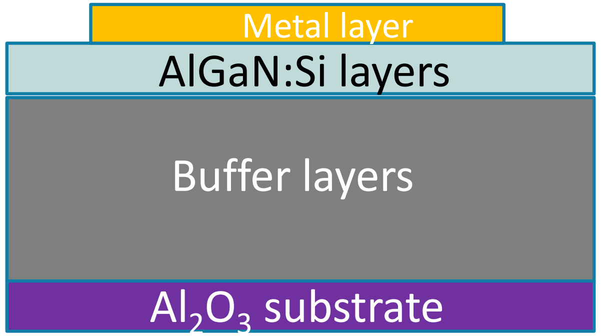




Now if we increase f_0 parameter we can get the same result with higher slow to fast component ratio, because we adjust SNR to the same level => we can use detectors with threshold wavelength 280-290 nm, but need detectors with low capacitance

Slow to fast ratio = 1 corresponds to 300 nm threshold wavelength of photodetector (like CsTe photocathode, see M. Kobayashi et al., *Nucl. Instrum. Meth. A*, **270**, 106 (1988)*)*

Schottky diode for BaF_2 fast component selection

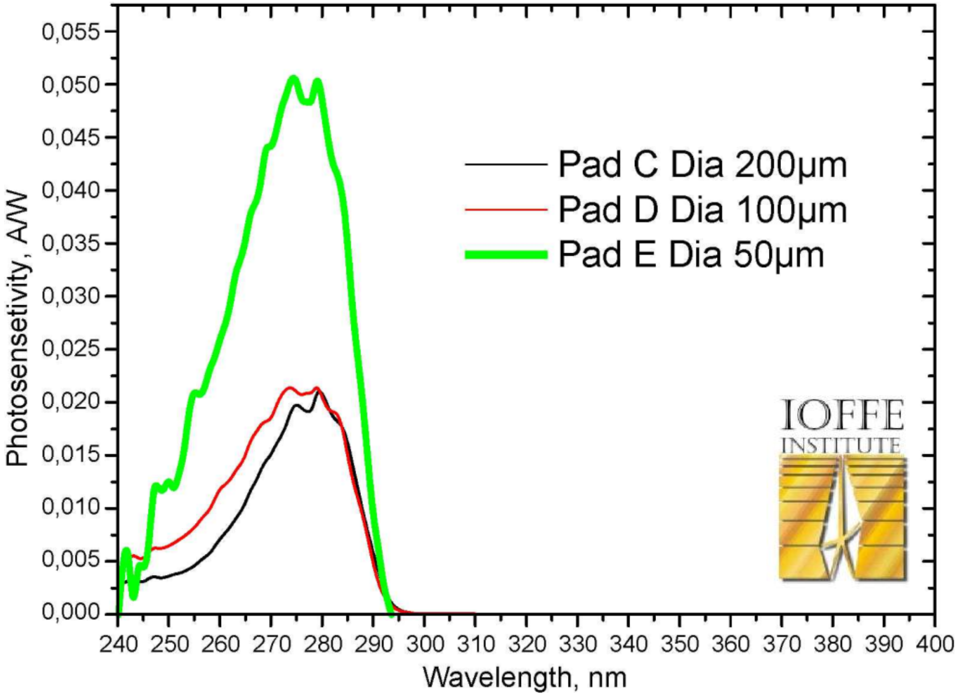


Metal layer

AlGaN:Si layers

Buffer layers

Al_2O_3 substrate



Dark current ~0.5 uA at -5V
QE is 22% @ 280nm

We can use AlGaN to grow structure for Schottky photodiode. At the moment we have photodiodes with 50 mA/W sensitivity for Vbias = 0

Conclusion

- We used AlGaN alloy with Al mass fraction up to 0.55 in p-type layers to create photocathode and MCP device that can be used for effective fast BaF_2 component registration and slow component suppression
- Based on data collected from cosmic rays investigation we showed that efficiency of slow component suppression grows with Al mass fraction in upper AlGaN:Mg layers of cathode heterostructure and one can achieve more than 60 time suppression
- Math. model for signal of photodetector is discussed
- AlGaN Schottky barrier photodiode for BaF_2 fast component selection is proposed