MCP devices with AlGaN photocathodes for BaF2 fast component detection

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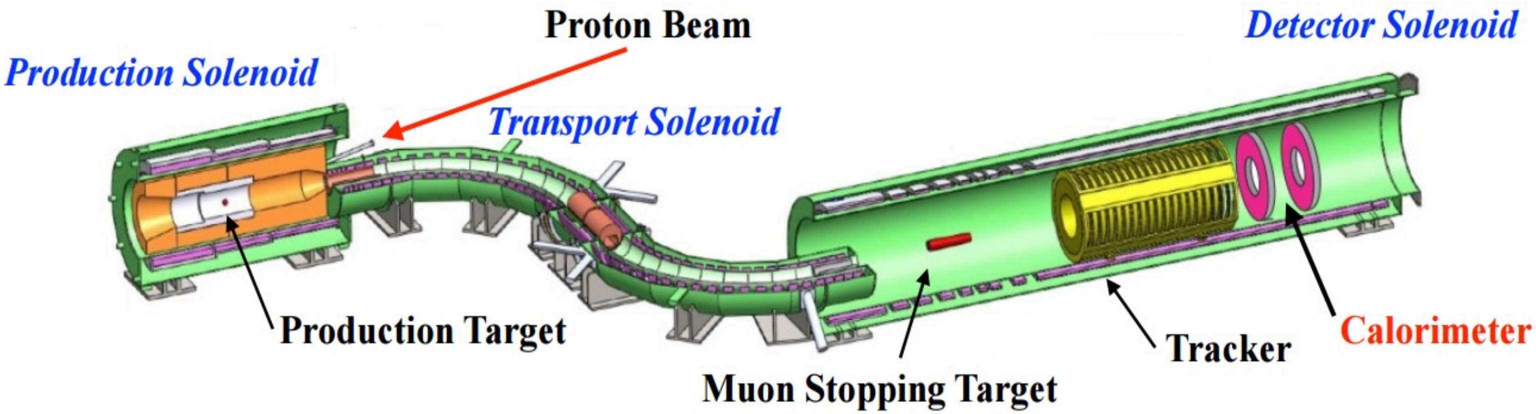
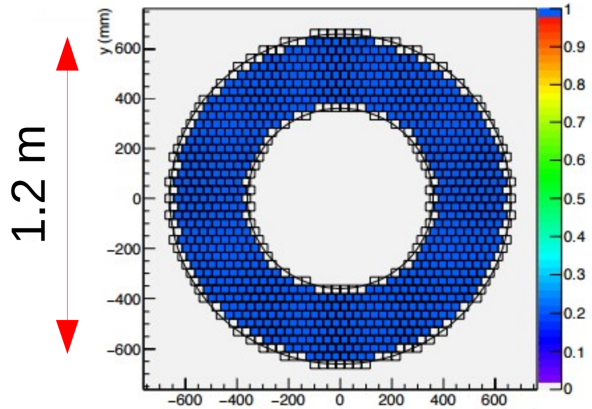
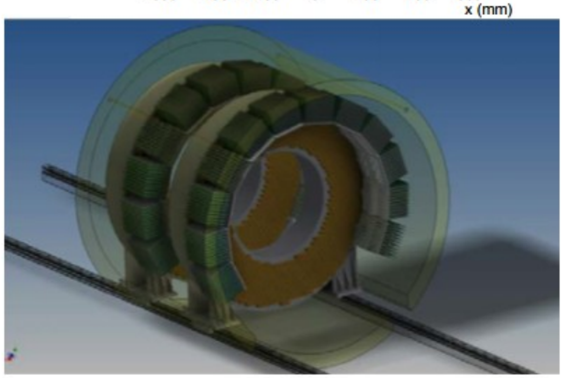
Mu2e

Mu2e electromagnetic calorimeter



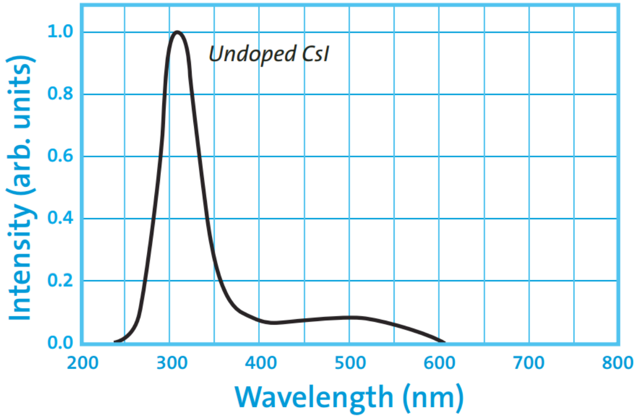
- Two disks with inner radius 35.1 cm and outer radius 66 cm
- ~700 crystals per disk
- Square crystals (34x34x200 mm3)





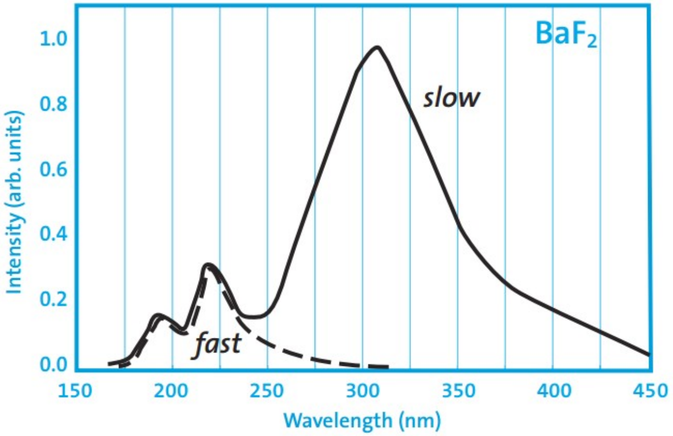
CsI and BaF_2 scintillators for the Mu2e electromagnetic calorimeter

Stage I. CsI(undopped) scintillators
- emission peak ~310 nm,
- decay time 16 ns
- radiation hardness up to 100 krad



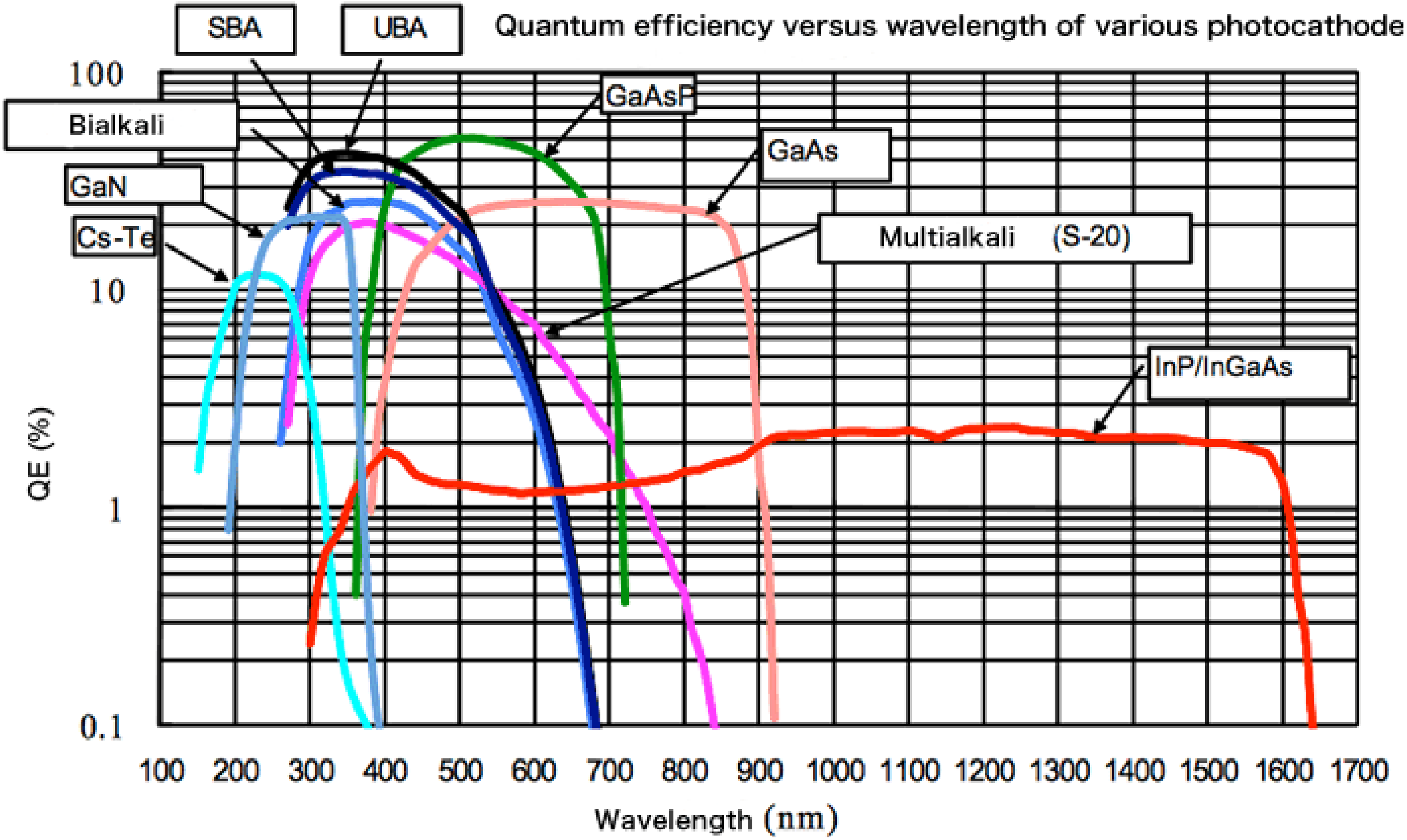
Stage II. BaF_2 scintillators
- emission peaks fast ~220 nm, slow ~310 nm
- decay time 0.8 ns (fast), 600 ns (slow)
- radiation hardness up to 10 Mrad*

*for Saint-Gobain BaF_2 crystals



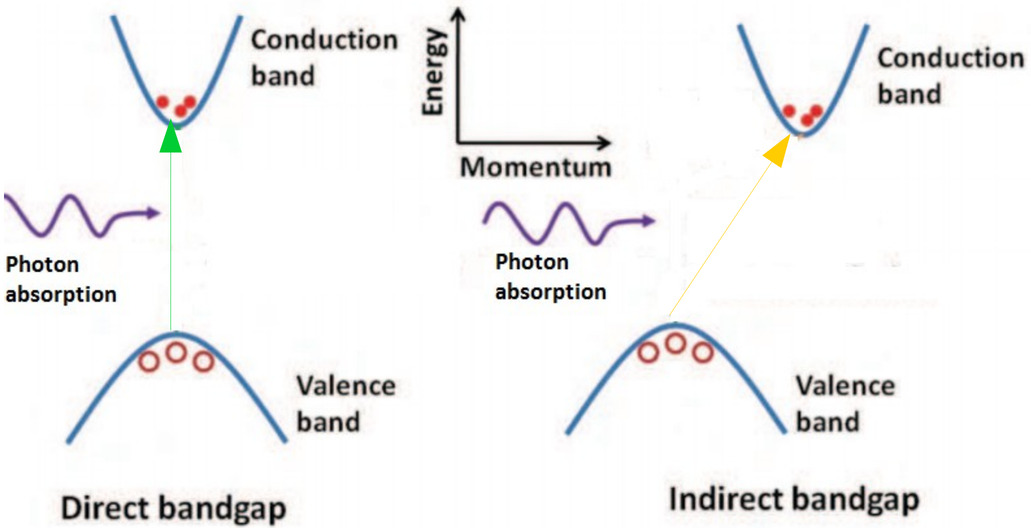
Both crystals have middle UV range emission spectrum. Fast component of BaF_2 is emmited in UVC (< 280 nm) range.

UVC range photocathodes

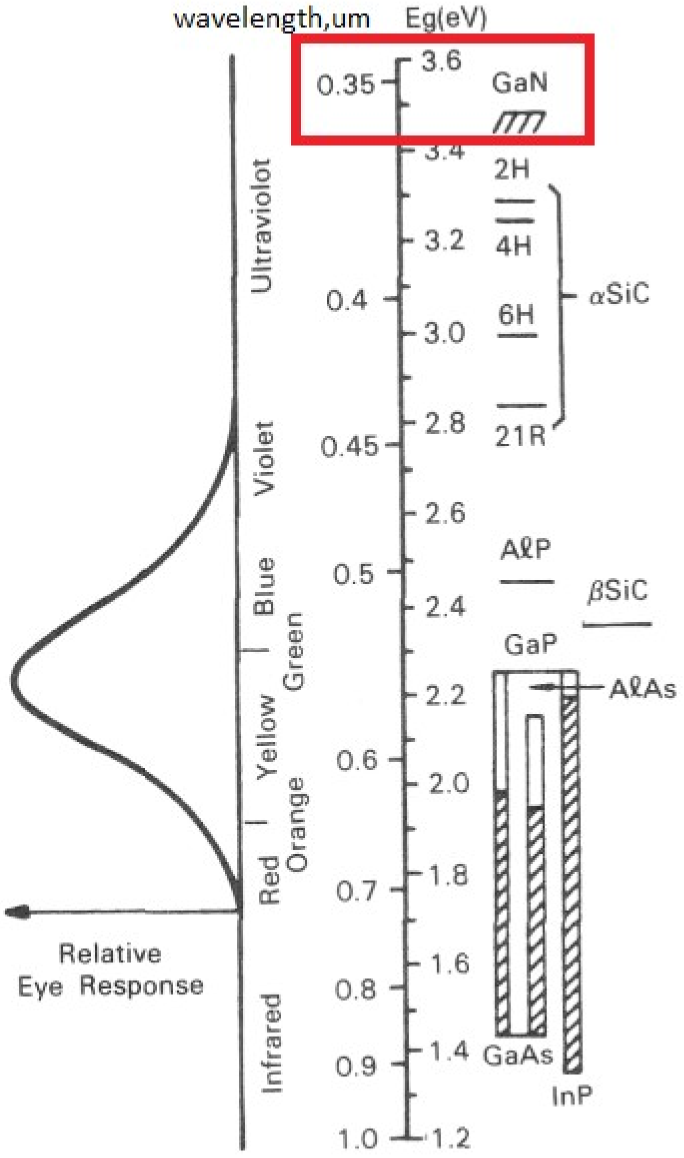


Cs-Te, GaN/AlGaN, Bialkali photocathodes are suited for UV range.
QE is the question.

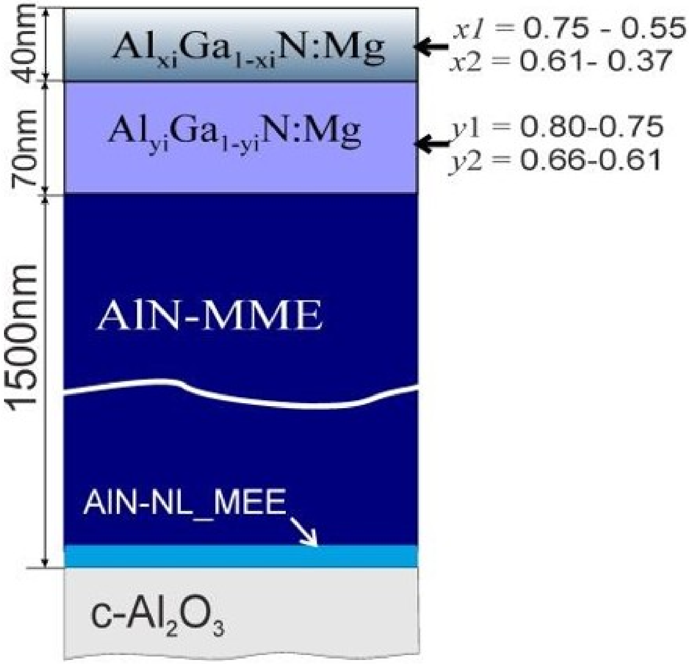
Semiconductor's band gap



Energy spectrum of absorption in semiconductor layer is mainly defined by band gap - energy difference (in electron volts) between the top of the valence band and the bottom of the conduction band.



GaN/AlGaN heterostructures for photodetectors

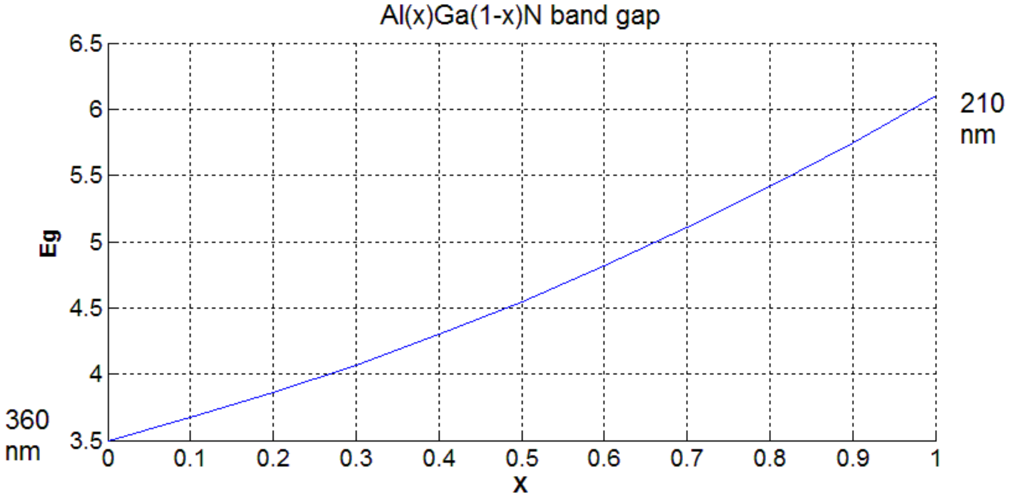


AlGaN alloy is very promising material for UV photodetecting devices, because

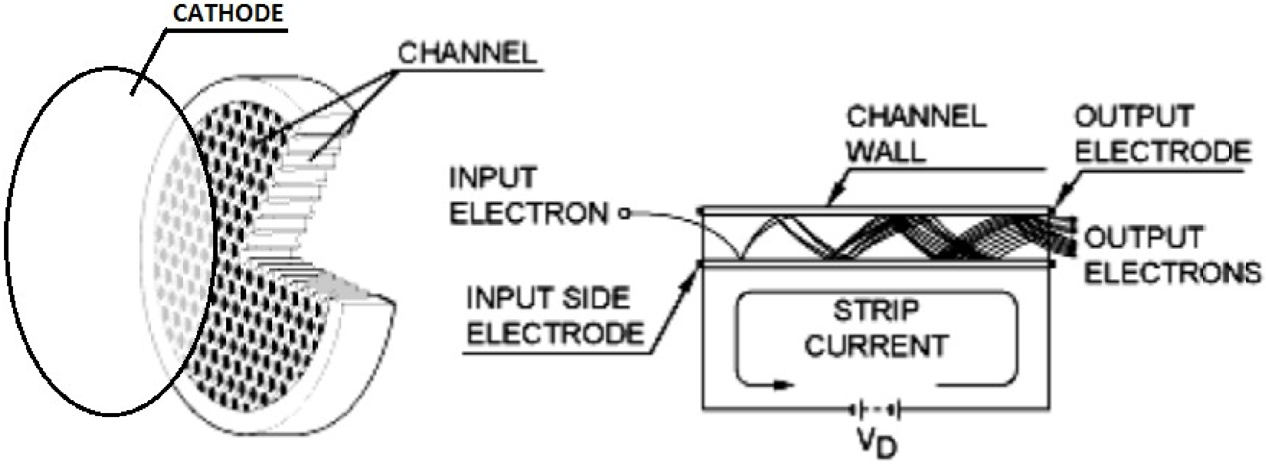
- It is direct band gap semiconductor
- High chemical resistance
- High radiation resistance

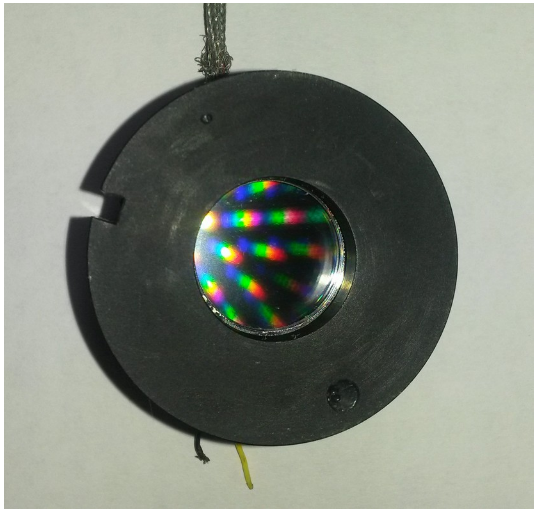
One can change band gap of $Al_xGa_{1-x}N$ alloy by varying Al mass fraction. The band gap behavior is described by equation:

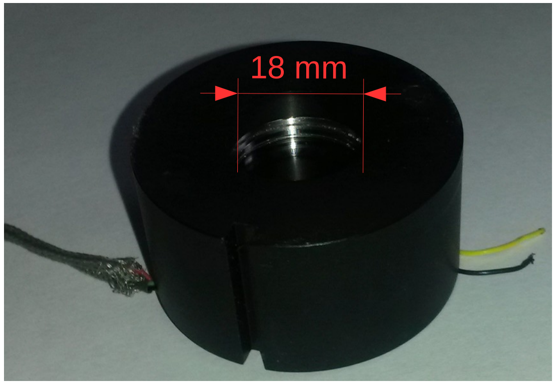
$$Eg = (1 - x)*Eg(GaN) + x*Eg(AlN) - b*x*(1 - x)$$



Photomultiplier based on microchannel plate (MCP) with AlGaN-based photocathodes with a negative electron affinity





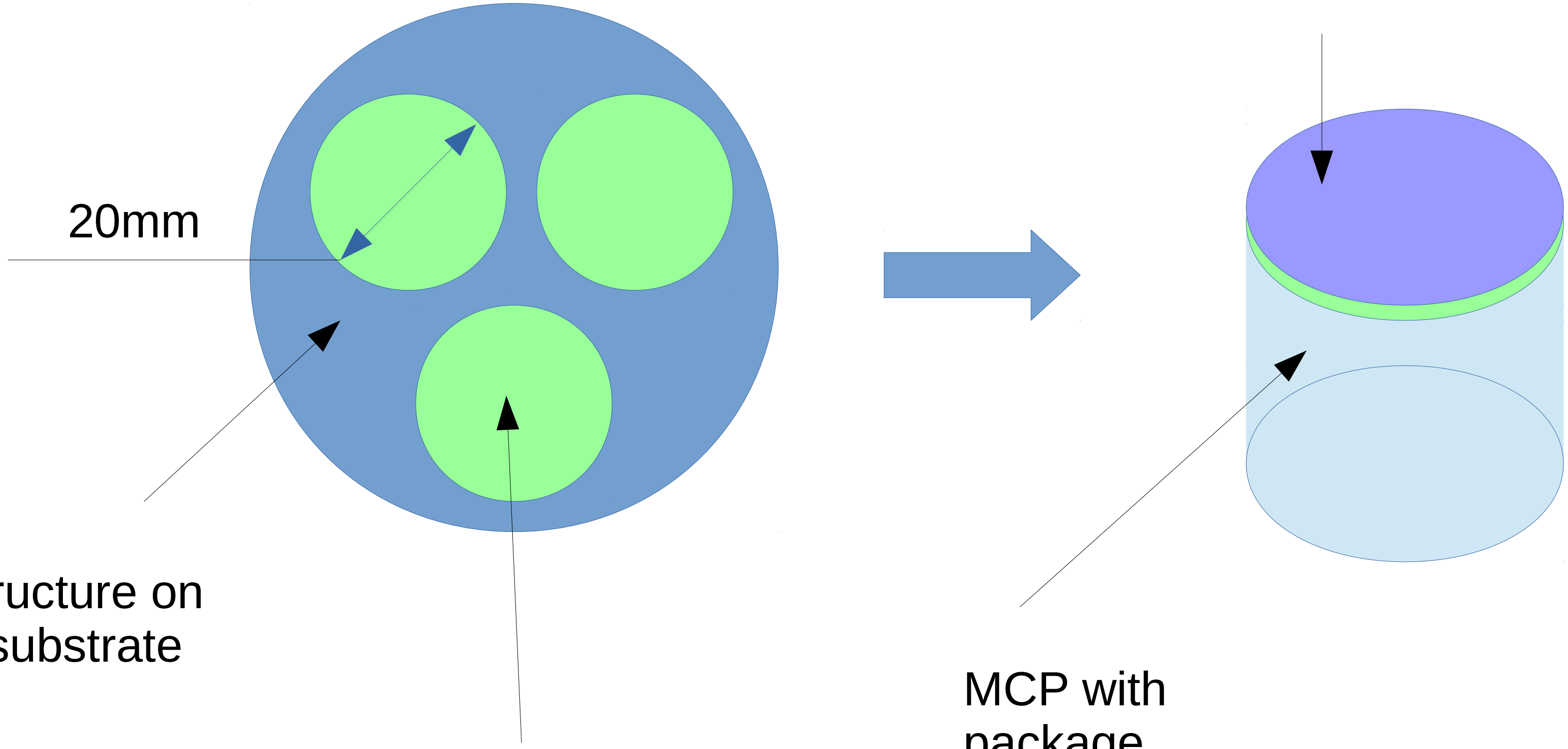


MCP consists of a two-dimensional periodic array of very-small diameter glass capillaries (channels) fused together and sliced in a thin plate. A single incident particle enters a channel and emits an electron from the channel wall.

AlGaN photocathodes with 320 & 260 nm long-wavelength edges were combined with MCP in a single device with 18 mm window diameter.

AlGaN MCP production roadmap

Heterostructure production (MBE, MOCVD) → cutting → Cs activation → packaging



Cs activation layer

20mm

AlGaN heterostructure on saphire substrate

Photocathode

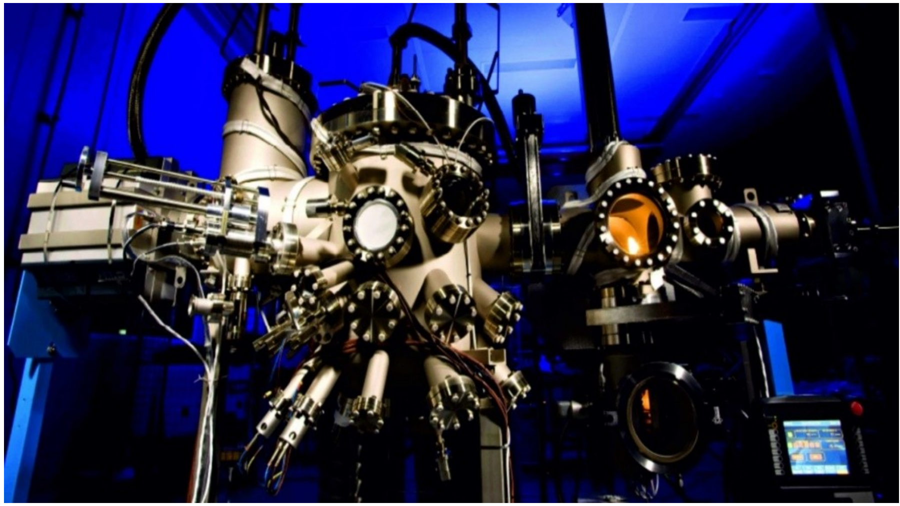
MCP with package

AlGaN MCP production roadmap. Heterostructure production

We consider 2 basic methods of heterostructure production

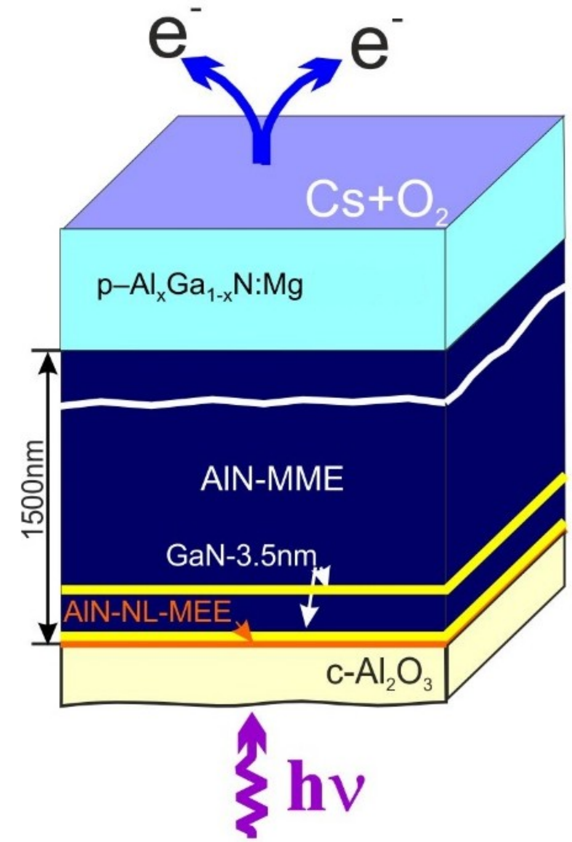
1) Plasma-Assisted Molecular Beam Epitaxy
    - higher precision
    - more complex heterostructure
    - low perfomance

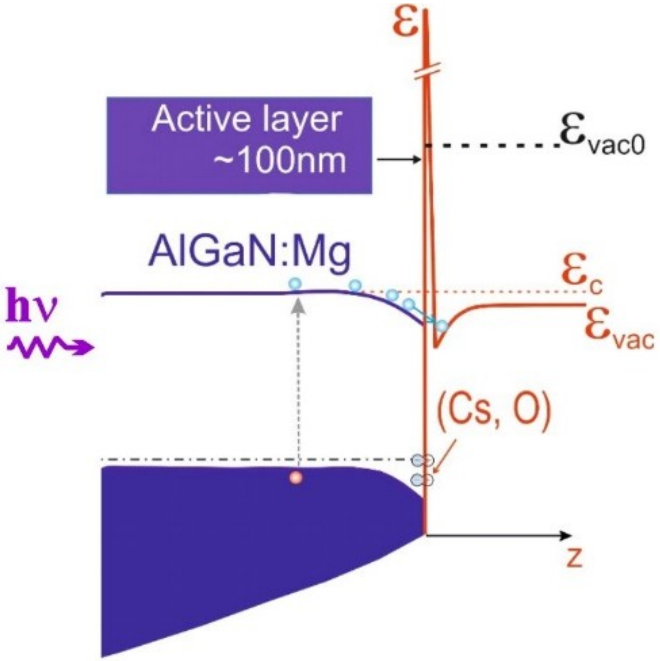
2) Metalorganic Chemical Vapour Deposition (MOCVD)
    - perfomance
    - reproducibility



MBE setup in Ioffe
Institute, St. Petersburg

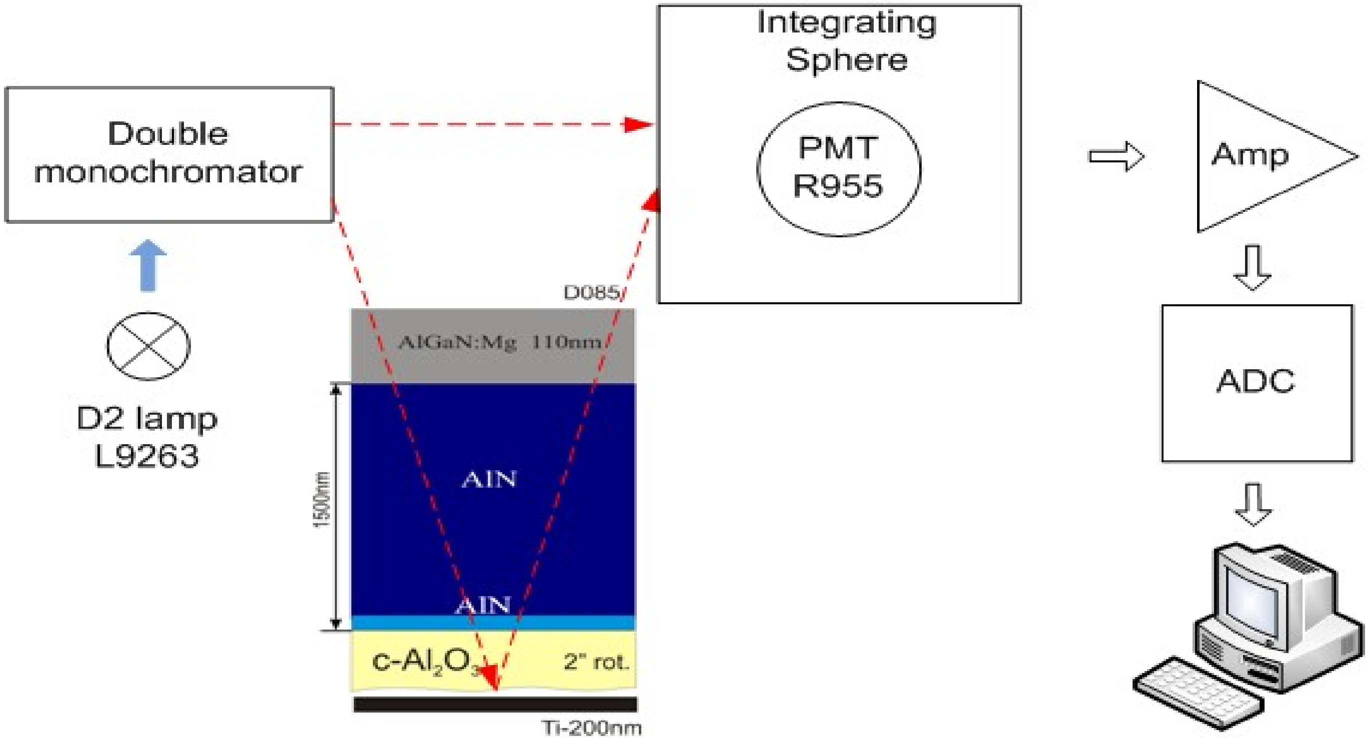
AlGaN MCP production roadmap. Cathode Cs activation for negative electron affinity





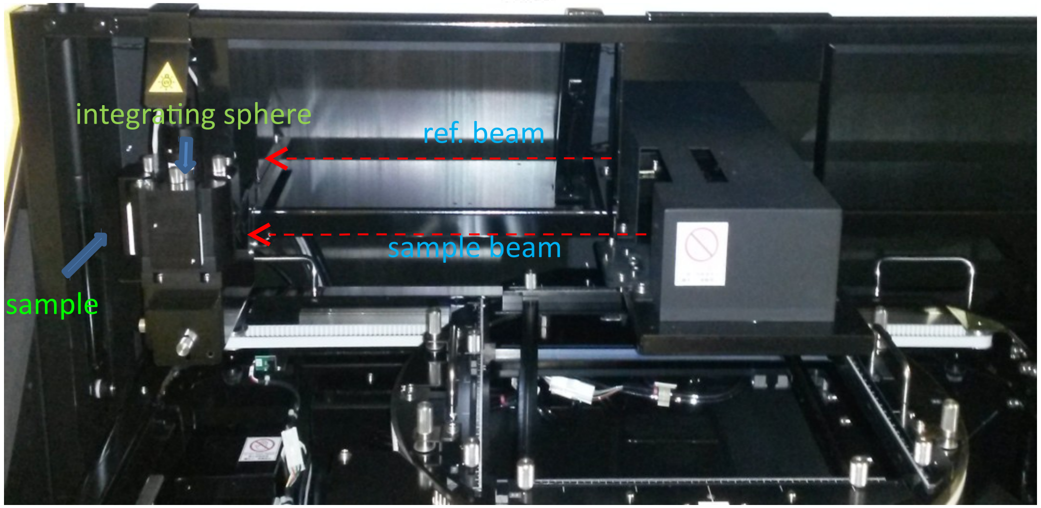
Structures are grown with Al fraction gradient in top layer. To get negative electron affinity structures should be activated with Cs after grow procedure. Three structures for cathodes with 260 nm, 280 nm and 320 nm long-wavelength edge were produced.

UV cathodes. MBE production method. Heterostructure characterisation

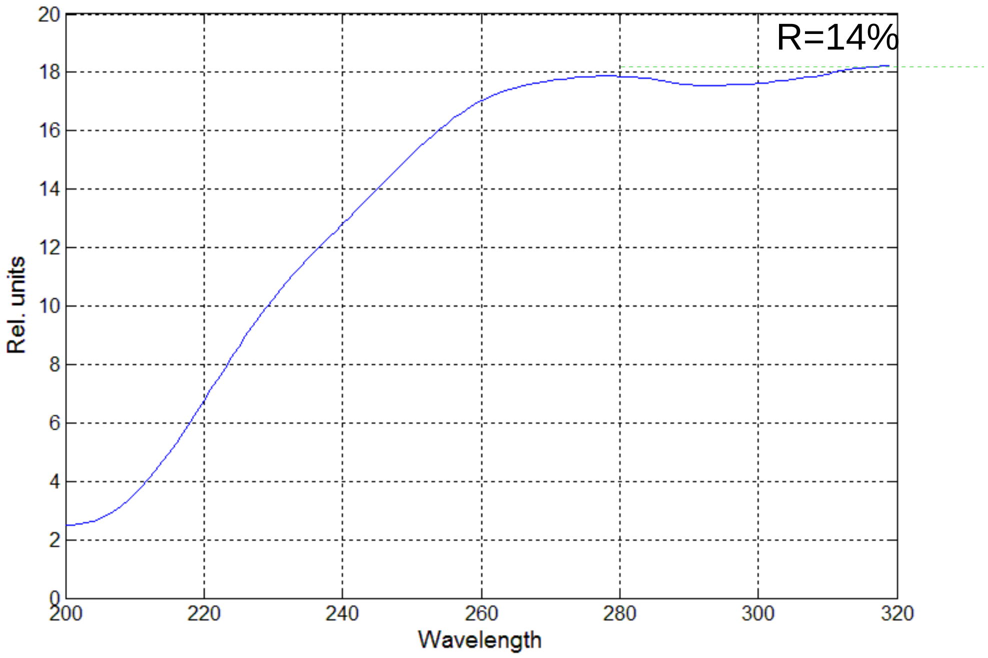


We got heterostructures with 260 nm and 280 nm red-edge from Ioffe Institute, St. Petersburg.

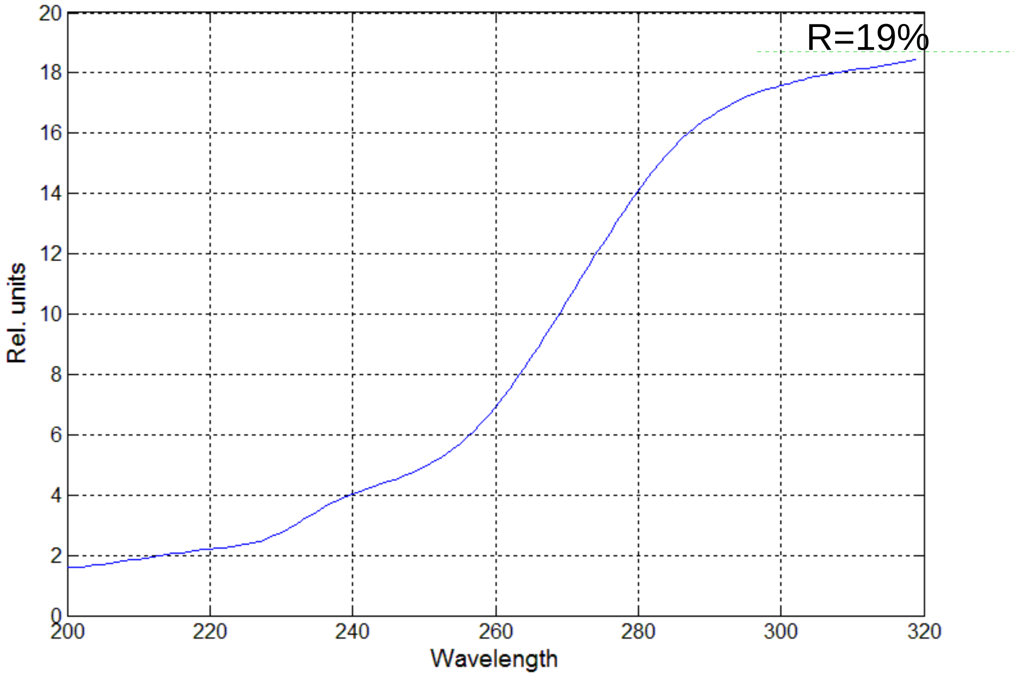
Then we used double beam spectrophotometer to measure spectrum of light passed through structure and reflected from metallic titan layer.



UV cathodes. MBE production method. Heterostructure characterisation



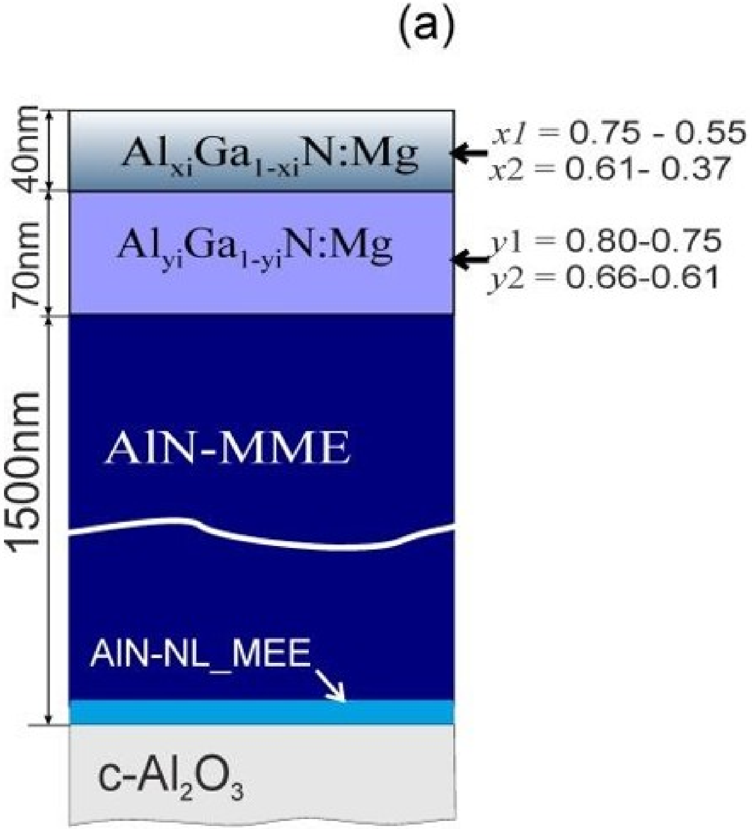
a) AlGaN structure with edge ~260 nm

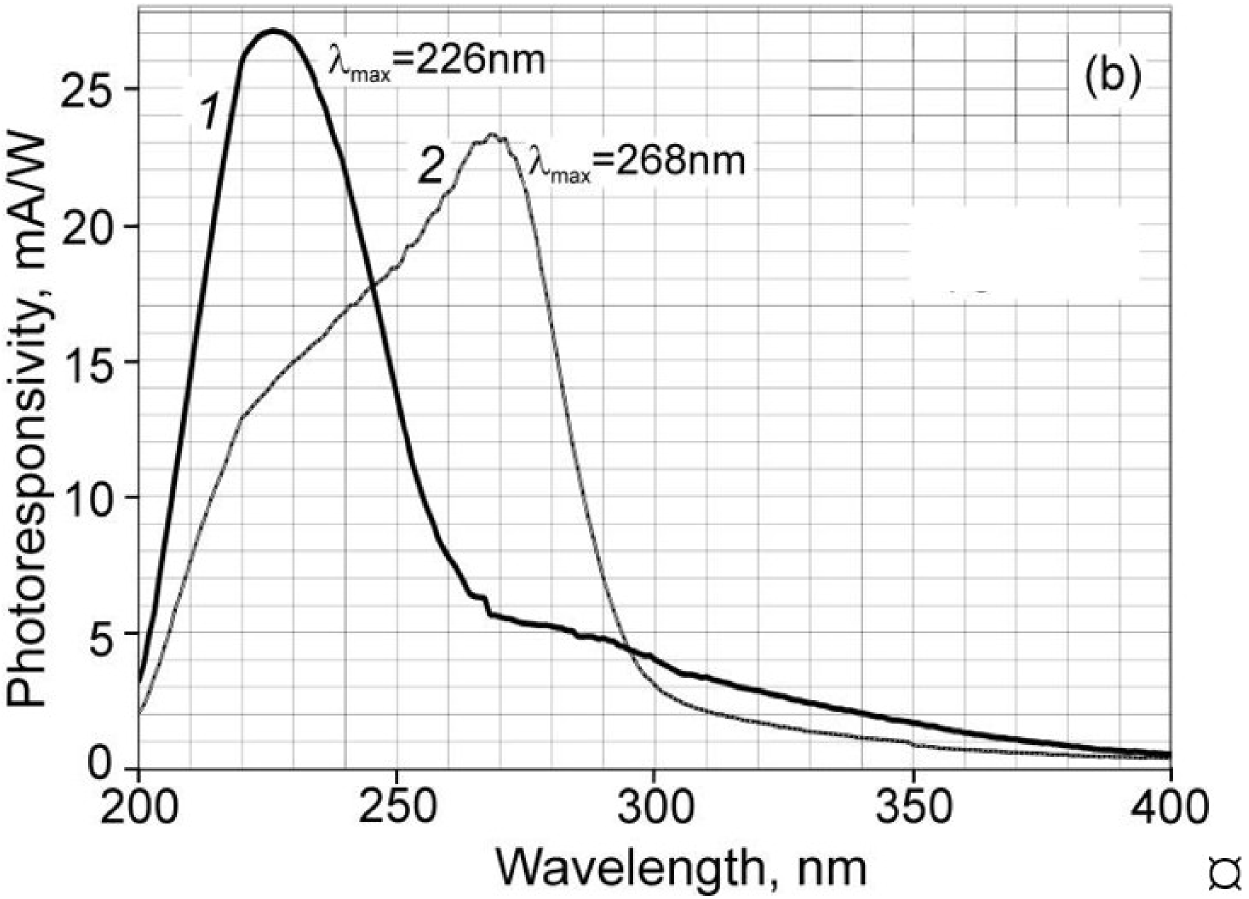


b) AlGaN structure with edge ~280 nm

The long-wavelength edge of absorption spectrum is succesfully controlled by changing Al mass fraction in AlGaN alloy. Wavelength decreases when Al fraction is grown.

UV cathodes. MBE production method. MCP device spectrum sensivity



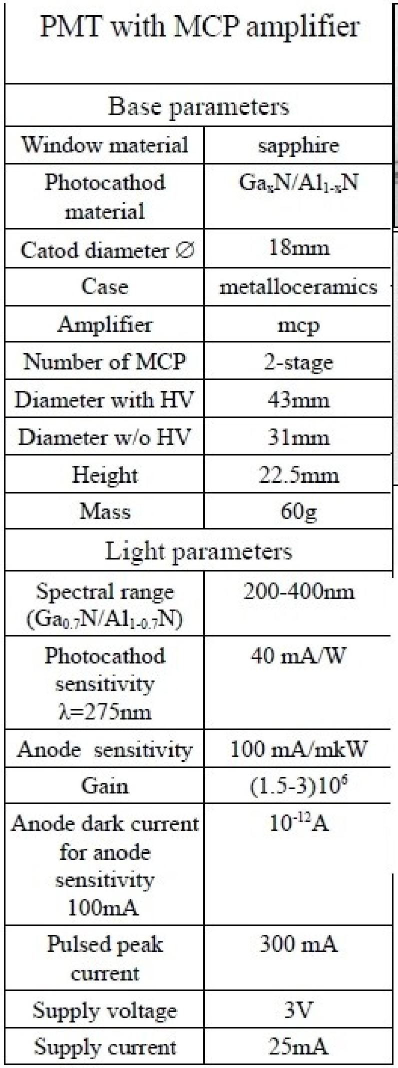


Good spectral range, but high dark noise at level 1 uA

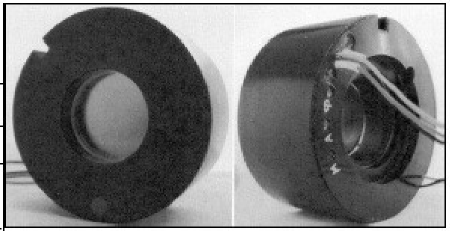
MCP with UVC photocathodes. MOCVD method

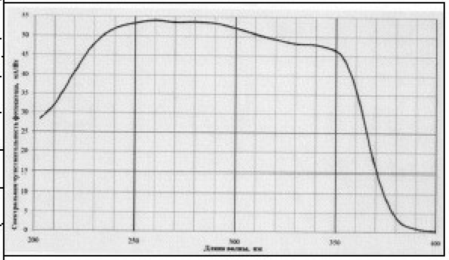
We also have got 320 red-edge complete MCP device with heterostructure produced with MOCVD technology.

Now there is possibility to produce 290 nm red-edge devices and experiments with 260 nm red-edge MOCVD heterostructures have started

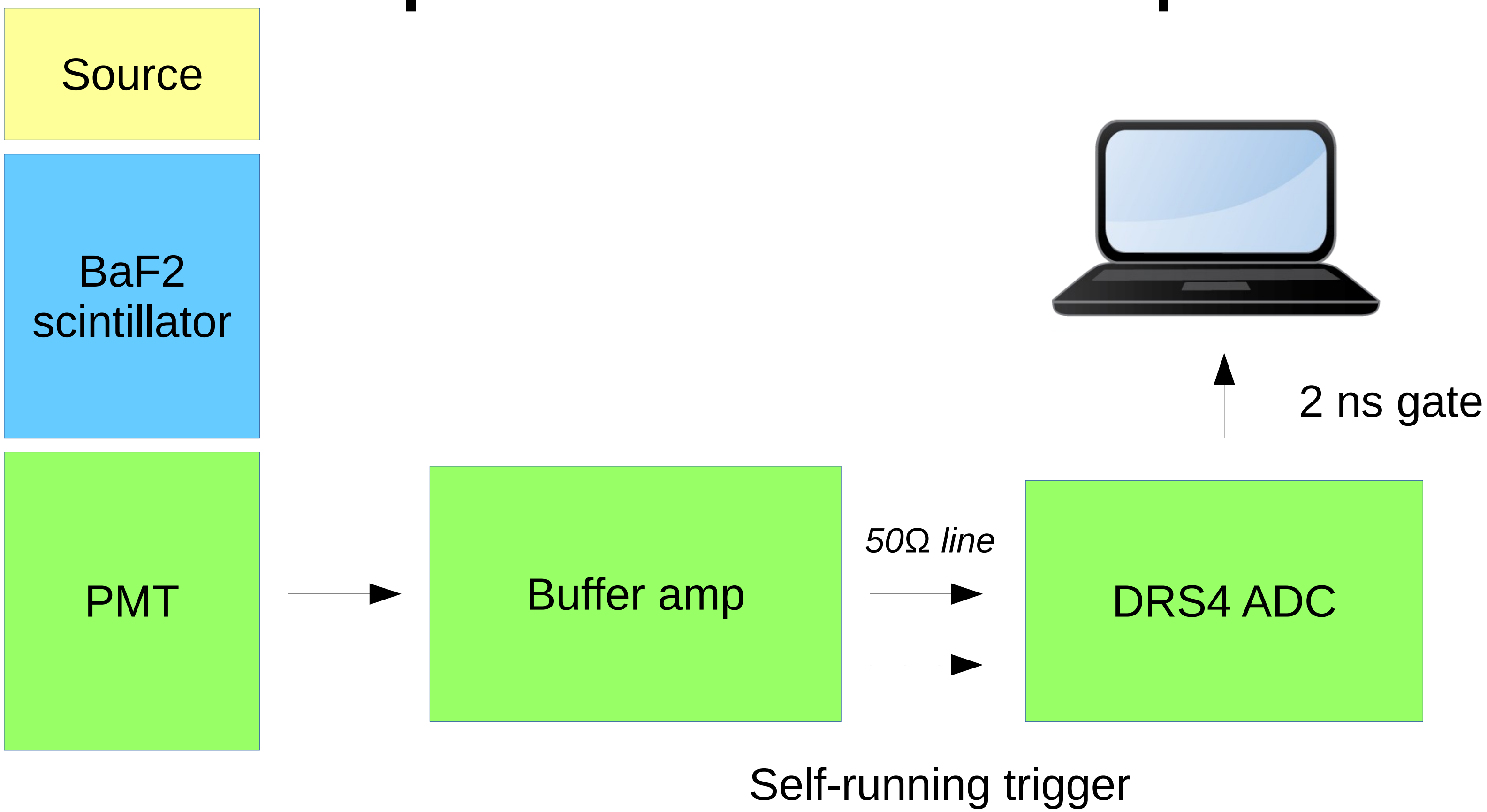


PMT with MCP amplifier	
Base parameters	
Window material	sapphire
Photocathod material	$Ga_xN/Al_{1-x}N$
Catod diameter ∅	18mm
Case	metalloceramics
Amplifier	mcp
Number of MCP	2-stage
Diameter with HV	43mm
Diameter w/o HV	31mm
Height	22.5mm
Mass	60g
Light parameters	
Spectral range ($Ga_{0.7}N/Al_{1-0.7}N$)	200-400nm
Photocathod sensitivity λ=275nm	40 mA/W
Anode sensitivity	100 mA/mkW
Gain	$(1.5\text{-}3)10^6$
Anode dark current for anode sensitivity 100mA	10^{-12}A
Pulsed peak current	300 mA
Supply voltage	3V
Supply current	25mA





MOCVD 320 nm AlGaN MCP Radiation spectrum measurement. Experimental setup



Source

BaF2 scintillator

PMT

Buffer amp

50Ω line

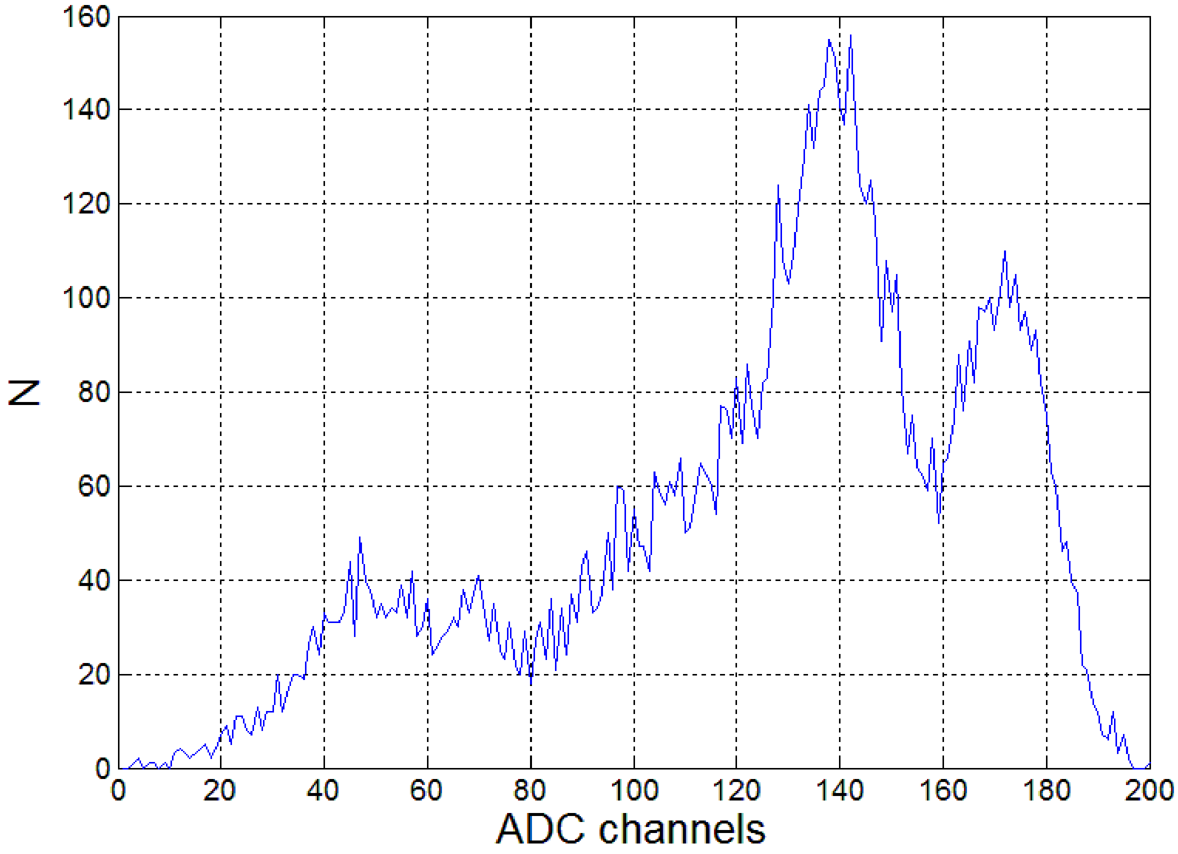
DRS4 ADC

2 ns gate

Self-running trigger

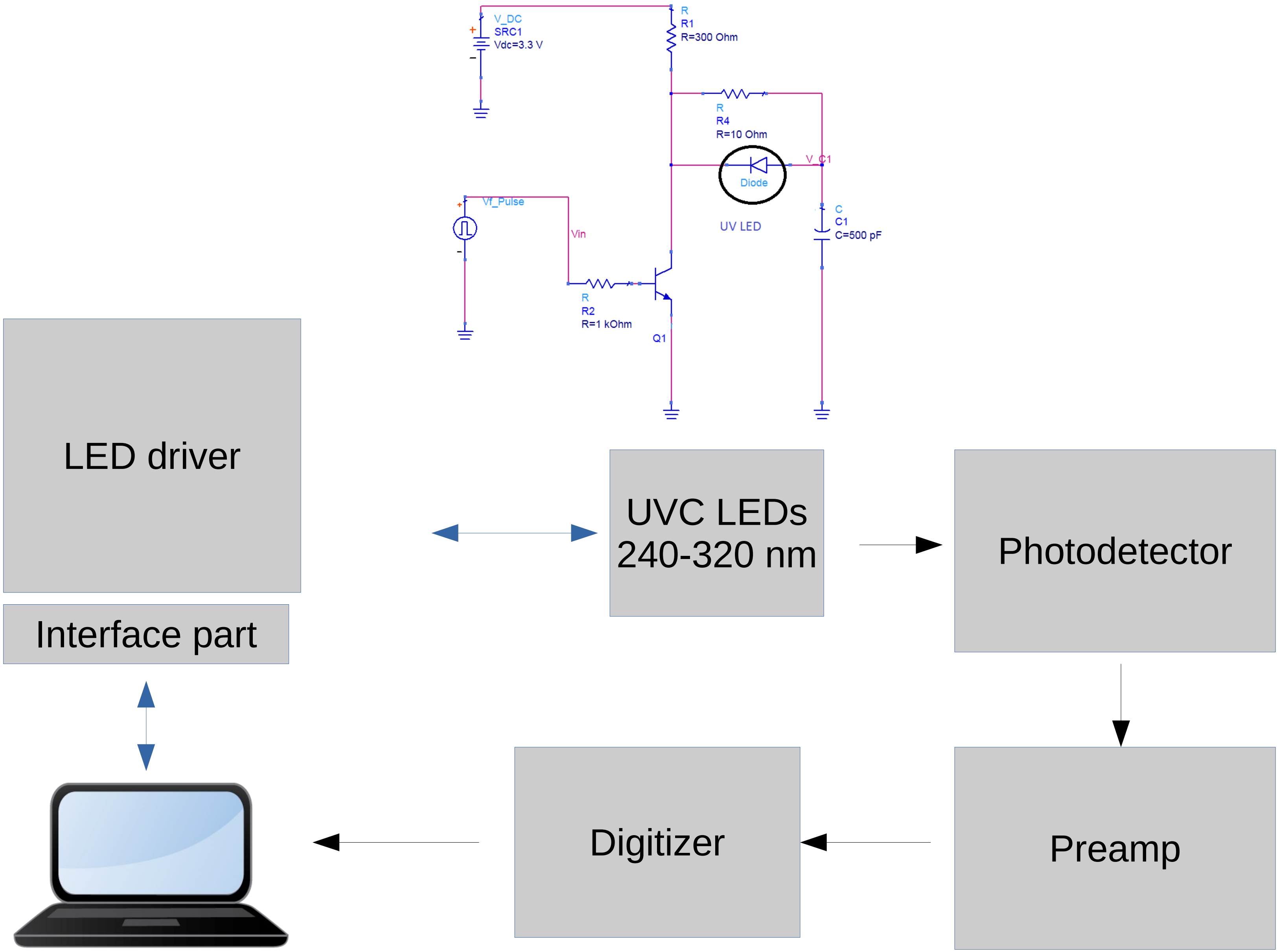
To estimate photodetector efficency a simple experiment was proceeded. We used small BaF2 scintillator to measure a gamma radiation spectrum of weak radiactive Co60 source. With 320 nm cathode we still have high level for slow component, so one need use 2ns gate to supress it.

320 nm AlGaN MCP, spectrum measurement.



Photomultiplier with BaF_2 crystal was used to measure Co60 spectrum. For mixed signal (fast + slow component, 2 ns gate) we can obtain energy resolution ~10% FWHM.

UVC detectors measurement stand



LED driver

Interface part

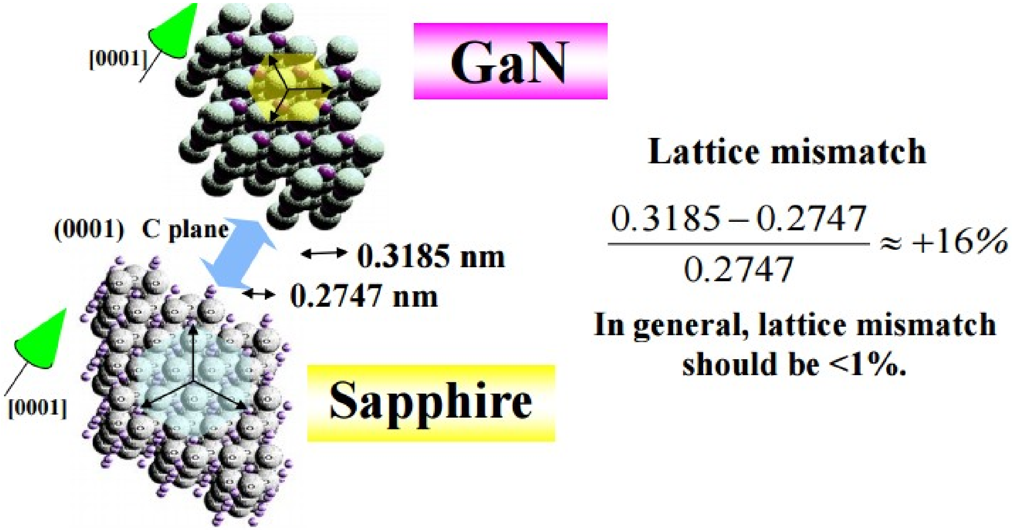
UVC LEDs
240-320 nm

Photodetector

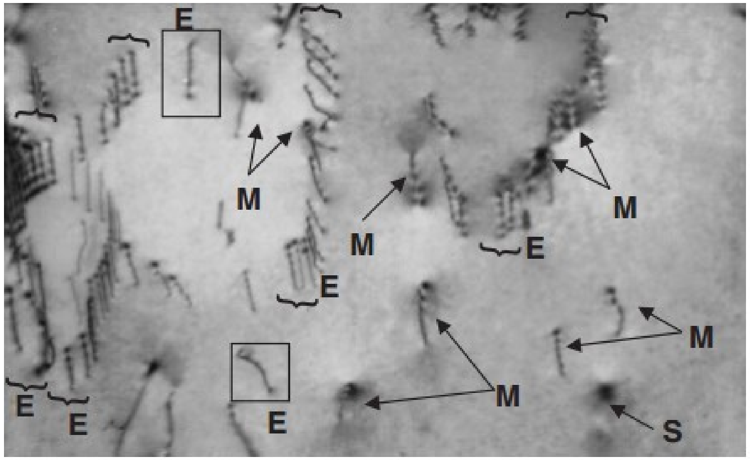
Preamp

Digitizer

GaN/AlGaN photodetectors. Dislocations and quantum efficency



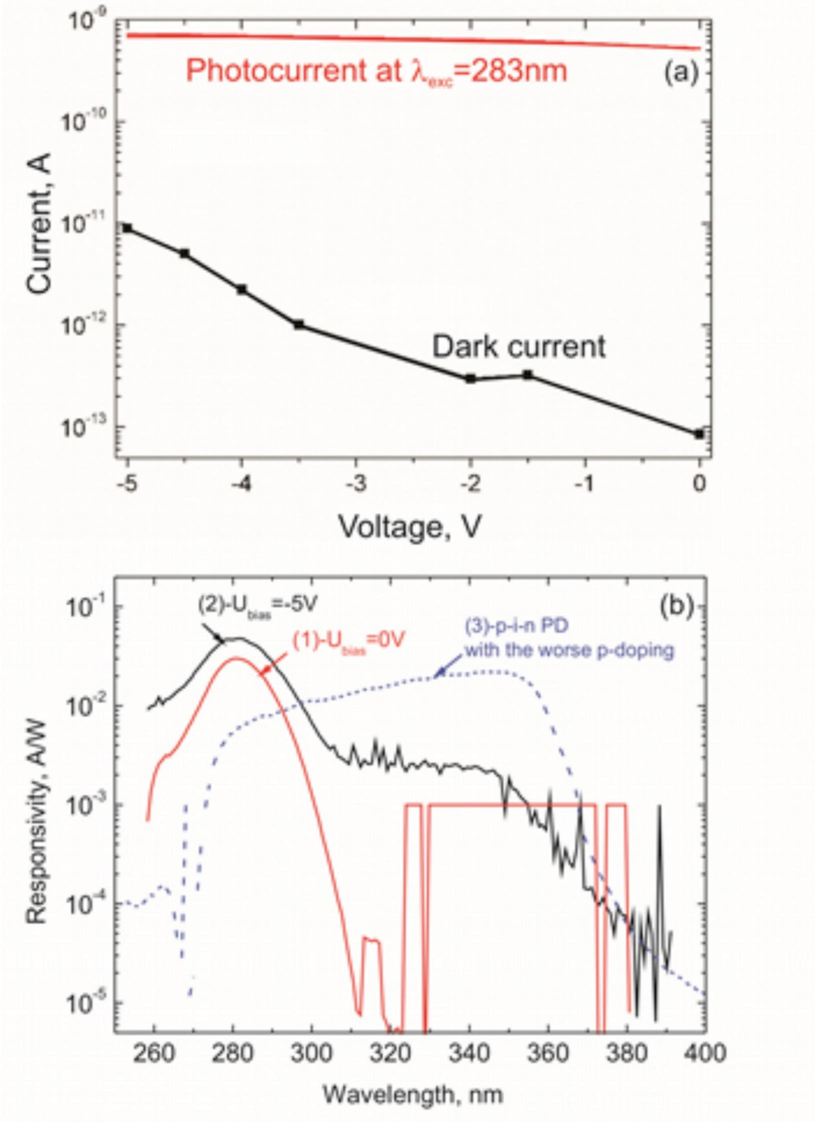
GaN and Al_2O_3 lattice mismatch

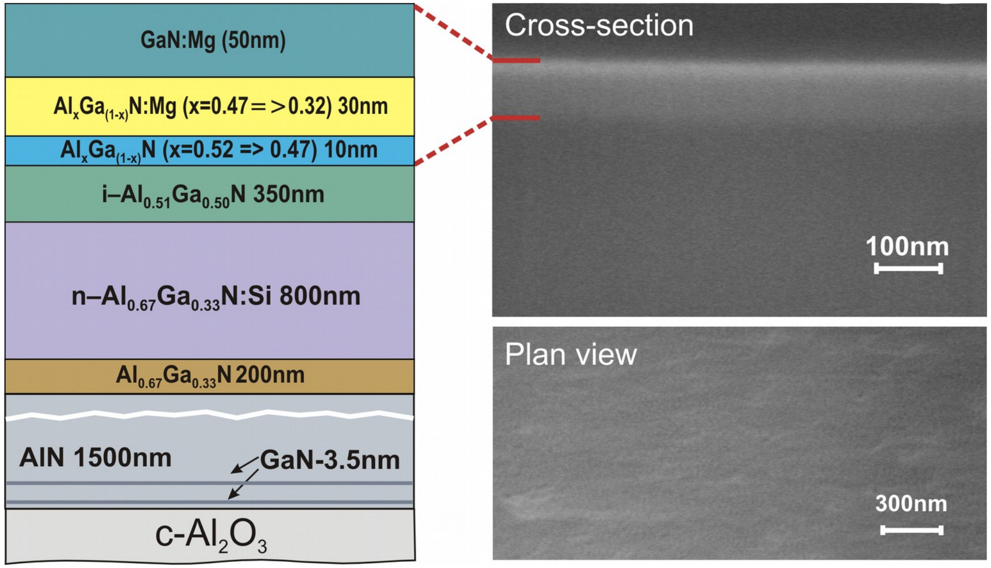


Plan-view images of AlGaN layer grown on saphire. Dislocations of different types: S — screw, E-edge, M — mixed. *Imura et al. 2007, JJAP, 46 1458*

The growth of AlGaN/GaN on sapphire substrates is a big challenge due to the large lattice mismatch and thermal expansion mismatch. The typical threading dislocation density in the AlGaN layers grown on the sapphire template with buffer layers is still as high as 10^{8}-10^{9} cm^{-2}. Treading dislocations act as non-radiative recombination centers, thereby resulting in low quantum efficiency (QE).

Possible alternatives: p-i-n diodes

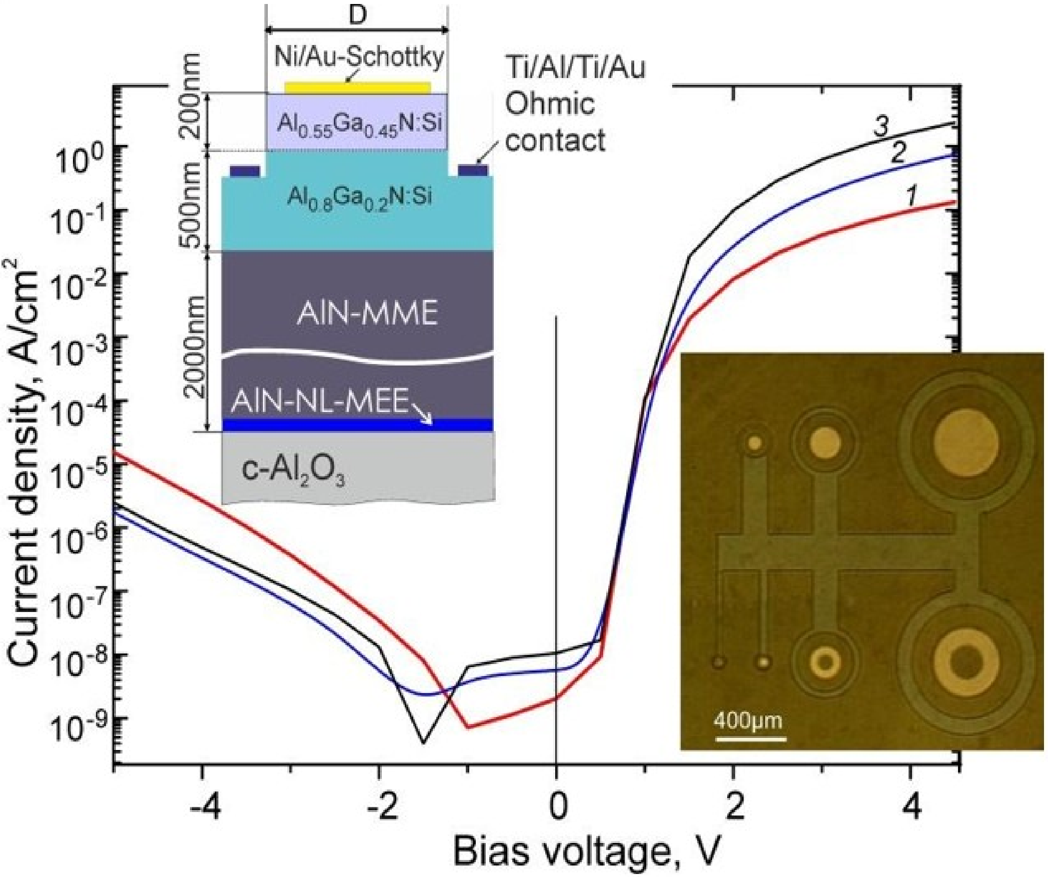


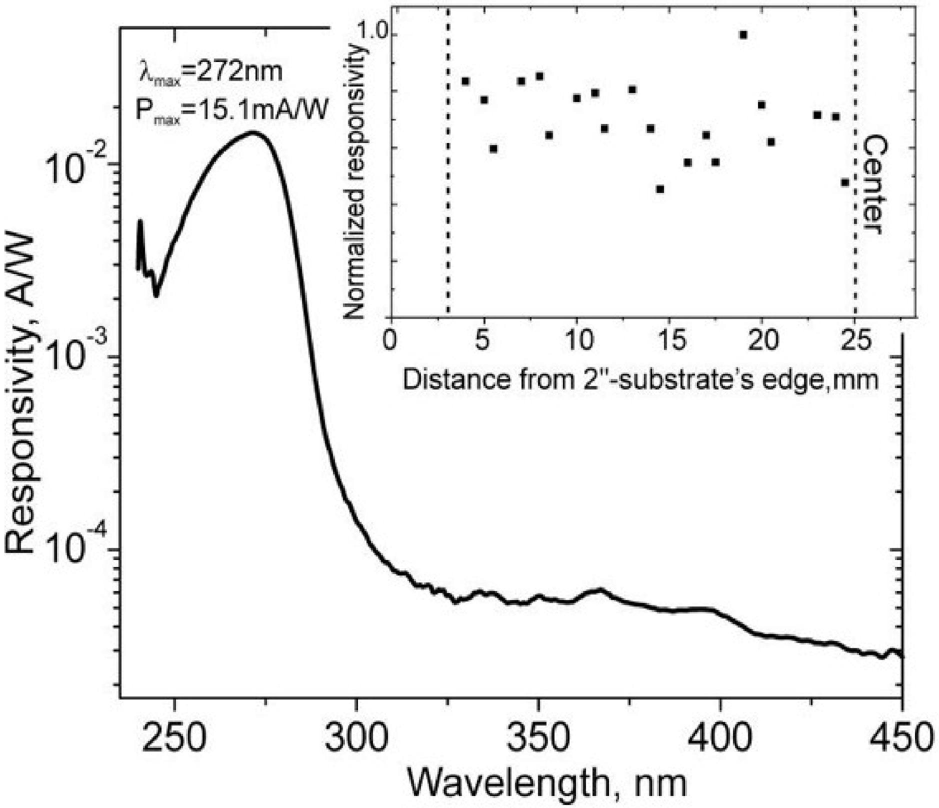


Heterostructure for p-i-n photodiode and (a) sensitivity of p-i-n photodiodes, measured without reverse bias (1), with bias -5V (2), with the worse p-doping quality (3)

V.N. Jmerik, N.V. Kuznetsova, D.V. Nechaev et al. Tech. Phys. Lett. (In print)

Possible alternatives: Schotky diodes





Cost & time estimations

In one year time horizon

for UVC photocathodes

- One need ~20k$ to get stable & reproducible 260 nm red-edge MCP photomultipier

In 2-3 years

- One need ~80k$ to produce & try other semiconductor devices such as Schottky & p-i-n diodes, that suit to our noise, area and gain requirements

Conclusion

- Proposed photomultiplier device with microchannel plate based on AlGaN photocathode with long-wavelength edge 260-320 nm, suited for spectrometry tasks with BaF_2 fast emission component
- We have got technology of semiconductor UVC-range photodetectors production on cheap sapphire substrate, but one need to improve heterostructure surface quality to decrease dark noise

Thank you for your attention !