DEVELOPMENT OF VERY LOW THRESHOLD DETECTION SYSTEM FOR LOW-BACKGROUND EXPERIMENTS.

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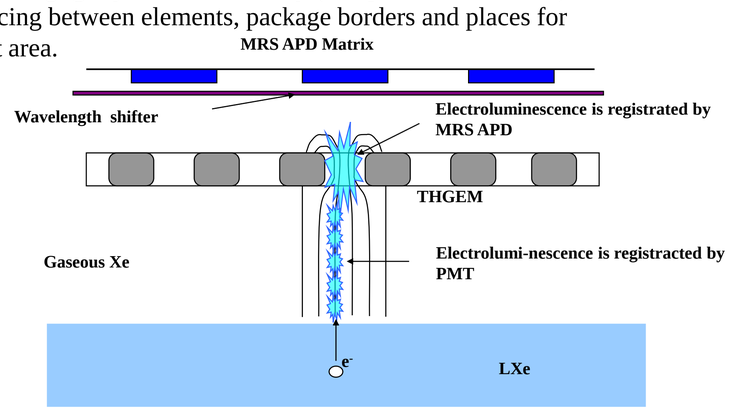
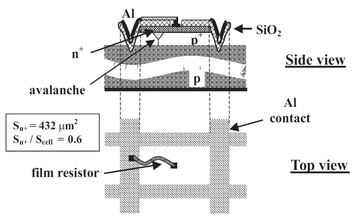
Introduction

In noble gas detectors of Dark Matter particles (WIMPs) of current generation, detection of scintillation and electroluminescence is performed by photomultipliers (PMTs). In future Dark Matter experiments, with increasing sizes and masses of detectors and reduction of radioactive background of experimental setups down to the ultralow values of 1 event/100 kg/year a question will arise on replacement of the PMTs which are currently the most radioactive elements to less radioactive photodetectors. Several experimental groups, which develop detectors for the Dark Matter experiments, are investigating new semiconductor devices — multipixel avalanche Geiger photodiodes, MRS APD (the widely used names are: SiPM, MPPC, MPGP). These photo detectors operate in a single photon counting mode and may replace PMTs in future because they are expected to contribute the negligibly low radioactivity (compared to the PMTs). Moreover, they are very thin. MRS APD can be assembled in a matrix with a ratio of active to total area of about 70-80% due to spacing between elements, package borders and places for contacts bonding. The cost of the matrix of the MRS APD s is currently nearly approaching the cost of the PMTs with the equivalent area.

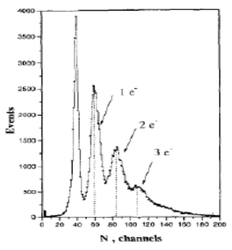
The main obstacles now for replacement of the PMTs by them are the lack of sensitivity in the VUV region of luminescence of noble gases and the high intrinsic thermionic noise level (in comparison with the noise level of the same area PMT). These obstacles do not allow one to build a large-area photosensitive plane for detection of the scintillation signal. However, these photodetectors, apparently, could be used for detection of the electroluminescent signal from the very low-energy events. Elegant system comprised of MRS APD together with a wavelength shifter (WLS) and a thick gas electron multiplier (THGEM) could be used for Dark Matter experiment. Additional amplification of the charge in the THGEM holes gives the large light signal of electroluminescence detected with an array of MRS APD . This readout system provides the mm accuracy for the very low-energy events, that is important for the reliable separation of the rare physical events from the background ones caused by spontaneous emission of the electrons from the liquid noble gas surface.



MRS APD



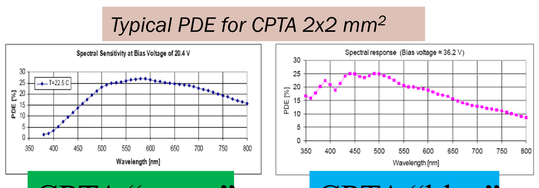
The very first Metall-Resitor-Semiconductor APD (MRS APD, SiPM) was invented in USSR in 1989. The idea was to create a photodiode as an array of microcells assembled on a common silicon substrate and to operate it at supply voltage above the value corresponding to the initiation of a breakdown to reach high gain. During discharge the subsequent voltage drop across the individual resistor (resistive layer) leads to the avalanche quenching and to localization of the discharge within the illuminated microcells, while the rest of the photodiode surface remains in the working state.



LED pulse spectrum (A. Akindinov et al., NIM387 (1997) 231)

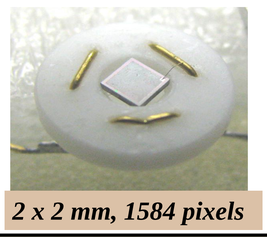
the total signal is a sum of the pulses with equal amplitude from all fired cell

Typical PDE for CPTA 2x2 mm²



CPTA "green" CPTA "blue"

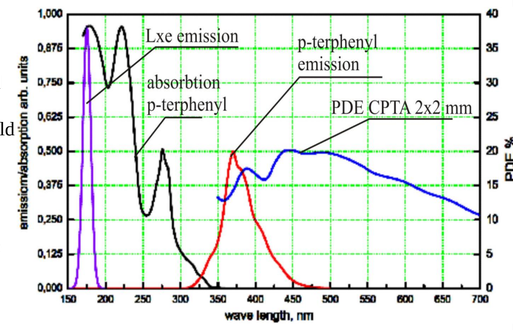
Since the Geiger discharge probability R_G is higher for electron than for holes, and an absorption length in silicon is different for different wavelength, there are two currently existing basic structures: $n^+–p–\pi–p^{++}$ for long wavelengths "green", and $p^+–n–\upsilon–n^{++}$ for short wavelengths "blue" .



2 x 2 mm, 1584 pixels

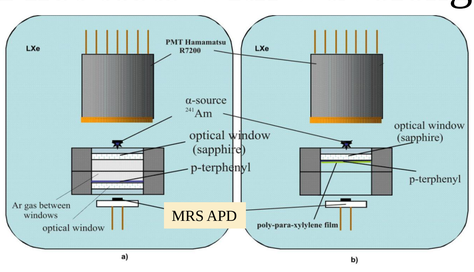
Wavelength shifter

A p-terphenyl (1,4-diphenylbenzene) has been chosen as a wavelength shifter. Absorption spectrum of a molecular solution of *p*-terphenyl in an *n*-heptane has two maxima: at λ = 276 nm with molar extinction coefficient ε = 33800mol^{-1}*l*cm^{-1} and λ = 206.5 nm and ε = 56300 mol^{-1}*l*cm^{-1}. These maxima correspond to singlet transitions S0=>S1 and S0 => S2 with $E_{S0 \Rightarrow S1}$= 4.5 eV and $E_{S0 \Rightarrow S2}$= 6 eV. A fluorescence quantum yield of p-terphenyl is as high as 0.9, and emission spectrum has a maximum at 338 nm. There are no data on p-terphenyl absorption below 200 nm (S0 => S3). The energy of the S0 => S3 transition can be obtained from an empirical rule for p-electron singlet states of aromatic molecules: $E_{S0 \Rightarrow S2}$= 1.35 $E_{S0 \Rightarrow S1}$ and $E_{S0 \Rightarrow S3}$= 1.6 $E_{S0 \Rightarrow S1}$ =1. For p-terphenyl one obtains $E_{S0 \Rightarrow S2}$ = 6.075 eV which corresponds to 204 nm. The energy of the S0=> S3 transition is estimated then as $E_{S0 \Rightarrow S3}$ = 7.2 eV which corresponds to 172 nm. Therefore, the p-terphenyl must intensively absorb the Xe emission light (a molecular continuum in a vacuum ultraviolet region with a maximum at 175 nm).



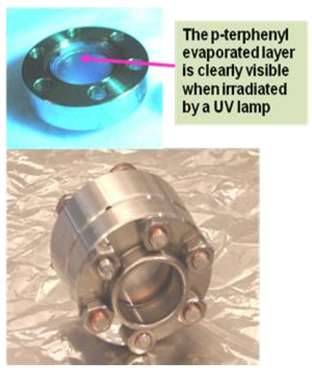
Since absorption and fluorescence spectra of molecular crystals are usually slightly different from those of molecular solutions, we have studied absorption of a thin (50 nm) polycrystalline p-terphenyl layer vacuum deposited on a fused silica optical window. The absorption spectrum has been measured in the wave length range from 180 to 350 nm. The peak corresponding to the S0 =>S2 transition has shifted from 206.5 to 220 nm while the peak corresponding to S0=>S1 transition remained at the same wave length. Therefore, the thickness 150 nm of a polycrystalline p-terphenyl layer is enough for absorption of 99.9% of the xenon light. The measured fluorescence spectrum of the polycrystalline p-terphenyl is shown by curve red in figure. The spectrum has a maximum at 370 nm.

First tests with wavelength shifter and MRS APD



The p-terphenyl is known to be quite volatile. It is even possible that the p-terphenyl layer may be sublimated and completely pumped out (according to our experience) if the pumping process is sufficiently long. On the other hand, the long pumping is required to obtain the good vacuum and the high purity of the LXe detection medium. The p-terphenyl can also seriously contaminate the test chamber and the gas system.

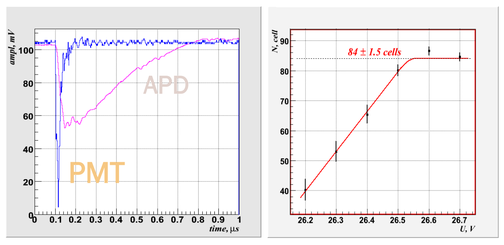
To avoid this, we protected the LXe from p-terphenyl pollution by two ways. In the first one, the vacuum deposited on an optical window p-terphenyl layer with a thickness of 450 nm was encapsulated between two windowed 1.33" CF flanges (see figure a).



This window was located in front of the photodetector. The window was made of sapphire which is transparent for VUV. Sealing of the construction was performed in an argon atmosphere to exclude the presence of oxygen between the windows (oxygen strongly absorbs the VUV light). In the second case, the p-terphenyl layer was made thinner (140±15 nm) and, visually, with much better quality. It was coated then by a 1-μm poly-para-xylylene film (see figure b). Polypara-xylylene (Parylene N) was chosen due to its well known properties such as the very low permeability to gases, and the possibility to form a conformal optically transparent film practically free of pin-holes even for several tens °A thicknesses. A newly developed by CPTA LTD, Russian Federation "blue sensitive" MRS APD was used for our experimental study. The size of the photodetector is 2x2 mm, and it contains 1584 cells (40 x 40 cells, with some dead area left for ultrasonic welding of a wire).

Data analysis and results

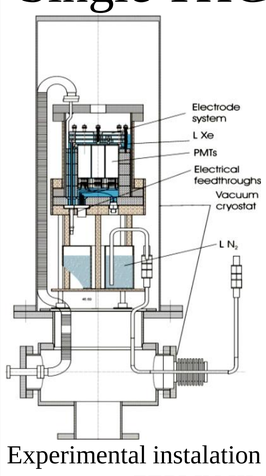
Data analysis included event-by-event calculation of the areas of the recorded signals (both the MRS APD single-cell noise ones and those produced by scintillation in the LXe) and plotting the area distributions. A ROOT code was used for data processing. Typical waveforms of signals from the PMT and from the MRS APD are shown on the left figure. The shape of the PMT signal is in accordance with a decay time of LXe scintillation (27 ns). The decay time of the MRS APD signal is defined by a cell capacitance and a resistance of a cell polysilicone resistor



To ensure that the photo detector did operate at a plateau of photo detection efficiency (PDE), the signals were recorded at different bias voltages. The voltage at which the number of fired cells in the alpha peak position reached a plateau was chosen as an operation point. In the first and second series of measurements (figure a and figure b, correspondently), this was at 26.4 V and 26.6 V with a plateau value of Ncells = 27.0 ± 0.5 and Ncells = 84.0 ±1.5. To obtain the real number of photoelectrons Nphe one must correct these numbers for the cross-talk between MRS APD cells. The correction is made with a formula: $N_{phe} = N_{cells}$ (1-α) where a cross-talk probability a is obtained from the ratio of the peaks corresponding to one and two cells in the noise distribution

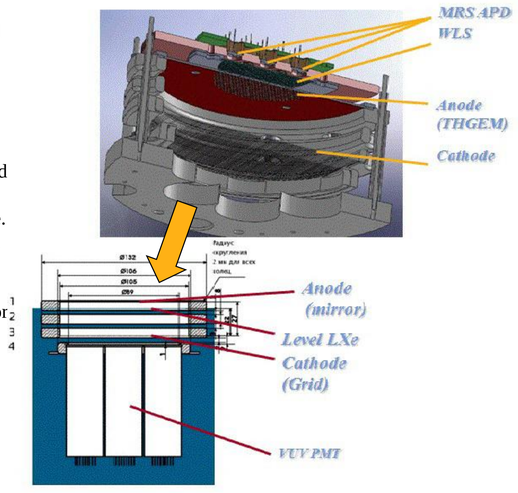
Series of measuremts	N_{cells}	PDE^0 ,%
p-terphenyl is sealed between two optical windows	24±0.5	9.7±1.2
p-terphenyl is coated by a poly-para-xylylene film.	72±1.5	8.4±1.1

Single THGEM Experimental setup

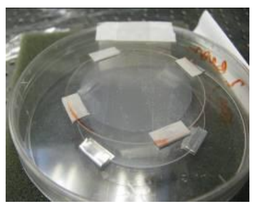


Experimental instalation – prototype ZEPLIN III

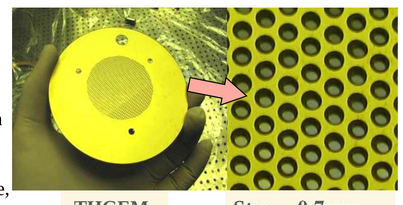
After first successful tests with MRS APD (produced by CPTA company) and WLS coupling the system consisted of THGEM, WLS and an array of 19 MRS APD was designed and has been assembled. A successful performance of a new detection system (THGEM+WLS+SiPM) in the two-phase xenon chamber has been demonstrated. It should be remarked that such a system with a multichannel readout was developed and tested in the liquid Xe for the first time. During the tests, it has been shown that THGEM can operate in a two-phase mode, giving substantial increase of the electroluminescence signal, and thus, providing the higher sensitivity of a two-phase detector to the extremely weak ionisation signals.



Components of the detector

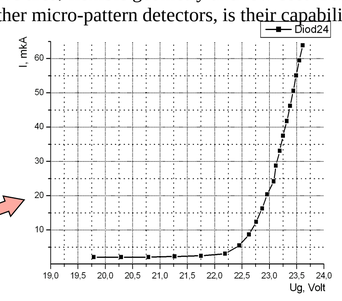


The recently developed gas electron multiplier (GEM) consists of a thin polymer foil, metal-coated on each side, and perforated by a high density of holes. With suitable potentials applied, it acts as powerful preamplifier for electrons released by ionizing radiation in a gas. The advanced features of GEM -based detectors are high counting rate, excellent spatial resolution, good imaging capability, operation in magnetic field, large sensitive area, flexible geometry and low cost A unique property of GEM s, as compared to other micro-pattern detectors, is their capability to operate in cascade.

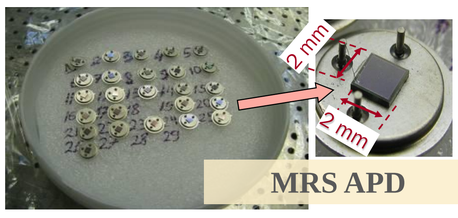


THGEM: **Step - 0.7 мм, Diameter. 0.4 мм, thickness 0.25 мм**

Wave length shifter (p-terphenyl is coated by a poly-para-xylylene film)

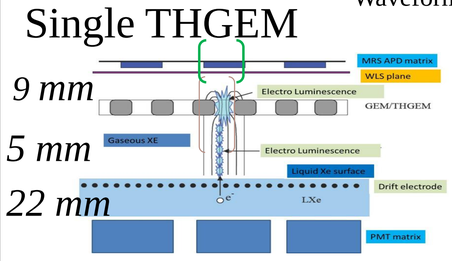


Typical current–voltage characteristic MRS APD

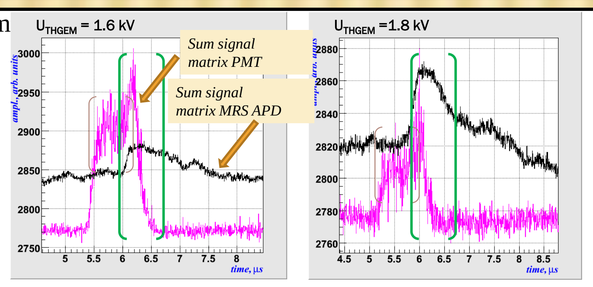


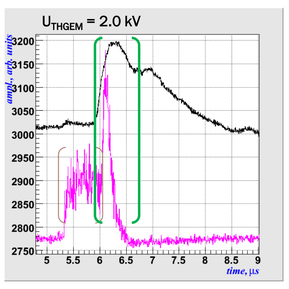
MRS APD

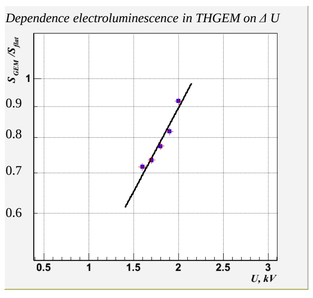
Single THGEM

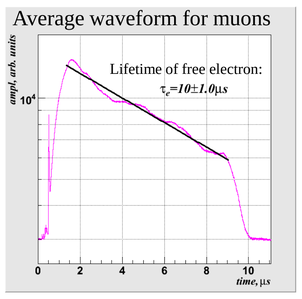


Waveform



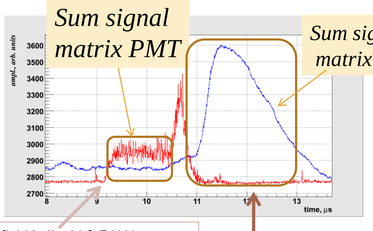






Results

DOUBLE GEM

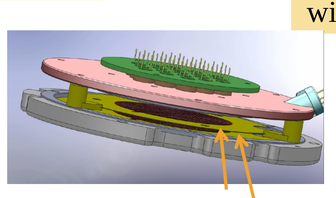


For field in liquid 2.5 kV/cm and in gas 4.90 kV/cm Area corresponds to 5950 ph.e. and 850 e (7 ph.e./e.)

~ 10 cells/e Can be achieved.

For THGEM2 U=1.6 kV MRS APD array signal ~150 cells

~300 for THGEM2 U=2.1 kV For 1V overvoltage ->3% PDE (MRS APD +WLS) Fill factor for array ~6% -> 50% So, it can be increased by a factor of 60, i.e. ~9000 cells



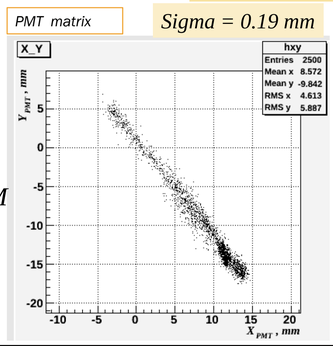
2nd THGEM

1st THGEM

XY position of the event is determined by a centroid method with the use of signals from several APDs and PMT

Reconstruction of muon track by:

PMT matrix — Sigma = 0.19 mm



MRS APD Matrix — Sigma=0.036 mm