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Performance of MPPC at low temperature*

AN Zheng-Hua(安正华)[1;1)] LÜ Jun-Guang(吕军光)[1] SHI Feng(石峰)[1] HU Tao(胡涛)[1]
CAI Xiao(蔡啸)[1] YU Bo-Xiang(俞伯祥)[1] FANG Jian(方建)[1] XIE Yu-Guang(谢宇广)[1]
WANG Zhi-Gang(王志刚)[1] XUE Zhen(薛镇)[1] SUN Xi-Lei(孙希磊)[1] LÜ QI-Wen(吕绮雯)[2]
ZHANG Ai-Wu(章爱武)[1] NING Fei-Peng(宁飞鹏)[1] ZHOU Li(周莉)[1] SUN Li-Jun(孙丽君)[1]
GE Yong-Shuai(葛永帅)[1] LIU Ying-Biao(刘颖彪)[1] WU Chong(吴冲)[3]

[1] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[2] Shanxi University, Taiyuan 030006, China
[3] College of Science, China University of Petroleum, Beijing 102249, China

Abstract: The performance of a MultiPixel Photon Counter (MPPC) from room to liquid nitrogen temperatures were studied. The gain, the noise rate and bias voltage of the MPPC as a function of temperature were obtained. The experimental results show that the MPPC can work at low temperatures. At nearly liquid nitrogen temperatures, the gain of the MPPC drops obviously to 35% and the bias voltage drops about 9 V compared with that at room temperature. The thermal noise rate from 10^6 Hz/mm at room temperature drops abruptly to 0 Hz/mm at −100 ℃. The optimized operation point can be acquired by the experiment.

Key words: silicon photomultiplier, MPPC, low temperature, gain, noise rate

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1 Introduction

Detection of scintillation light is a common and important method used in high energy physics and nuclear physics experiments. For example, in an experiment to directly detect dark matter particles in noble gas, the scintillation light was produced in liquid noble gas when elastic WIMP-nuclei collisions occurred [1, 2]. However, normally PMTs cannot be operated at low temperatures. The ideal photo detectors in the search of dark matter should satisfy the properties of low radioactivity, high photon detection efficiency and low temperature operation. The Geiger-mode APD (G-APD) which consists of multiple APD (avalanche photo-diode) pixels operated in Geiger mode is a new semiconductor photon sensor which has many features to meet these demands, such as a high gain up to 10^6, a low bias voltage (<100 V), insensitivity to a magnetic field, room temperature operation, high photo detection efficiency (PDE), high time resolution, low power consumption and robustness.

Like PMTs, G-APD can detect single photos. Therefore it is named silicon photomultiplier (SiPM). The SiPM is a multipixel semiconductor photodiode operating in limited Geiger mode or Geiger mode. The pixels are joined together on a common silicon substrate. Each SiPM pixel has the same structure, bias voltage and independent resistor. Typical pixel densities are 100–1600 pixels per mm^2 with pixel dimensions from 25×25 μm^2 to 100 μm×100 μm. The spectral response range for incident photons extends from 270 nm to 900 nm [3].

Many companies and research groups produce SiPMs. Each producer gives the device a different name. One should keep in mind that such names as Silicon PhotoMultiplier (SiPM), MultiPixel Photon Counter (MPPC), Solid State PhotoMultiplier (SSPM), multipixel Geiger-mode Avalanche Photo-Diode (G-APD) are all referring to photo detectors based on the same operation principle described above.

The main parameters of the MPPC include gain, PDE, operation voltage, the temperature coefficient

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* Supported by Technological Innovation Project of Institute of High Energy Physics
1) E-mail: anzh@ihep.ac.cn

of reverse voltage, the dark count rate, the dark current, the afterpulse rate and so on. The properties of SiPMs have been widely studied at room temperature [4]. A study on liquid xenon scintillation detection down to 168 K has been performed too [5]. However, its performance at the temperature of liquid argon (−186 ℃) and liquid nitrogen (−196 ℃) have not been fully characterized. For the feasible investigation of a MPPC for light readout applications within liquid argon targets, its low temperature performance has to be studied first. This is the main purpose of the work.

In this paper we present experimental measurements of the basic parameters of a Hamamastu MPPC (manufactured by Hamamatsu Photonics, Japan [6]) as a function of temperature from −194.5 ℃ to 30 ℃.

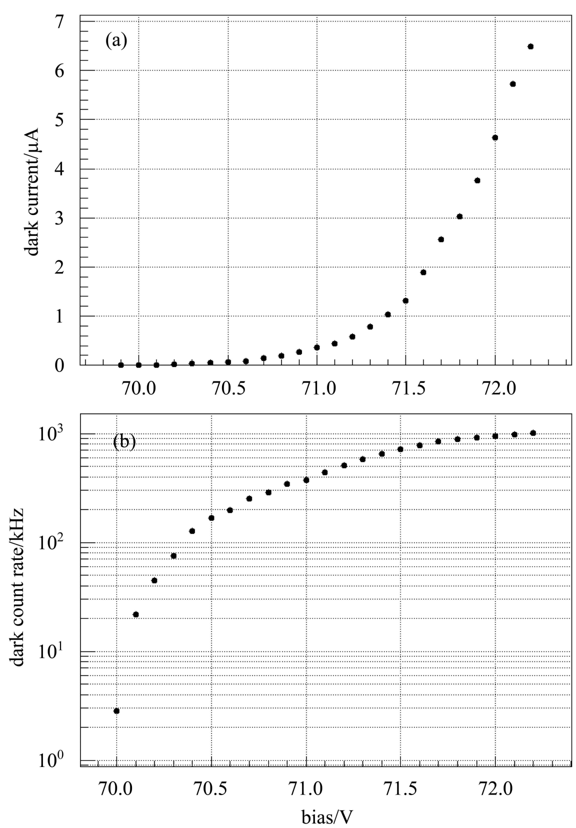

Fig. 1. (a) The relationship between the dark currents of MPPCs and the supplied bias voltages of MPPCs at room temperature; (b) The relationship between the dark count rate of MPPCs and the supplied bias voltages of MPPCs at room temperature.

The MPPC which was used in the experiment is 1 mm×1 mm and 100 pixels (S10362-11-100C). Different MPPCs of the same type will have different operation voltages. In general, we can use the dark current and dark count rate to get the optimized bias voltage of the MPPC. To find out the room temperature performance of the MPPC which we will study at low temperature, the dark current and dark count rate as the function of supplied bias voltage of the MPPC were measured first in our laboratory. Fig. 1 shows the dark currents and the dark count rate of the MPPC dependence on the supplied bias voltages at room temperature. In the measurement of leak current, a picoammeter KEITHLEY 6485 was used. From Fig. 1, it can be seen that the dark current and dark count rate of the MPPC increases exponentially with the increase of the bias voltage. When the bias voltage is 72 V, the dark current of the MPPC can reach 4.7 μA and the dark count rate of the MPPC can reach 1×10^6 Hz. The high level of intrinsic thermionic noise of about 1 MHz/mm^2 at room temperature is regarded as the difficulty of using a MPPC as a photon detector. It limits their application to wider fields. Since MPPC is a semiconductor detector, it can be expected that the noise rate of the MPPC will drop when it operates at low temperature and has a high PDE. So it is necessary to study the performance of A MPPC operating at low temperatures.

2 Experimental setup

Figure 2 shows the experimental setup of the MPPC at a low temperature. The setup consists of an inner steel test chamber held in a concentric outer chamber. Both chambers are contained in an aluminum vacuum liquid nitrogen Dewar. Careful addition of liquid nitrogen to the cryogenic jacket enables the temperature of the MPPC to be kept stable at any time. The accuracy of the temperature can reach ±0.2 ℃. The 1 mm^2 MPPC device is positioned near the centre of the inner chamber where one end of an optical fiber 1 mm in diameter is located. The other end of the fiber is adhered to a light emitting diode (LED), emitting a wavelength of 460 nm with a fast rise-time. The light passes through the fiber and reaches the MPPC device. The output of the optical fiber is positioned less than 1 mm from the MPPC device so that the total area of the MPPC can be illuminated. The bias voltage and preamplifier are powered using a Dinginess DC power supply. The signal from the MPPC is amplified by preamplifiers AMP_0604 (Photonique) and OREC 9530 since the gain of the MPPC is small at low temperature. The output signal is fed in a Philips 7166 QDC. Pulses from the generator are split into two. One lights the

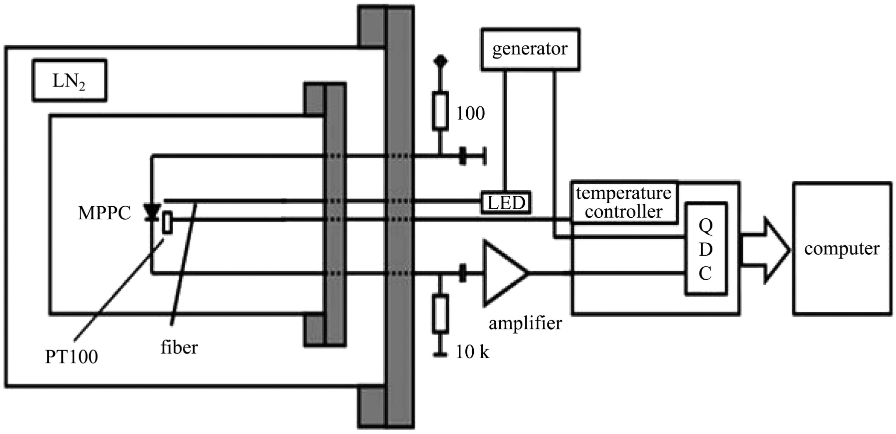

Fig. 2. Schematic of the liquid nitrogen Dewar used in the measurement.

LED. The other goes to QDC as a gated logic signal to ensure a valid event. The count rate is recorded by a scalar ORTEC 872 with a 0.5 photon amplitude threshold. A PT100 platinum resistance thermocouple is attached to the MPPC to provide accurate temperature information.

The dark count rate and the gain are measured with 0.1 V intervals starting from the breakdown voltage. The thermo noise rate, the total count rate and the signal count rate are recorded. Using the multi-photon electron spectrum and the single photoelectron peak at bias voltage, the gain of the MPPC can be calculated.

3 Experimental results

3.1 The gain of the MPPC

The MPPC gain is determined by the charge accumulation in a pixel capacity of a single pixel. The gain of a single photoelectron is gain=$Q_{\rm MPPC}/e$, where $Q_{\rm MPPC}$ is the charge of output, and e is the electron charge unit 1.6×10^{-19} C. The output signal charge of the MPPC [7] is:

$$Q_{\rm MPPC}=QE(\lambda)\cdot P_{\rm G}[V_{\rm A}-V_{\rm B}(T)]\cdot C_{\rm J}(T)\cdot[V_{\rm A}-V_{\rm B}(T)], \tag{1}$$

where QE is the quantum efficiency, $P_{\rm G}$ is the Geiger discharge probability, $C_{\rm J}$ is the junction capacitance which is a function of temperature, and $[V_{\rm A}-V_{\rm B}]$ is the overvoltage bias ($V_{\rm A}$ is the bias voltage of the MPPC, $V_{\rm B}(T)$ is the breakdown voltage of the MPPC). Typically, the gain of single pixel is about 10^6, in the same order of magnitude as that of normal PMTs. From Eq. (1), it can be easily deduced that the gain increases linearly with the overvoltage and also changes with the junction capacitance which has a relationship with the temperature. So the gain will change with bias voltage and temperature.

In order to observe a single photoelectron spectrum easily, the intensity of the LED is adjusted to very low. The gains of the MPPC are obtained by fitting the single photoelectron spectra, multi-photoelectron spectra and subtracting pedestals.

The gain of the MPPC as a function of the bias voltage for different temperatures is presented in Fig. 3. There are thirteen gain curves shown. From Fig. 3, it can be seen that the gain and the bias voltage decrease with temperature. The maximum gain of the MPPC can reach 3.8×10^6 at 20 ℃. In the range of the studied temperature, as the bias voltage increases, the gain increases linearly. There are two features in the figure. For temperatures between 30 ℃ to -120 ℃, the change of gain with temperature is obvious and steady. For temperatures between -140 ℃ to -194.5 ℃, the change of gain with temperature is not linear. As the temperature decreases, the change in gain is not obvious. And at nearly liquid nitrogen temperatures, the gain of the MPPC drops to 1×10^6 which is about 35% of its room temperature.

3.2 Temperature coefficient of reverse voltage of the MPPC

In order to describe the sensitivity of the MPPC to temperature, we define a temperature coefficient of reverse voltage (TCRV). The TCRV means that the bias voltage changes per unit temperature, while keeping the gain of the MPPC constant

The sensitivity of voltage and temperature to gain can be obtained from Fig. 3. From the figure, at a gain of 2×10^6, the TCRV of the MPPC is a constant 54 mV/℃ between -60 ℃ and 30 ℃ (see Fig. 4(a)).

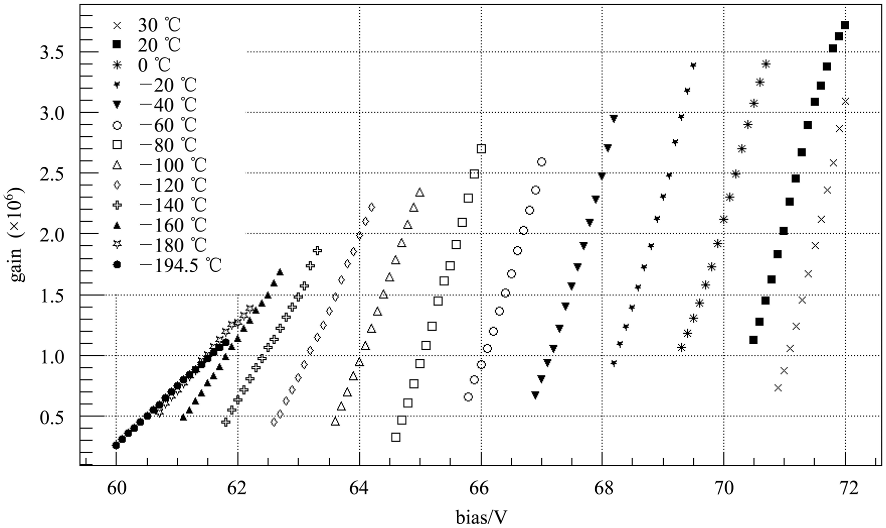

Fig. 3. The gain of the MPPC as a function of the bias voltage for different temperatures.

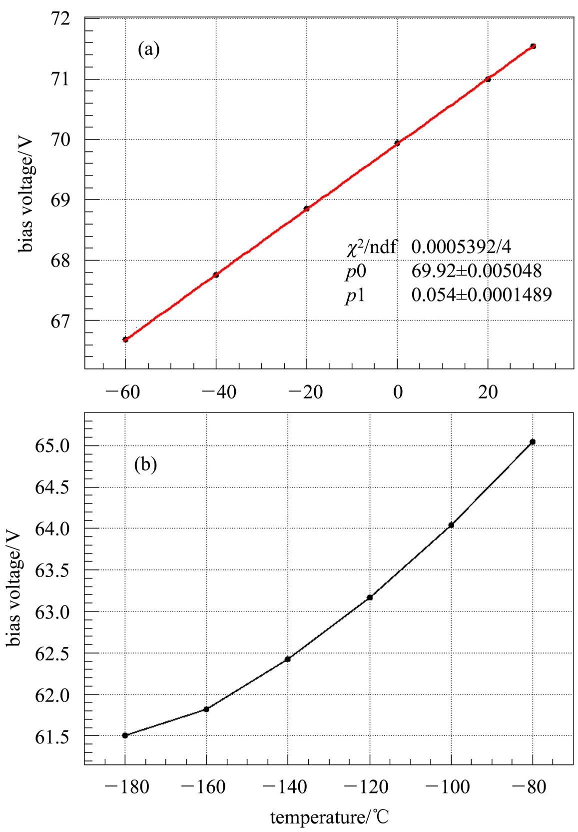

Fig. 4. (a) Bias voltage vs. temperature (−60 ℃–30 ℃) with the gain 2×10^6 of MPPC; (b) Bias voltage vs. temperature (−180 ℃–−80 ℃) with the gain 1×10^6 of MPPC.

In the temperature range from −20 ℃ and 20 ℃, the manual of the MPPC shows that the TCRV is 56 mV/℃ [6]. That means the TCRV manual can be used down to −60 ℃. Because the TCRV is a constant, it is very convenient for use in applications. A circuit of temperature compensation can be designed to get the gain of the MPPC at a constant. But when the temperature is below −60 ℃, the variation in the gain of the MPPC is not uniform and the TCRV is not a constant. Fig. 4(b) shows the bias voltage vs. temperature with the gain at 1×10^6 of the MPPC. It can be found that when the temperature is below −60 ℃, the curve of the bias voltage vs. temperature is not linear and bias voltage drops slowly with temperature. A Geiger-mode operation reduces the temperature sensitivity, but temperature stabilization or compensation is still required for any applications using MPPCs, especially at low temperatures (<60 ℃).

3.3 The thermal noise rate and afterpulse rate of the MPPC

A breakdown of the MPPC can be triggered by an incoming photon or by any generation of free carriers. It is impossible to discriminate which signal is caused by photons or carriers. Therefore, the main source of noise which will have influence on light detection of low intensities is the dark counts. They are composed of the primary pulses triggered by carriers thermally generated or field-assisted in the sensitive volume and the afterpulse which is caused by carrier trapped at lattice defects and has a delayed release after a short time [8].

At room temperature, a typical value of the thermal noise count rate is about 1 MHz/mm^2 with a threshold of half of the photon amplitude. It is the main part of dark count. Because of the high count rate of thermal noise, it is difficult to observe the afterpulse count rate. Thermally generated free carriers can be reduced by cooling MPPC. Therefore, when

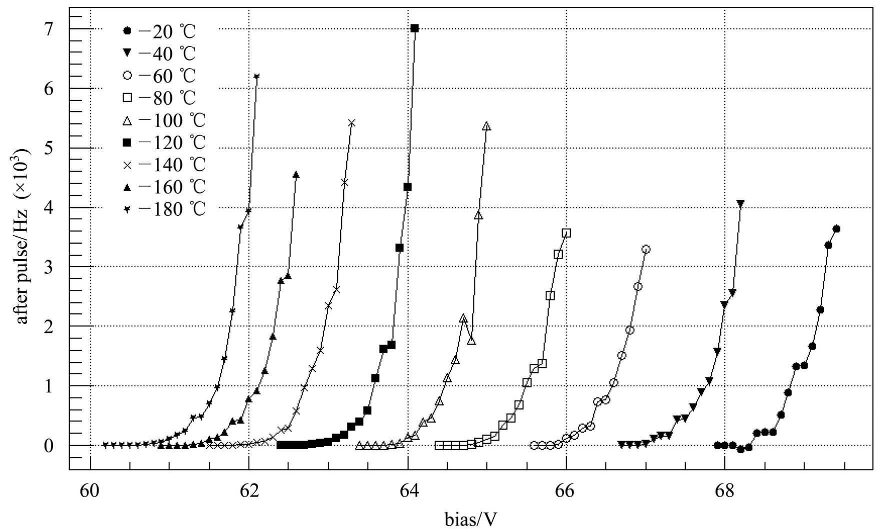

Fig. 5. The afterpulse count rate of the MPPC as a function of the bias voltage for different temperatures.

the random thermal noise reduces with decreasing temperature, pulses following the true signal can be obviously seen.

Figure 5 shows the afterpulse count rate of the MPPC as a function of the bias voltage at different temperatures. The effective detection of an afterpulse is between −194.5 ℃ to −20 ℃. From Fig. 5 it can be seen that the count rate of afterpulses is not reduced by cooling and just increases as bias voltage increases and reaches up to 10^3 Hz. Afterpulses are spurious pulses following the true signal and sometimes they pile up with true signals causing detection errors. The higher the bias voltage, the higher the probability that carriers may be trapped by crystal defects, so afterpulses will increase. We can deduce that the count rate of afterpulses is independent on temperature and it is influenced by the material and manufacture of the MPPC.

3.4 The optimized bias voltage of MPPC at different temperatures

To find out the optimized bias voltage of the MPPC at different temperatures, we use two parameters. One is the photon-counting capability. The other is the count rate of afterpulses. The photoelectron spectrum of the MPPC shows an excellent photon-counting capability which is even better than that of PMT. The photon-counting capability is very important for extremely weak light intensity applications. So the ability of single photon resolution can be used to decide the optimized bias voltage of the MPPC. At the same time, because the count rate of afterpulses is independent of temperature and dependent on bias voltage, the count rate of afterpulses can also be used to find out the optimized bias voltage of the MPPC at different temperatures. Using the multi-photoelectron spectra and afterpulse count rate (∼150 Hz), we can find the optimized bias voltage of the MPPC at different temperatures.

Figure 6(a) shows the optimized bias voltage as a function of temperature. With the decrease in temperature, the bias voltage drops about 54 mV/℃ between −60 ℃ and 30 ℃ and drops slowly between −194.5 ℃–−60 ℃. Fig. 6(b) shows the thermal noise count rate as a function of temperature at the optimized bias voltage. As the temperature decreases, the thermal-electron excitation obviously drops. It reduces 90% per 20 ℃ decrease and it will drop abruptly to 0 Hz at −100 ℃.

Figure 6(c) presents the gain of the MPPC as a function of temperature at the optimum bias voltage. With a variation in temperature, the gain of the MPPC changes dramatically. When the temperature is −80 ℃, the decreasing gain reaches a point of inflexion. Below this point, the gain decreases slowly. At the optimized bias voltage and at −194.5 ℃, the gain of the MPPC drops abruptly to 35% of its room temperature gain.

The multi-photoelectron pulse charge spectrum of the MPPC with bias voltage (62.4 V) at −140 ℃ is exhibited in Fig. 6(d). For the MPPC at low temperatures, the successive 1–19 photoelectron peaks demonstrate an excellent photon-counting capability. Only 10 photoelectrons can be identified at room temperature. This is mainly due to the electric noise and high thermal noise count rate of the MPPC device. In fact, from our experiments, we find that at nearly −140 ℃ the MPPC reached the highest photon-

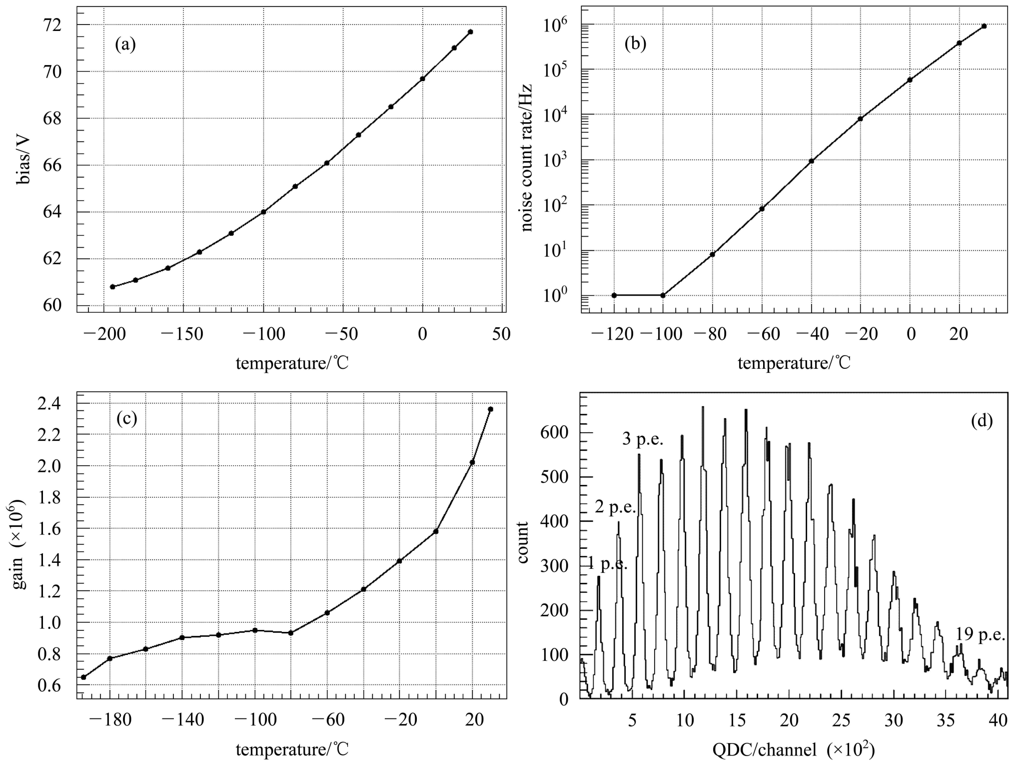

Fig. 6. (a) The MPPC optimized bias voltage as a function of temperature; (b) The thermal noise count rate as a function of temperature at the optimum bias voltage; (c) The gain of the MPPC as a function of temperature; (d) Multi-photoelectron pulse charge spectra of the MPPC at −140 ℃.

counting capability. When operating at lower temperatures, with the gain decreasing, the signal to noise ratio of the MPPC gets worse, and the photon-counting capability decreases.

4 Conclusion and discussion

In this paper, we have reported the basic properties of a MPPC at low temperatures. The changes in gain, afterpulse rate and bias voltage of the MPPC with temperature are obtained. The experimental results show that the MPPC can work at low temperatures down to −194.5 ℃. At nearly liquid nitrogen temperature, the gain of the MPPC drops obviously to 35% and the bias voltage drops about 9 V compared with at room temperature. Thermal noise rate from 10^6 Hz/mm at room temperature drops abruptly to 0 Hz/mm at −100 ℃.

Although MPPC devices have not yet achieved the performance parameters of traditional quartz PMTs, especially in terms of the active area and high rate capability, the development of MPPC devices is ongoing and an improved performance is assured due to the vast number of applications that would benefit from the technology. The low temperature performance of the MPPC confirms the cryogenic operation for direct dark matter detection at liquid argon temperature.

The properties of the MPPC device at low temperatures still need a systematic study. The PDE and cross-talk as a function of bias voltage at different temperatures are the subject of our subsequent research.

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