Geiger Mode APD performance in a cryogenic two-phase Ar avalanche detector based on THGEMs

A. Bondar a, A. Buzulutskov a,*, A. Grebenuk a, A. Sokolov a, D. Akimov b, I. Alexandrov b, A. Breskin c

a Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia
b Institute of Theoretical and Experimental Physics, 117218 Moscow, Russia
c Weizmann Institute of Science, 76100 Rehovot, Israel

Abstract

Characteristic properties of a Geiger Mode APD (G-APD) in a THGEM-based cryogenic two-phase Ar avalanche detector were studied in view of potential applications in rare-event experiments. G-APD signal amplitude and noise characteristics at cryogenic temperatures turned out to be superior to those at room temperature. The effective detection of avalanche scintillations from THGEM-multiplier holes in two-phase Ar has been demonstrated using a G-APD without wavelength shifter. At an avalanche gain of 60, the avalanche scintillation yield measured by the G-APD was as high as 0.9 photoelectrons per avalanche electron, extrapolated to 4\pi acceptance.

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1. Introduction

In the concept of cryogenic two-phase avalanche detectors [1,2] the two-phase electron emission detector [3] is operated in an electron-avalanching mode using Gas Electron Multipliers (GEMs) [4] or thick GEMs (THGEMs) [5]. The development of such detectors is motivated by applications in rare-event experiments and in medical imaging: in coherent neutrino-nucleus scattering [6], dark matter search [7], solar and large scale neutrino detectors [8,9], and in Positron Emission Tomography [2]. In particular for the former application, a low-noise self-triggering detector is required with ultimate sensitivity, operated in single-electron counting mode. Most promising results were obtained with two-phase Ar avalanche detectors providing gains reaching 10^5 with GEMs [10,11,12] and gains reaching 3\times10^3 with THGEMs [13].

In this work we study a novel technique of signal recording in two-phase avalanche detectors, namely an optical readout of avalanche-induced scintillation photons from THGEM holes with Geiger Mode APDs (G-APDs, [14]). In detectors requiring ultimate sensitivities the optical readout, as compared to the charge readout, might be preferable in terms of overall gain and noise. In addition, the G-APD performance at low temperatures is expected to be superior to that at room temperature; however, existing data in such conditions vary in the literature [15,16,17,18,19,20], which motivated our new investigations.

Earlier studies of optical readout from THGEM in two-phase Ar [21] used G-APDs coated with a wavelength shifter (WLS), sensitive to VUV scintillation. In contrast, in the current work no WLS was used. This was based on the observation that Ar has effective avalanche-induced scintillations in the near infrared (NIR) [22], where the photon detection efficiency (PDE) of the G-APD can reach 20%. We present the first results on the optical readout from a THGEM multiplier in two-phase Ar with an uncoated G-APD; more elaborated results will be presented elsewhere [23].

2. Experimental setup

The experimental setups and procedures for investigating
our first generation of two-phase avalanche detectors were already described in [10,11,12,13]. A new cryogenic chamber was recently assembled, with a larger volume (9 l), larger X-ray windows and better temperature stability (Fig. 1). In the two-phase mode, the chamber comprised a cathode mesh at the bottom, immersed in a 1 cm thick liquid Ar layer and a 25×25 mm² double-THGEM assembly placed in the saturated vapor above the liquid. The Ar was purified by an Oxisorb filter, providing an electron life-time of >20 µs in the two-phase mode. The THGEM geometrical parameters were the same as in [13].

A G-APD (MRS APD “CPTA 149-35”, [24]) was placed at a distance of 4 mm behind the second THGEM. It was optimized for the green-red range; it had a 4.41 mm² active area, 1764 pixels, a capacitance of 150 pF and a PDE of ~15% at 800 nm [24,25]. The quenching resistor of each pixel was measured to be 25 MΩ and 5.7 GΩ at room temperature and at 88 K respectively.

The signal from the G-APD was read out via a 1 m long twisted-pair cable connected to a fast amplifier (CPTA, [24]) with 300 MHz bandwidth and an amplification factor of 30. The ionization (anode) signal was read out from the last electrode of the second THGEM using a charge-sensitive amplifier with a shaping time of either 0.5 or 3 µs.

When studying the G-APD characteristics, the THGEM multiplier was inactive. In this case, at room temperature, the G-APD single-pixel amplitude was measured using the noise-amplitude spectrum. At cryogenic temperatures, however, the G-APD noise rate was too low. For this latter case the G-APD single-pixel amplitude, as well as the relative PDE, was measured using the amplitude spectrum of Ar scintillation light-pulses produced by a pulsed X-ray tube (with a frequency of 200 Hz) in the gas gap between the second THGEM and the G-APD.

For studying the two-phase avalanche detector performance with THGEM + G-APD, the signals were induced by 60 keV X-rays from an 241Am source.

3. Results

In Fig. 2 the G-APD pulse shapes of noise signals are compared at room and cryogenic temperatures, i.e. at 295 and 87 K: the single-, double- and triple-pixel signals are well identified. It is interesting to note that the pulse-shape is basically independent of the temperature, in contrast to observations in [16]. We did not observe any indications of after-pulses, in particular at cryogenic temperatures, for time scales of up to 10 ms.

The major part of the signal had a width of 20 ns, reflecting the time structure of the Geiger discharge in the pixel. In addition the signal had a longer opposite-polarity tail, reflecting the characteristic response of the fast amplifier. The original bipolar pulses were transformed to unipolar, with a shaping time of 100 ns, the area of which provided the amplitude of the G-APD signals.

Fig. 3 shows the G-APD amplitude noise spectrum at 87 K and at a bias voltage of 44 V. The single-, double- and triple-pixel amplitude signals are well separated, providing the single-pixel amplitude to be well defined. From this spectrum one can estimate the cross-talk between pixels at this operation voltage: its value averaged over several measurement runs was about 40%. Accordingly, in the following the photoelectron yield is corrected for cross-talks by dividing by a factor of 1.4.

Fig. 4 shows the G-APD gain-voltage characteristics, namely the single pixel charge as a function of the bias voltage, at different temperatures. Here the over-voltage is defined as the difference between the bias and the breakdown voltage, the latter being defined at the intersection of the gain-voltage characteristic with the abscissa. One can see that the typical linear growth of the pixel amplitude ends by its saturation, at over-voltage of 7 V and 14 V at room and cryogenic temperatures respectively. Moreover, the maximum pixel amplitude (in the saturation mode) at cryogenic
Fig. 4. G-APD single pixel charge as a function of the bias voltage at different temperatures: at 87 K, 140 K and 295 K.

Fig. 5. G-APD noise rate as a function of the bias voltage at different temperatures. The fits to the data points are performed with an exponential function for the 87 and 140 K data, and with a linear function for the 295 K data.

Fig. 6. G-APD relative photon detection efficiency (PDE) as a function of the bias voltage at 87 K. Shown is the average photoelectron number per scintillation pulse, induced by the X-ray pulse, recorded within a 600 ns gate.

As expected [17], compared to room temperature the breakdown voltage is decreased at cryogenic temperatures (Fig. 4): from 34.5 to 30 V respectively. On the other hand, the amplitude characteristics at 87 and 140 K turned out to be practically identical, though the noise rates are different (see Fig. 5).

Fig. 5 confirms the significant differences in G-APD performance between room temperature and cryogenic temperatures. The noise rate was measured by counting the noise pulses in a fixed time interval, the noise signals being recognized by their characteristic pulse-shape (Fig. 2). As expected, the noise rate considerably decreases with the temperature decreases: at 87 K it can be as low as 1 Hz at over-voltage of 8 V. Furthermore, the data points are described by different functions, indicating different mechanisms for the charge carrier generation: we used a linear function for the room temperature data, and an exponential function for the data at cryogenic temperatures.

Fig. 6 illustrates the dependence of the G-APD relative PDE on the bias voltage at 87 K; it shows the value proportional to the PDE, namely the G-APD average photoelectron number per scintillation pulse, induced by the X-ray pulse, recorded within a certain time gate. The PDE reaches a plateau at over-voltage of 5 V; a similar behavior was observed at 140 K.

We assume that the effects observed in the present work indicate more complicated mechanisms for the G-APD performance at cryogenic temperatures than what is expected from earlier studies [16,17,18]; but the particular mechanism may be strongly dependent on the G-APD structure.

We have observed avalanche scintillations in a THGEM-based two-phase Ar avalanche detector using a G-APD without WLS, i.e. insensitive to UV. Consequently, the scintillations most probably occurred in the NIR as discussed in section 1. As example, a scintillation and an ionization signal, induced by a 60 keV X-ray, are presented in Fig. 7, at a double-THGEM gain of 60 and a G-APD voltage of 44 V. The fast G-APD signal provides an effective means to study the electron emission and avalanche mechanisms in two-phase Ar. Its time structure reflects the electron emission processes at the liquid-gas interface [26]: the pulse spike at the beginning is induced by the fast electron emission component and the tail by the slow component (see details in [23]).

At this particular solid angle and avalanche gain (~60) the average number of photoelectrons (pe), recorded by the G-APD and corrected for cross-talks, was about 130 pe for a 60 keV X-ray converted in liquid Ar, producing about 900 initial electrons in the gas phase (prior to multiplication in the THGEM). That means that for the effective operation in a single electron counting mode (> 3 pe per initial electron), the solid angle, the THGEM gain and the light yield should be jointly increased by a factor of 20, which is possible to access.

The avalanche scintillation light yield can be better estimated from Fig. 8, showing the G-APD-to-THGEM amplitude ratio distribution; here the amplitudes are expressed in photoelectrons (pe) and avalanche electrons (e) respectively. The distribution average amounts to 0.0034 pe/e.
Fig. 8. G-APD to THGEM amplitude ratio distribution induced by 60 keV X-rays in two-phase Ar at 87 K and 1.0 atm, at a double-THGEM gain of 60, a G-APD bias voltage of 44 V, and an electrical field within the liquid Ar of 1.8 kV/cm. The vertical scale is 100 and 50 mV/div, respectively. The time scale is 2 µs/div. The THGEM amplifier shaping time is 0.5 µs. The integrated G-APD amplitude (middle trace) is 560 photoelectrons.

Taking into account the G-APD average solid angle with respect to the second THGEM, $\Delta \Omega/4\pi = 2.7 \times 10^{-3}$, and correcting for cross-talks, we obtained the following G-APD yield extrapolated to $4\pi$ acceptance: 0.9 pe/e or, accounting for the G-APD PDE of 15% at 800 nm, 6 photons/e. This is a rather high yield; it should be compared to the value of ~1 photon/e presented in [22] for avalanche scintillations in Ar in the NIR region.

4. Conclusions

A novel optical concept of signal recording in two-phase avalanche detectors, with a G-APD measuring the THGEM avalanche scintillation photons, has been studied in view of potential applications in rare-event experiments. The G-APD amplitude and noise characteristics at cryogenic temperatures turned out to be superior to those at room temperature; in particular at 87 K, the noise rates were of few Hz at the PDE efficiency plateau and the maximum G-APD gain was higher by a factor 4 compared to room temperature operation.

The effective detection of avalanche scintillations from THGEM multiplier holes in two-phase Ar has been demonstrated with G-APDs not coated with a WLS. At an avalanche gain of 60, the THGEM + G-APD yielded about 130 photoelectrons per 60 keV X-ray converted in liquid Ar. The avalanche scintillation yield measured by the G-APD was 0.9 photoelectrons per avalanche electron, extrapolated to $4\pi$ acceptance.

In practice, the optical readout of two-phase detectors would comprise a matrix of G-APDs placed behind the THGEM multiplier with a pitch of ~1 cm, to cover the active area with a spatial resolution sufficient for rare-event experiments. For example, for a 100 kg liquid Ar TPC with a volume of $40 \times 40 \times 40$ cm$^3$ the total number of G-APDs would amount to 1600, which is not too much. Such a THGEM + G-APD assembly would be robust, relatively cheap and would have good performance. Further studies are in progress.

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