IEEE Transactions on Nuclear Science, Vol. NS-30, No. 1, February 1983

THE GAS PHOTODIODE AS A POSSIBLE LARGE-AREA PHOTON DETECTOR

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1. Introduction

At the increasingly high energies and multiplicities of secondary particles produced by present-day accelerators, and with the availability of cheap, low-noise amplifiers, the possibility of using vacuum photodiodes as detectors of the light-flashes produced in the scintillators has been successfully investigated[1,2]. Vacuum diodes, having unitary gain, are particularly attractive in conjunction with large-yield scintillators such as NaI and BGO crystals; an electromagnetic calorimeter composed of 1,000 NaI crystals coupled to commercial vacuum photodiodes is already operational at CERN[3]. The smaller light yield obtained in lead-glass calorimeters, however, seems not to allow the use of vacuum diodes as detecting elements; moreover, the size of such devices is limited by the necessity of withstanding the atmospheric pressure, and they cease to operate in the presence of moderate magnetic fields.

Following the proposal of one of us[4], we have further investigated the possibility of using gas-filled photodiodes as a moderate gain, magnetic-field-insensitive alternative to the vacuum diodes. Attempts have been made to operate the devices with gas pressures approaching the atmospheric, a solution that would open the way to the construction of large-surface very thin detectors. The properties and limitations observed so far in a dozen of prototype gas-filled diodes, custom manufactured to our specifications, are described here.

2. Generalities on the Gas Photodiodes and the Testing Procedure

Gas-filled photodiodes have been used for decades as cheap, reliable, photon detectors with moderate gains, e.g. for reading the sound track recorded optically in movies. Replaced by solid-state detectors, they have virtually disappeared from most manufacturer's catalogues. The usual gas filling was argon at pressures around or below 1 Torr, and typical sensitivities between 50 and 100 μA/lm were quoted[5]. We have obtained from two phototube manufacturers, EMI**) and ITL***), several samples of gas-filled photodiodes in a large range of sizes, filling gas, and pressures; all devices had a bialkali photocathode with a borosilicate window. To allow a quick survey, we have used existing envelopes, which are therefore not optimized in size and thickness for use in an actual calorimeter system. The best results in all geometries have been obtained using a solid photocathode which faces, at a few millimetres distance, a semitransparent resistive anode coated on the input window; the largest device tested so far (produced by ITL) had an active diameter of 80 mm (see Fig. 1).

Fig. 1 Some of the custom-made gas photodiodes, having an active photocathode diameter from 19 to 80 mm.

To test the devices, we have used as light sources the attenuated white emission from a tungsten filament, two kinds of light-emitting diodes (LEDs) with emissions around 460 nm and 560 nm, and a N_2 pulsed laser (emitting at 337 nm); the pulse response has been investigated, generating short (100 ns) light-flashes with the LEDs, or with the nitrogen laser having less than one nanosecond flash length. Quantum efficiency measurements were realized with a monochromator, using as reference a bialkali phototube (RCA 8850) used at gain one; the tube had a certified peak efficiency of 30%. The typical efficiency of a vacuum reference photodiode, from the same batch as the gas-filled one, was lower and around 10% (Fig. 2) probably because of the manual processing. The best argon-filled low-pressure diodes reached about the same value, whilst a high-pressure methane photodiode (see Section 4) had about 7% efficiency (the lower curve in the figure).

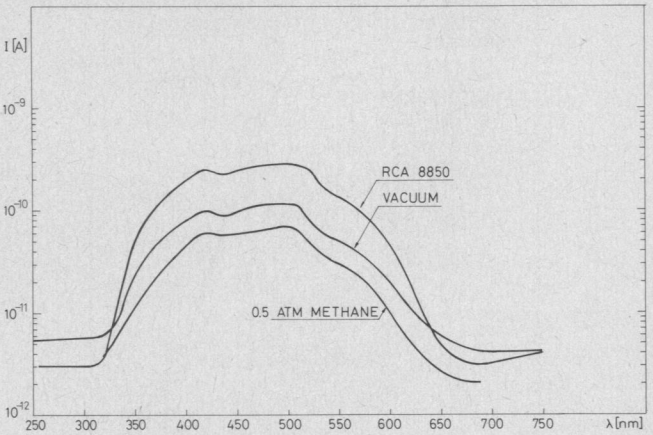

Fig. 2 Relative quantum efficiency versus wavelength of several devices. The reference phototube (used as diode) had a certified efficiency of 30%. Efficiencies of a vacuum and methane-filled diode are compared, the argon diodes have typical efficiencies between these two values.

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0018-9499/83/0200-0134$01.00 © 1983 IEEE

3. Experimental Results: Argon-Filled Photodiodes

So far we have tested half a dozen argon-filled prototypes manufactured, with various geometries, by EMI and ITL in a range of pressures between 0.1 Torr and 210 Torr. The active diameter varied between 20 and 80 mm, and the anode/cathode gap from 0.7 to 9 mm. Both solid and semitransparent photocathode structures were tried, although only the first kind of geometry gave satisfactory results (probably because of some difference in the manufacturing procedure). The anode was realized in this case with either a micromesh or a resistive semitransparent layer coating the inside surface of the window. Some gain instabilities were recorded in the first case, probably because of the charging up of the underlying glass surface. The best results in terms of quantum efficiency (around 10%) and stable gains (up to 50) were obtained in a 1.5 mm gap device filled at a pressure around 1 Torr; Fig. 3 shows the voltage-current d.c. characteristics measured for a continuous illumination with a green LED emitting around 460 nm. Typical dark currents are below a few picoamperes at the highest voltage attained before breakdown. A gain of 30-40 could be considered as safe for stable operation.

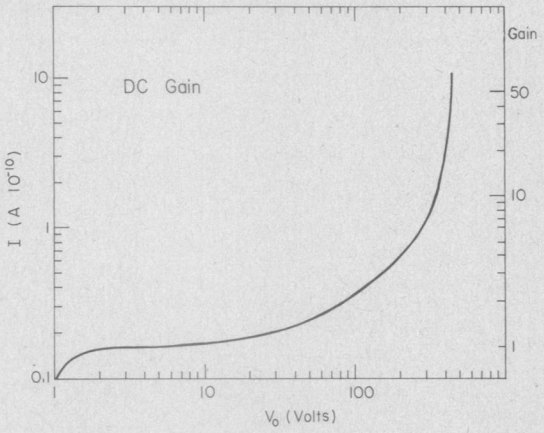


Fig. 3 DC current voltage characteristics of a 1 Torr argon-filled photodiode

The pulsed characteristics of the diodes were studied applying a short (100 ns) current pulse to the LED.

The photodiode output pulse was amplified by a charge amplifier; the picture in Fig. 4 shows the evolution of the detected charge signal at increasing values of the operating voltage; the horizontal scale is 500 ns/div. The smaller signal corresponds to simple

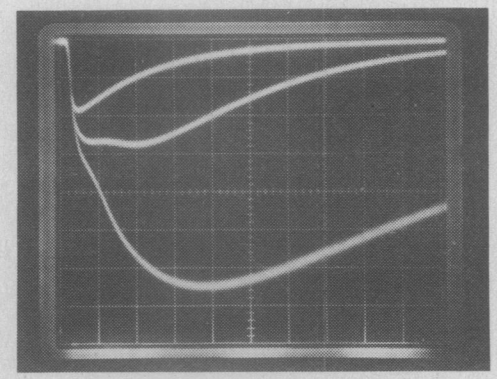


Fig. 4 Development of the detected signal on 1 Torr argon diode at increasing operating voltages with a charge amplifier having 1 μsec time constant; the smaller pulse corresponds to simple collection. The horizontal scale is 500 nsec/div.

electron collection during 100 ns (the duration of the light-flash) followed by the decay constant of the charge amplifier. At the onset of charge multiplication, most of the signal is due to the motion of positive ions within the avalanche, a known property of gaseous counters.

The noise characteristics of the diode-amplifier system have been studied, recording the pulse-height spectra at low light levels. A typical ungated amplitude spectrum measured for about 10^3 photoelectrons at a photodiode gain of 10 is shown in Fig. 5; it has a FWHM of 25%, corresponding to 2500 electrons (250 photoelectrons); the amplifier noise contributed to the dispersion with about 1500 electrons FWHM (the lower peak corresponds indeed to the highest part of the noise spectrum).

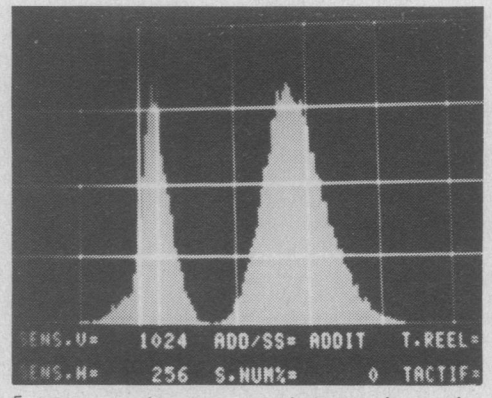


Fig. 5 Pulse-height resolution obtained with the diode operated at a gain of 10, at a light level corresponding to 10^3 photoelectrons (higher peak). The amplifier noise is shown by the lower peak.

Pursuing the aim of obtaining a high-pressure gas device, we have tested a prototype filled with argon at 210 Torr. The outcome was, however, negative; as compared to the vacuum characteristics, the high-pressure device shows a much reduced quantum efficiency and no evidence of photoelectron collection plateau before multiplication (Fig. 6). Evacuating again the same tube during the manufacturing process, the original characteristics are restored, showing that the degradation is not due to some kind of photocathode damage. We believe that in the increased density the ejected photoelectrons suffer too much back-scattering from the argon molecules and are repelled back to the photocathode. As will be shown in the next section, this is perhaps not a general property of all gases, leaving us with the hope of obtaining a high-pressure working device.

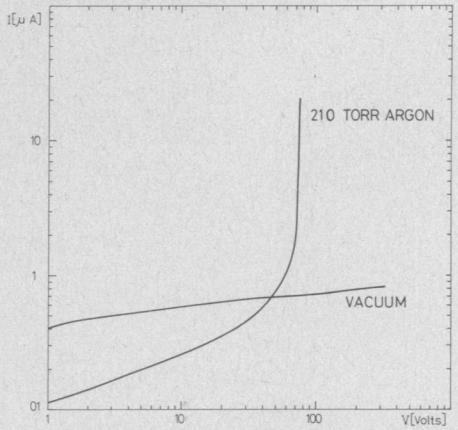


Fig. 6 Voltage-current characteristics of a high pressure argon photodiode, as compared to a vacuum reference.

4. Photoelectron Collection Efficiency in High-Pressure Gases

As indicated above, a bad photoelectron collection efficiency was obtained in the diodes filled with argon at pressures approaching the atmospheric pressure. To investigate this point further and to find the optimum filling pressure without the delay and the expense of obtaining a real device, we have implemented a special multiwire proportional chamber as a photon-sensitive device. This chamber, which has a solid aluminium cathode that could be illuminated through a window and a semitransparent mesh cathode, could be operated with a large range of pressures and gas fillings. Despite the very low (10^{-4} or so) quantum efficiency of the metal photocathode, enough photoelectrons could be extracted to allow a good current measurement, from the collection to multiplication. A typical result obtained for argon is shown in Fig. 7. The curves repeat the trend already observed in the gas photodiodes: at low pressures there is a collection plateau followed by multiplication, while at increasing pressures the plateau gradually disappears. Again, owing to the nature of the photocathode, this shows that the effect of high pressures is to reduce the collection efficiency (probably through electron back-scattering). Essentially the same trend was observed in helium and xenon.

Surprisingly, however, the behaviour in methane is entirely different: although, of course, at increasing pressures one needs higher working voltages, the plateau structure is preserved, indicating a good photoelectron collection up to and above atmospheric pressures (Fig. 8). The same trend has been observed in isobutane.

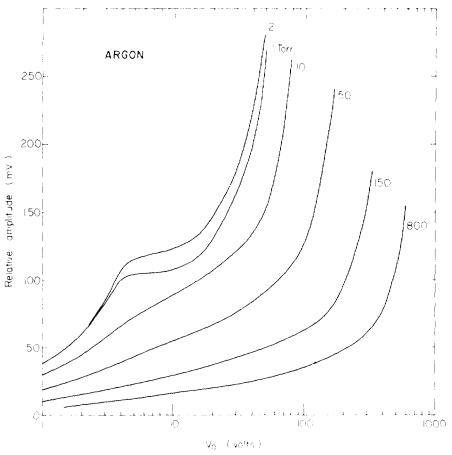


Fig. 7 Voltage-current characteristics measured in a parallel plate chamber with a metal photocathode, at increasing pressures of argon.

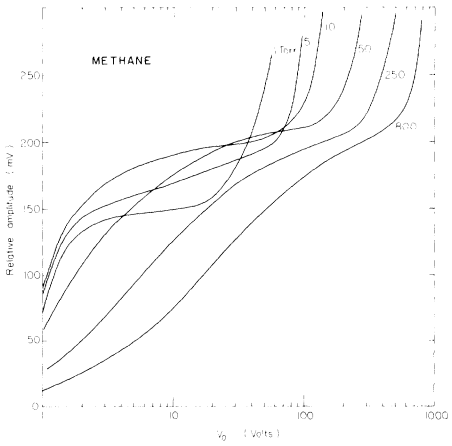
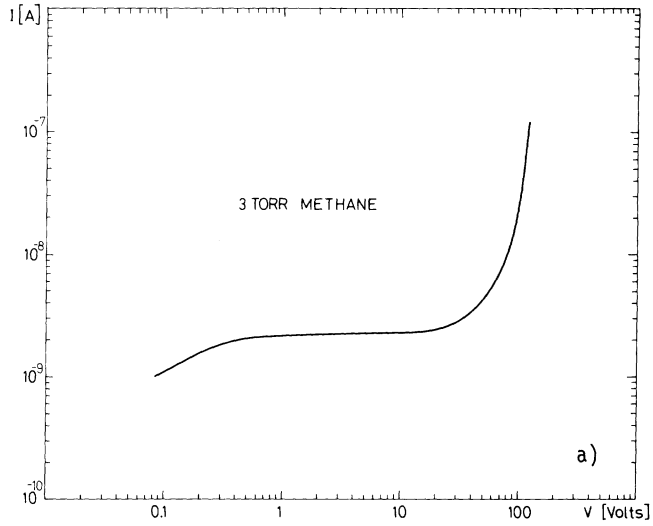


Fig. 8 As for Fig. 7, at increasing pressures of methane.

We tentatively explain such behaviour as being the effect of a much reduced thermal-electron cross-section for the hydrocarbons as compared to noble gases, together with a smaller back-scattering probability for the lower atomic number molecules.

5. Experimental Results: Methane- and Isobutane-Filled Photodiodes

We have obtained from ITL several methane- and isobutane-filled photodiodes; in all cases, research grade gas was used with a guaranteed impurity level below 5×10^{-4}. As already indicated in Section 2 and shown in Fig. 2, even at the highest methane pressure (½ atm) the quantum efficiency is only slightly degraded as compared to a vacuum reference diode. The degradation is observed at the introduction of the gas, probably because of some residual impurities in the tubing, and can probably be avoided by a more careful manipulation. Figure 9 shows the current-voltage characteristics of a 3 mm gap photodiode filled with CH_4 at a pressure around 3 Torr. Compared to the similar argon-filled device (Fig. 3), the methane data show a much better collection plateau and stable gains above 60-70.



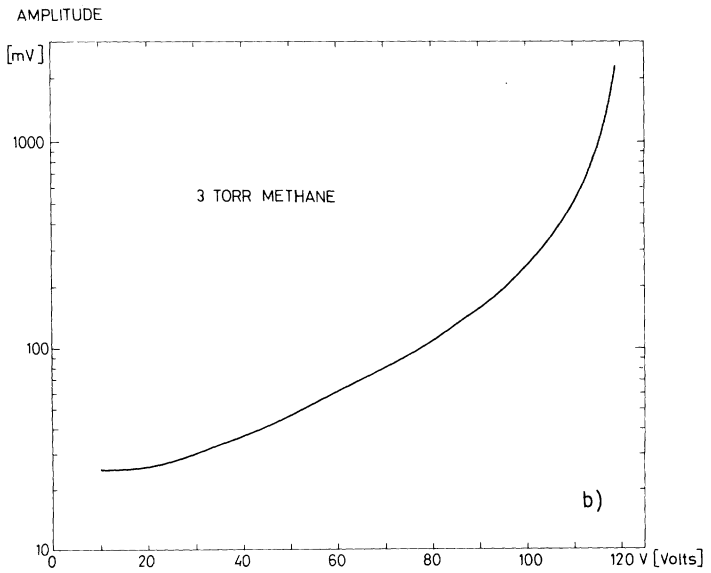


Fig. 9 Voltage-current characteristics measured in a 3 Torr methane-filled photodiode (a). Plotted on a linear voltage scale, the pulse height shows a faster than exponential increase at high gains (b).

As suggested by the results described in the previous section, photoelectron collection remains good at high pressures. Figure 10 shows the current-voltage characteristics in the collection region for uniform illumination measured in a 0.5 atm methane-filled diode of a 5.5 mm gap, as compared to the reference vacuum element. Although not reaching the same value -- probably because of some initial degradation of the photocathode -- the collection curve exhibits a plateau, as against the equivalent argon data (Fig. 6). Unfortunately we could not reach the multiplication region in the device because of an internal discharge above 2500 V; this seems to be due to a defective internal geometry that could be corrected further.

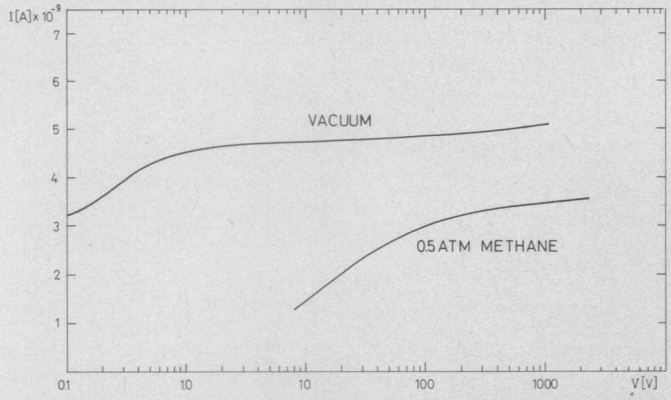


Fig. 10 Voltage-current characteristics in the collection region of a gas diode filled with 0.5 atmosphere methane, compared to a vacuum reference diode of the same geometry.

A long term degradation of quantum efficiency has, however, been observed in the low pressure methane and isobutane devices operated at gain under continuous illumination. For methane diode at a detected primary current of 3.0×10^{-8} A and a gain of 20 corresponding to a photon flux of $\sim 5 \times 10^{10}$ cm^{-2} s^{-1} the quantum efficiency dropped to half of the original value (i.e. down to 5%) after 3.5 hours of operation which is equivalent to a total positive charge deposited on the cathode of 2×10^{-4} Coulombs. This appears to be a permanent damage to the photocathode due either to bombardment by positive ions or to the deposition of some dissociation products.

For low rate applications, as for example in calorimeters used around colliding beams, the observed decrease of performance may be acceptable; for example, for a rate of one flash of 10^6 photoelectrons per second, at a gain of 50, a 10% decrease in gain would occur after 10^3 days of continuous operation.

No change in the characteristics over a much longer span of time (three weeks of continuous illumination at a current of 5 μA) has been observed in the high-pressure device, operated in the collection region. As already mentioned, this diode could not be operated in multiplication.

The pulsed characteristics of the CH_4 photodiode were studied using a pulsed nitrogen laser emitting at 337 nm, and generating a very short (less than 1 ns wide) light-flash. Figure 11 shows the response of the 3 Torr CH_4 diode as seen on a charge amplifier, at a gain around 50; the horizontal scale is 5 μs/div. The fast electron and the ion components are clearly identified. Using a fast current amplifier, we have sorted out the electron component (which accounts for about $^1/_3$ of the total charge signal, see Fig. 11). Figure 12 shows the detected signal, again at a (total) gain of 50; the horizontal scale is 4 ns/div.

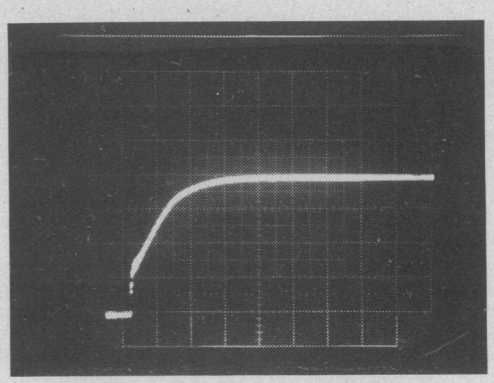


Fig. 11 Charge signal detected on the 3 Torr CH_4 filled diode, at a gain around 40. Horizontal scale 5 μsec/div. The electron and ion components are clearly identified.

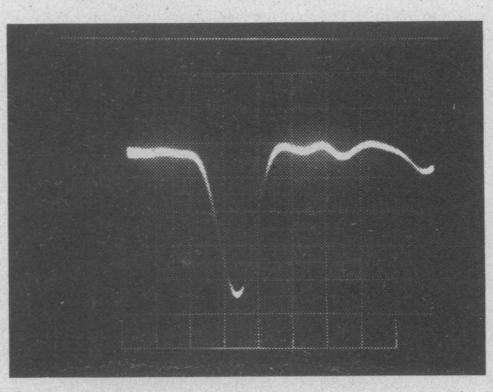


Fig. 12 Current pulse on the 3 Torr CH_4 diode at the same gain as for Fig. 11: the signal corresponds to the electron component only. Horizontal scale 4 nsec/div.

6. Summary and Conclusions

Testing extensively a dozen custom-manufactured gas photodiodes, we have observed stable and reproducible characteristics of the argon-filled devices at pressures around 1 Torr, with gains up to 30-40. Methane-filled diodes operate at even higher gains (60-70) at around the same pressure, and have a faster response; they show, however, long-term degradation at relatively low light fluxes. At higher pressures, while the argon-filled device is largely degraded, high quantum efficiency and a good collection plateau is observed in methane. When operated in the collection mode, the CH_4 high-pressure device does not show any sign of degradation.

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