# CHAPTER 11
# HPD (Hybrid Photo-Detector)

*HPD (Hybrid Photo-Detector) is a completely new photomultiplier tube that incorporates a semiconductor element in an evacuated electron tube. In HPD operation, photoelectrons emitted from the photocathode are accelerated to directly strike the semiconductor where their numbers are increased. Features offered by the HPD are extremely little fluctuation during the multiplication, high electron resolution, and excellent stability.*

# 11.1 Operating Principle of HPDs

As shown in Figure 11-1, an HPD consists of a photocathode for converting light into photoelectrons and a semiconductor element (avalanche diode or AD) which is the target for "electron bombardment" by photoelectrons. The HPD operates on the following principle: when light enters the photocathode, photoelectrons are emitted according to the amount of light; these photoelectrons are accelerated by a high-intensity electric field of a few kilovolts to several dozen kilovolts applied to the photocathode; they are then bombarded onto the target semiconductor where electron-hole pairs are generated according to the incident energy of the photoelectrons. This is called "electron bombardment gain". A typical relation between this electron bombardment gain and the photocathode supply voltage is plotted in Figure 11-2. In principle, this electron bombardment gain is proportional to the photocathode supply voltage. However, there is actually a loss of energy in the electron bombardment due to the insensitive surface layer of the semiconductor, so their proportional relation does not hold at a low voltage. In Figure 11-2, the voltage at a point on the voltage axis (horizontal axis) where the dotted line intersects is called the threshold voltage [Vth]. Electron bombardment gain increases in proportion to the electron incident energy in a region higher than a photocathode supply voltage near the threshold voltage.

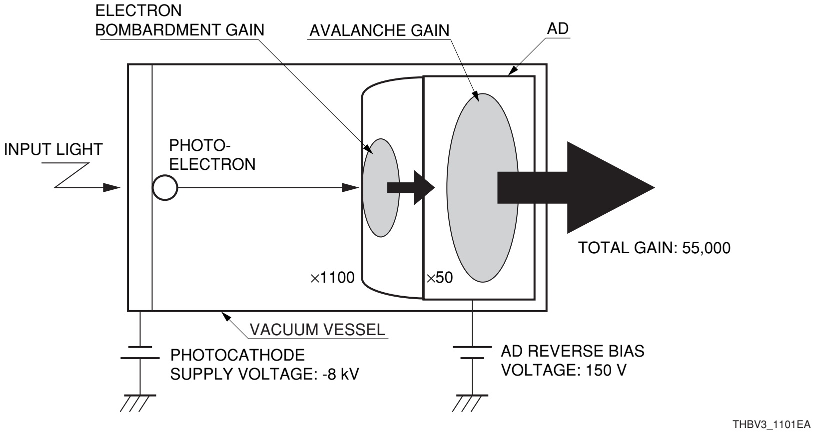


**Figure 11-1: Schematic diagram of HPD**

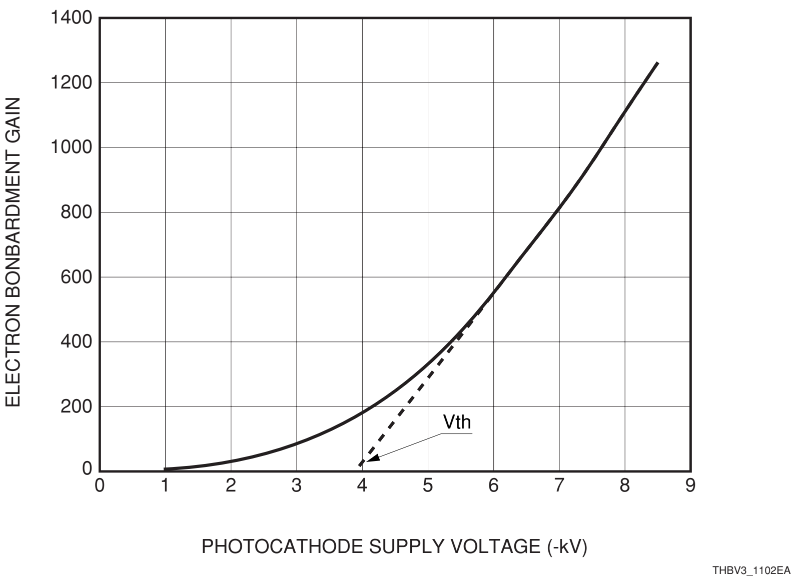


**Figure 11-2: Electron bombardment gain characteristics**

The internal silicon avalanche diode (AD) in an HPD generates an electron and hole pair per incident energy of approximately 3.6 eV. The electron bombardment gain Gb can be expressed by using the electrical potential difference Vpc [V] between the photocathode and the semiconductor element (This is equal to the photocathode supply voltage.) and the threshold voltage [Vth] determined by the semiconductor element.

$$Gb = \frac{(Vpc\text{-}Vth)}{3.6} \quad \text{(Eq. 11-1)}$$

In Figure 11-2, Vth is approximately 4 kilovolts.

The cluster of secondary electrons acquired by electron bombardment is further multiplied by the avalanche gain in the semiconductor (avalanche diode) according to the bias voltage applied to the semiconductor. If the gain of the avalanche diode (AD) is Gt, then the HPD total gain G is calculated as follows:

$$G = Gb \times Gt \quad \text{(Eq. 11-2)}$$

In the case of the R7110U series HPD, the electron bombardment gain Gb is approximately 1,100 when the photocathode supply voltage is -8 kilovolts. Furthermore, the avalanche gain G of approximately 50 times can be attained by applying a proper reverse voltage to the AD. Thus the total gain G will be approximately 55,000.

## 11.2 Comparison with Photomultiplier Tubes

This section compares HPD with photomultiplier tubes widely used in low-light-level measurement and discusses their different characteristics. The electron bombardment gain of an HPD corresponds to the gain attained by the first dynode of a photomultiplier tube. As stated earlier, the HPD delivers an electron bombardment gain of about 1,100 (at photocathode voltage of -8 kilovolts) which is much higher than conventional photomultiplier tubes, so that the gain fluctuation can be significantly reduced. This means that when used in pulsed light measurement in a region of several photons, the HPD can measure a pulse height distribution with separate peaks that correspond to 1 to 5 photoelectrons. In this point, the HPD is superior to conventional photomultiplier tubes. Moreover, the HPD multiplication mechanism is simple so that it exhibits advantages in applications where quantitative property, reproducibility and stability are essential factors. Table 11-1 compares major HPD and ordinary photomultiplier tube characteristics.

| Item | HPD | Description |
|---|---|---|
| Pulse height resolution | Extremely good | Since HPD has a high electron bombardment gain that corresponds to the first dynode gain of conventional photomultiplier tubes, a pulse height distribution with separated peaks created by 1 to 5 photoelectrons can be output. Using a low noise amplifier is important to make full use of the HPD characteristics. |
| Multiplication fluctuation | Extremely small | Fluctuation in the HPD electron multiplication is reduced nearly to the theoretical limit due to high electron bombardment gain. |
| Drift and life | Good | Short-term instability is called "drift", while long-term variation is called "life". Since HPD has no dynodes, both drift and life characteristics are superior to those of photomultiplier tubes. |
| Light hysteresis | Good | When incident light is changed in a step function, the output might not be comparable with the same step function. This phenomenon is called "hysteresis".<br>The HPD multiplication process is simple since electrons emitted from the photocathode only enter the AD. Light hysteresis characteristics are good compared to those of photomultiplier tubes. |
| Afterpulse | Extremely good | In pulse measurement, spurious pulses might appear following the output pulse of a true signal. These spurious pulses are called "afterpulses". Since the HPD structure is simple, there are very few afterpulses compared to those of photomultiplier tubes. |
| Linearity | Good | The HPD offers good output current linearity over a wide range of input light levels. However, the output deviates from the ideal linearity when extremely strong light is input. The HPD output linearity is limited by two factors: electrical resistance of photocathode and avalanche multiplication linearity. |
| Gain | Low ($5 \times 10^4$) | In applications for detecting low-level light at high speeds, using an ordinary photomultiplier tube with a high gain will prove best. Since the HPD gain is lower than photomultiplier tubes, it should be used with a low noise amplifier. |
| Gain variation | Extremely small | The HPD features very small variations in the electron bombardment gain. |
| Uniformity | Good | Uniformity is the variation in sensitivity versus the photocathode position. HPD electron bombardment gain does not depend on the incident position so that the anode output exhibits good uniformity characteristics. |
| Temperature characteristics | Gain depends greatly on temperature. | Gain depends on temperature characteristics of the internal AD into which electrons are bombarded. |
| Vibration resistance | Good | HPD is highly resistant to vibration due to its simple structure. |
| Collection efficiency | Extremely good | Electron trajectories in HPD were designed so that all electrons emitted from the photocathode strike the internal AD for electron bombardment multiplication. (However, there are a few electrons that reflect off the surface of the AD but these have no effect on the signal.) |

**Table 11-1: Comparison with photomultiplier tubes**

# 11.3 Various Characteristics of HPDs

## 11.3.1 Multi-photoelectron resolution

Since the electron bombardment gain that corresponds to the gain of the first dynode of a conventional photomultiplier tube is as high as 1,100 (at photocathode voltage of -8 kilovolts), the HPD offers ideal signal amplification with very little fluctuation in the multiplication. For example, when pulsed light adjusted so the photocathode emits 3 photoelectrons on average is repeatedly input to an HPD, multiple peaks corresponding to 1 to 5 photoelectrons can be detected by measuring the output pulse height. Figure 11-3 shows this example. The reason why these multiple peaks can be detected is that fluctuation in the electron multiplication is extremely small. This is the HPD's most significant feature. Due to this feature, single-electron pulse-height resolution, which is about 30 % (FWHM), is also excellent.

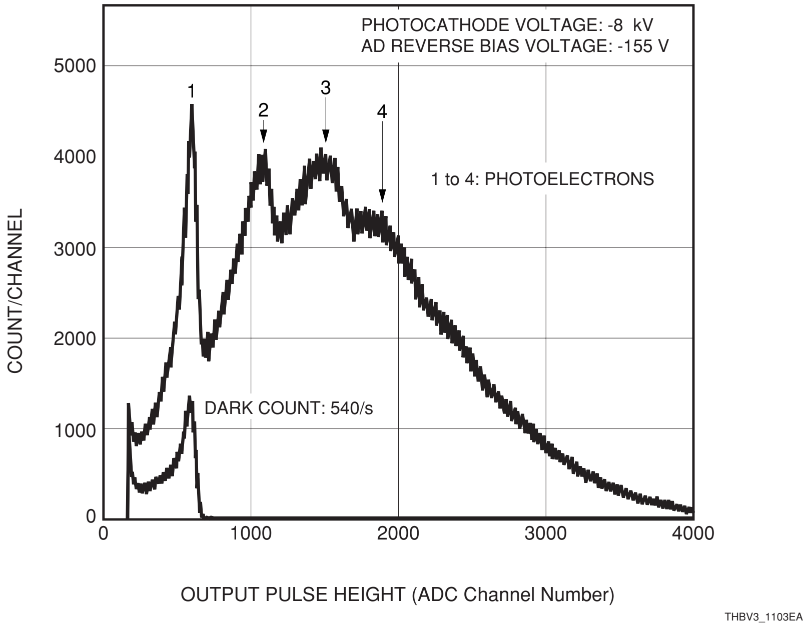


**Figure 11-3: Multi-photoelectron counting characteristics**

## 11.3.2 Gain characteristics and electron bombardment gain uniformity

As explained in the operating principle section, the HPD gain is expressed by the product of the electron bombardment gain Gb and the avalanche gain Gt. (See Eq. 11-2.) As shown in Figure 11-2, when a certain threshold voltage is exceeded, the electron bombardment gain of the R7110U series increases in proportion to the photocathode supply voltage according to Eq. 11-1. The avalanche gain characteristics of the internal AD are plotted in Figure 11-4. The avalanche gain gradually increases from a point where the voltage applied to the AD exceeds about 100 volts and sharply increases when the breakdown voltage (voltage at which the leak current reaches 1 microampere) is approached. It is difficult to maintain stable operation if the reverse bias voltage is set near the breakdown voltage around which the gain increases sharply. Generally, the HPD should be used at an avalanche gain of 50 or less. The avalanche gain differs slightly depending on the production lot of the semiconductor element. In the case of the semiconductor element shown in Figure 11-4, the avalanche gain is 10 at 138 volts, 30 at 149 volts and 60 at 153 volts. Figure 11-4 also shows leak current characteristics versus the reverse bias voltage applied to the AD. These gain characteristics are common to all models of the R7110U series.

The avalanche gain has temperature dependence as discussed later in section 11.3.8, " Temperature characteristics".

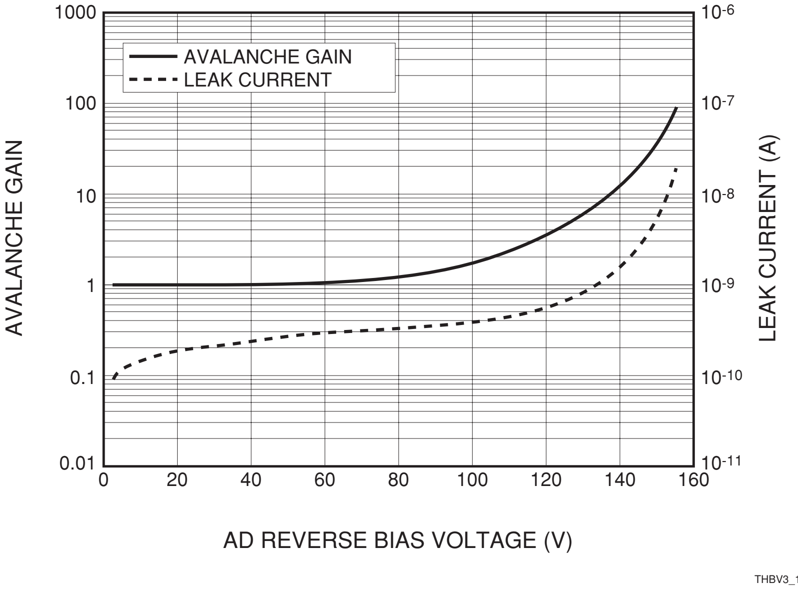


**Figure 11-4: Avalanche gain and leak current characteristics of internal AD**

Individual differences in electron bombardment gain characteristics of the R7110U series are shown in Figure 11-5 and Table 11-2. The HPD electron bombardment gain depends on the electron accelerating voltage and the structure of the AD's electron incident surface. Generally, the AD's electron incident surface is uniform, so individual differences in electron bombardment gain are very small as long as the photocathode supply voltage is the same. This is a large advantage not available from photomultiplier tubes using an array of dynodes.

On the other hand, there are individual differences in avalanche gain even if operated at the same AD reverse bias voltage. Although care should be taken regarding this point, adjusting the reverse bias voltage allows you to easily adjust the avalanche gain to the same level. In this case, unlike photomultiplier tubes, there are almost no adverse effects on time characteristics.

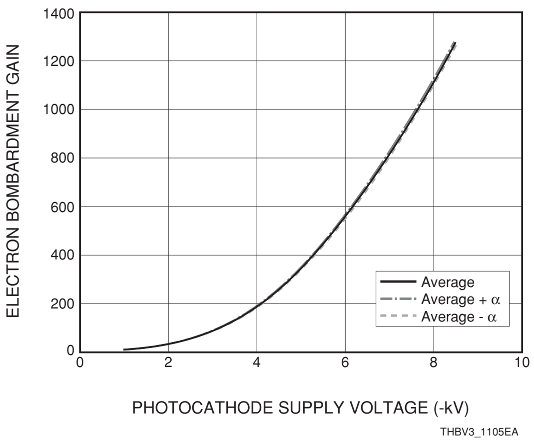


**Figure 11-5: Individual differences in electron bombardment gain**

| Photocathode Supply Voltage (-kV) | Average Electron Bombardment Gain | Standard Deviation (σ) |
|---|---|---|
| 1 | 9.3 | 0.3 |
| 2 | 31.9 | 0.6 |
| 4 | 181.9 | 2.4 |
| 6 | 560.0 | 6.9 |
| 8 | 1118.3 | 9.9 |
| 8.5 | 1270.7 | 13.4 |

Number of Samples: 19

**Table 11-2: Numerical data**

## 11.3.3 Time response characteristics

Figure 11-6 shows a typical output waveform of the R7110U series. This output waveform was obtained by inputting a light pulse from a PLP (semiconductor pulse laser of approximately 60 picoseconds FWHM and 400 nanometers wavelength). Time response characteristics of the R7110U series are determined by the capacitance (approx. 140 picofarads) of the internal AD which becomes nearly constant when a bias voltage higher than 60 volts is applied to the AD since the AD is fully depleted. The difference in the pulse height between peaks at an AD reverse bias voltage of 100 volts and 153 volts indicates the difference in the avalanche gain between each bias voltage. Transit time spread (TTS) of single photoelectron pulses is approximately 450 picoseconds for the R7110U series. These time characteristics are common to all models of the R7110U series.

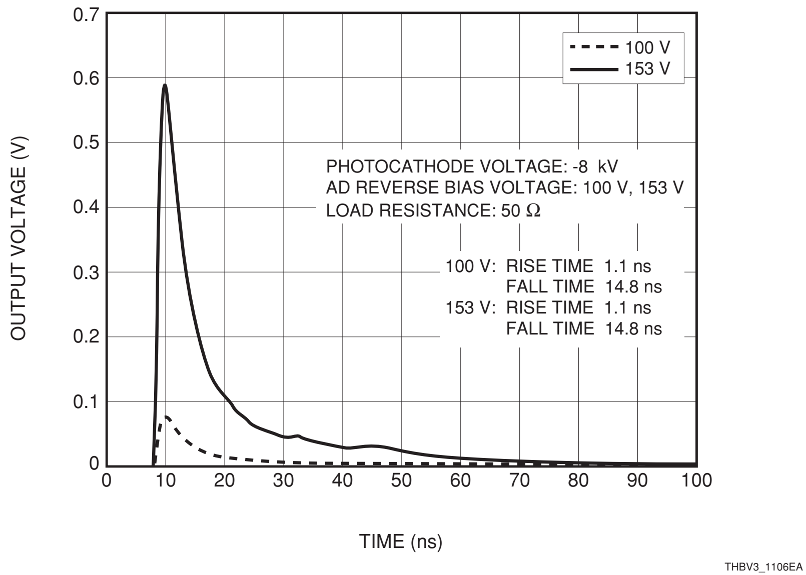


**Figure 11-6: Time response waveform**

## 11.3.4 Uniformity

Uniformity is the variation of sensitivity versus the photocathode position. Typical anode uniformity characteristics for the R7110U-07 (effective photocathode area: 8 millimeters in diameter) are shown in Figure 11-7. The HPD anode uniformity is determined by the photocathode sensitivity uniformity and the AD gain uniformity. The figure demonstrates that the HPD has very uniform sensitivity.

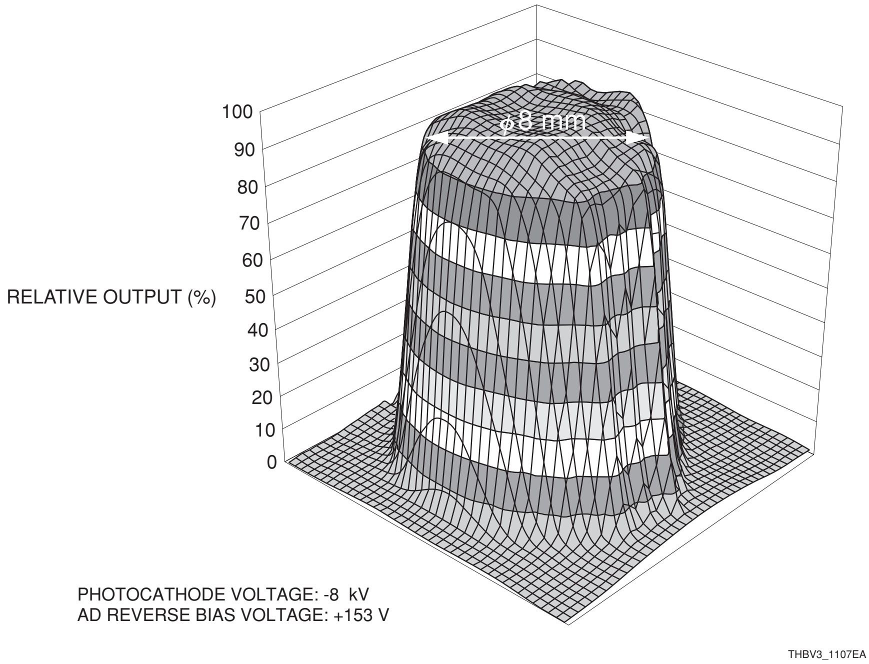


**Figure 11-7: Uniformity**

## 11.3.5 Light hysteresis characteristics

When incident light is changed in a step function, the output might not be comparable with that same step function. This phenomenon is called "hysteresis". Hysteresis characteristics of an HPD are shown in Figure 11-8. In the case of photomultiplier tubes, light hysteresis tends to occur in the multiplication process repeated by the dynodes. On the other hand, HPD exhibits extremely good hysteresis because the multiplication process is simple since the electrons emitted from the photocathode only enter the AD.

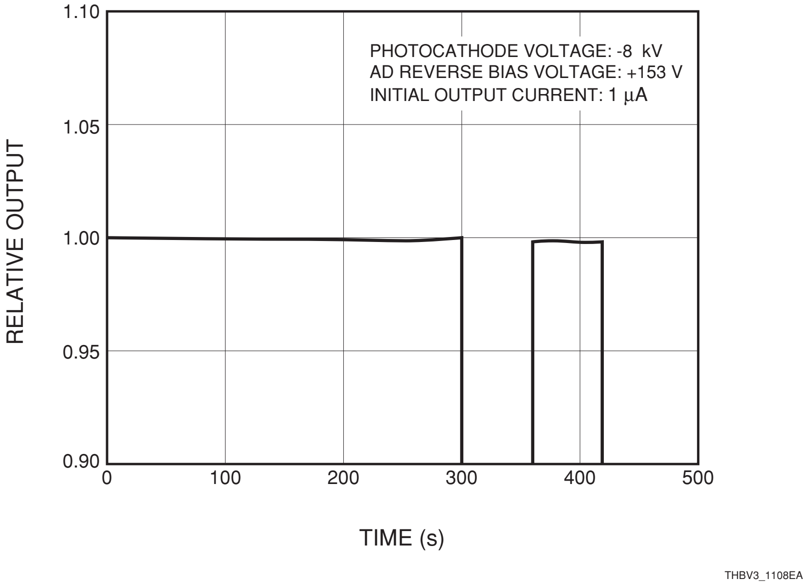


**Figure 11-8: Light hysteresis characteristics**

## 11.3.6 Drift characteristics (short-term stability)

Figure 11-9 shows typical output variations of the R7110U series, measured over a short time period of 12 hours (720 minutes). In photomultiplier tubes, drift is mainly caused by deterioration of the dynodes. Since HPD has no dynodes, good drift characteristics are ensured.

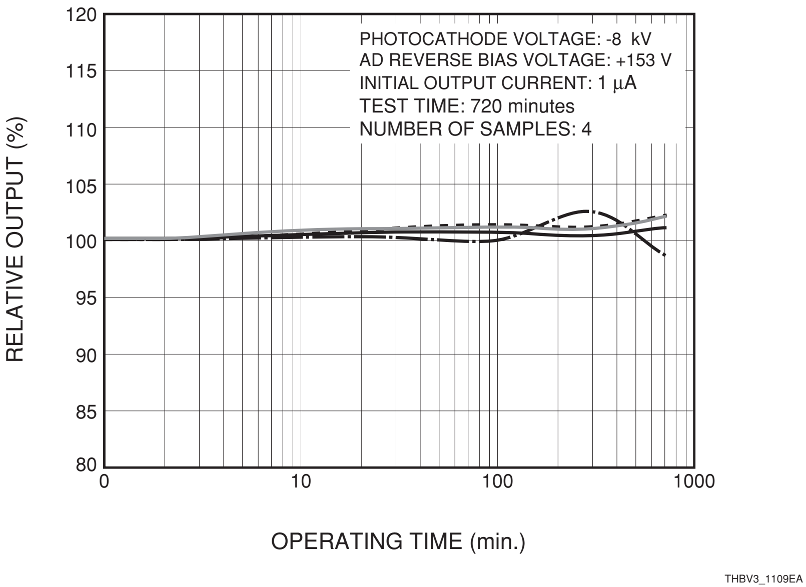


**Figure 11-9: Drift characteristics**

## 11.3.7 Magnetic characteristics

The HPD operation is very simple in that photoelectrons emitted from the photocathode are directly bombarded into the semiconductor (avalanche diode or AD). This makes the electron trajectories simple enough so that the photoelectrons can be focused onto the semiconductor by an electron lens. Because of this, the effective photocathode area is limited to a size equal to the effective diameter of the AD (3 millimeters for the R7110U series). Due to this structure, theoretically the output will not change even in a strong magnetic field as long as its direction is parallel to the HPD tube axial direction.

## 11.3.8 Temperature characteristics

Typical temperature characteristics of AD leak current in the R7110U series are shown in Figure 11-10. Each reverse bias voltage shows a similar tendency in that the AD leak current increases with temperature. The avalanche gain, in contrast, decreases with temperature rise as stated below. (See Figure 11-11.) Nonetheless, the leak current increases with temperature.

Figure 11-11 shows temperature characteristics of avalanche gain. In a range from -10°C to 35°C, the avalanche gain temperature coefficient does not change greatly. It is approximately -1 %/°C at an AD reverse bias voltage of 138 volts. However, it increases to about -2.1 %/°C at 149 volts and to -3.3 %/°C at 153 volts. The AD temperature must therefore be controlled to ensure stable HPD operation while obtaining a high avalanche gain. When the HPD is used with the AD reverse bias voltage maintained at a constant value, there is an extreme increase in gain as the temperature lowers. So care must be taken to prevent the AD from being damaged.

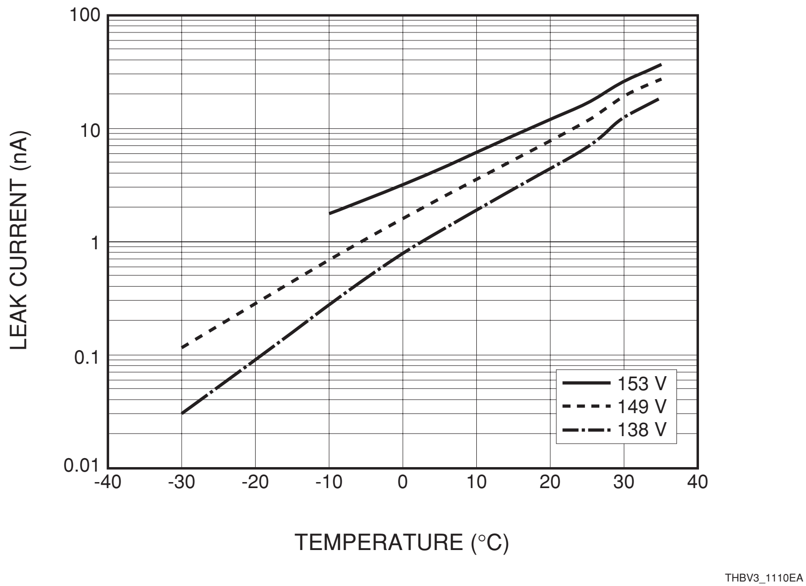


**Figure 11-10: Temperature characteristics of AD leak current**

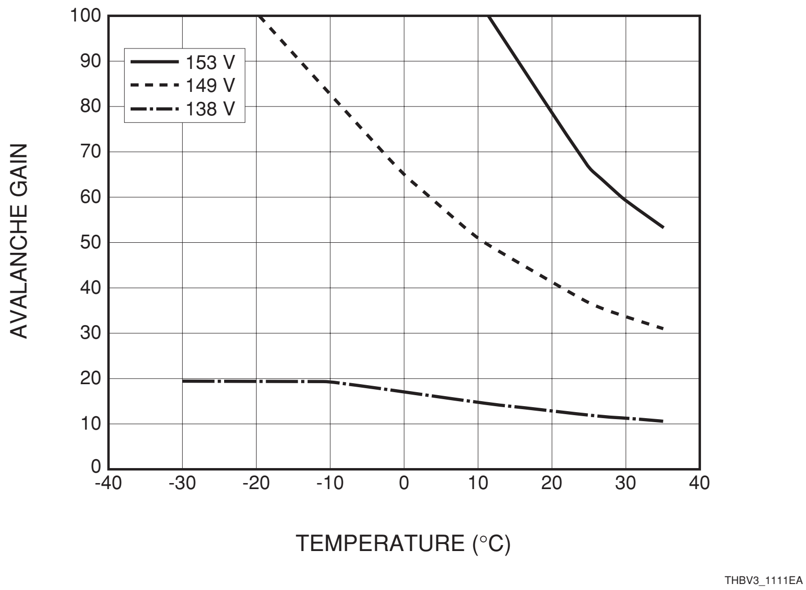


**Figure 11-11: Temperature characteristics of AD avalanche gain**

# 11.4 Connection Examples (R7110U Series)

## 11.4.1 When handling DC signal (including connection to transimpedance amp)

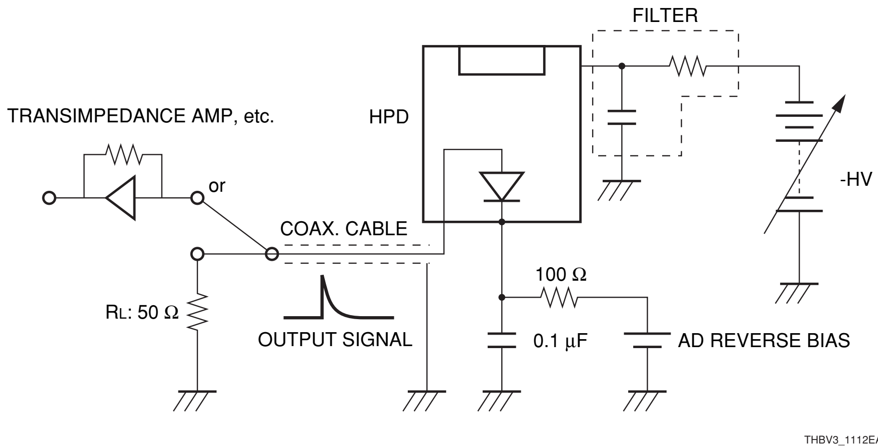


**Figure 11-12: DC mode connection example**

### 11.4.2 When handling pulse signal (including connection to charge amp)

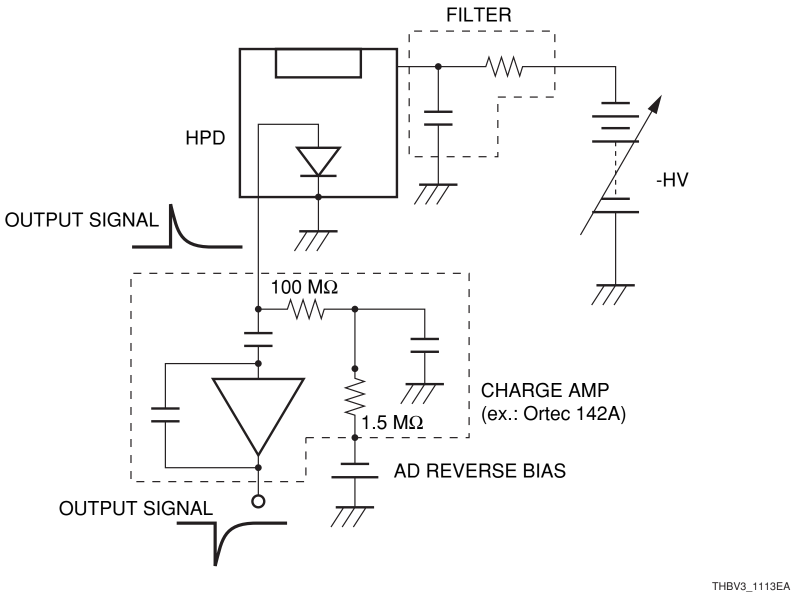


**Figure 11-13: Pulse mode connection example**

## References in Chapter 11

1) Hamamatsu Photonics: "Hybrid Photo Detector (HPD) R7110U Series" technical manual