

## High Speed Solid State Detectors for Fibre Optic and Very Low Light-Level Applications

EG&G 30902E avalanche photodiode utilises a silicon detector chip fabricated with a double-diffused "reach through" structure. This structure provides high responsivity between 400 and 1000 nanometers as well as extremely fast rise-and-falltimes at all wavelengths. Because the fall-time characteristics have no "tail", the responsivity of the device is independent of modulation frequency up to about 800 MHz. The detector chip is hermetically-sealed behind a flat glass window in a modified TO-18 package. The useful diameter of the photosensitive surface is 0.5mm.

EG&G Type C30921E utilises the same silicon detector chip as the C30902E, but in a package containing a lightpipe which allows efficient coupling of light to the detector from either a focused spot or an optical fibre up to 0.25mm in diameter. The internal end of the lightpipe is close enough to the detector surface to allow all of the illumination exiting the lightpipe to fall within the active-area of the detector. The hermetically-sealed TO-18 package allows fibres to be epoxied to the end of the lightpipe to minimise signal losses without fear of endangering detector stability.

The C30902E and C30921E are designed for a wide variety of uses including optical communications at data rates to 1 GBit/second, laser range-finding, or any other applications requiring high speed and/or high responsivity. Devices are available mounted in FC and ST fibre optic receptacles with integral ball lenses for good fibre coupling efficiency. These are C30902E types of devices.

The C30902S and C30921S are selected C30902E and C30921E photodiodes having extremely low noise and low bulk dark-current. They are intended for ultra-low light level applications (optical power less than 1 pW) and can be used in either their normal linear mode

- High Quantum Efficiency  
77% Typical at 830nm
- C30902S and C30921S in Geiger Mode:
  - Single-Photon Detection Probability to 50%
  - Low Dark-Count Rate at 5% Detection Probability - Typically  
15,000/second at +22° C  
350/second at -25° C
  - Count Rates to  $2 \times 10^6$ /second
- Hermetically Sealed Package
- Low Noise at Room Temperature
  - C30902E, C30921E -  
 $2.3 \times 10^{-13}$  A/Hz<sup>1/2</sup>
  - C30902S, C30921S -  
 $1.1 \times 10^{-13}$  A/Hz<sup>1/2</sup>
- High Responsivity -  
Internal Avalanche Gains in Excess of 150
- Spectral Response Range - (10% Points)  
400 to 1000 nm
- Time Response - Typically 0.5ns
- Wide Operating Temperature Range -  
-40° C to +70° C
- Fibre Optic Connectorised Versions Available

---

( $V_R < V_{BR}$ ) at gains up to 250 or greater, or as photon counters in the "Geiger" mode ( $V_R > V_{BR}$ ) where a single photoelectron may trigger an avalanche pulse of about  $10^8$  carriers. In this mode, no amplifiers are necessary and single-photon detection probabilities of up to approximately 50% are possible.

Photon-counting is also advantageous where gating and coincidence techniques are employed for signal retrieval.

## Electrical Characteristics<sup>1</sup> at TA = 22° C

	C30902E, C30921E			C30902S, C30921S			Units
	Min.	Typ.	Max.	Min.	Typ.	Max.	
Breakdown voltage, $V_{BR}$ .....	-	225	-	-	225	-	V
Temperature Coefficient of $V_R$ for Constant Gain .....	0.5	0.7	0.8	0.5	0.7	0.8	V/°C
Gain .....	-	150	-	-	250	-	
Responsivity:							
At 900 nm .....	55	65	-	92	108	-	A/W
At 830 nm .....	70	77	-	117	128	-	A/W
Quantum Efficiency:							
At 900 nm .....	-	60	-	-	60	-	%
At 830 nm .....	-	77	-	-	77	-	%
Dark Current, $I_d$ .....	-	$1.5 \times 10^{-8}$ (Figure 6)	$3 \times 10^{-8}$	-	$1 \times 10^{-8}$ (Figure 6)	$3 \times 10^{-8}$	A
Noise Current, $i_n$ : <sup>2</sup> $f = 10$ kHz, $\Delta f = 1.0$ Hz .....	-	$2.3 \times 10^{-13}$ (Figure 3)	$5 \times 10^{-13}$	-	$1.1 \times 10^{-13}$ (Figure 3)	$2 \times 10^{-13}$	A/Hz <sup>1/2</sup>
Capacitance, $C_j$ .....	-	1.6	2	-	1.6	2	pF
Rise Time, $t_r$ : $R_L = 50 \Omega$ , $\lambda = 830$ nm, 10% to 90% points .....	-	0.5	0.75	-	0.5	0.75	ns
Fall Time: $R_L = 50 \Omega$ , $\lambda = 830$ nm, 90% to 10% points .....	-	0.5	0.75	-	0.5	0.75	ns
<b>Geiger Mode (See Appendix)</b>							
Dark Count Rate at 5% Photon Detection Probability <sup>3</sup> (830 nm):							
22°C .....	-	-	-	-	15,000	30,000	cps
-25°C .....	-	-	-	-	350	700	cps
Voltage Above $V_{BR}$ for 5% Photon Detection Probability <sup>3</sup> (830 nm) (See Figure 8) .....	-	-	-	-	2	-	V
Dead-Time Per Event (See Appendix) .....	-	-	-	-	300	-	ns
After-Pulse Ratio at 5% Photon Detection Probability (830 nm) 22° C <sup>4</sup> .....	-	-	-	-	2	15	%

1 At the DC reverse operating voltage  $V_R$  supplied with the device and a light spot diameter of 0.25 mm (C30902E, S) or 0.10 mm (C30921E, S). Note that a specific value of  $V_R$  is supplied with each device. When the photodiode is operated at this voltage, the device will meet the electrical characteristic limits shown above. The voltage value will be within the range of 180 to 250 volts.

2 The theoretical expression for shot noise current in an avalanche photodiode is  $i_n = (2q(I_{ds} + I_{db}M^2 + P_oRM)F)B_w^{1/2}$  where  $q$  is the electronic charge,  $I_{ds}$  is the dark surface current,  $I_{db}$  is the dark bulk current,

$F$  is the excess noise factor,  $M$  is the gain,  $P_o$  is the optical power on the device, and  $B_w$  is the noise bandwidth.

For these devices  $F = 0.98(2-1/M) + 0.02M$ . (Reference: PP Webb, RJ McIntyre, JJ Conradi, "RCA Review", Vol. 35, p.234, (1974).

3 The C30902S and C30921S can be operated at a substantially higher Detection Probabilities. See Appendix.

4 After-Pulse occurring 1 microsecond to 60 seconds after main pulse.

## Optical Characteristics

C30902E, C30902S

Photosensitive Surface:

Shape ..... Circular  
 Useful area ..... 0.2 mm<sup>2</sup>  
 Useful diameter ..... 0.5 mm

Field of View:

Approximate full angle for totally  
 illuminated photosensitive surface ..... 100 deg

C30921E, C30921S

Numerical Aperture of Light Pipe ..... 0.55  
 Refractive Index (n) of Core ..... 1.61  
 Light Pipe Core Diameter ..... 0.25 mm

## Maximum Ratings, Absolute-Maximum Values

Reverse Current at 22°C:

Average value, continuous  
 operation ..... 200  $\mu$ A  
 Peak value (For 1 second duration,  
 non-repetitive) ..... 1 mA

Forward Current,  $I_f$  at 22°C:

Average value, continuous  
 operation ..... 5 mA  
 Peak value (For 1 second duration,  
 non-repetitive) ..... 50 mA

Maximum Total Power

Dissipation at 22°C ..... 60 mW

Ambient Temperature -

Storage,  $T_{sig}$  ..... -60 to +100 °C

Operating,  $T_A$  ..... -40 to +70 °C

Soldering:

For 5 seconds ..... 200 °C

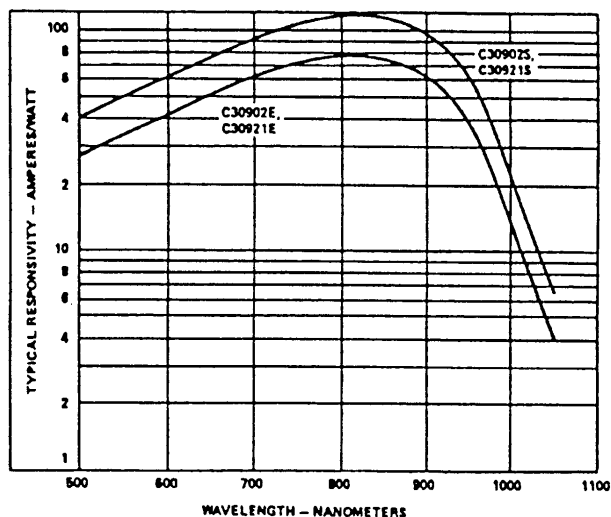


Fig. 1 Typical Spectral Responsivity at 22°C

LS-8131

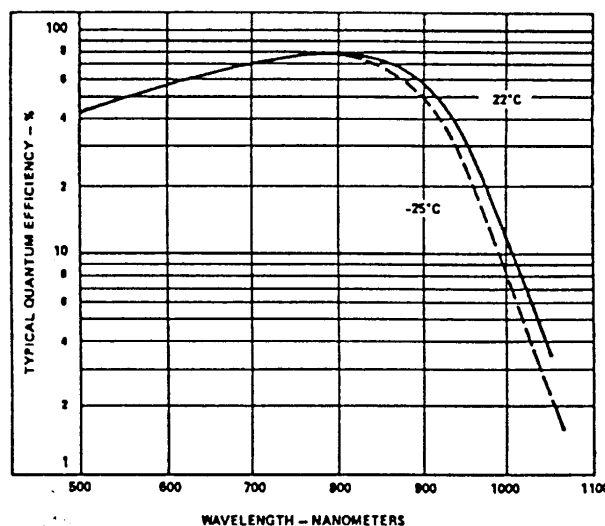
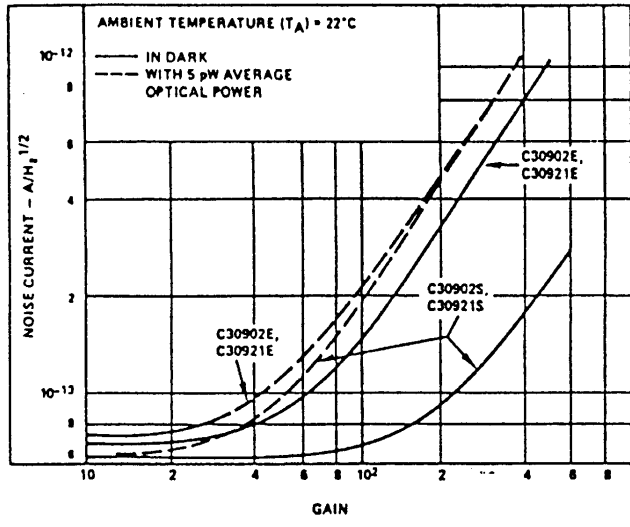


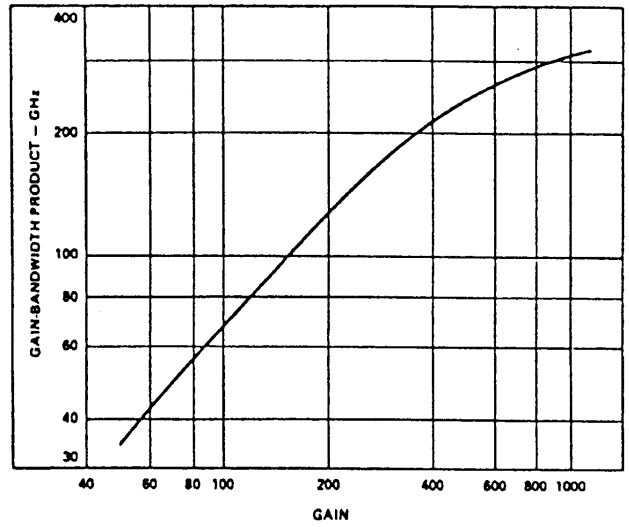
Fig. 2 Typical Quantum Efficiency vs Wavelength

LS-8132



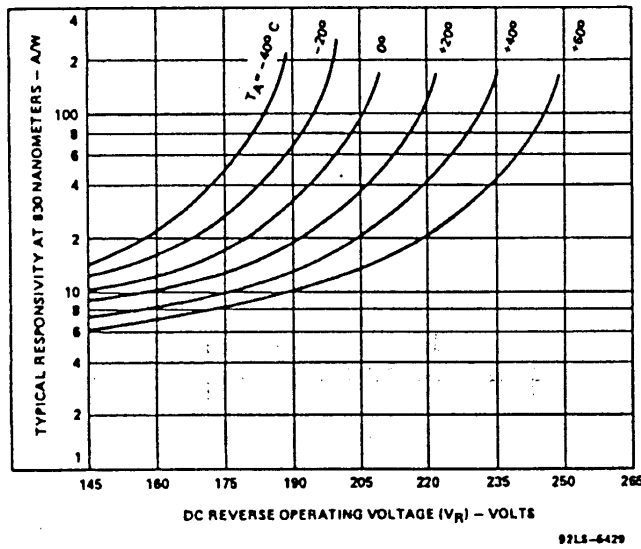
LS-8133

Fig. 3 Typical Noise Current vs Gain



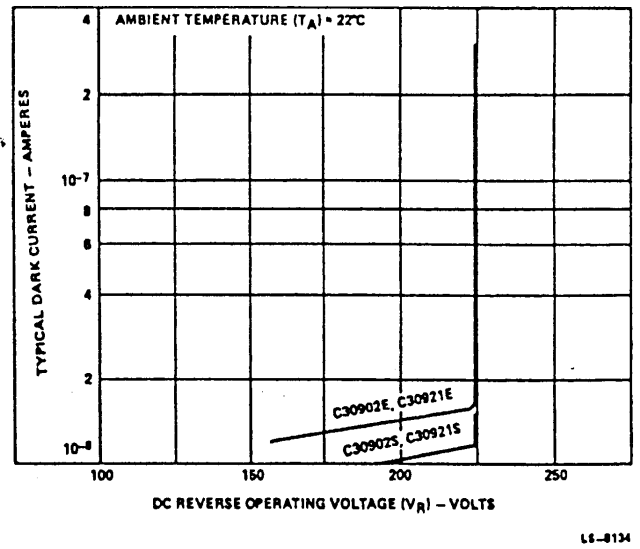
82LS-5437

Fig. 5 Typical Gain-Bandwidth Product vs Gain



82LS-6429

Fig. 4 Typical Responsivity at 830 nm vs Operating Voltage



LS-8134

Fig. 6 Typical Dark Current vs Operating Voltage ( $V < V_{BR}$ )

Note: Operation below 145 volts is not recommended, since the device is not fully depleted below this value.

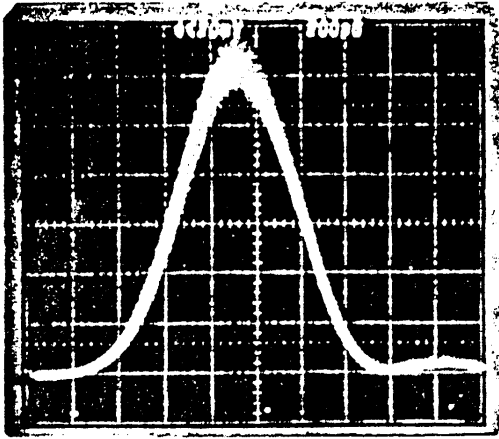


Fig. 7 Avalanche Photodiode Response to a 100 ps Laser Pulse as Measured with a 350 ps Sampling Head. (Horizontal Axis: 200 ps /Division  
Normal Linear Mode  $V_R < V_{BR}$

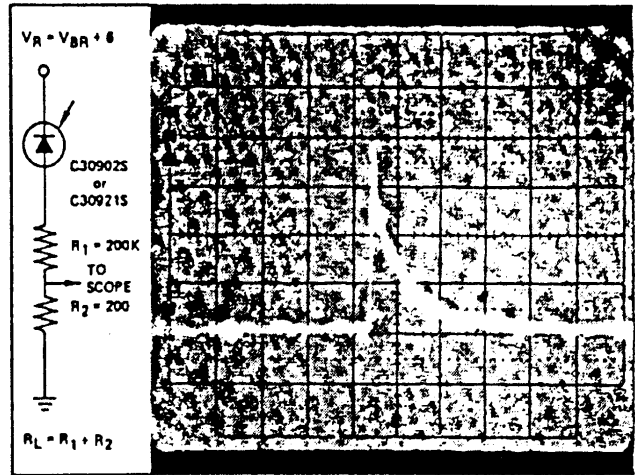


Fig. 9 Passively Quenched Circuit and Resulting Pulse Shape

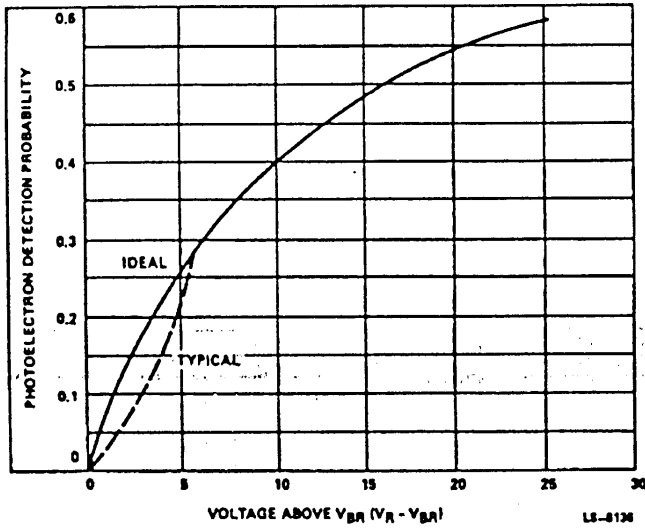


Fig. 8 Geiger Mode, Photoelectron Detection Probability vs Voltage Above  $V_{BR}$  ( $V_R < V_{BR}$ )

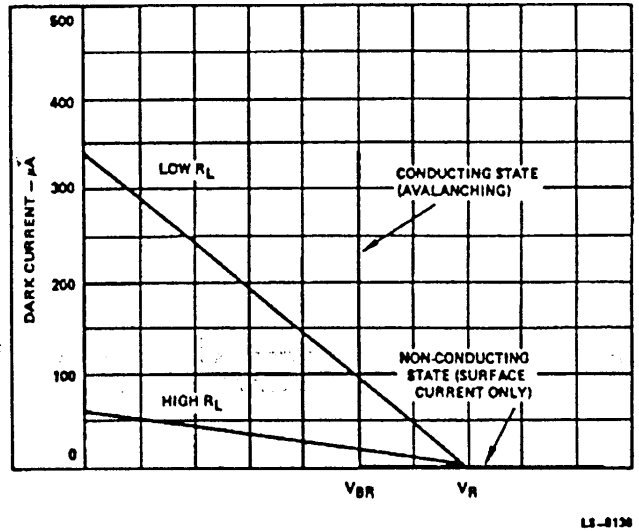


Fig. 10 Load Line for C30921S in the Geiger Mode

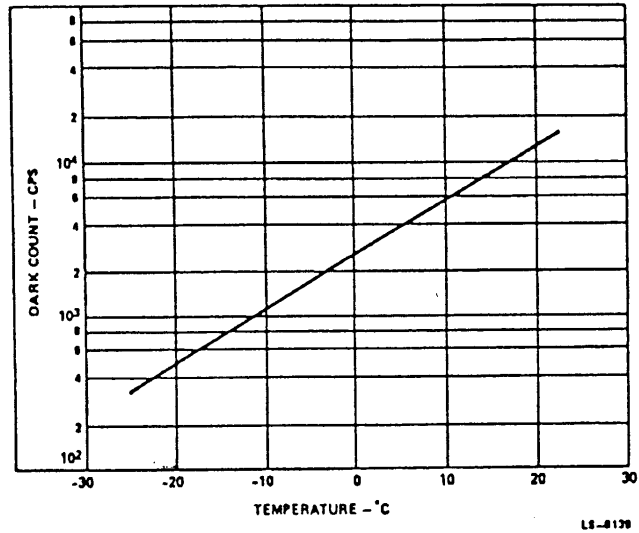


Fig. 11 Typical Dark Count vs Temperature at 5% Photon (830 nm) Detection Efficiency

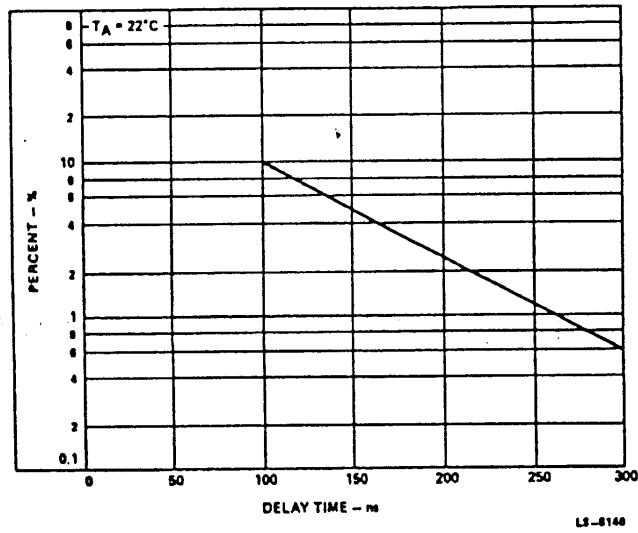


Fig. 12 Chance of an After-Pulse Within the Next 100 ns vs Delay-Time in an Actively Quenched Circuit.  
(Typical for C30902S, C30921S at  $V_{BR} + 25$ )

## Appendix

### Operation of the C30902S & C30921S in the Geiger Mode

#### Introduction

When biased above the breakdown voltage, an avalanche photodiode will normally conduct a large current. However, if the current is such that the current is limited to less than a particular value (about 50 mA for these diodes), the current is unstable and can switch off by itself. The explanation of this behaviour is that the number of carriers in the avalanche region at any one time is small and fluctuating wildly. If the number happens to fluctuate to zero, the current must stop. It subsequently remains off until the avalanche pulse is retriggered by a bulk- or photo-generated carrier.

The C30902S and C30921S are selected to have small bulk-generated dark-current. This makes them suitable for low-noise operation below  $V_{BR}$  or of photon-counting above  $V_{BR}$  in the Geiger mode. In this so-called Geiger mode, a single photoelectron (or thermally-generated electron) may trigger an avalanche pulse which discharges the photodiode from its reverse voltage  $V_R$  to a voltage slightly below  $V_{BR}$ . The probability of this avalanche occurring is shown in Figure 8 as the "Photoelectron Detection Probability" and as can be seen, it increases with reverse voltage  $V_R$ . For a given value of  $V_R - V_{BR}$ , the Photoelectron Detection Probability is independent of temperature. To determine the Photon Detection Probability, it is necessary to multiply the Photoelectron detection Probability by the Quantum Efficiency, which is shown in Figure 2. The Quantum Efficiency also is relatively independent of temperature, except near the 1000 nm cut-off.

The C30902S and C30921S can be used in the Geiger mode using either "passive" or "active" pulse quenching circuits. The advantages and disadvantages of each are discussed below.

#### Passive-Quenching Circuit

The simplest, and in many cases a perfectly adequate method of quenching a breakdown pulse, is through the use of a current-limiting load resistor. An example of such a "passive" quenching circuit is shown in Figure 9. The load-line of the circuit is shown in Figure 10. To be in the conducting state at  $V_{BR}$  two conditions must be met:

1. The avalanche must have been triggered by either a photoelectron or a bulk-generated electron entering the avalanche region of the diode. (Note: holes are inefficient at starting avalanches in silicon.) The probability of an avalanche being initiated is discussed above.
2. To continue to be in the conducting state, a sufficiently large current, called the latching current  $I_{LATCH}$ , must be passing through the device so that there is always an electron or hole in the avalanche region. Typically in the C30902S and C30921S,  $I_{LATCH} = 50 \mu A$ . For currents  $(V_R - V_{BR})/R_L$  much greater than  $I_{LATCH}$ , the diode remains conducting. If the current  $(V_R - V_{BR})/R_L$  is much less than  $I_{LATCH}$ , the diode switches almost immediately to the non-conducting state. If  $(V_R - V_{BR})/R_L$  is approximately equal to  $I_{LATCH}$ , then the diode will switch at an arbitrary time from the conducting to the non-conducting state depending on when the number of electrons and holes in the avalanche region statistically fluctuates to zero.

When  $R_L$  is large, the photodiode is normally nonconducting, and the operating point is at  $V_R - I_{d0}R_L$  in the non-conducting state. Following an avalanche breakdown, the device recharges to the voltage  $V_R - I_{d0}R_L$  with the time constant  $CR_L$  where C is the total device capacitance including stray capacitance. Using  $C = 1.6pF$  and  $R_L =$

200.2K $\Omega$  a recharge time constant of .32 microseconds is calculated, in reasonable agreement with observation as shown in Figure 9. As is also evident from Figure 9, the rise-time is fast, 5 to 50 nanoseconds, decreases as  $V_R - V_{BR}$  increases, and is very dependent on the capacitances of the load resistors, leads, etc. The jitter at the half-voltage point is typically the same order of magnitude as the rise-time. For timing purposes where it is important to have minimum jitter, the lowest possible threshold of the rising pulse should be used.

#### Active-Quenching Circuit

Until the C30902S or C30921S is recharged, the probability of detecting another incoming photoelectron is relatively low. To avoid an excessive dead-time when operating at a large voltage above  $V_{BR}$ , an "actively quenched" circuit can be used. The circuit temporarily drops the bias voltage for a fraction of a microsecond following the detection of an avalanche discharge. This delay time allows all electrons and holes to be collected, including most of those temporarily "trapped" at various impurity sites in the silicon. When the higher voltage is reapplied, there are no electrons in the depletion region to trigger another avalanche or latch the diode. Recharging can now be very rapid through a small load resistor. Alternatively, the bias voltage can be maintained but the load resistor is replaced by a transistor which is kept off for a short time after an avalanche, and then turned on for a period sufficient to recharge the photodiode.

#### After-Pulsing

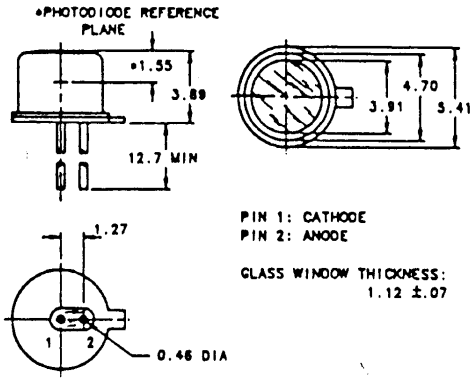
An after-pulse is an avalanche breakdown pulse which follows a photon-generated pulse and is induced by it. An after-pulse is usually caused by one of the approximately  $10^6$  carriers which pass through the diode because of the first avalanche. This electron or hole is captured and trapped in some impurity site in the silicon, as previously described. When this charge-carrier is liberated, usually in less than 100 nanoseconds, but sometimes several milliseconds later, it may start another avalanche. The probability of an after-pulse occurring more than one microsecond later is typically less than 2% at 2 volts above  $V_{BR}$ , using the circuit shown in Figure 9. After-pulsing increases with bias voltage. If it is necessary to reduce after-pulses, it is recommended that one keeps  $V_R - V_{BR}$  low, use an actively-quenched circuit with a long delay-time (see Figure 12), or a passively-quenched circuit with a long  $R_L C$  constant. Stray capacitances must also be minimised. Electronic gating of the signal can be performed in certain situations. Should after-pulses be a serious complication in a particular application, operation below  $V_{BR}$  with a good amplifier might be considered.

#### Dark Current

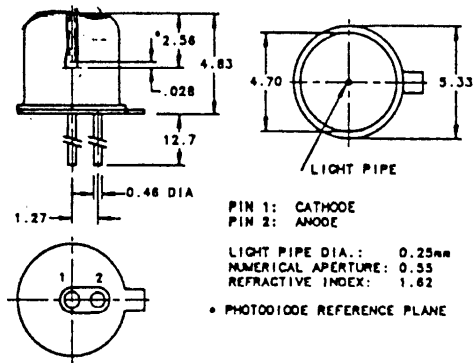
Both the C30902S and C30921S have been selected to have a low dark-count rate. Cooling to  $-25^\circ C$  can reduce this by a factor of 50, since the dependence of dark-count rate on temperature is exponential.

The Dark-Count increases with voltage following the same curve as the Photoelectron Detection Probability until a voltage where after-pulsing is responsible for a feedback mechanism which dramatically increases the dark-count rate. This maximum voltage is circuit dependent, and is not warranted other than the values listed on page 3. In most cases, with a delay time of 300 ns, the diode can be used effectively at  $V_R$  up to  $V_{BR} + 25 V$ .

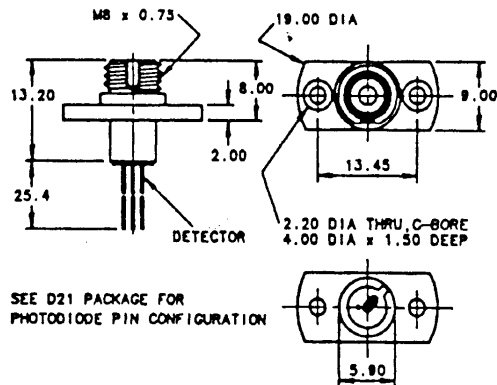
The C30902S and C30921S should not be forward biased or, when unbiased, exposed to strong illumination. These conditions result in a greatly enhanced dark-count which requires up to 24 hours to return to its nominal value.



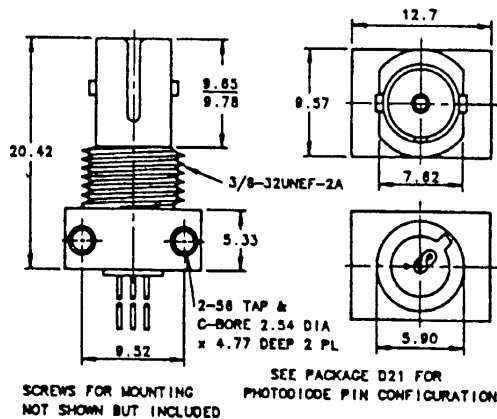
C30902E/S



C30921E/S



C30902BFC



C30902BST