CR-110 charge sensitive preamplifier: application guide

General Description

Cremat's CR-110 is a single channel, low noise charge sensitive preamplifier intended for use with various types of radiation detectors including semiconductor detectors, photomultiplier tubes (PMTs), photodiodes, avalanche photodiodes (APDs), and various gas-based detectors. The CR-110 is small (less than one square inch in area), allowing for compact multichannel detection systems to be created using a modular design. The CR-110 can provide equal performance with pulses of either polarity.

Detector coupling

The CR-110 can be used either in a *direct coupled* (DC) mode, or an *AC coupled* mode. These configurations are discussed below. If the detector current exceeds ±10 nA, it is recommended that an AC coupled mode be used to prevent the resulting DC offset of the preamplifier output from saturating.

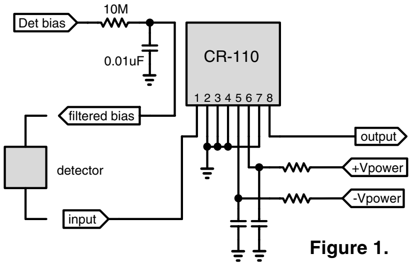

Figure 1.

Direct coupled operation

The above figure illustrates a typical configuration in which the CR-110 preamplifier is used to readout a detector in a 'DC coupled' configuration. Detector current flows directly into the preamplifier input, which is held at approximately a couple tenths of a volt below ground potential. Detector current also produces an offset in the preamplifier output voltage at a rate of 0.2 V per nA. A DC coupled configuration is recommended unless high detector current causes the DC level at the output to saturate.

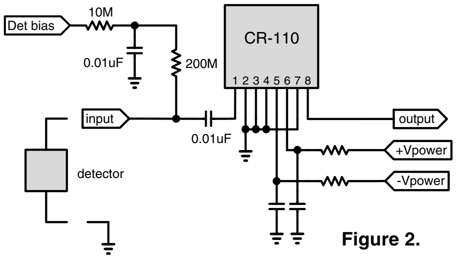

Figure 2.

Bypassed (AC coupled) operation

In cases in which detector current exceeds approximately ±10 nA, an AC coupled configuration is recommended to prevent the DC level of the output from saturating. The above figure shows the connections typically made in such a situation.

Package Specifications

The CR-110 circuit is contacted via an 8-pin SIP connection (0.100" spacing). Leads are 0.020 inches wide. Pin 1 is marked with a white dot for identification.

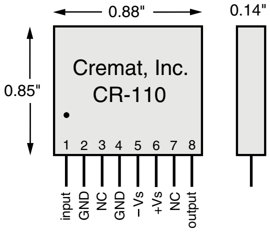

Figure 3.

Equivalent circuit diagram

The figure below shows an simplified equivalent circuit diagram of the CR-110, which is a two stage amplifier. The first stage is high gain, and the second stage is low gain with an emphasis on supplying sufficient output current to drive a terminated coaxial cable.. Pin numbers corresponding with the CR-110 preamplifier are shown. R_f (100 MΩ) and C_f (1.4 pF) are the feedback resistor and capacitor respectively.

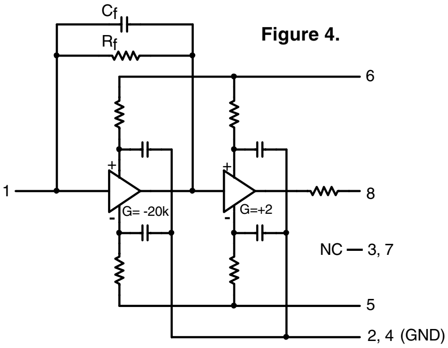

Figure 4.

Specifications

Assume temp =20 °C, V_s = ±9V, unloaded output

	CR-110	units
Preamplification channels	1	
Equivalent noise charge (ENC)*		
ENC RMS	180	electrons
	0.03	femtoCoul.
Equivalent noise in silicon	1.6	keV (FWHM)
Equivalent noise in CdZnTe	2.1	keV (FWHM)
ENC slope	3	elect. RMS /pF
Gain	1.4	volts /pC
Rise time †	7	ns
Decay time constant	140	µs
Unsaturated output swing	-6 to +6	volts
Maximum charge detectable per event	2.6×10^7	electrons
	4.2	pC
Amplification polarity	inverting	
Power supply voltage (V_s)		
maximum	V_s = ±13	volts
minimum	V_s = ±6	volts
Power supply current	11	mA
Power dissipation	see Figure 7	
Operating temperature	-40 to +85	°C
Output offset	-0.5 to -0.1	volts
Output impedance	50	ohms
Maximum output current (under load)	70	mA

* Measured with input unconnected, using Gaussian shaping amplifier with time constant =1 µs. With a detector attached to the input, noise from the detector capacitance, leakage current, and dielectric losses will add to this figure.

† Pulse rise time (defined as the time to attain 90% of maximum value) has a linear relationship with input capacitance. Value cited in the table assumes zero added input capacitance. To calculate pulse rise time for practical situations, use the equation: $t_r = 0.4\ C_d + 7$ ns, where t_r is the pulse rise time in ns, and C_d is the added capacitance (e.g. detector capacitance) in pF.

Minimization of Electronic Noise

The magnitude of the equivalent noise charge (ENC) of charge sensitive preamplifiers is affected by a number of different factors. Although these factors produce a certain unavoidable level of noise, additional and preventable noise may also be introduced into the detection system by some aspects of the circuit design. The purpose of this section is to help the engineer design detector circuits having the minimum electronic noise possible, given the constraints of the detector.

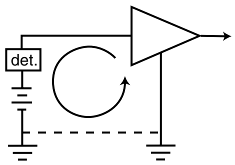

Figure 5. Ground loops, caused by multiple paths to ground, can make a detection system sensitive to external RF.

One of the more avoidable noise sources which may be present is inductive 'pick-up' from nearby circuitry. This can generally be eliminated by adequately shielding the detection circuitry and by avoiding 'ground loops' in the layout of the circuitry. The power supply may also contain 'ripple' that will not be completely rejected by the amplification circuitry. For this reason, it is advisable to RC filter both the positive and negative power supply lines at a point close to the preamplifiers. In addition to ensuring a quiet power supply, it is also important to RC filter the detector bias supply at a point near the detector and preamplifier. The types of noise described in this paragraph can be identified by their periodic behavior. With careful circuit design, these noise sources can be eliminated as significant factors affecting the performance of the circuitry.

One final note on providing clean power supply voltages: Surprisingly, some power supply regulation ICs (such as the LM317 and LM337) produce outputs that are very noisy. This noise can couple to the preamplifier output, producing unsatisfactory results. If these regulator chips are used to provide supply voltages for the CR-110, it is recommended that an RC filter combination of 4.7Ω/1000μF be used to filter both the positive and negative power supplies. Alternatively, a quieter regulator circuit (such as that used in the CR-150-X evaluation boards) could be used. See http://www.cremat.com/CR-150.pdf for more information on this regulator circuit.

In typical detection systems using charge sensitive preamplifiers, the ENC (equivalent noise charge) is due to a combination of 5 factors:

1). The *series thermal noise* of the input JFET in the preamplifier (which is proportional to the total capacitance to ground at the input node),

2). The *parallel thermal noise* of the feedback resistor and any 'biasing' resistor attached to the detector,

3). The *shot noise* of the detector leakage current,

4). The *series 1/f noise*, which is produced by the electrical contacts of the detector and preamplifier input JFET,

5). The *parallel f noise* caused by the proximity of lossy dielectric material near the preamplifier input node.

These noise sources can often be individually quantified in an operating detection system by measuring the dependence of the ENC on the "shaping time" of the pulse amplifier which usually follows the preamplification stage. This method is described in more detail in the article:

> Bertuccio G; Pullia A; "A Method for the Determination of the Noise Parameters in Preamplifying Systems for Semiconductor Radiation Detectors", Rev. Sci. Instrum., 64, p.3294, (1993).

Other articles which describe typical noise sources and signal processing techniques when using charge sensitive preamplifiers are:

> Radeka V; "Low-Noise Techniques in Detectors", Ann. Rev. Nucl. Part. Sci., 38, p.217, (1988).
>
> Goulding FS; Landis DA; "Signal Processing for Semiconductor Detectors", IEEE Trans. Nuc. Sci., NS-29, p.1125, (1982).

In the interest of avoiding unnecessary noise, there are a few factors requiring attention. If AC coupling is used, an important decision to make is the value of the "bias resistor" (resistor placed between the detector and the filtered detector bias supply). Because this resistor is effectively "in parallel" with the preamplifier input, it is a source of *parallel thermal noise*. The magnitude of this noise is proportional to the reciprocal of the square root of the resistor value. To choose a good value for this resistor, one should have approximate knowledge of the detector leakage current. It should be noted that the thermal noise of the bias resistor has the same power spectrum as the *shot noise* produced by the detector leakage current. To keep the bias resistor from being a significant source of noise, one should choose a bias resistance that keeps the thermal noise of the bias resistor significantly less than the detector shot noise. The point at which the thermal noise of the resistor equals this shot noise is when the bias resistor voltage drop is =2kT/q, or approximately 50 mV. If the voltage drop is significantly greater than this, then you can be certain that the thermal noise of the resistor is not limiting the performance of the circuit. To be safe, you can use a bias resistor that will drop approximately half a volt. Because the CR-110 uses a 100 MΩ feedback resistor (which produces its own thermal noise) there is no need to increase the value of the bias resistor higher than approximately 200 MΩ. Another consideration in the choice of bias resistor is that a very large voltage drop across it (in excess of several volts) may significantly subtract from the voltage drop across the detector.

Another source of electronic noise is the thermal noise of resistances effectively "in series" between the detector and the preamplifier input. The thermal noise voltage that the effective series resistance produces is converted to a "noise charge" (remember that the preamplifier output is proportional to the charge flowing into the input) which is proportional to the capacitance to ground at the preamplifier input. Of course it is recommended that the circuitry minimize the series resistance between the preamplifier input and the detector, and usually this resistance can be reduced to a figure of less than a few ohms. Unfortunately, effective resistance in the input stage of the preamplifier add to this figure, making it the dominant source of the "series thermal noise". As mentioned, this noise component is proportional to the capacitance at the preamplifier input, and for this reason it is important to seek to minimize the input capacitance as much as possible. Using even short sections of coaxial cable to connect a detector to the preamplifier, for example, can significantly degrade the noise performance. Assuming a shaping time of 1μs, this noise component adds 3 electrons RMS of noise charge for each pF of capacitance added to the input.

Another noise concern in the design of your detection system is the introduction of *parallel f noise*, which is introduced by the proximity of lossy dielectric materials at the preamplifier input. To minimize this source of noise, which in some situations can be quite significant in magnitude, detector circuit designs should keep the input traces on the circuit board as short as possible. This is because the circuit board itself is often the lossy dielectric material introducing this form of noise. Epoxy and glass, which are usually considered to be good dielectrics (and circuit board materials) in most circuit applications, are actually too lossy to be used in the usual manner when designing detector circuits. Better construction materials are Teflon and to a lesser extent alumina. These materials, however, are more unusual and expensive than standard FR-4. To avoid the expense of Teflon boards, consider lifting the input lines off the circuit board in some fashion, perhaps by suspending the input lines above the board using Teflon standoffs. If electronic noise is not a primary consideration, however, it may suffice to use short traces on an epoxy-based circuit board. The use of coaxial cable to couple the detector to the preamplifier may introduce noise, not only by adding capacitance (as mentioned previously), but also because of the lossiness of the cable's dielectric layer. If coaxial cable absolutely must be used between the detector and preamplifier, its length should be as short as possible.

Estimating the Electronic Noise in a Detection System

It is often useful to know what the expected electronic noise will be in a detection system while the system is still in the design phase.

The following equation can be used to estimate the noise level in a detection system based on the CR-110 charge sensitive preamplifier. Estimates have been made for factors (d) and (e) mentioned previously, assuming short traces on an FR-4 circuit board (such as those found on Cremat's CR-150-AC-C evaluation board). This equation may be useful in allowing the user to calculate the optimal shaping time (τ in μs) minimizing the electronic noise (ENC in electrons rms) for a given detector capacitance (C_{in} in pF) and detector leakage current (I_d in pA).

$$\mathrm{ENC} := \sqrt{\frac{43\cdot\left(C_{in}+15\right)^2}{\tau}+8\cdot\tau\cdot\left(I_d+800\right)+50000}$$

Frequently Asked Questions

What are charge sensitive preamplifiers?

Charge sensitive preamplifiers were developed to detect the total amount of charge flowing from a detector as the result of a 'pulse' event, such as the detection of individual particles or gamma-rays. The preamplifiers integrate the pulse of current flowing from the detector over time (by virtue of a small capacitance in the feedback loop) to produce an output which is proportional to the charge into the preamplifier input. A large valued resistor in parallel to the feedback capacitor slowly discharges the capacitor, restoring the preamplifier output to its original state. Unlike voltage sensitive preamplifiers, charge sensitive preamplifiers must have low input impedance so that the preamplifier can easily sink (or supply) charge from the detector.

How are charge sensitive preamplifiers more suitable for use with particle detectors than voltage sensitive preamplifiers?

Ionizing events within detectors generally produce an amount of ionized charge that is proportional to the energy of the incoming particle or gamma-ray. For this reason, the detector preamplifier should be configured in a way to produce an output that is precisely proportional to this ionized charge. Voltage sensitive preamplifiers were first used to read out solid state detectors when they were first developed in the '40s. A problem was noted, however, in that the signal voltage at the preamplifier input was not only proportional to the ionized charge, but also inversely proportional to the input capacitance. Because the detector capacitance is usually a weak function of the temperature, temperature drifts were causing drifts in the preamplifier gain and degrading the energy resolution. For this reason the charge sensitive preamplifier was developed, which has a gain equal to the reciprocal of the feedback capacitance, and more importantly independent of the input capacitance. For many decades, charge sensitive preamplifiers have been the standard design for use in detectors where the energy measurement of individual ionizing events is of interest.

The decay time of the preamplifier output pulse is quite long. Do I have to worry that pulses will build on previous pulses and cause a 'pile up' of events?

The point at which to be concerned about the effects of pulse 'pile up' is after the preamplifier output pulse has been filtered through a shaping amplifier. The shaping amplifier (also called 'linear amplifier', 'spectroscopy amplifier', or 'pulse amplifier') dramatically changes the shapes of the pulses, generally giving them a longer risetime and a much quicker fall time, and restores the baseline to prevent pile up as much as possible. Events that appear to pile up before the shaping amplifier often become very clearly separated after the shaping amplifier.

What is the bandwidth of the CR-110?

The term 'bandwidth' is generally not used when discussing charge sensitive preamplifiers - instead one describes their rise time due to a delta current pulse input (which charges the feedback capacitance), and their decay time due to the discharge of the feedback capacitance through the feedback resistance. In general, one seeks a fast pulse rise time, but not necessarily a short decay time. In fact, if the feedback resistor value were substantially decreased in order to quicken the decay time, the added thermal noise due to this decreased resistance would be unacceptable.

How can we check to see whether the preamplifiers are operating within the specified noise level?

The method described here requires the following:

1. A test circuit board (such as the CR-150-X) with an appropriate power supply.
2. A low noise Gaussian shaping amplifier, having a shaping time of 1 μs. The CR-200-1μs Shaping Amplifier used with the CR-160 evaluation board would be suitable.
3. A pulse height analyzer.
4. A tail pulse generator or square wave generator.
5. A silicon p-i-n photodiode (Hamamatsu S1223 or equivalent), and a bias supply (100 volts if using the Hamamatsu S1223).
6. A small ^{241}Am isotopic source.

To measure the noise of the preamplifier, the gain of the detection system must first be precisely measured (in keV per channel). To do this, construct the circuit shown in **Figure 2** (the CR-150-AC-X test board could be used for this). A p-i-n photodiode should be used as the 'detector', and a bias power supply should reverse bias the detector to its maximum allowed value. The ^{241}Am source should be oriented so that its emissions can irradiate the photodiode. The circuitry and photodiode should be in a well shielded, light tight box. Route the preamplifier output to the Gaussian shaping amplifier (1 μs), which should have its output routed to a pulse height analyzer. Acquire a ^{241}Am pulse height spectrum, in which you should be able to clearly detect the 60 keV gamma-ray emission (see **Figure 6**). Note the channel number at which the 60 keV photopeak is observed. The gain of the detection system is the ratio: peak channel number / 60 keV.

Next, disconnect the input lead of the preamplifier (pin 1) from the test circuit board. This can be done a using a variety of methods, but make sure that pin 1 is left floating and does not touch the circuit board or other components. Connect the tail pulse generator (or square wave generator) to the preamplifier via a small valued capacitor of no more than just a couple pF. Alternatively, you can use a 'dangling wire' connected to the tail pulse generator and rely on the small capacitive coupling between the input and the wire to make this connection (be sure, though, that the wire does not move during the subsequent measurements). Acquire a pulse height spectrum of the tail pulse signal, which should appear as a Gaussian distrubution. Measure the width of this distrubution by measuring, in channels, the full width at half the maximum value (denoted as FWHM). The noise can then be calculated by dividing by the previously measured gain, to yield a figure having units keV FWHM (Si). To convert this figure to the more generally applicable units of electrons RMS, divide by 0.0036 keV (the ionization efficiency of silicon) and divide again by 2.355 (converting FWHM measurements to RMS).

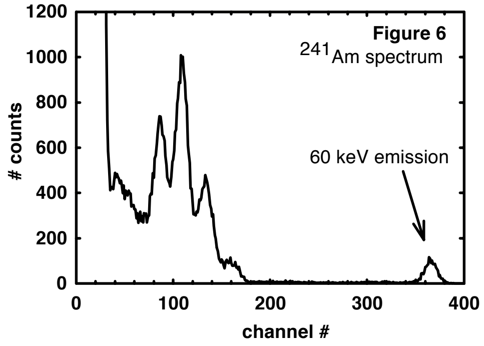
Figure 6
^{241}Am spectrum

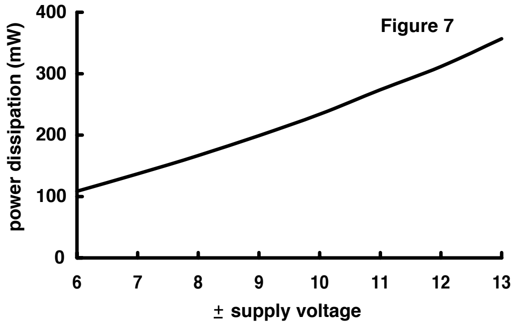
Figure 7

Figure 7 above shows the power dissipation of the CR-110 charge sensitive preamplifier as a function of power supply voltage. This assumes the output is unloaded and the input unconnected.

Table 1: Sensitivity Versions

preamp model	gain (mV / pico-Coulomb)	max. detect. pulse (e$^-$)	Equiv. noise in silicon keV (FWHM)
CR 110	1400	10^7	1.7 keV
CR 111	150	10^8	6.0 keV
CR 112	15	10^9	65 keV
CR 113	1.5	10^{10}	230 keV

Table 2: Model specifications (electrons)

preamp model	noise (ENC) in e$^-$ RMS*	noise (ENC) slope e$^-$/pF	rise time (C_d=0pF)	rise time slope
CR 110	200 e$^-$	4 e$^-$/pF	7ns	0.4ns/pF
CR 111	630 e$^-$	3.7 e$^-$/pF	3ns	0.25ns/pF
CR 112	6,800 e$^-$	28 e$^-$/pF	6ns	0.25ns/pF
CR 113	24,000 e$^-$	27 e$^-$/pF	20ns	0.25ns/pF

Table 4: Ordering Information

Model No.	Description	Order No.
CRXXX	Charge sensitive preamp, SHV, 2kV/10nF, 1.4V/pC	HY100
CR 110	Charge sensitive preamp, SHV, 2kV/10nF, 150mV/pC	HY110
CR 111	Charge sensitive preamp, SHV, 2kV/10nF, 15mV/pC	HY111
CR 112	Charge sensitive preamp, SHV, 2kV/10nF, 1.5mV/pC	HY112
CR 113	Charge sensitive preamp, SHV, 4kV/4.7nF, 1.4V/pC	HY113