APPLYING THE MODEL 1211 CURRENT PREAMPLIFIER TO TUNNELING MICROSCOPY

DL INSTRUMENTS

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INTRODUCTION

The choice of the proper current preamplifier can greatly enhance the results obtainable from tunneling microscopy techniques. The DL Instruments Model 1211 has shown itself to be the best commercially available unit. for the critical parameters of 60 Hz rejection, wide bandwidth at high gain and low random noise performance. Using this instrument, one will achieve measurements much superior to those achievable with the best competitive picoammeter, the Keithley Model 427.

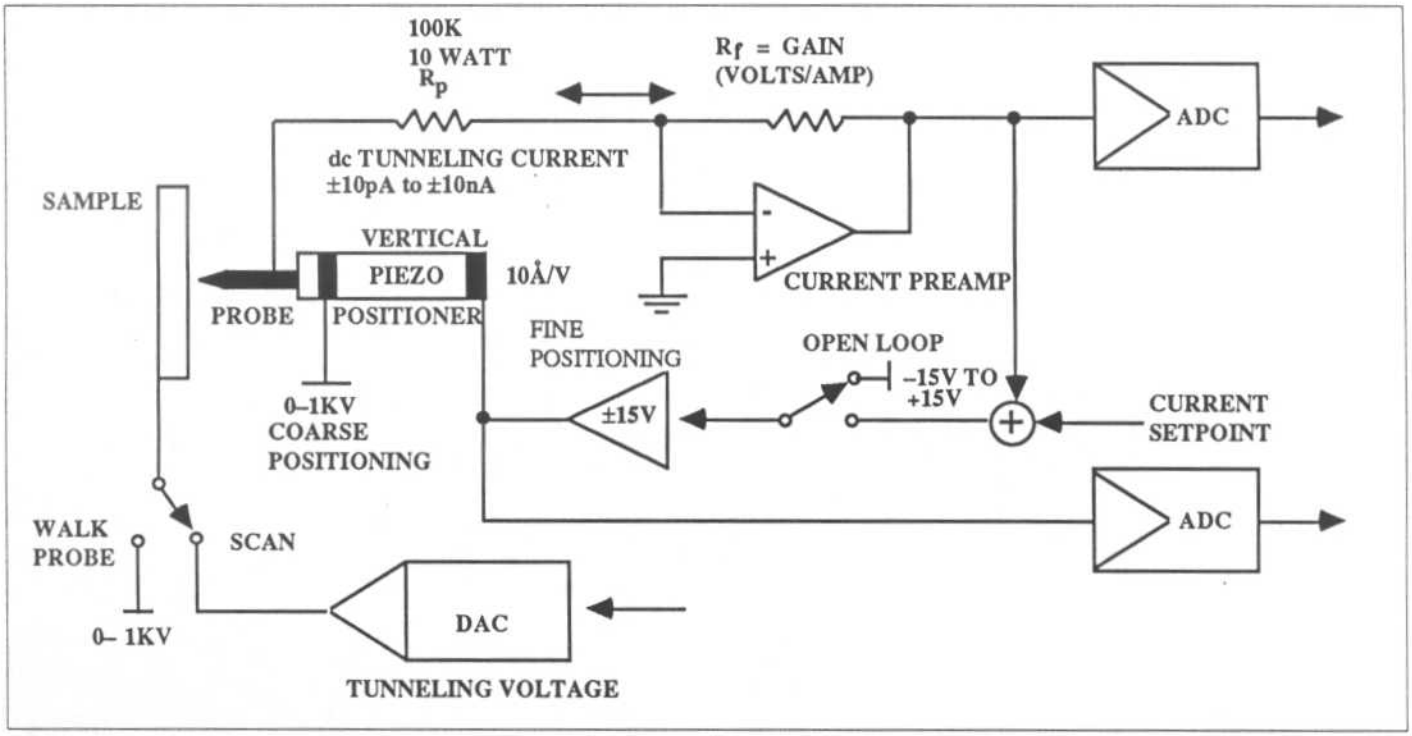

FIGURE 1: TYPICAL TUNNELING MICROSCOPE ELECTRICAL CIRCUIT

TUNNELING MICROSCOPY, A TYPICAL SETUP

A "walker" mechanism advances the probe tip toward the sample to get within the 10,000Å range of the vertical piezo positioner. This is done with perhaps a 1000 volt sample–to–probe bias so that distance can be gauged via field emission current. The bias is then dropped in stages as the probe is moved toward the sample and gets within the extension range of the vertical positioner. Finally the point is reached at which the probe is within the ±100Å range of the fine position amp, where upon the tunneling voltage is switched in and the vertical feedback control loop is closed to maintain constant tunnel current. This forces the tip to remain at a constant altitude above the sample, typically10Å. Horizontal piezo translators (not shown in Figure 1) then scan the tip across the surface, with the vertical servo maintaining a constant tip-to-surface spacing.

In simple surface profiling, the vertical drive voltage is recorded for each point of the scan for processing into an atom-by-atom image. A typical tunneling current might be 100 pA. The process takes a relatively long time — on the order of 1 minute for a 100Å by 100Å area.

A much faster technique involves momentarily opening the control loop and rapidly scanning the tip position. The variations in tunneling current (rather than drive voltage) are observed.

When the tunneling voltage is modulated, the dI/dV function can map surface states, identify atoms or plot the spatial distribution of bandgaps. This technique can involve the averaging of repeated scans and typically requires tunneling currents on the order of 10 nA.

CURRENT PREAMP REQUIREMENTS

60 Hz REJECTION

Hum pickup often represents the most severe problem facing tunneling microscopy. By necessity, the hookup of the circuitry to the probe assembly requires a number of long, fine, unshielded wires which are ripe for magnetic coupling of stray power line energy. Also, long cables are usually required to get the tunneling current from the experiment to the current preamp, leading to all manner of grounding, isolation and shielding woes. We are told that the Model 1211 substantially outperforms all competitive instruments in the avoidance of hum pickup.

BATTERY OPERATION

An absolute must in order to get rid of 60 Hz hum according to some of our users. Others notice no difference when changing from line to battery power.

INPUT PROTECTION

Use an external 100 KΩ 10 watt resistor in series with the current preamplifier input. It can be mounted in a shielded box (Pomona 2391) right at the current preamp input. This protects the current preamp against prolonged 1 kV input overloads should the tip contact the sample during field emission coarse positioning. The Keithley 427 uses internal protection against high level input overloads, but at the cost of Johnson noise several times larger than theoretical, since a high value protection resistor is placed inside the op-amp feedback circuit. Installing an external series resistor does not degrade either frequency or noise performance, since its value is very low compared to the probe impedance.

See Appendix B for an internal modification to the 1211 to make it less susceptible to damage by input overvoltage.

RANDOM NOISE

This is not much of an issue when doing repetitive dI/dV scans at higher currents. However at the lower currents employed for slowly scanned profiles, the instrumentation noise becomes more significant in attaining accurate vertical positioning. The culprit here is not the normally specified open circuit input current noise, which often nearly equals the theoretical Johnson noise of the transimpedance feedback resistor R_f ($i_n = \sqrt{4KT/R_f} = (128pA/\sqrt{Hz})/\sqrt{R_f}$. Rather, the trouble arises with the input noise voltage e_a of the current preamp —a parameter often omitted from specification sheets. This voltage reacts with the source capacitance to yield random noise component, $i_c = e_a\, 2\pi fc$ amperes/$\sqrt{Hz}$ which is proportional to both frequency and source capacitance. The long cables often encountered running from preamp to probe can have a significant capacitive noise effect (29 pF/foot for RG-58 co–ax, for instance).

Since the current preamp operates broadband in tunneling work, the noise must be integrated over the bandwidth being used to arrive at the total noise level, I_c, due to voltage noise.

$$I_c = \sqrt{\int_{f_1}^{f_2} i_c^2\, df}$$

The I/f noise at low frequencies complicates the calculation. The most reasonable approach is to divide the frequency range into two segments and carry out separate integrations to get good approximations of the total noise. The Model 1211, has a noise curve that can be represented as follows:

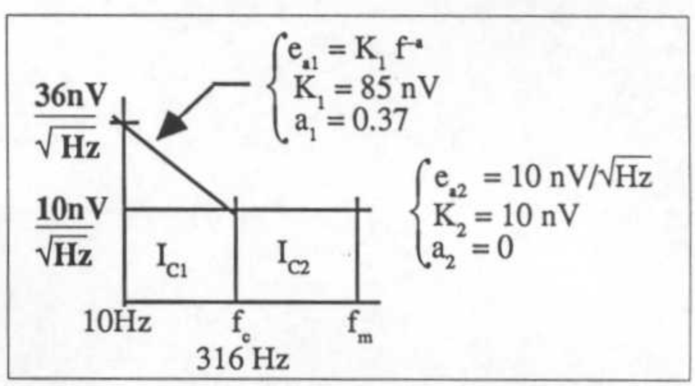

FIGURE 2 TYPICAL MODEL 1211 VOLTAGE NOISE CURVE

$$I_c = \sqrt{I_{c1}^2 + I_{c2}^2}$$

$$I_{cx} = \frac{2\pi c K}{\sqrt{3-2a}} \sqrt{f_2^{\,3-2a} - f_1^{\,3-2a}}$$

$$I_{c1} = \frac{2\pi c K_1}{\sqrt{3-2a_1}} f^{\,3/2-a_1} = (355 \text{ nV})\ c\ f^{\,1.13}$$

$$I_{c2} = \frac{2\pi c K_2}{\sqrt{3}} \sqrt{f_m^{\,3} - f_c^{\,3}} = (36 \text{ nV})\ c \sqrt{f_m^{\,3} - 316^3}$$

If one were rapidly scanning using a gain of 10^8 V/A (f_m = 15 kHz bandwidth) and the cable capacitance equaled 200 pF, the the two noise contributions would be:

I_{c1} = 355nV x 200pF x $316^{1.13}$ = 48 fA

$I_{c2} \cong$ 36nV x 200pF x $15K^{3/2}$ = 13.2 pA

Compared to this, the expected open circuit current noise of the preamp would be quite small:

$\sqrt{4KTB/R}$ = 128 pA/$\sqrt{20 \text{ kHz}/10^8\ \Omega}$ = 1.81pA.

As a second example, consider the case of using a 100 Hz rolloff at a gain of 10^{10} V/A when doing slow surface profiling. We have a noise contribution (due to I_{C1} only) given by:

I_{c1} = 355nV x 200 pf x $100^{1.13}$ = 13fA

In this case, the open circuited input noise is no longer negligible: the theoretically expected value is 128pA/$\sqrt{100 \text{ Hz}/10^{10}\Omega}$ = 12.8 fA (25 fA actual open circuit noise for Model 1211). A Keithley Model 427 would generate roughly I_{c1} = 50 fA in this instance due to its high input voltage noise.

One can observe this noise effect readily using an oscilloscope to view the output of the Model 1211 Current Preampamplifier at a gain of 10^8 V/A. With the input of the preamp open circuited (no cable attached) and the preamp bandwidth wide open (15 kHz) the scope will exhibit little noise. We would expect 128 pA $\sqrt{15\text{kHz}/10^8}$ x gain x 6Vpp/vrms = 156 pA x 10^8 x 6 = .94 mVpp "grass". If one then attaches 7 feet of open circuited R58 cable (200 pf) the grass will grow to 13.2 pA x 10^8 x 6 = 8 mVpp. Add more cable and the noise gets proportionally worse.

LOOP STABILITY

When positioning the probe vertically, the loop response must be rolled off heavily to prevent oscillations at the approximately 1 kHz mechanical resonance frequency of the probe assembly. For low speed profiling, one could provide the lowpass corner frequency by setting the risetime control to the appropriate rolloff frequency. For the Model 1211, one must take care that its internal rolloff rate switch has been changed from the normal 12 dB/octave rolloff to 6 dB/octave. Failure to do so would result in loop oscillation. Be aware that the front panel 10% – 90% risetime controls are calibrated for the 12 dB, not the 6 dB, rolloff rate. See Appendix A.

For rapidly scanned work requiring wide bandwidth, one would operate the 1211 with a fast risetime and provide a switchable RC time constant elsewhere in the loop.

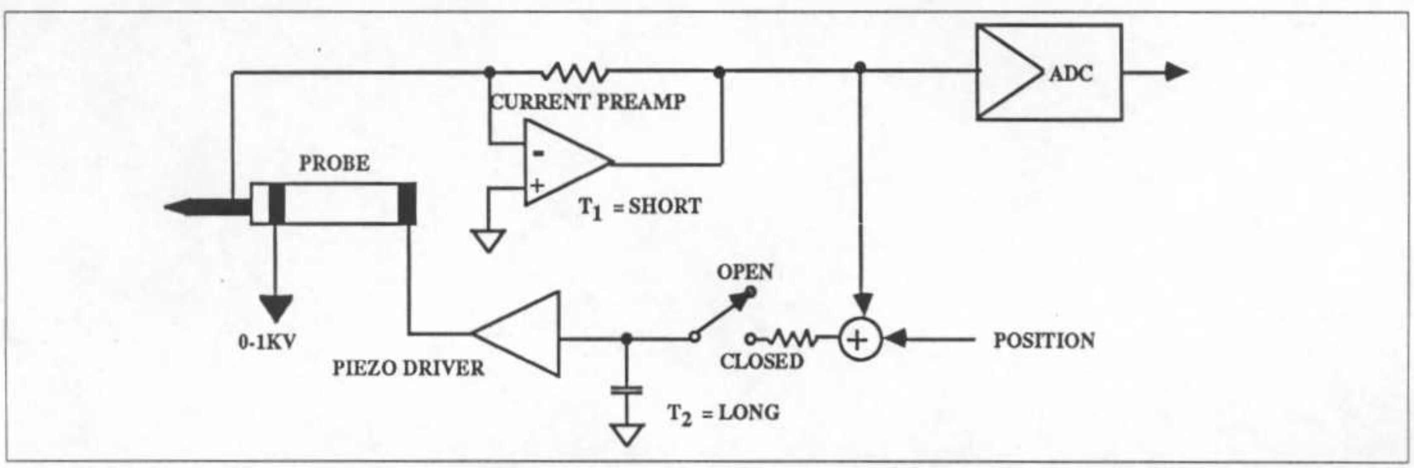

FIGURE 3 SLOW/FAST TIME CONSTANT SWITCHING FOR OPEN LOOP SCANNING

TRIBOELECTRIC EFFECT

Flexing of input co–axial cables can generate frictional emf due to the rubbing of the conductors against the insulation. To prevent noise due to mechanical vibration, one should install the preamp in a relatively vibration–free environment. It also helps to tape down cables and use low noise cable, such as ITHACO P/N 100AE cable.

MODEL 1211 OPEN CIRCUIT NOISE

The following table lists the noise measurements made on a typical ITHACO Model 1211 Preamplifier. The Model 1211 incorporates voltage amplification using its X.1, X1, X10 sensitivity switching. Furthermore, a 2X gain is employed at its lower sensitivity settings, leading to a smaller actual R_f value and more noise than the sensitivity setting would imply. This is reflected in the table.

The higher noise at low gain is due to 1211 preamp output voltage noise, which for the above unit would be $540nV/\sqrt{Hz}$ at X.1, $75nV/\sqrt{Hz}$ at X1 and $42nV\sqrt{Hz}$ at X10.

FREQ. Hz.	SENSITIVITY A/V	Rf ohms	IDEAL NOISE $\sqrt{4KT/R_f}$, $Hz^{-1/2}$	MEASURED NOISE X.1	X1	X10
1K	10^{-3}	500	5.75 pA	54 pA	75 pA	418 pA
1K	10^{-4}	5K	1.82 pA	5.5 pA	7.65 pA	42.7 pA
1K	10^{-5}	50K	.575 pA	.74 pA	.93 pA	4.25 pA
1K	10^{-6}	500K	182 fA	183 fA	203 fA	470 fA
1K	10^{-7}	5M	57.5 fA	56 fA	54 fA	73.5 fA
1K	10^{-8}	100M	12.8 fA	13.8 fA	14.0 fA	14.2 fA
100	10^{-9}	1G	4.07 fA	4.70 fA	4.26 fA	4.94 fA
100	10^{-10}	10G	1.28 fA	2.60 fA	2.11 fA	2.13 fA
100	10^{-11}	10G	1.28 fA	2.85 fA	2.20 fA	3.20 fA

TABLE 1 MODEL 1211 NOISE CHARACTERISTICS VS SENSITIVITY

PEAKING

Current preamplifiers exhibit a rise in gain near the upper corner frequency due to input shunt (e.g., cable) capacitance. This can be especially troublesome at the higher sensitivities. This results not only in ringing or possible oscillation, but also increased random noise by enhancing the high frequency response of the preamp.

Solutions to this problem are to use lower gain or minimize cable capacitance.

APPLICABLE DOCUMENT

For more information, see IAN 50 "Noise Analysis and Gain Considerations in Selecting the Right Current Preamplifier".

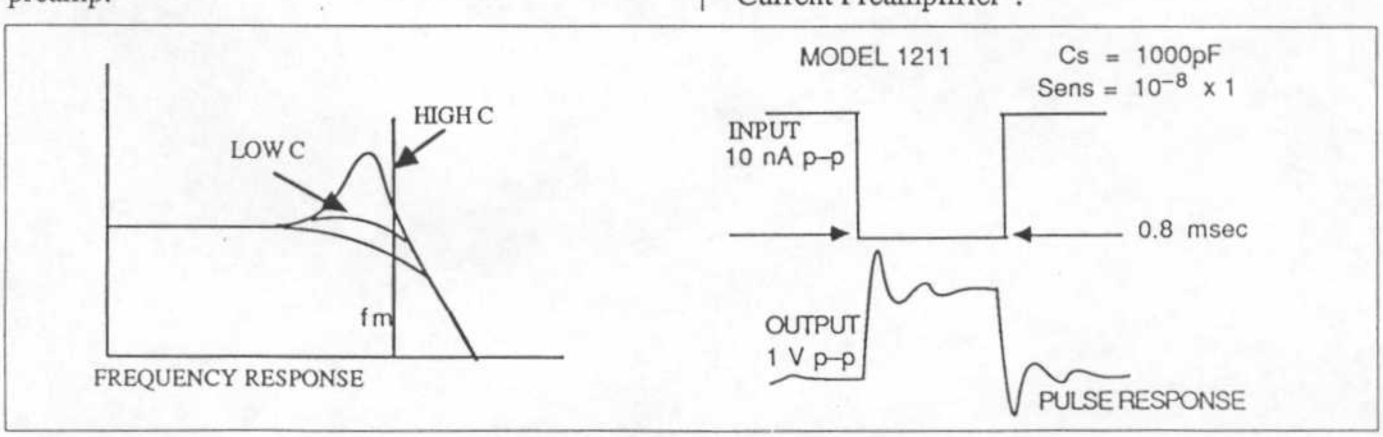

FIGURE 4 CURRENT PREAMP PEAKING

APPENDIX A

MODEL 1211 RISETIME, BANDWIDTH RELATIONSHIPS

The Model 1211 contains an output lowpass filter to limit bandwidth and reduce broadband noise. The front panel control for this is calibrated in terms of 10% - 90% risetime t_r for the 12 dB/octave, 2-pole, rolloff mode. The question arises what is the corresponding time constant, transfer function and bandwidth? Also, how do we compensate if one chooses to use the 6 dB/octave rolloff via internal switch? This information is summarized below.

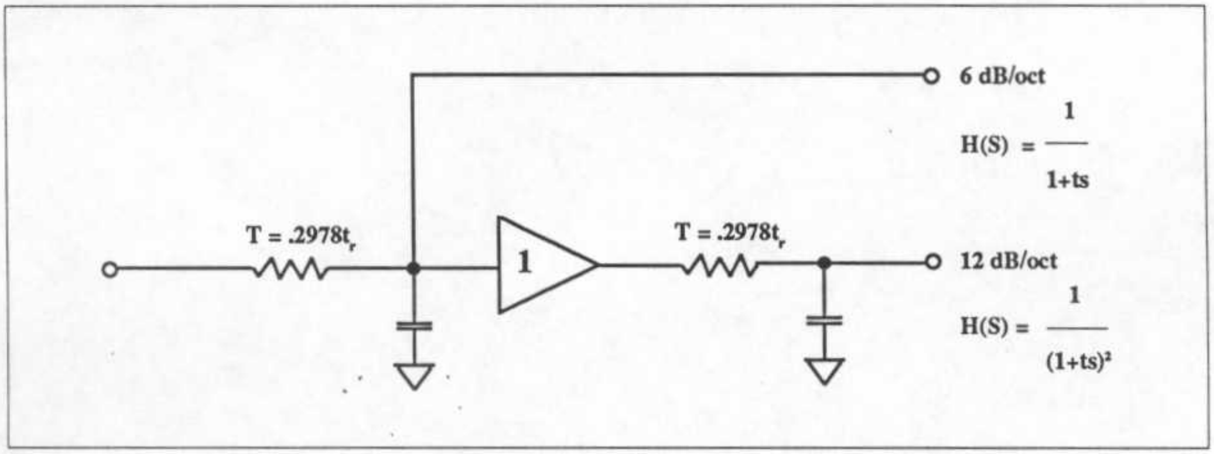

FIGURE 5 MODEL 1211 OUTPUT FILTER

Model 1211 Risetime Control Setting (msec)	12 d/b/Octave Rolloff			6 dB/Octave Rolloff		
	3 dB (f_b) bandwidth (Hz)	6 dB (f_c) corner (Hz)	Equiv NBW (1/8T Hz)	3 dB (f_c) bandwidth (Hz)	Equiv NBW (1/4T Hz)	Actual 10%-90% Risetime (msec)
.01	34,400	53,400	42,000	53,400	84,000	.00654
.03	11,500	17,800	14,000	17,800	28,000	.00196
.1	3,440	5,340	4,200	5,340	8,400	.0654
.3	1,150	1,780	1,400	1,780	2,800	.0196
1	344	534	420	534	840	.654
3	115	178	140	178	280	.196
10	34.4	53.4	42.0	53.4	84.0	6.54
30	11.5	17.8	14.0	17.8	28.0	65.4
300	1.15	1.78	1.40	1.78	2.80	196
1 sec	.344	.534	.420	.534	.840	654

TABLE 2 MODEL 1211 BANDWIDTHS AND RISETIMES

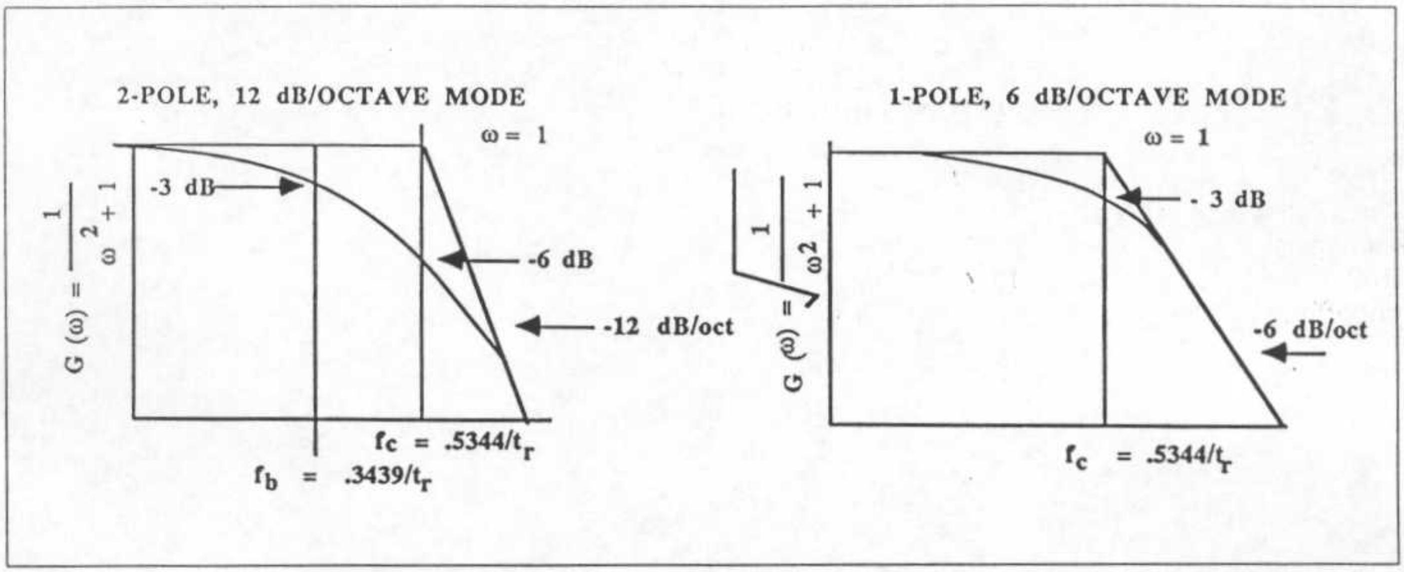

FIGURE 6 MODEL 1211 ROLLOFF CURVES

The bandwidths in Table 2 are valid assuming they are narrower than the values given in Table 3 for the various gain selections. Similarly, the risetime values in Table 2 are valid only if the panel control setting is slower than the values listed in Table 3.

SENSITIVITY CONTROL SETTING (A/V)	TYPICAL WIDE OPEN BANDWIDTH (kHz)	SPECIFICATION FOR MIN RISETIME (Msec)
10^{-3}	65	.010
10^{-4}	60	.010
10^{-5}	55	.010
10^{-6}	32	.015
10^{-7}	20	.025
10^{-8}	15	.040
10^{-9}	4	.250
10^{-10}	1.5	.450
10^{-11}	.5	1.10

TABLE 3 MODEL 1211 MAXIMUM BANDWIDTH AND MINIMUM RISETIME VERSUS SENSITIVITY

APPENDIX B

IMPROVED INPUT OVERVOLTAGE PROTECTION FOR MODEL 1211

The signal input of the Model 1211 employs a protection circuit consisting of R51 and dual FET diode CR11. The circuit prevents destruction of the input amplifier in the event of moderate level input overvoltages.

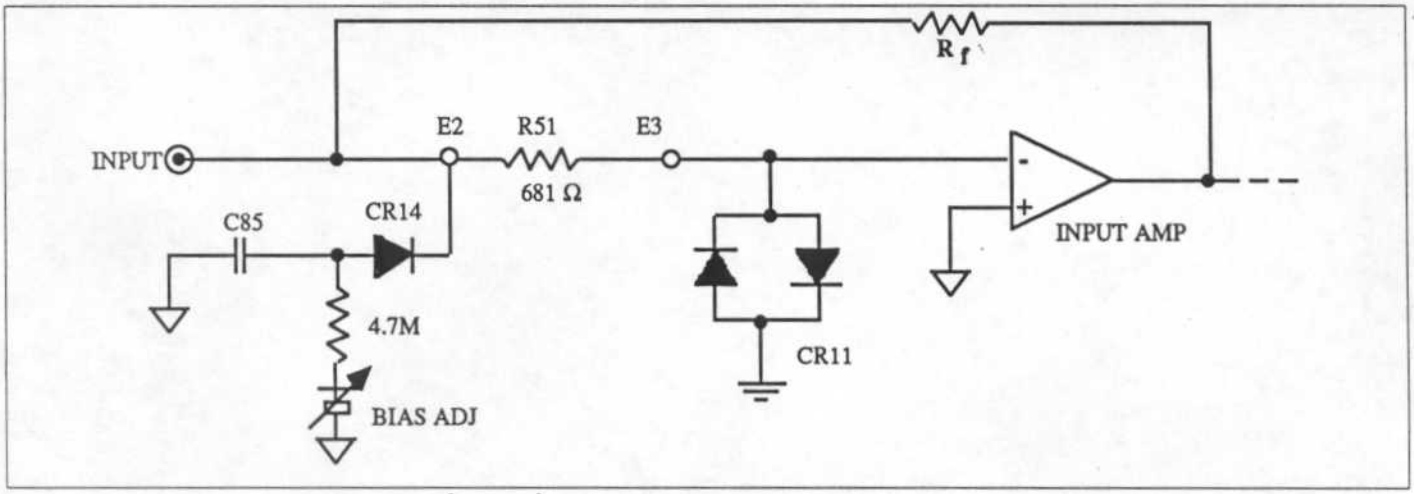

FIGURE 7 MODEL 1211 INPUT CIRCUIT (Original Version)

Unfortunately R51 does not protect input bias compensation FET diode CR14. CR14 develops a temperature dependent, reverse leakage current which absorbs the input bias current of the input amp. If a large input voltage step is applied to the input from a capacitative source (i.e. due to cable capacitance), C85 will provide a low impedance pulse path to ground. Even if the pulse forward biases CR14, it can be damaged by the large rate of rise across its terminals. A high value series input resistor (e.g., 100K) will not be effective by itself in preventing damage. If CR14 is damaged, the symptom will be an excessive input offset current with the 1211 input open circuited.

The solution is to move the cathode of CR14 to the other end of R51. This, in conjunction with a 100KΩ series input resistor, will offer greatly improved protection against kilovolt level input overvoltages. The change is made by moving the anode lead of CR14 from its original connection point at terminal post E2 to terminal post E3 (see 1211 Manual, Figure 7.8). The lead will need lengthening with a bit of bus wire and insulation with teflon sleeving. All 1211 units shipped after 8/7/87 will have this change and units sent in for calibration or repair will automatically receive the update. Units in the field should also be revised.

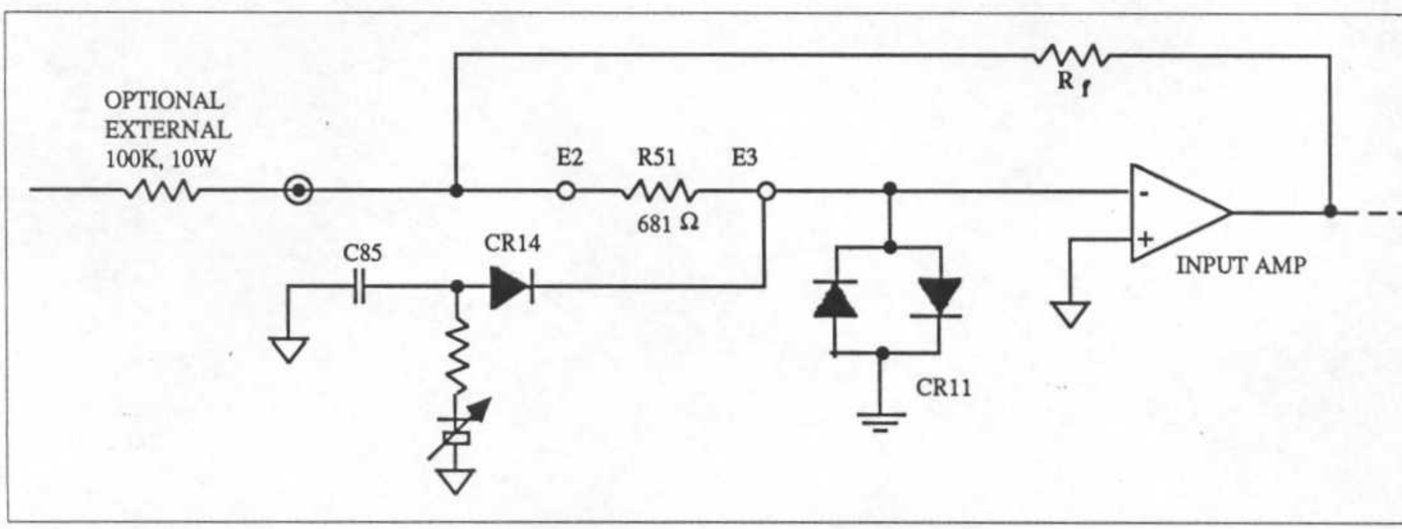

FIGURE 8 IMPROVED 1211 INPUT CIRCUIT