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NOISE MEASUREMENTS ON A P-SURFACE CHANNEL CCD MULITPLEXER.(U)
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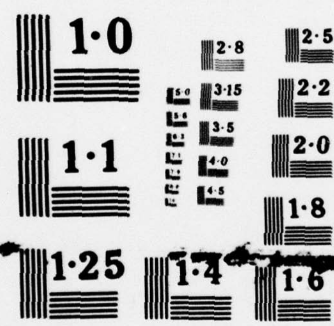
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Noise Measurements on a P-Surface Channel CCD Multiplexer

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The noise performance of a p-surface channel CCD multiplexer was measured at room temperature and at 160°K. Theoretical calculations were made of the contributions from kTC noise, dark current noise and interface state trapping noise. The calculated values agree well with the experimental results. The design goal for these devices was temporal noise voltage of 15μV (3500 rms noise carriers) referenced to the input. Cooled to 160°K we measured a noise voltage of 16μV (3750 rms noise carriers) referenced to the input. The spatial or fixed pattern
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20. Abstract (Continued)

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NOISE MEASUREMENTS ON A P—SURFACE CHANNEL CCD MULTIPLEXER

I. Introduction

The noise performance of a p-surface channel CCD multiplexer was measured at room temperature and at 160°K. Theoretical calculations were made of the contributions from kTC noise, dark current noise, and interface state trapping noise. The calculated results agree well with the experimental values. The noise of the on-chip source follower output stage was below the 900 rms holes noise floor established for the measuring system by the sample and hold. The calibration of the equipment was checked by comparing the theoretical and measured noise values for optically injected charge carriers. The agreement was better than 10% as others have observed.[1] We measured 1 to 2 times theoretical kTC noise with the potential equilibration input which is what others have seen. The design goal for these devices was a temporal noise voltage of 15μV (3500 rms noise holes) referenced to the input. Cooled to 160°K we measured a noise voltage of 16μV (3750 rms noise holes) referenced to the input. The spatial or fixed pattern noise was much larger: 12 mV (2.9×10^6 rms noise holes) referenced to the input. The noise measured on a device irradiated to 1×10^4 rads (Si) under bias was approximately twice the value for an unirradiated device.

Note: Manuscript submitted May 14, 1979.

II. Description of the Multiplexer

The multiplexer used in these experiments is a four-phase p-surface channel CCD multiplexer made by TRW. The device consists of 32 parallel inputs which are multiplexed to a single serial output.

Figure 1 is a schematic representation of the parallel to serial multiplexing performed by the CCD shift register. The signals to be multiplexed are applied to the input gates. A potential equilibration input is used in which the source diode injects charge into the potential well under the input capacitor and fills it with charge above the potential of the input gate. TRW calls the input capacitor the Poly I Scupper. The source diode potential is then lowered and charge drains back from the input capacitor into the diode until limited by the signal potential. Thus, leaving a charge in the input capacitor proportional to the difference between the signal voltage on the input gate and the reference voltage on the input capacitor. All 32 channels are sampled simultaneously. During this input cycle the CCD transfer clocks are not enabled, but bias is applied such that a potential ready to receive charge from the input capacitor exists under all phase 2 gates. A channel access pulse is applied to transfer, in parallel, the signal from the channels into the CCD shift register. In order to handle the required dynamic range, the signal charge from each channel is divided among 3 bits of the CCD shift register. The charge packets from adjacent channels are separated in the CCD by an empty isolation bit. This isolation bit provides an additional 20 db reduction in channel to channel crosstalk which might occur due to charge transfer loss.[2,3] After the CCD register is loaded, the chip enable turns on the CCD clocks, transferring the signal charge to the output node. At the output node, the three bits from each channel plus the isolation bit are reassembled into one charge packet corresponding to the original input signal from that channel.

Figure 2 is a photomicrograph of the multiplexer chip. The most prominent features are the 32 large input capacitors. Above the input capacitors are the connections to the input gates. The CCD analog shift register is directly below the input capacitors and the output node is on its' right hand end. The reset transistor and the source follower output transistor are located below the output node.

Figure 3 is an electrical schematic of the multiplexer chip. It is divided into two parts, the signal input part and the shift register part. The signal input part is duplicated 32 times. The shift register is a 4-phase-p-surface channel 128-bit device. The schematic shows the final bit of the CCD shift register and the output transistor. The output node is reset once every 4 clock pulses so that the signal charge which was divided among 3 CCD bits is reassembled, along with the

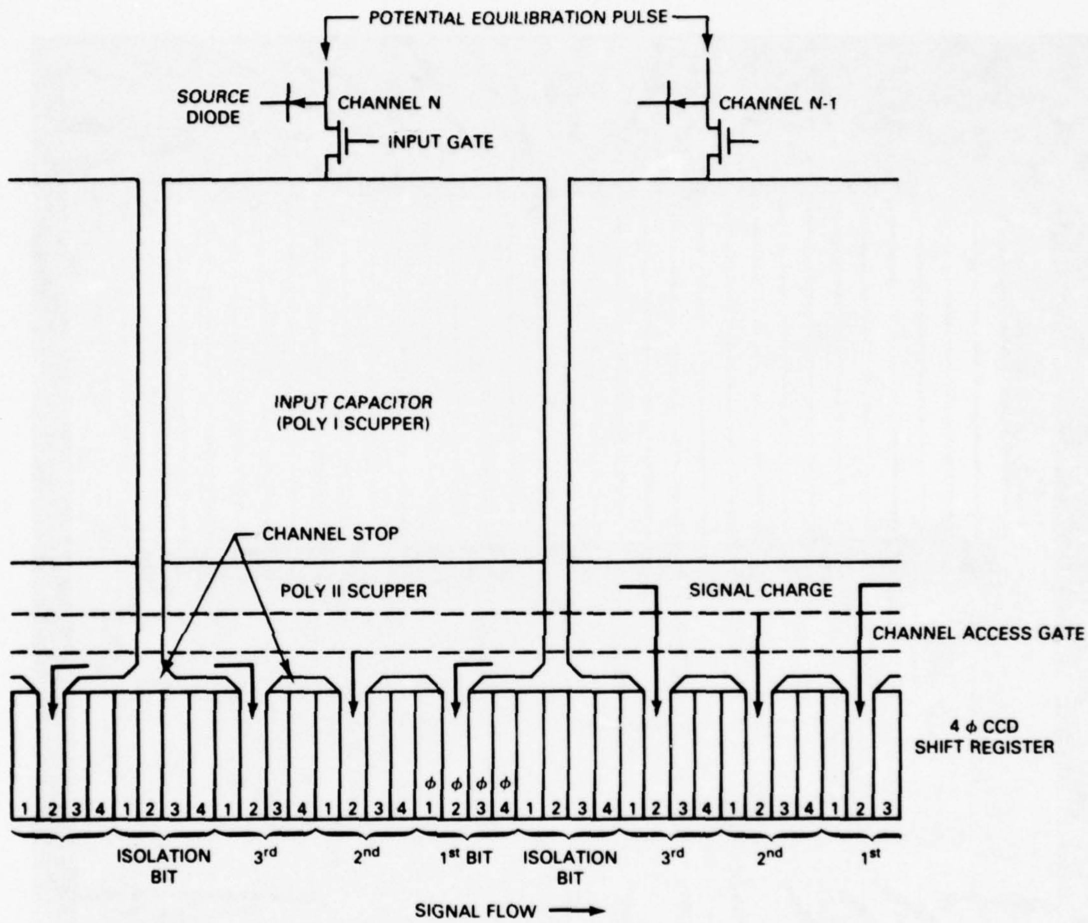

Fig. 1 - Simplified multiplexer operation diagram

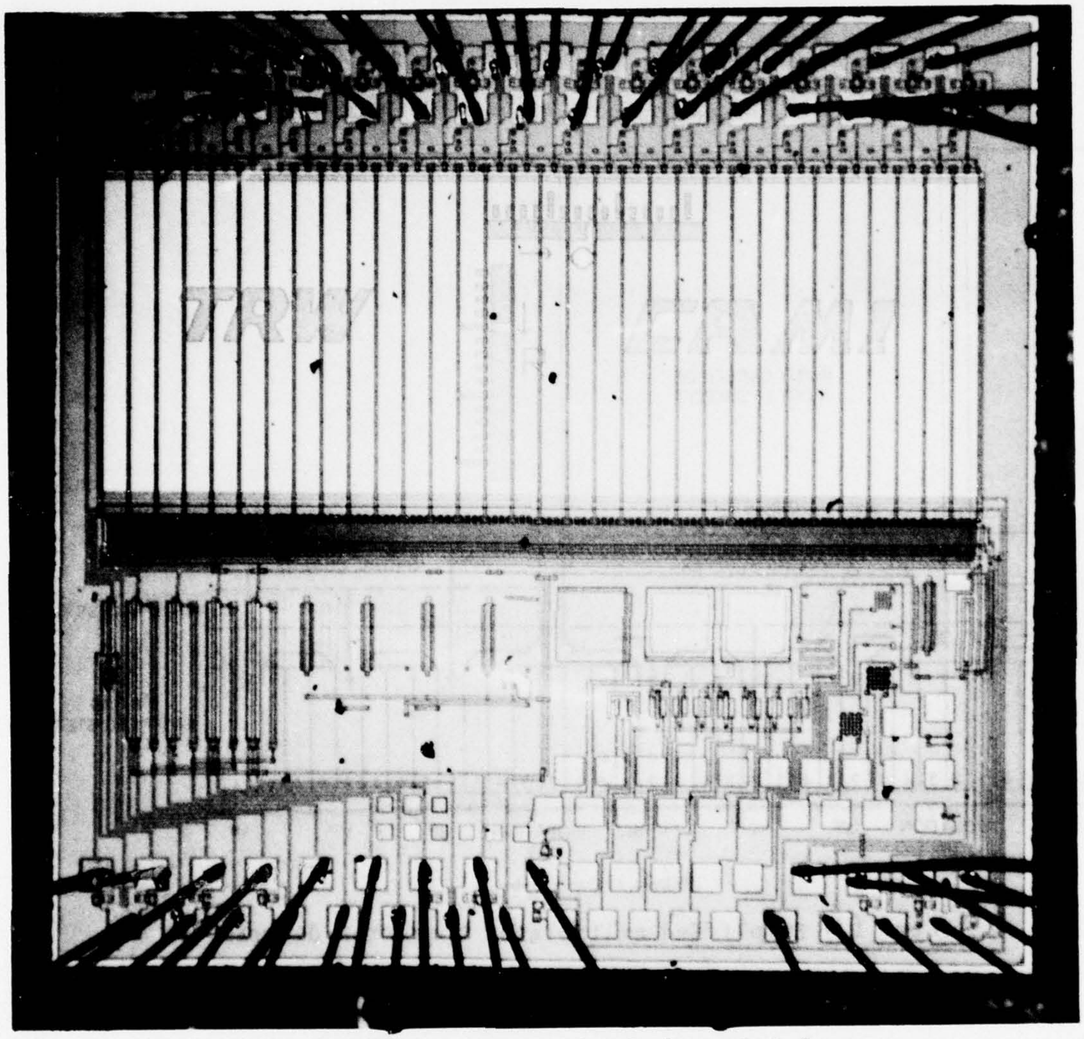

Fig. 2 - Photomicrograph of the multiplexer

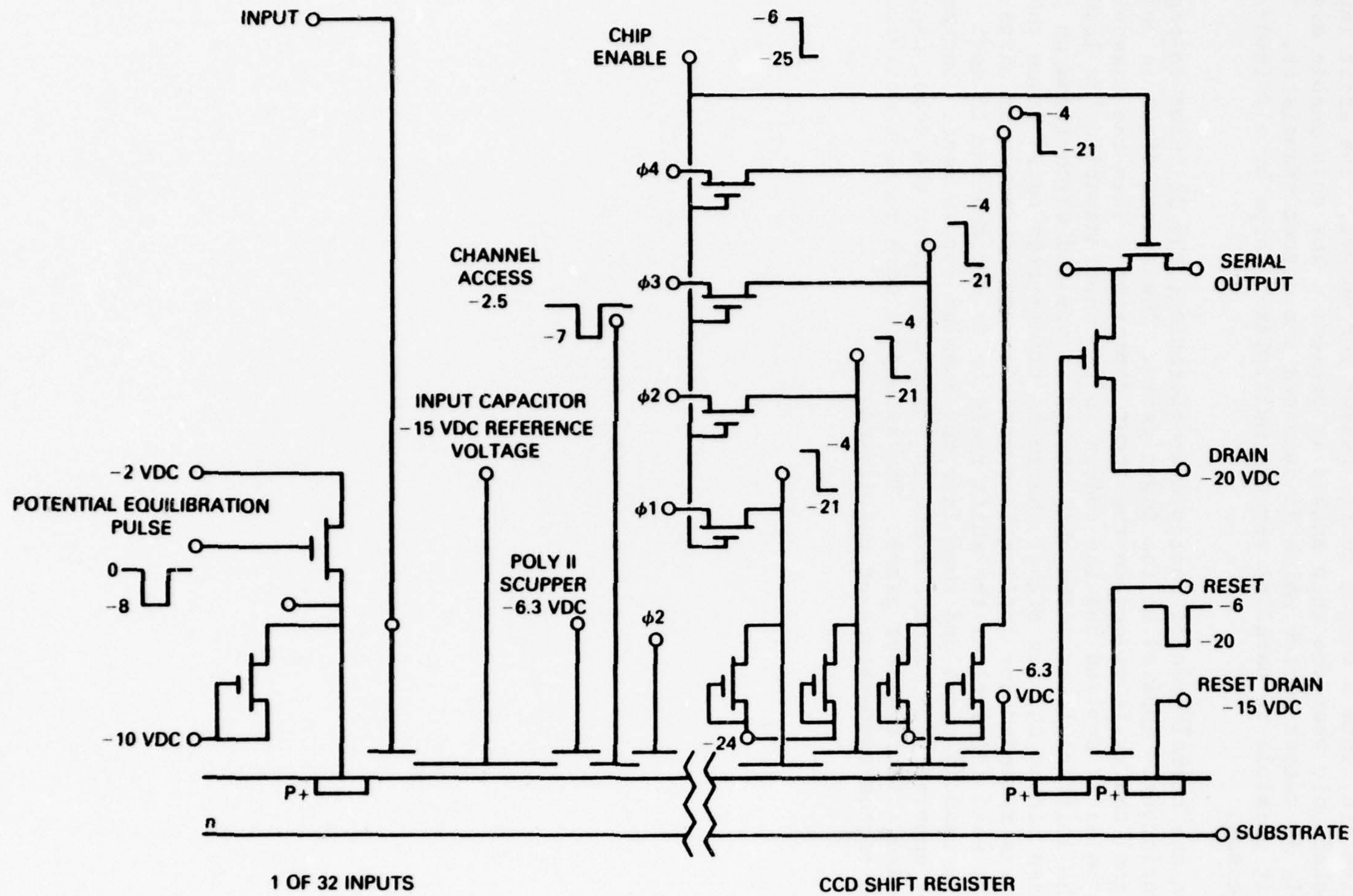

Fig. 3 - Multiplexer electrical schematic

isolation bit, into a single charge packet for output. The shift register is clocked only when the chip enable is present. The chip enable also controls an output switch which disconnects the output transistor. This makes it possible to parallel several multiplexer chips by a "wired-or" arrangement.

In the normal mode of multiplexer operation, the 32 input voltages are continuously applied to the input gates. The source diode is pulsed and signal charge is placed in the input capacitor. Then the channel access pulse is applied and the charge in the input capacitor is loaded into the shift register. The chip enable is applied which turns on the CCD phase clocks and the signal charge is transferred out. Since the device was intended for applications where several multiplexer chips would be used in parallel the shift register is clocked for 13 msec (time to read it once) and then left not enabled for 40 msec. During the not enabled time, dark current is integrated under the input capacitors and shift register gates. The amount of dark current collected depends on the temperature of the device.

III. Experimental Procedure

Figure 4 shows a block diagram of the equipment used for the low temperature noise measurements. The CCD is mounted on a cold finger which is cooled by liquid nitrogen. The temperature at the end of the cold finger is regulated by a heater. A thermocouple was mounted on the CCD and connected to a strip chart recorder for continuous monitoring of the CCD temperature.

The bias supplies and TTL level timing generators are mounted in a relay rack next to the dewar. The drivers which convert the TTL-level clock pulses and gating signals to voltage levels suitable for the CCD are mounted in a box on top of the dewar.

The output of the on-chip source follower is fed to the dc restoration circuit which removes the dc offset from the signal. Next the signal from a selected channel of the multiplexer is sampled and held. The signal is amplified with a PAR 113 low noise preamp and fed to the spectrum analyzer. the number of equivalent noise carriers is measured by plotting the output of the spectrum analyzer and integrating the noise voltage over the Nyquist bandwidth. A computer program has been written which digitizes the spectrum analyzer plots and calculates the number of equivalent noise holes by evaluating the following integral:

$$n^2 = \frac{1}{R^2} \int_0^{\frac{f_c}{2}} v^2(f) \frac{1}{G^2(f)} \, df$$

where: n = equivalent noise holes
R = responsivity of the CCD in volts/electron
V(f) = normalized noise voltage from the spectrum analyzer plots
G(f) = $\sin(\pi f t_c)/\pi f T_c$
T_c = $1/T_c$
f_c = clock frequency of the CCD

The uncertainty in the random spectral components is reduced by rms averaging many spectra. Our measurements were made by averaging 128 spectra. This results in a spectrum with a 90% confidence level of $\pm$ 0.7db which translates into $\pm$ 8% uncertainty in the number of noise charges. The multiplexer was designed to operate with a 200 msec frame time when cooled. However, we used a 40 msec frame time in the room temperature measurements to prevent excessive well filling by the dark current. In order to make direct comparison between 160°K and room temperature measurements we operated with a 40 msec frame time when cooled. A 40 msec frame time results in a signal with a 25 Hz Nyquist frequency. At this frequency a 20 sec segment of time data must be

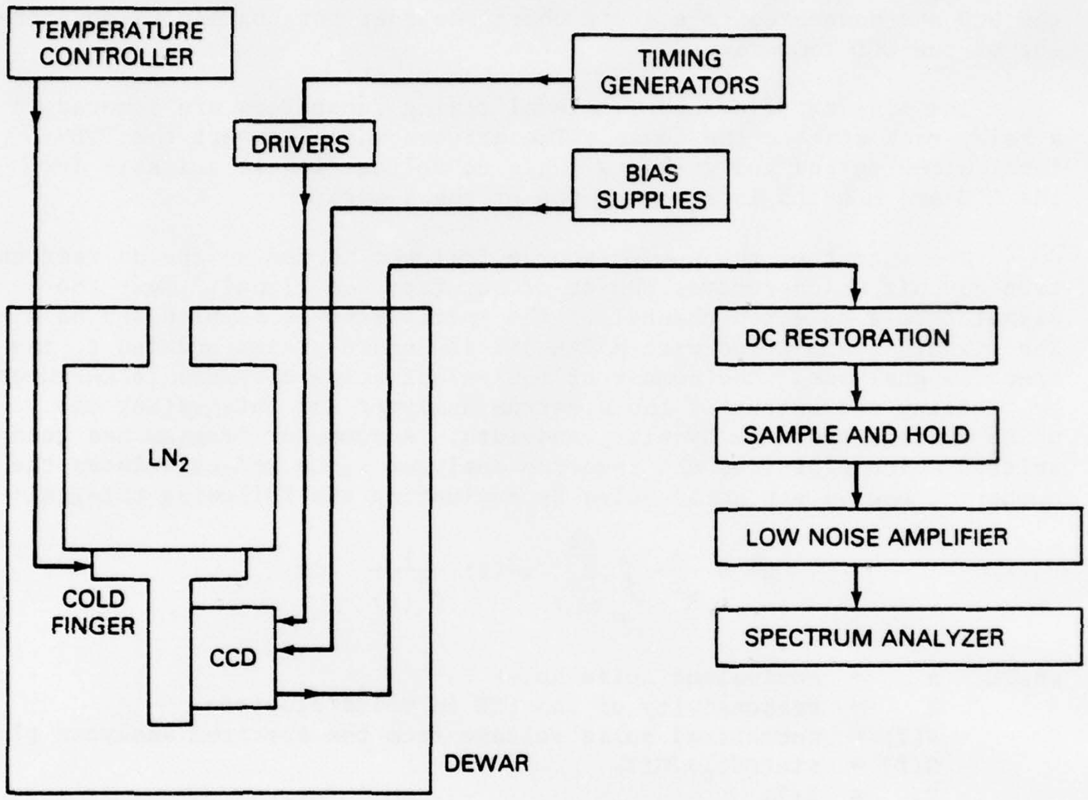

Fig. 4 - Block diagram of the low temperature noise measurement

taken to provide the information required for the spectrum analyzer to compute the Fourier Transform spectrum. It takes 20 minutes to collect and rms average 128 noise spectra. For longer frame times the data collection time increases proportionately.

Figure 5 shows a typical noise spectrum. The large spikes are due to 60 Hz ripple and clock feedthrough which have been aliased into the Nyquist bandwidth by the electrical input sampling of the CCD and by the sample and hold. These spikes thus represent a coherent signal and when the spectra are digitized for calculation of the number of equivalent noise carriers these spikes are not included.

The noise of the sample and hold circuit was measured by placing a 10K Ω metal film resistor across the input to simulate the on-chip source follower load resistance. Relating the measured noise to the number of equivalent noise charges at the input of a cooled device gives 900 noise charges. Due to responsivity variations with temperature, the sample and hold circuit establishes a noise floor of 1000 noise charges referenced to the multiplexer input in a device at room temperature.

The noise of the on-chip source follower was measured on a cooled device. The clocking direction was reversed and the channel was always accessed so that any dark current charges collected in the shift register would be collected at the input diode. Under these conditions the noise of the source follower is below the noise floor established by the sample and hold circuit.

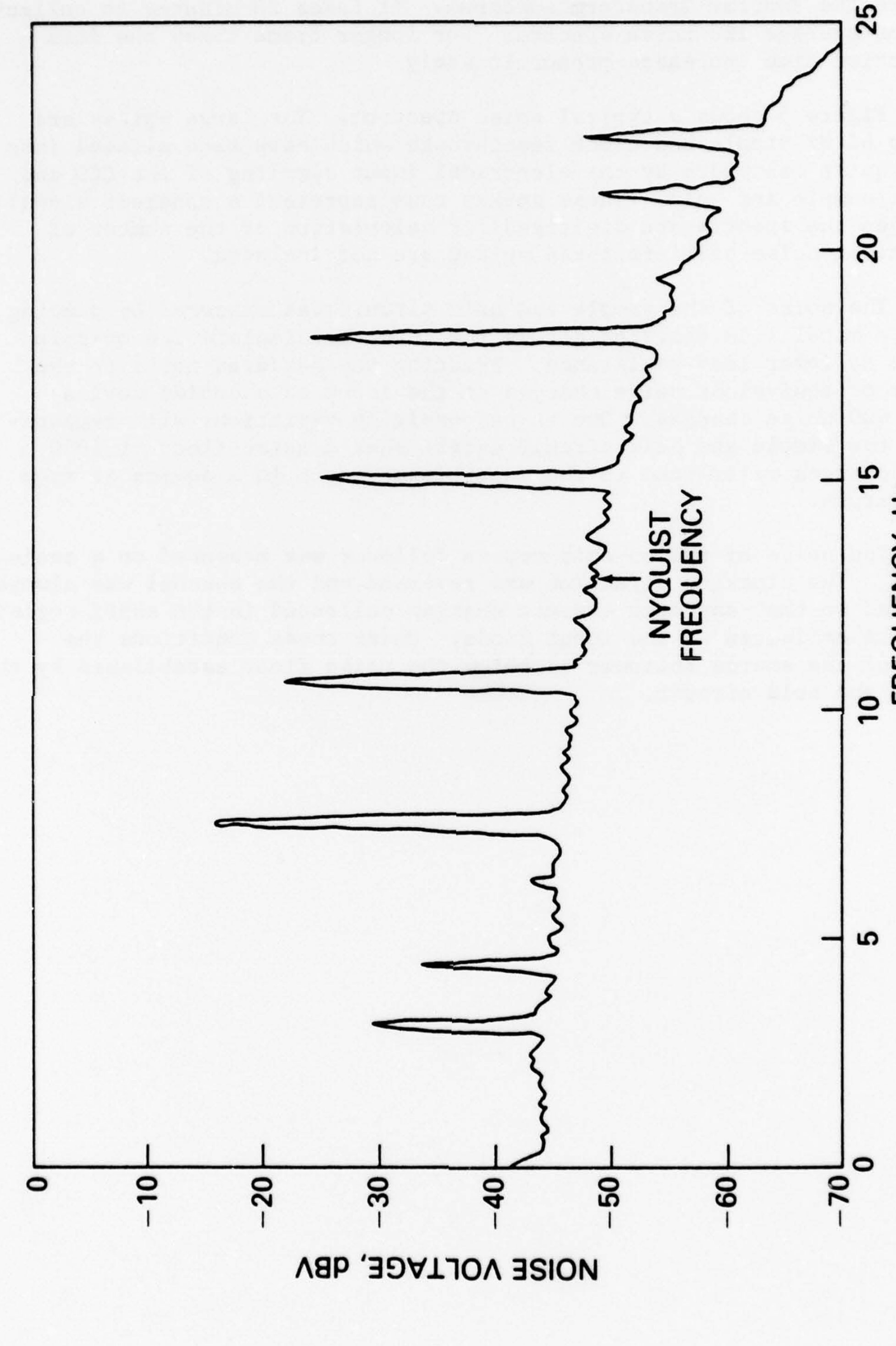

Fig. 5 - Typical noise spectrum

IV. Responsivity Measurement

The responsivity of the multiplexer is defined as the ratio of the output voltage to the number of holes in the input capacitor which give that output. This quantity provides the key to relating the measured noise voltages to the number of equivalent noise charges at the CCD input. The responsivity of the devices was measured by changing the system timing so that the shift register ran continuously. In this continuous mode of operation the reset current was measured and divided by 4 times the master clock period (since 4 CCD bits contain the information from one channel) to determine the amount of charge in each channel.

The responsivity of the multiplexer used in these experiments is given in Table 1.

Table 1

Measured Multiplexer Responsivities

Device	300°K Fullwell R	300°K Halfwell R	160°K Fullwell R	160°K Halfwell R	
CAM 934-5/7	6.57×10^{-8}	6.53×10^{-8}	7.16×10^{-8}	7.13×10^{-8}	unirradiated
CAM 934-7/6	6.51×10^{-8}	6.45×10^{-8}	7.1×10^{-8}	7.1×10^{-8}	unirradiated
CAM 934-6/9	6.63×10^{-8}	6.49×10^{-8}			unirradiated
CAM 934-6/8	5.68×10^{-8}	5.33×10^{-8}	5.9×10^{-8}	5.9×10^{-8}	irradiated to 1×10^{4} rad (Si)
CAM 934-5/8	6.3×10^{-8}	6.0×10^{-8}			

A full well is 4.3×10^{7} charge carriers on input capacitor.

Responsivity, R (volts/charge carrier) measured at the output of the sample and hold.

V. Theoretical Noise Calculations

The following noise sources were considered in the theoretical analysis: kTC noise, dark current noise and interface state trapping noise. The potential equilibration input results in a charge variance of kTC on the input capacitor. There is an unrelated kTC noise on the output due to resetting the output node. In the devices tested at room temperature, dark current is collected in the input capacitor and the shift register. When the devices are cooled to 160°K this noise source is not significant. A theoretical analysis shows that the operating node of the multiplexer greatly reduces the effect of noise generated by interface state traps.

A. kTC Noise

The kTC noise on the input is determined by the 37.3 pf input capacitance. The kTC noise on the output due to resetting the output node is determined by the 1.06 pf output node capacitance. The rms charge carrier fluctuation, N, is calculated by the formula:[4]

$$\bar{N} = \frac{1}{q}(kTC)^{1/2}$$

where: $q = 1.6 \times 10^{-19}$ coul
$k = 1.38 \times 10^{-23}$ J/°K
T = temperature in °K
C = capacitance

The calculated values are summarized below.

	Temperature	rms Noise Holes
Input kTC	300°K	2450
	160°K	1790
Output kTC	300°K	410
	160°K	300

The large input capacitance results in a large number of rms noise charge carriers, but since the rms noise voltage is calculated by the formula

$$\bar{V}_n = \left(\frac{kT}{C}\right)^{1/2}$$

the input referred noise voltage due to kTC is reduced and will be low compared to the noise of the signal source to be multiplexed.

B. Dark Current Noise

The room temperature dark current of device CAM 934-5/7 was measured. The output voltage due to the dark current collected in 40 msec integration time was 0.16 volts. Dividing by the responsivity gives the number of dark current holes.

$$0.16/(6.5\times10^{-8}) = 2.46\times10^{6} \text{ holes}$$

Multiplying this by the charge on an electron and dividing by the integration time gives the average dark current collected.

$$(2.46\times10^{6})\ (1.6\times10^{-19})/(40\times10^{-3}) = 9.84\times10^{-12} \text{ amp}$$

All 4 shift register bits contribute their dark current when the charge is summed at the output node. Thus the total dark current collection area equals the area of the input capacitor plus the area of 4 shift register bits.

$$1.25\times10^{-3} + 4(5.75\times10^{-5}) = 1.48\times10^{-3} \text{ cm}^2$$

Thus the current density is:

$$9.84\times10^{-12}/(1.48\times10^{-3}) = 6.6\times10^{-9} \text{ amp/cm}^2 \text{ at } 300^{\circ}\text{K}$$

Because the dark current is proportional to $T^{3/2}\ e^{-\frac{1.1ev}{2kT}}$, the dark current drops to an undetectable value when the device is cooled to 160°K.[5]

Taking a room temperature dark current value of 6.6×10^{-9} amp/cm^2, the charge collected in one bit of the CCD shift register in 40 msec is

$$(6.6\times10^{-9})\ (5.75\times10^{-5}\text{cm}^2)\ (40\times10^{-3} \text{ sec})/(1.6\times10^{-19}) = 95\times10^{3} \text{ holes}$$

The shot noise on this dark current is 310 rms holes. When the 4 bits are added at the CCD output the noise is added in quadrature to give a total of 620 rms holes.

The charge collected on the input capacitor is

$$(6.6\times10^{-9})\ (1.25\times10^{-3}\text{cm}^2)\ (40\times10^{-3} \text{ sec})/(1.6\times10^{-19}) = 2.06\times10^{6} \text{ holes}$$

The shot noise on this dark current is 1440 rms holes.

C. Interface State Trapping Noise

Since the CCD shift register did not have an input diode, the transfer inefficiency of the multiplexer was derived from crosstalk measurements at room temperature and found to be 5×10^{-4}. This information may be used to calculate the number of surface states with the formula.[6]

$$\epsilon = \frac{qkTN_{ss}}{C_{ox}\ V_s}\ \ln\ (P+1)$$

where ϵ = transfer inefficiency, 5×10^{-4}
q = 1.6×10^{-19} coul
k = 8.62×10^{-5} ev/°K
T = 300°K
N_{ss} = surface state density
C_{ox} = 3.544×10^{-8} F/cm^2 for 1000 Å gate oxide
V_s = voltage swing on transfer gates, 13v
p = Number of Phases, 4

Substituting into the formula gives

$$N_{ss} = 3.5\times10^{10}/\text{ev cm}^2$$

If the CCD shift register had an independent input diode, the interface state density of the shift register could be determined by the periodic pulse technique.[7] Due to the fat zero used in the crosstalk measurements the transfer inefficiency we have measured is smaller than that which would be obtained with the periodic pulse technique. Hence, the value we have calculated for N_{ss} is smaller than the value which would be derived from periodic pulse measurements. For this reason in calculations we take $N_{ss} = 5\times10^{10}$/ev cm^2.

A theoretical analysis shows that the mode of operation of the multiplexer greatly reduces the effect of interface state trapping noise. In order to increase the dynamic range of the multiplexer, the charge on the input capacitor is divided among 3 bits of the CCD shift register and reassembled at the output node. This integration has the effect of a low pass filter which removes a large portion of the transfer noise.

From equation 22 in reference 1 we see that the spectral density of the noise introduced by a transfer is

$$S_i(f) = 4n < q^2 >_{TP} f_o |g(f)|^2 (1-\cos \frac{2\pi f}{f_o}) \text{ watts/Hz} \qquad (1)$$

where: n = number of transfers

$\langle q^2 \rangle_{TP}$ = variance of the charge for a single transfer

f_o = clock frequency of the shift register

$|g(f)|^2$ = magnitude of output amplifier transfer function

We can calculate the total noise power over the Nyquist bandwidth by

$$\text{Noise}^2 = \frac{2}{f_o} \int_o^{\frac{f_o}{2}} S_i(f)df \text{ watts} \qquad (2)$$

If we consider noise just from the shift register alone and exclude the output stage of the multiplexer then $|g(f)|^2 = 1$ and we substitute into the integral

$$\text{Noise}^2 = \frac{2}{f_o} \int_o^{\frac{f_o}{2}} 4n \langle q^2 \rangle_{TP} f_o \left(1-\cos \frac{2\pi f}{f_o}\right) df$$

$$\text{Noise}^2 = \frac{2}{f_o} 4n \langle q^2 \rangle_{TP} f_o \int_o^{\frac{f_o}{2}} \left(1-\cos \frac{2\pi f}{f_o}\right) df$$

$$\text{Noise}^2 = \frac{2}{f_o} 4n \langle q^2 \rangle_{TP} f_o \left\{ \frac{f_o}{2} \right\}$$

$$\text{Noise}^2 = 4n \langle q^2 \rangle_{TP} f_o \text{ watts at shift register output} \qquad (3)$$

When the multiplexer is operating, the output source follower is reset once per 4 CCD bits. This means that the 3 bits of signal information for each channel and the isolation bit are integrated on the input capacitor of the source follower with a time constant, T_c, equal to the time between reset pulses. Thus in the spectral density formula (1) we can let $g(f)$ be the transfer function of an integrator. Thus:

$$|g(f)|^2 = \frac{1}{4\pi^2 f^2 T_c^2}$$

Now substituting into equation (2), the integral for noise power we get

$$\text{Noise}^2 = \frac{2}{f_o}\int_o^{\frac{f_o}{2}} 4n <q^2>_{TP} f_o \frac{1}{4\pi^2 f^2 T_c^2} (1-\cos\frac{2\pi f}{f_o}) \, df$$

$$= \frac{2}{f_o} 4n <q^2>_{TP} f_o \frac{1}{Tc^2}\int_o^{\frac{f_o}{2}} \frac{1}{4\pi^2 f^2} (1-\cos\frac{2\pi f}{f_o}) \, df$$

$$\text{Noise}^2 = 4n <q^2>_{TP} f_o [\frac{1}{T_c^2} \quad \frac{0.38684}{f_o^2}] \text{ watts with integrator} \qquad (4)$$

The CCD shift register was operated at a clock frequency of 400 kHz and the time constant for the integration is 10μsec, the time required to transfer 4 CCD bits into the output node. Thus we can evaluate the term of the noise expression which represents the effect of the integrator on the noise

$$[\frac{1}{Tc^2} \quad \frac{0.38684}{f_o^2}] = 0.024$$

Thus we see by comparing equations (3) and (4), that combining 4 bits at the output of the shift register results in a significant reduction in the transfer noise due to surface states, i.e., 2.5% of the nonintegrated value.

The fast interface state noise may be calculated with the formula:[4]

$$\text{Noise}^2 = 2N_T \, kT \, N_{ss} \, A_g \, \ln^2 \, (\text{rms holes})^2 \qquad (5)$$

where: N_T = number of transfers
k = Boltzmann's constant, 8.62×10^{-5} ev/°K
A_g = area of transfer gate, 5.75×10^{-5} cm^2
N_{ss} = surface state density
T = temperature, °K

Since the charge on the input capacitor is divided among 3 bits of the 4 phase CCD shift register, the output of channel 2 consists of 3 charge packets which have been transferred 20, 24 and 28 times respectively. The output of channel 31 consists of 3 charge packets which have been transferred 484, 488 and 492 times respectively.

The formula for the noise spectral density (4) can be converted from noise power to noise charge per packet by dividing by f_o.

$$\text{Noise}^2 = 4n <q^2>_{TP} (0.024) \, (\text{rms holes})^2 \qquad (6)$$

Comparing the formulas for fast interface state noise with the spectral calculation, equations (5) and (6), we see

$$4n \langle q^2 \rangle_{TP} = 2\ N_T\ kT\ N_{ss}\ Ag\ \ln 2$$

which for a surface state density of $N_{ss} = 5\times10^{10}/\text{ev cm}^2$, a gate area of $5.75\times10^{-5}\ \text{cm}^2$ and a temperature of 300°K reduces to:

$$4 \langle q^2 \rangle_{TP} = 103068$$

Now substituting into the spectral noise equation (6) gives:

$$\begin{aligned} \text{Noise}^2 &= 4 \langle q^2 \rangle_{TP}\ N_T\ (0.024) \\ &= 2474\ N_T\ \text{holes}^2 \end{aligned}$$

Using typical values for N_T we find:

Channel	N_T	Noise Charge
2	24	245 rms holes
31	488	1100 rms holes

In addition to the transfers in the shift register there is transfer noise due to the transfer from the input capacitor to the shift register. That noise may be calculated from the formula.

$$\text{Noise}^2 = 2kT\ N_{ss}\ Ag\ \ln 2$$

where: Ag = area of input capacitor, $1.25\times10^{-3}\ \text{cm}^2$
N_{ss} = $5\times10^{10}/\text{ev cm}^2$

Thus, the transfer noise from the input capacitor is 1500 rms holes. Adding the noise from the shift register and the input capacitor in quadrature gives interface state trapping noises of:

channel 2	1520 rms holes
channel 31	1860 rms holes

Thus when the noise of the transfer from the input capacitor is included there is only a small difference in interface state trapping noise between channel 2 and channel 31.

Performing the calculations again for 160°K and $N_{ss} = 5 \times 10^{10}$ we find:

channel 2	178	rms holes
channel 31	800	rms holes
Input Capacitor	1090	rms holes

Adding the noise from the shift register and the input capacitor in quadrature gives a total interface state trapping noise for the cooled devices of:

channel 2	1100	rms holes
channel 31	1350	rms holes

D. Summary of Calculated Noise Levels

We can now calculate the expected noise levels for the multiplexer and the results are summarized in Table 2.

Table 2

Calculated Noise Levels for the TRW Surface Channel Multiplexer

Output Signal Magnitude	Potential Equilibration Input 300°K 0v	Potential Equilibration Input 300°K 1v	Potential Equilibration Input 160°K 0v	Potential Equilibration Input 160°K 1v	Biased for Optical Input 300°K 0v	Biased for Optical Input 300°K 1v	Biased for Optical Input 160°K 0v	Biased for Optical Input 160°K 1v	Summary of Theoretical Values 300°K	Summary of Theoretical Values 160°K
Input kTC		2450		1790					2450	1790
Output kTC	410	410	300	300	410	410	300	300	410	300
Dark Current, Shift Register	620	620			620	620			620	
Dark Current, Input Capacitor					1440	1440			1440	
Trapping Channel 2		245		178		245		178	245	178
Channel 31									1100	800
Trapping Input Capacitor		1500		1090		1500		1090	1500	1090
Sample and Hold	1000	1000	900	900	1000	1000	900	900	1000	900
Quadrature Sum for Channel 2	1250	3150	950	2300	1900	2450		1460		
Optical Shot Noise						3950		3750		
Quadrature Sum						4650		4000		

Noise values in number of rms holes referenced to the multiplexer input.

VI. Noise Measurements

A. Optical Injection Measurements

Since the noise expected from optically generated charge carriers is easily calculated, we checked the calibration of the noise measuring system by illuminating the device and measuring the noise. The input to the device was operated in the dynamic input mode rather than in the potential equilibration node because most of the optically generated charges are collected under the input capacitor. In the potential equilibration node with zero electrical input, the input gate is biased so that the optically generated carriers are all drained out into the input diode. In the dynamic input node with zero electrical input, the input gate is biased so that there is no connection between the input diode and the input capacitor. Thus the optically generated charges which collect under the input capacitor are only removed by the channel access pulse transferring them into the shift register. At room temperature a significant amount of dark current is collected. The shot noise on this dark current causes the noise levels on the dynamic input with no electrically introduced charge to be larger than the noise levels on the potential equilibration input with no electrically introduced charge.

The no electrical input condition was used to measure the noise due to dark current. Then the device was optically illuminated and the magnitude of the electrical signal which resulted was recorded along with the measured number of noise charges. The theoretically expected value of shot noise was found by dividing the signal magnitude by the responsivity to determine the number of charge carriers in each channel. The rms number of shot noise holes is just the square root of the number of charge carriers. Table 3 presents data taken on device CAM ?34-7/6 at 300°K and 160°K. We have assumed that interface state trapping is dependent on the amount of signal in the well[8] and that in the unilluminated case it is negligible and that in the case of an optical signal it corresponds to the theoretical value we calculated for $N_{ss} = 5\times10^{10}$. The noise measured in the unilluminated case is due to output kTC, dark current, and sample and hold system noise. The optical injection experiments were performed on channel ?. The measured optical shot noise was determined by subtracting in quadrature the theoretical interface state trapping noise and the noise measured in the unilluminated condition from the measured noise charge. The contribution from interface state trapping was 1520 rms noise carriers at 300°K and 1104 rms noise carriers at 160°K. From the table we see that the measured optical shot noise is 2% to 10% higher than the theoretical values as others have observed.[9]

B. kTC Noise

Table 4. Compares the measured input noise to the theoretical kTC noise for a typical device at 300°K and 160°K. As in the optical injection experiment we have assumed that interface state trapping is dependent on the amount of signal in the well and that is is negligible with no electrical

Table 3

Optical Injection Noise Measurements

Temp	Signal	Measured rms Noise Carriers	Measured Optical Shot Noise	Optical Shot Theory	Difference
300°K	unilluminated	1840			
	0.54v	3900	3050	2900	+5%
	1.04v	5000	4400	4000	+10%
	1.54v	5800	5300	4900	+8%
	2.06v	6500	6050	5700	+6%
	2.5[illegible]v	6900	6450	6300	+2%
160°K	unilluminated	980			
	0.50v	3300	2950	2700	+9%
	1.05v	4400	4150	3800	+9%
	1.56v	5100	4900	4700	+4%

Device CAM 934-7/6, Channel No. 2, $N_{ss} = 5\times10^{10}$/ev cm^2

Table 4

Comparison of Measured Input Noise to Theoretical kTC Noise

Temp	Signal (volts)	Measured rms Noise (carriers)	Measured Electrical Imput Noise (carriers)	Theoretical kTC Noise (carriers)	Times kTC Noise
300°K	0	1400			
	0.49	3300	2550	2450	1.04
	1.00	4100	3550	2450	1.4
	1.49	4300	3750	2450	1.5
	2.00	4300	3750	2450	1.5
	2.50	4400	3900	2450	1.6
	2.00	4450	3950	2450	1.6
160°K	0	1000			
	0.98	3600	3300	1800	1.8
	0.98	3800	3500	1800	1.9
	1.00	3750	3450	1800	1.9
	1.01	3450	3100	1800	1.7

Device CAM 934-7/6, Channel No. 16, Potential Equilibration Input signal and that, with an electrical signal, it corresponds to the theoretical value calculated for $N_{ss} = 5\times10^{10}$/ev cm^2. The noise measured in the zero signal, or empty well case, is due to output kTC, dark current, and sample and hold system noise. The measured input kTC noise was determined by subtracting in quadrature the theoretical interface state trapping noise and the noise measured in the zero electrical signal condition from the measured noise charge. The contribution from interface state trapping was 1520 rms noise carriers at 300°K and 1100 rms noise carriers at 160°K. The data shows that the potential equilibration input gives 1 to 1.6 times kTC noise at 300°K. This is comparable to the noise performance reported by others.[9] At 160°K the potential equilibration input gives 1.7 to 1.9 times kTC noise.

C. Interface State Trapping Noise

The noise in device CAM 934-5/7 was measured as a function of channel number at room temperature and the squared number of noise electrons has been plotted in Figure 6. The upper row of data points was taken with a 1 volt output from the multiplexer. The lower set of data points was taken in the empty well condition. In the empty well case no interface state trapping noise is seen as expected.[8] In the case of the 1 volt output there is a trend toward greater noise in the higher numbered channels as is evident from the figure. However, the trend is small and represents a difference between channels 2 and 31 of about 1100 rms noise charges due to interface state trapping. This indicates a surface state density of approximately 1×10^{11}/ev cm^2 when compared to the theoretical calculations.

D. Fixed Pattern Noise

The fixed pattern noise was measured by applying the same input voltage to all 32 channels and measuring the output voltages. For example, in the case of a 1/2 well signal in device number CAM 934-6/9, the mean output voltage was 1.44 volts and the standard deviation was 0.19 volts. This corresponds to an input referenced fixed pattern noise of 2.9×10^6 rms charge carriers and an input referenced noise voltage of 1.2×10^{-2} volts. 25% of the channels fall outside the 1 σ limits and the absolute limits on the output signal were +37% to -20% from the mean.

E. Irradiated Device

Multiplexer CAM 934-6/8 was irradiated to a dose of 1×10^4 rad(Si) at 300°K before the noise measurements were made. The irradiation resulted in increased dark current and higher overall noise levels as expected. Typical noise data obtained with this device is shown in Table 5. The measured electrical input noise was calculated by quadrature subtraction of the noise carriers measured with zero electrical input from the noise carriers measured

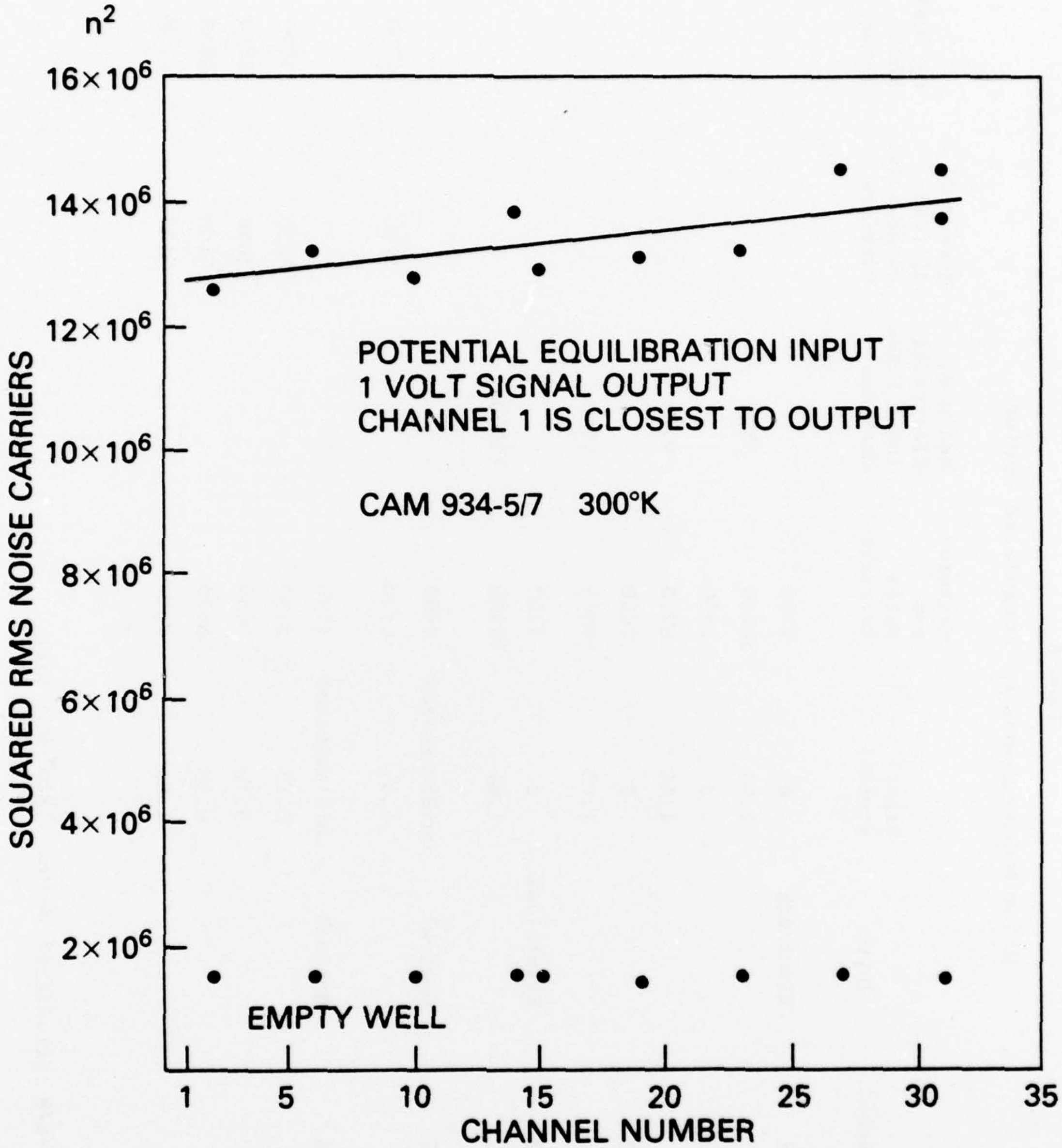

Fig. 6 - Interface state trapping noise

Table 5

Noise Measurements on Irradiated Device

Temperature	Channel	Input	Signal (volts)	Measured rms Noise Carriers	Measured Electrical Input Noise Carriers	Measured Optical Input Noise Carriers	Optical Shot Theory
300°K	2	Electrical	0	2600			
			1.00	10200	9850		
	16		0	2550			
			1.00	9900	9550		
	31		0	2400			
			1.00	9900	9600		
160°K	2	Electrical	0	1250			
			1.04	10100	10000		
300°K	2	Optical	unilluminated	3900			
			1.05	6900		5700	4200
160°K	2	Optical	unilluminated	1190			
			0.15	3100		2850	1590
			0.30	4050		3850	2250
			0.59	5300		5150	3150
			1.05	6500		6400	4200

Device CAM 934-6/8 Irradiated Device 1×10^4 Rad (Si) with an electrical input. The measured optical shot noise was calculated by quadrature subtraction of the noise carriers measured in the unilluminated case from the noise carriers measured with an optical input. No correction has been made for interface state trapping noise. It is well known that ionizing radiation increases the interface state density in MOS structures. Several workers have seen an increase in charge transfer inefficiency in surface channel CCD's after irradiation which they attribute to increased interface state trapping. Most of the increase in noise in the irradiated device is probably due to the increase in interface state traps. At 300°K the irradiated device is 1.8 times noisier than unirradiated devices with an empty well input and 2.5 times noisier with a 1 volt electrical input. At 160°K the irradiated device is 1.3 times noisier than unirradiated devices with an empty well input and 2.7 times noisier with a 1 volt electrical input. The responsivity of the cooled device was estimated by assuming the room temperature responsivity changed with temperature in the same ratio as for the unirradiated devices. The value of 5.9×10^{-8} volts/hole cooled was used for calculations.

F. Summary of Theoretical and Experimental Results

Table 6 is a summary of the theoretical and observed noise charge referenced to the multiplexer input. The agreement between theory and experiment for the unirradiated devices is quite good. Irradiation of a device resulted in additional noise. The effects of radiation have not been treated by the theoretical analysis. The noise charges have been converted to a noise voltage referenced to the input by the relation $Q=CV$ where $C = 37.3$pf, the capacitance of the Input Capacitor, and this data is also given in the Table. The design goal for these devices was an input referenced noise voltage of 15μV (3500 rms noise holes). Cooled to 160°K we measured an input referenced noise voltage of 16μV (3750 rms noise holes) in the unirradiated devices. The input referenced noise voltage measured at 160°K of a device which had received 1×10^4 rad (Si) at 300°K was 43μV.

Table 6

Summary of Theoretical and Experimental Results

Input	Signal volts	Temp °K	Theory rms Noise Carriers	Theory μV	CAM 934-5/7 rms Noise Carriers	CAM 934-5/7 μV	CAM 934-7/6 rms Noise Carriers	CAM 934-7/6 μV	CAM 934-6/8 Irradiated rms Noise Carriers	CAM 934-6/8 Irradiated μV
Potential	Empty	300	1250	5.4	1200	5.1	1300	5.6	2550	11
Equilibration	1.0	300	3150	13	3700	16	4050	17	9900	42
	Empty	160	950	4.1	980	4.2	970	4.2	1250	5.4
	1.0	160	2300	9.9	3700	16	3750	16	10100	43
	Unilluminated	300	1900	8.2			1840	7.9	3900	17
Biased for	1.04	300	4700	20			5000	21		
Optical	Unilluminated	160	950	4.1			980	4.2	1190	5.1
Input	1.05	160	4050	17			4400	19		

All noise values are referenced to the multiplexer input.
The theoretical data is derived from Table 2.
A 1 volt output signal is approximately 1/3 full well.

VII. Conclusion

This report describes analyses and experiments performed to characterize the noise of a p-surface channel CCD multiplexer made by TRW. The noise sources considered were:

- kTC Noise
- Dark Current Noise
- Interface State Trapping Noise
- Fixed Pattern Noise
- Output Amplifier Noise

The overall design goal for these devices was a noise voltage of 15μV (3500 rms noise holes) referenced to the input. Cooled to 160^{o}K, we measured a noise voltage of 16μV (3750 rms noise holes) referenced to the input. The noise measured on a device irradiated to 1×10^4 rad (Si) under bias was approximately twice the value for an unirradiated device. The dominant noise source in the unirradiated devices was input kTC followed by interface state trapping noise.

kTC Noise

Our measurements show 1 to 2 times theoretical kTC noise due to the potential equilibration input. Or an input referenced noise voltage of 13μV (3100 rms noise holes) at 160^{o}K.

Dark Current Noise

Dark current is a contributing factor only in the room temperature tests. At 160^{o}K the dark current was negligible for the frame times expected in the application of this device.

Interface State Trapping Noise

Carrying the signal in 3 CCD bits to increase the dynamic range of the multiplexer has the added advantage of reducing the interface state trapping noise. The main contribution to interface state trapping noise is the transfer of signal charge from the input capacitor to the CCD shift register. This noise source contributes an input referenced noise voltage of 4.7μV (1100 rms noise holes) at 160^{o}K.

Fixed Pattern Noise

The fixed pattern noise in these devices was relatively large. A uniform input voltage gave a mean output voltage of 1.44 volts with a standard deviation of 0.19 volts. This corresponds to a noise charge of 2.9×10^{-6} rms carriers for an input referenced noise voltage of 1.2×10^{-2} volts.

Output Amplifier Noise

The noise in the output amplifier was below the noise floor of the sample and hold in the measuring system.

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